Cost-effective solutions for river water quality improvement in Eindhoven supported by sewer-WWTP-river integrated modeling

L. Benedetti[1], J. Langeveld[2], J.J.M. de Klein[3], I. Nopens[4], A. van Nieuwenhuijzen[5], T. Flameling[6], O. van Zanten[6] and S. Weijers[6]

[1] Waterways srl, Via del Ferrone 88, 50023 Impruneta (FI), Italy
[2] Delft University of Technology, Stevinweg 1, 2624 CN Delft, the Netherlands
[3] Aquatic Ecology and Waterquality Management Group, Wageningen University and Research centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[4] BIOMATH, Department of Mathematical Modelling, Statistics and Bioinformatics, Ghent University, Coupure Links 653, 9000 Gent, Belgium
[5] Witteveen+Bos, PO Box 233, NL-7400 AE Deventer, The Netherlands
[6] Waterschap De Dommel, 5280 Boxtel, The Netherlands

ABSTRACT

The KALLISTO project aims at finding cost-efficient sets of measures to meet the Water Framework Directive (WFD) derived goals for the Dommel River (The Netherlands). An integrated model, which showed to be a powerful tool to analyze the interactions within the integrated urban wastewater system, was first used to evaluate measures in the urban wastewater system using the existing infrastructure and new RTC strategies. As the latter resulted to be beneficial but not sufficient, this contribution investigates the potential benefit of additional infrastructural measures to improve the system cost-effectively and have it meet the WFD goals and this using an integrated perspective. Finally, a scenario analysis was conducted to investigate the impact of uncertainty in the main model assumptions and model parameters on the performance robustness of the selected set of measures. Apart from some extreme worst-case scenarios, the proposed set of measures turned out to be sufficiently robust and significantly more cost-effective compared to using a more traditional non-integrated approach.

KEYWORDS: Scenario analysis, WWTP modeling, Monte Carlo simulation, waste water treatment, uncertainty analysis

INTRODUCTION

The Dommel is a relatively small and sensitive river flowing through the city of Eindhoven (The Netherlands) from the Belgian boarder in the South into the river Maas in the North, receiving discharges from the 750,000 PE wastewater treatment plant (WWTP) of Eindhoven and over 200 combined sewer overflows (CSOs) from 10 municipalities. In summer time, the WWTP effluent covers up to 50% of the base flow of the Dommel River, which does not yet meet the requirements of the European Union Water Framework Directive (WFD). Waterschap De Dommel, the utility responsible for this compliance, has launched 2 years ago the comprehensive research project KALLISTO in order to find the most cost-effective set of measures for meeting the WFD requirements of the Dommel River by an integrated strategy for the urban wastewater system. The focus is on protection of the aquatic environment in the Dommel River from oxygen dips and ammonia peaks caused by the combined discharges of the biologically treated WWTP effluent, a rain water buffer settling tank (RBT) at the WWTP and the over 200 CSOs within the Eindhoven area. In addition, the level of nutrients and suspended solids in the Dommel River has to be reduced to allow compliance with the maximum summer average concentration levels in the river of 0.15 mg Ptotal/l and 4 mg Ntotal/l and to control solids and sludge accumulation in the river.

The traditional approach applied in Europe before the introduction of the WFD in 2000, of defining nation-wide emission standards and efficiency requirements for CSOs or and WWTPs, may result in ineffective and inefficient WFD requirements, as the sensitivity of the receiving waters combined with the loads from the WWTPs and the CSOs locally determines the required efforts. In the last decade, water authorities gradually shifted their approach towards integrated urban water management, supported by research advances on: (1) the interactions between the sewer system, WWTP and receiving waters (Rauch and Harremoës, 1996; Langeveld, 2004); (2) the relation between ecological status and physical-chemical status of receiving waters (e.g. Struijs *et al.*, 2011) and (3) on the availability of software that allows using integrated models (Benedetti *et. al*, 2009). In this work a previously developed integrated model (Langeveld *et al.*, submitted) was used. The specific objectives of this contribution were the identification of integrated solutions that include RTC and capital-intensive measures.

METHODS

Scenarios

The optimization of the integrated urban water system Eindhoven has been done with a step-wise process (see Figure 1). In this paper steps 3b and 3c are discussed. First a list of measures was defined, which comprises both traditional measures such as increase of CSO storage capacity and new measures investigated at pilot scale in the project, such as the treatment of wet-weather flows with a dissolved air flotation (DAF) unit, fine screens or lamella settlers.

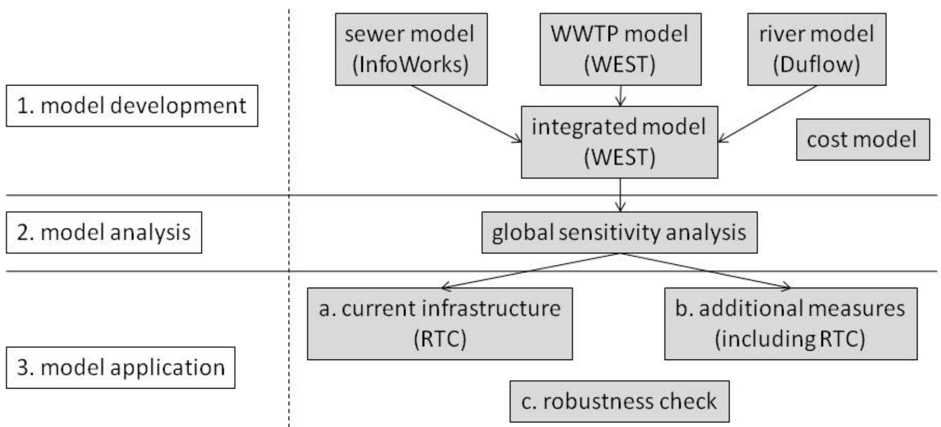

Figure 1. Step-wise process for integrated modeling in the Kallisto project.

The total list of measures evaluated is summarised in Table 1. Each distinct scenario that was evaluated is composed of a combination of measures from Table 1. The scenarios are outlined in more detail in the results section. During optimisation with respect to effectiveness, these measures are sized iteratively until all evaluation criteria for river water quality are met.

Cost model

To be able to determine the specific costs of the different scenarios, a cost model was developed. Within this model, all required measures related to a scenario (clearly defined with respect to the measures and their required sizing to meet the envisioned river water quality) are basically designed and equipped with investment and operational costs based on variable cost functions. From these cost functions the CAPEX and OPEX are calculated based on linear depreciation, allowing to select the scenario that meets the requirements at lowest costs of ownership.

Uncertainty analysis / robustness check

To check the robustness of the eventual identified preferred cost-effective scenario to the assumptions made, an uncertainty analysis was conducted. This was done by evaluating 10-y simulations of worst-case scenarios regarding the important assumptions in model inputs and parameters (mostly river model parameters and sewer inputs). For each simulation, only one assumption was varied from the default values of the selected upgrade scenario to observe the individual impact. Parameters that can be more or less easily measured/controlled, like PST and DAF performance, were not considered as in a long-term evaluation we can assume that those parameters are known and within control authority, even if they could exhibit short-term variability (which should not last long due to an appropriate operator action).

Table 1. List of measures evaluated in the different tested scenarios.

Measure	Field of application/objective
RTC in the sewer system	Minimisation of DO dips and/or NH_4 peaks in river by optimizing the use of the available system capacity
DAF, fine screens, lamella settler, fuzzy filter	Pre-treatment of wastewater during DWF Treatment of WWF
CSO storage (storm water settling tanks, green storage)	Reduction of CSO emissions
Dry buffers at WWTP inlet	Reduction of influent peak load in storm events to minimise NH_4 peaks in WWTP effluent
River aeration	Reduce DO dips in river
Effluent aeration	Reduce DO dips in river due to low WWTP effluent DO
Additional aeration capacity and volume in WWTP, increase of MLSS concentration	Enhance nitrification process to reduce NH_4 peak concentrations in river
Equalisation pond/wetland	Equalisation of WWTP effluent to reduce NH_4 peak concentrations to the river
Increase interceptor/pumping capacities	Reduce DO dips in river
Increase hydraulic capacity of biological treatment at WWTP	reduce NH_4 peaks and DO dips in river
Sand filter for treatment of WWTP effluent	Reduce N_{total} and P_{total} in effluent

RESULTS

Scenario description and evaluation

Some measures aim at a specific water quality issue, i.e. (1) DO depletion, (2) ammonia toxicity, and (3) summer average nutrients level, whereas others affect more than one issue. For DO depletion, two groups of measures can be distinguished: (a) measures that reduce the CSO emission such as additional storage and (b) river and effluent aeration. It was found previously that RTC in the sewer system showed to be effective as well, but not capable of fully solving the DO problem (Langeveld *et al.*, submitted). The DO depletion at lower protection level can be prevented by the construction of additional storage capacity in order to prevent CSOs. This requires in this case a total of 200,000 m^3 additional storage capacity at the CSOs in Eindhoven (equivalent to 10 mm calculated over the impervious area of 2000 ha of the city of Eindhoven) divided over 10 separate locations. Another way to deal with DO depletion effectively is to apply river aeration (Alp and Melching, 2011). This would require 5 aeration stations in the Dommel River with a total capacity of 1,460 kg O_2/day. Table 2 summarizes the investment costs, capital costs and operational costs of additional storage and river aeration. River aeration clearly is beneficial with respect to cost effectiveness.

Table 2. Costs of measures to reduce DO depletion and achieve basic DO levels.

Measure	Investment costs	CAPEX	OPEX
Additional storage	€ 79,800,000	€ 3,830,000	€ 79,500
River aeration	€ 1,040,000	€ 96,700	€ 117,000

The low level of required summer averages of Ntotal and Ptotal can be achieved by a combination of measures at the WWTP, incorporating application of DAF as pre-treatment, additional C-dosage, an increase of MLSS requiring additional capacity of the secondary clarifiers by increasing the depth, and an increase of aeration capacity. A simpler measure would be to construct a sand filter for effluent filtration aiming at reducing nitrate and Ptotal.

The reduction of ammonia peaks in the Dommel River proved to be the most difficult challenge. Three scenarios were tested to solve the peak NH_4 concentration problem (see Tables 3 and 4):

A. create additional dry storage capacity at the WWTP to reduce the peak loads in the WWTP influent;
B. create equalisation of WWTP effluent in a wetland;
C. increase nitrification capacity at the WWTP.

The additional dry storage capacity of 300,000 m^3 (scenario A) had to be accompanied by some additional measures in order to be able to meet the requirements for NH_4 in the River Dommel: RTC aiming at minimising NH_4 peaks, an increase of aeration capacity at the WWTP and a 20% increase of the MLSS concentration. The equalisation of WWTP effluent with a wetland (scenario B) was also not sufficient to meet the NH_4 requirements and in this case additional aeration capacity at the WWTP proved to be necessary to achieve the goal. The increase of nitrification capacity (scenario C) proved to be successful by using a DAF as pre-treatment technique, combined with additional aeration capacity. For all three scenarios it was necessary to include in-stream aeration in the river to solve the DO depletion problem (at basic level, not at critical level) and a sand filter to achieve the summer average nutrient requirements.

Scenario C, based on applying advanced pre-treatment (like DAF units) at the WWTP showed to be the most cost effective measure (Table 3). With regard to the total costs of scenario A, B and C, it should be considered that the reference scenario consisting of conventional methods of solving water quality issues like uncoupling of paved area and building sewer storage facilities at CSOs would require a yearly cost of approximately € 15 million (similar to scenario A). Table 4 illustrates the achieved improvement of river water quality between the current situation and the different scenarios consisting of sets of additional measures.

Table 3. Summary of scenario analysis.

Scenario	**A**	**B**	**C**
Measure in all scenarios	river aeration + effluent aeration; sand filter for effluent filtration; RTC to reduce NH_4 peaks; additional aeration capacity at WWTP		
Measures	300.000 m^3 dry storage	400.000 m^3 wetland	DAF pre-treatment
Investment costs	€ 160,140.000	€ 90,410.000	€ 36,780.000
CAPEX	€ 11,295,000/year	€ 8,328,000/year	€ 3,052,000/year
OPEX	€ 3,670,00/year	€ 3,194,000/year	€ 4,641,000/year
Total annual costs (CAPEX + OPEX)	€ 14,965,000/year	€ 11,522,000/year	€ 7,693,000/year

Table 4. Results of scenario analysis tested to solve the peak NH_4 concentration problem; scores from 1 (very good quality) to 5 (very bad quality); for details on the evaluation framework, see Langeveld *et al.* (submitted); to be noted that to achieve DO quality for critical species with scenario C, only an increase of in-stream aeration would be necessary.

	Duration →	1 - 5 h	6 - 24 h	> 24 h		current						scenario A						scenario B						scenario C					
	Limit ↓	Simulation result ↓																											
Frequency per year	12	1.5	0.7	0.3	NH4	2	5	5	11.7	60.2	45.6	1	1	5	0.6	5.7	37.3	1	2	4	0.1	6.6	17.8	1	2	2	2.4	9.9	9.2
	4	2	1.2	0.5		5	5	5	12.9	54.4	36.8	1	1	4	0.2	1.8	6.2	1	2	4	0.0	2.4	7.8	1	2	1	0.6	2.9	1.9
	1	2.5	1.5	0.7		5	5	5	11.1	41.3	18.9	1	2	4	0.0	1.0	1.3	1	2	5	0.0	0.7	2.8	1	2	1	0.0	0.9	0.3
	0.2	4.5	3	1.5		1	5	4	0.0	0.7	0.3	1	1	2	0.0	0.0	0.2	1	1	1	0.0	0.0	0.1	1	1	1	0.0	0.0	0.1
	12	5.5	6	7	DO critical	1	5	5	4.1	38.6	30.7	1	1	2	0.4	1.9	6.2	1	1	2	0.6	3.2	6.8	1	5	5	3.1	27.6	30.4
	4	4	5.5	6		1	5	5	1.0	23.9	18.8	1	1	1	0.0	1.1	0.8	1	1	1	0.0	1.7	1.5	1	4	5	0.0	6.2	8.4
	1	3	4.5	5.5		1	5	5	0.3	9.0	11.6	1	1	1	0.0	0.0	0.1	1	1	2	0.0	0.0	0.7	1	1	4	0.0	0.0	1.9
	0.2	1.5	2	3		1	4	5	0.1	0.4	1.5	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0
	12	3	3.5	4	DO basic	1	1	1	0.3	1.6	2.2	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0
	4	2.5	3	3.5		1	1	1	0.2	0.8	1.7	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0
	1	2	2.5	3		1	3	4	0.0	1.1	1.5	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0
	0.2	1	1.5	2		1	4	4	0.0	0.3	0.3	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0

Uncertainty analysis – robustness check

The uncertainty analysis results (not shown) indicate that the performance of the selected scenario C is robust to changes in the model assumptions. Concerning NH_4 in the river, some decrease of performance is only noticed in the simulation with the climate change scenario (increase summer rainfall intensity). As for DO, only very small changes occur in the river, as any impact on DO is counter-balanced by in-stream aeration, which is controlled. Despite a significant change in river aeration operational cost, water quality will not be affected.

CONCLUSIONS

The integrated model of the sewer and WWTP of Eindhoven and of the Dommel River (based on fully calibrated detailed models) together with a cost model, was used to evaluate cost-effective upgrade scenarios to comply with specific water quality regulation. The results of the evaluation showed that:

- several upgrade options are available to reach the desired water quality for DO and NH_4
- there are substantial cost differences between scenarios, with clear advantages in using in-stream aeration for DO depletion and WWTP DAF pre-treatment for NH_4 peaks
- the selected scenario is robust to uncertainty in the main assumptions concerning model parameters and inputs.

The integrated model, once developed, proved to be a very powerful tool to quickly investigate interactions, synergies and conflicts in the whole urban wastewater system, allowing for the identification of effective solutions to achieve the defined receiving water quality objectives.

ACKNOWLEDGMENTS

The project is funded by KRW-innovation subsidy from AgentschapNL (www.agentschapnl.nl). The Dutch Foundation for Applied Water Research (STOWA) is engaged in the project to communicate and publish the research results.

REFERENCES

Alp, E. and Melching C.S. (2011) Allocation of supplementary aeration stations in the Chicago waterway system for dissolved oxygen improvement. *Journal of Environmental Management* **92**, 1577-1583.

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

Langeveld, J.G. (2004) Interactions within the Wastewater System. PhD thesis. Technische Universiteit Delft, Delft.

Langeveld, J.G., Benedetti, L., de Klein, J.J.M., Nopens, I., Amerlinck, Y, van Nieuwenhuijzen, A., Flameling, T., van Zanten, O. and Weijers, S. (submitted) Impact-based integrated real-time control for improvement of the Dommel River water quality. *Urban Water Journal*.

Rauch, W. and Harremoës, P. (1996) The importance of the treatment plant performance during rain to acute water pollution. *Water Science &Technology* **34**(3-4), 1-8.

Struijs, J., De Zwart, D., Posthuma, L., Leuven, R.S.E.W. and Huijbregts, M.A.J. (2011) Field sensitivity distribution of macroinvertebrates for phosphorus in inland waters. *Integrated Environmental Assessment and Management* **7**(2), 280-286.