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KALLISTO: Cost Effective and Integrated Optimization of the Urban Wastewater System Eindhoven --Manuscript Draft--

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KALLISTO: Cost Effective and Integrated Optimization of the Urban Wastewater System Eindhoven

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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). Within the project, both acute and long-term impacts of the urban wastewater system on the chemical and ecological quality of the river are studied with a monitoring campaign in the urban wastewater system (WWTP and sewers) and in the receiving surface water system. 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 use of additional infrastructural measures to improve the system cost-effectively and have it meet the WFD goals. 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.

Keywords: Cost-effective systems upgrade; Cost modelling; Impact based real-time control; Integrated urban wastewater system modelling and optimization; Receiving water quality; 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 (see Figure 1). 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 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 (RBT) settling tank 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 be able to comply with the maximum summer average concentration levels in the river of 0.15 mg P_{total}/l and 4 mg N_{total}/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, like SIMBA (www.ifak.eu), SYNOPSIS (Butler and Schütze, 2005) and WEST (www.mikebydhi.com; Vanrolleghem *et al.*, 2005). This approach requires multi-objective optimization of the performance of the integrated urban wastewater system (Rauch and Harremoës, 1999).

Waterschap De Dommel, the utility responsible for the compliance to the WFD of the Dommel river, has launched 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. This project brings together (next to the utility) all involved stakeholders: all cities (see figure 1) within the river catchment as well as knowledge institutes and consulting firms with specific expertise on the different subsystems. 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.

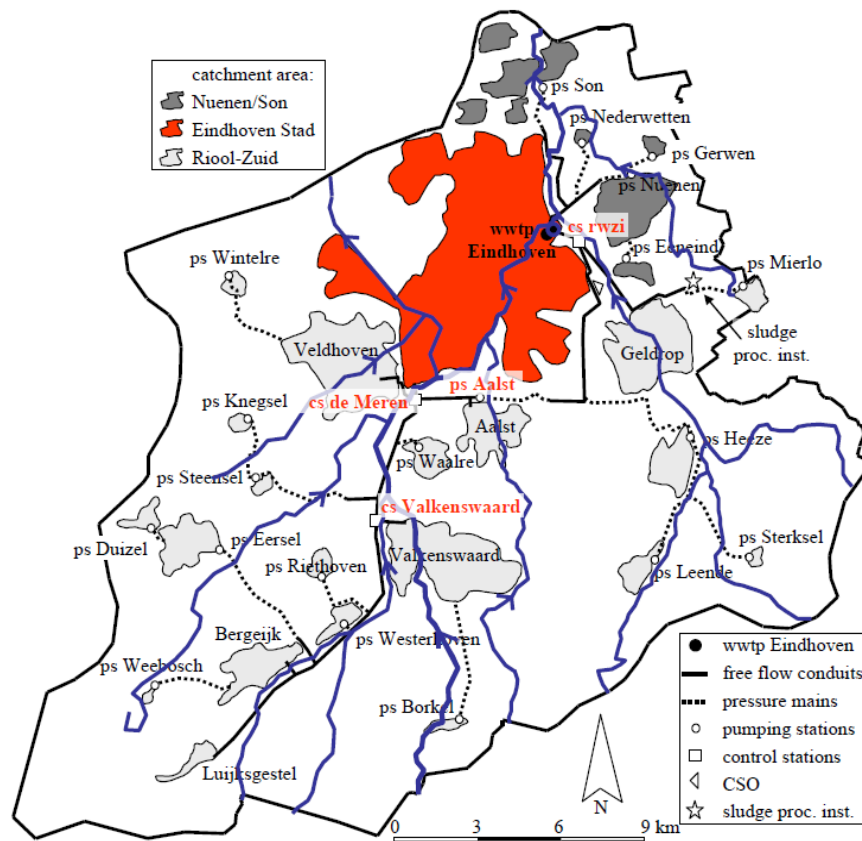


Figure 1 The wastewater system of Eindhoven and its receiving waters.

MATERIAL AND METHODS

The KALLISTO project consisted of several steps as indicated in Figure 2. Previous work focussed on the realisation of the integrated system model (step 1), the model analysis (step 2) and on the design of RTC strategies (step 3a) (Langeveld *et al.*, submitted). This paper presents the conclusive results of the KALLISTO project, in particular regarding the scenarios evaluated with additional measures, the cost considerations and the uncertainty analysis (robustness check) (steps 3b&c).

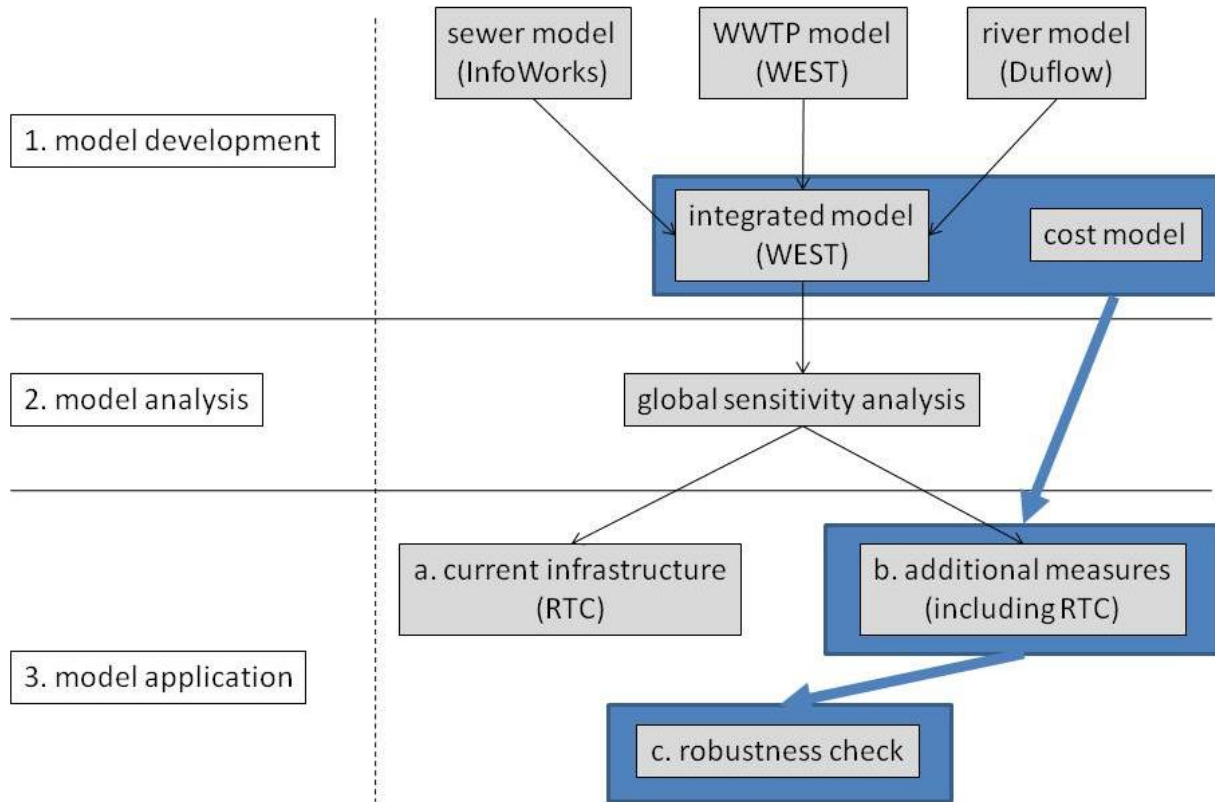


Figure 2. Overview of the different steps of the KALLISTO project; with blue background the steps described in this work.

Scenarios

The optimization of the integrated urban water system Eindhoven has been done with an iterative process as highlighted in Figure 3. 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 (Mels *et al.* 2001; Van Nieuwenhuijzen and Van der Graaf 2011), fine screens or lamella settlers (Weijers *et al.*, 2012). 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 further 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.

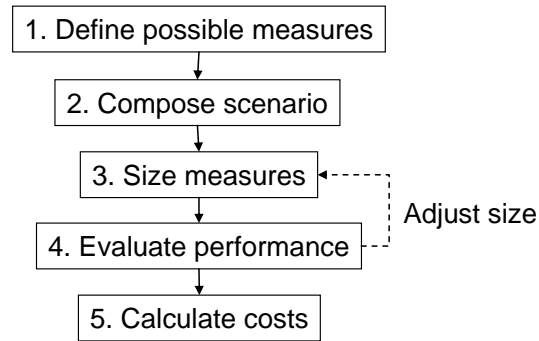


Figure 3. Approach used in scenario analysis.

Table 1. List of measures evaluated in 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 during storm events to minimise ammonium concentration peaks in WWTP effluent
River aeration	Reduce DO dips in river
Effluent aeration	Reduce DO dips in river due to WWTP effluent
Additional aeration capacity in WWTP, increase in MLSS, increase of aeration volume at WWTP	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 peak concentrations and DO dips in river
Sand filter for treatment of WWTP effluent	Reduce N _{total} and P _{total} in effluent

Cost model

To be able to determine the 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 (e.g. RIONED 2011, Holzwarth and Rechenberg, 2007) 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. The cost criteria in Table 2 were used to determine CAPEX and OPEX.

Table 2. Cost function parameters adopted in the cost analysis.

Parameter	Value	unit
Interest rate	4.5	%/y
Inflation rate	2	%/y
depreciation period civil investment	40	years
depreciation period electro-mechanical investment	18	years
depreciation period IT investment	18	years
depreciation factor DAF / filter units	0.088	-
depreciation factor rain water buffer	0.051	-
depreciation factor sewer storage buffer	0.048	-
depreciation factor wetland / green storage buffer	0.044	-
depreciation factor aeration systems	0.093	-
depreciation factor pumps	0.093	-
depreciation factor IT / control	0.126	-
depreciation factor average	0.078	-
factor unforeseen expenditures	15	%
VAT	19	%
energy costs (incl. VAT)	0.15	EUR/kWh
costs metal salts (incl. VAT)	210	EUR/m ³ 10% PolyAlCl ₃
costs methanol (incl. VAT) as carbon source	300	EUR/m ³ 10% Methanol
labour	50,000	EUR/year/person
maintenance buildings	0.5	% of investment /y
maintenance installations	3.0	% of investment /y

Uncertainty analysis / robustness check

To check the robustness of the 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. For each simulation, only one assumption was varied from the default values of the selected upgrade scenario to observe the individual impact. Parameters that cannot be more or less easily measured/controlled, like PST and DAF performance, have not been considered as in a long-term evaluation we can assume that those parameters are known and under control, even if they could exhibit short-term variability (which should not last long due to an appropriate operator action). The same goes for biological parameters in the WWTP, as they are mostly correlated and long-term values should not change; only one was included (K_{NH_AUT}) as it is important and difficult to measure and represents uncertainty in nitrification. The list of parameter values used in simulations for uncertainty analysis is in Table 3.

RESULTS AND DISCUSSION

Scenarios

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).

Table 3. Parameter values used in simulations for uncertainty analysis; no.6: the % increase is applied to events >15mm from May to September; no.7: default is the 50th percentile of measurements, the value for uncertainty is the 75th percentile.

no.	location	parameter	unit	default value	value used in UA
1	WWTP influent fractionator	f_{S_A}	-	0.38	0.2
2	WWTP influent fractionator	f_{X_S}	-	0.45	0.3
3	WWTP secondary settler	v_0	m/d	474	300
4	WWTP process	K_{NH_AUT}	g/m ³	0.05	1
5	catchment	Population increase	%	0	5
6	catchment	Storm intensity increase	%	0	28
7	sewer to river	CSO concentrations (BOD, COD, NH ₄)	g/m ³	47, 162, 3.2	71, 197, 3.65
8	sewer to river	fBOD1_BOD	-	0.85	0.95
9	sewer to river	fBOD1_BOD	-	0.85	0.5
10	sewer to river	fBOD2_CODmBOD	-	0.4	0.7
11	WWTP to river	fBOD1p_BODf	-	0.3	0.7
12	WWTP to river	fBOD2p_BODs	-	0.5	0.3
13	WWTP to river	fBOD2p_BODs	-	0.5	0.7
14	river	KBODs	1/d	0.7	0.5
15	river	KBODs	1/d	0.7	1
16	river	Kd1	1/d	0.4	0.3
17	river	Kd1	1/d	0.4	0.8
18	river	Kd2	1/d	0.3	0.2
19	river	Kd2	1/d	0.3	0.6
20	river	SOD	g/m ² /d	5	8

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 m³ 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 O₂/day. Table 4 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 4. 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 N_{total} and P_{total} 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 P_{total}. The costs of both measures are summarized in Table 5.

Table 5. Costs of measures for additional nutrient removal.

Measure	Investment costs	CAPEX	OPEX
Additional treatment capacity	€ 19,300,000	€ 1,497,000	€ 1,456,000
Advanced effluent filtration	€ 14,670,000	€ 1.291.000	€ 1,548,000

The reduction of ammonia peaks in the Dommel River proved to be the most difficult challenge. Three scenarios (see Tables 6 and 7) were tested to solve the peak NH₄ concentration problem:

1. Create additional dry storage capacity at the WWTP to reduce the peak loads in the WWTP influent
2. Create equalisation of WWTP effluent in a wetland
3. Increase nitrification capacity at the WWTP

The additional dry storage capacity of 300,000 m³ (scenario A) had to be accompanied by some additional measures in order to be able to meet the requirements for NH₄ in the River Dommel: RTC aiming at minimising NH₄ 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 NH₄ 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 6). 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 6. Summary of scenario analysis.

Scenario	A	B	C
Measure in all scenarios	River aeration + effluent aeration Sand filter for effluent filtration RTC aiming at reducing NH ₄ concentration 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 7. Results of scenario analysis tested to solve the peak NH₄ 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 (Table 8) indicate that the performance of the selected scenario C is robust to changes in the model assumptions (Table 3). Concerning NH₄ in the river, an important decrease of performance is only noticed in the simulation with the value of K_{NH₄AUT} set to its maximum value, which is anyway a rather unrealistic possibility, as the value of that parameter is not likely to increase in the future. Also the simulations with the climate change scenario and the one with CSO concentrations increase give visible changes, but definitively minor. 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.

Table 8. Results of uncertainty analysis for the most significant changes in assumptions; U04, U06, U07: uncertainty simulations number 4, 6 and 7 respectively (see Table 3); scores from 1 (very good quality) to 5 (very bad quality); for details on the evaluation framework, see Langeveld *et al.* (submitted).

	Duration →	1- 5 h 6- 24 h > 24 h				scenario C			U04			U06			U07														
	Limit ↓	Simulation result ↓																											
Frequency per year	12	1.5	0.7	0.3	NH4	1	2	2	2.4	9.9	9.2	1	5	5	3.3	26.0	33.9	1	3	2	3.1	12.1	11.1	1	2	2	1.8	10.2	10.8
	4	2	1.2	0.5		1	2	1	0.6	2.9	1.9	2	4	4	2.3	7.2	6.4	1	3	2	1.0	4.6	3.4	1	2	2	0.8	3.1	2.4
	1	2.5	1.5	0.7		1	2	1	0.0	0.9	0.3	2	5	4	0.6	3.5	1.6	1	4	2	0.0	1.7	1.0	1	4	1	0.0	1.8	0.5
	0.2	4.5	3	1.5		1	1	1	0.0	0.0	0.1	1	1	1	0.0	0.0	0.1	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	3.1	27.6	30.4	1	5	5	2.4	24.5	28.1	1	5	5	3.0	30.2	28.9	1	5	5	2.7	28.2	30.3
	4	4	5.5	6		1	4	5	0.0	6.2	8.4	1	4	4	0.0	6.3	8.0	1	4	5	0.0	7.7	9.5	1	5	5	0.0	8.1	9.0
	1	3	4.5	5.5		1	1	4	0.0	0.0	1.9	1	1	4	0.0	0.0	1.9	1	1	5	0.0	0.0	4.4	1	1	5	0.0	0.0	2.6
	0.2	1.5	2	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	1	1	1	0.0	0.0	0.0
	12	3	3.5	4	DO basic	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	1	1	0.0	0.0	0.0
	4	2.5	3	3.5		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	1	1	1	0.0	0.0	0.0
	1	2	2.5	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	1	1	1	0.0	0.0	0.0
	0.2	1	1.5	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	1	1	1	0.0	0.0	0.0

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 describe the dynamics of the whole urban wastewater system and 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 achieve the desired water quality in terms of DO and NH₄
- there are substantial cost differences between scenarios, with clear advantages in using in-stream aeration for DO depletion and WWTP DAF pre-treatment for NH₄ peaks
- the selected scenario is robust to uncertainty in the main assumptions concerning model parameters and inputs.

The integrated model 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.

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