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Impact-based integrated real-time control for improvement of the Dommel River water quality

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The KALLISTO project aims at finding cost-efficient sets of measures to meet the Water Framework Directive (WFD) derived goals for the river Dommel. 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 an integral monitoring campaign in the urban wastewater system (WWTP and sewers) and in the river. Based on this monitoring campaign, detailed models were calibrated. These models are partly simplified and integrated in a single model, which is validated using the detailed submodels. The integrated model was used to study the potential for impact-based real-time control (RTC). Impact based RTC proved to be able to improve the quality of the receiving waters significantly, although additional measures remain necessary to be able to meet the WFD requirements.

Keywords: real time control; integrated modeling; monitoring; calibration; global sensitivity analysis; water framework directive

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1. Introduction

In the European Union, the Water Framework Directive (WFD) enforces a good ecological and chemical status of all surface waters, which is to be accomplished before 2015 (2000/60/EC 2000). Many surface waters throughout Europe still do not meet the WFD requirements due to discharges of combined sewer overflows (CSOs) and effluents of wastewater treatment plants (WWTPs). The extent of non compliance and the need for measures are to be decided in 2012, based on the results of the monitoring programs, established since 2009 (Commission Report 2009). It is expected that measures to improve the status will be necessary on many locations.

Water Board De Dommel – the public company responsible for the quality of the Dommel River (the Netherlands), including collection and treatment of sewage from the city of Eindhoven and surrounding municipalities – currently faces receiving water problems related to intermittent discharges from CSO and WWTP effluents, specifically oxygen depletion and ammonium peaks in the Dommel River.

The traditional approach applied in many countries in Europe before the introduction of the WFD, of defining nation-wide emission standards and efficiency requirements for CSOs and WWTPs, may result being ineffective and inefficient with respect to the 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, many water authorities gradually shifted their approach towards integrated urban water management, supported by research advances in knowledge 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, Van der Molen and Pot 2007) and (3) on the availability of software that allows using integrated models (Alex *et al.* 1999, Leinweber *et al.* 2001, Schütze *et al.* 2002, Butler and Schütze 2005, Vanrolleghem *et al.* 2005).

In many receiving waters, especially rivers receiving substantial discharges from CSOs and WWTPs, transient conditions causing acute effects like dissolved oxygen (DO) depletion, ammonium toxicity and hydraulic stress are the main limiting factor for achieving a good ecological status. WWTP effluent is typically to the main cause of ammonium peaks in receiving waters, whereas CSO emissions typically contribute to DO depletion, as ammonium concentration levels of CSO

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spills are typically significantly lower than in WWTP effluent (Langeveld 2004). As a reduction of ammonium peaks in WWTP effluent can be achieved by minimizing the flow to the WWTP and a reduction of CSO volumes can be achieved by maximizing the flow to the WWTP, the optimal use of the available infrastructure depends on the objective selected. This requires multi-objective optimization of the performance of the integrated urban wastewater system (Rauch and Harremoës 1999).

Integrated real-time control is generally believed to be a good option to cost-effectively meet the water quality objectives (Olsson 2012). The potential of integrated real-time control is determined by the characteristics of the urban wastewater system in terms of control power and the relative impact of the urban wastewater system on the receiving waters.

Zacharof *et al.* (2004) and Schütze *et al.* (2008) describe a methodology to screen an integrated urban wastewater system for its control potential. Their procedure is developed into a planning tool named PASST (Planning Aid for Sewer System Real Time Control), available at www.dwa.de. This methodology has been used to screen the RTC potential of the Eindhoven wastewater system (see Appendix). The result of this screening was "Suited for control", which confirms the opinion of the responsible authorities on the potential of RTC for the Eindhoven area.

The wastewater system of Eindhoven and surroundings has already been equipped with RTC control stations in the interceptor sewer since the early 1970s (Figure 1). The original RTC strategy aimed at maximizing the use of the in-sewer storage capacity and of the hydraulic capacity of the downstream WWTP, resulting in a volume-based RTC strategy (see also Langeveld and Clemens 2013).

The combination of the availability of control structures and new system requirements makes the Eindhoven case an ideal one to study the benefits of impact-based RTC of integrated urban wastewater systems (IB-RTC for IUWS), also referred to as water quality based RTC (Vanrolleghem *et al.* 2005).

This paper presents the results of the development of an impact-based RTC strategy in the Eindhoven region. The objective of the study was to maximize the performance of the existing wastewater system in order to minimize the additional investments required to be able to comply with

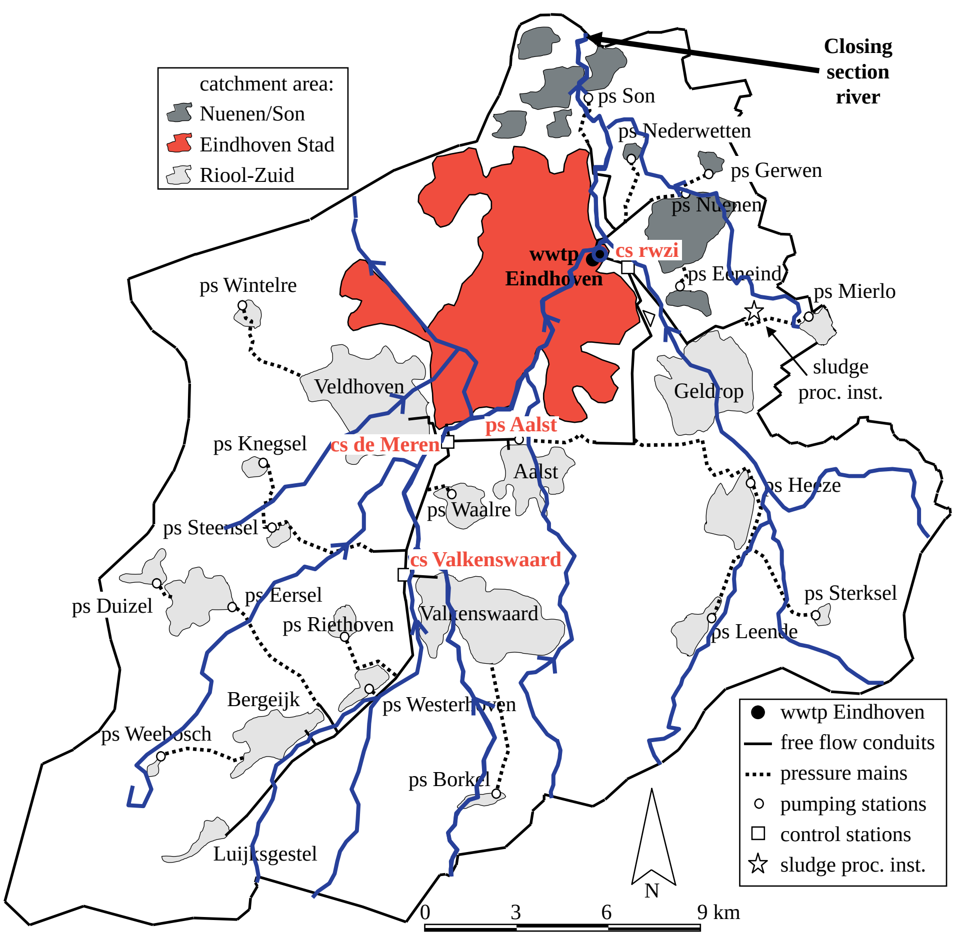

Figure 1. Schematic of the urban wastewater system of Eindhoven and its receiving waters.

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the WFD. This study is part of the (applied) research project Kallisto (Weijers *et al.* 2012), aiming at cost-effectively meeting the WFD requirements. The paper describes the development and calibration of the detailed sub-models for sewer, WWTP and receiving water. These models are partly simplified and integrated in a single model, which is validated using the detailed submodels. The integrated model is then subjected to a global sensitivity analysis (GSA) in order to identify relevant control structures. Based on the results of the GSA and available knowledge on system performance, a number of impact-based RTC strategies have been derived and assessed with the integrated model. The optimal RTC strategy will be further developed and implemented in the near future.

2. Material and methods

2.1. System description

The Dommel River is a relatively small lowland river with a base flow of 2–4 m^3/s. The river receives the effluent of a 750,000 PE WWTP with a load of 136 g COD day^{-1} PE^{-1} and intermittent discharges from over 200 CSOs, in a system draining 4000 ha of impervious area. In summer time and for dry weather flow conditions, the WWTP effluent can constitute up to 50% of the base flow of the river. The base flow in the river Dommel is controlled by flow diversion works just upstream of the city of Eindhoven and the WWTP.

2.2. Description of available monitoring data

The monitoring network, in operation since 2006, comprises rain gauges, flow and water level sensors in the contributing sewer systems, UV/VIS, measuring COD_{eq} and $COD_{dissolved,\ eq.}$ and ammonium sensors at the inlet of the WWTP and nitrate, ammonium, phosphate and oxygen sensors in the reactors of the WWTP. Details are given in Table 1. The data sets provide information on variations in pollutant loads and concentrations of WWTP influent as well as on the impact of these fluctuations on the performance of the WWTP (Schilperoort *et al.* 2012). The DO and NH_4 sensors in the river provide information on the impact of CSO and WWTP effluent discharges on river water quality.

The monitoring data was validated prior to data analysis, which involved checks on completeness, min-max and drifts (Bertrand-Krajewski and Muste 2008, Schilperoort *et al.* 2008).

2.3. Evaluation framework for receiving water quality

As part of the Kallisto project, an ecological evaluation framework was devised based on the relationship between dissolved oxygen and ammonium and the presence of macro-invertebrates (De Klein *et al.* 2012). From the Dutch Limnodatabase over 50,000 records were selected of critical species in lowland rivers, representative for the Dommel River. The data were transformed into response curves, from which critical concentrations were derived. In the final assessment framework, like in the Urban Pollution Management (UPM) Manual (FWR 1998), the quality criteria are defined in terms of minimum DO and maximum NH_4 in several combinations of frequency and duration of exceedance (Table 2), to be used in the evaluation of scenarios simulated for long periods (e.g. 10 years). For example, the NH_4 concentration should not

Table 1. Availability of continuous monitoring data.

Type of measurement	Availability (from- till)	Monitoring frequency	Remarks
Precipitation	1951–now	1 h^{-1}	Rainfall measurement of the Royal Netherlands Meteorological Institute
	2006–2009	5 min^{-1}	25 rain gauges of Waterboard the Dommel
	2010–now	5 min^{-1}	Eight rain gauges of Waterboard the Dommel and municipality Eindhoven combined with rain radar
Water level	2006–now	1 min^{-1}	Water level sensors in all pumping stations and control structures of Figure 1
			Water level sensors at 26 CSOs Municipality Eindhoven
	2010–now	1 min^{-1}	Water level at 200 CSOs
Flow	2006–now	1 min^{-1}	Flow monitoring at all pumping stations, control structures and Dommel River
	2006–2009	1 min^{-1}	Flow sensors at connections of municipal sewers to transport/interceptor sewer
Water quality	2006–now	2 min^{-1}	UV-VIS at WWTP influent
		1 min^{-1}	NH_4 at WWTP influent
		1 min^{-1}	PO_4 at WWTP primary clarifier effluent
		2 min^{-1}	UV-VIS at WWTP primary clarifier effluent
		1 min^{-1}	NH_4, NO_3 and PO_4 at WWTP effluent
		1 min^{-1}	DO at WWTP aeration tank
		1 min^{-1}	DO at three locations in Dommel River
	2010–now	1 min^{-1}	DO at six locations in Dommel River
		1 min^{-1}	NH_4 on one location in Dommel River

Table 2. Evaluation framework for long-term simulations; thresholds and allowed exceedance frequencies (number per year) for NH_4 (g/m^3) and DO (g/m^3) in the river Dommel.

		NH_4 critical (g/m^3)			DO critical (g/m^3)			DO basic (g/m^3)		
Duration		1–5 h	6–24 h	> 24 h	1–5 h	6–24 h	> 24 h	1–5 h	6–24 h	> 24 h
Tolerated frequency per year	12	1.5	0.7	0.3	5.5	6	7	3	3.5	4
	4	2	1.2	0.5	4	5.5	6	2.5	3	3.5
	1	2.5	1.5	0.7	3	4.5	5.5	2	2.5	3
	0.2	4.5	3	1.5	1.5	2	3	1	1.5	2

exceed a level of 1.5 mg NH_4-N/l more than 12 times per year for durations between 1 and 5 h. For DO, two levels are defined, one based on the occurrence of critical species and one on other species.

2.4. *Modeling approach of detailed models*

2.4.1. *Sewer model: hydraulics*

A detailed hydrodynamic sewer model has been built in InfoWorks version 9.5 (www.innovyze.com) based on the 10 individual models of each municipality. The hydrodynamic model counts 21,955 nodes and 24,863 conduits, 108 weirs and 39 pumps. The model is 'calibrated' using a dedicated approach to detect database errors and model anomalies. This approach does not aim at a perfect fit per event by adjusting model parameters related to the hydrological rainfall-runoff model, such as initial loss and infiltration in semi-impervious areas, as determining these parameters requires much more information than contained in the available monitoring data. Instead, the approach used comprised three steps:

Step A. Engineering validation and check on erroneous modelers' choices: as the first version of sewer models was developed by the municipalities (or their consultants) using different modeling approaches for e.g. the runoff parameters in the hydrological model or roughness coefficients, the model had to be adjusted to one standard. In addition, standard engineering validation procedures available in InfoWorks were applied.

Step B. Calibration of dry weather flow (DWF). DWF curves were derived from the monitoring data for each catchment using the monitoring data at pumping stations and control stations. The diurnal pattern of wastewater production was adjusted per catchment with, where appropriate, a distinction between week and weekend days. Time varying extraneous water was included as annual profile.

Step C. Calibration of wet weather flow (WWF) and storm events. The calibrated radar data was used to simulate a number of storm events per catchment. Depending on the length of the specific time series and quality of the available monitoring data, between 8–20 storm events per catchment were used to compare model results with monitoring data of the CSOs. The objective of this WWF calibration was not to get a perfect fit between model predictions and monitoring data by adjusting parameters of the hydrological inflow model, but instead to discover and identify significant errors in the underlying database of the models. In this stage, erroneous CSO weir levels and sewer invert levels, errors in the size of the connected impervious area, wrong pumping capacities and the impact of sewer sediment (in some parts conduits were over 50% filled with sediment) were detected. A difficult parameter in the calibration phase was the pumping capacity available at the WWTP for the discharge from Eindhoven, which ranged between 5000 and 20,000 m^3/h. As this pumping capacity has a significant impact on the sewer system performance and on the agreement between model and monitoring data, it had to be adjusted per storm event. Figure 2 illustrates the model performance after applying the described calibration procedure for a storm event for the sewer model of the city of Eindhoven, the largest catchment (2139 ha) in the study area.

2.4.2. *Sewer model: water quality*

Since water quality modules in sewer models are still considered not sufficiently reliable (Bertrand-Krajewski 2007), an empirical model was developed and used to generate the WWTP model input for DWF and WWF. This model uses the long high-frequency time series available from the sensors placed at the WWTP inlet, generating NH_4, PO_4, COD, CODs and TSS hourly time series in function of flow rate at the WWTP inlet (Schilperoort 2011), as illustrated in Figure 3. For all the CSO outputs into the river, an event mean concentration (EMC) was applied. This EMC has been derived from two years of monitoring data at two CSOs in Eindhoven. This method is comparable to the method advocated by Mourad *et al.* (2006). Table 3 summarizes the derived EMCs.

2.4.3. *WWTP model*

The WWTP Eindhoven treats the incoming wastewater in three parallel lines biologically with a maximum hydraulic load of 26,000 m^3/h. Each line consists of a primary settler,

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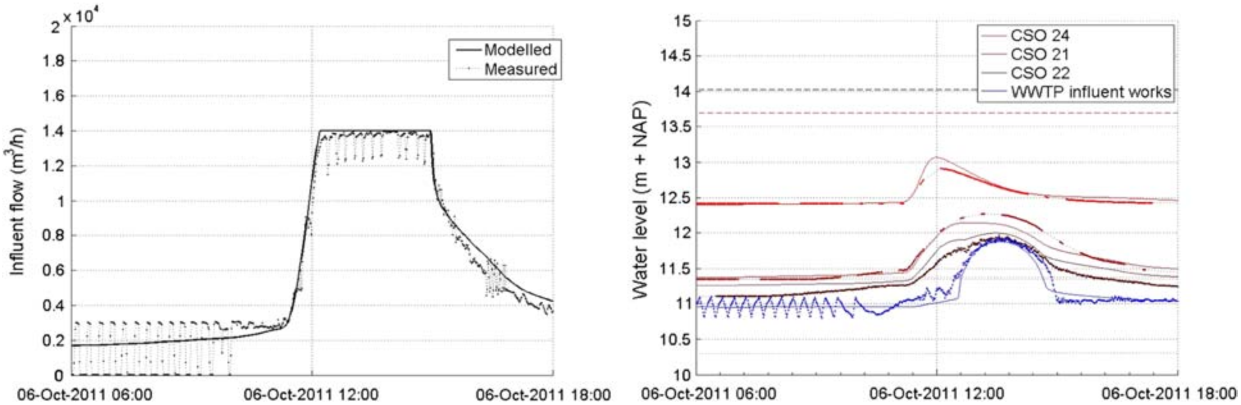

Figure 2. Pumped flow (m^3/h) from Eindhoven at influent works (left) and water level (m + NAP) at influent works and three upstream CSOs (number 21, 22 and 24) (right) for storm event 6 October 2011. Dotted lines are monitoring data, solid lines model results.

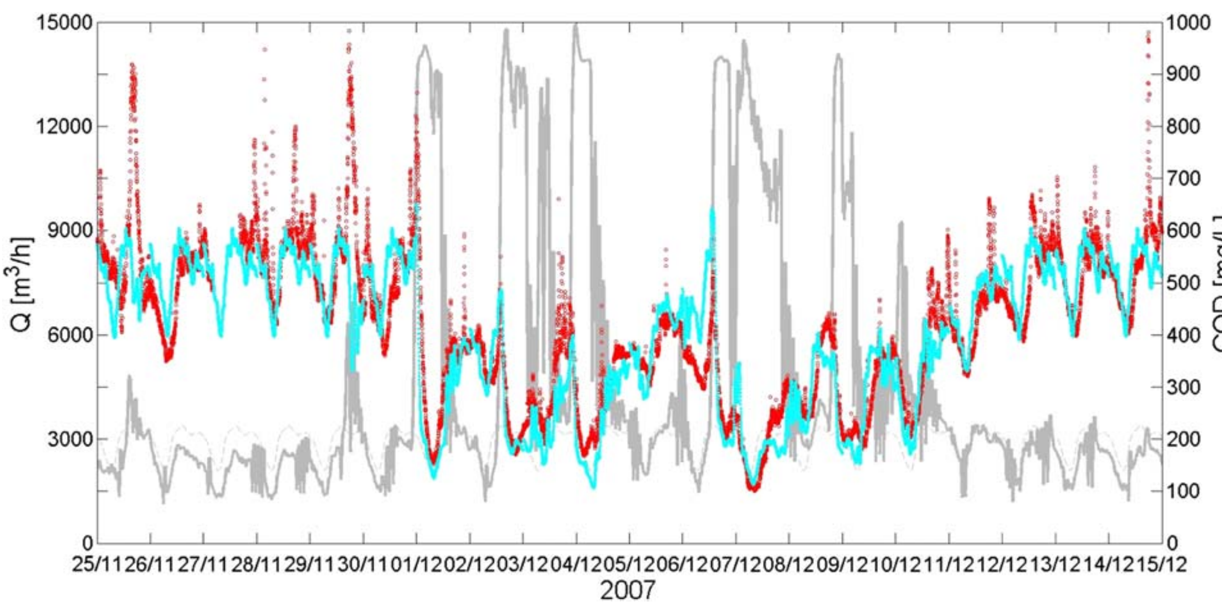

Figure 3. (Colour online) Example of results for the empirical model generating pollutants concentration at the interface between the sewer and the WWTP, in function of how the incoming flow (Q) relates to the 95%ile of the average dry weather flow (DWF); grey = Q, dashed grey = 95%ile of average DWF, red = measured COD, blue = modeled COD.

Table 3. EMCs derived from monitoring data Eindhoven (Moens *et al.* 2009)

Parameter	Number of samples (n)	EMC (average of EMCs of monitoring data)	Ninety percentile of concentrations in monitoring data	Max of concentrations in monitoring data
BOD (mg O_2/l)	216	47	92	460
COD (mg O_2/l)	212	162	385	1380
PO_4 (mg P/l)	207	1.8	3.5	9.7
N_{Kj} (mg N/l)	204	8.4	15	38
NH_4 (mg N/l)	207	3.2	5.3	18
TSS (mg SS/l)	225	188	435	1150

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a biological tank and four secondary clarifiers. It uses a modified University Cape Town (UCT) configuration (Tchobanoglous *et al.* 2003). In parallel, a stormwater settling tank can treat up to 9000 m^3/h, resulting in a total hydraulic capacity of 35,000 m^3/h.

The plant is modeled with the WEST simulator (www.mikebydhi.com) using the ASM2d biokinetic model modified by Gernaey and Jørgensen (2004). The available (continuous) monitoring data (see Table 1) and process control data allowed a thorough calibration combined with an analysis of the required model structure (Cierkens *et al.* 2012). The model is calibrated using the BIOMATH calibration protocol (Vanrolleghem *et al.* 2003) adopting the 'good modeling practice' approach (Rieger *et al.* 2012), i.e. the practice of adjusting as little as possible model parameters of the ASM model, while paying more attention to the quality of data and of information on system characteristics and operation. Several calibration rounds and analyses of the most applicable model structure resulted in a well performing model, with the following adjustments to the original standard model structure:

- Use of standard oxygen transfer efficiency (SOTE) instead of a simpler aeration model (Cierkens *et al.* 2012), resulting in an accurate description of the oxygen concentration in the aeration tank when using measured air flow rate as model input (Figure 4, right).
- A more advanced model for the primary clarifier, describing variations in its removal efficiency due to inflow variations, resulting in an accurate description of the denitrification process avoiding the need of adjusting ASM model parameters (Figure 4, left).
- Use of an improved model for the secondary settler (Bürger *et al.* 2011), incorporating compression in the sludge blanket and dispersion in the feed layer.

The performance of the WWTP model with respect to ammonium is given in Figure 5. It is noteworthy that, when using a high frequency input data set for COD, the model only needed minor calibration – only the parameter $K_{NH,A}$ (ammonium half-saturation constant for autotrophs) needed adjustment.

2.4.4. *Receiving water model*

For the Dommel River and its main tributaries, a surface water model was setup using the Duflow Modelling Tool (Stowa / MX.Systems 2004). DUFLOW is based on the one-dimensional partial differential equation that describes non-stationary flow in open channels. DUFLOW allows constructing 1D-hydrodynamic models including substance transport and processes.

The Dommel River system is schematized in 70 river sections, 10 structures and 34 discharge points, representing (clusters of) CSOs and the WWTP effluent. Input from upstream rural catchments was calculated on an hourly basis using a fixed rainfall-runoff relation multiplied by the area of the specific catchment. CSO flows were derived from sewer models, with fixed concentrations of DO, NH_4, BOD and COD. Inflow from the WWTP of Eindhoven was based on measured values of discharge and effluent quality. In the integrated model, the inflow from the WWTP is generated by the WWTP model.

For the water quality processes a DO/NH_4 model was set up, for this application adapted from Ambrose *et al.* (1988). The main DO processes in the model comprise BOD decay (fast and slow), reaeration, plant production and respiration, nitrification and settling of particulate organic matter (Figure 6).

The model was run for the period September 2009 to September 2010, with a time step of 30 min. During this period several CSO events occurred with a clear impact on the river water quality. There is a good agreement of modeled and measured DO concentrations, as shown in Figure 7 for August 2010. The figure shows that the recovery period of a CSO event is rather long, four to five

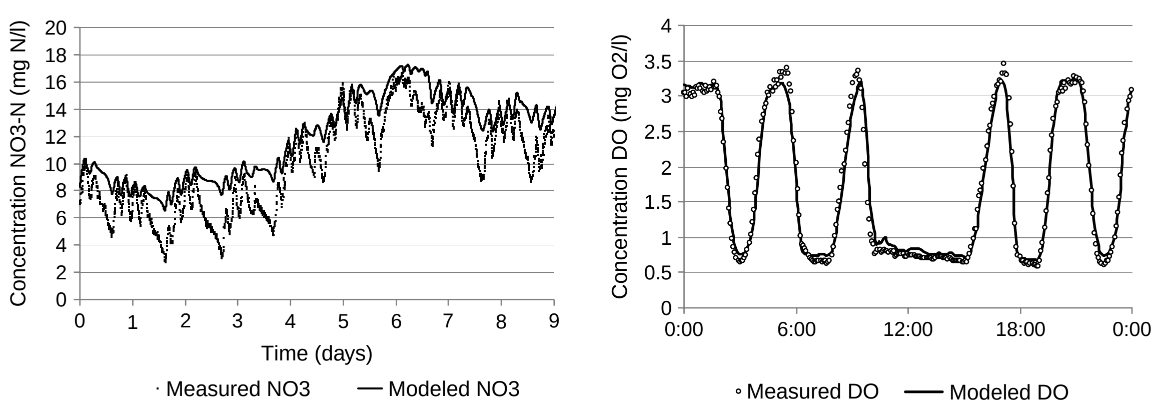

Figure 4. Performance of WWTP model: nitrate in effluent (left) and DO in aeration tank (right).

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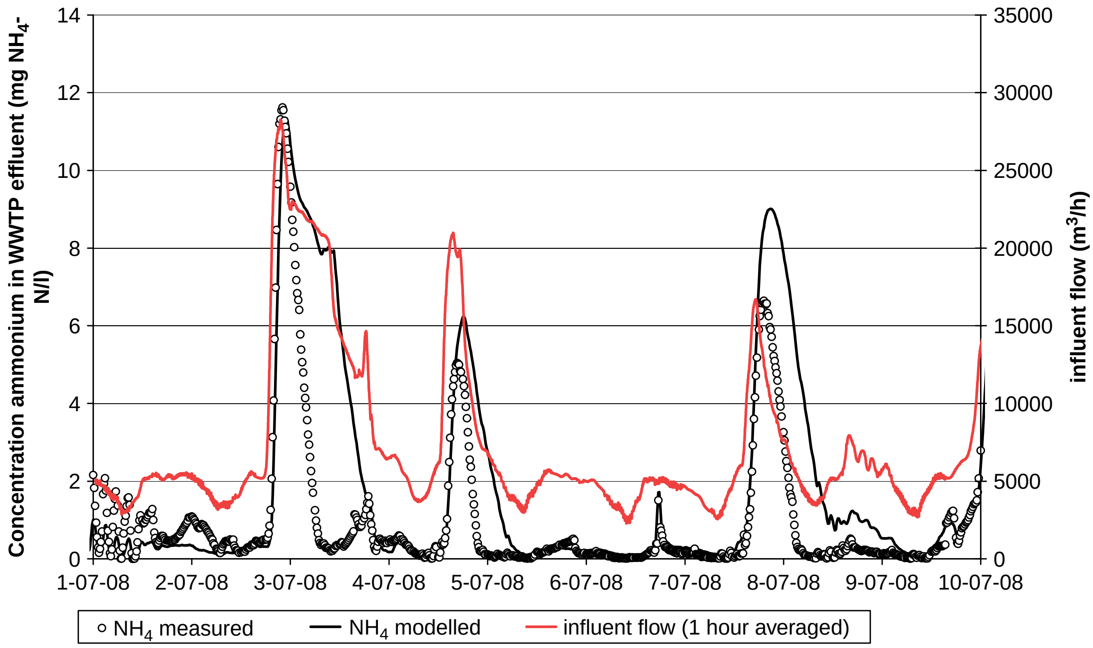

Figure 5. Performance of WWTP model: concentration of ammonium in WWTP effluent.

days due to the build-up of organic material on the sediment, just downstream the CSO. In the model, this is captured by sedimentation of the particulate fraction of the incoming BOD, which is not transported or diluted after settling.

2.5. Modeling approach of integrated models

The earlier described calibrated detailed models have been integrated into a single executable model with reduced model complexity. This approach allows overcoming:

- The communication problems between different software platforms, which reduces the possible scenarios to be run that require true integration, especially regarding integrated RTC (Vanrolleghem *et al.* 2005).
- The simulation speed problem of the detailed models, allowing to reduce the time needed to run each (long term) scenario by several orders of magnitude (Benedetti *et al.* 2009).

The integrated model, developed to allow the evaluation of RTC strategies and of additional measures aiming at

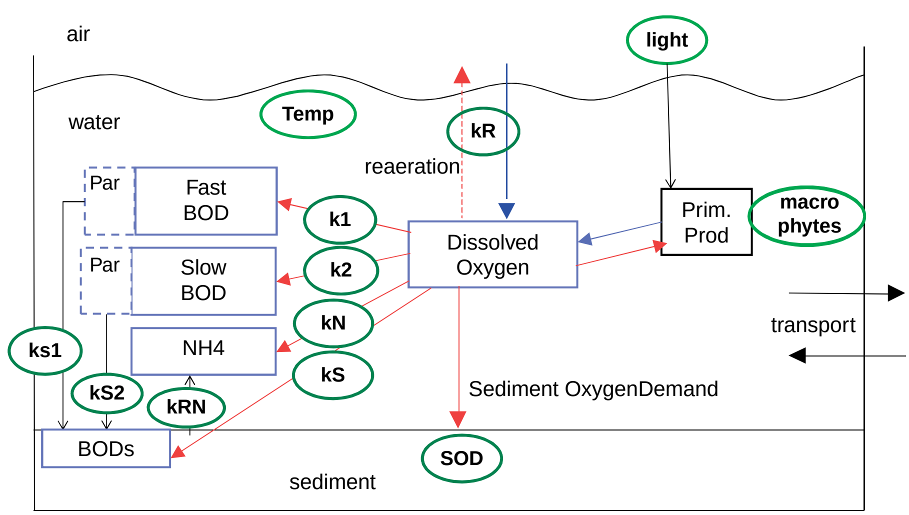

Figure 6. Overview of the water quality processes in the river model.

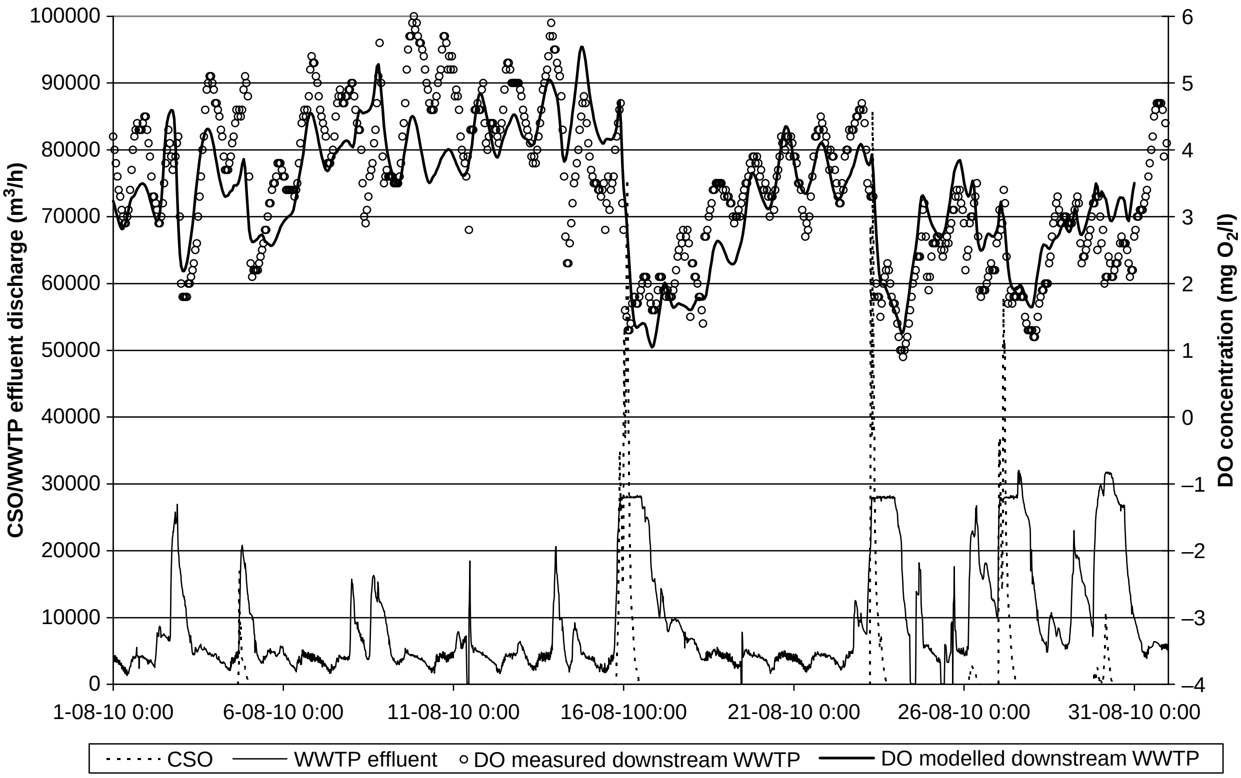

Figure 7. Performance of river model for a range of loadings from WWTP and CSOs.

increasing the water quality of the Dommel River, was implemented in WEST and includes:

- For the sewers, a tanks-in-series (TIS) hydraulic model, which is a simplified version of the detailed sewer models of all catchments and sewers in the ten involved municipalities with simplification also at spatial level, lumping catchments and modeling only significant pipes and overflows. Pipes were considered significant if they determine the discharge from catchments discharging under gravity and if they are part of the transport system.

These TIS models were calibrated against the full hydrodynamic model in InfoWorks with respect to CSO volumes (Figure 8). The only adjustment made during the calibration was the throttle flow in catchments discharging under gravity. The catchments equipped with a pumping station did not require adjustments. The Eindhoven system (comprising 50% of total impervious area connected) has the highest annual CSO discharge volumes, followed by Veldhoven and Valkenswaard, each comprising $\pm 10\%$ of the total impervious area connected). The emission from Veldhoven includes

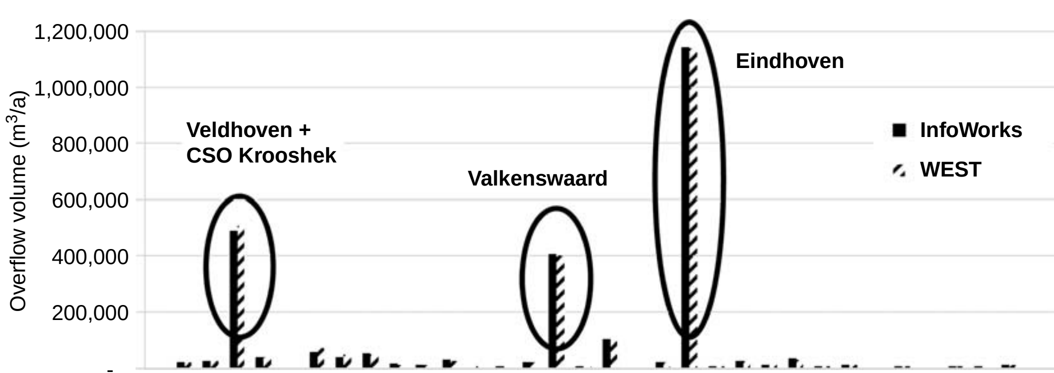

Figure 8. Comparison of annual overflow volumes from the main CSOs in the sewer system, produced by the detailed InfoWorks model and by the simplified WEST model.

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the emission from CSO Krooshek, located in the transport sewer.

- For the WWTP, the model is an exact copy of the detailed one and the water quality model did not need simplification given the fact that it is not the computationally demanding part of the IUWS model;
- For the river, a TIS model was made for hydraulics, and the water quality model is the same as the detailed one; the spatial discretisation depends on the significant inputs and on the river hydraulics.

2.6. Global sensitivity analysis

A global sensitivity analysis (GSA) was performed to identify those control structures that exhibit a significant impact on receiving water quality. The wastewater system comprises over 80 pumping stations, four RTC control structures (Langeveld and Clemens 2013), a controllable river diversion works and full process control at the WWTP. The GSA had to reveal the key control structures for the RTC strategy.

The GSA followed the methods described in Benedetti *et al.* (2011) consisting of Monte Carlo (MC) simulations followed by linear regression analysis. Prior to the GSA, a first screening took place to exclude the smaller pumping stations, located upstream of the main sewer systems, from further analysis. After this first screening, 24 parameters were selected to be used in the GSA, see Table 4. These 24 parameters included 15 sewer pumping or interceptor capacities, eight control settings in the WWTP and the river diversion flow. The parameters were varied within the physical boundaries of the currently existing infrastructure, i.e. pumps are operating in a range between 1.25 times DWF and WWF capacity, being the installed pumping capacity. The parameters were sampled with Latin Hypercube Sampling from uniform distributions with boundaries assigned according to the operational limits of the parameters. Each of the three GSAs performed (with three different input files for the integrated model) counted 1200 MC simulations, which was judged to be sufficient (Benedetti *et al.* 2011). The three input files each contained a different rainfall event, with return periods of 0.075, 0.25 and 5 years^{-1} respectively. Each simulation included 11 days of hourly input and output data. The sensitivities were calculated based on several evaluation criteria (24 in total):

Table 4. Parameters used in sensitivity analysis

Parameter	Description	Min	Max
c_107 Qmax	interceptor capacity Bergeijk (m^3/d), incorporating effect of performance of control station Valksenwaard	DWF x 1.5	WWF capacity
c_119 Qmax	interceptor capacity Valkenswaard (m^3/d), incorporating effect of performance of control station De Meeren	DWF x 1.5	WWF capacity
c_122 Qmax	pumping capacity Waalre (m^3/d)	DWF x 1.5	WWF capacity
c_123 Qmax	interceptor capacity Aalst (m^3/d)	DWF x 1.5	WWF capacity
c_127 Qmax	pumping capacity Mierlo (m^3/d)	DWF x 1.5	WWF capacity
c_128 Qmax	interceptor capacity Geldrop (m^3/d)	DWF x 1.5	WWF capacity
c_136 Qmax	pumping capacity Heeze-Leende (m^3/d)	DWF x 1.5	WWF capacity
c_142 Qmax	pumping capacity Veldhoven (m^3/d), incorporating effect of performance of control station/main pumping station Aalst	DWF x 1.5	WWF capacity
c_143 Qmax	pumping capacity Veldhoven (m^3/d)	DWF x 1.5	WWF capacity
c_150 Qmax	pumping capacity Gestelse Ontginning (m^3/d)	DWF x 1.5	WWF capacity
c_161 Qmax	pumping capacity Meerhoven (m^3/d)	DWF x 1.5	WWF capacity
c_200 Qmax	pumping capacity Son (m^3/d)	DWF x 1.5	WWF capacity
c_214 Qmax	pumping/interceptor capacity Nuenen (m^3/d)	DWF x 1.5	WWF capacity
c_24 Qmax	pumping capacity Eindhoven (m^3/d)	DWF x 1.5	WWF capacity
c_99 Qmax	interceptor capacity Luycksgestel (m^3/d)	DWF x 1.5	WWF capacity
MLSS factor	factor multiplying the design sludge concentration in activated sludge tanks (-)	0.8	1.2
NH4 set-point aeration	ammonium set-point in aeration tank (mg/l)	0.4	1
NO3 set-point recB	recirculation set-point for denitrification (mg/l)	1	6
Q biology	flow capacity of biological treatment (m^3/d)	210000	630000
Q buffer	flow capacity of storm water tank (m^3/d)	0	210000
RAS ratio	return activated sludge rate (-)	0.5	1.5
recA ratio	recirculation ratio	0.5	1
river diversion factor	diversion factor diverting flow from Dommel River to Eindhoven Canal (upstream of CSOs Eindhoven and WWTP (-)	0.5	1.5
WP aerator on	threshold of aeration requirement for activation of additional aeration (Nm^3/d)	136800	766800

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- duration of threshold exceedance and minimum for DO in six river sections,
- duration of threshold exceedance and maximum for NH_4 in six river sections.

The GSA has been performed using a previous version of the integrated model than the one presented in Section 2.4 and used to evaluate the RTC strategies in Section 2.6. The main differences are in the empirical model used to generate influent profiles for the parameter ammonium, which originally overestimated the peak loads in the influent during wet weather flow, in the COD fractionation of CSO discharges and in some river model parameter values.

2.7. *Composition and evaluation of RTC strategies*

The knowledge on the dynamics of the integrated urban wastewater system and its interactions, derived from the calibration of the sub models and the analysis of the available monitoring data, combined with the GSA results, was used to compose RTC strategies that aim at reducing the acute impacts of urban water discharges.

These RTC strategies are evaluated using the framework shown in Table 2, based on simulating 10-year time series with the integrated model.

3. Results and discussion

3.1. *Global sensitivity analysis*

The GSA results show that both the DO and ammonium concentration in the receiving water are sensitive to control actions. Figure 9 summarizes the resulting DO concentration levels of 1200 GSA runs for a small and big storm event by showing 5th, 50th and 95th percentile curves in the closing river section, which is the most northern part of the Dommel River, see Figure 1. For the smaller storm, the range between the percentile lines is much larger compared to the range for the big storm event. This indicates that control actions have more impact for smaller storms than for larger storms, which was to be expected. In addition, the results show that, next to finding RTC measures that improve the situation, it is also possible to do worse than the current situation (black line) simulated with the same version of the integrated model.

Figure 10 shows the GSA results for ammonium for the closing section of the receiving water. Unlike for DO, nearly all simulations result in a lower maximum ammonium concentration in the receiving waters. This is most likely due to the selected ranges in the GSAs, where the hydraulic capacities of pumps and interceptor sewers are varied in a range between 1.25 times the DWF and the WWF, which is the current capacity. As a result, the WWTP receives a lower peak flow during a simulated storm event, which enhances the nitrification process (Langeveld 2004). The range in concentration levels varies for both the small and big storm event with 3.5 mg NH_4-N/l. For the small event it is even possible to nearly cancel the ammonium peak in the river. For the big event the NH_4 concentration peak in the river can be reduced from 5 to as low as 1.5 mg NH_4-N/l. The results for ammonium show again that the Eindhoven urban wastewater system has a strong potential for impact-based RTC.

The linear regression resulted acceptable as the values of the coefficient of determination were always sufficiently large. Figure 11 shows the regression coefficients as percentage of total sensitivity for the small storm event ranking the sensitivity of operational parameters on the minimum DO and on the maximum ammonium in the closing river section. A positive sensitivity indicates that an increase of the parameter leads to an increase of the calculated quantity (DO and ammonium), and vice versa. For DO the most sensitive parameters are $Q_{biology}$ (+) C_{24}

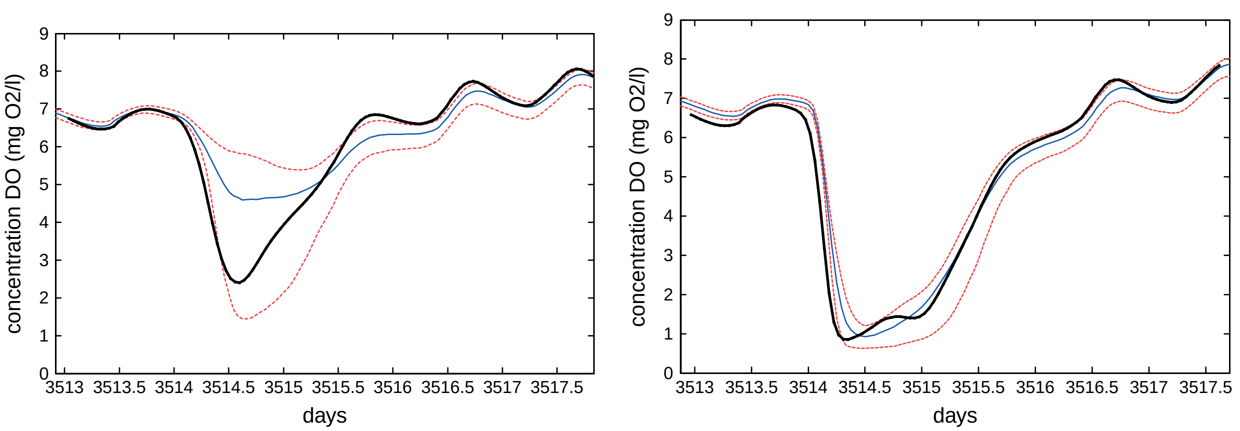

Figure 9. (Colour online) Example of GSA results; X-axis time in days and Y-axis DO concentration in mg/L in the closing river section, with 0.075-y^{-1} storm (left) and 5-y^{-1} storm (right); the red lines are the 5th and 95th percentiles, the blue line is the median, the black line the current situation.

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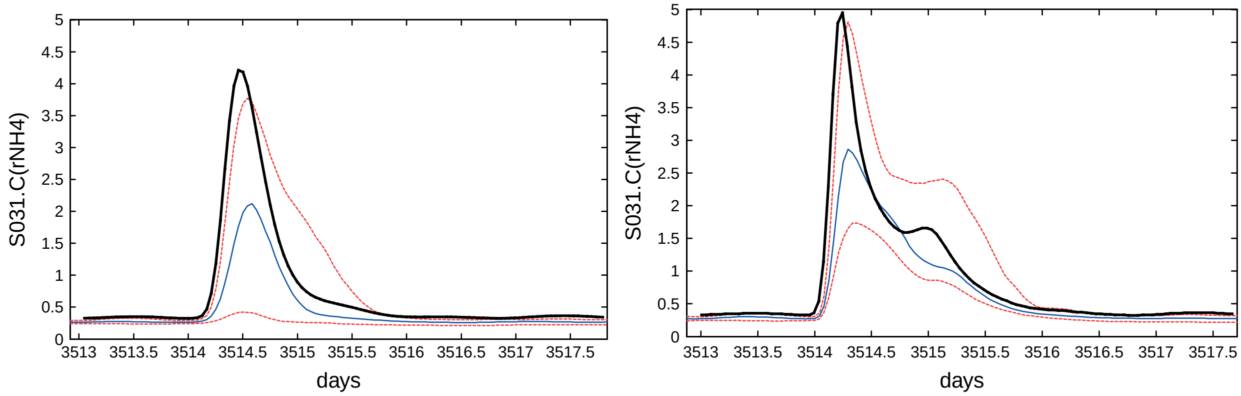

Figure 10. (Colour online) Example of GSA results; X-axis time in days and Y-axis NH_4 concentration in mg/L in the closing river section, with 0.075-y^{-1} storm (left) and 5-y^{-1} storm (right); the red lines are the 5th and 95th percentiles, the blue line is the median, the black line the current situation.

Q_{max} (-) and Q_{buffer} (-), for NH_4 they are the same, but in a different order and different sign C_{24} Q_{max} (+), $Q_{biology}$ (-) and Q_{buffer} (+). This means that in the closing river section for both DO and NH_4 it is beneficial e.g. to send as much wastewater to the WWTP as possible (an increase in $Q_{biology}$ increases the minimum DO and decreases the maximum ammonium). The operational parameters at the WWTP, such as the mixed liquor suspended solids (MLSS) concentration, return activated sludge rate (RAS) and NH_4-DO aeration cascade controller set-point show to have significantly less impact. The sensitivity on control of the river diversion works is not high in the closing river section. In the sections upstream of the WWTP, the river diversion factor is a relevant parameter with a positive impact on DO and negative for ammonium, due to a relatively high background concentration in the river base at the time.

The results for the medium and large storm are comparable to the result for the small storm in terms of showing the same parameters to be most sensitive. The ranking of parameters and the direction of their contribution varies between events and between locations along the river.

Over all, the GSA showed that measures that are positive for DO are not always positive for ammonium, thus confirming literature that these two objectives can be conflicting (Rauch and Harremoës 1999).

As stated before, the results of the GSA are based on an older version of the integrated model. The most noticeable difference between the older version used for the GSA and

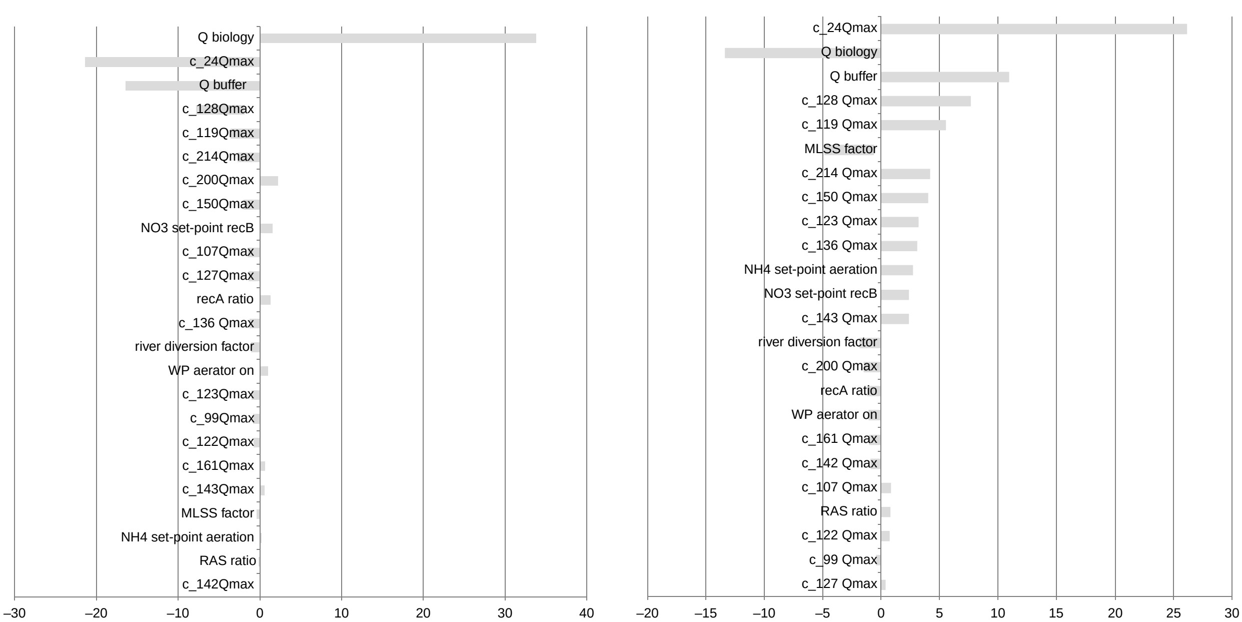

Figure 11. Example of GSA results; regression coefficients (as % of total sensitivity) ranking the sensitivity of operational parameters on the minimum DO (left) and maximum NH_4 (right) in the closing river section for the small storm.

in the latest version used for the assessment of RTC strategies are lower ammonium peaks (5 mg N/l for the large storm in the older version and 3.3 mg N/l in the latest version) and more delayed DO depletion in the Dommel River, lasting three days longer in the latest version of the model. The objective of the GSA was to identify the most sensitive operational parameters. As the improvements made to the integrated model are not related to operational parameters and the sensitivity was analyzed per receiving water quality problem, the results of the GSA in terms of relative contribution to receiving water quality are still valid.

Table 5. Control rules per strategy.

Strategy 0, RTC general.

Strategy 0, "RTC general" has the following rules:

1. If the degree of filling of the RBT > 90%, then reduce discharge of pumps of the catchments to the indicated limited flow rate as long as these catchments have free storage capacity available.

Overview of default and limited flows at the locations controlled to reduce RBT spilling.

	Aalst pumping station (AG)	Eindhoven Stad (ES)	RioolZuid (RZ)	NuenenSon (NS)
Default flow (m^3/h)	7560	15,000	17,000	3000
Limited flow (m^3/h)	4000	11,000	12,000	2500

2. And if the local degree of filling of a catchment exceeds 90%, then the pumps are switched back to the default flow capacity.

3.If the degree of filling of the transport sewer downstream of control station De Meeren > 90%, then throttle the flow of CS De Meern at 1500 m^3/h.

Strategy 1, Minimisation of ammonium peaks.

Strategy 1 NH4 builds on strategy 0 RTC general by adding the following rules:

4. If the total inflow at the WWTP > 15.000 m^3/h then switch of pumps serving the RioolZuid catchment as long as the degree of filling of RioolZuid < 90% of the total storage capacity of 31,072 m^3 and switch of the pumps serving the NuenenSon catchments as long as the degree of filling of the NuenenSon transport sewer < 90% of the total in pipe storage capacity of 5317 m^3 and limit the flow of Aalst pumping station to 4000 m^3/h.

This rule activates the in sewer storage capacity.

5. If the degree of filling of RioolZuid exceeds 90%, then allow pumps serving RioolZuid to pump at maximum capacity (17,000 m^3/h) and start using the RBT with the flow from catchment Eindhoven City.

This rule prevents unnecessary CSO discharges in RioolZuid

6. If the degree of filling of the transport sewer between control station De Meern and Aalst pumping station < 90% of the total volume of 7598 m^3, then Aalst pumping station discharges at maximum 4000 m3/h, else Aalst pumping station discharges at a maximum flow of 7560 m^3/h.

This rule prevents unnecessary CSO discharges upstream Aalst pumping station

7. if the CSOs in Eindhoven stad start operating, switch setpoint of river diversion works from 1.5 m^3/s to 3 m^3/s.

This rule will increase dilution by increasing the river baseflow

Strategy 2, RTC DO.

The RTC DO strategy builds on strategy 0. RTC general.

8. If the degree of filling of downstream interceptor sewers > 20% then catchments with green buffers discharge with a limited pumping capacity of 1.5 times DWF, else full pumping capacity is made available

9. If the degree of filling of the Eindhoven stad catchment > 80% then storage tanks empty at a maximum capacity of 3 times DWF, else if the degree of filling of the Eindhoven stad catchment < 50%, storage tanks are emptied at full capacity.

Strategy 3. RTC DO-NH_4.

This strategy also builds on strategy 0 and combines all the rules from strategy 1 and strategy 2.

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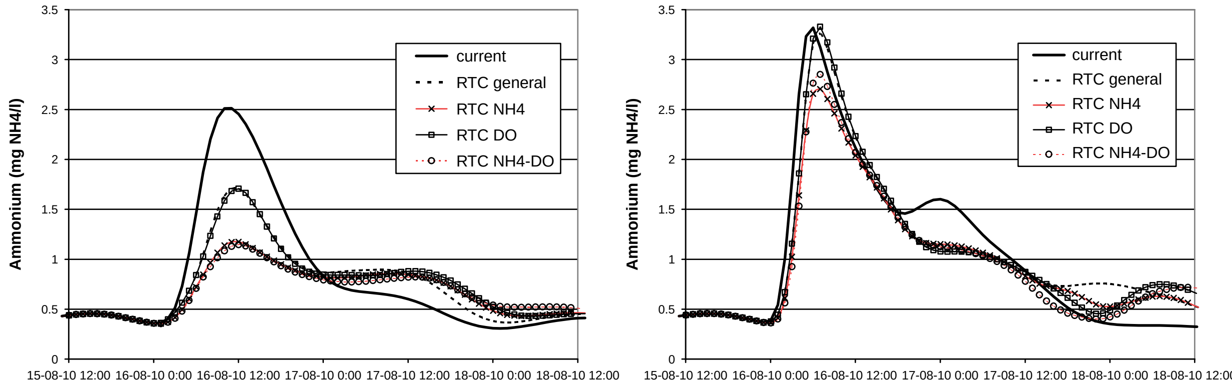

Figure 12. Impact of applying RTC strategies on ammonium concentration in the Dommel River downstream of Eindhoven for a small storm event (left) and for a large storm event (right).

3.2. *Impact-based RTC strategies*

The GSA revealed the possible impact of optimizing each controller. Four strategies have been developed and tested with the integrated model. Each strategy is implemented by employing if-then-else rules in the integrated models. These if-then-else rules allow straightforward testing of the strategy. These rules will be refined and optimised during the anticipated full scale testing. The rules for each strategy are shown in Table 5.

Strategy 0. RTC general. Improved use of the rain buffer tank (RBT) at the WWTP and of the control station De Meren. This strategy aims at minimizing the emission (in terms of pollutant load) from the Eindhoven sewer system, as the effluent of the RBT is less polluted (settled) than untreated CSO discharges from Eindhoven and at preventing unnecessary CSO events of CSO Veldhoven Krooshek, a CSO located in the transport system (see Langeveld and Clemens 2013). CSO Krooshek has to function as emergency overflow, but, due to changes over time in the operation of the transport system, it spills very regularly for long durations, see Figure 8.

Strategy 1. Minimization of ammonium peaks in the river. The GSA revealed that ammonium peaks are mostly due to the WWTP effluent. This strategy aims at minimizing the impact of storm events on WWTP performance by retaining the flow as much as possible by dynamically activating the in-sewer storage (indicated as "*RTC NH4*").

Strategy 2. Minimization of dissolved oxygen dips in the river. This strategy maximizes the use of the hydraulic capacity of the WWTP and the available storage volume in sewer districts with storm water settling tanks and green buffers with a typical storage capacity of 120 m^3/ha of connected impervious area in order to minimize the untreated discharge by CSOs (indicated as "*RTC DO*").

Strategy 3. Combination of the previous two, resulting in multi-objective optimization, as they have conflicting objectives (indicated as "*RTC NH4-DO*").

The impact of the strategies on ammonium and DO in the receiving water quality are respectively given in Figures 12 and 13 for the small and large storm events used in the GSA. For the small event, *RTC General* and *RTC DO* reduce the ammonium peaks in the Dommel River from 2.5 mg N/l to 1.7 mg N/l. The *RTC NH4* and *RTC*

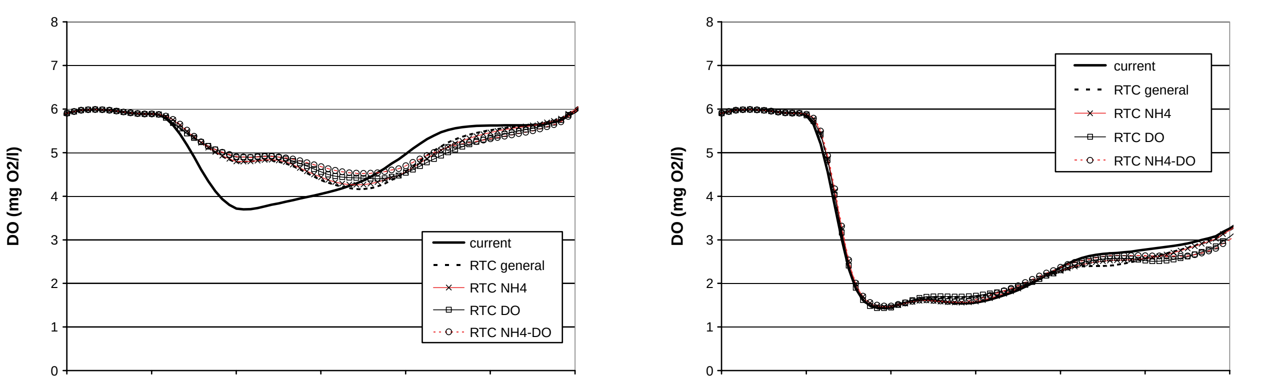

Figure 13. Impact of applying RTC strategies on DO concentration in the Dommel River downstream of Eindhoven for a small storm event (left) and for a large storm event (right).

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Table 6. Assessment of the potential of impact-based RTC based on 10-year time series, in the closing river section; for each scenario, at the right side the 12 criteria are given with their numerical value, while at the left side the classes 1 or 2 in white cells identify criteria for which the allowed frequency is not exceeded, and the classes 3, 4 and 5 in gray cells identify criteria for which the allowed frequency is exceeded.

NH_4 critical		*Duration of the event*			current						RTC gen.						RTC NH_4						RTC DO						RTC NH_4-DO					
		1–5 h	**6–24 h**	**> 24 h**																														
Tolerated	**12**	1.5	0.7	0.3	2	5	5	11.7	60.2	45.6	3	5	5	12.8	65.4	39.9	2	5	5	10.0	65.4	41.0	3	5	5	13.1	69.7	38.1	2	5	5	9.0	67.9	38.4
frequency	**4**	2	1.2	0.5	5	5	5	12.9	54.4	36.8	5	5	5	9.6	42.8	39.3	4	5	5	5.0	29.6	38.4	5	5	5	9.3	41.6	39.6	3	5	5	4.6	26.7	39.8
per year	**1**	2.5	1.5	0.7	5	5	5	11.1	41.3	18.9	5	5	5	4.4	26.5	16.1	5	5	5	2.6	15.0	14.5	5	5	5	3.6	25.2	14.4	5	5	5	2.5	13.1	12.8
	0.2	4.5	3	1.5	1	5	4	0.0	0.7	0.3	1	2	2	0.0	0.2	0.2	1	1	1	0.0	0.1	0.1	1	4	2	0.0	0.3	0.2	1	1	1	0.0	0.1	0.1
DO critical	Duration of the event																																	
		1–5 h	**6–24 h**	**> 24 h**																														
Tolerated	**12**	5.5	6	7	1	5	5	4.1	38.6	30.7	1	5	5	4.5	30.9	29.8	1	5	5	4.0	29.8	29.7	1	5	5	4.9	29.3	29.2	1	5	5	3.2	28.6	29.0
frequency	**4**	4	5.5	6	1	5	5	1.0	23.9	18.8	1	5	5	1.4	17.4	17.6	1	5	5	1.0	15.4	17.4	1	5	5	0.8	16.7	17.1	1	5	5	0.6	15.9	16.5
per year	**1**	3	4.5	5.5	1	5	5	0.3	9.0	11.6	1	5	5	0.4	6.2	10.1	1	5	5	0.2	5.1	10.3	1	5	5	0.3	6.6	9.8	1	5	5	0.3	5.4	8.6
	0.2	1.5	2	3	1	4	5	0.1	0.4	1.5	1	5	5	0.1	0.8	1.3	1	5	5	0.0	0.8	1.3	2	5	5	0.2	0.9	1.3	1	5	5	0.0	0.9	1.2
DO basic	Duration of the event																																	
		1–5 h	**6–24 h**	**> 24 h**																														
Tolerated	**12**	3	3.5	4	1	1	1	0.3	1.6	2.2	1	1	1	0.4	2.0	2.4	1	1	1	0.2	1.9	2.4	1	1	1	0.3	1.7	2.2	1	1	1	0.3	1.5	2.0
frequency	**4**	2.5	3	3.5	1	1	1	0.2	0.8	1.7	1	1	1	0.5	1.1	1.6	1	1	1	0.3	1.3	1.7	1	1	1	0.3	1.1	1.7	1	1	1	0.3	1.1	1.8
per year	**1**	2	2.5	3	1	3	4	0.0	1.1	1.5	1	2	4	0.0	0.7	1.3	1	2	4	0.0	0.8	1.3	1	2	4	0.0	0.7	1.3	1	2	3	0.1	0.7	1.2
	0.2	1	1.5	2	1	4	4	0.0	0.3	0.3	1	4	2	0.0	0.4	0.2	1	4	2	0.0	0.3	0.2	1	2	2	0.0	0.2	0.2	1	4	2	0.0	0.3	0.2

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NH4-DO strategies do even better and reduce the ammonium peak to 1.2 mg N/l. For the big event, the reduction of the peak ammonium concentration in the Dommel River is smaller. The best strategy, *RTC NH4*, results in a decrease in the peak concentration from 3.3 to 2.7 mg N/l, while *RTC general* and *RTC DO* do not improve the situation.

With respect to DO, for the small storm all RTC strategies improve the river water quality. They all delay the DO dip and increase the lowest concentration from 3.8 to around 4.2 mg O_2/l. For the big storm, none of the control strategies has an impact on the DO dip. This 5-y event is 'beyond control', i.e. largely exceeds the system capacity. This clearly shows the limits of the RTC potential.

For ammonium, RTC has significant potential, whereas for DO this potential is only available for smaller storms. The results also reveal that the optimal strategy depends on the type of event, indicating that weather forecasts, possibly short-term radar or 'nowcasting', should be incorporated in the development of the control system and decision support system in which it will be embedded. The quality of the forecasts, however, still requires further improvement as state of the art nowcasting (e.g. Achleiter et al. 2009) does not yet produce results accurate enough to be quantitatively applied in control systems.

The examples of a small and big storm given in Figures 12 and 13 illustrate the potential impact of the derived RTC strategies. In order to be able to assess the potential of RTC to improve the ecological conditions in the Dommel River, a 10-year time series (years 2001–2010) has been run with the integrated model and then evaluated using the framework shown in Table 2. The results of this evaluation are given in Table 6, using a five class ranking, which is typical for WFD reports:

- Class 1 simulated frequency less than 0.5 times the tolerated frequency.
- Class 2 simulated frequency less than 1 time the tolerated frequency.
- Class 3 simulated frequency more than 1 time the tolerated frequency.
- Class 4 simulated frequency more than 1.2 times the tolerated frequency.
- Class 5 simulated frequency more than 2 times the tolerated frequency.

With respect to ammonium, the *RTC NH4* and *RTC NH4-DO* scenarios reduce the exceedance of the threshold values, especially for short and medium durations and for events with a higher return period/lower frequency per year. E.g., in the current situation the threshold of 1.5 mg N/l is exceeded 41.3 times per year for durations between 6 and 24 h, where one time per year is tolerated. The *RTC NH4* and *RTC NH4-DO* scenarios reduce this exceedance frequency to 15.0 and 13.1 times per year, which is a significant reduction. The *RTC General* and *RTC DO* scenarios also improve the situation, but not to the same extent. Though, these reductions achieved are not sufficient to be able to meet the requirements with RTC as a sole measure to prevent ammonium peaks above the threshold.

With respect to DO, the *RTC DO* scenario nearly solves the exceedance of the standards for 'DO basic' which is sufficient to accommodate less critical species. The *RTC DO* scenario performs better on this criterion than the other scenarios. For the DO critical criterion, the improvement of none of the RTC scenarios is sufficient to meet this.

The results show that even though RTC is insufficient as a sole measure to meet the criteria, the number of exceedances for ammonium and DO decrease significantly for some RTC strategies. This shows that with the simple and inexpensive RTC strategies applied, the performance of the integrated urban wastewater system can be improved significantly compared to current operation. It is concluded that RTC can significantly contribute to the performance of the IUWS. The extent of the impact depends on the type of event and on the objective selected for evaluation.

4. Conclusions

In this paper we described the procedure applied to identify the potential for impact-based real-time control for improvement of the Dommel River water quality, using an integrated model for the urban wastewater system. As the integrated model was our 'working tool', much attention has been paid to the development and calibration of the detailed sub-models for sewer, WWTP, and receiving waters. This focus on the quality of the sub-models proved to be necessary, as during the calibration of these sub-models many errors in underlying databases and operational set-points have been detected. Without this calibration, large errors would have been incorporated in the integrated model, likely resulting in erroneous conclusions.

The GSA proved to be a powerful tool to identify the control structures with a significant impact on receiving water quality. The results of the GSA, combined with the knowledge on the dynamics of the integrated system derived from the model calibration phase, allowed the definition of RTC scenarios.

Based on the evaluation of the RTC scenarios it is concluded that for the Eindhoven case:

- Impact-based RTC can improve receiving water quality significantly using available control structures.
- The impact of the RTC scenarios evaluated is insufficient to be able to meet the water quality requirements without additional measures.

- Minimizing DO depletion or ammonium peaks requires a different strategy. The 'optimal' strategy in this case will be the one that requires the least additional measures. This issue is addressed further within the Kallisto project.

Based on the results of this project, Water Board De Dommel will further develop the impact based RTC concept and perform full scale testing of the derived strategies.

Acknowledgements

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Appendix: Supplementary material

Table 1. Characteristics of the Eindhoven Urban Wastewater System.

Criterion	Evaluation	Eindhoven case
A. Catchment	Scores (value in brackets)	
A.1 Catchment area (Flow length in the main collector)	Long > 5 km (2) Medium (1) Short < 1 km (0)	30 km (2)
A.2 Differences between current and planned development of the area	Large (2) Small (1) None (0)	None (0)
B. Wastewater production		
B.1 Areas with increased pollution of surface runoff	Several (2) 1–2 (1) None (0)	None (0)
B.2 Variability in time and space of wastewater production (e.g. producers of heavily polluted wastewater, connections from separate systems)	High (2) Medium (1) None (0)	High (2)
C. Sewer system		
C.1 Number of existing control devices (e.g. pumps, slides, weirs)	Several (4) 1–2 (2) None (0)	44 (4)
C.2 Slope of trunk sewers	Flat < 0,2% (4) Medium (2) Steep > 0,5% (0)	Flat (4)
C.3 Capable loops in the sewer system	Several (4) 1–2 (2) None (0)	None (0)
C.4 Number of existing storage tanks (tanks and storage pipes > 50 m^3)	> 4 (4) 1–4 (2) 0 (0)	
C.5 Number of discharge devices		200 (4)
C.6 Total storage volume (tanks and storage pipes)	> 6 (4) 2–6 (2) 52 (0) > 5000 m^3 (4) 2000–5000 m^3 (2) < 2000 m^3 (0)	280.000 m^3 (4)
C.7 Specific storage volume (= total storage volume related to impervious area)	> 40 m^3/ha (4) 20–40 m^3/ha (2) < 20 m^3/ha (0)	> 70 m^3/ha (4)
C.8 Number of collectors to the WWTP	> 2 (3) 2 (1) 1 (0)	3 (3)
D. Operational system behaviour		
D.1 Local flood areas		None (0)
D.2 Number of non-uniformly used tanks	Several (2) 1–2 (1) None (0) > 1 (4) 1 (2) None (0)	> 1 (4)
D.3 Non-uniform discharge behaviour		Significant (4)
E. Receiving water	Significant (4) Medium (2) Insignificant (0)	
E.1 Local differences in hydraulic capacity	Strong (4) Medium (2) None (0)	Medium (2)
E.2 Local differences of load capacity (e.g.swimming, fish farming, protected areas)	Significant (4) Medium (2) Insignificant (0)	Medium (2)
E.3 Sensitivity of the receiving water body	Very sensitive (2) Less sensitive (0)	Very sensitive (2)
F. Wastewater treatment plant (WWTP)		
F.1 Admissible combined wastewater inflow	(*) > 1,0 $f_{S,QM}$ _$Q_{S,aM}$ + $Q_{F,aM}$ (3), = $f_{S,QM}$ _$Q_{S,aM}$ + $Q_{F,aM}$ (1) < f $f_{S,QM}$ _$Q_{S,aM}$ + $Q_{F,aM}$ (0)	> 1,0 (3)
F.2 Sensitivity of WWTP to hydraulic or pollutant peaks	Very sensitive (2) Less sensitive (0)	Very sensitive (2)
Total score (Scores: 0–24: probably not suitable for RTC, 25–35: probably suitable for RTC, > 35 very suitable for RTC)		46

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