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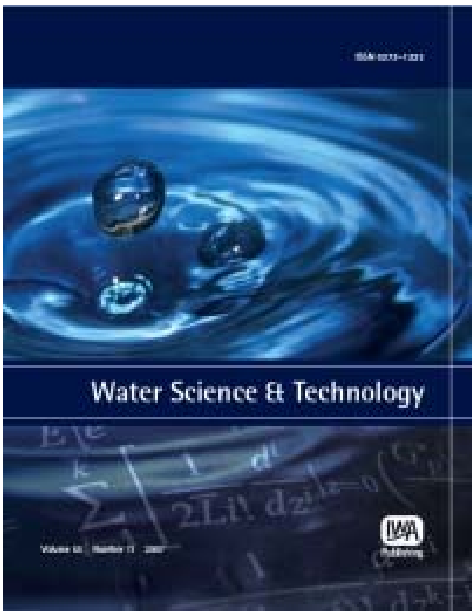
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Modelling and monitoring of integrated urban wastewater systems: review on status and perspectives

Lorenzo Benedetti, Jeroen Langeveld, Adrien Comeau, Lluís Corominas, Glen Daigger, Cristina Martin, Peter Steen Mikkelsen, Luca Vezzaro, Stefan Weijers and Peter A. Vanrolleghem

ABSTRACT

While the general principles and modelling approaches for integrated management/modelling of urban water systems already present a decade ago still hold, in recent years aspects like model interfacing and wastewater treatment plant (WWTP) influent generation as complements to sewer modelling have been investigated and several new or improved systems analysis methods have become available. New/improved software tools coupled with the current high computational capacity have enabled the application of integrated modelling to several practical cases, and advancements in monitoring water quantity and quality have been substantial and now allow the collecting of data in sufficient quality and quantity to permit using integrated models for real-time applications too. Further developments are warranted in the field of data quality assurance and efficient maintenance.

Key words | data quality, integrated urban wastewater system (IUWS) modelling, river water quality modelling, sewer modelling, systems integration, WWTP modelling

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INTRODUCTION

Integrated urban wastewater management presents big challenges but also great opportunities to minimize both the impact on the receiving water and the costs associated with that. Options like impact-based real-time control (RTC), global sewer control, construction of retention volumes and treatment facilities, water reuse, etc. can all be better designed and evaluated by using models and data that include all involved units. The problem becomes more complex, but the larger number of degrees of freedom allows for better solutions to be found. Modelling of the integrated urban wastewater system (IUWS) is a powerful tool to identify synergies and to globally optimize the wastewater system performance, to find more cost-efficient solutions to achieve the desired overflow, effluent and receiving water quality. In general, when we design/upgrade a (wastewater) system, we look first for effectiveness of the design, then for efficiency. It is evident that both can be improved by integration, but that comes at the cost of increasing the complexity of the system to be managed, therefore increasing the apparent uncertainty and the efforts to understand interactions. The positive aspects of complex systems are the synergy effects and the increase in robustness and resilience, all aspects that should be the objectives of good system design, achieved by introducing properties like degeneracy (Whitacre & Bender 2010) and evolvability/adaptiveness.

There is renewed interest in the development and application of improved integrated urban systems modelling tools to support an integrated approach for the assessment and definition of system planning needs, as well as for discharge permit negotiations (Blumensaat *et al.* 2012). This growing need is largely driven by regulatory and economic factors, more specifically, the financial constraints faced by many municipalities in being able to meet multiple regulatory obligations for various components of their urban wastewater and stormwater management systems. In Europe, the Water Framework Directive (WFD) (CEC 2000) requires the adoption of a river basin scale management of water issues and the achievement of full cost recovery of water services. In the USA, the US Environmental Protection Agency (USEPA) recently issued an Integrated Planning and Permitting Initiative (Stoner & Giles 2011) along with an integrated planning framework that will help clean-water agencies, utilities and municipalities identify cost-effective and protective solutions to meet their wastewater and storm water obligations under the Clean Water Act, and then prioritize investments to address the most pressing water quality issues first. The recent development of the Canada-wide Strategy for the Management of Municipal Wastewater Effluent (CCME 2009) and recent (2012) federal regulation under the Fisheries Act (1985) will spur a review of risks for wastewater treatment and combined sewer overflow (CSO) infrastructures, as applicable for receiving water circumstances.

The increasing use of natural waters for recreational purpose (with associated health issues) requires important investments whose impact can be assessed efficiently by using integrated tools. Other incentives for the use of such tools are coming from the demand side, where different water qualities are required by different water users at minimum cost, promoting an efficient (re-)use of water, therefore asking for more integration between water users and producers. At a different level, more integration is also required to increase the energy and nutrient recovery capabilities of wastewater systems. Another issue relates to river quality monitoring; i.e. perturbations in the data that are identified as wet weather influence are only seen in heavily affected rivers, while a fair number of river systems show stochastic behaviour in their quality which is attributed to other factors in the river catchment; this highlights the need for detailed, dynamic modelling as only in this way will the effect of the urban system become visible under the temporal variability induced by other impacts.

The main goal of this paper is to summarize the developments that occurred in the last decade on modelling of IUWSs, taking as a starting point the principles clearly and extensively illustrated by Rauch *et al.* (2002). Those developments fall principally into the domains of computational instruments and monitoring equipment, which both enabled the implementation of full-scale integrated models used for decision making in engineering projects. Some recently published practical examples of the latter are also summarized from that point of view. Finally, perspectives on expected research and development are introduced.

MODELLING

Sub-models

In catchment/sewer modelling the main distinction is between models with full hydrodynamics (de Saint-Venant equations) in terms of partial differential equations (PDEs) and models with simplified hydrodynamics (tanks-in-series (TIS) approach) written as ordinary differential equations (ODEs). In the first type of models usually the spatial discretization is finer (a larger number of smaller catchments and pipes), so that the combination of PDEs and more complex models leads to much longer simulation time (orders of magnitude) than in the second type of models for the same systems. Of course, full hydrodynamic models provide more detailed information, especially on water levels and velocities, but the results obtained with simplified ODE models are usually of sufficient quality for the main purpose for which they are developed, i.e. predicting water flows and volumes in the context of water quality studies.

One of the weak points in urban wastewater studies remains to be the reliability of water quality models for the sewer system (Bertrand-Krajewski 2007), due to the limited knowledge on the chemical, biological and transport processes occurring in the sewers and on the systems characteristics affecting physical–chemical processes like sedimentation and resuspension. Several specific process models were published, but their applicability is usually limited to the local conditions for which they were developed. Some examples are: (1) sulphide control (Sharma *et al.* 2008; Vollertsen *et al.* 2011), (2) methanogenesis (Guisasola *et al.* 2009), and (3) sewer exfiltration (Ellis *et al.* 2009). In order to predict the water quality of CSOs, alternatives to process models are empirical models based on CSO monitoring (Mourad *et al.* 2006; Schilperoort *et al.* 2012). As for the prediction of the wastewater treatment plant (WWTP) influent quality, either the same methods as for CSOs can be adopted (sewer process or empirical models) or dedicated approaches can be developed, i.e. WWTP influent generators, described below in a dedicated section.

A recent addition to sewer models is the introduction of a description of overland flow (Maksimović *et al.* 2009), which enables the modelling of urban pluvial flooding using high-resolution, accurate digital elevation model data collected by, for example, the LiDAR technique. The main focus in the literature is on the issue of computation times and the selection of an appropriate schematization (1D/2D) (Leandro *et al.* 2009). Other issues are related to difficulties in calibration of the parameters describing the runoff routing process in the 2D model, as the identifiability of all these parameters is very low because typically monitoring data are only available in the sewer and not on the contributing areas nor in the gully pots.

For WWTP models, activated sludge models (ASMs) are still state of the art (Gernaey *et al.* 2004), normally used in combination with TIS hydraulic modelling. Several ASM extensions have been published for specific purposes (see Corominas *et al.* (2010) for a list), and some may be of interest for applications of integrated modelling, e.g. Guo *et al.* (2012) and Vezzaro *et al.* (submitted).

Hydraulic river models can be divided into PDE and ODE models in the same way as for the sewer models, while for river water quality, the main advancements toward model integration have happened already with the work of Reichert *et al.* (2001), with the harmonization of state variables in ASMs and the river water quality model.

WWTP influent generators

In the context of integrated urban wastewater modelling, the WWTP influent is the outcome of the sewer model. However, given the difficulty of mapping the water quality from its very source (dwelling appliances, stormwater, urban wash off, groundwater infiltration) (Butler *et al.* 1995; Almeida *et al.* 1999; Bechmann *et al.* 1999; Ort *et al.* 2005) and the different levels of complexity of the sub-models involved, WWTP influent models have become useful tools to complete the information provided by the sewer model or to check its quality (Devisscher *et al.* 2006; Langergraber *et al.* 2008; Mannina *et al.* 2011). Indeed, water quality from sewer models is often limited to suspended solids and one or a few soluble pollutants, whereas the ASMs require more detailed composition information.

Simple influent models based on the use of harmonic functions (second order Fourier series) have been used to describe diurnal variations of wastewater flow and concentration in dry weather conditions (Carstensen *et al.* 1998; Langergraber *et al.* 2008). The parameters of these models should be adjusted for each case study, although (in general) they are largely correlated with the size of the plant under study, which allows some approximate values to be found (Langergraber *et al.* 2008). These models have been successfully applied for influent flow forecasting (Carstensen *et al.* 1998), design studies (Alex *et al.* 2007; Spering *et al.* 2008) and operation and control performance evaluation (Alex *et al.* 2009).

Another set of solutions has been based on the construction of databases. The idea is to learn from the available data and to generate new data sets in coherence with the patterns observed. This approach is very flexible and has been used with very different purposes, for example to show the benefits of using advanced control in wastewater treatment plants (Devisscher *et al.* 2006), or to model the micro-pollutants release in urban areas (De Keyser *et al.* 2010).

A third set of solutions for influent generators has been based on the use of phenomenological (mechanistic) models. In this line of thought, the model of Gernaey *et al.* (2011) – originating from a disturbance scenario generator included in the Benchmark Simulation Model No. 2 (Nopens *et al.* 2010) – provides a time series of dynamic influent data of flow rate, temperature and pollutant concentrations in terms of the state variables of ASM1, ASM2d or ASM3 models (as desired). The main advantage of this generator is that the user can introduce data about the catchment area (number of person equivalents, sewer network complexity, relationship between impermeable and permeable areas, frequency of rain events, etc.) or hypothetical scenarios (neighbourhood growth, new industrial discharges, different rainfall characteristics, etc.) and generate influent data profiles according to that. Early applications of this approach have shown its usefulness to produce uncertainty analysis frameworks (Benedetti *et al.* 2008), in applications of artificial neural networks for WWTP performance assessment (Ráduly *et al.* 2007), or even in the context of micro-pollutants fate modelling (Lindblom *et al.* 2006).

Integration

One of the challenges in model integration is the linking between the different water quality models, which usually have different sets of state variables. The simplest approach is to fractionate or aggregate analogous state variables, developing one model connector for each couple of models (Benedetti *et al.* 2004). This approach has evolved into a formalized method which ensures closed elemental mass and charge balances (Vanrolleghem *et al.* 2005b). Another option that would be available, but has so far been applied only to linking unit models within the WWTP fence, is to develop a model that can be applied to all system units with one set of components (therefore no need for coupling) with processes that switch on or off according to environmental conditions (Grau *et al.* 2007).

Concerning software aspects of model coupling, in case different software packages have to be connected to make an integrated modelling exercise, the OpenMI platform is an available tool (www.openmi.org). It requires the software to be linked to be modified to comply with the OpenMI requirements, and it also introduces simulation overhead because of the need to exchange data between software (Leta *et al.* 2012). In the particular case of 'simplified' models (e.g. with only ODEs), the possibility to implement all of them in the same modelling software is also available. This allows: (1) the communication problems between different software platforms to be overcome, which reduces the possible scenarios to be run that require true integration, especially regarding integrated RTC; and (2) the simulation speed problem of the detailed models to be overcome, allowing reduction of the time needed to run each (long-term) scenario by several orders of magnitude (Benedetti *et al.* 2009). This approach has been adopted using commercial software like WEST (www.mikebydhi.com) – by for example Vanrolleghem *et al.* (2005a), Benedetti *et al.* (2009) – and SIMBA (www.ifak.eu) – by for example Erbe & Schütze (2005), or with specifically developed research tools, for example by Fu *et al.* (2009b) and Freni *et al.* (2010).

Systems analysis

Thanks to developments in computational efficiency of the above-mentioned software tools and to the increase in hardware computational power, the possible uses of integrated modelling have largely expanded. It is currently possible to apply sensitivity and uncertainty analysis methods using Monte Carlo (MC) simulations to such IUWS models, either during the model development process or during model use – see for example Astaraie-Imani *et al.* (2012), Benedetti *et al.* (2008, 2010), Freni *et al.* (2011), Fu *et al.* (2009a) and Langeveld *et al.* (2012) – and long-term simulations can be conducted as well, including the study of integrated RTC – for example Achleitner *et al.* (2007) and Langeveld *et al.* (2012).

MONITORING

The literature on monitoring in IUWS typically focusses on sensor development, data acquisition and data management. However, appropriate models require more than sensor data only. Figure 1 distinguishes three groups of data which are relevant to create and evaluate models. The three main groups of data distinguished are as follows.

- *Basic data, comprising system data, control algorithms and setpoints*. These information sources describe the characteristics of a wastewater system. In addition, they describe the components to be managed and the performance requirements of each component.
- *Complementary data, comprising data on observed wastewater system behaviour*. Inspections, observations and complaints comprise data which are not driven by the process and have a very incidental character. They provide additional, but often essential, information on the

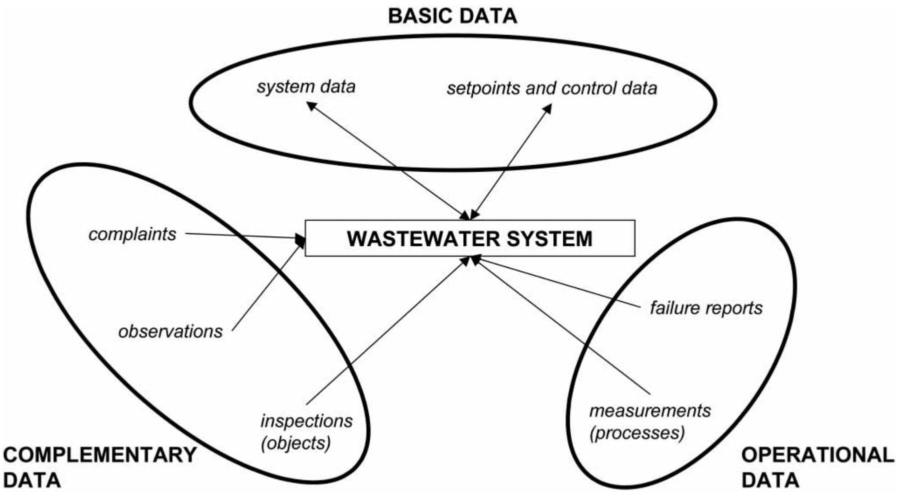

Figure 1 | Operation and maintenance data for wastewater systems.

performance of (components of) the wastewater system. Inspections, for example, enable condition monitoring of components such as sewers, pumping stations and clarifiers, which later can be incorporated in the models or used to explain differences between model results and monitoring data. However, the inspections of different parts of the wastewater system are not uniform because methods and frequencies largely differ.

- *Operational data, comprising data typically related to process control and operation*. This includes measurements and failure registrations. Failure registrations and process data are normally collected for several purposes, including warning the maintenance service, process control or assessment of wastewater system performance. They describe the actual performance of (a component of) the wastewater system.

The combined data of these three groups provide the information necessary to assess IUWS performance. This section further describes the developments in sensors and automation of the last decade. Complementary information can be found in Campisano *et al.* (2013).

Continuous monitoring has seen rapid development, made possible by the development of reliable and robust sensors (increasingly allowing monitoring in harsh environments like sewers) and the availability of computational power (enabling the processing of very large datasets) and developments in telecommunication/internet (allowing efficient data collection). The state of the art in monitoring is discussed for three sectors of interest: precipitation, hydraulics and water quality.

Precipitation

Traditional tipping buckets or rain gauges based on weighing precipitation are still commonly applied. Especially in urban areas, it is hard to find locations suitable for proper installation of these rain gauges to meet the World Meteorological Organization requirements (WMO 2008). In addition, it is widely recognized that in order to be able to assess, for example, urban flooding with 1D/2D models, a dense network with a high spatial and temporal resolution is a prerequisite. This need for high quality data from dense networks stimulates research in alternatives to traditional rain gauges. Latest developments are acoustic disdrometers (Winder & Paulson 2012), optical disdrometers (Jaffrain *et al.* 2011), the use of microwave links from commercial cellular communication networks (Overeem *et al.* 2011) and various applications of X- and C-band radar (Einfalt *et al.* 2005; Shepherd *et al.* 2009). When these new types of precipitation monitoring data are appropriately calibrated, integrated modelling can benefit from precipitation data with both a high temporal and spatial resolution.

Hydraulics in sewers, pumping stations, WWTPs and rivers

Monitoring hydraulics in wastewater systems is a routine activity for many wastewater system operators (Olsson 2012). In sewers and pumping stations, pressure sensors are most commonly applied. In addition, ultrasonic level sensors have seen a widespread application for situations with sufficient free space above the maximum water level. Electromagnetic flow monitoring is still the most reliable method to monitor flow in completely filled conduits. For open channels, image processing is an interesting new technique for flow monitoring (Jeanbourquin *et al.* 2011).

Water quality

The holy grail in IUWS monitoring is the development of reliable and affordable sensors for continuously monitoring water quality. Métadier & Bertrand-Krajewski (2011) give an interesting example of the added value of continuous monitoring for the analyses of dynamics of sewer systems. WWTP effluent has shown to be the flow most easy to monitor. The more upstream in a WWTP or even in a sewer, and the more downstream (in the receiving water), the more difficulties arise in monitoring due to the harsh environment in sewers, and specific requirements arise such as no interference with (sediment) transport processes complicating monitoring water quality. Conversely, water quality monitoring in WWTPs has already a long history of successful applications, although the level of success is strongly correlated to the added value of the sensor to the operator (Olsson 2012): the lower the added value, the less effort is invested in operation and maintenance of the sensor, thus rapidly resulting in unreliable data.

Recent developments in water quality sensors are distributed temperature sensing, allowing the monitoring of temperature at a fine spatial and temporal scale (Hoes *et al.* 2009; Tyler *et al.* 2009), UV-visible (UV-VIS) sensors allowing the monitoring of a range of substances, such as chemical oxygen demand (COD), NO_3 and total suspended solids (Gruber *et al.* 2006; Schilperoort *et al.* 2012) and passive samplers (Blom *et al.* 2002). In addition, a renewed attention is being given to the combination of available robust sensors such as conductivity and turbidity and to relate these signals to a parameter of interest, e.g. COD or P_{total} (Lepot *et al.* 2012).

Recent developments of sensors at WWTPs mainly aim at improving their reliability (Rieger *et al.* 2005).

Outlook on monitoring

Advances in sensor technology, telecommunication and computational power are increasing the availability of affordable and reliable sensors for monitoring the data required for integrated assessment of urban (waste)water systems. The main challenges for widespread application are maintenance of monitoring equipment and timely detection of malfunctioning sensors in order to achieve an acceptable level of data availability. Missing data on, for example, precipitation can render a complete data set useless for calibration of integrated models.

A first step to achieve an acceptable level of data availability is designing monitoring networks with sufficient redundancy to account for inevitable data losses and to extend the monitoring period long enough to be able to capture the relevant phenomena. Apart from this, significant efforts have to be made towards increasing the availability of rapid and thorough data validation routines for routinely assessing the quality of the monitoring data and professional data management (Bertrand-Krajewski & Muste 2008; Rieger & Vanrolleghem 2008; Schilperoort *et al.* 2008; Alferes *et al.* 2012). These validation routines can also be used to direct cleaning and maintenance of sensors (Rieger & Vanrolleghem 2008).

EXAMPLES

Three cases where integrated modelling and monitoring are applied in practice are provided here. They have been selected among published studies (where the reader can find more details) to show how the capabilities of current integrated modelling tools allow real problems to be solved and support to be provided for actual decision making, rather than remain at the (semi-)hypothetical level as most of the literature contributions on the subject have been in the last decades. Other examples of recent IUWS modelling applications can be found, for example, in Blumensaat *et al.* (2009) and Pawlowsky-Reusing *et al.* (2008).

Congost

In the Congost catchment (north-east Spain), streams are characterized by harsh hydrological fluctuations, with very low flow rates in summer and high flow rates in autumn. During low river flow conditions, WWTP discharges contribute significantly to the total river flow (up to 50%) and hence their impact can be very high. There are also disturbances affecting the system (e.g. rain or changes in the wastewater loads) and process failures (e.g. problems in the blowers of the WWTPs) which can be tackled with integrated management of the urban wastewater system. Together with the water-board in charge of sanitation around the Congost catchment (CDCRB) research has been conducted in the last 10 years to find solutions to confront these problematic situations by means of integrated modelling. The real case study (area of 70 km^2 with a total connected population of 100,000 inhabitants) includes two sewer systems, two WWTPs (one smaller upstream, La Garriga WWTP, and one larger downstream, Granollers WWTP), an operational connection channel between the two WWTPs, storage tanks and a river stretch.

In a first stage of the studies that started 10 years ago the selected software packages to model hydraulics and water quality were Infoworks CS, GPS-X and Infoworks RS for the sewer systems, WWTPs and river respectively. Besides these, a specific piece of software was developed to transfer data between the modelling software packages. Once this model integration platform was built and calibrated (Devesa 2006), and taking into account the expert knowledge of the CDCRB managers, several management scenarios were evaluated (Devesa *et al.* 2009).

In a second stage, an integrated model was built in WEST, which thanks to its increased computational efficiency allowed MC simulations and a global sensitivity analysis to be conducted to identify the most important operational settings and to perform a screening of the best combinations of operational settings with respect to immission-based river water quality criteria. The results for all studied scenarios are summarized in Table 1. The percentage of improvement calculated from the results obtained with current operating conditions compared to the best combinations of operational settings obtained from the simulation exercises is shown for the two connected wastewater systems and for two criteria, the minimum dissolved oxygen (DO min) and the maximum ammonium (NH_4^+ max) in the river. This improvement (very significant for reducing the ammonium peaks) was achieved by properly using the storage tanks before the two WWTPs, by taking advantage of the connection between the plants to allocate wastewater to the most appropriate system, as well as by setting adequate aeration and recycle flow rates (Prat *et al.* 2012a).

Table 1 | Percentage of improvement for the different scenarios after using a model-based approach to find best combinations of operational settings

	Percentage of improvement			
	La Garriga system (river upstream)		Granollers system (river downstream)	
Scenarios	DO min	NH_4^+ max	DO min	NH_4^+ max
Dry weather	5	49	7	22
Storm event	11	60	10	19
High load upstream WWTP	5	43	32	73
High load downstream WWTP	17	70	37	66
Population increase	12	76	1	50
Temperature decrease	–2	55	32	58
Low river flow	13	65	9	28
Blower failure upstream WWTP	34	56	33	68
Blower failure downstream WWTP	9	63	24	56

The expert knowledge together with rules generated from an interpretation of the simulation results is integrated in an environmental decision support system that is helping water managers to take decisions (Prat *et al.* 2012b).

Copenhagen and Aarhus

These two major Danish municipalities have invested considerable resources into the urban re-qualification of dismissed harbour areas during the last decades. As part of these requalification development plans, special attention was paid to achieving bathing water quality in the urban recipient. This resulted in major infrastructural investments (detention basins, elimination of overflow structures, etc.) combined with the implementation of integrated RTC systems.

Integrated urban water models are already applied in the two cities. In both cases detailed hydrodynamic models (based on the MIKE family – www.mikebydhi.com) are combined with weather radar nowcasting to simulate and assess the effect of different integrated control strategies. In Copenhagen, the ISH project (Intelligent Wastewater Handling) led to the integration of a MIKE model of a 76 km^2 catchment with a WEST model of the Lynetten WWTP (750,000 population equivalent (PE)) (Petersen *et al.* 2011). Currently, these models are used by the water utility to evaluate and improve the performance of RTC strategies. In Aarhus the integrated model of the Marselisborg catchment (22 km^2) also includes detailed models for the Aarhus stream, the connected catchment, and the harbour area. The models will be used for controlling the drainage network and monitoring of the quality of the receiving waters (including quality-based warning for bathing areas). The models are expected to be fully operational in summer 2013.

These catchments (and the respective integrated models) represent some of the case studies where the knowledge developed within the Storm- and Wastewater Informatics project (SWI – www.swi.env.dtu.dk) is put into practice by the local water utilities (which also participate in SWI). Within the SWI framework, rainfall nowcasting, based on weather-radar measurements, and hydrodynamic models (both detailed and stochastic) provide estimates of the water fluxes across the urban catchment, allowing a better control and a consequent reduction in the risk of flooding and overflows. Demonstration projects, such as the METSAM project (environmental effective technology for control of drainage and wastewater treatment systems), are already applying these concepts in full scale (Vezzaro *et al.* 2012). Control of WWTP based on catchment flow forecasting is currently applied in the city of Aalborg (Poulsen *et al.* 2013) and it is in the testing phase at the Lynetten WWTP. Future implementation in the next years will include, among others, assimilation of information from on-line sensors into integrated models, water quality-based integrated control, and full integration between catchment and WWTP control strategies.

Eindhoven

The Dommel is a relatively small and sensitive river flowing through the city of Eindhoven (The Netherlands) from the Belgian border in the south into the river Meuse in the north, receiving discharges from over 200 CSOs from 10 municipalities and from the 750,000 PE WWTP of Eindhoven (downstream of the city and of most CSOs). In summer time, the WWTP effluent equals the base flow of 1.5 m^3/s of the Dommel River just upstream of the WWTP, a similar situation as the one at the first case study, Congost. The Dommel River does not yet meet the requirements of the European Union WFD, i.e. the water quality issues to be addressed are DO depletion, ammonia peaks and seasonal average nutrient concentration levels (Weijers *et al.* 2012).

Because solving the water quality issues in a traditional sectored and emission-based approach would result in a very costly set of measures, with uncertain results, the Waterboard De Dommel has invested in gaining more knowledge on system dynamics and performance. Since 2006 an integrated monitoring network in the sewer, WWTP and river has been set up and is being updated and extended to be able to deliver the information required. The monitoring network comprises rain gauges, rain radar, flow and water level sensors in the contributing sewer systems, UV-VIS and ammonium sensors at the inlet of the WWTP, nitrate, ammonium, phosphate and oxygen sensors in the reactors of the WWTP and ammonium and DO sensors in the Dommel River (Langeveld *et al.* 2012). In addition, much effort has been invested in the development of models for sewer, WWTP and river, and on integrated

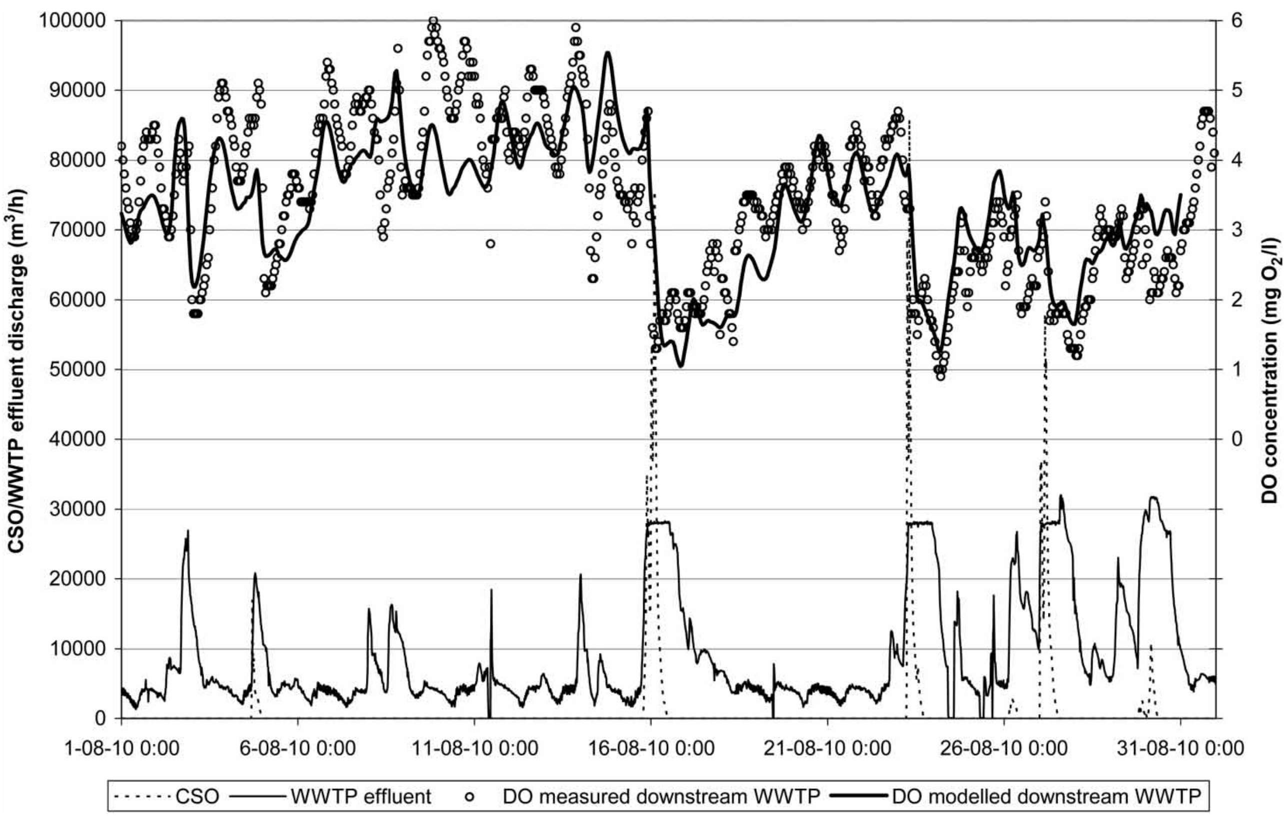

Figure 2 | Performance of integrated model (DO in a river section downstream of the WWTP) for 1 month of simulation with typical storm events leading to DO depletion.

modelling (Langeveld *et al.* in press). An example of the monitoring and modelling results of the critical DO depletion period in August 2010 is shown in Figure 2.

The monitoring and modelling efforts have already enabled optimization of the subsystems of sewerage and WWTP and have been used to derive an optimal and robust set of measures in the system to meet the WFD requirements at lowest possible costs (Benedetti *et al.* in press).

An important feature of the integrated model is its simulation speed, highlighting the actual feasibility of this type of study: the model, implemented in WEST and running on a 3.4 GHz processor, simulates 10 years with hourly inputs and outputs in less than 2 hours.

PERSPECTIVES

In the near future, the more likely fastest developing application of integrated water systems modelling will be 'more of the same', i.e. repeating real case studies like the ones described in this article, wherever the regulatory framework, the economic incentives scheme and the utility company culture allow its benefits to emerge. More specifically, controlling in real time the sewer–WWTP system opens up large opportunities for improved performance of the existing infrastructure, allowing the delay of capital investments in the short–medium term.

Another interesting use will be setting WWTP (and CSO) effluent permits based on the receiving water quality. There is a gap between the EU Urban Waste Water Treatment Directive (CEC 1991) that regulates discharges from WWTPs and the EU WFD that sets limits for pollutants in receiving water bodies. Corominas *et al.* (2013) describe this gap and suggest that current wastewater treatment legislation should be updated to include an integrated perspective. In current engineering practices, receiving water quality models are often used by regulators to derive emission limits, to which safety factors are applied that are then passed on to the wastewater collection and treatment utilities, which have to base their design and upgrade on such prescription. Design engineers then usually apply additional safety factors to their calculations, possibly resulting in systems performing in excess of what would be required to achieve the original water quality objectives. A different approach would be to use dynamic integrated models to evaluate the impact of sewer and WWTP design alternatives directly on the receiving water quality, and possibly assess them on the basis of concentration/duration/frequency of exceedances of selected chemicals – like already suggested in the Urban Pollution Management (UPM) Manual (FWR 1998) – in case the regulation allows it (de Klein *et al.* 2012).

Priority should be given in general to improved data collection, and especially for the parts of the system weaker in terms of model prediction capabilities, like sewer water quality. Along the same lines, it must be considered that an alternative to mechanistic models is the use of empirical models built using long time series of data collected with online sensors (Langeveld *et al.* 2012). Reducing the uncertainties in model predictions of those sub-models by gathering more and better data would thus increase the confidence in the integrated models' predictions, as (sewer) water quality is the main uncertainty contributor to the receiving water quality prediction (Willems 2008; Freni *et al.* 2011).

Beyond the 'traditional' sewer–WWTP–river model integration, further extension of the boundaries is likely to take place, including water production and supply facilities, industries, decentralized storm- and wastewater treatment facilities, in view of the implementation and optimization of water reuse and recycle schemes. Recent advances also include the development of socio-technical models (De Haan *et al.* 2012) or urban growth models (Veerbeek *et al.* 2012) allowing the study of scenarios of urban development including water and social issues.

At different integration levels, further integration can be foreseen in the joint study of the water–energy–nutrients cycles at urban scale. We need practical, implementable models to answer questions such as: what is the most appropriate scale to manage water, heat, organic matter, and nutrients; what are the trade-offs offered by greater and lesser integration of the water supply, rainwater harvesting, and resource streams; how many water supply and resource management streams make sense?

Currently, large research projects are focussed on integrated modelling (e.g. at the EU level: www.trust-i.net, www.sanitas-itn.eu, www.prepared-fp7.eu), producing the next generation of tools and professionals, enabling a wider adoption of the IUWS modelling principles.

CONCLUSIONS

The following are the main conclusions:

- integrated modelling is beneficially applied in practice;
- aspects like model interfacing and WWTP influent generation have been investigated and several new or improved systems analysis methods have become available;

- new/improved software tools coupled with the current high computational capacity have enabled the application of integrated modelling to several practical cases;
- advancements in monitoring water quantity and quality have been substantial and allow collection of data in sufficient quality and quantity to permit using integrated models for real-time applications too. Further developments are warranted in the field of data quality assurance and efficient maintenance.

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