PULLING TOGET

Integrated modeling improves water quality outcomes and reduces utility risks and costs

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As interconnected regulatory, operational, and planning activities grow ever more complex, existing practices often fall short of being desirably well-integrated analytical approaches. The water sector lacks tools necessary to address key integrated planning elements, such as characterization of existing interconnected systems performance, cohesive evaluation and screening of alternatives leading to effective capital improvements, and measurement of success for implemented improvements. Meanwhile, the U.S. Environmental Protection Agency's (EPA) Integrated Municipal Stormwater and Wastewater Planning Approach Framework (IPF) provides an impetus for utility managers to best allocate their utility's limited Clean Water Act (CWA) compliance funds to improvements that result in the highest water quality benefits. Integrated modeling approaches can provide the necessary analytical tools to complement and enhance the process of integrated planning, thereby efficiently improving water quality.

Why integrated modeling?

Managers of urban water systems face significant challenges and pressures, including the following.

- Aging infrastructure means assets are getting older and bring associated operations and maintenance pressures.
- Continued urbanization leads to changes in land use and impervious surfaces that increase risks of flooding, system wet-weather flows, and degraded receiving-stream health and water quality.
- Climate change is creating more frequent extreme storms that cause flooding, intense wet-weather flows, system overflows, and noncompliance at existing facilities.
- Regulatory pressures drive wet-weather, discharge-compliance challenges with more stringent water-quality-based controls on receiving streams.
- Funding gaps grow harder to manage while maintaining low customer user fees and increasing levels of service.
- Public engagement is growing with increased significance of public acceptance of green infrastructure and sustainable solutions.

Managers must address these related challenges with complex management decisions affecting a wide range of interrelated, dependent domains, typically including stormwater and wastewater collection systems, treatment facilities, and receiving waters. (See Figure 1, p. 61.) Effective decisions require a reasonable understanding of the response of these domains to dynamic hydrologic, hydraulic, and water-quality conditions in an integrated fashion.

What is integrated modeling?

Integrated modeling traditionally has been defined as modeling the interaction between two or more physical systems, such as a sewer system, treatment facility, and receiving water. This definition, however, is limited to only physical systems. Integrated modeling today generally includes three key points, according to P.M. Bach *et al.* in the 2014 article, "A critical review of integrated urban modelling – Urban drainage and beyond" published in *Environmental Modelling & Software*:

- modeling multiple components (biophysical, economic, and beyond) and interactions among components;
- considering acute, chronic, and delayed impacts of water quantity and quality processes over longer time periods; and
- addressing microscale (local processes) and macroscale (big picture) to better inform decision-making, policies, or scientific knowledge.

Integrated modeling may bring together groundwater, watershed, and air domains for comprehensive assessment of interactions and effects. Here, the focus is on modeling of interconnected urban water systems, including collection and treatment of stormwater and wastewater together with assessment of effects on receiving water quality.

This type of integrated urban water systems (IUWS) modeling enables simulation of important physical, chemical, and biological processes occurring in the relevant urban system domains in an integrated fashion. This approach provides a more holistic understanding of the interaction of various urban systems with receiving water hydraulics and water quality. IUWS leads to more appropriate systems improvement decisions that better allocate scarce utility resources.

Several potential barriers stand in the way of widespread adoption of IUWS modeling. These barriers are administration/institutional and technical in nature. These factors must be kept in mind when planning an integrated modeling application. However, overcoming these barriers leads to better understanding of systems and the application of truly integrated models. These barriers include administrative fragmentation, stakeholder engagement, lack of skilled staff, model and software fragmentation, modeling system complexity, data requirements, and computational power.

Administrative fragmentation. Management and planning of stormwater, wastewater, and treatment components often reside under different departments (or separate utilities) with separate funding streams and regulatory drivers. "Silo thinking" and fragmented responsibilities make collaboration challenging. This can lead to imperfect information and subsequent fragmented decision-making.

Stakeholder engagement. Inconsistent presentation and differing vocabularies cause confusion for both utility staff and stakeholders. Stakeholder engagement often is planned but not implemented, and relating compelling success stories often becomes difficult because the benefits cannot always be monetized.

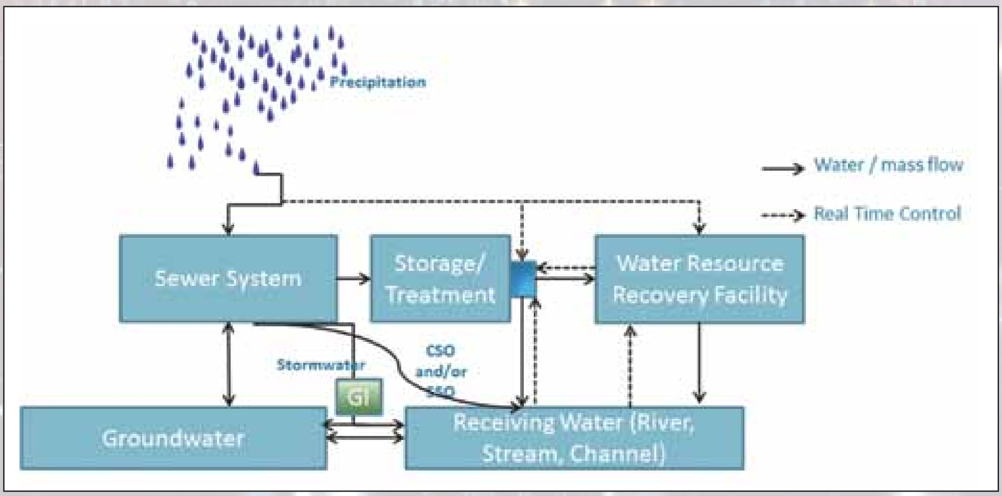
Lack of skilled staff. Working with IUWS models generally requires highly skilled personnel to manage and conduct complex modeling of physical, chemical, and biological processes. Finding the right people to operate at various levels of software applications and with abilities to effectively relate to the stakeholders, managers, and utility leadership can be difficult.

Model and software fragmentation. Stormwater, wastewater collection, treatment processes, and receiving water often use individual modeling software platforms to build understanding and insight. Integrated modeling typically requires the independent application of these multiple separate models with results from one being fed with difficulty into another. Sometimes, variables used in one model are incompatible with variables in a "downstream" model, requiring "translators" between models.

Modeling system complexity. Individual system behaviors vary dramatically in spatial and time scales. Overly simplified equations and algorithms may reduce the quality of results. Risk-aversion to and lack of understanding of all physical system aspects in each domain covered by the models with wider scopes leads to underutilization of these models.

Data requirements. Integrated modeling can require large

Figure 1. Main elements of an urban water drainage system (adapted from Rauch *et al.*, 2002)



CSO = combined sewer overflow.
SSO = sanitary sewer overflow.
GI = green infrastructure.

Participate in an integrated urban water systems group

To help address the challenges of making integrated urban water systems (IUWS) a valuable part of integrated planning, the Water Environment Federation (WEF; Alexandria, Va.) has formed the Integrated Modeling Workgroup (IMW). This group will promote activities to address how best to advance the science and engineering of integrated modeling and how best to apply it for the benefit of utilities and the environment.

IMW includes members of the WEF Collection Systems, Stormwater, and Watershed Management committees, as well as the Modeling Expert Group of the Americas, which is a subcommittee of the Municipal Resource Recovery Design Committee. IMW is actively informing utilities, consultants, and researchers about IUWS and integrated modeling in general and seeking stakeholder input on these topics.

IMW plans to coordinate with the International Water Association's Working Group on Modelling of Integrated Urban Water Systems to stage both a workshop and a technical session at WEFTEC® 2015, and develop a white paper to provide a vision for the continued evolution of integrated modeling.

and varied data sets, which can be costly to collect and manage unless carefully organized. These data sets also increase the complexity – and therefore the time – for model calibration. In a typical situation in current practice, not enough directly collected data exist to develop the necessary insight from IUWS modeling.

Computational power. More comprehensive decision support systems may be more computationally intensive and require high-end computers/information technology systems.

Case studies

IUWS modeling to support holistic planning efforts has been in *active* practice for more than a decade outside the U.S. However, true integration within the U.S. has been practiced only in recent years. Selected case study overviews from Europe and the U.S. demonstrate that IUWS modeling provides utilities with analytical tools that consider the tradeoffs in addressing bottom-line compliance issues through different management actions. These cases show how IUWS leads to sounder and more efficient bases for decision-making.

Case Study No. 1: Eindhoven, Netherlands

The Dommel River is a relatively small, sensitive river flowing through the city of Eindhoven in the Netherlands. It receives discharges from the Eindoven water resource recovery facility (WRRF) that treats a flow equivalent to a population of 750,000. The river also receives more than 200 combined sewer overflows (CSOs) from its 10 municipalities.

In summer, the WRRF effluent makes up as much as half of the Dommel's base flow. The river does not yet meet the water quality requirements of the European Union Water Framework Directive (WFD). Waterschap De Dommel, the utility responsible for this compliance, launched a comprehensive project to find the most cost-effective set of measures to protect the Dommel River from oxygen dips and ammonia peaks caused by the combined discharges. In addition, nutrient and suspended solids concentrations need to be reduced to allow compliance with maximum summer averages. The goals are 0.15 mg/L total phosphorus (TP) and 4 mg/L total nitrogen (TN) as well as to control solids accumulation in the river during the summer season.

The traditional approach applied in Europe before the introduction of the WFD in 2000 defined nationwide emission standards and efficiency requirements for CSOs and WRRFs. This piecemeal approach may result in ineffective and inefficient measures, as the sensitivity of the receiving waters combined with the loads from the WRRFs and the CSOs determine the required efforts on a site-specific basis.

Figure 2. Results of scenario analysis tested to solve peak ammonia concentration problem

DoE →	1-5 h	6-24 h	> 24 h		current						scenario A						scenario B						scenario C					
YFL ↓	CT ↓																											
12	1.5	0.7	0.3	NH_4	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	2.0	1.2	0.5	NH_4	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	NH_4	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	3.0	1.5	NH_4	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	6.0	7.0	DO critical	1	5	5	4.1	38.6	30.7	1	1	2	0.4	1.9	0.2	1	1	2	0.3	3.2	6.8	1	5	5	3.1	27.6	30.4
4	4.0	5.5	6.0	DO critical	1	5	5	1.0	23.9	18.8	1	1	1	0.0	1.1	6.2	1	1	1	0.0	1.7	1.5	1	4	5	0.0	6.2	8.4
1	3.0	4.5	5.5	DO critical	1	5	5	0.3	9.0	11.6	1	1	1	0.0	0.0	0.8	1	1	2	0.0	0.0	7.0	1	1	4	0.0	0.0	1.9
0.2	1.5	2.0	3.0	DO critical	1	4	5	0.1	0.4	1.5	1	1	1	0.0	0.0	0.1	1	1	1	0.0	0.0	0.0	1	1	1	0.0	0.0	0.0
12	3.0	3.5	4.0	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	3.0	3.5	DO basic	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	2.0	2.5	3.0	DO basic	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	1.0	1.5	2.0	DO basic	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

DoE = duration of exceedance.
YFL = yearly frequency limit.
CT = concentration threshold.
NH_4 = ammonia.
DO = dissolved oxygen.

The four right-hand columns show the yearly number of times that the model predicts the concentration threshold for a parameter would be exceeded, classified by the duration and by the return period of the the exceedance. The colorful columns indicate whether these exceedances would outnumber the yearly frequency limit (YFL) set for a parameter. The blue 1s and green 2s indicate no exceedance; yellow 3s, orange 4s, and red 5s indicate the degree of the exceedance.

In this chart, Scenario C best addressed ammonia – all blue or green – but failed to remedy fully (compared to "current") the critical dissolved-oxygen parameter.

For the Dommel, detailed models of the sewer, WRRF, and the river were developed in dedicated software platforms and calibrated individually with ample data from monitoring campaigns. These models subsequently were reduced in complexity and integrated into a single model, thereby avoiding the need to couple different software platforms.

The reduced model was validated thoroughly for one complete year's simulation, including all types of dry and wet weather. The model adequately described the system performance with lesser computational effort. This lesser effort was a prerequisite for the subsequent steps in the project, which would involve many long-term simulations.

In the second step, the integrated model was applied to better understand the complex interactions among different components. The model characterized the effect a certain change in one system component (*e.g.,* operational change in the sewer) can have on another component of the system (*e.g.,* the ecological quality of a particular river stretch). The latter is a typical example of impact-based evaluation of measures in the urban water system.

A dedicated evaluation framework based on ammonia and

More resources on integrated modeling

Integrated Municipal Stormwater and Wastewater Plans
November 2014
U.S. Environmental Protection Agency
http://1.usa.gov/1IrEwmU

EPA's integrated planning approach is explored in detail on this Web page. It provides links to relevant resources and case studies about integrated planning that provide examples of how communities can develop plan components.

Deterministic Modelling of Integrated Urban Drainage Systems
March 2002
Authors: W. Rauch, J.-L. Bertrand-Krajewski, P. Krebs, O. Mark, W. Schilling, M. Schütze, and P.A. Vanrolleghem
Water Science and Technology

This article reviews the state of the art in deterministic modeling, outlines experiences, and discusses problems and future developments. It states that "integrated modelling is a complex exercise not only due to the sheer size of the model, but also due to the different modelling approaches that reflect the history of the sub-models used and of the purpose they were built for."

A Critical Review of Integrated Urban Modelling – Urban Drainage and Beyond
April 2014
Authors: P.M. Bach, W. Rauch, P.S. Mikkelsen, D.T. McCarthy, and A. Deletic
Environmental Modelling & Software

Based on review of 30 years of literature, the authors reflect upon integrated modeling in the scope of urban water systems, and set forth a typology to classify integrated urban water system models. The authors also discuss key considerations, common methodologies for model development, and calibration/optimization and uncertainty. The article suggests that integrated urban water models should be used to look at the interplay between social/economical and biophysical/technical issues.

Cost-Effective Solutions for Water Quality Improvement in the Dommel River Supported by Sewer-WWTP-River Integrated Modelling
May 2013
Authors: L. Benedetti, J.G. Langeveld, J. de Jonge, J.J.M. de Klein, T. Flameling, I. Nopens, A. van Nieuwenhuijzen, O. van Zanten, and S. Weijers
Water Science and Technology

This detailed writeup of the Dommel River case study (mentioned in article above) describes the power of mathematical modeling for decision support in the context of complex urban water systems. The article includes descriptions of uncertainty analysis facilitated by the use of an integrated approach.

Model Meets World: Guiding an Evolving Integrated Model
September 2015
Authors: E. Rubchinskaya, D. Sutton, C. Ranck, and S. Rowe
WEFTEC® 2015

This paper, scheduled to be presented at WEFTEC 2015, summarizes the modeling framework used by Citizens Energy Group (CEG) to support its wastewater initiatives from the perspective of a large wastewater utility under a consent decree with a commitment to efficiently provide sewer service to its ratepayers. The initiatives have required CEG's system modeling staff not only to model the wastewater collection system, but also both advanced wastewater treatment facilities as well as in-stream flow and water quality. The paper discusses CEG's challenges and successes in developing and maintaining a truly integrated wastewater model.

dissolved oxygen in the river was developed, defining critical values of ammonia and dissolved oxygen based on frequency-duration curves for the most sensitive organisms in the Dommel River. (See Figure 2, p. 62.) A global sensitivity analysis (GSA) was conducted on the operational parameters of the system and repeated using different storms with distinct severity and return period. The GSA revealed that the current infrastructure, when properly operated and controlled with real-time controls, can handle small and intermediate intensity storms but not large ones. In addition, the components of importance in the urban water system that have real-time control potential were identified.

In the third step, the integrated model was used to investigate alternative scenarios within the current infrastructure as well as evaluating the effect of installing additional infrastructure. A subset of scenarios was run for a long simulation period using 10-year time series obtained from available monitoring data. Real-time control scenarios within the current infrastructure suggested that different strategies are required depending on the type of storm and on the selected objective. It also became obvious that the current real-time control potential of the system was not sufficient to achieve the expected compliance at all times.

Promising technologies were incorporated in the simulated infrastructure, then modeled and evaluated using the 10-year period. The measures focused on reducing ammonia peaks and oxygen depletion in the Dommel or on improving the average long-term water quality by lowering TP and TN emissions. Ammonia peaks and oxygen depletion were, for instance, reduced by added aeration at the WRRF and by river aeration. Decreased TP and TN emissions were realized by effluent polishing or an improved bioreactor. Some measures, such as increase of the biological capacity, had both effects. The optimal scenario finally was checked for robustness using a worst-case analysis, which considered the uncertainty in the main assumptions.

The robust integrated model of Eindhoven's urban water systems has allowed rapid assessment of discharge and water quality effects for a wide range of scenarios. (See Figure 2, p. 62.) This knowledge has led to a projected savings of more than 60% of the initially estimated total cost of more than □150 million – combining capital and operating expenses – to meet WFD objectives.

Case Study No. 2: Indianapolis

In August 2011, Indianapolis transferred its wastewater system assets to Citizens Energy Group, and CWA Authority Inc. formed to take control of the wastewater system. Citizens' internal system modeling team utilizes its collection system model for such applications as design support, regulatory reporting, capacity assessments, operational troubleshooting, and master planning. The system modeling team used a SharePoint-based request management system to track all geographic information system and modeling requests for its internal customers.

Citizens uses an integrated collection system, river system, and advanced wastewater treatment facility model to ensure long-term data retention, reduced IT support, and staff efficiency. The river system model includes water-quality capability for bacteria and dissolved oxygen. A dissolved oxygen sub-model includes the nitrogen cycle and algae.

The primary benefit of having all modeling information housed in a single database is the efficiency of not having to transfer data between multiple models. With the completion of the integrated model in December 2014, Citizens has the ability to rapidly evaluate what-if scenarios dynamically for collection system, river system, and water quality effects.

So far, in 2015, the integrated model has been applied or is in the progress of being applied to such tasks as

- identifying capital savings (estimated at $500 million) from the previous sanitary sewer master plan developed in 2004, based in part on model-suggested balancing of capacity for the interceptor system and the two treatment plants;
- developing an integrated collection- and stream-system configuration that provides capital savings and is projected to achieve the targeted CSO performance and reduce peak flood levels in the Pogues Run creek;
- optimizing select CSO control projects for volume captured and in-stream *E. coli* bacteria; and
- evaluating in-stream water-quality sensitivity to current and prospective National Pollutant Discharge Elimination System effluent limits at the two treatment facilities.

Integrated modeling delivers cost-effective water-quality benefits

As described in this article, utility managers are responsible for complex management decisions affecting a wide range of interrelated, dependent domains, typically including stormwater and wastewater collection systems, treatment facilities, and receiving waters. Effective decisions require a reasonable understanding of the response of these domains to changing hydrologic, hydraulic, and water-quality conditions. As demonstrated through the case study overviews presented, IUWS modeling can provide a more holistic understanding of the interaction of various urban systems with receiving-water hydraulics and water quality. IUWS modeling leads to more robust and efficient foundations for decision-making and makes better use of scarce utility resources.

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