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Industrial Electrical Engineering and Automation

Integrated Modelling and Control of Urban Wastewater Systems

Literature Review

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INTEGRATED MODELLING AND CONTROL OF URBAN WASTEWATER SYSTEMS
- LITERATURE REVIEW

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Abstract

This review paper aims at studying the existing modelling techniques for catchment and sewer models both for flow and quality aspects. The study of existing modelling techniques forms an important background to my research project aiming at developing an integrated urban wastewater system (IUWS) benchmark model. It is essential to choose simplified and conceptual approaches for the benchmark model to make the model computationally efficient and to avoid parameter identifiability issues with the scarce data availability, especially for water quality models. The review describes different modelling possibilities for various components of an urban wastewater system. It also highlights the challenges and the lack of agreement in modelling of sewer and catchment quality aspects like sedimentation and resuspension phenomena.

Modelling and control of integrated urban wastewater systems forms another major part of the review. The state-of-the-art in modelling and control aspects of IUWS is reviewed. It is noticed that there has been considerable theoretical studies on these aspects. Uncertainty and sensitivity analysis studies have also been performed for some of the proposed integrated models. Nevertheless, there has been limited practical implementation of integrated control systems and the use of integrated models for design and analysis of urban wastewater systems. An integrated benchmark system can be a useful tool in this context to evaluate various control strategies and provide a platform for researchers and practitioners to study, develop and implement system-wide control strategies.

Keywords: Sewer model, Catchment models, Integrated urban wastewater system, Modelling and Control.

1. Introduction

An urban wastewater system consists of the following major components:

1. Catchment
2. Sewer system
3. Wastewater treatment plant (WWTP)
4. Receiving water

Wastewater from domestic and industrial sources is collected and conveyed to the WWTPs through sewer systems. Precipitation (rain and snowmelt) is transported to the sewer system through various connections (gully inlets, manholes and open channels) located across the urban catchment. Catchment processes like infiltration, evaporation, interception and depression storage affect the quality and quantity of stormwater that is transported to the sewer system. A combined sewer system conveys both the dry weather and precipitation flows together while a separate sewer system has different drainage systems for each of them. The transported wastewater is treated in WWTPs and is discharged to the receiving waters. Stormwater is sometimes discharged directly to the receiving waters through combined sewer overflows (CSOs) present in the sewer network.

Separate models for each of the above mentioned components exist and are used widely (e.g. Henze et al., 2000; Rossmann, 2009; Shanahan et al., 2001). Various modelling approaches are available for describing different processes in the individual sub systems. Different commercial softwares represent these processes in varying degrees of detail (e.g. Achleitner et al., 2007; Ifak, 2007).

The report describes catchment and sewer system modelling approaches. Simplified and conceptual modelling approaches are mainly discussed in this review. Further, the report attempts to review the state-of-the-art in modelling and control of integrated urban wastewater systems (IUWS).

2. Modelling the urban catchment system

Modelling the urban catchment wastewater flow involves models for generation of dry weather flows and rain generated runoff. Additionally, models accounting for transport of the generated wastewater through the catchment are also required. Models for both flow rate and pollutant loads are available. Some of the commonly used modelling approaches are described below (Butler and Davies, 2004).

2.1. Dry weather flows: Dry weather flow and pollutant generation due to domestic and industrial usage are very crucial to model various downstream systems like sewers, WWTPs and rivers. The diurnal variation in flow and pollutant load from domestic sources can be modelled in different ways. Software packages either require a user defined diurnal variation pattern or provide a simple framework to generate them (e.g. Ifak, 2007; Gernaey et al., 2011). Another approach is to use a Fourier series to simulate the diurnal variation in dry weather flows (Langergraber et al., 2008). A more detailed approach can be used to predict the temporal and spatial variation of dry weather flows arising from domestic sources taking into consideration their usage patterns (Butler, 1991; Butler, 1993).

2.2. Rainfall: Rainfall intensity data from the catchment is generally used as an input for sewer and catchment models. Another approach is to use statistical analysis of historical rain data to produce Intensity-Duration-Frequency (IDF) curves. Rainfall intensities for a single rain event with a given duration and frequency can be calculated based on these curves. Such rainfall intensities are representative of the rainfall pattern in the given area. IDF curves can be used to generate simple block rain events. Such block rains are used mainly in the design of sewer system.

2.3 Rainfall-Runoff generation: A model for rainfall-runoff generation calculates the amount of surface runoff generated due to a rain event in an urban catchment. Rainfall from impervious areas reaches the sewer system without any major losses. Interception losses can be neglected. Evaporation losses need to be considered depending on the temperature of the catchment. On the other hand, only a part of the rainfall on pervious areas reaches the sewer. Various processes like depression storage, infiltration, evaporation etc. affect the quality and quantity of water that reaches the sewer system from pervious areas. The net runoff can be calculated by subtracting the initial and continuing losses from the total rainfall input.

All the continuous losses can be represented in a lumped form with a dimensionless rainfall-runoff coefficient. The effective rainfall is represented as a fraction of the net rainfall intensity obtained after subtracting the initial losses.

$i_e = C i_n$	**Eq. 1**

where i_e is the effective rainfall intensity (mm/h), i_n is the net rainfall intensity (mm/h) and C is the dimensionless rainfall runoff coefficient.

Various factors like the land type, usage and surface slope determine the runoff coefficient.

An improvement over the above method is to divide the area into *N* segments, each constituting a fraction A_j with a specific runoff coefficient C_j. The net rainfall intensity is obtained by summation of net rainfall intensities in each segment.

$i_e = i_n * \sum_{j=1}^{N} C_j * A_j$	**Eq. 2**

After accounting for all the losses, the net rainfall is transferred to the nearest sewerage input through surface routing. Surface routing can be modelled in different ways.

1. Unit Hydrographs: A unit hydrograph represents the linear response of a catchment to 1-inch of excess precipitation for a given duration. The response to a rain event of given intensity and duration can be obtained by superposition of multiple unit hydrographs and convolutions.
2. Reservoir Models: The flow transport from the catchment to the sewerage can be described by a conceptual reservoir model. Simple linear reservoir models are normally used. Reservoir models are described in detail elsewhere (along with sewer hydraulics).
3. Time-Area curves: In this approach, the catchment is divided into areas (A_j) with equal travel time called isochrones. The flow rate at the end of the catchment at any particular time *Q(t)* is given by the below formula. I_i is the rainfall depth at the ith block of N duration blocks. The final hydrograph is obtained by plotting the flow rate of the catchment at different time intervals.

$Q(t) = \sum_{i=1}^{N} \frac{dA(j)}{dt} I_i$	**Eq. 3**

2.4. Pollutant generation and transport in urban catchment

Pollutant transport from the urban catchment to sewers takes place during both wet and dry periods. During dry weather conditions, pollutants from domestic and industrial sources are transported directly to the sewer system. The diurnal concentration profiles for pollutants can be used to model the pollutant generation (Gernaey et al., 2011). Surface pollutants can also be transported to the sewer system through street cleaning and winds during dry days.

During rain events, the pollutants in the streets and buildings are washed off along with the rain water and are transported to the sewer system. Pollutant buildup and washoff models are commonly used to model the transport of pollutants during wet weather conditions in an urban catchment. Other simpler models based on event mean concentrations and regression equations also exist.

2.4.1. Event Mean Concentrations (EMC)

A uniform event mean concentration for each pollutant is assumed for the entire rain event. It is assumed that the concentration of pollutant remains constant during the rain event. This method is suitable to use along with a detailed flow model. The flow rate at each time step can be integrated with the EMC to produce the pollutant load. While this method can be useful to predict the total pollution load during a rain event, it cannot predict the concentration changes during the duration of a rain event. A log normal distribution can be used to approximate the variation in pollutant concentration during the rain event.

2.4.2. Rating Curves: Rating curves are statistical tools that determine the relationship between concentration and runoff volume. The curves are arrived at by regression analysis of the historic data.

2.4.3. Buildup and Washoff Models

Buildup and Washoff models are the most commonly used approaches for modelling water quality in an urban catchment. These are conceptual models that represent the simplified mechanism of pollutant buildup and washoff processes. Model parameters need to be calibrated using data from the catchment.

Pollutant buildup can be attributed to various factors like land use, population, seasonal variations, street cleaning and surface conditions etc. All these factors can be lumped into a single representative parameter called as surface accumulation rate constant (a). This parameter defines the weight of pollutants accumulated (M_s) for a given area (A) and a given time period. The buildup model can be further extended to limit the pollutant concentration from increasing linearly. A removal rate (b) is introduced into the buildup equation.

$\frac{dM_s}{dt} = aA - bM_s$	**Eq. 4**

Additionally, the washoff is modelled as a first order equation with a washoff constant (k_4).

$\frac{dM_s}{dt} = -k_4 i M_s$	**Eq. 5**

The negative sign indicates removal of pollutants from the surface as a result of washoff. The rate of pollutant washoff depends on the amount of pollutant accumulated (M_s) and also on the rain intensity (i).

3. Modelling the sewer system

Sewer system models mainly include transport models for flow and pollutants through the urban drainage. Additionally, models for solids sedimentation and resuspension are also included in this review. Pollutant transformations within the sewer system are not described in this review.

3.1. Sewer Hydraulics

Sewer system models are primarily developed to understand the hydraulic behaviour of wastewater within the sewers. Various approaches ranging from full Saint Venant's equation to conceptual reservoir models are used for this purpose.

3.1.1. Saint-Venant Equation

The Saint Venant equation describes the hydrodynamic behaviour of flow in open channels. This open channel flow model is also applied for the modelling of sewer hydrodynamics. It consists of a continuity equation and a momentum equation.

$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$	**Eq. 6**
$gA(S_0 - S_f) = \frac{\partial y}{\partial x} + \frac{\partial}{\partial x}.\left\{\frac{Q^2}{A}\right\} + \frac{\partial Q}{\partial t}$	**Eq. 7**

where A is the cross sectional area of the channel (m^2), *Q* is the flow rate (m^3/s), *x* is the distance along the x-axis (m), S_0 is the bottom slope, S_f is the friction slope, *y* is the channel depth (m), *g* is the acceleration due to gravity (m^2/s).

These equations are partial differential equations in time and space and require special numerical procedures to solve them. The procedures are well established and various commercial softwares are available to efficiently model hydrodynamics in a sewer system.

In the context of integrated modelling, especially when using a single platform to model all the components of an integrated urban water system, these hydrodynamic models pose challenges in terms of model complexity and hence longer simulation times. To overcome this problem, conceptual reservoir models are used.

3.1.2. Conceptual Reservoir Models

Different conceptual approaches can be broadly classified into:

1. Linear reservoir model
2. Multi linear reservoir model
3. Nonlinear reservoir model

3.1.2.1. Linear reservoir model: The sewer system can be simply represented as a (series of) varying volume storage tank(s) with outlet.

$\frac{dV}{dt} = Q_{in} - Q_{out}$	**Eq. 8**
$V = \frac{1}{K} Q_{out}$	**Eq. 9**

where *V* is the volume of the reservoir (m^3), Q_{in} is the inflow to the reservoir (m^3/s), Q_{out} is the outflow from the reservoir (m^3/s), *1/K* is the residence time constant (s).

The output is described as a linear function of storage. This approach is based on the concept of Nash cascades used for hydrological routing models in catchments (Viessmann et al., 1989). The parameter *1/K* has a unit of time and can be considered as the hydraulic residence time of the system. The sewer system can be considered as a series of linear reservoirs each with varying or similar residence times. This simplification reduces the computational and calibration efforts for the sewer system flow model. The obvious disadvantage is the decrease in closeness of the simulation results with the actual data especially in cases with back water effects, flooding etc.

3.1.2.2. Multi linear reservoir model

Multi linear models are a combination of different linear relationships between various components of sewer flow.

The Muskingum method is a multi-linear model where the storage (*V*) is a function of both the inflow (Q_{in}) and outflow (Q_{out}) (Cunge, 1969). This equation can represent the differences in the rising and falling limb of the hyetograph obtained during a rain event. This approach has been adopted in some of the simplified sewer models (Achleitner et al, 2007).

$\frac{dV}{dt} = Q_{in} - Q_{out}$	**Eq. 10**
$V = K(xQ_{in} + (1 - x)Q_{out})$	**Eq. 11**

where *1/K* is the residence time constant (s) and x is a dimensionless factor.

3.1.2.3. Nonlinear reservoir model

Although a simplified description of the sewer flow can be obtained by a linear reservoir model, the response in reality is hardly linear. To include various non linearities in the system, the output is modelled as a nonlinear function of storage. Nonlinear functions can be used to replace the series of linear reservoirs with a single nonlinear reservoir model. The nonlinearity parameters can be computed based on the pipe geometry (Mehler, 2000). This approach is used in the modelling software SMUSI (Muschalla et al., 2006). A very simple nonlinear storage throughflow relationship can be implemented and a series of such nonlinear reservoirs can be used to simulate sewer hydraulics (Gernaey et al., 2011). *c* represents the residence time constant (s).

$\frac{dV}{dt} = Q_{in} - Q_{out}$	**Eq. 12**
$Q_{out} = cV^{1.5}$	**Eq. 13**

3.1.2.4. Backwater effects: Backwater effects occur when the maximum pipe flow is not sufficient enough to transport the flow downstream. A hydrodynamic model with detailed description of sewer characteristics can simulate backwater effects effectively. A simplified hydrological model like a linear reservoir model cannot simulate such effects as it considers the flow as a linear function of storage. Different approaches are available to simulate backwater effects in a conceptual model. The KOSIM model approach (Solvi, 2006) is described below.

In KOSIM, a splitter-combiner approach is used. In this method, any excess flow from a pipe is sent through a splitter that divides the flow into maximum flow and backwater flow. The backwater flow is connected to the previous pipe using a combiner. This method represents closely the actual flow behaviour during rain events when the water flows from the downstream to upstream pipes.

3.2. Pollutant transport in sewers

3.2.1. Advection-Dispersion Model: Soluble pollutant transport can be modelled using the advection-dispersion equation.
The full advection-dispersion equation is represented as follows:

$\frac{\partial C}{\partial t} + u * \frac{\partial C}{\partial x} - K * \frac{\partial^2 C}{\partial x^2} = 0$	**Eq. 14**

where *C* is the pollutant concentration (kg/m^3), *u* is the flow velocity (m/s) and *K* is the dispersion coefficient (m^2/s).
In the case of sewer systems, the dispersion term can be neglected which can result in the following equation:

$\frac{\partial C}{\partial t} + u * \frac{\partial C}{\partial x} = 0$	**Eq. 15**

As in the case of Saint Venant equations, the advection-dispersion equation is also a partial differential equation in time and space and hence requires more sophisticated numerical solvers than those used to solve the ordinary differential equations.

3.2.2. CSTR Models: A simplified approach is to model the sewer system as a series of CSTR tanks with fixed volume (*V*). The following equations hold for each tank. The mass balance equation is represented as:

$\frac{d(V * C)}{dt} = Q * C_{in} - Q * C$	**Eq. 16**
$\frac{dC}{dt} = Q/V(C_{in} - C)$	**Eq. 17**

where Q is the flow rate and C_{in} , C are inflow and outflow concentrations.

3.3. Sediment transport

Detailed models were developed in the 80s to model sediment deposition and transport in open channels (Van Rijn, 1984a; 1984b). Such models are applied directly or modified to be suitable for sewer systems (Novak and Nalluri, 1984). These are complex models requiring detailed information about the sewer pipe and sediment characteristics. A detailed review of various sewer sediment modelling techniques is available (Bertrand-Krajewski et al., 1993). Deterministic models like MOSQITO (Hydraulics Research, 1989), MOUSETRAP (Crabtree et al., 1995; DHI, 1993) and simplified models like FLUPOL (Bujon et al., 1992), HYPOCRAS (Bertrand-Krajewski, 1992), STSim (Schlütter, 1999) and HORUS (Zug et al., 1999) were developed. Here, a few of the underlying models used in commonly available sewer models are discussed.

Ackers-White Model: Ackers-White total load model (Ackers and White, 1973; 1980) was first developed for open alluvial channels. Alluvial channels are characterized by self-formed morphology mainly due to sediment transport and deposition. The model was later adapted to circular pipes (Ackers, 1984). Deterministic sewer models like MOSQITO and MOUSE use such models. They are difficult to implement in a conceptual sewer system model owing to the lack of detailed sewer characteristics data.

Velikanov approach: This method is based on turbulent analysis (Bujon, 1992) and is popular due to its simplified approach. It is based on efficiency coefficients that further define limit sediment concentrations for erosion and deposition of solids in sewers.

$C_{min} = \eta_{min}\rho_s\rho_m(\rho_s - \rho)^{-1}\left(\frac{U}{w}\right)J$	**Eq. 18**
$C_{max} = \eta_{max}\rho_s\rho_m(\rho_s - \rho)^{-1}\left(\frac{U}{w}\right)J$	**Eq. 19**

where C_{min}, C_{max} are the limit sediment concentrations (g/L). η_{min}, η_{max} are the respective dimensionless efficiency coefficients. ρ_m, ρ_s and ρ are the densities of mixture (sediment+water), sediment and water (kg/m^3) respectively. U is the mean flow velocity through pipe section (m/s), w is the sediment settling velocity (m/s) and J is the slope of energy line.

If the actual concentration

$C < C_{min}$ Erosion until $C = C_{min}$

$C_{min} < C < C_{max}$ Sediment transport without deposition or erosion

$C > C_{max}$ Deposition until $C = C_{max}$

This simplified approach is used in modelling softwares like FLUPOL and HORUS.

There has been a recent development of conceptual and parsimonious sediment transport models (Mannina et al., 2010; Willems, 2009). It can be clearly seen that there are different approaches proposed for the modelling of sediment transport and no standard model is available yet. Although there is an increasing necessity to predict the pollutant outflow at combined sewer overflows (CSOs) in order to understand the impact on rivers, only simplified approaches are currently being used. Lack of a detailed physical understanding of the sewer sedimentation processes and also non availability of sewer quality data impedes the development of modelling tools to study sewer solid transport phenomenon.

There is a wide range of modelling options to model the flow and transport of wastewater and pollutants in the catchment and sewer system. In general, the models for flow are well developed and are widely used. The development of models for pollutant transport, especially particulates, and also modelling various physicochemical and biological transformations is still an ongoing activity. This is a major limitation for integrated models that can simulate quality parameters in the entire urban wastewater system (UWS). Simplified quality models are preferred not only as they need less computation time but also due to the fact that there is no consensus yet on the detailed models for quality aspects in UWS.

4. Modelling of integrated urban wastewater systems

Integrated models combine different subsystems of an urban wastewater system by modelling the interactions between them. A model can be called integrated if it includes the interactions between at least two sub systems (Rauch et al., 2002). Integrating the sub system models can be a challenge as each of these models is made for a different purpose. The models hence run on different time scales and have state variables that are not directly comparable between each other (Schmitt et al., 2006).

Although the idea of integrated modelling was proposed more than 30 years ago (Beck, 1976), it has not been explored much until the last decade. One of the early integrated models was developed by Beck and Finney. (1987). The model consists of a simple system which includes: 1) system input generator that generates inflows to the river and wastewater treatment plant; 2) A dynamic wastewater treatment plant model; and, 3) a model of the receiving water flow and quality. The model was mainly used to study the operational management strategies to reduce the stress on downstream rivers. Many authors (e.g. Harremoës et al., 1993; House et al., 1993) identified the interactions between different sub systems in an urban wastewater system and stressed for the development of holistic approaches to improve the quality of receiving waters. Lijklema et al. (1993) summarized the findings in the INTERURBA workshop (1992) presenting the state of the art in modelling of various sub systems and problems in integrating them. The paper strongly recommended the need to design and operate sewers and WWTPs based on the receiving water quality impacts. It is clearly pointed out that the traditional methods for designing sub systems without considering the receiving water quality impacts are no longer viable. With the research community recognizing the need for integrated approaches in managing urban wastewater systems, there has been a renewed interest in integrated modelling of urban wastewater systems during the late 90s. Various factors contributing to this include the availability of technical know-how and also increased computational power (Harremoës et al., 1993). The enforcement of Water Framework Directive to have a good chemical and ecological status of the receiving water necessitated a shift from emission based to receiving water quality based approaches for the management of urban wastewater systems (Vanrolleghem et al., 2005b) and hence generated a new interest in the field of integrated control.

A review of early attempts in integrated modelling of UWS was given by Rauch et al. (2002). A detailed review of integrated modelling studies performed by different research groups in Europe was given by Schütze et al. (2002).

Models describing the dynamics of individual sub systems exist and are good enough to meet the specific operational requirements of these subsystems (e.g. hydraulic models in sewers, biological process models for WWTPs etc.). The state variables and the influencing processes are different for each of these sub systems. Fronteau et al. (1997) highlighted the differences in states and processes used in the modelling of individual components of the UWS. The paper suggested reconciliation of sub system models especially sewer system models. Another approach is model simplification. With respect to integrated modelling, the sub system models should be simplified (in most cases) or tailored to describe the state variables for receiving waters only in order to keep the models simple and to the purpose (Rauch et al., 1998). Conversion factors for state variables between different sub systems were developed as a pragmatic alternative (Vanrolleghem et al., 1996). With the availability of integrated models, different model based evaluations of the UWS were carried out subsequently. Crabtree et al. (1996) used a combination of deterministic and simplified models to demonstrate the benefits of integrated models for pollution control. The modelling study provided a strong case for implementing integrated planning in lieu of traditional approaches. In fact, it has been noted the traditional approaches did not provide any performance improvements in terms of receiving water quality whereas the integrated approach has done so at lesser cost. Schütze (1998) developed the SYNOPSIS model that combines different sub system models running on different software platforms. Various control strategies ranging from offline control based on predefined set points to global optimization methods are presented in the thesis. The Integrated Catchment Simulator (ICS) combines MOUSE, STOAT and MIKE programs and can be run simultaneously with bidirectional exchange of information between subsystems (Mark and Williams, 2000). A methodology for development of integrated UWS models was presented in a series of papers (Schilling et al., 1997; Rauch et al., 1998; Vanrolleghem et al., 1999; Muschalla et al., 2009). The papers highlighted various stages in an eleven step procedure for analysis, planning and implementation of an IUWS with an objective to improve receiving water quality. A series of papers highlighting the state of the art, current status and future of river water quality models are published (Shanahan et al., 2001; Reichert et al., 2001; Vanrolleghem et al., 2001). A continuity based methodology to develop interfaces between different sub system models was developed (Vanrolleghem et al., 2005a). Benedetti et al. (2007) developed an interface to link the ASM1 and RWQM1 models. Later, attempts to model the whole system on a single software platform and further simplification of the models to suit the purpose were made. Erbe (2002a) argued for the implementation of different sub system models on a single modelling platform and demonstrated the application of integrated models using a case study in Odenthal, Germany. Similar studies to evaluate operational strategies were conducted in Copenhagen (Harremoës et al., 2002). Erbe (2002b) presented a review of different integrated modelling attempts and the underlying softwares used in these studies. Meirlaen (2002) combined different modelling approaches and implemented an integrated model in the WEST simulation platform. A surrogate modelling approach using detailed models for calibration of simple mechanistic models was employed in this paper. Surrogate models as a replacement for computationally intensive deterministic models and relocation of system boundaries in time and space were used as approaches to simplify and integrate different components of an urban wastewater system onto a single platform (Vanrolleghem et al., 2005b).

Simple models are computationally less intensive and produce similar results although with higher uncertainty levels (Mannina, 2005; Mannina et al., 2006). Model simplifications were made in all the three components of an UWS. Such simplified models allowed for intensive model based optimization of IUWS models. Sophisticated optimization algorithms were used for studying the potential performance enhancement. (Muschalla, 2008; Fu et al., 2009) and real time control strategies (Fu et al., 2008). Integrated models were also used to analyze future scenarios arising from the growth of urban areas and the resulting impact on urban wastewater infrastructures (Doglioni et al., 2009; Astaraie-Imani et al., 2012) and mitigation strategies to reduce the impact of such developments (Fu et al., 2010). Statistical frequency analysis methods were employed to study the performance of integrated urban water systems (Fu and Butler, 2012).

There has been a significant effort in the last few years in analyzing the uncertainty arising due to different factors in integrated models. Influence of model parameters and sub systems on different model outputs were studied in integrated models (Mannina et al., 2006) and simplified drainage models (Freni et al., 2009) using the GLUE approach (Beven and Binley, 1992) and Monte Carlo simulations by varying the parameters in a given range assuming uniform distribution (Freni et al., 2011a). Identifiability analysis was performed to assess the model complexity given a specific catchment data set. It can be possible to reduce the uncertainty in the model output by reducing the model complexity based on the available data (Freni et al., 2011b). Design of data monitoring programmes depending on the model identifiability analysis was carried out (Freni et al., 2012). The location and monitoring variables that reduce the model uncertainty are determined using identifiability analysis. Although work has been done in uncertainty analysis of integrated modelling more efforts into such studies are needed.

It can be said that there is an increasing interest in integrated models for the entire UWS. Research is mainly focusing on integrating the existing sub models and simplification of the sub system models wherever required. With a complex IUWS model, the need for a framework for parameter identification and calibration is recognized and some methodologies are proposed. Integrated models have several uncertainties associated with various factors both in modelling and data collection. Uncertainty and sensitivity studies are being carried out to determine the efficiency of these models in predicting real life scenarios and also to understand the interactions between different sub systems of the UWS and their coupled nature.

5. Integrated control of urban wastewater systems

Availability of modelling tools and an increasing need to study urban wastewater systems with a view to improve the quality of receiving waters has led to the study of integrated control in an urban wastewater system context (Rauch and Harremoës, 1999; Schütze et al., 2002; Butler et al., 2005, Meirlaen et al., 2002).

The developments of integrated modelling and control are closely interlinked. Lijklema et al. (1993) presented a summary of the INTERURBA' 92 workshop highlighting the impact of different state variables on the ecosystem and also the state of the art in IUWS modelling. Early attempts at integrated control were made during the late nineties. A pollution based real time control strategy was evaluated by Petruck et al. (1998). Although the strategy needs information only from the sewer system, it aims at improving the quality of receiving water by discharging the most polluted water to the treatment plant and later filling up the storage tanks. Harremoës et al. (1994) presented various steps taken in Aalborg, Denmark taking into consideration the integrated nature of sub systems to perform design and control of the UWS. Schütze et al. (1999) has characterized integrated control in the context of urban wastewater systems based on the following two aspects and presented a methodology for implementation of integrated control strategies.

Integration of objectives: Control objectives in one sub system (sewer system, WWTP or receiving water) may be based on criteria measured in other sub systems (e.g. control in the sewer system to minimize shock loads to the WWTP).
Integration of information: Control decisions in one subsystem may be based on the information about states in another subsystem (e.g. control of aeration rate in the WWTP based on flow rate in the upstream sewer system).

The control algorithm describing the control actions can either be on online or offline control based on IF-ELSE rules and decision matrices.

Local control aimed at optimizing the performance of the individual sewer system or WWTPs may not necessarily improve the performance of the receiving water. Integrated control strategies aimed at improving receiving water quality are necessary (Schütze et al., 2002).

With growing interest in modelling and control of integrated urban wastewater systems, structured approaches and frameworks were proposed for the study of integrated control (Breinholdt, 2008). Owing to the complexity of the system, several objectives should be optimized for an effective integrated control. Some of these objectives can be mutually conflicting. Simulation studies on integrated control are cost intensive. A real time control potential calculator can be used at an early stage before investing in an extensive integrated control study (Zacharof et al., 2004).

A few practical implementations of integrated control are illustrated below. The implementation of water quality based control in Aalborg can be considered as one of the first attempts at integrated control of urban wastewater systems (Nielsen and Nielsen, 2005). Integrated real time control of an SBR reactor and a combined sewer system has been achieved in the town of Messel, Germany (Wiese et al., 2005). The cycle time in the SBR is controlled based on the flow data and rain data from the sewer system and catchment. Another similar attempt to integrate the operation of WWTP and optimize according to online measurements and Sewer system was made by Seggelke et al. (2005). A state-of-the art integrated modelling attempt aiming at controlling the urban system of Eindhoven, Netherlands was made by KALLISTO project (Weijers et al., 2012).

In spite of the theoretical studies, there is limited practical application of integrated control in urban wastewater systems. Also the fact that different wastewater infrastructures (like sewers, WWTPs) fall under different institutions makes it difficult for an integrated approach to control an UWS (Breinholdt et al., 2008). With the future clearly pointing towards integrated management of urban wastewater systems, the need for development of efficient integrated control strategies is growing. A benchmarking tool that can provide a common platform and evaluation criteria to compare different control strategies is very essential. Benchmarking is currently limited to wastewater treatment plants (Copp et al., 2002; Jeppsson et al., 2007; Nopens et al., 2010). A logical extension to the BSM2 benchmark would be to extend it spatially to include the sewer system and receiving water. The extended benchmark coupled with new models for sensors and actuators in IUWS can be a useful tool to develop, compare and evaluate different integrated control strategies (Jeppsson et al., 2013).

6. Summary & Conclusions

The report presents various approaches for modelling the sewer and catchment processes in an UWS. For the purpose of integrated modelling, the modelling approaches should be conceptual and computationally less intensive. Also, only those processes that are necessary are highlighted. One major limitation in the current state of the art is lack of consensus on sediment transport models in sewer system. To gain a clear understanding of the benefits of holistic modelling approaches in UWS, focus on developing sewer quality models is essential. Further, the report reviews modelling and control approaches for UWS. Integrated modelling and control has shown great potential to improve the receiving water quality and avoid local optimization of individual UWS components. It is highlighted that such integrated studies are being limited to modelling studies and very few reach practical implementations. A spatial extension of benchmark simulation models can provide a useful platform for modelling community to perform system wide analysis of UWS and to evaluate different control strategies in an objective manner.

7. References

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8. Available software for integrated modelling and control

WEST

The WEST modelling software offers WESTforIUWS that can simulate the sewer, catchment, WWTP and river components of an IUWS. It offers possibilities to evaluate water quality based objectives in both long term and short term evaluation periods. Additionally, uncertainty and sensitivity analysis of the models can also be performed. Currently, WEST is the most widely used software for integrated modelling and control studies

SIMBA

SIMBA is Matlab/SIMULINK based software that is developed by Ifak, Germany. It consists of a model library to simulate processes in sewers, WWTPs and rivers. It allows for the integration of SWMM5 software to support hydrodynamic simulations of the sewer system. Simplified hydrologic models are also available. Additionally, it facilitates easy integration of control studies. There is a possibility to program the controllers in IEC 61131-3 standard languages like structured text

CITY DRAIN

CITY DRAIN is an open source Matlab based toolbox for IUWS evaluations. The models for the sewer and river are hydrologic and it also has a simplified WWTP model. It gives the users a possibility to create their own user define blocks in addition to the existing model library. It allows for a fast simulation of the IUWS owing to its simplified nature.