International Conference on Pumps, Electromechanical Devices and Systems Applied to Urban Water Management
PEDS 2003, Valencia, Spain, 22 – 25 April 2003

Real-Time Control of Urban Water Systems

Manfred Schütze[1], Alberto Campisano[(2)], Hubert Colas[(3)],
Peter Vanrolleghem[(4)], Wolfgang Schilling[(5)],

[(1)] Institute for Automation and Communication, Department for Environmental Software and Control, ifak Magdeburg e. V., D-39179 Barleben, Germany; Fax +49-39203-81100; manfred.schuetze@ifak-md.de
[(2)] Dipartimento di Ingegneria Civile e Ambientale, University of Catania; Viale Andrea Doria, 6, I–95125 Catania, Italy; Fax +39-095-7382748; acampisa@iiiga.ing.unict.it
[(3)] BPR-CSO, 5100, Sherbrooke E, suite 400, Montreal, Québec, Canada H1V 3R9; Fax +1-514-257-2414; hcolas@bpr-cso.com
[(4)] BIOMATH, Ghent University, Coupure Links 653, B-9000 Gent, Belgium; Fax +32-9-264 6220; peter.vanrolleghem@rug.ac.be
[(5)] Department of Hydraulic and Environmental Engineering, Norwegian University of Science and Technology, N-7491 Trondheim; Fax +47-73591298; wolfgang.schilling@bygg.ntnu.no

Abstract

This paper presents a review of the current state of the art of real time control (RTC) of urban water systems with emphasis on wastewater and urban drainage issues. The paper provides concise definitions of terms frequently used in the literature. Control options for the transport and treatment systems are discussed. Recent developments of the integration of the complete urban wastewater and drainage system including consideration of the receiving water are described. This allows information from all parts of the system to be used for control decisions and can lead to a significant improvement of the system performance. Some fundamental concepts of this approach are outlined. Particular emphasis in this paper is laid on methodologies of how to derive a control procedure for a given system. As an example of an RTC operational in practice, the Québec Urban Community global predictive RTC system for the urban drainage network is presented. The paper concludes with an outlook into current and future developments in the area of real time control.

1. Introduction

Urban water and wastewater systems, consisting of raw water source, water purification plant, water conveyance and distribution network, sewer and drainage system, wastewater treatment plant and receiving water as their main elements, can be found throughout the world (Figure 1). Figure 1 also indicates that there are usually only weak links between the water supply portion

[1] The authors are members of the IAHR/IWA Joint Committee on Urban Drainage, Working Group on Real Time Control of Urban Drainage Systems. The paper is presented by Wolfgang Schilling

and the wastewater/drainage portion of an urban water system. Thus, both sub-systems are mostly operated independently.

Many urban water systems are operated with little or no real time control (RTC). On the other hand, some cases exist that exhibit quite sophisticated forms of control. What are the benefits? What are the drawbacks? Why should we embark on real-time control? This survey paper attempts to give an introduction to the current state of the art of real time control in urban water systems emphasizing the wastewater and drainage aspects of these systems. It is essentially based on a conference contribution by the same authors presented at the 9th International Conference on Urban Drainage in Portland/Oregon, September 2002.

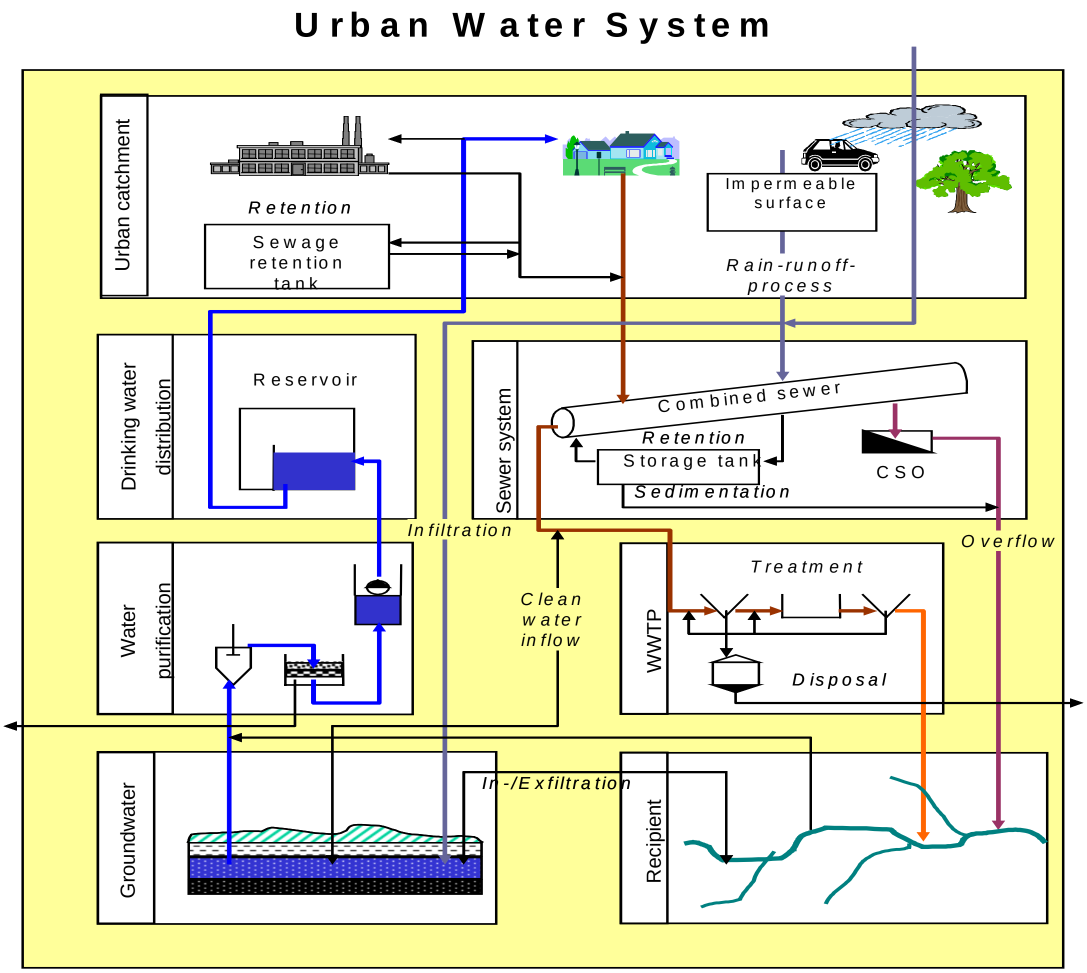

Figure 1: The urban water system with some important fluxes of water and water-borne matter (Krebs, 1996). Note that normally there are no interconnections between the drinking water and the wastewater sub-systems, thus, knowing the operational state of one side does not give an advantage to operate the other side (exception: if the wastewater recipient is also the raw water source).

The question: "Why should we bother with real time control?" has a simple answer, at least conceptually: "Urban water systems are designed for static/stationary loading but are operating under dynamic loading". In other words: Only in the rare case of the design loading the system operates optimally. In all other operational situations the built-in capacity of the system is not used, or less often but more importantly, it is used in a way that the objectives cannot be met. In the first situation invested capital is not productive, in the second situation damage occurs: customers do not get water, receiving waters are polluted, or the city is flooded. The disturbing feature of this sub-optimum operation is that parts of the system might be idling while, at the same time, other parts are overloaded. This is where real time control becomes an option: Manipulate the system such that its capacity could be used better in order to achieve improved performance of the system: more reliable water supply, less pollution, less flooding.

The larger the discrepancy is between the planned ("design load") and the real operation of an urban water system, the larger is the potential benefit of real time control. With that respect urban wastewater systems, and here particularly combined sewer systems with biological treatment plants discharging into receiving waters with different sensitivity display an enormous variation of "loading versus capacity". Additionally, controlling such systems implies significant technical difficulties (e.g. need for robust hardware, complicated processes, vaguely defined performance criteria) such that they are ideal cases to discuss the potential benefits and pitfalls of this technology.

2. Definitions and key terms

This section introduces some of the fundamental concepts and terms of RTC. Subsequent sections discuss how control procedures are actually determined for a given case, followed by an example of an implementation of real time control in Québec City/Canada. Further sections outline some important practical issues as well as current and future trends of RTC.

Definition:
An urban water system is controlled in **real time** if process variables are monitored in the system and continuously used to operate actuators during the process.

Processes might concern quantity of water (flow rate, storage, pumping, etc.) as well as quality (sedimentation, treatment, etc.). In principle, the control of the process can be schematised by means of **control loops** (Figure 2), which can be implemented by means of hardware components including **sensors**, which monitor the process evolution, **actuators**, which influence the process, **controllers**, which adjust actuators to achieve minimum deviations of the controlled process variable from its desired value (**set-point**), and **data transmission systems** transmitting data between the different devices.

RTC in urban water systems poses stringent requirements on sensors, such as measurement accuracy and reliability, physical and chemical resistance and suitability for continuous recording and remote transmission. S**ensors** used include:

- *Rain gauges* such as weighing gauges, tipping buckets and drop counters. Rain measurement can also be obtained by meteorological radars enabling also short term rain forecasts.
- *Water level gauges* such as floating hydrometers, bubblers, pressure inductive gauges and sonic gauges. Water level gauges are essential for monitoring the state of storage or to convert levels to flow rates in conduits where backwater effects are not dominant.

- *Flow gauges* such as level-flow converters, ultrasound velocity meters, electromagnetic flow meters.
- *Quality gauges* such as sensors organic pollution (TOC, readily biodegradable COD), nutrients (total, ammonia and nitrate nitrogen, and phosphorus), biomass (turbidity or respiration activity), toxicity (via respirometry), etc. These sensors supply information of high value, however, they also require significant operation and maintenance skills. Simpler, but more robust measurement devices, which often are used as surrogates for the actual variable of interest, include sensors for pH, conductivity, redox potential, UV and IR absorbance. However, for these considerable efforts are required to create the interpretation modules that convert the raw sensor output into the required information.

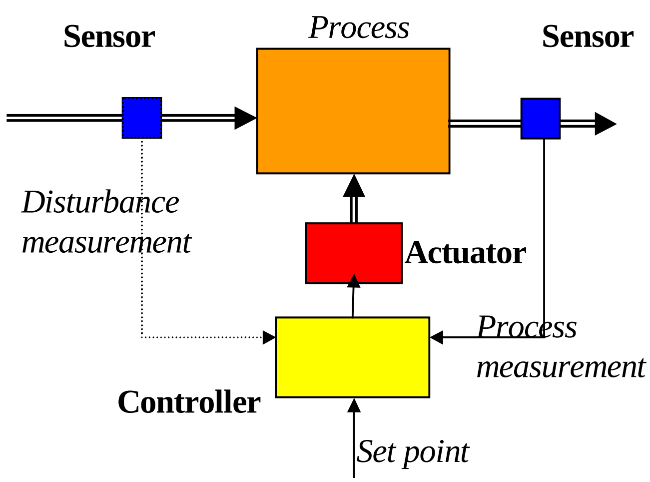

Figure 2. Feed-forward control (disturbance measurement) and feedback (process measurement) control loop. Simple arrows indicate data flow, double arrows indicate hydrodynamic processes. Bold letters indicate hardware and italic letters indicate variables.

Actuators in urban wastewater systems include:
- *pumps* (axial or screw) with constant or variable speed;
- *gates* (sluice, radial or sliding) which restrict the flow in a sewer or at the outlet of a detention tank; they are usually activated by motors and used for generate in-line storage or for diverting flows into other parts of the system;
- *weirs* (transverse, side spill) which can either be static structures, for example, to reduce overflow discharges over a combined sewer overflows, or which can be moveable and adequately positioned in order to generate storage volume (Campisano et al., 2000, 2001). *Inflatable dams* can be used in large trunk sewers to activate in-line storage;
- *valves* are used to restrict flows in pressure pipes;
- other actuators, such as movable air-controlled *siphons* used for storage, and movable *flow splitters* which separate flow into two ore more paths.
- *chemical dosing devices* that adjust the conditions in the tanks to achieve a certain performance, e.g. supply of readily biodegradable COD to enhance denitrification, injection

of acid/base to control pH, addition of polymer or ballasting particles to enhance settling of flocs;
- *aeration devices* are an essential and very cost-determining part of most of the wastewater treatment plants. Oxygen is indeed necessary for some of the important biological pollutant removal processes, e.g. nitrification. Many different types exist with the more cost-effective ones being the fine bubble aeration systems.

The **control loop** defined in Figure 2 is the basic element of any real time control system. In **feedback** loop control, commands are actuated depending on the measured deviation of the controlled process from the **set-point**. Unless there is a deviation, a feedback controller is not actuated. A **feedforward** controller anticipates the immediate future values of these deviations using a model of the process. Then it activates controls ahead of time to avoid the deviations. A **feedback / feedforward** controller is a combination of these two types.

A standard controller used for **continuously** variable actuator settings are the proportional-integral-derivative **PID-controller** and its simplifications (P, PI, PD). Its signal to the actuator is a function of the difference between the measured variable and the set-point. The parameters in that function have to be calibrated unless the controller is equipped with an **auto-tuning** facility. Calibration is performed through analysis of the underlying differential equations, or through real or simulated experiments (e.g. Campisano and Modica, 2002).

Two-point or on/off-control is the simplest and most frequently applied way of **discrete** control. It has only two positions: on/off or open/closed. An example is the two-point control of a pump to fill a tank: the pump is switching on at a low level and off at a high level. The difference between the two switching levels is called **dead band**. **Three-point** controllers are typically used for actuators such as gates and movable weirs, etc. In the middle position of the controller, the output signal remains in its previous state and in the other positions it assumes either maximum or minimum, respectively.

Today, digital **programmable logic controllers (PLC**) largely replace analogue controllers. Typically, a PLC controls and co-ordinates all functions of an outstation (i.e. a monitoring and/or control site in the field). These include acquisition of measurement data, pre-processing (smoothing, filtering, etc.), checks for status, function, and limits, temporary data storage, calculation of control action, and receive and report data from and to the central station. In the control room, a **supervisory control and data acquisition (SCADA)** system manages all incoming and outgoing data. Alarms are generated here, and operators monitor and control the processes (e.g. change of set-points). **Data transmission systems** may be realised by means of leased or dedicated telephone lines, or by wireless communication systems, such as radio, cellular systems or satellite telecommunication devices.

Real time control systems, in particular those with frequent man-machine interaction, also need to be equipped with user-friendly operator (user) **interfaces**. Today, active wall panels are replaced by computer screens to display standard features applied in a variety of application fields (synoptic screens, showing current values, trends and alarms).

In relation to the degree of automation of the RTC system, the type of control may be **manual** if the actuators are adjusted by operators, **supervisory** if the system actuators are operated by automatic controllers with their set-points being specified or approved by operators, or **automatic** if the control is realised in a fully automatic way by a process computer, including in all cases manual override capabilities.

With regard to the complexity of a real time control system, the following distinctions are made in the literature. A system is operated on a **local control** level if the actuators are not remotely operated from a control room and if process measurements are taken directly at the actuator site and the actuators are not remotely operated from a control room. Local control may represent a good solution in the case of one actuator only, but if the system is more complex or if all actuators have to be operated jointly, **global control** becomes necessary. In this case, sensors communicate their data to actuators located in other parts of the system. Alternatively, a central control room receives all the measurement data of local sensors and centrally operates the actuators in a coordinated way.

Current research is also focussing on **integrated control** (Schütze et al., 1999)**.** This control level involves simultaneous and coordinated control of sub systems such as the water purification plant and the distribution system, or the sewer system and wastewater treatment plant. This approach allows for analysing both quantitative and qualitative aspects of the water and wastewater services including the environmental conditions of the receiving waters (Schütze et al., 2002a; Rauch and Harremoës, 1999; Meirlaen et al., 2002a, 2002b; Nielsen and Nielsen, 2002). Integrated control opens up significant additional potential for control and for improving the performance of water supply and wastewater systems. It could be shown in a recent study (Schütze et al., 2002b) that many instances of wastewater systems do have control potential when applying integrated control, even in cases where neither local nor global control scenarios appear to increase the performance of the wastewater system. Practical examples of integrated real time control include Québec - see Section 5, but also Aalborg (Nielsen and Nielsen, 2001) and Odenthal (Erbe et al., 2002). An even higher level of integration, i.e. of water supply and wastewater systems is not so interesting, because knowing the state of one system would not yield significant advantages for the operation of the other system.

3. Control objectives

The general objectives in controlling urban water systems are not different from their general operational objectives: Supply drinking water with sufficient reliability (i.e. quantity, quality, safety), collect and treat sewage, drain rainfall runoff and prevent flooding and receiving water pollution – all to be achieved in the most cost-efficient manner. This list already illustrates why controlling wastewater systems is more complex than drinking water systems. Wastewater control includes several objectives, some of which are even conflicting (e.g. drainage and pollution control in combined sewer systems). Because of their large loading variations and their complex objectives such system are discussed now in more detail.

Traditionally, sewer system, treatment plant and receiving water have been considered as separate units. Also control, where it was performed, was - and often still is - done for each of these parts separately, see Schilling (1989), Olsson and Newell (1999) and Jeppsson et al. (2002).

When formulating control objectives, more generally, defining performance indicators for combined sewer systems, one traditionally uses auxiliary criteria such as minimise overflow volumes or frequencies. Additional objectives could include, for example, avoidance of flooding and the equalisation of peak discharges towards the treatment plant or the reduction of sewer sediments by deliberate flushing. In practical applications, also the reduction of costs constitutes an important objective, if not the driving one, of real time control implementations. Control aims at improving the performance of the system, by essentially using the existing infrastructure (or trying to avoid large investments for static expansions of the system in order to meet the demands) in a more sophisticated way than letting the wastewater running downhill. For some cases, application of real time control contributed to significant cost savings.

Control is also applied at wastewater treatment plants in various forms: applications range from oxygen control in the aeration tank to highly sophisticated forms of control, involving on-line simulation models (Jumar and Tschepetzki, 2001; Nielsen, 2001). Control objectives for treatment plants usually include, among others, maintaining effluent standards and minimisation of costs.

Recent studies suggest that traditional criteria do not necessarily describe the performance of the urban wastewater system in terms of water quality of the receiving water body (Rauch and Harremoës, 1996; Butler and Schütze, 2001; Butler et al., submitted). This motivates considering to what extent real time control can be used to improve river water quality, despite the fact that the traditional auxiliary criteria still form the base for standards in many countries. Also, the fact that often different departments or even different utilities are responsible for different parts of the wastewater system may hinder such coordination. Whilst the discussion on discharge-based versus environmental quality based legislation has been ongoing for years (Tyson et al., 1993), an important paradigm shift can now be observed: Although still many years ahead before being imposed completely, the EU Water Framework Directive (WFD) (CEC, 2000) requires an ecological quality driven approach of river basin management which evidently will have implications on urban wastewater system management within Europe and elsewhere. The directive asks for a major leap forward in management practice calling for the effect of all wastewater discharges into a receiving water body, irrespectively where they come from. Thus, it supports an integrated control approach where the complete wastewater system will need to be regarded as one control system.

4. Development and Analysis of Control Procedures

A real time control system usually is structured in different hierarchical levels, i.e. field (process), system and management levels (Figure 3). The management level involves the specification of the overall way of operation. On the system level, the magnitude and the time sequence of the various set-points in the real time control system are specified. On the field level, controllers adjust actuators to achieve minimum deviations of the regulated variables from their set-points.

A core task in developing of any RTC system is the determination of an appropriate control procedure for the given wastewater system. A **control procedure** (in some publications called “control algorithm” or “control strategy”) is defined as the time sequence of all actuator set-points in a RTC system.

Synonymously, also a set of rules which specify such a time sequence can be termed a control procedure. In almost all cases with multiple control loops it can be shown that an optimum control algorithm consists of time varying set-points. Some control procedures can be represented also as **decision matrices**. Each element of the matrix represents the control action that has to be carried out for a given combination of state and input (loading) variables. Decision matrices allow for very fast on-line execution of control procedures. Simplifications of decision matrices include **decision trees (rule bases)** that are a set of "if-then-else" statements.

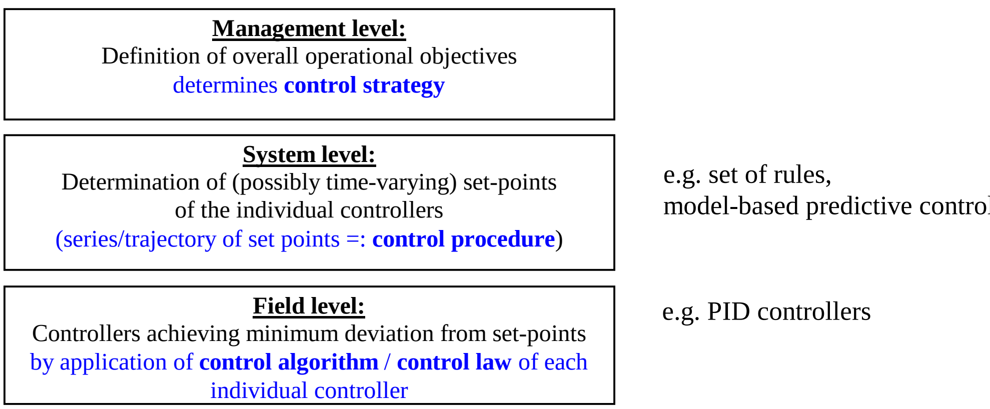

Figure 3. Various levels in a real time control system (adapted from Schütze et al., 2002)

The subsequent paragraphs will outline how a control procedure can be found on the system level. Its actual implementation (on the field level), involving controllers of various types, can then be done by control engineers. Certain overall specifications, such as which elements of the system are to be controlled, will have to be made on a managerial level prior to determination of a control procedure.

Heuristic approaches to determine a suitable control procedure can be based on the experience of the operating staff. A set of potential procedures (including, for example, a default fixed set-point procedure) is specified and then improved by an iterative procedure involving a simulation model of the system. Evaluating the results of a number of simulation runs, testing a number of strategies, improves the procedure by trial-and-error. If no more improvement is possible in this iterative procedure, it is assumed that an optimum procedure has been found. A variation of this approach consists in the design of local control for the actuators of the wastewater system, followed by setting up global control schemes only at those parts of the network where these result in an improvement (Schütze and Einfalt, 1999). An upper boundary for the reduction of overflow volumes by application of real time control can be easily obtained by simulation (Einfalt and Stölting, 2002).

Besides simple, but laborious, trial-and-error methods, also mathematical optimisation techniques (see, for example, Dochain and Vanrolleghem, 2001, for a review) have been applied successfully to the development of control procedures **(off-line optimisation)**. Values are determined for the parameters of control rules which are optimum with regard to the specified performance criteria (Schütze et al., 1999, 2002a). Since here the simulation model is applied off-line, the simulation models can be fairly complex and computation time is less of an issue in this approach. Hence a more detailed system representation can be chosen when modelling the system and also longer term impacts of control actions can be evaluated here.

An alternative approach to determine a control procedure consists in setting up an on-line simulation model, which, at every control time step (e.g. five minutes), evaluates the impacts of a number of potential control actions and then actually applies that one which showed to be most beneficial in the evaluation procedure (**model based predictive control**), e.g. Rauch and Harremoës (1999). By performing on-line calibration and thus updating the model based on current measurements of the system state, predictions of future system states with fairly high accuracy can be obtained. For determining the best possible control action, optimisation routines can be applied, too **(on-line optimisation)**. It should be noted, however, that here calculation time can be a critical issue, since a potentially large number of different control actions and their impacts on the wastewater system will have to be evaluated within fairly short time. A number of such systems are in planning or in operation (see further below; Nielsen and Nielsen, 2002; Scheer and Nusch, 2002).

A number of different optimisation techniques can be applied in off-line and on-line optimisation approaches. Optimisation allows evaluation of the control performance on an absolute ("the best") rather than a relative ("a better") scale. Here, the problem is translated to the minimisation of an **objective function** subject to **constraints**. Overviews of various optimisation methods are given by Dochain and Vanrolleghem (2001) and Schütze et al. (2002a). Although the application of optimisation methods, and, more generally, the development of control procedures, usually aim at determining the optimum (best possible) control action under the given conditions, a *suboptimum control decision* is often sufficient for RTC (as long as it can be ensured that this decision does not lead to a performance of the system inferior to the no-control scenario). This is of particular importance in cases where an optimum solution cannot be found within the given time constraints for control.

5. An implementation of RTC: The Québec Urban Community RTC system

The Québec Urban Community (QUC) has implemented a global optimal predictive real time control system and has operated it since summer 1999. It involves solution of a multi-objective optimisation problem. It consists of finding the flow set points that minimise the value of a multi-objective (cost) function, with respect to physical and operational constraints. For QUC’s westerly network, all constraints are linear in order to reduce computing time. The system’s non-linear behaviour is described by the multi-objective function. The control objectives are, in decreasing order of priority: the minimisation of overflows, the maximisation of the use of the treatment plant capacity, the minimisation of accumulated volumes and, finally, the minimisation of variations of the set-points.

Along with these global control objectives and local weights defined in the objective function, an uncertainty factor is associated with the optimisation variables to take into account the fact that predictions in the far future are more uncertain than in the near future. The linear equality constraints are used to define the relationships between the optimisation variables. In particular, the set of equality constraints include a linear hydraulic ARMA model. The inequality constraints are used to set physical and operating boundaries. They limit accumulated volumes in the tunnels and flow rates below the pipes' hydraulic capacities. They also constrain flow set points below maximal values computed at the local sites and limit flows conveyed to the WWTP.

This procedure for flow control is constrained by flow limitations at certain critical points, and is not allowed to provoke any surcharge flows in sewers. The sewer network uses a distributed control procedure divided into three hierarchical levels: Level 1 consists of local control of the actuator, whilst Level 2 includes coordinated control of several Level 1 stations. Global optimal predictive real time control, finally, represents the third level of control in the Québec system.

The real time control system is implemented at a central station and uses flow monitoring and water level data, rainfall intensity data, radar rainfall images and 2-hour rain predictions. Set-points are translated into moveable gate positions at local stations by Programmable Logic Controllers (PLC). The system presently controls 5 moveable gates and receives information from 17 flow monitoring and weather stations (Pleau et al., 2000). It is designed to ultimately control some 30 flow regulators and have a total of nearly 70 measurement locations. The related optimisation problem defined for the controlled section of QUC's westerly network comprises 1380 constraints and 1196 variables. The optimisation problem is solved at every control time step (5 minutes) by a non-linear programming algorithm (Pleau et al., 2001).

The Westerly sewer network (Figure 4) comprises of three major interceptors (Métropolitain-Nord, Versant-Nord and Versant-Sud) and two tunnels (Versant-Sud and Affluent). The Versant-Sud tunnel has a diameter of 2.47 m, a length of 4.6 km for a total volume of 15 628 m^3, whilst the Affluent tunnel has a diameter of 2.45 m, a length of 3.4 km) for a total volume of 16 137 m^3. These two tunnels have a combined storage volume of approximately 15 000 m^3. Twenty-two regulating and overflow structures permit to control the flow in the interceptors. Prior to the implementation of Global Optimal Predictive Real-Time Control during summer 1999, altogether nine structures had significant overflows during rainfall events.

In the first phase of its implementation, this RTC system manages the flow on the western portion of the QUC network. By only optimizing the use of two existing tunnels and the capacity of the westerly wastewater treatment plant, real time control achieved a 70% reduction in overflow volume in 2000. The cost of this phase was only US-$ 2.6 million compared to an estimated US-$ 15.5 million to build retention facilities to attain an equivalent control level over the Québec Urban Community territory, such as would be done through conventional engineering design (Lavallée et al., 2001).

Figure 5 presents a comparison of overflow volumes at the major overflow sites and at the WWTP for two management strategies (dynamic, i.e. RTC, and static) for the 13th of August rainfall events. Static management represents the network management strategy "before 1998" (i.e. before any RTC implementation). The data marked "dynamic" are actual operation measurements, whilst the static scenario is simulation results of what would have occurred under the same situation prior to the implementation of RTC.

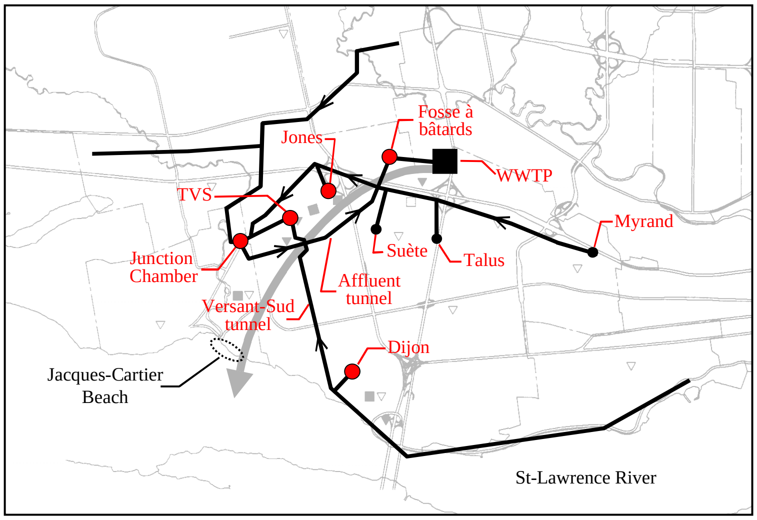

Figure 4. QUC's control sites and retention tunnels

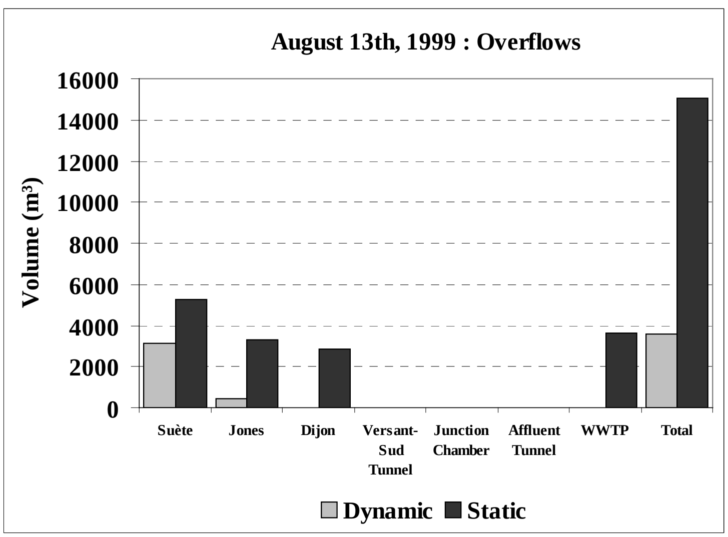

Figure 5. Overflows at each control site for the rainfall event of 13 August 1999

When compared to the results obtained with static management, global overflow volume reductions per site with RTC vary between 40% (Suète) and 100% (Dijon) while global reductions per event are close to 70%.

Figure 6 demonstrates how the control scheme behaves in order to make maximum use of the available storage and treatment capacity. Flows conveyed to the WWTP correspond to the treatment capacity while avoiding overflows. This objective is achieved through the control scheme by retrieving the hydraulic capacity of the WWTP from tide tables stored in the RTC database for the 2-hour prediction horizon. With this information, the flow conveyed at the WWTP is able to match the hydraulic capacity assuming there is enough water accumulated in the Affluent tunnel.

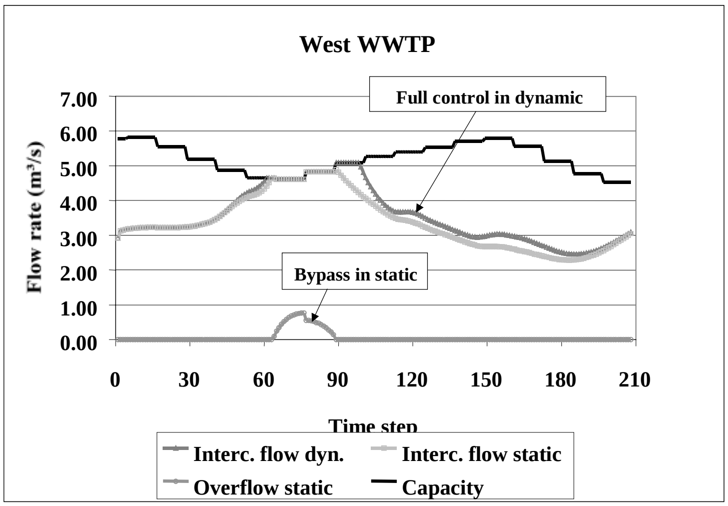

Figure 6. Flow rates at West treatment plant with static and global optimal predictive RTC

6. Lessons learned: Important practicalities

Some of the lessons learned from the Québec real time control system and from other applications can be summarized as follows:

Costs: RTC can help avoid costly capital improvements by better using existing facilities. There might be extra costs involved in the planning stage for RTC, but this cost is usually marginal when compared to the entire planning process. Furthermore, RTC can be implemented rapidly, 1 to 2 years for design and construction, which can provide significant and rapid environmental benefits. RTC can also help avoid building new retention, conveyance or treatment facilities, resulting in significant capital expenditure savings (Schilling, 1994; Lavallée et al., 2001). Therefore, real time control should be included as an option in the planning process for an urban wastewater system improvement program. Useful prior to a detailed feasibility study and cost-benefit analysis is a pre-assessment of the RTC potential of the given site. Some quick-and-easy-to-apply criteria for such an evaluation of the RTC potential of sewer systems are suggested by Schilling (1994). A CD to be published by the RTC Working Group of the German Wastewater

Association ATV will contain an extended version of this list, complemented by some additional material guiding the practical engineer in RTC implementation projects (Scheer and Weyand, 2002).
Safety: The requirement of safety can be translated into a simple rule: the worst-case scenario should be to fall back on a system behavior equivalent or better than the situation before the introduction of RTC. Safety is complementary to reliability and is warranted by the inclusion of fail-safe or backup devices in the design of equipment. Safety is ensured through good engineering practices.

Reliability: a careful selection of equipment, such as sensors, actuators, telemetry and data processing equipment is a good starting point to ensure reliability. But any electronic or mechanical device is prone to failure, especially when submitted to the harsh sewer environment. This clearly distinguishes real time control of urban wastewater systems from many other applications of control engineering. Therefore, equipment failures need to be considered as inevitable and measures have to be devised which ensure the reliability of the system. Such measures include, for example, operation and maintenance guidelines, provision of redundancy of critical sensors and actuators, multi-path, multi-channel communications, data validation and tagging, and the use of a robust simulation and, where appropriate, optimisation software.

Adaptability: the RTC system has to adapt to varying conditions, including equipment failures and varying rainfall intensities and space and time distribution. For the Québec case study, it was found that, using an on-line calibrated model-based approach, a multi-variate objective function, and a set of physical and operational constraints, best adaptability to the intrinsic varying wet weather conditions could be achieved.

Flexibility: although modelling is necessary for the evaluation of RTC potential and for the design of RTC procedures, RTC is real-life operation. Design of infrastructure can only provide guidance to its setup, but not all possible situations can be taken into consideration. Unexpected situations will occur in real life. Hence, the RTC system should be designed with capabilities to adapt to a larger spectrum of such unexpected situations. For example, a power failure of one hour at the Québec City wastewater treatment plant caused no overflows because the central control algorithm was able to trigger its control, and proactively, rather than reactively, utilised all available control sites and storage capacities in the system and devices, thus handling such a degraded situation. Furthermore, a real time control system should be designed in such a way that it also provides scope for system modifications and extensions. Therefore, it should preferably be based on industry standards rather than proprietary modules, commercially available software rather than custom made, parameterized and modular rather than hard coded programs.

System integration: system integration is the key to the technical success of the RTC system. A RTC system is composed of many devices, equipment, programs, etc., that need to communicate in a common language. Data need to be synchronized and be updated much more quickly for control than for supervisory purposes only, especially in sewer systems with short runoff concentration and flow times.

Ownership and *acceptance* of the control system: another key to the success of a RTC system lies in the ownership by the staff at all levels of the organization that will be responsible for operation and maintenance of the control system. This aspect cannot be stressed enough, as lack of emphasis of such involvement of the staff is responsible for many bad experiences in the past in the operation of real time control systems. An approach to ensure such ownership includes the joint involvement of operators, design engineers and control systems and information technology experts. It is crucial that they are actively involved very early in the process, and that their inputs are considered in the design of the system. Training and documentation should not contain any unnecessary technical jargon and should be adapted to the different levels of staff, taking into account their different level of responsibilities and functions within the operating company or authority. Acceptance of the system may, in some cases, be further increased if the ultimate control decision is taken by the operator (assisted by the control system), and not by the computer itself (**operator-in-the-loop**).

Consenting procedure: Prior to commissioning a RTC system, approval needs to be sought from the authorities responsible for consenting the system. Therefore, it is necessary that these authorities are convinced of the benefits of the real time control system. Usually, it has to be demonstrated that the real time control system can meet the required standards. The proposed control procedure, including failure scenarios, will have to be documented well. Negotiations with the consenting authorities, which should be included early in the design of the RTC system, will have to define criteria against which proper operation of the RTC system is to be judged. This could include a check whether the previously agreed control rules are always followed. For systems without explicit control rules (e.g. on-line optimisation systems) different criteria may have to be applied.

7. Current trends, future developments

In this section, some ideas and trends that the authors expect to develop in the coming decade are presented. Starting from the visible shift in operational objectives driven by re-oriented legislation, future characteristics of practical tools for RTC design and implementation are presented. These include, in particular, modelling approaches, measurement systems, actuators and, of course, new control strategies and procedures which are more closely linked to the new objectives.

Applications: A predecessor to many RTC systems are monitoring systems where vital functions of water supply, wastewater and drainage systems are continuously supervised. Often such monitoring systems are gradually augmented and ultimately become RTC systems. As water supply is more urgently needed than wastewater management and because of its fewer technical complications monitoring and control are more applied in the water supply sector as compared to wastewater and urban drainage. This trend might shift in the future because if wastewater and drainage performance has to be improved extremely large investments are required. In such situations RTC is an attractive option because the approach can reduce investment needs.

Objectives: Knowledge gaps still exist, for instance and most importantly, what the relation is between the water quantity and quality variables that have been in use for so many years for the assessment of the quality of the urban wastewater system design and operation, and the ecological quality the WFD requires river basin managers to focus on. As a consequence, important research efforts have been initiated to better understand these links and (soft) modelling approaches seem to get a lot of attention in this respect (Schleiter et al., 1999).

Models: Continued efforts will be devoted to make the existing integrated simulators (see below) accessible and sufficiently performing for practical development of RTC solutions for urban wastewater systems. Important aspects that are expected to be focused upon are model reduction, surrogate models (e.g. neural networks and simplified models that can mimic complex behaviours in a sufficiently accurate way), proper consideration of effects relevant to RTC (such as pump switching involving time lags) and more efficient numerical routines for model solving and optimisation. On the other hand, continued efforts are also expected in the development of models that are compatible with the other subsystems and have an increased prediction performance (Rauch et al., 2002).

Uncertainty: There is no doubt that the profession shows an increased awareness of the inherent uncertainty in modelling these large complex systems (Beck, 1987; Lei & Schilling, 1994; Willems, 2000; Rousseau et al., 2001; Pleau M. et al. 2002). One of the options that is promoted is to adopt a different type of models that can intrinsically deal with uncertainty, e.g. so-called grey-box models (Bechmann, 1999). An alternative consists of maintaining the deterministic models that are in wide-spread use today, but put an uncertainty propagation layer around these models (Monte Carlo simulation) to get an assessment of the uncertainty one has to deal with in the variables of interest. This approach was adopted successfully in WWT design and operation (Rousseau et al., 2001) and is currently under evaluation for use in RTC design of integrated urban wastewater systems.

Measurements: When considering the data on which RTC relies, the future will show a trend similar to what is observed in wastewater treatment operation (Jeppsson et al., 2002): sensors will become more focused by providing relevant data on the problem at hand, and deal with the painstaking fouling problems whilst at the same time minimising maintenance requirements. Increased attention will be given to data management (databases, GIS supporting systems to present the data) in order to deal with the problem of “data drowning”. Further, increased attention will be devoted to automated fault detection (“do we have an erroneous measurement?”) and diagnosis (“what is this error caused by?”) (Olsson & Newell, 1999) such that RTC systems can fall back to alternative control schemes that do not rely on the faulty data.

Actuators: It is the belief of the authors that no important developments will occur in the field of the actuators. Rather existing actuators will be used in a more creative way and more objective-driven. The exception may be some developments at the level of implementing actuators in river systems (aeration, flow regulation) as the in-river conditions will become increasingly focused and therefore acted upon. Such ideas have already been proposed by Reda (1996) and are implemented in the Seine river in Paris (Krier, 1998).

Control procedures: It is expected that the change in control objectives will automatically lead to more integrated control systems that use information from the complete urban wastewater systems to act on different points in this system. Hence, the strategies that will be adopted are inherently MIMO (multiple input – multiple output) in nature. This does not necessarily imply that complex control laws/algorithms will have to be adopted. Rather an intelligent and supervised combination of simple SISO (single input - single output) control laws that can easily be tuned is foreseen to be implemented. The systematic development, evaluation and tuning (Schütze et al., 2002a) of these procedures is expected to be done with integrated simulators that are currently in full development (Meirlaen et al., 2001; Rauch et al., 2002; Schütze and Erbe, 2002). Also, simultaneous consideration of several concurrent objectives in the determination of control actions constitutes a promising area for development (Rauch and Harremoës, 1999; Schütze et al., 2002c). In view of the uncertainty aspects mentioned above, robustness of the controllers' performance will be one of the aspects taken into account during their selection and tuning (Meirlaen, 2002). In terms of operator involvement, it is expected that considerable efforts will be devoted to keep the operator/supervisor/manager in the control loop. Hence, there will be increased need for data management and decision support systems that will require extensive GIS support.

In conclusion, the authors expect that an increasingly adopted solution of dealing with the challenge imposed by the river (ecology) driven objectives as, for instance, laid out in the EU WFD will be based on simple and robust, but creatively laid-out RTC systems, developed in simulators that allow to evaluate in-river objectives given by local (ecological) requirements.

8. Conclusions

As key lessons on the current state of the art in real time control of urban water and wastewater systems can be stated

- Larger urban water supply, drainage and wastewater systems often include centralised supervisory systems with control capability, that are sometimes operated on an ad-hoc basis.
- Methodologies and tools are available which allow real time control of urban water and wastewater systems to be considered as an option to minimise adverse impacts on the environment, improve systems performance, and to minimise costs;
- In combined sewer and biological wastewater treatment systems both the control potential and the implementation difficulties seem to be very significant.
- Due to improved methods, even those wastewater systems may have potential for real time control where, in the past, RTC was not considered as an option;
- Further improvements are required in a few areas, such as water quality sensor development and consideration of uncertainties.

Acknowledgments

Peter Vanrolleghem gratefully acknowledges the financial support of the EU projects HarmoniCA (EVK1-CT-2002-00192) and CD4WC (EVK1-2001-00286).
Wolfgang Schilling gratefully acknowledges the financial support of the EU projects CARE-W (EVK1-CT-2000-00623), CARE-S (EVK1-CT-2002-00106), and CityNet (EVK1-CT-2002-80013).

References

Bechmann, H. (1999). *Modelling of Wastewater systems*. PhD thesis. Technical University of Denmark. Lyngby

Beck, M.B. (1987). Water quality modeling: A review of the analysis of uncertainty. *Wat. Res. Res*., 23, 1393-1442.

Butler, D., Lau, J., and Schütze, M. (submitted). Is combined sewer overflow spill frequenc/volume a good indicator of receiving water quality impact? submitted to *Urban Water*.

Butler, D., and Schütze, M. (2001). *Integrating simulation models with a view to optimal control of urban wastewater systems*. Workshop on Vulnerability of water quality in intensively developing urban watersheds. Making the case for High-performance integrated control. Athens, Georgia, USA. 14 -16 May 2001

Campisano, A. and Modica, C. (in press). *PID* and *PLC* units for the real time control of sewer systems". In press. *Wat. Sci. Tech.*

Campisano, A. and Modica, C. (2002). *P* units calibration for the *RTC* of sewer collectors using a dimensionless approach. *Ninth International Conference on Urban Drainage*; Portland/Oregon, USA; September 2002

Campisano, A., Modica, C., Schilling, W.; and Risholt, L.P. (2000). RTC Applications to the Trondheim-Høvringen wastewater tunnel,. *Proc. 5th Intl. Symposium on Systems Analysis and Computing in Water Quality Management, WATERMATEX*, Gent, Belgium, vol. 3, pp 105-112, 18 - 20 September 2000.

Campisano; A., Schilling, W., and Modica, C. (2000). Regulator's setup with application to the Roma-Cecchignola combined sewer system, *Urban Water*, 2, 3, 235-242

CEC - Council of the European Communities (2000). *Directive of Establishing a framework for Community action in the field of water policy*. EC Directive No. 2000/60/EEC of 23 October 2000

Dochain, D., and Vanrolleghem, P.A. (2001). *Dynamical Modelling and Estimation in Wastewater Treatment Processes*. IWA Publishing. London

Einfalt, T., and Stölting, B. (2002). Real-Time Control for two communities - technical and administrational aspects. *9th Int. Conference on Urban Drainage*; Portland/Oregon, USA; September 2002

Erbe, V., Risholt, L.P., Schilling, W., and Londong, J. (2002). Integrated modelling for analysing and optimisation of wastewater systems - the Odenthal case. *Urban Water* 4, 1, pp 63-71.

Fronteau C., Bauwens W., Vanrolleghem P., and Smeets M. (1996). An immission based evaluation of the efficiency of the combined sewer - water treatment plant system. *Proceedings 7th International Conference on Urban Storm Drainage*. Hannover, Germany, July 22-27 1996. Vol. 1, 467-472.

Goethals P.L.M., Vanrolleghem P.A., and De Pauw N. (2000). Water quality models and indexes as bridges in integrated ecological monitoring, assessment and management of running waters in Flanders. In: *Proceedings of the Freshwater Biological Association (FBA) Annual Scientific Meeting Knowledge, Understanding and Prediction in Aquatic Ecology*. Birmingham, United Kingdom, 14 -15 September

Jeppsson U., Alex J., Pons M.-N., Spanjers H., and Vanrolleghem P.A. (2002). Status and future trends of ICA in wastewater treatment - A European perspective. *Wat. Sci. Tech*. 45, 4-5, 485-494.

Krebs P. (1996). Interdependencies and dynamics within the urban water management. *EAWAG news*, 41 E, 14-16.

Krier, J. (1998). Des îlots de survie pour les poissons. *Paris-Québec International Symposium*, *Waterways Rehabilitation in Urban Environments*, Québec, 28 - 30 September, 431-444.

Lavallée, P., Bonin, R., Roy, B., Colas, H., and Pleau, M. (2001). Operation and Performance of an Optimized Real Time Control System for Wet Weather Pollution Control, International Water Association, *5th International Conference on Diffuse/Nonpoint Pollution and Watershed Management*, Milwaukee, 10 - 15 June

Meirlaen J. (2002). *Immission-based real time control of the integrated urban wastewater system*. PhD Thesis. Biomath – Ghent University, Belgium.

Meirlaen J., Huyghebaert B., Sforzi F., Benedetti L., Vanrolleghem P.A. (2001). Fast, simultaneous simulation of the integrated urban wastewater system using mechanistic surrogate models. *Wat. Sci. Tech.*, 43, 7, 301-310.

Meirlaen J., and Vanrolleghem P.A. (2002a). Model reduction through boundary relocation to facilitate real-time control optimisation in the integrated urban wastewater system, *Wat. Sci. Tech*., 45, 4-5, 378-381.

Meirlaen J., Van Assel J., and Vanrolleghem P.A. (2002b). Real time control of the integrated urban wastewater system using simultaneously simulating surrogate models. *Wat. Sci. Tech.*, 45 (3), 109-116.

Méthot, J.F. and Pleau, M. (1997). The Effect of uncertainties on the control performance of sewer networks. *Wat. Sci. Tech.*, 36, 5, 309-315

Nielsen, M.K. (2001). *Control of Wastewater Systems in Practice*. Scientific and Technical Report Part 3. IWA Specialist Group on Instrumentation, Control and Automation. Malmö.

Nielsen, B., and Nielsen, M.K. (2002). *From Pumping Station Control to Integrated System Control*. Unpublished report.

Olsson G., and Newell R.B. (1999). *Wastewater Treatment Systems - Modelling, Diagnosis and Control*. IWA Publishing, London, United Kingdom.

Pleau, M., Pelletier, G., Meunier, C., and Bonin, R. (2000). Real-Time Control for CSO Management : Quebec Urban Community System Start-Up. *Proceedings of the 29th annual WEAO Technical Symposium and OPCEA Exhibition*, Hamilton, Canada. 16 - 18 April

Pleau, M., Pelletier, G., Colas, H., and Bonin, R. (2001). Global predictive real-time control of Quebec Urban Community's westerly sewer network. *Wat. Sci. Tech.*, 43, 7, 123-130.

Pleau M., Pelletier G., Colas H. (2002) Reliability & robustness in real time control applications, *9th International Conference on Urban Drainage*, Portland, Or, Sept. 8-13, 2002.

Rauch, W., and Harremoës, P. (1996). Minimizing acute river pollution from urban drainage systems by means of integrated real time control. *Proc. of the 1st International Conference on New/Emerging Concepts for Rivers*. Chicago, September

Rauch, W., and Harremoës, P. (1999). On the potential of genetic algorithms in urban drainage modelling. *Urban Water* 1,1,79-90

Rauch, W., Bertrand-Krajewski, J.-L., Krebs, P., Mark, O., Schilling, W., Schütze, M., and Vanrolleghem, P.A. (2002): Deterministic modelling of integrated urban drainage systems; *Wat. Sci. Tech.*, 45 (3), 81-94.

Rauch, W., Aalderink, H., Krebs, P., Schilling, W., and Vanrolleghem, P. (1998). Requirements for integrated wastewater models - Driven by receiving water objectives. *Wat. Sci. Tech.*, 38, 11, 97-104.

Reda, A. (1996). *Simulation and control of stormwater impacts on river water quality*. PhD. Thesis. Imperial College of Science, Technology and Medicine. London

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyódy, L., and Vanrolleghem, P.A. (2001). *River Water Quality Model No. 1*. IWA Scientific and Technical Report No. 12. IWA Publishing, London

Risholt, L.P., Schilling, W., Erbe, V., and Alex, J. (2001). Pollution based real time control of wastewater systems, *2nd International Conference on Interactions between Sewers, Treatment Plants and Receiving Waters in Urban Areas - INTERURBA II*, Lisbon, Portugal, 157-166, 19 - 22 February

Rousseau D., Verdonck F., Moerman O., Carrette R., Thoeye C., Meirlaen J. and Vanrolleghem P.A. (2001) Development of a risk assessment based technique for design/retrofitting of WWTPs. *Wat. Sci. Tech.*, 43,7, 287-294.

Scheer, M., and Nusch, S. (2002). Optimum performance of a sewer and treatment system by application of real time control. *International Conference on Sewer Processes and Networks*; Paris, 15 - 17 April

Scheer, M., and Weyand, M. (2002). PASST - die Planungshilfe für Abflusssteuerung in Kanalnetzen. *Workshop Innovationen in der Abwasserableitung und Abwassersteuerung*, Dresden 14 - 15 March

Schleiter, I., Borchardt, D., Wagner, R., Dapper, T., Schmidt, K. D., Schmidt, H. H., and Werner, H. (1999). Modelling water quality, bioindication and population dynamics in lotic ecosystems using Neural Networks. *Ecological Modelling* 120, 271-286.

Schilling, W. (ed.) (1989). *Real-Time Control of Urban Drainage Systems. The state-of-the-art.* IAWPRC Task Group on Real-Time Control of Urban Drainage Systems. London

Schilling, W. (1994). Smart sewer systems improved performance by real time control". *Eur. Water Pollution Control*. 4, 5, 24-31

Schilling, W., Andersson, B., Nyberg, U., Aspegren, H., Rauch, W., and Harremoës, P. (1996). Real Time Control of Wastewater Systems, *Journal of Hydraulic Research*. 34, 6, 785-797

Schütze, M., and Einfalt, T. (1999). Off-line development of RTC strategies - a general approach and the Aachen case study. *8th Int. Conference on Urban Storm Drainage.* Sydney. 30 August - 3 September. 410-417

Schütze, M., and Erbe, V. (2002).: Integrated simulation of the Dhuenn river catchment - supported by a matrix-based model notation for the entire urban wastewater system. *International Conference on Sewer Processes and Networks.* Paris. 15 - 17 April

Schütze, M., Butler, D., and Beck, M.B. (1999). Optimisation of control strategies for the urban wastewater system - an integrated approach; *Wat. Sci. Tech.* 39, 9, 209-216

Schütze, M., Butler, D., and Beck, M.B. (2002a). *Modelling, Simulation and Control of Urban Wastewater Systems*. Springer Verlag London.

Schütze, M.; Butler, D.; Beck, M.B.; Verworn, H.-R. (2002b): Criteria for assessment of the operational potential of the urban wastewater system; *Wat. Sci. Tech.*, 45 (3), 141-148.

Schütze, M., To, T.B., Jumar, U., and Butler, D. (2002c). Multi-objective control of urban wastewater systems. *International Federation of Automatic Control 15th IFAC World Congress*. Barcelona. 21 - 26 July.

Schütze, M.; Campisano, A.; Colas, H.; Schilling, W.; Vanrolleghem, P. (2002d): Real-time control of urban wastewater systems - where do we stand today? *9th Int. Conf.Urban Drainage; Portland/Oregon*; Sept.

Thas, O., Vanrolleghem, P.A., Kops, B., Van Vooren, L., and Ottoy, J.P. (1997). Extreme value statistics: Potential benefits in water quality management. *Wat. Sci. Tech.*, 36, 5, 133-140.

Tyson, J.M., Guarino, C.F., Best, H.J., and Tanaka, K (1993). Management and institutional aspects. *Wat. Sci. Tech.*, 27, 12, 159-172.