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Real time control of urban wastewater systems—where do we stand today?

Manfred Schütze[a,*], Alberto Campisano[b,1], Hubert Colas[c,2], Wolfgang Schilling[d,3], Peter A. Vanrolleghem[e,4]

[a]*Department for Environmental Software and Control, Institute for Automation and Communication, ifak Magdeburg e. V., D-39179 Barleben, Germany*
[b]*Dipartimento di Ingegneria Civile e Ambientale, University of Catania; Viale Andrea Doria, 6, I-95125 Catania, Italy*
[c]*BPR-CSO, 5100, Sherbrooke E, suite 400, Montreal, Que., Canada H1V 3R9*
[d]*Institutt for Vassbygging, Norwegian University of Science and Technology, S. P. Andersens vei 5, N-7034 Trondheim, Norway*
[e]*BIOMATH, Ghent University, Coupure Links 653, B-9000 Gent, Belgium*

Abstract

This paper presents a review of the current state of the art of real time control (RTC) of urban wastewater systems. Control options not only of the sewer system, but also of the wastewater treatment plant and of receiving water bodies are considered. One section of the paper provides concise definitions of terms frequently used in the literature. Recent developments in the field of RTC include the consideration of the urban wastewater system in its entirety. This allows information from all parts of the wastewater system to be used for control decisions and can lead to a significant improvement of the performance of the wastewater system. 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 system operational in practice, the Québec Urban Community global predictive RTC system is presented. The paper concludes with an outlook into current and future developments in the area of real time control.

The authors are members of the Working Group on Real Time Control of the Joint Committee of the International Association of Hydraulic Research (IAHR) and the International Water Association (IWA).

Keywords: Model-based control; Real time control; Sewer system; Stormwater management; Urban runoff; Urban wastewater system

1. Introduction

Urban wastewater systems, having sewer system, wastewater treatment plant and receiving water as their main elements, can be found throughout the world. Many of them are operated with little or no control. On the other hand, there are some case studies with quite sophisticated forms of control. What are

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* Corresponding author. Tel.: +49 39203 81045; fax: +49 39203 81100.

E-mail addresses: manfred.schuetze@ifak-md.de (M. Schütze), acampisa@dica.unict.it (A. Campisano), hcolas@bpr-cso.com (H. Colas), wolfgang.schilling@bygg.ntnu.no (W. Schilling), peter.vanrolleghem@rug.ac.be (P.A. Vanrolleghem).

[1] Fax: +39 095 738 2748.

[2] Fax: +1 514 257 2414.

[3] Fax: +47 7359 1298.

[4] Fax: +32 9 264 6220.

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the benefits of such control? What are the drawbacks? The last state-of-the-art report on real time control of urban drainage systems has been published more then a decade ago (Schilling, 1989). What has happened since then? What are the recent developments in this area since then? Why should we embark on real time control? Also, many readers—now half a generation later—may be new to this topic. Therefore, this survey paper attempts to give an introduction to the current state of the art of real time control of urban wastewater systems.

The question raised ‘why should we bother with real time control today?’ has, at least, three valid answers: There is progress in measurement technology, the consideration of water-quality-based objectives and the integrated approach to control open up new potential, and, finally, methodologies and tools assisting in the development of control procedures have improved. Also a number of large-scale case studies demonstrate that real time control does indeed work in practice. This paper attempts to illustrate some of these concepts, with some emphasis being put on real time control (RTC) of sewer systems.

2. Definitions and key terms

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

An urban wastewater system is controlled in *real time* if process variables are monitored in the system and, (almost) at the same time, used to operate actuators during the flow process.

In principle, control of the process can be schematised by means of *control loops* (Fig. 1), 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.

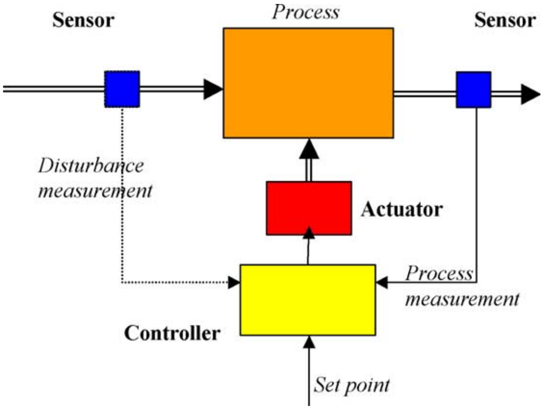

Fig. 1. Feed-forward (disturbance measurement) and feedback (process measurement) control loop. Simple arrows indicate data flow, double arrows indicate hydrodynamic action. Bold letters indicate hardware and italic letters indicate variables.

RTC in urban drainage wastewater systems poses stringent requirements on sensors, such as measurement accuracy and reliability, physical and chemical resistance and suitability for continuous recording and remote transmission.

Main sensors used include (more details can be found, for example, in Campisano and Modica, 2002a and in Jeppsson et al., 2002):

- *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 sewer storage or to convert levels to flow rates where backwater effects are not dominant.
- *flow gauges* such as level-flow converters, ultrasound velocity meters, electromagnetic meters.
- *quality gauges* such as sensors for 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, considerable efforts are required to create the interpretation modules that convert the raw sensor output into the required information.

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., 2000a,b, 2003). *Inflatable dams* can be used in large trunk sewers to activate in-line storage;
- *valves* are used to restrict flows;
- 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 within a biologically acceptable range, addition of polymer or ballasting particles to enhance settling of biological 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 above 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 (Campisano and Modica, 2002b).

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* 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, often, active wall panels and colour screens are used which 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 actuated by automatic controllers with their set-points being specified or approved by operators or by a supervising system, or *automatic* if the control is realised in a fully automatic way by a controller, 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. 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* may be more effective. 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 sewer system and treatment plant, possibly also of the receiving water body and of wastewater production (including forms of source control). This approach allows for analysing both quantitative and qualitative aspects of wastewater and for controlling the environmental conditions of the receiving waters (Schütze et al., 2002a; Rauch and Harremoës, 1999; Meirlaen and Vanrolleghem, 2002; Meirlaen et al., 2002; Nielsen and Nielsen, 2002). This opens up significant additional potential for control and for improving the performance of 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 control which takes into account some of these concepts include Québec—see Section 5, but also Aalborg (Nielsen and Nielsen, 2002) and Odenthal (Erbe et al., 2002).

3. Control objectives

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, for example, the reports by Schilling, 1989; Olsson and Newell, 1999; Jeppsson et al., 2002; Jumar and Tschepetzki, 2002).

When formulating objectives of control or, more generally spoken, defining performance indicators for sewer systems, one traditionally uses auxiliary criteria such as 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, at least, trying to avoid large investments for static extensions of the system in order to meet the demands) in a sophisticated way. For some case studies, 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, including predictive control of nitrogen removal (Alex et al., 2002) and on-line simulation models (Jumar and Tschepetzki, 2002; Nielsen, 2002). 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; Lau et al., 2002). This motivates to consider 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 companies are responsible for different parts of the wastewater system may hinder such coordination. Whilst the discussion on emission- or immission-based (indeed, the word does not exist—yet—in English) 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 (CEC, 2000) requires a river 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 administrative arrangements and in operators' management practice.

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 (Fig. 2). 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 procedure 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.

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

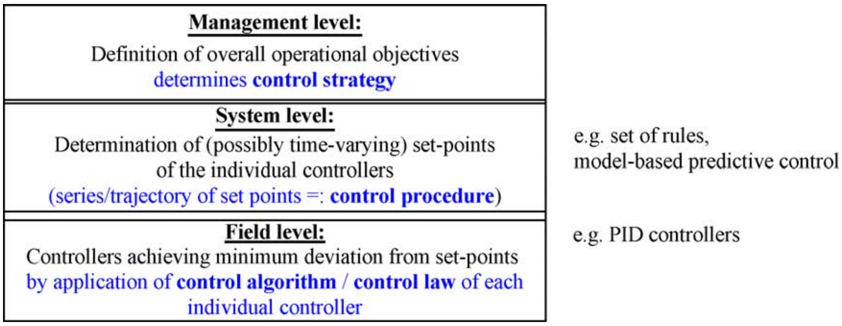

Fig. 2. Various levels in a real time control system (adapted from Schütze et al., 2002a).

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. It has been suggested to start an RTC implementation with the design of local control for the actuators of the wastewater system, followed by setting up global (and, possibly, integrated) 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. 5 min), 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*) (Fuchs et al., 1997; Rauch and Harremoës, 1999; Jumar and Tschepetzki, 2002). 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, depending on the complexity of the model used, 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 Section 5; 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

This section, describing as an example the RTC system of Québec Urban Community (QUC), illustrates that RTC does not merely consist of some theoretical ideas, but that it has indeed found its way into practical application. 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 (involving only two or three interconnected local stations). Global optimal predictive real time control, finally, represents the third control level in the Québec system. For this level, set-points are provided from a central station to all connected local stations (Méthot and Pleau, 1997). Usually, the global optimal predictive control mode is in operation. The central station determines the optimum set of control set-points, whilst control at levels 1 and 2 is responsible for relaying the set-points into gate positions.

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-h rain predictions. Set-points are translated into moveable gate positions at local stations by PLC. The system presently controls five 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 of 1380 constraints (i.e. mass balance, maximum and minimum allowable flows and volumes or water levels) and of 1196 variables (volume and flows calculated at each node and pipe in the linear model). The optimisation problem is solved at every control time step (5 min) by a non-linear programming algorithm (Pleau et al., 2001).

The Westerly sewer network (Fig. 3) comprises of three major interceptors (Métropolitain-Nord, Versant-Nord and Versant-Sud) and two tunnels (Versant-Sud

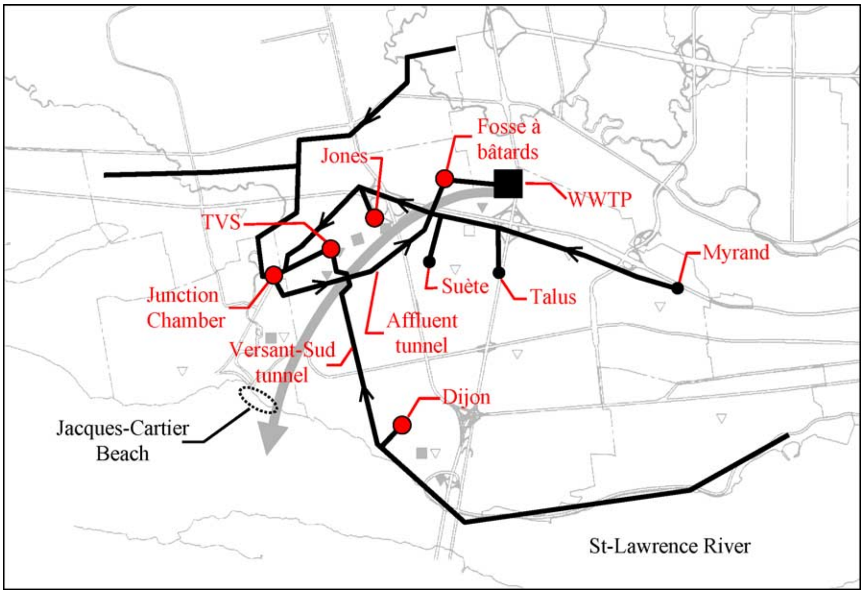

Fig. 3. QUC's control sites and retention tunnels.

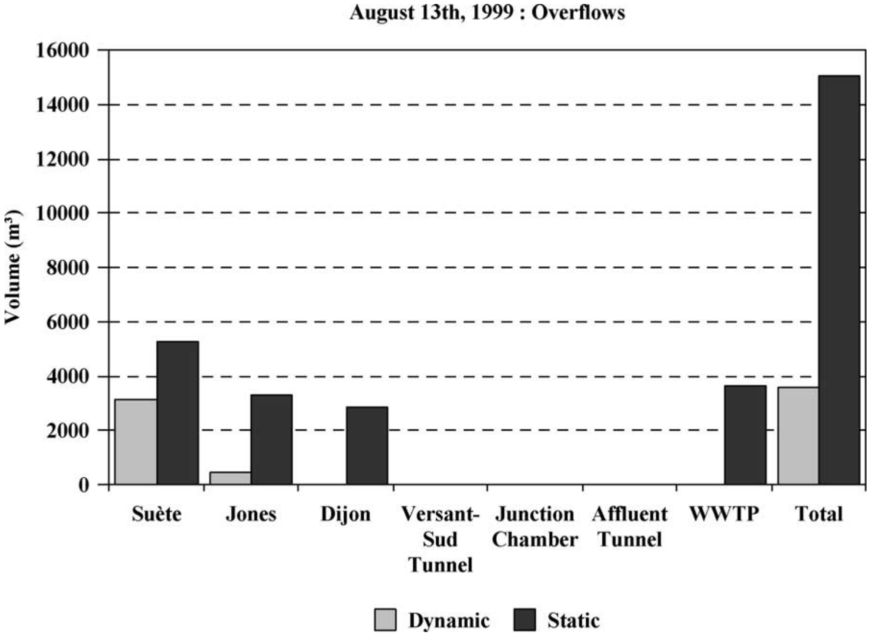

Fig. 4. Overflows at each control site for the rainfall event of 13 August 1999.

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. Here, the percentage reduction has been computed from measured operational data for global control versus simulated results of static control (as in the previous sewer system configuration) under the same measured input (rain, flow). 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 QUC territory, such as would be done through conventional engineering design (Lavallée et al., 2001).

Fig. 4 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 are simulation results of what would have occurred under the same situation prior to the implementation of RTC.

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%.

Fig. 5 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

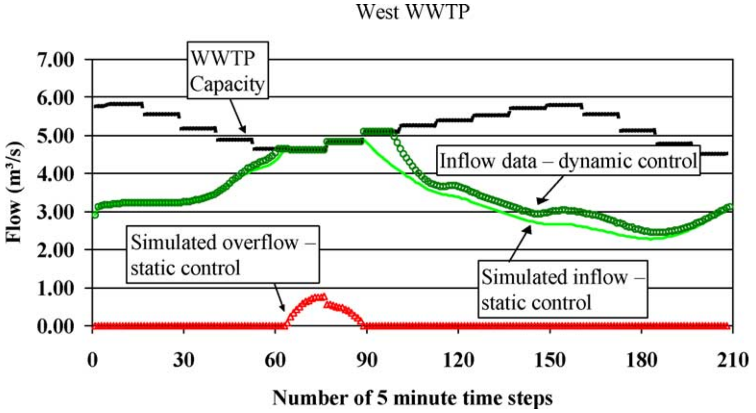

Fig. 5. Flow rates at West treatment plant with static and global optimal predictive RTC.

stored in the RTC database for the 2-h 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.

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. Costs of planning studies for RTC can be quite high: usually, a computer model for the system has to be set up, calibrated and verified. However, implementation of RTC, which makes use of existing wastewater infrastructure and also can provide significant and quick environmental benefits, can help to prevent building new tanks or extending the capacity of existing infrastructure at even higher costs, thus often resulting in significant 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 published by the RTC Working Group of the German Association for Water, Wastewater and Waste (ATV-DVWK) contains an extended version of this list (Scheer and Weyand, 2002; Schütze et al., 2004).

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 1 h 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 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.

Objectives. Many 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 EU's Water Framework Directive 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 mimick 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 allow consideration of effects of RTC on all parts of the wastewater system 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; Méthot and Pleau, 1997; Willems, 2000; Duchesne et al., 2001; Rousseau et al., 2001). 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).

Education. Among the most crucial issues with regard to the implementation of RTC systems lies in the awareness of the wastewater operator and of the planning engineer of the concepts, methods, benefits and problems of RTC. In order to provide him with the necessary background information, a CD has been published recently by the RTC Working Group of the German Association for Water, Wastewater and Waste (ATV-DVWK), providing the up-to-date concepts of RTC in interactive form and detailing its key issues. Whilst some guidelines have also been compiled in the past (Kellagher, 1996), these sometimes remained fairly inaccessible to a wider audience. The CD summarises the experiences gained in over 30 RTC implementations in Germany and offers guidance for future RTC projects. Some guidelines on RTC to be published in written form are also currently in preparation by this ATV-DVWK working group in Germany (details are available on request from the corresponding author).

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). Novel concepts also for individual parts of the system, e.g. for the operation of pumping stations, ensuring their optimum utilisation, have been suggested (Schütze and Alex, 2003). 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 Water Framework Directive 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 wastewater systems can be stated

- Today, improved devices, methodologies and tools for are available which allow real time control of urban wastewater systems to be considered as an option to minimise adverse impacts on the environment and to minimise costs.
- Due to improved methods, even those wastewater systems may have potential for real time control which, in the past, did not appear to be able to benefit from RTC.
- Further improvements are required in a number of areas, such as sensoring and consideration of uncertainties. Particular emphasis should also be given to the use of a clear terminology to enable better cooperation of scientists and experts of different areas relevant to RTC.

It can be stated that RTC is a challenging, but beneficial means of improving the performance of urban wastewater systems. The authors will be happy to provide further assistance in the planning, design and operation of RTC systems.

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