Urban Water Journal, 2013
Vol. 10, No. 5, 300–311, http://dx.doi.org/10.1080/1573062X.2013.763996

RESEARCH ARTICLE

Potential and limitations of modern equipment for real time control of urban wastewater systems

A. Campisano[a]*, J. Cabot Ple[b], D. Muschalla[c], M. Pleau[d] and P.A. Vanrolleghem[e,f]

[a]*Department of Civil and Environmental Engineering, University of Catania, Viale A. Doria 6, I-95125, Catania, Italy;* [b]*Clavegueram de Barcelona, S.A., Acer, 08022, Barcelona, Spain;* [c]*Institute of Urban Water Management and Landscape Water Engineering, Graz University of Technology, Stremayrgasse 10/I, A-8010, Graz, Austria;* [d]*BPR-CSO, 5100, Sherbrooke E, suite 400, Montreal, Quebec, Canada;* [e]*modelEAU, Département de génie civil et de génie des eaux, Université Laval, Québec, Canada;* [f]*DTU Environment, Technical University of Denmark, Department of Environmental Engineering, Lyngby, Denmark*

(*Received 29 March 2012; final version received 26 December 2012*)

Real Time Control (RTC) has become an accepted technique for improving the performance of Urban Drainage Systems (UDS) due to its flexibility and sustainability. Numerous implementations of RTC have been reported during the last decades. At the same time, guideline documents and state-of-the-art reports have been published. Whereas the general aspects and challenges of planning and installation of RTC systems are well covered, there is a lack of information about the adequate equipment for RTC of UDS. After identifying and briefly discussing the basic components of RTC systems for UDS, this paper describes the specific components in detail. This comprises the introduction of available technologies for sensors, actuators, controllers and telemetry systems in the context of RTC and the discussion of their potential and limitations. Lessons learned from the field operational experiences and future trends and challenges are identified.

Keywords: control; fault detection; instrumentation; RTC; SCADA; storm water management; telemetry; wastewater systems

1. Introduction

Real Time Control (RTC) is a cost/effective option to improve the performance of Urban Drainage Systems (UDSs) (Dirckx *et al.* 2011, Lacour and Schütze 2011).

RTC systems typically require monitoring the evolution of UDS processes by means of real time acquisition of measurements (water quantity and quality variables) and to simultaneously modify these processes according to specific control objectives.

During the last two decades, many applications demonstrated the successful implementation of RTC techniques in UDS of several cities including Québec, Canada (Pleau *et al.* 2001), Ense-Bremen, Germany (Weyand 2002), Saverne, France (Vazquez *et al.* 2003), Vienna, Austria (Fuchs and Beeneken 2005) and Barcelona, Spain (Puig *et al.* 2009).

Operational goals have included reducing flooding effects in urban areas, avoiding surcharges and excessive sediment deposition in sewers, reducing operational costs and pollution effects in receiving waters due to Combined Sewer Overflows (CSO), and enhancing treatment processes in wastewater treatment plants (WWTP).

However, up to today the major part of the urban wastewater systems throughout the world is still operated under static conditions, i.e. without any form of control nor monitoring of sewer networks, WWTP and receiving water bodies. One of the reasons for this situation is the reluctance of wastewater operators to introduce advanced technology in wastewater systems which is still perceived as complex and with some concern due to legal exposure and issues related to regulation (USEPA 2006).

Furthermore, although reliable equipment has become available nowadays overcoming many past technological obstacles at reasonable costs (Schütze *et al.* 2004a), outputs from real applications still show that the wrong choice of control equipment is one of the main factors causing the improper working of RTC systems in UDS. It thus presents an important drawback for the large diffusion of such systems worldwide (Schilling 1989, WERF 2002).

Field operational experience has clearly pointed out that not all devices which have been used in existing RTC implementations are adequate for control purposes. Technological equipment must be adapted to the continuous monitoring and control in remote conditions and must be able to resist (for a long time) the hostile wastewater environment. The high levels of humidity, the corrosive atmosphere, exposure to oils, greases, waste, debris and sediments cause the malfunction of various technological components. Under these conditions frequent failures can occur and, if the system is not planned to admit and react to such failures, wastewater system operators may decide to switch back to manual or no

*Corresponding author. Email: acampisa@dica.unict.it

control operation causing the RTC system to fall out of use.

The selection of the correct equipment together with the choice of an adequate communication system and the proper software to be used, is thus crucial for a durable and reliable installation of RTC systems in UDSs, especially now that the progress in measurement, calibration and control technologies has been such that new devices, tools and methodologies enable meeting water quality-oriented control objectives besides more traditional volume-oriented objectives.

The aim of this paper is to review equipment used for RTC purposes in UDS. Potential and main limitations of such equipment are discussed in an attempt to identify mature technologies on the basis of literature results and field experience from real RTC installations.

2. Basic components of RTC systems

The architecture of any RTC system (i.e. the conceptual organisation of the components) is basically structured in control loops which can be implemented by hardware components including sensors, actuators, controllers and telemetry systems (Figure 1). Sensors collect information about the current state of the wastewater system, actuators/regulators modify the monitored process and controllers adjust actuators with a certain objective, for instance, to minimise deviations of the monitored variable from its desired value (set-point). The telemetry system supports the data transfer among the different devices.

Control loops can be executed directly at the control site by a local RTC based on the adoption of local controllers. Otherwise, information acquired along the UDS has to be transmitted remotely from the local control systems to a central workstation where a supervisory control system manages all incoming and outgoing data. Both control levels, local and remote, may coexist. In this case, local control usually acts as a 'fail safe' security level which is triggered whenever either the remote controller is not working or communications fail. In other cases, the remote control level is just a monitoring system, and the control functions are entrusted to the local controller.

In the following sections, each hardware component is described in detail.

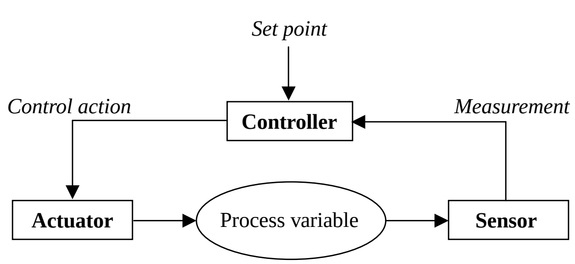

Figure 1. Sketch of a control loop. Arrows indicate data flows, bold letters indicate hardware components, italic letters indicate transferred information.

3. Sensors

Basically, sensor devices for RTC have to be characterised by their versatility to accurately follow the evolution of many processes. Additionally, such sensors have to be resistant to long-term physical and chemical attack, should be cheap and easy to use and to maintain. It means that when planning a RTC system, adequate structures have to be designed for installing the measuring devices. These structures should be accessible to operators for periodic checks on the sensors status and maintenance and have also to be equipped with a power supply facility to assure continuous monitoring. An important design issue at sites without permanent power is the battery life duration that may represent a limitation for remote control. In fact, experience shows that batteries can live from six weeks to well over a few years, depending on the frequency of measurement and on how often data is polled from the instrument (USEPA 2006).

The presence of sensors in the foul environment of wastewater systems requires additional equipment for cleaning of the instrumentation. These add to the cost and require extra work to install but may save considerable time in long-term maintenance.

In the sequel both quantity (rainfall, level, flow) and quality measuring systems are reviewed. Particular attention is given to the importance of fault detection methods.

3.1 Rainfall measurement

The availability of rainfall measurements is very important in RTC systems. In fact, the comparison between the total amount of rainfall and the available storage capacity that can be activated in the catchment during rain events is basic information required to derive potential benefits of RTC system implementation (Schütze *et al.* 2004b). Rainfall measurements are also required when implementing a model-based RTC system. Along with radar images, they are used as inputs to simulate the hydraulic behaviour of the UDS and to find the set points to be applied at the local controllers in order to meet the control objectives pursued.

The spatial distribution of rainfall measurements is a very important issue (Cutore *et al.* 2007). The technical literature includes recommendations regarding the rain gauge density required for design studies of sewer systems. Some manufacturers recommend at least one rainfall gauge on every 500 ha for good rainfall correlations. According to Schilling (1991) and Berne *et al.* (2004) this value may have to be lowered to 100 ha depending on the catchment size and the drainage system structure. These authors also report a rainfall data acquisition period of 1 min for RTC purposes.

Weighing gauges have been used for RTC applications worldwide. Although largely employed, sometimes they were found less sensitive in comparison to rain gauges based on optical drop counters or tipping buckets that also allow the measurement of low intensity rain (down to 0.005 mm/min). Some real applications (Pleau *et al.* 2002) have shown a low reliability of these gauges due to malfunctioning of mechanical and electronic components. In any case, gauges should be periodically (monthly) checked on site to make sure the strainer is free from obstructions caused by leaves or debris.

Increasing benefits can be obtained if rainfall information is available in advance. To this aim, modern RTC systems combine the information from traditional rainfall gauges with data coming from radar stations. The latter provide information concerning rain intensity and storm location, allowing rainfall predictions to be obtained and to extend the time horizon for arranging control actions (Pleau *et al.* 2001, Schütze *et al.* 2004a). Recent efforts to control UDS using radar information are documented by Fuchs and Beeneken (2005) and by Pleau *et al.* (2010). Main difficulties concern the possibility of using trusty rainfall predictions for model based RTC in catchments characterised by fast response time of storm water flows. Moreover, experience concerning information reliability shows discrepancies between rain gauge and radar accumulations in the range 5–15% (Vieux and Vieux 2005).

3.2 Water level

Most of the time RTC implementations are based on water level measurements. Water level sensors can, for example, be positioned into storage facilities to estimate the available storage volume by simple level-storage relationships (Campisano *et al.* 2000); into pipes to evaluate flow depths and to monitor surcharge conditions during rain events; upstream of moveable gates to evaluate flow discharges through the gate orifice; in sewer overflow structures for the continuous monitoring of the overflow discharges into the receiving waters; into the treatment plant for the evaluation of many treatment processes.

For all these processes, water levels can change rapidly so that, according to the RTC objective, specific water level sensors and measuring techniques should be used. Today, many kinds of sensors are adopted depending on the monitored process (ITA 2002, USEPA 2006):

- capacitive probes;
- pressure sensors;
- ultrasonic probes;
- microwave sensors.

Capacitive probes are particularly suitable for multi-point water level monitoring and are to be preferred when a high spatial resolution (of a few millimetres) is necessary (e.g. for a reliable evaluation of stored volumes in big and flat storage facilities). The main advantages of such a technology are that the sensors normally contain no moving parts, are easy to clean and can handle temperature and pressure variations. However, these sensors can significantly disturb the process so that they should not be used in small pipes.

Pressure sensors are submerged transducers located close to the bottom of the pipe and use diaphragms to sense differential pressure. In particular, modern resistive and piezo-electric pressure sensors are very accurate (measurement errors less than 1%) and are reliable for continuous measurement over a large range of levels even when covered with sediments.These kinds of sensors should be preferred for operational conditions characterised by high water levels in sewers. Specifically, they can be adapted to detect surcharge conditions in pipes and eventual overflows from manholes to the streets (Cembrano *et al.* 2004). Compared to capacitive probes, they provide a lower spatial resolution (10–20 mm) and need a more frequent calibration due to possible drift problems caused by gross solids hooking the sensor (ITA 2002).

Ultrasonic probes are suitable for the harsh wastewater environment because they are positioned above the water level but, in contrast to pressure probes, they cannot take the risk to be submerged. The typical accuracy is very high (± 0.25%) but they may suffer from interference from pipe sidewalls (they have to be mounted sufficiently far from the walls) and foam or floatables at the wastewater surface. Problems associated with corrosive vapour and freezing have been reported as well.

Microwave sensors (mainly transit time gauges) are a valuable alternative to ultrasonic probes. Like the ultrasonic ones, microwave sensors require little maintenance compared to pressure sensors. However, microwave technology has been shown to be more reliable than ultrasonic, since it is immune to problems associated to temperature variations or air currents along the measuring distance.Especially for ultrasonic and microwave technologies it is quite important to detect deviations (e.g. drifts) in the calibration of sensors. To this end annual checks of these instruments are to be conducted to avoid errors. It should be taken into account that, in case of large networks, this issue may require expensive calibration plans.

3.3 Flow rate

Often, the implementation of RTC strategies needs to know the flow rate in many sections of the sewer system and the treatment plant. When errors of some percent are acceptable, it may be sufficient to obtain preliminary flow rate information by level-flow converting relationships using weirs or gates (errors of about 2–4%), flumes (errors of about 3–5%), or various kinds of orifices. However, continuous maintenance is required for all these devices since sediment deposits (such as rags or other debris) can cause obstructions and can affect the flow rate measurement (ITA 2002).

Alternatively, if a higher accuracy and reliability is necessary, flow velocities have to be measured directly. Then, more sophisticated gauges have to be used such as electromagnetic meters or ultrasonic meters. However, their measurement accuracy is dependent on the layout of the flow monitoring points in the collection system and can be limited by the presence of oils and greases.

Electromagnetic meters are adopted for completely filled pipes (errors less than 1%) while ultrasonic meters (Doppler meters and transit time meters) are recommended for partially filled pipes (errors of about 5%) measuring multiple vertical flow profiles within the pipe (Hughes *et al.* 1996).

3.4 Water quality including solids monitoring

Thanks to recent developments, measurement of water quality is moving quickly from a laborious, low frequency sampling-and-lab-analysis approach to an automated, high-frequency in situ analysis activity (Winkler *et al.* 2008). Ten years ago the state-of-the-art consisted of concepts which mainly built on wet-chemistry analysis, requiring sample loops, filtration units and a climate controlled container to accommodate the analysers (Beck *et al.* 1998). Nowadays, even complete 'in-situ' concepts for water quality monitoring have proved to be applicable long-term (Pressl *et al.* 2004) thanks to the efforts to make the sensors 'survive' longer in the water environment. The membranes that are often part of the sensors have improved considerably regarding their fouling potential (Lynggaard-Jensen *et al.* 1996). Also, cleaning systems have been installed to wipe, brush or air sparge off foulants (Watts *et al.* 1990).

While the number of on-line measurable water quality variables remained limited for a long time, miniaturisation of wet-chemistry methods and spectroscopic methods with dedicated data analysis algorithms now allow for measurement of many important quality parameters, even in the difficult conditions encountered in sewer systems (Grüning and Orth 2002, Vanrolleghem and Lee 2003). One now generally accepts that measurement networks can be set up to provide data for the following measured variables: temperature, pH, turbidity, suspended solids*, organic carbon*, chemical oxygen demand*, conductivity, ammonia, nitrate and total nitrogen*. The variables with asterisks are calculated from UV/VIS spectra. While calculation with standard relationships is beyond the current capabilities, local re-calibration already allows getting adequate data quality (Gamerith *et al.* 2011).

The potential of water quality sensors is shown, as an example (in the sewer catchment of Brussels, Belgium) in Figure 2. The figure gives a truly nice idea of what water quality measurements can provide as information, in this case regarding the impact of rain events on water quality dynamics.

During wet weather flow, two phenomena typically occur in combined sewer systems. A *first flush* event resulting in a peak load of TSS (measured through turbidity analysis) to the plant (Figure 2 right) is observed when the storm event occurs after a long period of dry weather flow, which allowed sedimentation of TSS in the sewer system. The figure shows the same period as the latter half of the flow data (Figure 2 left). The peak brings about ten times the normal TSS load to the plant. This number is, however, dependent on the sewer system and the dry weather period preceding the event. Figure 2 also illustrates this dependence on the antecedent period as during the second storm (on 19/4) no TSS peak is observed.

A *dilution* effect due to the large amounts of rainwater is also observed. The figure illustrates this by showing conductivity measurements in the sewer. Unlike the first flush, dilution occurs with all storm events.

A few important variables remain unaccounted for in the on-line measurement portfolio, e.g. pathogens and micro-pollutants such as pharmaceutical and personal care products, heavy metals, pesticides, etc. While increasingly quick methods are under development for fast-throughput

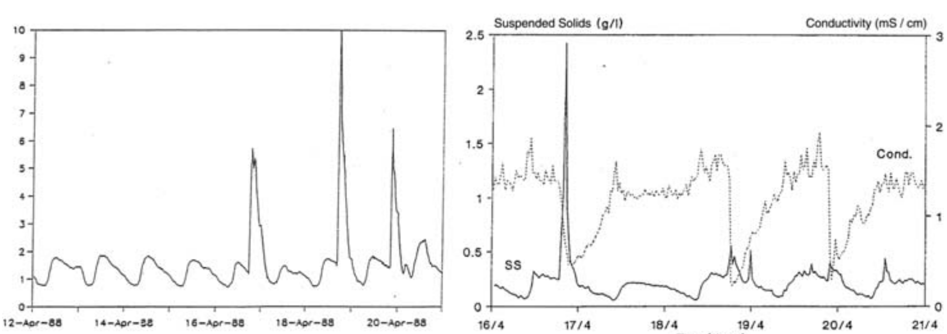

Figure 2. Illustration of the effect of rain events on flow (left) and water quality (right): conductivity (dilution) and suspended solids (first flush effect) measured in the catchment of Brussels (Belgium). Note that the right figure's time axis is the latter half of the left figure.

analysis in the lab (e.g. Fayad *et al.* 2010, Miles *et al.* 2011), the availability of such data for RTC still seems far away.

For now the practical use of water quality sensors in automatic control remains limited to WWTPs (Olsson *et al.* 2005) where they are not only applied for effluent quality control but also for reduction in resource use such as energy and chemicals. Very recently sewer systems have been equipped with UV/VIS spectroscopic sensors to control sulphide-induced corrosion problems by chemical addition (Oriol *et al.* 2010). Trial runs are also starting up regarding the use of on-line TSS measurements to control sewer systems (Hoppe *et al.* 2011).

3.5 Fault detection

Fault detection is an important issue for RTC systems to assess sensor reliability (Puig 2009). Today, a plethora of methods to detect faulty measurements is available (Venkatasubramanian *et al.* 2003a,b,c). Statistical Process Control (SPC) methods that have been applied range from univariate methods, like control charts (Schraa *et al.* 2006) to multivariate methods, e.g. based on Principal Component Analysis (PCA) (Rosen and Lennox 2001, Yoo *et al.* 2006).

While univariate methods analyse the time series of data obtained from a single sensor and check whether the measurement noise is acceptable, multivariate methods evaluate the interrelation of different measured signals.

Methods that rely on multiple data sources are used to validate individual sensors, to generate a diagnosis for sensor condition and to estimate a confidence index in the measurement. It applies basically when the same variables are measured two or more times. Redundancy is normally exploited by matching off-line measurements (as reference) with the on-line measurement. However, the measurement methods and protocols are often different for on-line and off-line data. A non-zero residual can therefore be allowed, but it must remain low and the residuals should remain very close to a normal distribution. Having a reference measurement, Shewhart control charts (checking measurements falling beyond a three-sigma limit) can be used to detect drift-, shift-, and outlier effects as illustrated in Figure 3 (Thomann *et al.* 2002).

Alternatively, analysis of residuals can be conducted assuming errors to be random variables that are normally distributed with zero mean and constant variance (homoscedasticity). This property can be evaluated using standard statistical tests (searching for serial dependency or autocorrelation) which can subsequently be used to detect sensor faults (Dochain and Vanrolleghem 2001).

4. Actuators

Actuators/regulators are the elements of a RTC system that are used to adjust flows and water levels in the controlled system. These actuators mainly include pumps, moveable weirs, gates, inflatable dams, valves and flow splitters. Today also some actuators to adjust quality processes have been developed and adopted for RTC purposes; these concern mainly chemical dosing devices and aeration devices.

Schilling *et al.* (1996) reported some basic principles for a successful actuator design. In particular, as for all the components of RTC systems, they have to be designed fail-safe so that the worst-case malfunctioning control scenario falls back on a situation equivalent to the ‘no control’ scenario. This means for example the introduction of a bypass in the design of a moveable gate or the adoption of an automatic fail-safe device which quickly deflates an existing inflatable dam in case of a power failure. Additionally, equipment sensitive to the harsh wastewater environment has to be simplified, protected and accessible for periodical maintenance. Finally, reliable and high-performance actuators are needed to minimise failures, to permit a high number of displacements (Pleau *et al.* 2002) and guarantee short opening and closing times (in the order of a few minutes for the complete opening/closing action) mainly depending on the catchment storm water flow response time.

4.1 Pumps

Pumps are adopted in combined sewers as flow regulators and are used to convey wastewater from depressed areas of a sewer system. Another main usage is a regular or emergency drainage of depressed areas (e.g. roads) during heavy rain events. They are also employed where high flow velocities are required or are installed close to storage facilities for emptying of the accumulated storage volumes. In wastewater treatment they are used to lift

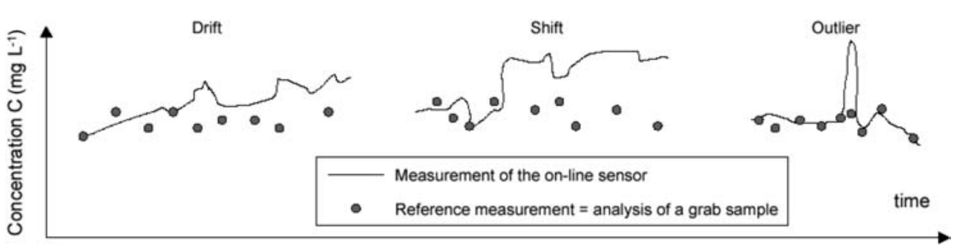

Figure 3. Out-of-control situations due to drift, shift and outlier effects (Thomann *et al.* 2002).

the water at the inlet and to convey process streams throughout the plant.

Today, axial or screw pumps with constant or variable speed are largely diffused in pumping stations for RTC aims, and a large amount of expertise has been collected concerning their optimal control both in term of practical experience and of theoretical results. Real applications have shown the achievable control performance and the possible risks when using the different kind of existing pumps (Cabrera and Cabrera 2003). Although more expensive in comparison to axial pumps, screw pumps are preferred in the presence of elevated sediment transport (Schilling 1989). Also, constant speed pumps are going to be replaced more and more by variable speed pumps maintaining the flow rate at the desired one, for instance resulting in improved control of WWTPs.

4.2 Weirs, gates and inflatable dams

Beside pumps, moveable weirs and gates are widely used in existing RTC systems. Moveable weirs can be installed as side-spill weirs as part of overflow devices and can be adopted for controlling combined sewer overflows (Campisano *et al.* 2000). It is also possible to place such actuators into a diversion chamber to split the flow discharge into several paths (Colas *et al.* 2001). In flat sewer systems another important possibility of these actuators is to activate in-line storage capacity upstream by installing them into main sewer collectors (Pleau *et al.* 2001). Newer applications of moveable weirs and gates extend the capability of activating in-line storage volume by using the devices as flushing units for sediment deposits and floatable control (Campisano and Modica 2003, Campisano 2009, Williams *et al.* 2009). For this, the stored water is used to generate intermittent dam-break waves. If properly designed, such an operation offers the possibility to prevent the accumulation of sediments (Dettmar and Staufer 2005) thus reducing pollution impacts to the receiving waters and personnel- and cost-intensive cleaning of the sewers (Campisano *et al.* 2004, 2006, 2007, 2008, Bertrand-Krajewski *et al.* 2005). If properly controlled, gates can be inserted at the outflow section of storage facilities and utilised as flow rate regulators offering, for instance, the possibility of extended storage time to improve the removal efficiency for suspended solids and agglomerated pollutants (Middleton and Barrett 2008). The use of gates or weirs upstream of a WWTP can also reduce the hydraulic shock loads consequent to heavy rain events (Meirlaen *et al.* 2002).

Weirs and gates are specifically designed for the site in which they have to be located and for the particular purpose they have to accomplish. Existing RTC systems show a wide variety of these kinds of devices, with reference to their design, to the kind of movement and to the material used for their construction. New developments allow a fast and robust operation. Some devices can fully move down or up to free-up the sewers cross-section completely. Specially constructed moveable weirs also guarantee the free-up of the cross-section in cases of malfunction (e.g. power blackout) just by gravity (Schaffner and Steinhardt 2011). In the meantime, nearly all hardware companies are able to provide gates that can be operated with a vertical characteristic curve.

Inflatable dams behave hydraulically as moveable weirs and are commonly adopted in combined sewer systems for maximising storage in trunk sewers. They are developed in rubberised fabric, mounted in the sewer bottom and usually activated by a water level sensor that controls a specific inflatation-deflatation device. Although very little maintenance is required, experience has shown that the air or water supply devices used to inflate the dams have to be inspected regularly (USEPA 1999).

4.3 Valves and flow splitters

Valves are mainly used to restrict wastewater flows. Normally they are installed in small circular pipes and used for obtaining accurate control of inlets into larger interceptors. Valves are also applied together with dosing devices in WWTP for controlling the injection of chemicals in wastewater. A detailed analysis concerning these devices for treatment processes is reported in Olsson and Newell (1999).

Flow splitters can be applied when specific conditions need to divert the flow into more paths. Literature shows that no important developments have recently occurred in the field of valves and flow splitters, but these two kinds of actuators are commonly used and hold high importance in existing RTC implementations for wastewater systems.

4.4 Chemical dosing devices

These actuators allow the improvement of performance of the system by adjusting the conditions of the wastewater in the tanks or into other facilities (Vanderhasselt *et al.* 1999). Chemical dosing concerns, for example, the supply of biodegradable COD to improve the denitrification processes, the addition of acid or base for maintaining pH within adequate range, or the addition of ballasting particles to increase the generation of biological flocs or settling of specific pollutants. Recently some new applications have been reported that use controlled dosing of chemicals for sewer corrosion control (Oriol *et al.* 2010, Zhang *et al.* 2011).

4.5 Aeration devices

Aeration devices are to be employed in wastewater treatment plants to provide the oxygen needed in several important biological pollutant removal processes such as oxidation of organic matter and nitrification. Many different types of aeration systems exist: fine bubble aeration systems are the most used because of their efficiency. Indeed, aeration gets a lot of attention as it typically is responsible for half the operating costs of a treatment plant. Dissolved oxygen control is therefore an essential ingredient of a modern wastewater treatment facility (Olsson and Newell 1999, Olsson *et al.* 2005). Remarkable benefits can also be obtained by applying aeration directly to river systems. An example of implementation of this kind of devices is the Seine River in Paris (Krier 1998).

5. Controllers

The manipulation of actuators in RTC systems is performed by controllers (or control units). In particular, these devices receive inputs from local sensors and provide output adjustments to actuators according to the objectives, such as set point values.

With the advent of the microprocessor technology, analogue control units have been replaced by digital control units such as Programmable Logic Controllers (PLCs) or Remote Terminal Units (RTUs).

PLCs, originally designed for discrete control applications in industrial processes, are structurally indicated for harsh environments characterised by high levels of humidity and adverse temperature. Instead, RTUs have the typical flexibility of personal computers allowing user friendly programming at relatively low costs.

However, these days, both RTUs and PLCs globally have similar potential since both of them can provide all the functions of an outstation, including acquisition of measurement data, pre-processing/validation (smoothing, filtering, etc.), checks for status, temporary storage of data, calculation of control action, and high connectivity for data exchange with a central station.

PLCs can be embedded (programmed) according to different logics. These logics are feedback rules/algorithms where the final action is often based on the deviation between a set point and the current value of the monitored variable.

On/Off and PID logic is widespread in embedded PLCs for RTC systems due to their conceptual simplicity. PID logic sends proportional (P), integral (I) or derivative (D) control action signals or a combination of these types (P, PI, PD, PID) to actuators (Campisano *et al.* 2010). The set point for the controller may be fixed and locally programmed or it may be modified in real time from a central station as result of the adopted RTC strategy (supervisory or cascade control).

Results from literature have shown PID controllers to provide accurate water level control upstream of moveable gates and weirs positioned at the outlet of sewer pipes and storage tanks (Campisano and Modica 2002).

Also many treatment processes at WWTPs can benefit from the adoption of PID control algorithms, such as the dynamic control of the dissolved oxygen (Ingildsen *et al.* 2002). Moreover, good results have been obtained from testing a feedback PI unit for the control of chemical dosage devices for phosphate precipitation (Ingildsen and Olsson 2002). Many more control strategies have been implemented at full-scale (for an overview, see Olsson *et al.* 2005) and simulation-based methods have been developed to objectively compare the performance of different strategies before implementation (Jeppsson *et al.* 2007).

Despite ease of application, PID controllers need tuning in order to reduce the system reaction time and the deviation from the set point and to avoid the occurrence of permanent oscillations of the controlled variable around the set point (Olsson and Newell 1999, Campisano and Modica 2002).

6. Telemetry systems

Telemetry systems are key to the success of an RTC system in UDSs. They ensure the transmission of information between the various hardware components of a remote station including sensors, actuators and controllers and possibly a central station where field data are displayed on a Human Machine Interface (HMI). These communications are under the supervision of a SCADA (Supervisory Control And Data Acquisition) system (USEPA 2006).

6.1 Performance, robustness and long-term reliability

In order to successfully implement a UDS using RTC, the telemetry system must be performing, robust and have long-term reliability.

Performance is related to the ability of the transmission system to convey data among the different local components and between the remote stations and the central station at a specific rate and with a given percentage of successful transmission. For good system performance, the percentage of successful data transmission should be above 95%, especially during wet weather periods (Colas *et al.* 2001).

Considering that in many RTC applications the local controller normally loops between 10 and 60 seconds, the transmission system must support a communication rate of less than 10 seconds between sensors, input/output units and actuators. Moreover, control algorithms implemented in a PLC should also be able to provide commands to actuators in less than 10 seconds.

System *robustness* refers to the capacity of the transmission system to guarantee good data transmission in the presence of system failures and communication breakdowns. In this context, an important advantage of local RTC is that communication links between RTUs and central station are not needed, making the system less prone to communication problems. This suggests that local control could be a suitable solution for small RTC systems for which a limited number of control variables is normally taken into account. Instead, for larger systems, the design of a robust transmission system, requires an implementation of robust communication protocols, to install redundant components, to have power backups (batteries, generators) and finally to have architectures that permit the transfer of data between the remote stations and the central station using different communication links. Moreover, for RTC systems where the set points are determined at the central station, the transmission rate has to be faster than the set point computation period in order to have the possibility to transfer set points more than once (Pleau *et al.* 2005). The use of heart beat signals is also useful in detecting communication breakdowns when they occur. This issue is mandatory whenever a double layer remote-local control is set; local and remote computers must know at any time, if communications are working properly.

The long-term *reliability* of the telemetry system is related to data quality. It is insured by purchasing reliable communication devices (i.e. industrial grade RTUs, PLCs, modems, cables and Ethernet switches) and software, and by implementing standard protocols using open architectures (e.g. TCP/IP, MODBUS, Profibus communication protocols) that allow the communication system to evolve together with the development of the sewer system. A reliable telemetry also needs a good maintenance program to be put in place including fault detection and preventative maintenance procedures. Specifically, software programs must be extensively tested to make sure that they can run bug-free over a long period of time.

6.2 Communication media

For communication between the remote and the central stations, different technological media can be selected:

- Phone lines (leased or dial-up);
- Ethernet networks over fibre optic or copper cables (private or leased networks);
- Cellular data communication services;
- Radio communication networks (licensed or unlicensed).

Technologies compatible with the Internet Protocol (IP) are likely to provide the best solution in terms of flexibility of use, scalability and compatibility. That protocol allows multiple endpoints to exchange data at the same time and is generally available over high-speed links (e.g. broadband wireless or DSL). Use of an IP-compatible network is required by most of the PLC technologies in order to update the remote stations' PLC program remotely. It is not mandatory for basic RTC telemetry but can greatly reduce time and expenses pertaining to the deployment and maintenance of the system.

Several technologies can be put together to suit the different needs of a communication network architecture. However, the telecommunication core should be based on a technology that suits the needs of a maximum number of remote stations in order to create a homogeneous system that would provide the best cost-benefit ratio.

Phone-based communication is largely adopted in existing sewer RTC systems for its low cost of installation. As the technology evolved, the use of modems communicating over leased or dial-up phone lines became more prevalent. In general, leased lines are most effective and cheaper for short distance links. Dial-up lines are to be preferred when data transmission over long distance is required (e.g., more than 10 km).

Communications using *Ethernet networks* are usually wire systems made of aerial and/or underground copper wires, fibre optic cables and coaxial cables. However, the authors think that, for UDS using RTC, fibre optic is the most attractive communication technology. It supports high speed communication over long distances, is immune to electrical interference and exhibits high system availability. Wire systems usually remain an expensive communication technology over a spread network due to installation cost.

For a few years now, *Cellular* providers have been offering data communication services for mobile or fixed stations (GSM, GPRS, UMTS technologies), depending on the service availability in the local area. With this technology, the communication link is established using a specific cellular radio modem unit (sold or rented by the cellular service provider) connected to the remote PLCs using IP. At the central station, the communication front end is normally connected to the cellular provider's main office through a dedicated data link. Today, the monthly fees for cellular services have considerably decreased, being generally comparable to those related to dial-up modems. Much attention should be paid to reduce the risks of cellular network break downs by introducing alternative redundant links between the RTC components.

Radio communication networks use private radio modems connected to I/O units to establish communication channels between the central station and the remote sites. Various Radio Frequency (RF) bands can be used, such as VHF (frequencies around 220–240 MHz), low UHF (around 330–512 MHz) and lower-mid UHF (900 MHz).

An alternative to RF bands consists in using unlicensed radio systems such as Spread Spectrum. This technology uses low powered units (limited to a maximum of one

Watt). Thus, for short distance (i.e., generally for 5 kilometres or less depending on ground conditions), Spread Spectrum technology can be a cost-efficient alternative. The recent spread spectrum technology units provide good efficiency and reliability at data rates that can reach 512 Kbps and even more.

A limitation of radio technologies is that they require the design and installation of antennas and masts, normally more complex than the design of other communication networks. However, once the system is started-up, the operational costs of a radio technology system are normally lower than any other communication network. Moreover, the radio system is entirely owned by the user, rendering the system easier to maintain and manage.

7. Future trends and challenges for RTC equipment

The demand for rehabilitation and good maintenance in sewers, river (ecology) quality driven objectives, and the demand for (online) quality measurements in high temporal resolution and automated fault detection systems are main drivers for new developments.

Several applications can be found in the last years where actuators, which are mainly installed and operated for flow regulation (e.g. moveable weirs), also started to be used to flush sewers affected by sediment deposition. At the same time, cleaning devices like flush shields are used for stormwater retention in a controlled manner. In the meantime a broad knowledge is available about the effectiveness of such cleaning devices, e.g. up to which point the energy of flush waves is high enough to re-suspend the sewer sediments (Campisano *et al.* 2007).

For an effective control strategy detailed information must be available about the amount and location of sediments. There are certainly a lack of available methods for monitoring sewer sediments directly or to estimate the needed information by directly measuring influencing parameters like velocity distributions and bottom shear stress (Staufer and Pinnekamp 2008). As the maintenance of sewers attracts more and more attention, it is expected that the development of such actuators and monitoring techniques for RTC purposes will go on in the near future. At the same time, control strategies have to be further developed to enable an effective management of sewer sediments.

A number of concepts for pollution based RTC and integrated RTC have been introduced during the last decade and have been proven mainly by simulation studies (Erbe and Schutze 2005, Vanrolleghem *et al.* 2005). Only recently, first implementations can be recognised for pollution based RTC (Hoppe *et al.* 2011). One crucial part of pollution based RTC concepts is that the dynamics of quality parameters like suspended solids, organic carbon or ammonia are required. Analysing implementations, it becomes obvious that online water quality measurements in harsh environments like combined sewer systems are still a challenging task (Schilperoort 2011). The high flow variability demands innovative concepts for the installation of the sensors; the surrounding condition in combined or sanitary sewer with its often corrosive atmosphere and ingredients like solid matter, faecal and colloidal dissolved substances causes serious maintenance problems. Some pilot installations indicate that operating online measurement stations over a long period is in principle possible (Gruber *et al.* 2005); however, depending on the kind of used sensors considerable maintenance efforts are needed. As already mentioned in Section 3, promising developments have taken place regarding online water quality sensors. On the one hand sensors become more robust, on the other hand the potpourri of quality parameters that can be measured online is extending continuously. The development of control strategies that use alternative quality parameters as decision variables, e.g. conductivity, is an important step to overcome the vulnerability of available water quality sensors.

Given the problems associated with the quality of the data the sensors provide, it is essential that faulty data are not used in control action calculation. It is therefore of paramount importance that data quality assessment tools are further developed and become an integrated part of operational control systems (Rieger and Vanrolleghem 2008). Only with such tools, more advanced measurement systems that can deliver key variables as certain water quality parameters, will become acceptable for practical implementation and will deliver a boost in performance of the control system.

8. Conclusions

Today, many UDSs are operated by a RTC system showing that the technology and equipment required to successfully implement a RTC system in a stochastic and harsh environment is available. In order to achieve the specific objectives of each application with a high level of security, the main components of a RTC system (sensors, actuators, controllers and telemetry) must be selected and implemented to properly operate over long periods of time.

In this paper, a survey of modern technologies adopted for the RTC of urban wastewater systems has been presented. Advantages and limits of many devices have been illustrated on the basis of the accumulated experience from different RTC systems implemented worldwide. From these experiences, it appears that many technologies and equipment have reached a mature stage and are well suited for UDS applications. This is true for several types of sensors including rain gauges and water level meters. Reliable actuators allowing fast and numerous gate displacements in a short period of time are also available for flow and water level control. In terms of telecommunication, many technologies including fibre optic and dedicated phone lines permit a fast data transmission rate with very few communication failures. However, other equipment such as water quality sensors still have to be improved or embedded in fault detection systems, which explains why most of the RTC systems developed for UDSs are currently operated to achieve environmental objectives that are only based on quantity parameters (e.g., flood protection, minimisation of CSO frequency and volume) and not on quality parameters.

In view of the increasing need for environmental protection, important developments are required in the field of water quality measurement devices. New reliable sensors and actuators with higher performance and reduced maintenance requirements have to be developed especially for the continuous monitoring and control of treatment plant processes and river system habitats.

Considering that the actual trends concerning sewer system optimisation focus on new procedures for rehabilitation and good maintenance, it is also expected that more attention will be dedicated to the development of new devices for RTC of solids in sewer pipes. Particular emphasis to the monitoring and flushing aspects of solids (solid transport, direct measurement of velocity distribution and flow shear stress) should be devoted in the next few years.

The different RTC applications investigated have shown that the success of a RTC system for UDS not only relies on the selected equipment and technology but also on maintenance procedures (preventive and predictive maintenance) and on the robustness of the RTC scheme. In particular, RTC design should include fault detection algorithms to insure that no poor quality information is used in the decision making process. Redundancy should also be incorporated in the design at critical locations (e.g., redundant sensors, safety gates, multiple communication channels) to increase the global reliability of the control system.

Acknowledgements

Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling. Part of the work by Peter Vanrolleghem was funded through an Otto Mønsted guest professorship at the Technical University of Denmark.

References

Beck, M.B., Watts, J.B., and Winkler, S., 1998. An environmental process control laboratory: At the interface between instrumentation and model development. *Water Science and Technology*, 37 (12), 353–362.

Bertrand-Krajewski, J.-L., Campisano, A., Creaco, E., and Modica, C., 2005. Experimental analysis of the Hydrass flushing gate and field validation of flush propagation modelling. *Water Science and Technology*, 51 (2), 129–137.

Berne, A., Delrieu, G., Creutin, J.D., and Obled, C., 2004. Temporal and spatial resolution of rainfall measurements required for urban hydrology. *Journal of Hydrology*, 299, 166–179.

Cabrera, E. and Cabrera, E., 2003. *Pumps, Electromechanical Devices and Systems Applied to Urban Water Management*. Lisse, The Netherlands: Balkema Publisher.

Campisano, A., 2009. Laboratory investigation on the performances of baffles for the capture of sewer floatables. *Water Science and Technology*, 60 (1), 29–36.

Campisano, A., Creaco, E., and Modica, C., 2004. Experimental and numerical analysis of the scouring effects of flushing waves on sediment deposits. *Journal of Hydrology*, 299 (3–4), 324–334.

Campisano, A., Creaco, E., and Modica, C., 2006. Experimental analysis of the Hydrass flushing gate and laboratory validation of flush propagation modelling. *Water Science and Technology*, 54 (6–7), 101–108.

Campisano, A., Creaco, E., and Modica, C., 2007. Dimensionless approach for the design of flushing gates in sewer channels. *Journal of Hydraulic Engineering*, 133 (8), 964–972.

Campisano, A., Creaco, E., and Modica, C., 2008. Laboratory investigation on the effects of flushes on cohesive sediment beds. *Urban Water Journal*, 5 (1), 3–14.

Campisano, A., Creaco, E., and Modica, C., 2010. RTC of valves for leakage reduction in water supply networks. *Journal of Water Resources Planning and Management*, 136 (1), 138–141.

Campisano, A. and Modica, C., 2002. PID and PLC units for the real-time control of sewer systems. *Water Science and Technology*, 45 (7), 95–104.

Campisano, A. and Modica, C., 2003. Flow velocities and shear stresses during flushing operations in sewer collectors. *Water Science and Technology*, 47 (4), 123–128.

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.

Cembrano, G., Quevedo, J., Salamero, M., Puig, V., Figueras, J., and Marti, J., 2004. Optimal control of urban drainage systems. A case study. *Control Engineering Practice*, 12 (1), 1–9.

Colas, H., Jolicoeur, N., Pleau, M., Marcoux, C., Field, R., and Stinson, M., 2001. The choice of a real time control strategy for combined sewer overflow control. *In*: *Proceedings 5th international conference on diffuse/nonpoint pollution and watershed management*, 10–15 June 2001. Milwaukee, USA: IWA Pub., Published in CD-ROM.

Cutore, P., Cristaudo, G., Campisano, A., Modica, C., Cancelliere, A., and Rossi, G., 2007. Regional models for the estimation of streamflow series in ungauged basins. *Water Resources Management*, 21 (5), 789–800.

Dettmar, J. and Staufer, P., 2005. Modelling of flushing waves for optimising cleaning operations. *Water Science and Technology*, 52 (5), 233–240.

Dirckx, G., Thoeye, Ch., De Gueldre, G., and Van De Steene, B., 2011. CSO management from an operator's perspective: A step-wise action plan. *Water Science and Technology*, 63 (5), 1044–1052.

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

Erbe, V. and Schutze, M., 2005. An integrated modelling concept for immission-based management of sewer system, wastewater treatment plant and river. *Water Science and Technology*, 52 (5), 95–103.

Fayad, P., Prévost, M., and Sauvé, S., 2010. Laser diode thermal desorption – atmospheric pressure chemical ionization tandem mass spectrometry analysis of selected steroid hormones in wastewater: Method optimization and application. *Analytical Chemistry*, 82, 635–645.

Fuchs, L. and Beeneken, T., 2005. Development and implementation of a real-time control strategy for the sewer system of the city of Vienna. *Water Science and Technology*, 52 (5), 187–194.

Gamerith, V., Steger, B., Hochedlinger, M., and Gruber, G., 2011. Assessment of UV/VIS-spectrometry performance in combined sewer monitoring under wet weather conditions. *In*: *Proceedings 12th international conference on urban drainage*, 10–15 September 2011. Porto Alegre, Brazil: IWA Pub., Published in CD-ROM.

Gruber, G., Winkler, S., and Pressl, A., 2005. Continuous monitoring in sewer networks an approach for quantification of pollution loads from CSOs into surface water bodies. *Water Science and Technology*, 52 (12), 215–223.

Grüning, H. and Orth, H., 2002. Investigations of the dynamic behaviour of the composition of combined sewage using online analyzers. *Water Science and Technology*, 45 (4–5), 77–83.

Hoppe, H., Messmann, S., Giga, A., and Gruening, H., 2011. A real-time control strategy for separation of highly polluted storm water based on UV–Vis online measurements–from theory to operation. *Water Science and Technology*, 63 (10), 2287–2293.

Hughes, A.W., Longair, I.M., Ashley, R.M., and Kirby, K., 1996. Using an array of ultrasonic velocity transducers to improve the accuracy of large sewer mean velocity measurements. *Water Science and Technology*, 33 (1), 1–12.

Ingildsen, P. Jeppsson, U., and Olsson, G., 2002. Dissolved oxygen controller based on online measurements of ammonium combining feed-forward and feedback. *Water Science and Technology*, 45 (4–5), 453–460.

Ingildsen, P. and Olsson, G., 2002. Exploiting online in-situ ammonium, nitrate and phosphate sensors in full-scale wastewater plant operation. *Water Science and Technology*, 45 (4–5), 139–147.

ITA, 2002. Optimal flow measurement, understanding selection, application, installation and operation of flowmeters. *In*: *Proceedings of ITA Workshop WK02FM-002*. Henderson, USA: Instrumentation Testing Association.

Jeppsson, U., Pons, M.-N., Nopens, I., Alex, J., Copp, J.B., Gernaey, K.V., Rosen, C., Steyer, J.-P., and Vanrolleghem, P.A., 2007. Benchmark simulation model no 2: General protocol and exploratory case studies. *Water Science and Technology*, 56 (8), 67–78.

Krier, J., 1998. Des îlots de survie pour les poissons. *In*: *Proceedings Paris-Québec international symposium, waterways rehabilitation in urban environments*, 28–30 September 1998. Quebec City: CET, 431–444.

Lacour, C. and Schütze, M., 2011. Real-time control of sewer systems using turbidity measurements. *Water Science and Technology*, 63 (11), 2628–2632.

Lynggaard-Jensen, A., Eisum, N.H., Rasmussen, I., Svankjær Jocobsen, H., and Stenstrøm, T., 1996. Description and test of a new generation of nutrient sensors. *Water Science and Technology*, 33 (1), 25–35.

Meirlaen, J., Van Assel, J., and Vanrolleghem, P.A., 2002. Real time control of the integrated urban wastewater system using simultaneously simulating surrogate models. *Water Science and Technology*, 45 (3), 109–116.

Middleton, J.R. and Barrett, M.E., 2008. Water quality performance of a batch-type stormwater detention basin. *Water Environment Research*, 80 (2), 172–178.

Miles, S.L., Sinclair, R.G., Riley, M.R., and Pepper, I.L., 2011. Evaluation of select sensors for real-time monitoring of Escherichia coli in water distribution systems. *Applied Environmental Microbiology*, 77, 2813–2816.

Olsson, G. and Newell, R.B., 1999. *Wastewater Treatment Systems – Modelling, Diagnosis and Control*. London: IWA Publishing.

Olsson, G., Nielsen, M.K., Yuan, Z., Lynggaard-Jensen, A., and Steyer, J.-P., 2005. *Instrumentation, Control and Automation in Wastewater Systems.* Scientific and Technical Report. London: IWA Publishing.

Oriol, G., Sutherland-Stacey, L., and Yuan, Z., 2010. Simultaneous online measurement of sulfide and nitrate in sewers for nitrate dosing optimisation. *Water Science and Technology*, 61, 651–658.

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

Pleau, M., Pelletier, G., Colas, H., Lavallée, P., and Bonin, R., 2002. Reliability and robustness in real-time control applications. *In*: E.W. Strecker and W.C. Huber, eds. *Proceedings 9th international conference on urban drainage*, 8–13 September 2002. Portland, OR, USA: ASCE, Published in CD-ROM.

Pleau, M., Colas, H., Lavallée, P., Pelletier, G., and Bonin, R., 2005. Global optimal real-time control of the Quebec urban drainage system. *Environmental Modelling & Software*, 20, 401–413.

Pleau, M., Fradet, O., Colas, H., and Marcoux, C., 2010. Giving the rivers back to the public. Ten years of Real Time Control in Quebec City. *In*: *Proceedings international conference on sustainable techniques and strategies in urban water management (Novatech2010)*, 27 June–1 July 2010. Lyon, France: GRAIE, Published in CD-ROM.

Pressl, A., Winkler, S., and Gruber, G., 2004. In-line river monitoring – new challenges and opportunities. *Water Science and Technology*, 50 (11), 67–72.

Puig, V., 2009. Fault detection and isolation in sewer networks. *In*: *Proceedings of 7th IFAC international symposium on fault detection, supervision and safety of technical systems, SAFEPROCESS'09*, 30 June–3 July 2009, Barcelona. Amsterdam, The Netherlands: Elsevier, 1282–1293.

Puig, V., Cembrano, G., Romera, J., Quevedo, J., Aznar, B., Ramón, G., and Cabot, J., 2009. Predictive optimal control of sewer networks using CORAL tool: Application to Riera Blanca catchment in Barcelona. *Water Science and Technology*, 60 (4), 869–878.

Rieger, L. and Vanrolleghem, P.A., 2008. monEAU: A platform for water quality monitoring networks. *Water Science and Technology*, 57 (7), 1079–1086.

Rosen, C. and Lennox, J.A., 2001. Multivariate and multiscale monitoring of wastewater treatment operation. *Water Research*, 35, 3402–3410.

Schilling, W., 1989. *Real-Time Control of Urban Drainage Systems. The State-of-the-Art. scientific and Technical Reports n°2*. London: IWA Publishing.

Schilling, W., 1991. Rainfall data for urban hydrology: What do we need? *Atmospheric Research*, 27 (1–3), 5–21.

Schilling, W., Andersson, B., Nyberg, U., Aspegren, H., Rauch, W., and Harremoes, P., 1996. Real Time Control of wastewater systems. *Journal of Hydraulic Research*, 34 (6), 785–797.

Schilperoort, R., 2011. *Monitoring as a tool for the assessment of wastewater quality dynamics*, Thesis (PhD). Technical University of Delft, The Netherlands.

Schraa, O., Tole, B., and Copp, J.B., 2006. Fault detection for control of wastewater treatment plants. *Water Science and Technology*, 53 (4–5), 375–382.

Schütze, M., Campisano, A., Colas, H., Schilling, W., and Vanrolleghem, P.A., 2004a. Real-time control of urban wastewater systems–where do we stand today? *Journal of Hydrology*, 299, 335–348.

Schütze, M., Erbe, V., Haas, U., Scheer, M., and Weyand, M., 2004b. PASST – A planning aid for sewer system real time control. *In*: *Proceedings of the 6th international conference on urban drainage modelling*, 15–17 September 2004, Dresden, Germany. London, UK: IWA Pub., Published in CD-ROM, 701–708.

Schaffner, J. and Steinhardt, R., 2011. Numerical investigations on the effect of sewer cleaning flush waves under the influence of downstream water levels. *In*: *2010 stormwater and urban water systems modeling conference – cognitive modeling of urban water systems*, 18–19 February 2010, Toronto, Ontario, Canada. Guelph, ON, Canada: CHI, Published in CD-ROM, 57–78.

Staufer, P. and Pinnekamp, J., 2008. In situ measurements of shear stresses of a flushing wave in a circular sewer using ultrasound. *Water Science and Technology*, 57 (9), 1363–1368.

Thomann, M., Rieger, L., Frommhold, S., Siegrist, H., and Gujer, W., 2002. An efficient monitoring concept with control charts for on-line sensors. *Water Science and Technology*, 46 (4–5), 107–116.

USEPA, 1999. *Combined sewer overflow technology fact sheet. Maximization of in-line storage*. Report 832-F-99-036, September 1999. Washington, DC: EPA.

USEPA, 2006. *Real time control of urban drainage networks*. Report 600-R-06-120, September 2006. Washington, DC: EPA.

Vanderhasselt, A., De Clercq, B., Vanderhaegen, B., Verstraete, W., and Vanrolleghem, P.A., 1999. On-line control of polymer addition to prevent massive sludge wash-out. *Journal of Environmental Engineering*, 125, 1014–1021.

Vanrolleghem, P.A. and Lee, D.S., 2003. On-line monitoring equipment for wastewater treatment processes: State of the art. *Water Science and Technology*, 47 (2), 1–34.

Vanrolleghem, P.A., Benedetti, L., and Meirlaen, J., 2005. Modelling and real-time control of the integrated urban wastewater system. *Environmental Modelling & Software*, 20 (4), 427–442.

Vazquez, J., Francois, M., and Gilbert, D., 2003. Real-time management of a sewage system: verification of the optimality and applicability of graphical linear programming compared to mixed linear programming [in French]. *Revue des Sciences de l'Eau*, 16 (4), 425–442.

Venkatasubramanian, V., Rengaswamy, R., Yin, K., and Kavuri, S.N., 2003a. A review of process fault detection and diagnosis – Part I: Quantitative model-based methods. *Computers in Chemical Engineering*, 27, 293–311.

Venkatasubramanian, V., Rengaswamy, R., and Kavuri, S.N., 2003b. A review of process fault detection and diagnosis–Part II: Qualitative models and search strategies. *Computers in Chemical Engineering*, 27, 313–326.

Venkatasubramanian, V., Rengaswamy, R., Kavuri, S.N., and Yin, K., 2003c. A review of process fault detection and diagnosis – Part III: Process history based methods. *Computers in Chemical Engineering*, 27, 327–346.

Vieux, B.E. and Vieux, J.E., 2005. Statistical evaluation of a radar rainfall system for sewer system management. *Atmospheric Research*, 77, 322–336.

Watts, J.B., Evans, K., and Molloy, A., 1990. A wastewater/water process monitoring system allowing operational control – Developed by an operational manager. *In*: R. Briggs, ed. *Advances in Water Pollution Control*. London: Pergamon Press, 143–154.

WERF, 2002. *Assess and Document Installed State-of-the-Art WWTP Sensing and Control Systems*. Draft Report, Project 99-WWF-4. Alexandria, Virginia: WERF.

Weyand, M., 2002. Real-time control in combined sewer systems in Germany–Some case studies. *Urban Water*, 4, 347–354.

Williams, K.J., Tait, S.J., and Ashley, R.M., 2009. In-sewer sedimentation associated with active flow control. *Water Science and Technology*, 60 (1), 55–63.

Winkler, S., Zessner, M., Saracevic, E., and Fleischmann, N., 2008. Intelligent monitoring networks – Transformation of data into information for water management. *Water Science and Technology*, 58 (2), 317–322.

Yoo, C.K., Villez, K., Lee, I.-B., Rosen, C., and Vanrolleghem, P.A., 2006. Multi-model statistical process monitoring and diagnosis of a sequencing batch reactor. *Biotechnology and Bioengineering*, 96, 687–701.

Zhang, L., De Gusseme, B., Cai, L., De Schryver, P., Marzorati, M., Boon, N., Lens, P., and Verstraete, W., 2011. Addition of an aerated iron-rich waste-activated sludge to control the soluble sulphide concentration in sewage. *Water and Environment Journal*, 25 (1), 106–115.