The Feasibility of Real Time Control of Combined Sewer Overflows

The benefits of implementing real time control of an urban drainage system may offset problems in project funding, inter-agency cooperation and liability considerations.

WOLFGANG SCHILLING

Urban drainage systems (UDSs) are often plagued with pollution problems due to flooding and combined sewer overflows (CSOs). The agencies responsible for these systems have become hard-pressed to come up with solutions to these problems. These agencies are also under public constraints to implement these solutions with the lowest possible cost, and to maximize other potential benefits that can be applied to other problems such as reducing energy costs and improving wastewater treatment and in-sewer sediment control. Real time UDS control offers one way to reduce flooding and pollution problems with relatively little investment cost.

What Is Real Time Control?

An UDS is controlled in *real time* if the process data that are currently monitored in the system are used to operate regulators during the actual flow process. Typically, the task is to activate a number of pumps, sluice gates, weirs, *etc.*, so that adverse effects *(e.g.,* flooding, CSOs) only occur if the system is at capacity *and* only at locations that result in the least damage. In *static* systems, these conditions can only be achieved in the rare case where the UDS is receiving its design load. If, for example, the outflow of a detention pond is controlled by an orifice, the optimal outflow rate is reached when the pond is full. During other periods, the outflow rate is smaller and, consequently, the emptying time is longer. As another example, a (static) high-side weir can be used to activate excess storage in a large sewer system. The overflow opening has to be large enough to allow for the design overflow rate. Thus, much of the available storage cannot be used in most situations.

Operational concepts of real time control systems (RTCSs) are concerned with the logical ways process information is used. Since static system deficiencies are well known, moveable (self-operating) regulators have been introduced to maintain a pre-set flow or water level. Many of these moveable regulators use process measurements taken directly at the regulator site *(e.g.,* float, counterweight, *etc.).* Therefore, such a system is termed a *local control* system.

Under local control, regulators are not remotely manipulated from a control center. In some situations, operational data are centrally acquired, but the regulators remain under local control. This type of configuration eases system supervision.

Local control is a good solution if the system has only one regulator *(e.g.*, an inflow equalization tank at a treatment plant). However, if several regulators operate independently, it might happen that, for example, an upstream pond empties into a downstream pond that is already overflowing. In that case, better operation is possible if the flow in both ponds is regulated in concert. This type of coordination can only be performed by taking process measurements further upstream, or downstream, of the regulator site *(regional control).*

When an RTCS is more complex and all of the regulators are operated in coordination, the system is managed under *global control*. In this case, all regulators are operated based on the data obtained from process measurements throughout the system. Global control in drainage systems is required when:

- Many regulators affect each other; or,
- The actual loading differs substantially from the design loading *(e.g.*, when rainfall is temporally and spatially variable).

In older global RTCSs, measurements are displayed on analog meters or strip charts located in a control center. The regulators are actuated manually with switches by operators. Since only limited information is available, operators need a very keen understanding of the dynamics of the control and drainage systems. In a global, or *supervisory*, control system, the regulators are adjusted by automatic controllers, but the operating personnel perform the system-wide coordination. A modern supervisory RTCS can be interactively supported by a simulator that permits modeling the control effects before they are executed. In addition, control situations can be evaluated against a database of previous control decisions, flow conditions and their results. In a fully *automatic* RTCS, all functions are carried out by a process computer so that operating personnel perform solely supervisory functions.

Feasibility Criteria

Real time control is operationally feasible when the following conditions are present:

- A deviation between the actual and the desired performance of a system occurs.
- A variety of these deviations exist, depending on the actual state and loading of the system.
- The means are available to manipulate the process to achieve better performance.

Operational problems must exist within the system. These problems must vary in type, time and space. In addition, unused storage and / or transport capacity must be available within the system.

Real Time Feasibility Criteria for Urban Drainage and Wastewater Systems. Before real time control application in an UDS can be considered in detail, the general criteria above have to be checked. The following criteria specific to an UDS might apply:

1. *Quantity*. Too frequent flooding in some sub-catchments is usually alleviated by new and larger conduits or storage. A real time control alternative might be to temporally divert flows via upstream CSO regulators or to route flows through less loaded parts of the system, ensuring that all accessible storage is filled.

2. *Quality*. Hydraulic overloading situations might exist where wastewater is discharged into receiving waters because the treatment plant is at capacity. Overdesigned sewers might be fitted with moveable regulators to create in-line storage. If the treatment plant's final clarifier is sensitive to extended stormwater loading, the CSO regulators might be controlled as a function of the level of the clarifier sludge blanket. If CSOs occur into receiving waters that have different sensitivities to the harmful effects of the CSOs, they might be controlled to discharge mainly into the waters that are the least sensitive, thus minimizing damage to the environment. CSO sites might also be selected to minimize the escape of sanitary sewage, if that flow can be monitored

and/or predicted. If a combined sewer system is used as a pipeline for sanitary flows from an upstream separate system, sanitary sewage tanks might be filled and emptied so that the sanitary sewage will not escape via the downstream CSO.

3. *Layout.* Typically, real time control benefits increase with the number of controllable elements (ponds, overflows, diversions, pumping stations, *etc.*), the size of the catchment area and the extent to which the network is looped.

4. *Investment Cost.* Real time control reduces the capacity (*i.e.*, transport, storage) needed to achieve a given performance level. On the local level, tank volume can be reduced by using a moveable throttle. On the global level, the coordination of storage/transport activation maximizes system effectiveness.

5. *Operation & Maintenance (O&M) Cost.* Special structures (throttles, weirs, pumping stations, screens, flushers, *etc.*) require O&M on a regular schedule. In topographically large systems, the effort (time, personnel) might be so high that some type of remote supervision and maintenance might be cost-beneficial. In low gradient areas, stormwater has to be pumped. Real time control can be used to postpone pumping and thereby avoid peak rate charges for pumping power.

6. *Legal.* An operating agency might be required to report on the performance of its UDS — the number, duration and volume of its CSOs. This obligation would at least require a datalogging system. If that system were centralized into a data acquisition system, it would serve as the first step to developing the data processing system necessary for real time control.

Except for the completely over- and underdesigned systems, almost every existing UDS can benefit from real time control. However, most RTCSs are implemented in combined sewer systems because they serve multiple purposes, undergo non-homogeneous loading and exhibit large discrepancies between their planned and actual performance.

Performance Monitoring & Screening Models. As soon as an UDS is synchronously monitored at strategic locations (such as hydraulic bottlenecks, major CSOs and ponds), system performance may be analyzed. Measured flow rates and levels arranged as hydrographs (*e.g.*, pond level *versus* time, overflow rate *versus* time) are needed. Only in extreme circumstances when capacity limits are reached simultaneously will operational problems occur at different locations and the value of real time control be nullified.

Extensive monitoring systems are expensive to install and operate. In the feasibility stage, it is therefore essential to use numerical simulation programs to analyze the potential performance of the UDS. However, most available programs do not accommodate real time functions; *i.e.*, they are not formulated as state-space models and do not interrupt the simulations to receive new information on controller setpoints, regulator movement, *etc.*, as would occur during real time operation.

Planning and Design of Real Time Control Systems

The preliminary analysis of an UDS should:

- Define the operational objectives of the UDS (*e.g.*, minimize flooding and CSOs, *etc.*).
- Identify principal UDS features, providing a means to note system "hot spots" (*e.g.*, hydraulic bottlenecks, CSO sites, regulator stations, *etc.*).
- Evaluate the potential for real time control through simulation or monitoring. Does idle capacity exist in the system during times of potential damage?

Real time control feasibility analysis should follow these stages:

- Determine the current performance of the UDS. Analyze historic events during which damage was observed and/or determine the statistics of damages through long-term simulation.
- Select locally controlled regulators and determine the performance of a locally controlled UDS. Can current capacity be better utilized?
- Optimize the control strategy and determine the maximum performance of the UDS under global control. How much improvement is made in reaching opera-

tional objectives compared to local control?

- Compare UDS performance against conventional (static) solutions *(e.g.,* larger sewers and tanks).
- Evaluate the cost effectiveness of all alternatives and choose the most cost-effective alternative.

Planning for RTCS design and implementation should develop:

- A control strategy that includes a sensitivity analysis and fail-safe precautions.
- An automation implementation survey that includes the requirements for information processing, presentation functions, operator functions, communications system, hardware specifications, *etc.*
- Software for system application, user interfaces and control.
- Detailed models of hydraulics, controller behavior, pollution discharges, *etc.*
- Factory and site acceptance tests.
- Personnel planning (education requirements, training, maintenance, *etc.).*
- A preliminary version of the system's operations manual.

Equipment & Hardware Requirements. Every RTCS has at least one *control loop* consisting of:

- A *sensor (e.g.,* water level gage) that monitors the ongoing process.
- A *regulator (e.g.,* pump, gate) that manipulates the process.
- A *controller* that activates the regulator in order to bring the process to its desired value *(set point).*
- A *data transmission* device that carries the measured data from the sensor to the controller and the signals of the controller back to the regulator.

From the large variety of available sensors, very few fulfill the requirements for real time control in an UDS. The requirement for continuous recording and remote data transmission (monitoring) is indispensible. The following sensors are widely applied:

- Rain gages (weight, tipping bucket, drop counting and radar principles)
- Water level gages (bubbler, air pressure, water pressure and sonic principles)
- Flow gages (level-to-flow conversion, ultrasound velocity measurement, electromagnetic induction)
- Limit switches (mercury float, diaphragm)

Rainfall intensity data can be used to provide short-term runoff forecasts. The forecasting horizon can be extended if rainfall forecasts are included (particularly using radar technology).

Level measurements are the backbone of every monitoring system. They are indispensable to determine the status of storage facilities or to convert level to flow rates at large sewers, overflow weirs, flumes, gates, *etc.* Water quality sensors play only a very minor role in the real time control of an UDS because the technology is lacking.

Sewer flow regulators include radial pumps (constant or variable speed) and screw pumps. Perpendicular, side-spill or leaping weirs are used to create storage in ponds or sewers. Self-operating weirs use a counter-weight or the buoyancy of an air tank to adjust crest height. An air-regulated siphon functions as a weir or a siphon depending on the air supply at its crest. Inflatable dams are broad-crested weirs that are used to activate storage in large trunk sewers. Gates — sluice, radial or sliding — are movable plates that constrict the flow in a sewer or in the outlet structure of a tank. Valves, such as plug, knife or butterfly valves, are devices within a pipe to throttle flows. A vortex valve rotates fluids, building an increasing resistance with increasing flow rate. It features neither external power supply nor moving parts. Other regulators include air-regulated inverted siphons, movable tide (backwater) gates and flow diversions that separate incoming flow into two outgoing paths.

Flow or water level regulators in UDSs are often very large and custom designed. However, some basic design principles are common to all successful devices:

- Regulators are designed to be fail-safe so that the malfunction of any vital parts results in an acceptable functional decline of the system. For example, sluice gates should have by-passes, and weirs should move into a safe position in case of a power failure.

- All components exposed to sewage and the sewer atmosphere are drastically simplified and corrosion resistant. Preferable construction material is stainless steel.
- Sensitive parts are located in an appropriate environment. For example, hydraulic and electric machinery are housed in a dehumidified vault, and programmable logic controllers and telemetry equipment are kept in a dehumidified and heated vault.
- All parts of a regulator station (including gates, sensors and motors) are accessible, maintainable and exchangeable.
- The regulators are set up so that their vital functions can be remotely supervised from the control center.

A data transmission system is necessary for a centralized RTCS. For very short distances, the transmission system can be analog (pneumatic, hydraulic or electric current). If the signals are converted to modulated voltage frequency, transmission distances can be increased. However, digital data transmission is increasingly applied, especially when transmission distances are great. Digital data is suitable for computer use without conversion, offers greater transmission reliability (against noise) than analog transmission and enables higher information transmission rates.

Transmission can be accomplished by wire or wireless. However, in many European countries, wireless transmission is restricted to mobile transceiver stations. Transmission by wire uses either privately owned, leased or dialed public telephone lines. Leased lines are mostly used to take advantage of the services offered by the telephone companies. Dialed lines are preferred if continuous data transmission over long distances is not required. In these cases, the lines are used only for security checks, episodic transfer of stored data or rainfall data transmission.

The required capacities of the data transmission channels depend on the number of data points, the scanning frequency and the amount of information per scan and data point. Current data transmission rates over public telephone lines range from 1200 to 9600 bits per second. Typically, a sluice gate regulator station has about 10 data points and a pumping station about 100 data points.

With the development of digital computers, a number of analog controllers can be replaced by a central digital computer. Computer-based control permits greater flexibility in controller calibration, control loop interconnection and set-point adjustment. With the advent of inexpensive microprocessors in the last few years, the vulnerability of such a central system could be overcome by implementing a main minicomputer and several local programmable logic controllers (PLCs) in the field. The PLC controls and coordinates all of the functions of an outstation, including acquiring measurement data; pre-processing (smoothing, filtering, *etc.*); checking for status, function and limits; storing data temporarily; local controls; and transfering data from and to the central station.

Differences between the PLCs and the central process computers are incremental. In a distributed RTCS, their tasks become more interchangeable. However, a number of major tasks usually remain for the central computer. These tasks include system-wide data acquisition, long-term storage, data management, operator interfacing, interactive simulation/optimization (decision support software) and automatic execution of control strategies.

Developing & Analyzing Control Strategies. The controllers adjust the regulators to achieve minimum deviations from the regulated flow, or level, of the set points. A control strategy is defined as the time sequence of all regulator set points in an RTCS. In almost all RTCSs that have multiple control loops, an optimum strategy is based on time-varying set points.

A control strategy must be physically executable. The flows and levels cannot be greater than the physically possible rates (static constraints). Also, the control strategy has to obey the physical laws of water motion in a drainage system; it must obey the dynamic constraints of continuity and energy balances. The dynamic constraint of a storage device is its mass balance; for a conduit, the flow transport function.

Real time control responds to the loading — storm inflows, pollutant loads, *etc.* — of the system. Therefore, a loading forecast is essential to making a decision on how to control flows. The more up-to-date these forecasts are, the better the control strategy can be. Options to determine the input of a drainage system are:

- Flow and level measurements in upstream sewers;
- Rain measurements and the application of rainfall/runoff models; and,
- Rain forecasts.

If none of this information is available, a local, or reactive, control strategy must be applied.

Since measurements include errors, it is important to check control strategies with respect to possible measurement errors or sensor failures. Practically speaking, control strategies have to be "cautious" to avoid "surprises." These surprises could be unexpected storm development or inflows from non-monitored tributary sewers, among other things. Control strategies are usually based only on measurements. However, it might be useful to develop the strategy using off-line simulation of the drainage process or even to include an on-line simulation model to "interpolate" process data that cannot be directly measured.

The description of the flow and pollutant routing process in the controllable part of the system has to be simplified in order to apply standard techniques for the numerical analysis. This simplification involves spatial and temporal aggregation, and linearization. The effects of these simplifications on the control performance in the RTCS have to be investigated (sensitivity analysis).

The most rigorous approach to finding a control strategy is by mathematical optimization, where control performance is evaluated on an absolute ("the best") rather than a relative ("a better") scale. Here, the problem becomes the minimization of an objective function that is subject to constraints. The objective function usually consists of a mixed integer/continuous, non-linear and non-monotone type. Since powerful analytical optimization techniques are not available for this kind of function, it must be further simplified.

One of the better known simplification techniques is linear programming wherein all decision variables (state and control variables) appear only in linear form. Once a control problem is formulated as a linear programming problem, it can be easily solved with commercially available software packages. Other optimization techniques are discussed in detail in the literature.

Heuristic methods for reaching a control strategy can be directly derived from the experience of the operating personnel. Usually, an initial control strategy (for example, the default fixed set-point strategy) is selected. By using that strategy for multiple simulation runs, it is improved by trial and error. If further improvement is impossible, it is assumed that an optimum strategy has been found.

Optimization, or search results, can be translated into decision matrices. Each element of the matrix represents the control decision that must be executed for a given combination of state and loading variables. Decision matrices permit very fast on-line execution of control strategies. A simplification of decision matrices are decision trees, which are composed of a set of "if-then-else" statements.

Controller Behavior Analysis. The control loop is the basic element of any RTCS. In a 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 in order to avoid the deviations. A feedback/feedforward controller is a combination of the two.

A standard controller used for continuously variable regulator settings is the proportional-integral-derivative (PID) controller. Simplified variants of the PID controller are also used — proportional (P), proportional-integral (PI) and proportional-derivative (PD) controllers. The controller's signal to the regulator is a function of the difference between the measured variable and the set point. The proportional gain, the reset time and the rate time are the controller parameters contained within that function. The controller has to be calibrated unless it is equipped with an autotuning facility. Calibration can be accomplished via the analysis of the underlying differential equations, or through real or simulated experiments. Since the controlled process is usually non-linear (*e.g.*, storage as a non-linear function of water level), the controller parameters are only valid in the vicinity of specified reference points such as water levels. For other reference points, other sets of parameters have to be found.

Two-point 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 reservoir. The pump switches on at a low level and off at a high level. The difference between the two switching levels is called the dead band.

Three-point controllers are typically used for such regulators as sluice gates, weirs, *etc.* In the middle position of the controller, the output signal is indifferent and in the other positions either maximum or minimum.

Once installed, controller behavior has to be tested. The interaction of neighboring controllers requires involved analyses based on a detailed hydrodynamic model that simulates controller functions. Full-scale experiments over the whole range of control variables have to be carried out to ensure that operational malfunctions such as overshoot or instability cannot occur. During start-up operation, the initially selected control parameters can be fine-tuned to approach optimum controller behavior.

Man-Machine Interfaces & Operational Tools. Any RTCS that is not operated under fully automatic mode needs a well defined operator/user interface. Historically, this interface was composed of analog displays, strip chart recorders and control switches using relay techniques. Today, active wall panels and color computer screens are used to display the standard application features. UDS-specific simulators are currently under development that provide an animated display of the state of the UDS, its loading and its dynamic evolution.

Such real time control simulators can be used to evaluate control strategies before they are actually executed. The simulator can be run in two ways: on- or off-line. The on-line version feeds the process measurements to the simulator in order to update the state variables. Once off-line, the simulator can be used to train personnel on system operation and to analyze past events. The development of these systems requires an extensive joint effort of the developing software engineer and the operating personnel in order to guarantee that only the necessary information is integrated into the systems and displayed.

Real Time Control System Operation

On the operations level, an interesting discrepancy between the planning/design stages of a project *versus* its operation/maintenance becomes apparent. Whereas design is executed by highly trained professional engineers and technicians, actual system operation is usually carried out by personnel with little or no technical training and who hardly possess the knowledge of "what it's all about." The lack of appropriately trained operating personnel is often used as an argument that real time control cannot be successfully implemented. Indeed, the performance of existing RTCSs is limited sometimes by the fact that the operators do not understand the purpose, or design, of the system. Successful RTCS operation requires intensive communication between all divisions and levels of a drainage agency. This management task is extremely difficult to accomplish, especially in large organizations.

In larger agencies, it seems practically impossible to imbed real time control planning and operation principles in either the traditional planning or operations divisions. Often, it is advisable to create a new operational control division. This division should originate from a performance monitoring group that already operates a measurement network, and should report directly to management. Thus, any resistance to new technologies or instigations of traditional division rivalries can be avoided and educated personnel can be hired as needed.

In small agencies, creating a new division is not an affordable alternative. In this case, the appropriate technologies should be chosen by the agency that enables the existing operating personnel, usually the treatment plant operators, to run the UDS under real time control.

Operations Manual. In any RTCS under supervisory control, the operating personnel have to be advised on how to proceed in every possible operational situation from the most routine to the most extreme emergency. Naturally, this training should be performed before critical situations arise. For example, the operator has to know and understand the operational objectives and their priorities — first overflow at x, then at y. Extreme situations such as which district to flood first have to be decided in advance. Operational advice and priorities should reflect a consensus of all involved parties — the public, the supervising agency's management and staff — and must be documented clearly. Without an operations manual, operators might be afraid to work with the RTCS for fear of being blamed in cases of mis-operation. An operations manual that clearly spells out what action to take in what specific conditions will mitigate this fear. However, since it is next to impossible to foresee all possible operational states of the system, the operators need to have some freedom to make *reasonable* control decisions for which they obviously have to be backed by management.

Performance Incentives. An RTCS utilizes a complete understanding of the UDS processes in order to monitor these processes for the manipulation of the input data in order to attain maximum performance of the existing UDS. The information gathered via real time control is valuable for the whole operating agency, including the traditional planning and O&M divisions. It is important that the new operational division not be regarded as "big brother," but as a producer of documented successes. These successes should be defined as the closest possible match between the envisioned and the actual problem solution. Successes and failures should be acknowledged by management or the supervising agency.

Administrative & Institutional Considerations

Non-technical aspects tend to dominate RTCS success or failure, regardless of the UDS or RTCS design. The successful operation of an RTCS often depends on cost, inter-agency collaboration, public regulations and liability factors.

Costs & Benefits. Relatively few UDSs are equipped with an RTCS. A major reason is the fact that UDSs are usually financed with grants from non-agency sources. These grants fund up to 95 percent of the UDS cost and come from such sources as state or federal authorities. These sources are not controlled by the operating agency, which is usually city, county or regionally based. A key problem to implementing an RTCS is that it is common for these "external" funding sources to provide no support for actually running the UDS. Consequently, UDSs are often planned, designed and implemented to incur minimum operational costs almost regardless of the investment cost (an extreme example is separation of combined sewer systems into separate systems). However, real time control is a low investment technology that requires a high degree of operational effort and cost. Therefore, it is penalized by the conventional funding mechanism.

Inter-Agency Collaboration. Typically, the cities in an urban area form a sanitary district. This configuration is suited for the management of a combined sewer system under dry weather conditions. Large trunk sewers are operated by the public works departments of the member cities, but the small interceptors and treatment plants are run by the sanitary district. However, difficulties arise if the system is loaded with stormwater so that flooding and combined sewer overflows might be possible. Even if the sanitary district is willing to accept additional combined sewer flows in times of storms, the usable storage in the interceptors might be very small. The member cities, on the other hand, are not eager to activate trunk sewer storage, since this might increase their flooding hazard. Obviously, these conditions do not favor implementing an RTCS, since such a system relies on the coordinated operation of the wastewater system as a whole.

Standards & Regulations. Most current technical standards and regulations for UDSs are imbedded in engineering traditions that do not promote "moving parts" and delicate equipment such as electronic sensors. Static loading and optimal functioning are usually assumed in the planning process. It is only recently, in some countries, that the actual performance of an UDS can be proven. Therefore, it will take another few years until data from continuous supervision and control of currently implemented RTCS sites can be included in standards.

Liability. Real time control provides the opportunity for intervention and influence on the performance of an UDS during its ongoing operation. Formerly, a flooded underpass was regarded as an "Act of God," provided that the UDS was planned correctly. Now, such an incident might be created by human intent or error. Even if it were not the result of a human decision, "victims" might at least assume so, with liability charges the logical consequence. A reasonable way out of this major institutional hurdle is to follow the detailed planning procedure outlined above, document its results and "translate" its consequences to all involved parties. The operations manual is an important part of that documentation. If the rationale behind this procedure and its results are well documented, the judicial "room to move" may presumably become very restricted.

Applications

The first RTCSs were implemented in the United States as demonstration projects at the end of the 1960s. The RTCS for the Northeast Ohio Regional Sewer District, serving Cleveland and 33 suburban communities, was one of the first in the country. Before remedial measures, almost every rain created CSOs at some 600 points into the Cuyahoga River and Lake Erie. The RTCS was initiated in 1975 with three regulators, and a greatly expanded system became operational in 1983. The system now controls 50 percent of the original CSO volume. Centrally adjustable controls are actuated by on-site microprocessors. The central control computer was intended for later simulation and optimization of controls. Seattle has operated an RTCS for more than 20 years to reduce CSOs. The system can be run in local automatic, central supervisory or central automatic modes. The latter mode was based on a system-specific if-then-else strategy. The system was recently upgraded and old computer hardware was replaced by state-of-the-art technology. Because of the system's success, plans for separating the CSO system have been abandoned. An additional benefit has been source detection of gasoline spills. Lima, Ohio, uses an RTCS for its combined sewer system that covers 15 square kilometers. Eight sluice gate regulators are run from the central control facility. Treatment plant inflows are also regulated in dry weather by control gates. The system is flushed after storms by automatically opening interceptor gates beginning downstream. After normal working hours, the system is run automatically without supervision.

In Europe, development started approximately ten years later. Today, in practically all Western European countries, there are RTCSs either in operation or under serious study. The Netherlands and Germany should be highlighted because of the numbers of existing systems in those countries. In France, some of the systems have applied advanced RTCS technology. Detailed RTCS descriptions can be found in the sources listed in the bibliography.

ACKNOWLEDGMENTS — *This article was presented on April 22, 1991, as part of the 1991 Freeman Lecture sponsored by BSCES and the Ralph M. Parsons Laboratory at the Massachusetts Institute of Technology. Much of the material presented in this article resulted from the various activities of the International Association for Water Quality (IAWQ) Task Group on Real Time Control of UDS. For further information on the group's activities, contact the author at: Swiss Federal Institute for Water Resources & Water Pollution Control, 8600 Dübendorf, Switzerland.*

WOLFGANG SCHILLING *received his civil engineering degree from the University of Hannover in Germany. In 1979–80 he was a graduate student and research assistant at the Massachusetts Institute of Technology with Prof. R.L. Bras. In 1983 he received his Ph.D. from the University of Hannover. In 1984–85 he was a guest scientist at Colorado State University and the University of Ottawa. He has been a Senior Research Associate, responsible for the urban hydrology group, at the Swiss Institute for Water Resources and Water Pollution Control since 1988.*

BIBLIOGRAPHY

Abraham, C., & Börker, H.W., "Automatic Flow Control in Combined Sewer Systems — Effectiveness and Implementation Problems," *Water Science Technology*, Vol. 13, No. 9, pp. 269–275, 1981.

ATV, "Standards for the Dimensioning and Design of Stormwater Overflows in Combined Wastewater Sewers," in German, Worksheet A 128, Abwassertechnische Vereinigung e.V., St. Augustin, April, 1991.

Bachoc, A., Delattre, J.M., Jaquet, G., & Frerot, A., "Hierarchical Monitoring of Sewer Systems — A Case Study: The Seine St. Denis County," Proc. 3rd Int. Conf. Urban Storm Drainage, Göteborg, Sweden, June 4–8, 1984.

Brueck, T.M., Knudsen, D.I., & Peterson, D.F., "Automatic Computer-Based Control of a Combined Sewer System," *Water Science Technology*, Vol. 13, No. 8, pp. 103–109, 1981.

Buczek, T.S., & Chantrill, C.S., "A Computer-Based System for Reduction of Combined Sewer Overflow in a Metropolitan Wastewater Collection System," 57th Ann. WPCF Conf., New Orleans, Act. 1–4, 1984.

Döring, R., Hartong, H., Jacquet, G., Petersen, S.O., & Schilling, W., "Real Time Control of Urban Drainage Systems," handout material for the Intensive Short Course, not published, 1989/1990/1991.

Drake, R.A.R., ed., *Instrumentation and Control of Water and Wastewater Transport and Treatment Systems*, Pergamon Press, Oxford, England, 1985.

Einfalt, T., Grottker, M., & Schilling, W., "Applications of Operations Research to Real Time Control of Water Resources Systems," Proc. First Europ. Jun. Scient. Worksh., Swiss Fed. Inst. Wat. Res. Wat Poll. Contr., Report no. 3, Dübendorf, Switzerland, 1990.

Gibbs, C.V., Alexander, S.M., & Leiser, C.P., "System for Regulation of Combined Sewerage Flows," *Journal of Sanitary Engineering Div.*, ASCE, Vol. 98, No. SA6, pp. 951–972, December 1972.

Giessner, W.R., Cockburn, R.T., Moss, F.H., & Noonan, M.E., "Planning and Control of Combined Sewerage Systems," *Journal of Environmental Engineering Div.*, ASCE, Vol. 100, No. EE4, pp. 1013–1032, August 1974.

Grigg, N.S., Labadie, J.W., Trimble, G.R., & Wismer, D.A., "Computerized City-Wide Control of Urban Stormwater," Technical Mem. No. 29, ASCE Urban Water Resources Research Program, New York, February, 1976.

Hogarth, L.N., "The Conception, Design, and Construction of Metropolitan Toronto Mid Toronto Interceptor Sewer," *Canadian Journal of Civil Engineering*, Vol. 1, No. 1, pp. 47–56, 1977.

IAWPRC, "Real Time Control of Urban Drainage Systems: The State-of-the-Art," Scientific and Technical Report No. 2, Pergamon Press, London, 1989.

Kudukis, R., & Pew, K.A., "Automated Regulators for Combined Sewer Overflow Control," *Prog.Wat.Techn.*, Vol. 9, Nos. 5/6, pp. 349–354, 1977.

Labadie, J.W., Grigg, N.S., & Bradford, B.H., "Automatic Control of Large-Scale Combined Sewer Systems," *Journal of Environmental Engineering Div.*, ASCE, EE1, Vol. 101, pp. 27–39, February 1975.

Leiser, C.P., "Computer Management of a Combined Sewer System," Seattle Metropolitan Municipality, Seattle, US EPA, Report No. 670/2–74–022, NTIS PB 235717, July 1974.

McPherson, M.B., "Feasibility of the Metropolitan Water Intelligence System Concept," ASCE, Urb. Wat. Res. Res. Progr., Techn. Mem. No. 15, December 1971.

McPherson, M.B., "Integrated Control of Combined Sewer Regulators Using Weather Radar," US EPA, Report No. 600/2–81–041, NTIS PB175805, March 1981.

Papageorgiou, M., "Automatic Control Strategies for Combined Sewer Systems," *Journal of Environmental Engineering Div.*, ASCE, Vol. 109, pp. 1385–1402, 1983.

Paquin, G., "Wastewater Interception in the Communaute Urbaine de Montréal Territory," Proc. SWMM Users Group Meeting, US EPA, Report No. 600/0–79–026, pp. 135–153, May 24–25, 1979.

Pew, K.A., Callery, R.L., Brandstetter, A., & Anderson, J.J., "Data Acquisition and Combined Sewer Controls in Cleveland," *Journal of the Water Pollution Control Federation*, Vol. 45, No. 11, pp. 2276–2289, November 1973.

Schilling, W., "A Survey on Real Time Control of Combined Sewer Systems in the United States and Canada," in R.A.R. Drake, ed., *Instrumentation and Control of Water and Wastewater Treatment and Transport Systems*, Pergamon Press, Oxford and New York, pp. 595–600, 1985.

Schilling, W., & Petersen, S.O., "Real Time Control of Urban Drainage System: Validity and Sensitivity of Optimization Techniques," First IAWPRC Int. Symp. on Systems Analysis in Water Quality Management, London, 30.6.–2.7, 1986.

Shelley, P.E., & Kirkpatrick, G.A., "Sewer Flow Measurement — A State-of-the-Art Assessment," US EPA, Report No. 600/2–75–027, November 1975.

Van, H.N.N., Osseyrane, M., & McPherson, M.B., "Integrated Control of Combined Sewer Regulators," *Journal of Environmental Engineering Div.*, ASCE, Vol. 109, No. EE 6, pp. 1342–1360, 1982.

Watt, T.R., Skrentner, R.G., & Davanzo, A.C., "Sewerage System Monitoring and Remote Control," US EPA, Report No. 670/2–75–020, May 1975.

WPCF, "Process Instrumentation and Control Systems," *Manual of Practice OM-5: Operations and Maintenance*, Water Pollution Control Federation, 1984.