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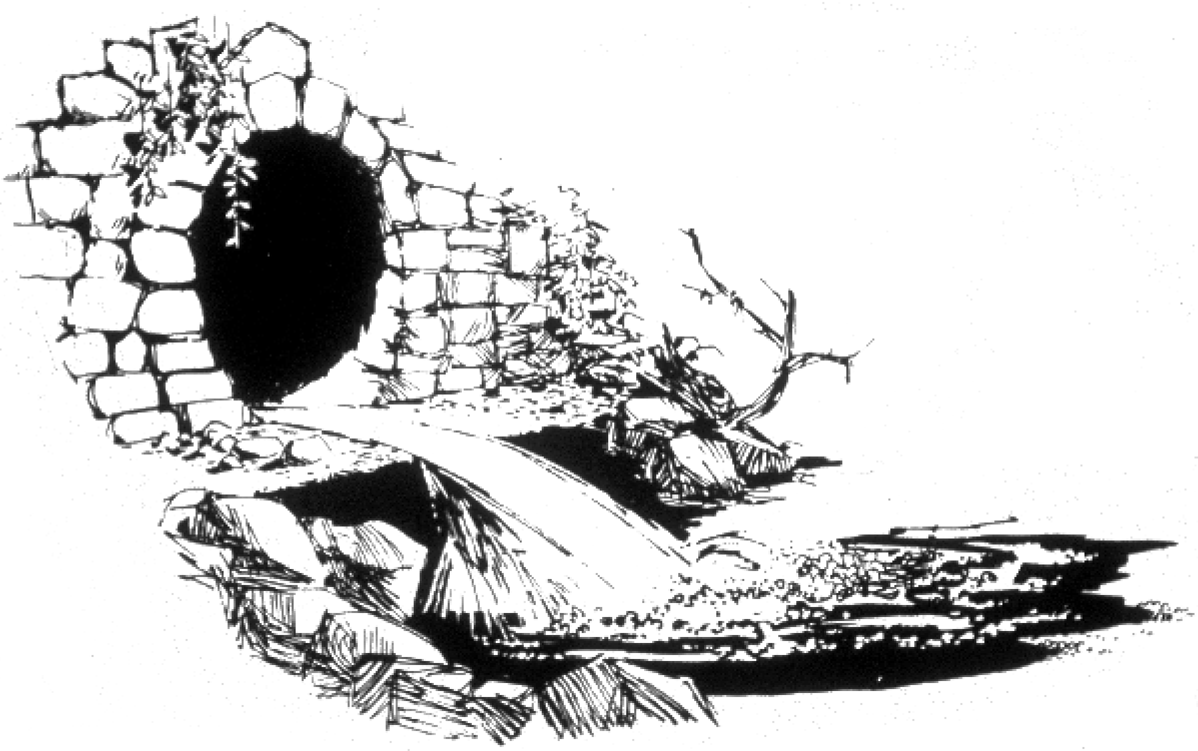
Real Time Control of Urban Drainage Networks



Notice

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Foreword

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Abstract

Real-time control (RTC) is a custom-designed, computer-assisted management technology for a specific sewerage network to meet the operational objectives of its collection/conveyance system. RTC can operate in several modes, including a mode that is activated during a wet weather flow event to control local flooding and sewage releases. RTC of conveyance systems has been emerging as an attractive and cost-effective approach that can be undertaken in addition to (or in lieu of) more traditional construction-focused alternatives such as sewer separation or construction of storage facilities. Although there are still relatively few documented applications of RTC to large urban sewerage systems, the technology has been successfully implemented.

RTC implementation includes several different aspects, including hydraulics, instrumentation, remote monitoring, process control, software development, mathematical modeling, organizational issues, and forecasting of rainfall or flows. Addressing each of these issues in detail would require a large document, beyond the scope of this report. Accordingly, the report provides a summary and a broad introduction to these different issues and does not elaborate on them in great detail.

The main goal of the report is to provide a guide on RTC technology to facilitate its understanding and acceptance by the user community. The primary audience is the practicing engineer, in a municipality or in a consulting firm, who has had limited exposure to RTC. Also, the report should serve as a resource document for use by federal and state program officials and regulators, researchers, and the interested public.

There is no simple or single "recipe" for successful RTC implementation. The report provides some guidance for the methodology to be used in the design, development, and implementation of RTC systems, but it does not identify or recommend a single solution that will fit any municipality or any set of operational issues.

Contents

Figures

Tables

Glossary of Terms and Acronyms

ANSI	American National Standards Institute
CIS	Customer Information System
CMMS	Computerized Maintenance Management System
CSO	Combined Sewer Overflow
CS (gates)	Combined Sewer Overflow Gates (Milwaukee)
DSS	Decision Support System
ETV	Environmental Technology Verification (program)
FCC	Federal Communications Commission
FDT	Factory Demonstration Test
FRP	Fiberglass Reinforced Plastics
GCM	Global Circulation Models
GIS	Geographic Information System
HGL	Hydraulic Grade Line
HPC	Hydro-meteorological Prediction Center of NWS
IEC	International Electro-technical Commission
I/O	Input/Output
ISA	Instrument Society of America
ISS	Inline Storage System (deep tunnel in Milwaukee)
IT	Information Technology
ITA	Instrument Testing Association
JIWWTP	Jones Island Wastewater Treatment Plant (Milwaukee)
LIMS	Laboratory Information Management System
MMSD	Milwaukee Metropolitan Sewerage District
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NWS	National Weather Service
PID	Proportional Integrated Derivative
PLC	Programmable Logic Controller

PM	Project Management
Q/H	Flow versus Head relationship (curve)
RTC	Real Time Control
RTU	Remote Terminal Unit
SAD	System Availability Demonstration
SCADA	Supervisory Control and Data Acquisition
SDLC	Software Development Life Cycle
SI	System Integrator
SS (gates)	Gates at South Shore Treatment Plant (Milwaukee)
SSO	Sanitary Sewer Overflow
SSWWTP	South Shore Wastewater Treatment Plant (Milwaukee)
TS	Threat Score
US EPA	United States Environmental Protection Agency

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Chapter 1. Introduction

Real time control (RTC) includes practices and tools for actively managing the operation of wastewater networks and facilities. The goal of RTC is to improve the overall performance of urban sewer systems and integrate their operation with wastewater treatment facilities. In many cases, the specific driving force behind the implementation of RTC is the need to reduce wet weather overflows. RTC consists of operational strategies and/or algorithms that control the sewer collection system using online measurements that are collected in “real time,” thus adjusting the operation of the sewer system based on its current state and dynamic conditions. A more rigorous and detailed definition of RTC is provided later in this document.

Wastewater collection and conveyance systems represent a crucial part of the urban infrastructure. The cost and complexity of these systems is great, especially in highly urbanized areas. Managers, engineers, and operators of these systems are faced with difficult problems related to the operation and maintenance of their facilities. In addition to the issues related to the operation and upkeep of the system, many sewerage agencies are facing increasing public concern about the environmental impact of combined sewer overflows (CSOs) and local flooding. In many instances, these operational challenges need to be faced in an atmosphere of limited resources and fiscal pressures to "achieve more with less." Often, fiscal pressures are accompanied by concurrent increases in performance requirements from the regulatory agencies.

The design practices for sewer networks have historically been conservative and include significant safety factors that result in larger pipes in the collection system than typically needed. As sewerage network design does not normally include consideration of RTC, there are often opportunities to optimize the utilization of the existing system through operational strategies.

The problem of sewage releases to receiving streams or backups into basements, as well as local flooding, has traditionally been addressed by large-scale capital improvement programs that focus on construction alternatives such as sewer separation or construction of new conveyance pipes or storage facilities. The cost of such projects is often high, especially in older communities where the population density and the value of land is high. In the last few years, RTC of conveyance systems has been emerging as an attractive alternative. Although there are still only a few documented implementations of RTC this technology has been successfully implemented in several large urban sewerage systems.

Implementation of RTC includes several different aspects, including hydraulics, instrumentation, remote monitoring, process control, software development, mathematical modeling, organizational issues, and forecasting of rainfall or flows. Addressing each of these issues in detail would require a large document, beyond the scope of this report. This report is a broad introduction to these different issues; its objective is to bring these different aspects into view rather than elaborate on each of them in great detail. The primary goal is to introduce RTC to practitioners who have had limited exposure to RTC in the past and to make this technology more accessible and understandable.

The secondary goal of this report is to provide the reader with an entry point to learning more about RTC. The report includes examples of RTC projects and implementations and provides references to literature that contains more detailed information. It does not focus on the latest research on RTC but rather on information from different areas and aspects of RTC. The intention is to provide an overall introduction of this technology that is useful to practicing engineers in a consulting firm or in a municipality.

Although some of the RTC applications described in this report are advanced and complex, the reader should not interpret this to mean that all RTC must be advanced in order to provide value. In many cases, simple RTC strategies can yield benefits over the advanced and complex designs.

Most importantly, experience with RTC shows that there is no simple or single "recipe" for successful implementation. Accordingly, the report provides guidance on the design, development, and implementation of RTC systems and does not identify or recommend a single solution that will fit any municipality or any set of operational issues.

1.1 Definition of RTC

RTC can be broadly defined as: a system that dynamically adjusts the operation of facilities in response to online measurements in the field to maintain and meet the operational objectives, both during dry and wet weather conditions.

Flows and levels in sewer systems are typically manipulated by static facilities (e.g., weirs) that are not adjusted in real time. RTC adds a dynamic component, where some of the facilities are actively adjusted in real time based on system conditions.

The term "Real Time Control of Sewer Systems" has often been used to describe control systems that include system-wide ("global") control rules and may include such sophisticated components as linear optimization algorithms. Some of these complex systems have been reported in the literature and for many in the wastewater industry, the term "RTC" has somehow become synonymous with this type of complex system and application.

When municipalities consider RTC, they should consider a range of possible solutions, starting from simple and straightforward and potentially culminating in a "global predictive optimal" configuration. A complex system is by no means always the best choice.

1.2 How Would One Use RTC?

RTC may be used to achieve different operational objectives. These objectives will be not only site-specific (different urban communities will have different operational issues and priorities) but even within the same network they may change at different times (or under different conditions).

In order to better answer the above question, it may be useful to first define a simplified view of RTC functionality. An RTC system generally performs the following functions:

- Collects information about the current state of the sewer network
- Compares the current state of the sewer network with the desired state of the sewer network
- Determines the settings for the control facilities that will bring the sewer network (closer) to the desired state
- Implements the settings into actions of the final control elements (e.g., gates, pumps, inflatable dams)

During the process of designing an RTC system, it must be decided what the *desired state* (operational goals) of the sewer system will be. This, however, can be a bit tricky because of different operational goals that depend on the system state itself. For example, there may be different operational objectives during dry weather, in the middle of an intense storm, or during a security emergency.

RTC can be used for different purposes. Control strategies can address operational issues during both dry weather events and wet weather events. Examples of operational goals include:

- Reducing or eliminating sewer backups and street flooding

- Reducing or eliminating sanitary sewer overflows (SSOs)

- Reducing or eliminating CSOs

- Managing/reducing energy consumption

- Avoiding excessive sediment deposition in the sewers

- Managing flows during a planned (anticipated) system disturbance (e.g., major construction)

- Managing flows during an un-planned (not anticipated) system disturbance, such as major equipment failure or security related incidents

- Managing the rate of flow arriving at the wastewater treatment plant

To view RTC as only “a way to reduce CSOs” is therefore a bit restricted view because a well-designed RTC system may need to address a number of different operational goals at different times. This report includes information that mostly focuses on the goal of reducing CSOs but the methodologies and tools presented are equally applicable when some of these additional operational goals are to be considered.

1.3 When Would One Consider RTC?

In most cases, implementation of RTC can offer benefits and improve performance of an urban sewer system. The costs and the extent of the benefits that RTC can provide may differ from one sewer system to the next and therefore the answer (whether RTC is the appropriate solution) is not always straightforward. This section of the report provides some assistance to those municipal managers who are considering whether RTC will be beneficial for their specific issues.

It is important to point out that there are no technological barriers to implementing RTC. Fears from “new technology” are largely misplaced. RTC technology has been around for at least 20 years and many successful applications can be seen in many wastewater plants where RTC is more common. Although RTC implementations in collection systems remain relatively rare, there are several successful examples. The report by Schuetze et al., aims to facilitate a greater acceptance of RTC by the municipal engineers and managers and suggests a process for evaluating the applicability/suitability of RTC technology to a specific case.

Sometimes, issues with RTC implementation may be not technical but rather organizational or procedural. While the primary users of RTC are the operational staff, initial vision and enthusiasm for RTC systems may come from the management (“downtown” vs. “the field”). In some cases, application of RTC is suggested and encouraged by the upper management or by vendors and consultants who are engaged in the development and implementation of RTC. At the same time, the final success of an RTC system demands support from staff on the “operational front lines,” those who are directly involved in operations and who would be the primary users of the RTC system. It is important to understand that the success of an RTC project requires a good understanding of the organizational issues and that the RTC development strategies need to consider and ensure acceptance of the RTC system by the users.

Municipalities are often risk-averse. In such environments new or advanced technology (including RTC) may be perceived with some concern. However, since the benefits of RTC can be significant, this report aims to demonstrate that this technology can bring such benefits without a great risk.

Some of the remaining barriers to a broader implementation of RTC are:

- General perception that RTC must always be a complex system, and thus concern about these systems being "fragile" or unreliable. Hopefully, this report will show that such concerns can be addressed and that RTC scope can be adjusted to fit a site-specific set of operational needs.

- Most municipalities are concerned about legal exposure and issues related to regulation; if the sewer system does not include automation, and overflows occur, it is often seen as an "act of God" since nothing more could have been done. Therefore, the concern is that introducing automation and RTC may well open up "second guessing", increased scrutiny about operations, and increased reporting to regulatory agencies.

- RTC is often seen as a complicated "computer project" and there is general concern because IT projects have earned a reputation for being late and over budget.

This report cannot provide a single, simple recipe for overcoming all of the barriers but it "demystifies" RTC, describes the components, presents a methodology for development, and includes a number of examples. Hopefully, the information provided will facilitate the acceptance of this promising technology.

There are some cases where RTC can provide only very limited immediate benefits, at least in the short term. This could be the case, for example, if a collection system simply does not have any available in-line storage (i.e., if the pipes are close to full, even during dry weather, there is little that RTC can do by itself). However, even in those cases, it is prudent to consider RTC during planning of future facilities (e.g., if they provide additional storage capacity).

Chapter 2. Components of a RTC System

This section presents a typical layout for components that might be included within a RTC system. Some of these components are organized hierarchically; the components on the lower levels (e.g., instrumentation) are essential for RTC but some of the "higher level" components may be optional (RTC does not necessarily need to include them and could work without them).

The word "component" is used here to describe either equipment (e.g., sensor or a final control element such as gate or pump) or a software program (e.g., RTC algorithm, or a database). What these components have in common is that they are related to control actions and they may collect, process, or deliver data to other parts of the overall system. The components are most often graphically represented with boxes and the arrows that connect them indicate the communications and data that is passed on between the components (Figure 2-1).

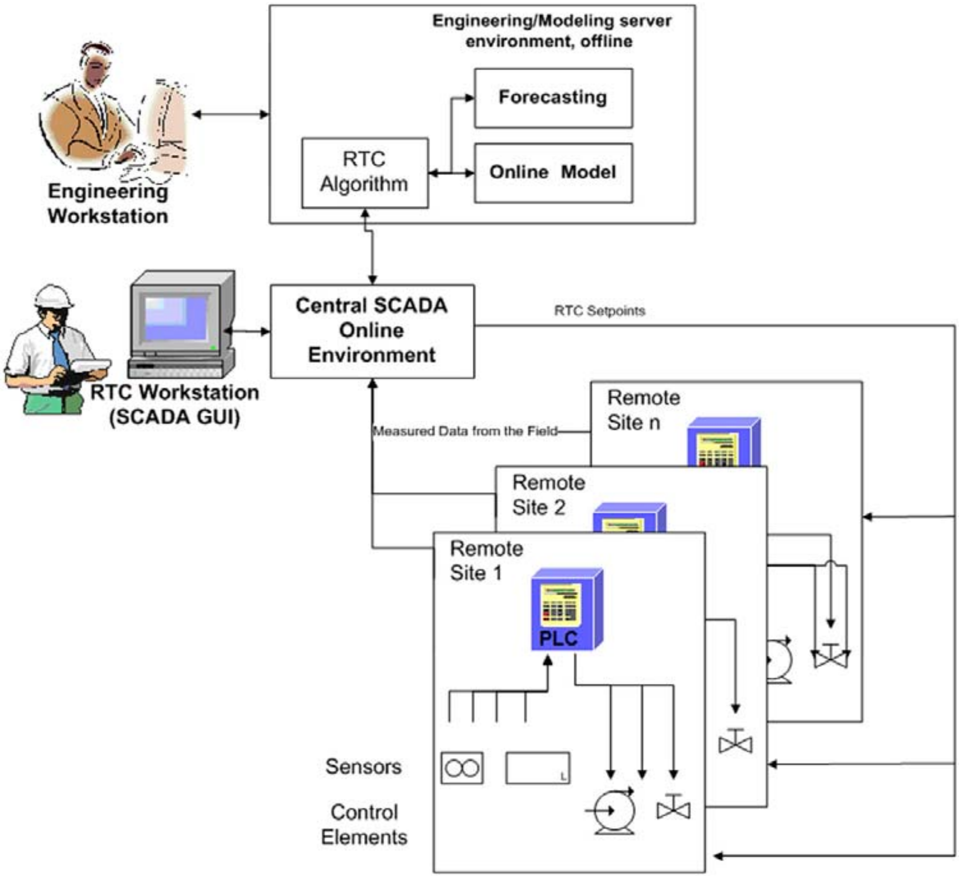


Figure 2-1. Components of a RTC System.

The organization of the components and the conceptual design of the RTC system is often referred to as "architecture." The structure of this document reflects, and partially follows, the architecture of the overall system. The architecture can be presented at different levels of detail; the overall components of the architecture are presented in Figure 2-1. An RTC system architecture may contain one or all of the components shown. This architecture illustrates a highly sophisticated RTC system; but not all the shown components are essential for a successful system.

Each remote site includes sensors (flow, level). Sensors are connected to the inputs of the local RTC device (in most cases a Programmable Logic Controller, PLC, or Remote Terminal Unit, RTU). The final control elements (e.g., gates, pumps) are connected to the output side of the PLC (or RTU). The PLC controls the final control elements based on the rules embedded (programmed) into the PLC. These rules are feedback algorithms, where action is based on the difference between a setpoint and the measured variable. For example, a PLC may be programmed to maintain a certain level in the wet well and will reduce the flow through the pump (on the effluent end of the wet well) if the level is too low or increase it if the level is too high.

Information captured in the field needs to be communicated from the remote stations to the computers and systems that will process, store, and archive it. Communication is an important link and reliability requirements often drive the need for redundancy in equipment. The Supervisory Control and Data Acquisition (SCADA) system includes standard graphics and user interface (GUI) tools that operators can access through the RTC workstation. In most cases, SCADA systems provide a number of displays ("screens"), organized so that operators can monitor the overall network and also zoom in on specific facilities. RTC software will, in most cases, be located on its own hardware (Systems Engineer Workstation), where system engineers will be managing the software related to RTC (e.g., RTC control algorithms, online models, forecasting algorithms, etc.). Algorithms are computational modules that solve one or more equations. Direct control of the control elements is almost always located on the PLC. The setpoint for the controller may either be fixed and programmed locally or it may be changeable and be downloaded in real time from the RTC algorithm. What these components have in common is that they collect and process signals and/or data and exchange signals/data with other parts of the overall system.

The facilities in a sewer system are spread throughout the service area and the "bottom layer" of automation resides in different geographical locations ("remote sites"). In each remote site, a local processing unit (PLC) collects the signals (measurements) from the sensors and also provides outputs (control setpoints and signals) to the control elements (pumps, gates, etc.) PLCs are usually programmed to execute control of the facilities within their area. These PLC programs include setpoints that are defined locally (within each PLC) and are also capable of receiving a "remote" setpoint from the central server.

The information from the remote sites is collected through telemetry and delivered to a central location via SCADA system. Usually, the information that is collected from the field is displayed in "real-time" to the operator at the RTC workstation as well as stored in the central servers that may be located at the main control facility. The central SCADA system also provides "remote" setpoints to each remote site. The information stored in the main SCADA servers includes the current (real time) and past (archived) measurements from all the remote sites. This information is normally used in the following ways:

- Operating staff make real time decisions based on the information that they receive online

- Engineers use the measured data to analyze system performance, develop computer models of the sewer system, and design new RTC algorithms

- The RTC algorithms are normally connected to the SCADA database; they retrieve the information about the status of the system, and provide the setpoints back to the SCADA system in real time

In the sections that follow, each of these components will be discussed in detail.

Chapter 3. Process Equipment

Sewer systems are conveyance networks; their role is to collect and transport the sewage to treatment facilities. In some cases, sewer networks need to have some flexibility so that flow rates can be adjusted to meet various operational objectives. The overall objective is to convey wastewater away from the people and the environment to protect public health and safety, property, and the environment. Process equipment provides the necessary flexibility to achieve this objective. A brief summary of process equipment is presented in this report since the main intended audience for this document (operators of sewer collection systems and practicing engineers) will already have a great deal of familiarity with such equipment and especially with the equipment that is part of their network.

Process equipment in a sewer system consists of gates, weirs, and pumps that serve as components in the broad category of diversion structures. These structures may contain movable elements and electrically operated equipment or sophisticated control systems associated with them. This chapter will discuss the elements associated with flow diversion structures (sluice gates, moveable weirs, and pumps).

The broadest category of sewer system process equipment involves the diversion structure. While most sewer systems are dendtritic in nature (tree-like structure with branches combining into trunks and leading to a single point at a treatment facility), the safe operation of the sewer network in many cases requires a diversion where flows can be diverted in different (typically two) directions. These are commonly found in combined sewer systems where high flows may be experienced during storm events. However, even in sanitary systems, there may be relief sewers or other alternative paths designed into the system that must be managed, either passively or actively through the use of moveable elements.

A passive diversion structure typically includes a fixed weir, a stop-log weir, or a manually adjusted slide gate. A leaping weir can also be used (Figure 3-1) or a "slot regulator" in conjunction with a dam can be used (Figure 3-2). These passive structures may contain orifice plates or other manually adjustable elements but for the purposes of RTC these would be treated as fixed elements. Typically, the adjustments are made only during installation/testing or for seasonal changes.

A configuration of a manually operated sluice gate is shown in Figure 3-3.

Passive control structures are configured to split the flows in different ways, depending on the system conditions (e.g., high flows vs. low flows). While passive diversions are not usually considered part of RTC (because they cannot be adjusted in real time), simulations and analyses of operational strategies often provide insight into how these passive structures could be adjusted for optimal effect. In an active diversion, flows can be affected by a control element that changes position in real time. Two examples of active elements are sluice gates and inflatable dams.

Sluice gates are most often implemented within regulator structures which are diversion structures that use moveable gates to regulate (actively change) the flow split. A typical configuration for a regulator structure is shown in Figure 3-4.

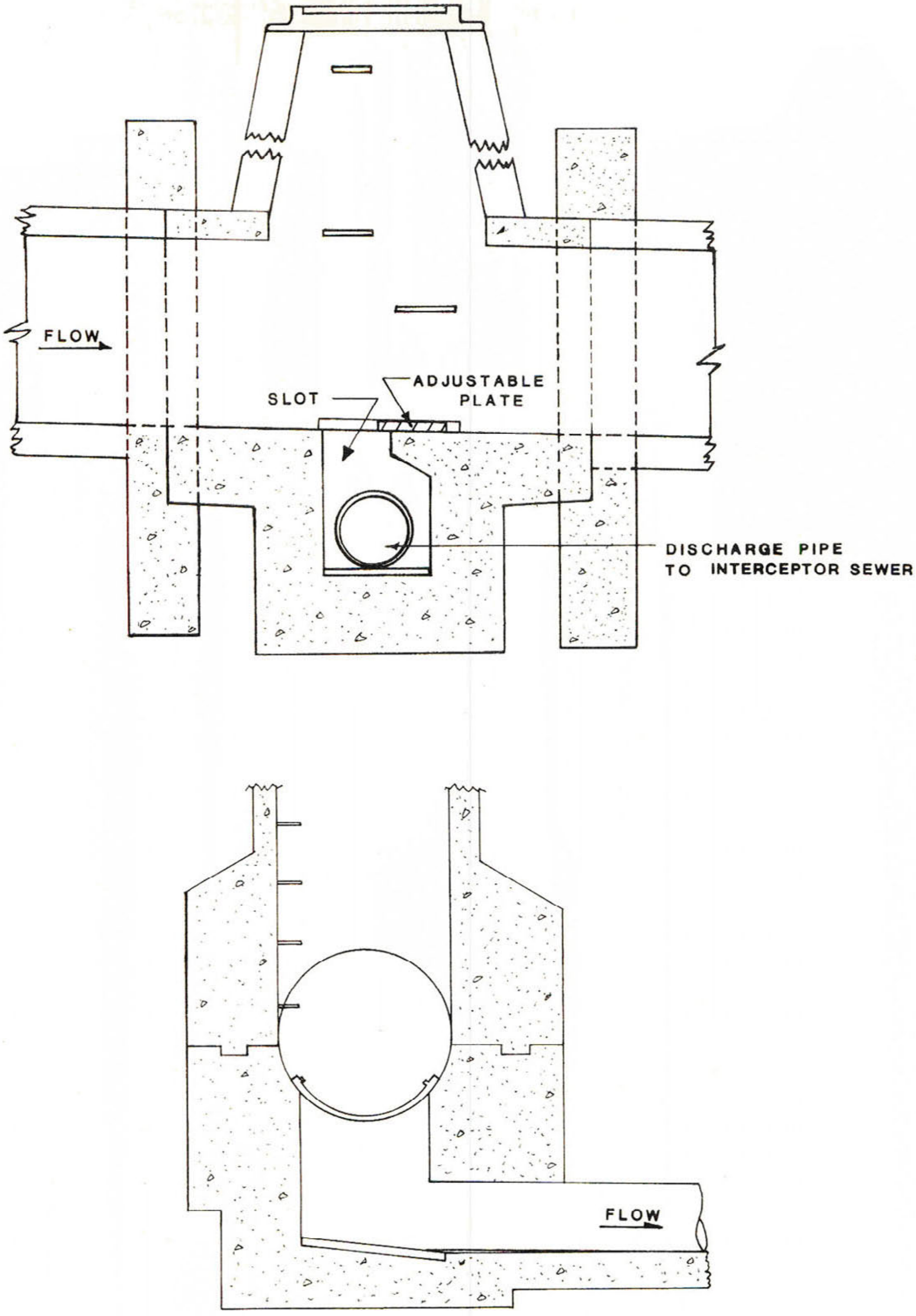


Figure 3-1. Cross sectional view of a slot regulator.

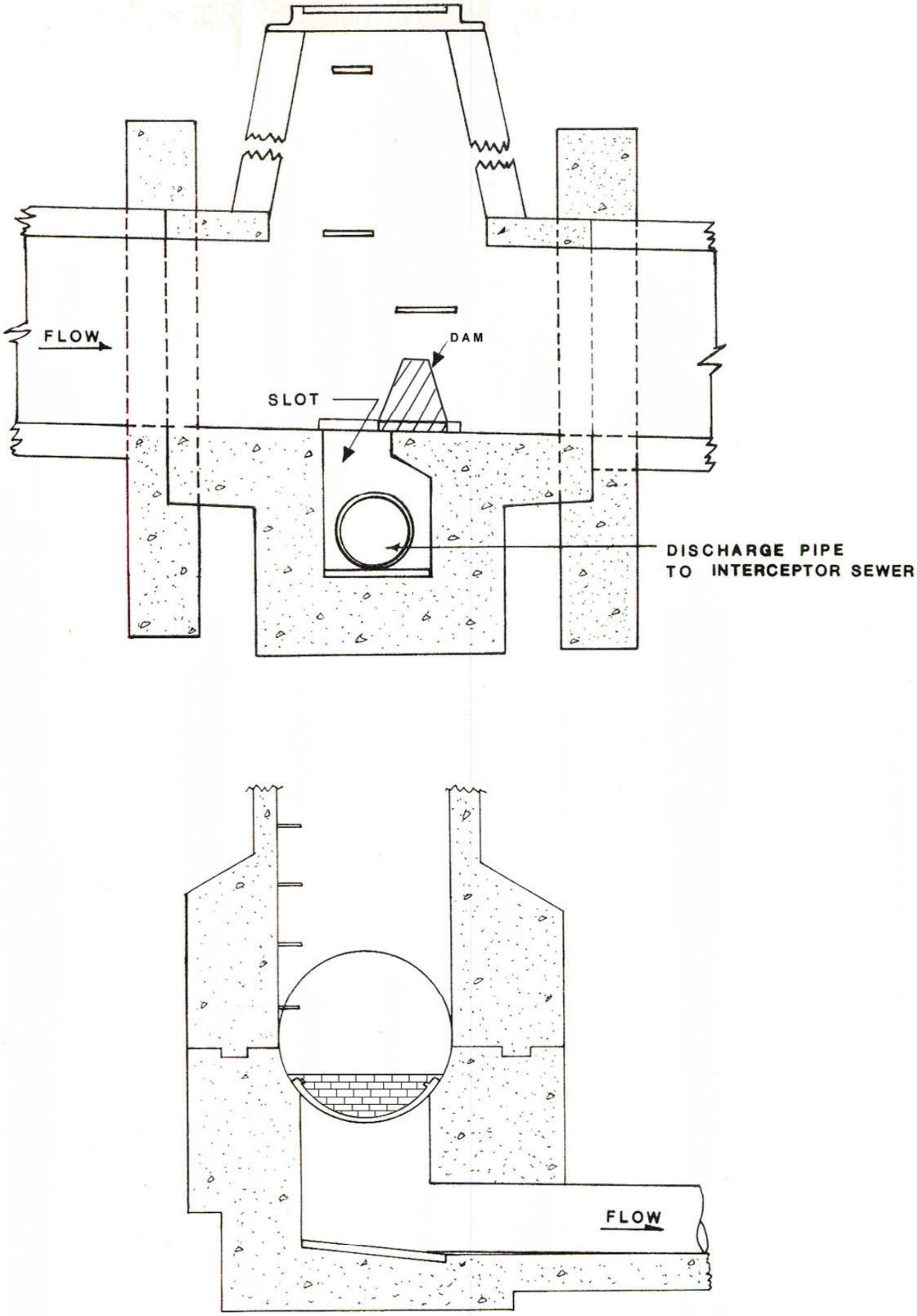


Figure 3-2. Cross sectional view of a slot regulator in conjunction with a dam.

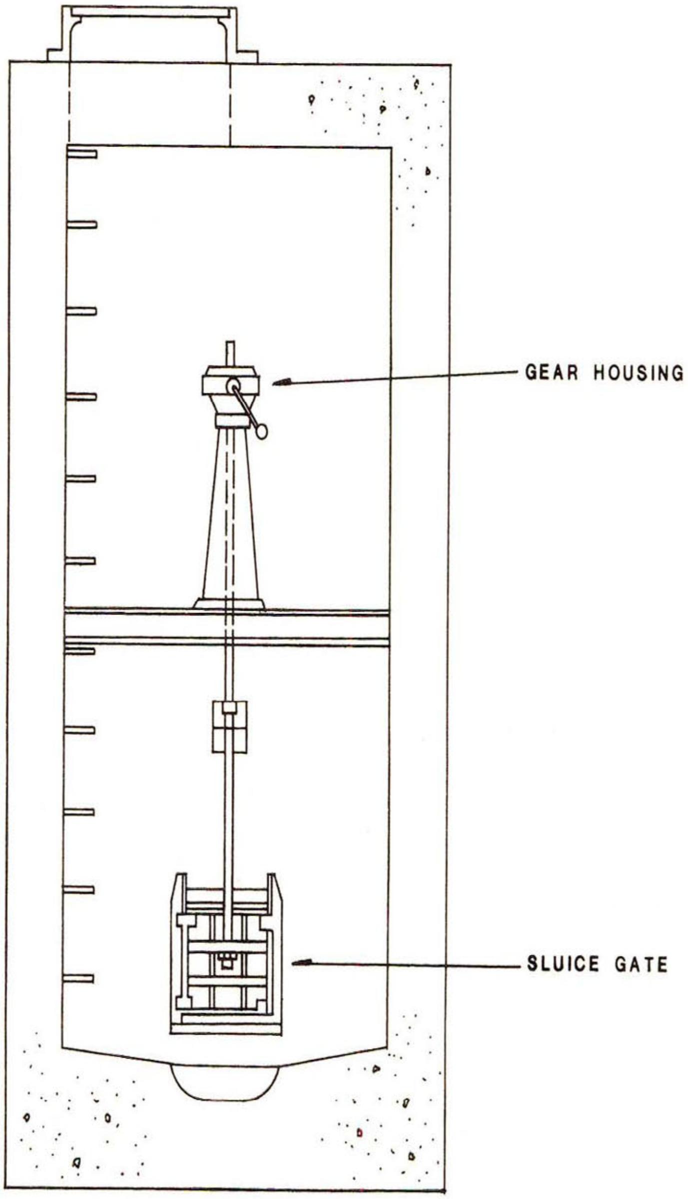


Figure 3-3. Cross sectional view of a manually operated sluice gate.

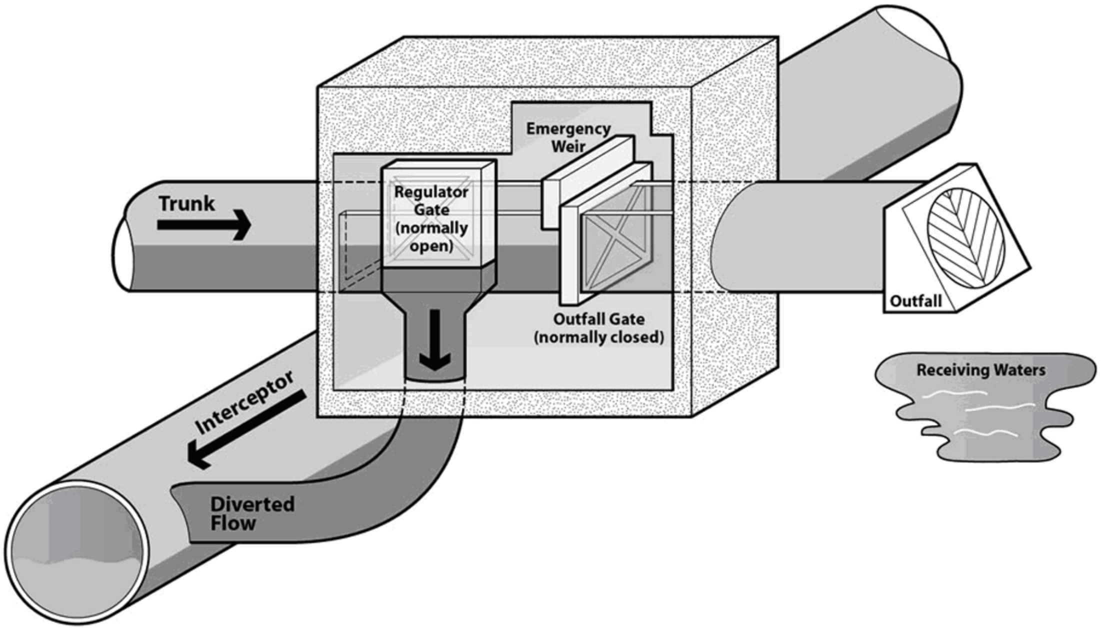


Figure 3-4. Typical regulator structure (courtesy of King County).

As shown in Figure 3-4, a typical regulator structure includes two gates; a regulator gate that controls the flow from the trunk sewers upstream into the interceptor that takes flows to the treatment plants and the outfall gate that controls the flows between the regulator station and the receiving water.

During dry weather flows, the regulator gate is fully open and all the flows are diverted to the treatment plant via the interceptor. The outfall gate is fully closed during dry weather operation. As the level increases in the interceptor during rain events, the regulator gate is usually throttled to avoid overloading the interceptor. When the regulator closes during wet weather, the level in the trunk sewer (and immediately upstream) rises. Once the level in the regulator station exceeds a certain value (setpoint), the outfall gate is opened to release the excess sewage and an overflow occurs.

As described, the regulator gate is controlled based on the interceptor level while the outfall gate is controlled based on the level in the trunk sewer entering the regulator station. Other control scenarios are possible; however, this is the most common regulator configuration in combined sewer systems.

3.1 Sluice Gates

Sluice gates are commonly vertical rising gates held in place by vertical grooves on either side of the sewer. Some sluice gates have a curved surface and are operated radially from a horizontal spindle or pinion. Sluice gates can be operated by a float mechanism or by an electric motor that receives commands from an electronic control system. Typically a sluice gate will serve one of two purposes:

- A normally closed gate will open to relieve a sewer during high flows, allowing part of the flow to go to a relief sewer or to an open channel

- A normally open gate will close to limit flows in order to protect downstream equipment or property

The earliest installations of automatic sluice gates used float devices to operate the gate (Figure 3-5). Depending on the location of the float, the gate can close in response to high flow downstream or it can close in response to high flow upstream. However, float-controlled chambers are limited in their ability to be modified to provide specific control sequences.

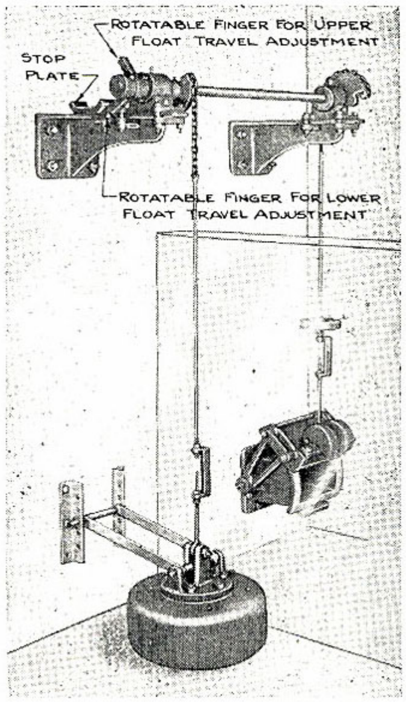


Figure 3-5. Radial gate operated by float.

Programmable electronic controls have become standard equipment for many remote facilities. These provide a very flexible method to provide control to diversion structures as well as to other control equipment, such as pumps or backup generators. They also can participate in a distributed control system that forwards alarm and event information to a central control or monitoring console.

Gates can be controlled effectively and without much risk, if they are set up properly. The following paragraphs outline simple methods for addressing some of the common concerns encountered when setting up the control of a gate.

In order to provide safe operation of the moveable gate, a limit on the speed of the gate is enforced, either through the gear ratio from the electric actuator or within the control unit itself. A gate that closes quickly during high flows can cause a wave that can travel upstream or downstream and has the potential for damaging other structures. The controller for the gate should be programmed to issue a no control action when the measured level is within a reasonable distance from the setpoint. This distance is called the deadband, and is required to prevent the gate from constantly moving small distances in an attempt to achieve the desired setpoint. The value of the deadband must be obtained through testing and field experience.

In locations where storage is desired, it is possible to use an inline sluice gate. However, in order to provide redundant flow paths in case of equipment failure (e.g., a stuck gate), either a bypass weir or other passive path is designed into the system. As discussed above in the description of a regulator station, several gates are often combined within one control structure. However, in many cases the locations of the gates, referred to as belonging to the same "station," may be several hundred feet apart, with separate power and telemetry feeds.

3.2 Movable Weirs

Movable weirs are a large class of structures that can behave like a fixed weir but can also be adjusted to provide diversion of flow at differing heights, depending on system conditions. A popular type of moveable weir that is used to restrict flow at varying levels is an inflatable dam. This large, industrial grade rubber bladder is installed along the invert of a large sewer (typically larger than 60-inch diameter) and connected to an air compressor that is controlled electronically. For most applications, the dam is normally inflated to prevent stormwater or combined sewage from passing on to an outfall and into a receiving waterway. Sewage or water stored upstream of the dam is diverted to a treatment system. During storm events that cause elevated flow conditions upstream, the pressure in the inflated dam can be lowered allowing flow to pass for the purpose of relieving the system upstream.

3.3 Pumping Stations

Pumping stations can be found in most medium to large sewer systems. A typical configuration for a pumping station is shown in Figure 3-6. Usually, although not shown in the generic figure, pump stations will also include weirs or gates to handle the overflow, to protect the facility during conditions of very high flows or emergencies.

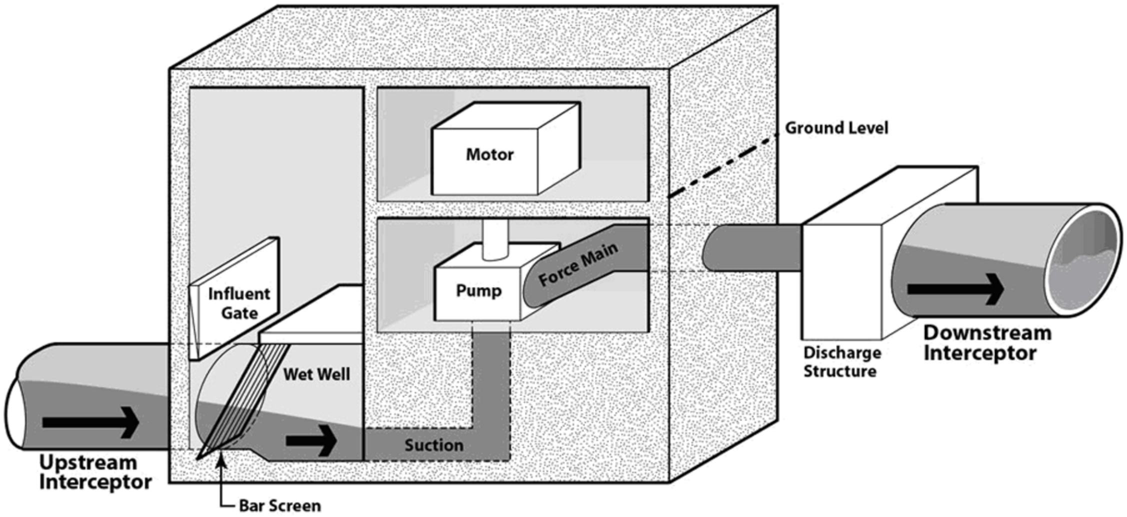


Figure 3-6. Schematic diagram of a typical pumping station (courtesy of King County, WA).

In order to provide reliable operation, at least two pumps are usually placed in a pumping station and controlled through a local electronic controller. These controllers often operate based on a level sensor placed in the wet well of the pump station. Pumps can operate at a fixed rate of rotation or they may be driven by a variable-speed motor. For fixed speed pumps, control can only occur by turning the pump on or off. Although variable-speed pumps can throttle the flow based on the speed of the impeller, multiple pumps are still used to provide additional pumping during high flow periods.

For safe and reliable operation of a pump station, the local controller is programmed to operate only on local signals at the station (typically the level in the wet well). This "pump program" is usually determined during station design and is not modified on a regular basis.

Remote control of the station is usually implemented by submitting a new setpoint to the local controller. This is an indirect method of control compared to directly sending a remote signal to start and stop individual pumps. By using a remote setpoint, the local pump program can be used to establish the conditions necessary to produce the setpoint and thereby rely on the inherent stability of the pump program.

Pump programs for a large pumping station will turn on additional pumps as the level in the wet well rises. This anticipates additional flow into the pump station that must be "matched" by the pumps in order to prevent flooding upstream. However, if sufficient storage exists upstream, regional or system-wide control algorithms may direct the station to reduce and store the flow in order to provide relief downstream. This "reduced flow" signal from the remote setpoint may be translated into a value for the process variable to which the pump program can react.

In some situations, pumps will be controlled using existing analog controllers. When computer controls are added, the analog controllers may remain in place which means that they will interact with the PLC and other RTC. In such a situation, the existing (analog) pump control will be based on fixed setpoints, such as the level in the wet well. When computer controls are added and the analog controllers remain, the computer may provide a new ("fake") wet well level setpoint that would indirectly achieve the desired pumping rate.

An additional control element that can be utilized is an influent gate to the wet well. In some cases, it may be desirable to lower the influent gate to control the level in the wet well and therefore produce the desired flow rate from the pump station. As in the previous example, this implementation is only practical if sufficient storage or alternative flow routing is available upstream. In general, pumping stations with large diameter sewers upstream that could provide storage are most commonly used in RTC applications.

Chapter 4. Instrumentation and Monitoring of Urban Drainage Networks

Instrumentation is the foundation of any RTC system; without reliable measurement(s), RTC cannot function properly. RTC systems typically require only a few types of basic measurements, such as water levels within pipes, manholes, and structures, as well as flow rates and rainfall amounts. Instruments for these types of measurements in the process industries have been available for many decades. Unfortunately, some of these "process industry" instruments are poorly suited for the "challenging" environment of the urban drainage network. This environment can include:

- Corrosive atmosphere (H_2S, NH_3, H_2SO_4)
- Sometimes explosive atmosphere (methane and hydrocarbons)
- High humidity
- Exposure to oils and greases, organic waste, industrial wastes
- Periodic submergence (pressurized)
- A wide range of process values (levels and flows)
- Deposition of solids on the bottom of the pipes (silting)
- Lack of nearby power and communications
- Limited surface access and almost always in a confined space

Fortunately, instrumentation for drainage networks has been developed over the past thirty or so years that specifically address each of these issues. In particular, these instruments have been designed to work in a corrosive and potentially explosive atmosphere with periodic submergence. The instrumentation developed in the 1990s with multi-path velocity measurements and built-in microprocessors is especially robust. In general, this instrumentation represents a mature technology with many thousands of installations providing reliable and accurate information.

Power is always required for instrumentation. For critical locations and measurements, a backup (or redundant) power source is desirable. If an instrument is to be used for RTC (not just for monitoring), requirements for reliability are higher and it is especially important to ensure uninterrupted operation. An important design parameter at sites without permanent power is the battery life for remote sites that cannot easily be connected to the electrical power grid. Batteries may provide the primary source of power. Battery life depends on the frequency of measurement and how often data is polled or downloaded from the instrument. Typical battery lives vary from six weeks to well over a year.

Maintenance of instrumentation is key to its reliability. Experienced operators will monitor and periodically check the trends of signals coming from all of the key instruments. Based on the trends, operators will identify (or “flag”) the instruments that are likely to be experiencing problems. When automation and RTC are introduced into the organization, organizational aspects of maintenance will come into play. It is important that the maintenance crews understand the RTC of the network, are familiar with maintenance issues specific to sewer networks (e.g., manhole access, traffic control) and also have proper experience with RTC equipment. For large systems, specialized maintenance crews can be a good approach.

Maintenance can also be improved by using Computerized Maintenance Management Systems (CMMS), software that helps operators manage the maintenance of the facilities and the equipment in the field. Due to the nature of their different functions, many agencies have a specific CMMS for the treatment plant and pump stations and another CMMS for the collection system. Staff will need to decide where the data and maintenance schedule and work orders will reside for the RTC structures.

4.1 Level Sensor Technology

Continuous level measurements are often required in pipes and structures of an urban drainage network. This section is limited to only continuous level measurements (analog values) and excludes point level measurements. Point level measurement devices are on/off switches that are triggered when the flow rises above or below the target level. All of the area/velocity flow meters discussed in the next section also require continuous level measurement. Various technologies have been successfully used for level measurement including mechanical, pressure transmitters, ultrasonic, and bubblers. The direct submerged pressure transmitters and two types of ultrasonic level technologies are the most often used and are discussed in more detail.

4.1.1 Direct Submerged Pressure Transmitters

Principle of Operation

Submersible transducers use diaphragms to sense differential pressure. Diaphragms are either flat or concentrically corrugated metal or ceramic disks. Process pressure applied across the diaphragm causes it to compress. Electrical signals proportional to differential pressure are obtained by mechanically connecting an electrical component such as a capacitor, strain gauge, resistive, or inductor to the diaphragm. These electrical signals are then converted to estimates of pressure and water depth and broadcast to the communication system. Submersible transducers are purchased with a sealed cable assembly to prevent the process from coming in contact with the sensing element electronics. Integral to the cable assembly is a breather tube that acts as the low-pressure reference leg for the transducer. The breather tube is routed beyond the maximum level of the process and is either vented into the enclosure or is routed to a breather bag. When the tube is vented to the atmosphere, a desiccant filter in the enclosure is needed to ensure that humidity does not have the ability to condense in the breather tube and cause inaccuracies in the level reading.

Materials of Construction

Process sensing elements are typically metal or ceramic. Typical process connection materials are 316-stainless steel, Hastelloy, and Monel.

Accuracy and Repeatability

Typical accuracies for submersible transducers are ±0.1% of the measurement range (span). For most sensors, the measurement range is 4 to 20 milliamps or sometimes 5 to 10 volts. The software maps the measurement range into engineering units (e.g., flow or pressure).

Installation on Maintenance

The direct submerged pressure transmitter is usually installed in the invert of the pipe or near the bottom of a structure. For pipe installations (usually in conjunction with a flow meter), care should be taken that trash will not catch on the mounting and that high velocities will not tear the instrument away. Usually, the manufacturer will supply a custom mounting bracket that fits the size of the pipe and is compatible with the piping material. Direct pressure transmitters can still provide accurate level measurements even when covered with silt. For level measurements in a structure (such as a lift station), it is often sufficient to suspend the direct pressure transmitter on a chain for easy access. Annual calibration checks of the level instrument should be conducted. Potential drift, which may be caused by debris hanging on the devices, should be checked monthly.

4.1.2 Ultrasonic Level Measurement

Principle of Operation

Ultrasonic level sensors typically are based on time-of-flight principle. A sensor (attached above the surface of the sewage/water) sends pulses so that the surface of the process being measured reflects the pulses back to the sensor. The required time of flight represents the path traveled in the empty portion of the pipe or process tank. The instrument is calibrated to calculate the difference between the maximum empty pipe (or tank) distance and the distance of the empty space representing the pipe diameter (or tank level). A variation found on some area/velocity flow meters utilizes an ultrasonic transmitter mounted on the invert of the pipe that shoots a signal upwards to find the water surface.

Ultrasonic wave velocity depends on temperature, pressure to a limited extent, and humidity to a minor extent. Where changing conditions are anticipated, automatic compensation can be provided. Only temperature is typically compensated for because other factors are usually negligible.

Sensors are available with frequencies from approximately 9 kHz (sonic) to 20 kHz plus (ultrasonic). The pulse generator can have a variety of shapes including cone, parabolic configurations, or threaded-pipe configuration for ease of connection directly to a stilling well pipe. Cone shape configurations are selected to minimize attenuation due to reflection. Ultrasonic level instruments are available with measuring ranges from 6 in. to 200 ft depending on sensing probe selection.

Signal attenuation (a reduction in signal strength) can be caused by absorption into the air, reflection away from receiver’s sensing area, and absorption by foam on top of the process being measured, or by the process medium. Propagation distance and wave frequency affect attenuation by absorption. As distance from the sensor to the liquid level increases, signal strength decreases in proportion to the distance squared. Persistent dense foam is typically a problem for sonic and ultrasonic devices.

Two common problems associated with vapor are corrosion and freezing. Heaters are available for sensors to prevent freezing and proper material selection can reduce the corrosion effects. Most transducers are designed to work in vented tank applications; however, if submerged pressurized conditions are a concern, manufacturers offer transducers capable of operating in pressure vessels greater than 50 psi.

Materials of Construction

Transducer probes are available in a variety of materials facilitating measurement of a wide variety of processes. Typically, the transducers are provided with polyvinylidine fluoride (PVDF) facings, or have polytetrafluoroethylene (PTFE) flange facings installed for corrosion resistance. PVDF facings can be utilized in process environments from -40^{o}F to 300^{o}F. For aggressive chemical or abrasive process level measurement, facings are available from other synthetic materials.

Accuracy and Repeatability

Accuracy of ±0.25% and repeatability of ±0.1% of span are typical. Air space conditions, water/sewage turbulence, foam, and interfering objects can reduce accuracy and repeatability. Manufacturers can assist in calculating the total attenuation attributed to the presence of interfering objects and process variations.

Installation

The mounting location of the transducer is determined from restrictions as recommended by the manufacturer. Typically, the sensor is mounted on the ceiling or over-head structural member at least 6in. above the maximum level to be measured; this distance is commonly referred to as the blanking distance. Blanking distances vary widely depending on the transducer selected. The transducer should be mounted far enough from the tank walls to prevent false echoes. The distance is dependent upon the beam angle of the transducer. The transducer should be mounted away from physical obstructions.

In structures, a stilling well (Figure 4-1) can be used with ultrasonic (or other level) sensors to dampen out liquid level turbulence, reduce foam, increase signal strength, eliminate noise from stray echoes, or reduced condensate problems. The stilling well is cut from a single piece of piping at least 4 in. in diameter. The bottom is cut at a 45-degree angle. Air relief holes should be drilled near the top of the stilling well where the transducer is mounted. For flumes and weirs, the stilling well can be mounted on the side of the primary element with a connecting pipe. The size of the connecting pipe determines the stability and damping of the level.

Maintenance Requirements

Sonic and ultrasonic level transducers do not contact the process fluid; therefore, they can be used in nearly every wastewater conveyance and treatment process. They are suitable for and are frequently used as secondary elements in flow measurement. The term "secondary" refers to the fact that the level measurement is used to infer a flow rate rather than directly measure it.

Periodic cleaning of the transducer facing may be required depending on the rate of accumulation of coating on the transducer surface. Annual calibration checks of the level instrument should be conducted, or when utilized for compliance, semi-annual or quarterly calibrations should be performed. A staff gauge to conduct calibration verification is frequently used, especially when the transducer is utilized as a secondary element in a flow measuring system.

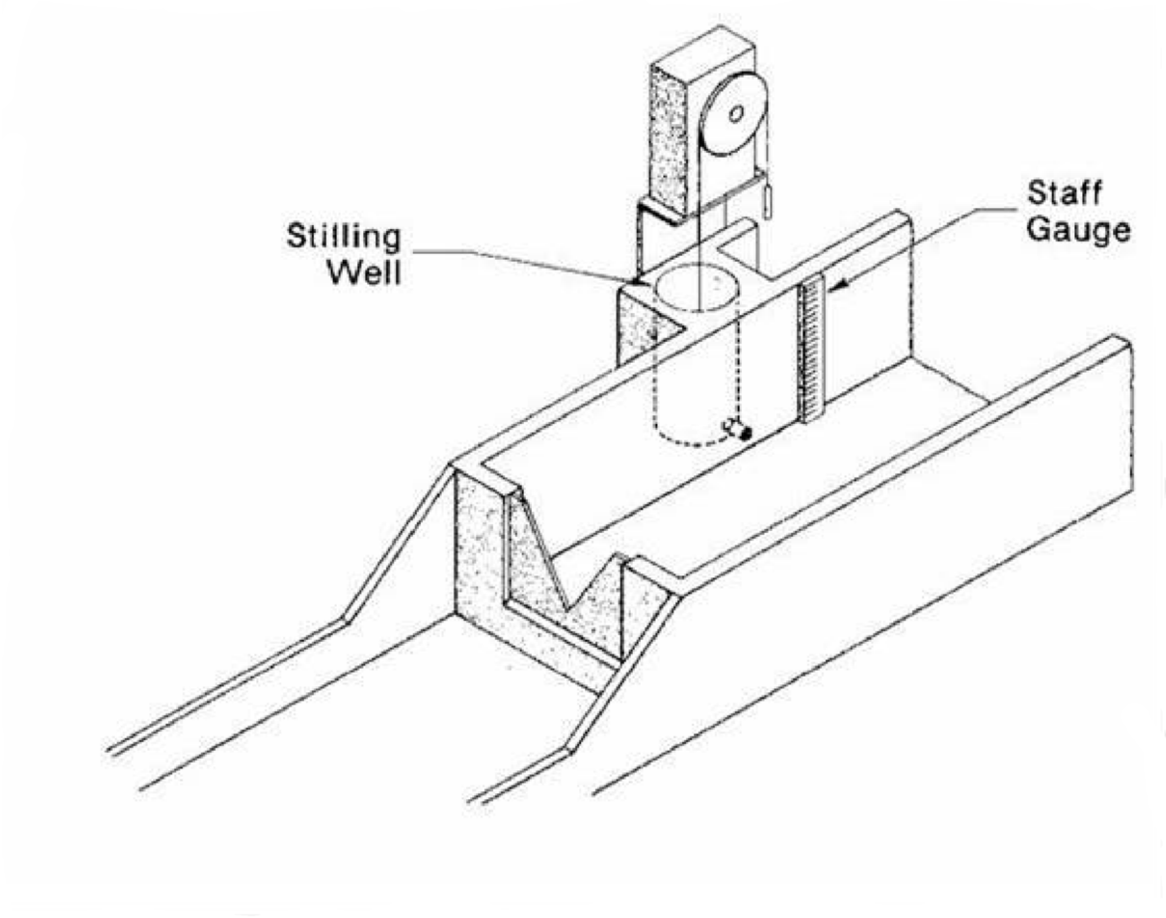


Figure 4-1. Diagram of a typical stilling well (courtesy of ISCO, Inc.)

4.2 Flow Sensor Technology

Continuous flow measurements are often critical to the control of an urban drainage network. Various technologies have been successfully used for flow measurement; however, flumes and area/velocity flow meters are most often used and are discussed in more detail in this section.

4.2.1 Flumes

Principle of Operation

The most common type of flume used in urban drainage networks is the Palmer-Bowlus flume, Figure 4-2. The flume is usually placed in a manhole or other access point and acts as a hydraulic control in which critical flow is developed. This condition is usually assured when water is backed up in the pipe above the flume and when discharge from the flume is super critical (typically a free fall). The flow rate is then a well know function of upstream water depth which can be measured with any of the level measurement technologies previously mentioned.

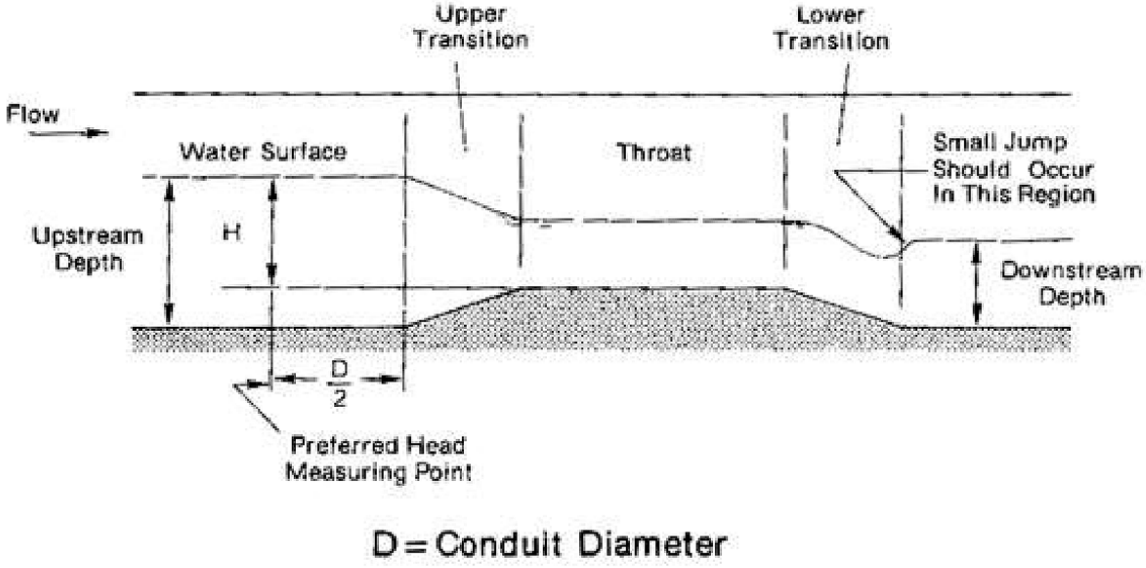


Figure 4-2. Diagram of a typical Palmer-Bowlus flume installation (courtesy of ISCO, Inc.).

Materials of Construction

Flumes may be fabricated out of any material that is stiff enough not to deform under the hydraulic load. Typically, fiberglass reinforced platic (FRP) or aluminum are used Cascading raw wastewater over a flume will often aerate the water and allow for the dissolved sulfides to be released from solution. If a flume is going to be a permanent installation, the material of construction should resist the corrosive action of the wastewater.

Accuracy and Repeatability

The accuracy of a measurement derived with a flume depends on a combination of the accuracies of the primary (flume) and secondary (level measurement) elements. For a correctly fabricated and installed flume, the estimated accuracy of the depth discharge equation is ± 3% of the flow rate. A combined flume and level-measurement accuracy of ± 5% of the flow rate is attainable with repeatability to ± 0.5% of the flow rate. Several additional sources of error, if uncorrected, can increase the error (decrease the accuracy) of the flow measurement. These include:

- Deviations of the throat width from standard dimensions

- Any longitudinal slope of the floor in the converging section. (Tests on a 0.075m (3in.) flume demonstrated that a downward sloping floor produced added errors of 3 to 10% from low to high flow conditions)

- A transverse slope of the flume floor

- Violation of the assumption of a free discharge caused by backwater in the downstream sections of the pipe, common during wet weather conditions

- Poor approach conditions

- An incorrect zero reference of the level-measurement device and, if a stilling well is used, the connector hole is improperly sized

Installation
The flume requires an approach channel long enough to create a symmetrical, uniform velocity distribution and a tranquil water surface at the flume entrance. A general rule is that at least two channel widths or ten throat widths of straight run are required upstream of the flume inlet. The elevation of the flume floor must be high enough to prevent submergence conditions at maximum flow and the floor section level longitudinally and transversely. Leakage under the flume should be avoided. The upstream level measurements of about 0.5 pipe diameters upstream of the flume entrance should be taken.

Maintenance Requirements
The flume should be checked periodically to ensure debris, especially rags, has not accumulated. Rags and other debris can interfere with the flow pattern through the flume. Calibration of the secondary level measuring device should be checked at least annually.

4.2.2 Area/Velocity Meters

Principle of Operation
All area/velocity flow meters work on the principal of multiplying an average velocity of flow by the cross-sectional area to calculate an average flow rate. All of these flow meters also use a level measurement to assist in calculating the cross-sectional area of flow. The many flow meters on the market, however, vary greatly in how the velocity is measured and how many measurements are required. Some flow meters use a single velocity measurement and an assumed depth-area-flow profile (which may have been determined experimentally for the site) to estimate the flow rate. Errors accumulate when the assumed profile changes due to upstream or downstream constrictions or changes in the pipe cross-section. Other more sophisticated instruments use multiple velocity measurements on multiple paths to determine the average velocity of each flow segment and then sum these individual subflows. These multi-path flow meters generally have less error over a greater range of flow conditions but also at a greater cost.

Area/velocity flow meters all must measure the level of water in the pipe to determine the cross-sectional area. The most common methods of measuring this level are direct submergence pressure transducers, ultrasonic transducers mounted on the pipe crown, and ultrasonic transducers mounted on the pipe invert. All were discussed in the previous section. Velocity is usually measured with one of two technologies, electromagnetic or ultrasonic Doppler.

Electromagnetic sensors are based on Faraday’s principle of electromagnetic induction, in which the induced voltage generated by an electrical conductor moving through a magnetic field is proportional to the conductor's velocity. The accuracy of electromagnetic sensors may be affected by buildup of oils and grease. Therefore, self-cleaning streamlined designs are particularly important.

Ultrasonic Doppler flow meters work on the principal of frequency shift due to relative motion. A signal of known frequency between 600 kHz and 1 mHz is sent into the fluid where it is reflected back to the transducer by suspended particulates and/or gas bubbles. Because the reflective matter is moving with the process stream, the frequency of the ultrasonic energy waves is shifted as it is reflected. The magnitude of the frequency shift is proportional to the particle (flow) velocity and is converted electronically to a linear flow signal. The more sophisticated Doppler meters will use one signal to generate a vector of velocities along the entire path.

Area-velocity flow meters often have software that provide an option to calculate the flow rate based on depth and the Manning equation alone by assuming a normal flow condition (non-backwater, less than full pipe). This feature is useful as an added check if the velocity data appears suspect.

Materials of Construction
Flow meters must be constructed for submerged and potentially explosive conditions. Applicable ratings are IP 67 (equivalent to NEMA 6P) and Class1, Division 1. IP 67 is s standard for protection against temporary immersion in up to 1 m of water for 30 min. Class 1, Division 1, is a safety standard for equipment operating in hazardous environments where flammable gases, vapors, liquids, combustible dusts, or ignitable fibers are likely to exist under normal operating conditions.

Accuracy and Repeatability
Accuracy of flow measurements vary greatly depending on flow conditions at the measurement point and the particular technology used. In general, single point flow meters are not as accurate over the entire range of flows. Depending on the assumed flow profile, errors can exceed 25% of the true flow rate under poor conditions. The multi-path instruments may have errors as low as 1 to 3% of the true flow rate.

Installation
Each specific manufacturer will provide mounting hardware depending on the pipe size and material of construction. As much upstream straight lengths of pipe (minimum 10 pipe diameters) as possible should be provided to create a symmetrical, uniform velocity distribution.

Maintenance Requirements
The area/velocity flow meter should be checked periodically to ensure debris, especially rags, has not accumulated. Electromagnetic sensors should be cleaned periodically per manufacturer's recommendations.

Flow Meter Testing and Verification
There are two primary sources of third party verification of flow meter technology. The Instrumentation Testing Association (ITA) tested six area/velocity flow meters from five manufacturers in a full-scale sewer application in 1998. This evaluation report is available for purchase at their web site (www.instrument.org). The U.S. Environmental Protection Agency's Environmental Technology Verification (ETV) program (www.epa.gov/etv/verifications/verification-index.hmtl) tested two area/velocity flow meters from a single manufacturer. These tests reports are available (at no cost) online, and show typical errors for laboratory and field conditions.

4.3 Rainfall Sensor Technology

Rainfall meters are used to measure precipitation. Historically, these measurements are used for calibration of hydrologic and hydraulic models. In RTC systems, these measurements can be used as part of a forecast of the affects of precipitation (see next section).

4.3.1 Principle of Operation

Most rainfall meters work on a very simple principle. Water is collected in a small "bucket" until 0.01 in. accumulates. This precise volume then tips the bucket, provides a momentary contact closure, and empties the bucket. The contact closure is monitored by an electronic unit that accumulates the closures over various time periods and communicates these values. This class of rainfall meters is collectively called tipping bucket rain gauge and are built to standards set by the National Weather Service. The unit can be heated in the winter time to melt snowfall.

4.3.2 Materials of Construction, Installation, and Maintenance

Rainfall gauges are typically constructed of epoxy or enamel coated aluminum and anodized aluminum and/or stainless steel. The rainfall meter and collector should be located on a flat, level surface in an open area with no overhanging obstructions. They should not be mounted on a steel or iron surface. Some manufacturers recommend one rainfall gauge every 2 mi^2 for good rainfall correlations. Every few months the collector should be checked to make sure its strainer is free from obstruction of leaves, pine needles, and other debris.

4.4 Rainfall Forecasting Technology

Precipitation forecasts are difficult to perform and evaluate because of the large number of variables and variety of forecasting objectives a wastewater agency might have. The factors that define a forecast include the forecast horizon and the intensity, duration, volume, spatial and temporal distribution within the storm, and possibility even the type of precipitation.

4.4.1 Forecasting Objectives

The forecast horizon is the period over which the forecast applies. Clearly, the accuracy of any forecast technology will decrease as the beginning of the forecast horizon is set further into the future. The length of the horizon also affects accuracy. A pin-point forecast of precipitation over a short period in the future, for example 12 to 18 h from the present time, can be very difficult to perform with great success. However, the specific time of day when the rainfall occurs could be important because wastewater systems usually have more capacity at night.

Precipitation is a process that varies in time and space. Each wastewater agency is affected differently by precipitation and thus, each will have different forecasting objectives. In some cases, the location of the precipitation within the service area could be very important while with others, the intensity of the rainfall might be a critical operational factor. It is nearly universal that agencies are mainly concerned with extreme storms having a large total rainfall volume, although the definition of large and the storm durations of interest vary from place to place. This adds to the difficulty of acquiring accurate forecasts because extreme storms, particularly high intensity events, are subject to greater spatial variability than lighter events.

In many locations, the type of precipitation, rain versus snow, can be very important. In Milwaukee, Chicago, Boston, and New York, the largest overflow events are created when intense rain falls upon an existing snow cover. Such rain on snow events necessarily take place during the winter season when the rain portion of the event could occur as snow with a slight change in conditions. Typically, a relatively narrow band of snow will be generated 50 to 150 mi north of a low pressure center as it moves northeast along a frontal boundary. A slight change in trajectory or timing can easily turn a snow event into rain.

4.4.2 Forecasting Approaches

The primary methods employed in forecasting precipitation are climate modeling and synoptic forecasting. A climate model is a computer simulation of the atmosphere process affecting weather. This generally involves the movement and interaction of air masses which are driven by the jet stream and the earth's rotation. As a result, many climate models are global circulation models (GCM). These models simulate processes across the entire planet which means they have fairly low resolution (usually a minimum of 50 to 100 km), and because of very long run times and high computer processing requirements, GCM are typically developed and operated by government agencies. The US Naval Observatory has a model called NOGAPS, Environment Canada operates the CGCM3 model, and the Hadley Centre in England has its own Hadley Model. There are also regional climate models which simulate climatic processes over a limited area but at a much greater level of spatial resolution. Regional models have the potential to be more accurate in predicting rainfall depth and intensity and to define the spatial distribution of rain over an area as small as a wastewater district, which is impossible in a GCM. To be successful, regional climate models must account for local anomalies such as urban heat islands or the effects of large lakes. Even the presence of crops on agricultural lands can influence local weather. Thus, building and operating a regional model can have extensive data and input requirements. Regional models are accurate over a limited area and accuracy diminishes greatly near the model boundaries. Boundary conditions must be provided as input throughout the simulation and are subject to significant errors.

Another computer modeling technique is the statistical model. Statistical models evaluate a time series of recent observations and synthesize a forecast of future values. Statistical models are generally in the experimental stage and are not currently in wide use as a rainfall forecasting tool. These models require a large amount of reliable historical data to build and calibrate the model. Continued use of the model then depends on the availability of the observations used to build it. However, urban development and funding often leads to changes in the location or condition of the monitoring equipment which then affects the reliability of the statistical model.

Synoptic forecasts are made by trained professionals who use atmospheric measurements, recent history, experience, and judgment to develop a prediction. Most professionals also utilize the results of GCM runs in formulating their synoptic forecasts. A key element in creating a synoptic forecast is precipitable moisture. An air mass with a known temperature and dew point temperature has a particular precipitable moisture content. This is the amount of water that would be precipitated if the air mass were suddenly cooled to its dew point. By assessing the likelihood and degree of such cooling, the synoptic forecaster can predict the volume of future precipitation.

Finally, it is worth mentioning ad hoc forecasters; i.e., people who are very experienced with the weather in a particular geographic area. Although they have no formal training in climatology, their experiences allow them to make remarkably reliable forecasts. The best ones include farmers, trail guides, park rangers, and frequently, operators of wastewater collection systems. Ad hoc forecasters use observations of wind, clouds, and pressure along with their vast experience augmented, perhaps, by radar summaries, to develop a prediction of future rainfall. This type of forecasting technology, that includes an experienced operator armed with radar, local observations, and an internet connection, is probably the most common forecasting technology employed by wastewater agencies.

4.4.3 Evaluation of Technologies

In practice, forecasters rarely rely on a single approach; rather, forecasters use a hybrid of model results, synoptic analysis, and judgment. There is little evidence to suggest that any of these methods perform better than the others. The biggest problem is, in fact, attempting to define success in forecasting and being able to gather the data necessary to evaluate a significant unbiased sample of forecasts.

A company known as Great Lakes Forecasting has been preparing synoptic forecasts of 24-h precipitation for the Milwaukee area for more than 10. The forecasts are generally prepared at midnight for the subsequent 24-h period thus it is possible to develop a consistent comparison between the forecast volume and the actual volume of precipitation. Figure 4-3 is a plot of forecast volume versus actual volume for forecasts made between September 1997 and December 2001. This plot shows that these particular forecasts tend to underestimate the precipitation quantity. The problem appears to get worse with increasing actual storm size.

A statistic known as the threat score (TS) is used to measure the adequacy of quantitative precipitation forecasting methods. The threat score is the ratio of correct predictions divided by the number of opportunities where opportunities are instances of predicted or actual events. More precisely, it is defined as:

$$TS = \frac{\#\, correct\, forecasts}{\#\ forecast\, events + \#\, actual\, events - \#\, correct\, forcasts}$$

In this context, an event is a precipitation volume of a particular size range, duration, and period of occurrence. The National Weather Service Hydrometeorological Prediction Center (HPC) maintains records of various forecasts and corresponding threat scores.

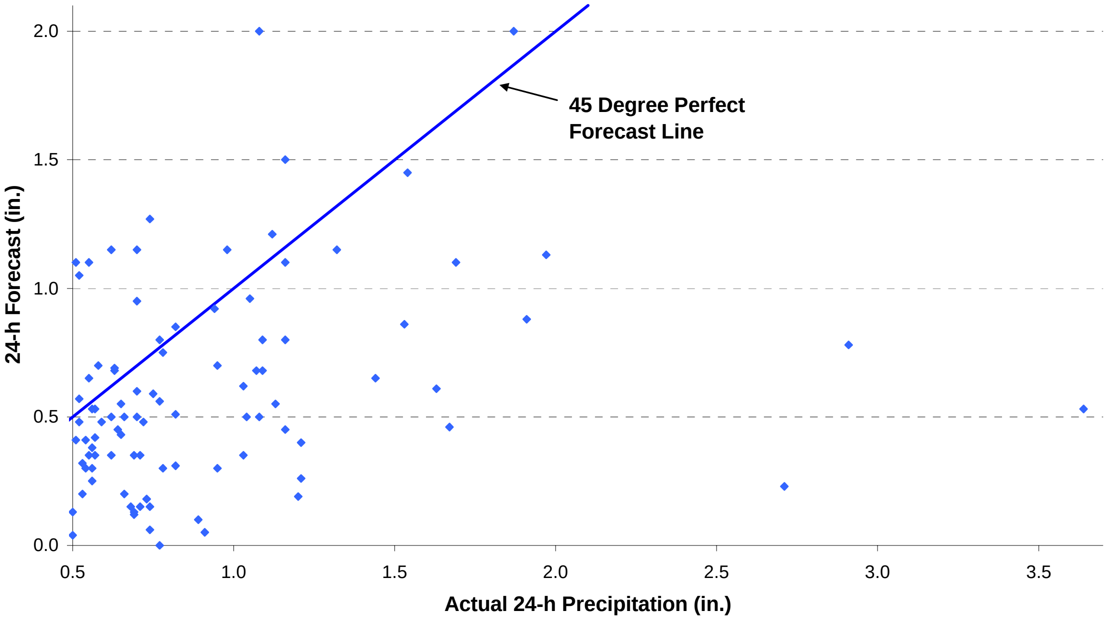


Figure 4-3. Plot of forecasted rain event volume versus actual volume. (Internet Source: National Weather Service)

Results of historical forecasts are shown in Figures 4-4 through 4-5. Figure 4-4 compares TS values for water year 2005 for storms of various volume classes (less than 0.5, 0.5 to 1.0, and 1.0 to 2.0 in.) with a few anomalies, the data shows that the threat score gets much lower for the larger storms and is typically less than 0.25, sometimes much less.

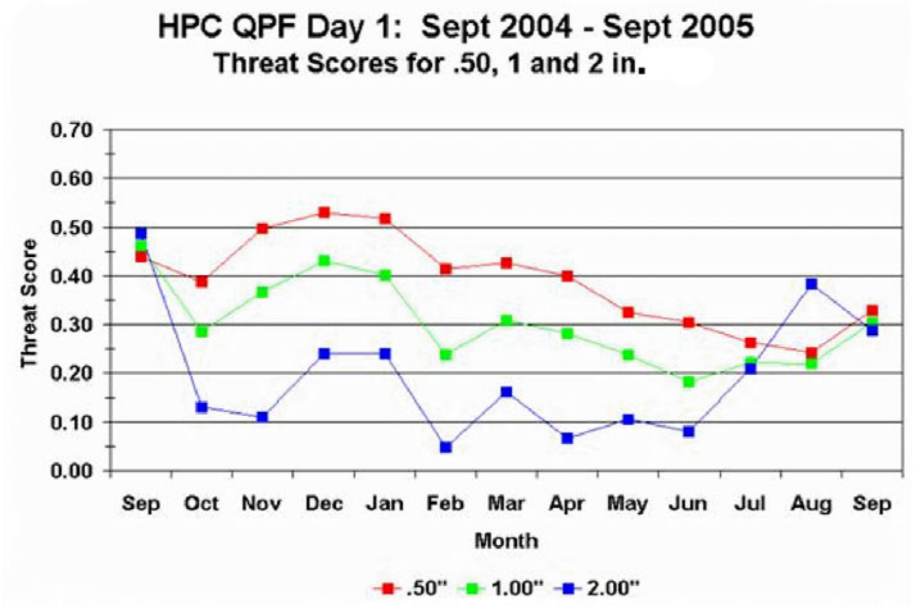


Figure 4-4. Plot of threat scores over time for different storms. (Internet Source: National Weather Service)

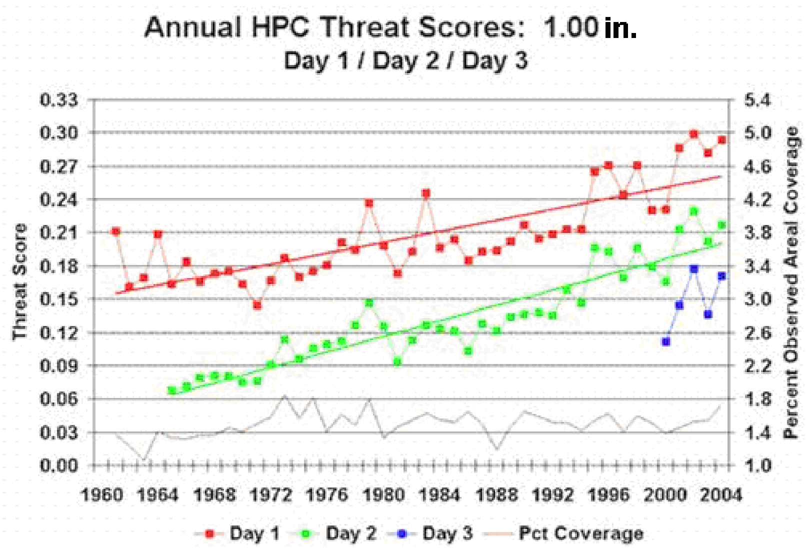


Figure 4-5. Plot of threat scores over time for different forecast horizons. (Internet Source: National Weather Service)

Figure 4-5 shows the annual average TS for the 1-, 2-, and 3- day forecast horizons. This plot shows, as expected, that the forecasts 2 or 3 days in the future are much less reliable than that for the 24 h immediately following the prediction. This plot also shows how increasingly sophisticated GCM and accurate measurements have improved forecasting accuracy. For the 1.0 in. storm shown, however, the TS have improved from about 0.16 to nearly 0.27 in. in about 45 yrs. Even with such improvements, about 73 % of forecasts will be incorrect in some fashion. Figure 4-6 compares several of the forecasts that were available in 2005 demonstrating the superiority of the HPC forecast over models alone.

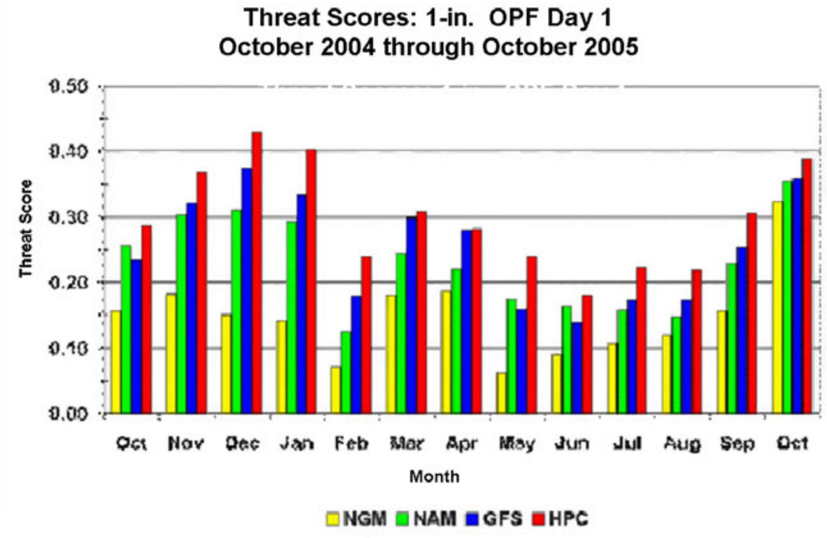


Figure 4-6. Plot of threat score comparisons over time for different forecasting methods. (Internet Source: National Weather Service)

Chapter 5. SCADA

5.1 Introduction to SCADA

The term SCADA is an acronym for Supervisory Control And Data Acquisition (Figure 5-1). In its truest sense, a SCADA system acquires process data from field instruments and final control elements and then presents that information to a centralized location so that a human operator can initiate supervisory control commands. In the early days of SCADA systems, this description accurately portrayed system operation. The components that interfaced to the final signals (RTUs) had limited computational capabilities and even more limited memory. Therefore, it was impractical to consider any RTC rules executing in the RTUs themselves and manipulating the facilities. Since the computer components used at the centralized control location (sometimes referred to as Master Station or top-end) were more sophisticated, some early systems had limited supervisory control algorithms that executed on the central computer and provided supervisory commands to the RTUs based on field signals.

Over the years, microprocessor technology has evolved, becoming much more powerful and inexpensive. In addition, the cost of digital memory has decreased to the point that it is no longer a significant consideration in control system design. SCADA system designs have taken full advantage of the advances in computer technology. Modern systems now employ RTUs or PLCs with more computing power and memory than the Master Station computers of old. As such, modern SCADA system designs regularly employ sophisticated RTC algorithms which execute in the RTU itself. The central human operator is kept constantly apprised of the automatic controls being implemented by the remote units and can always assume remote, manual control. In certain instances, the system operator may be required to "approve" planned control actions prior to their being implemented remotely.

Figure 5-1. Picture of a SCADA control console.

5.2 Communications Options

The fundamental purpose of a SCADA system is to communicate data and control commands from a centrally located operator to geographically dispersed remote locations. Some form of electronic media is required to support this communication.

5.2.1 Telephone

Early SCADA systems typically employed tone signals transmitted over leased telephone circuits. As communications technology evolved, the use of modems communicating over leased or dial-up telephone lines became more prevalent. Due to the low cost of installation, telephone-based communication systems are still widely used in SCADA system applications.

5.2.2 Fiber-Optic Cable

Many utilities sought to eliminate the recurring costs (monthly charges) and maintenance uncertainties associated with telephone-based systems. From a system performance standpoint, one of the most attractive communications alternatives is the use of dedicated, fiber-optic cable (Figure 5-2). Fiber-optic cable supports high-speed communications, is immune to electrical interference, and exhibits high system availability. However, the cost for fiber-optic cable is often prohibitive, especially for long distance installations. In recent years, the cost of the fiber-optic cable itself has been reduced dramatically making the installation cost the primary consideration. A number of utilities have adopted the practice of installing fiber-optic cable as an integral part of all pipeline construction projects. By doing so, the cost of the fiber-optic circuits represents only an incremental amount of the overall construction costs. In other SCADA system applications in which the remote sites are located in largely urban areas, some utilities have been able to negotiate the use of spare fibers in the local cable TV supplier's network. Conversely, some utilities who have installed fiber-optic cable as a part of their SCADA system have included additional unused or "dark fiber" for future use by the utility or to lease to cable TV, businesses, or other utilities.

Figure 5-2. Picture of a fiber equipment rack.

5.2.3 Radio Systems

A more common alternative for SCADA system communications is the use of some type of wireless network. There are a wide range of radio systems that have been adapted to SCADA system communications. Systems using licensed, 900 MHz radios were widely used in the late 1990s, with many systems still in operation. Some SCADA system designs took advantage of the trunked radio systems that many utilities have in place to support voice communications. Trunked radio systems utilize several pairs of frequencies to enhance transmission. Most trunked radio systems are in the neighborhood of 800 MHz. In some cases, to support higher throughput requirements, dedicated microwave links have been employed for SCADA communications. All of these alternatives provide high-speed data communications. However, they are all also complex systems which are costly to design, install, and maintain. In addition, many utilities have experienced problems obtaining the required FCC radio licenses to support these systems, especially in dense urban environments.

In recent years, a number of unlicensed radio systems have become available. These systems have evolved using technology developed to support pager and cell phone applications. The unlicensed systems employ low-power radios (less than 1 watt) and transmit effectively over short distances, generally one mile or less (Figure 5-3). One of the most popular unlicensed radio technologies is Spread Spectrum. In performing Spread Spectrum, the radio transmitter takes the input data and spreads it in a predefined method. Each receiver must understand this predefined method and "despread" the signal before the data can be interpreted. There are two basic methods to performing the spreading: (1) frequency hopping, and (2) direct sequencing. Frequency hopping spreads its signals by "hopping" the narrow band signal as a function of time. Direct sequencing spreads its signal by expanding the signal over a broad portion of the radio band.

Figure 5-3. Picture of a radio transmission tower.

The Federal Communication Commission allows the use of Spread Spectrum technology in three radio bands, 902-928 MHz, 2400-2483.5 MHz and 5752.5-5850 MHz for transmission under 1 watt of power.

5.2.4 Other Techniques

In addition, depending on the specific geographic topology of the SCADA system components and the existing infrastructure of the utility, there is a wide range of other available communication techniques available including point-to-point microwave (both licensed and unlicensed), satellite-based systems, etc. Many utilities have begun to use cellular telephone-based communications. As emerging communications technologies, such as wireless Internet access, continue to evolve, they will be applied to SCADA system applications.

5.3 Communications Methodologies

One of the factors that can have a significant influence on the type of communications media to be used is the methodology employed by the SCADA system to exchange data between the master station and the RTUs. The most common methodology is referred to as “master-slave”. In this scheme, the master station polls each RTU in a pre-determined, round robin fashion. In the simplest implementation, each RTU reports the current value of each input/output (I/O) point in its database and the master station transmits the required state of all control points. In a more sophisticated scheme referred to as “report-by-exception,” the RTU reports only those discrete points that have changed state and those analog points that have changed by more than an adjustable deadband. Likewise, the master transmits only those control points that have changed since the last RTU scan. Report-by-exception schemes reduce the amount of communications traffic, allowing the use of lower throughput communication media, but are more complex to program.

Another communications methodology which can be used to limit the amount of data transferred between the master station and RTU is referred to as “RTU cry-out”. In this scheme, the RTU itself initiates communications to the master station when data changes beyond an adjustable deadband. This communications method requires sophisticated software to arbitrate when two or more RTUs cry-out at the same time; however, it can be very effective especially in mostly quiescent applications.

An additional system requirement that affects the choice of communications media is the need for peer-to-peer communications. In some SCADA applications, it is necessary for one RTU to communicate directly with one of its peer RTUs. For example, a remote pump station may be controlled by a tank level measured by another RTU. In these applications, both the communications media and methodology must be designed to allow communication between RTUs without the intervention of the master station.

5.4 Local Control Devices

As discussed previously, there are two general categories of devices that can be used as local control devices: Programmable Logic Controllers (PLCs) and Remote Terminal Units (RTUs). The evolution of these two types of devices was distinctly different.

PLCs (Figure 5-4) were originally designed as replacements for discrete relay logic. As such, PLCs were ideal for discrete control applications, but were not well suited for continuous control. Another strength of PLCs was their rugged design which allowed them to operate with minimal failures in harsh industrial environments.

Figure 5-4. Picture of a typical PLC.

RTUs (Figure 5-5) were developed as proprietary devices that employed microprocessor technology and custom operating systems and programming languages. Since RTUs were essentially computers, sophisticated control strategies utilizing both discrete and continuous logic could be developed. Early RTUs were constrained by the limited computing power of the available microprocessors and the high cost of memory.

Figure 5-5. Picture of a typical RTU panel.

Recent advances in PLC design have eliminated their shortcomings in regard to continuous control applications. The International Electrotechnical Commission (IEC) has developed the IEC 1131-3 standard which defines five PLC programming language standards as follows:

- Ladder logic
- Sequential function chart
- Function block diagram
- Structured text
- Instruction list

Most modern PLCs support the full range of IEC 1131-3 languages allowing very sophisticated RTC applications to be developed. The choice between using PLCs or RTUs as local control devices is largely determined by preference. As recent advances in technology have blurred the line between an RTU and PLC, the term "RTU" will be used to indicate a generic field automation unit in the remainder of this section.

5.5 SCADA Design Considerations

There is a wide range of practical considerations associated with the design of a SCADA system. Perhaps the most varied and complex issues are associated with the physical installation of the RTUs. By the very nature of wastewater collection and conveyance systems, the RTUs that are part of the SCADA system will most likely be installed in somewhat challenging environments. Design considerations for RTU installation include: equipment enclosures, environmental conditioning, and field interface wiring.

5.5.1 Equipment Enclosures

Remote site conditions associated with a wastewater SCADA system are typically not conducive to the electronic components that are part of the RTUs. In order to protect the RTU components and to extend their useful life, particular care must be given to the design of the RTU enclosures. The National Electrical Manufacturers Association (NEMA) has developed a set of standards for equipment enclosures which define the expected operational environment for electronic equipment. Adhering to these standards for RTU enclosures will help to ensure that the RTU equipment is adequately protected. Table 5-1 summarizes NEMA enclosure standards.

5.5.2 Environmental Conditioning

In addition to selecting the appropriate enclosure, it is important to ensure that the required environmental conditioning is provided for the RTU equipment. Temperature extremes, both heat and cold, have detrimental effects on the RTU's electronic equipment. The typical operating range for RTU components is 0 – 60 ^{o}C. For installations in colder climates in which subzero operating conditions are likely, thermostatically-controlled enclosure heaters are generally included as part of the RTU design requirements.

There are a number of different design approaches available for use with RTU installations which exhibit high ambient temperatures. For outdoor installations, a simple sun shield is often sufficient to keep the cabinet temperatures within an acceptable range. For additional cooling, thermostatically-controlled cooling fans can be added to the RTU design. For the most extreme conditions, sealed-system air conditioning units can be utilized.

A document published by the National Fire Protection Association (NFPA) entitled NFPA-820 Standard for Fire Protection Measures in Wastewater Treatment and Collection Facilities, addresses the means of protection to be applied for electrical equipment installed in hazardous locations as defined by NFPA-70 National Electrical Code. Although locating equipment in hazardous locations should be avoided, sometimes it is unavoidable. These documents should be referenced when considering environmental conditioning.

5.5.3 Field Interface Wiring

The field interface wiring associated with SCADA system RTUs (Figure 5-6) represents a sizable portion of the overall system costs. Not only are the initial costs for purchasing and installing the field interface cables significant, the costs and complexity for maintaining the integrity of this wiring over the life of the SCADA system must be considered in system design. Unfortunately, in many existing SCADA systems, after years of add-ons and expansion, the field wiring is a tangle of poorly labeled cables along with undocumented field conditions. Troubleshooting or expanding these systems can be a daunting task. There are a number of design techniques which can be used to lower the life-cycle costs associated with field interface wiring. To begin with, a comprehensive standard should be employed for wire labeling. Several standard organizations, such as ISA and ANSI, provide suggested labeling schemes. Whichever standard is selected, it is critical that all interface wiring be clearly labeled with permanently affixed wire tags. It is a good practice to install wire tags on both ends of interface cables, especially long ones.

Table 5-1. NEMA Enclosures Standards

Type	Use	Protection Against
1	Indoor	Incidental contact; falling dirt
2	Indoor	Type 1 plus dripping and light splashing of liquids
3	Indoor or Outdoor	Type 1 rain, sleet, snow, and windblown dust Undamaged by external formation of ice on enclosure
4	Indoor or Outdoor	Type 3 plus splashing water and hose-directed water
4X	Indoor or Outdoor	Type 4 plus protection against corrosion
5	Indoor	Type 2 plus settling airborne dust, lint, fibers, and flyings
6	Indoor or Outdoor	Type 4 plus entry of water during occasional temporary submersion at limited depth
6P	Indoor or Outdoor	Type 4 entry of water during prolonged submersion at limited depth
7	Indoor	Capable of withstanding pressures from internal explosion of specified gases, and contain such explosion sufficiently that explosive gas-air mixture existing in atmosphere surrounding the enclosure will not be ignited.
9	Indoor	Capable of preventing entrance of dust. Enclosed heat generating devices shall not cause external surfaces to reach temperatures capable of igniting or discoloring dust on the enclosure or igniting dust-air mixtures in the surrounding atmosphere.
12	Indoor without knockouts	Type 2 plus circulating dust, lint, fibers, and flyings
12K	Indoor with knockouts	Type 2 plus circulating dust, lint, fibers, and flyings
13	Indoor	Type 12 plus the spraying, splashing, and seepage of water, oil, and noncorrosive coolants

Another technique that should be considered in RTU installation design is the use of separate, dedicated field termination panels. These panels, which include modular termination assemblies, can be installed in advance of the RTU enclosures. This practice allows the field interface wiring to be installed and tested while the SCADA system is still being developed in the factory. Then, once the system has passed factory testing, the RTU enclosures can be installed and field wiring completed using factory-fabricated interface cable assemblies.

One technology that promises to simplify the issues associated with field interface wiring is “smart” process equipment and instruments. Instead of requiring individual interface cables for each signal, these devices utilize serial cables that can provide control and monitoring information about all signals associated with the device. Some protocols allow multiple devices to be multi-dropped on the same cable. There are currently a number of smart instrument protocols, including HART, FieldBus, and ProfiBus. As this technology evolves and is applied on a more widespread basis, the costs and design considerations associated with field interface wiring will be simplified.

Figure 5-6. Picture of interface wiring.

5.6 Other Design Considerations

There are a number of other non-technical considerations which can have a significant impact on the success of a SCADA system project. These considerations include: system documentation requirements, training requirements, and system testing requirements.

5.6.1 System Documentation Requirements

System documentation is one of the most important, yet often overlooked aspects of SCADA system implementation projects. System specifications typically define the appropriate levels of engineering, user, and technician documentation. The problem is that the delivery of system documentation usually occurs late in the project when everyone’s attention is focused on getting the SCADA system installed and operational. One approach for addressing this issue is to require three distinct submittals for each required document: preliminary, draft, and final. The preliminary version of a manual should define the format of the manual and provide sufficient detail to review the basic outline and scope of the topics which will be addressed. This submittal should be required early in the project as soon as 90 days after notice to proceed. It is best to get agreement on the format and content of the manuals as soon as possible. The draft submittal of each document should be generally complete (at least 90%) and should be clearly marked to indicate where all missing or incomplete information will be included. Ideally, draft documentation submittals should be required at 30 days prior to the start of factory testing. This requirement will encourage the contractor to apply resources to development of system documentation while the majority of the development team is still intact. Final versions of system documentation should be required before the start of field acceptance testing.

5.6.2 Training Requirements

Training is another aspect of SCADA system implementation projects that sometimes doesn't receive the attention that it deserves. Comprehensive training should be provided to system users on a number of different levels, including overview, user, engineer, system administrator, and maintenance. Overview training should be presented to all users to provide a basic introduction to the SCADA system but is especially important for utility management. User training should cover not only the basic operation of the SCADA system but should also address aspects of system operation specific to the particular application. In order to accomplish this course content, a member of the client's staff will need to work with the system supplier in developing the training materials. Engineer training should cover the steps necessary to expand the SCADA system, such as adding new RTUs, adding new database points, and adding or changing graphic displays, control strategies, or reports. System administrator training should address such tasks as tape backups and recovery, software upgrades, and maintenance of system files, such as operator log-in IDs and access rights. Maintenance training should focus on the steps necessary to troubleshoot system malfunctions. Typically, system hardware maintenance is limited to the PLC/RTU level. Most modern SCADA systems utilize standard, off-the-shelf computer components at the top-end level. Repair of this type of hardware is usually best left to the computer manufacturer. It is important for the owner's staff to be able to troubleshoot RTU and communication system problems and make repairs from system spare components.

5.6.3 System Testing Requirements

The SCADA system should undergo a comprehensive system test process to demonstrate that the system performs as an integrated unit. The contractor, as a normal course of system development, should conduct all element, subsystem, and system tests necessary to ensure the proper operation of the control system at various stages of system development. This type of testing will normally be unwitnessed; however, the owner should reserve the right to witness these tests if concerns arise about the progress of system implementation. Four formal, witnessed tests should be conducted on the SCADA system:

- Factory Demonstration Test
- I/O Point Checkout
- Site Demonstration Test
- System Availability Demonstration.

Factory Demonstration Test

The Factory Demonstration Test (FDT) should be a comprehensive demonstration of every functional aspect of the SCADA system. The contractor should develop a test procedure that clearly describes each individual test, including setup, simulation required, and expected results. The test procedure should be reviewed by the owner and engineer. The SCADA system should not be shipped to the project site for installation until there has been a successful completion of FDT. The FDT usually includes a list of functions that are checked off during the test.

I/O Point Checkout

As the SCADA system is being installed, the contractor should perform a complete, end-to-end checkout of every I/O point. I/O Point Checkout should be witnessed by the owner and should be conducted on an RTU-by-RTU basis. After the contractor has completed installation of an RTU (including all associated instrument calibration), the contractor should test every input and output point for proper operation. End-to-end testing should use the process graphic displays to verify proper operation of the I/O points all the way to the operator control console.

Site Demonstration Test

A Site Demonstration Test of the functions, software, and performance of the SCADA system should be conducted after all system elements have been installed and the I/O Point Checkout has been completed. The system site demonstration tests should be performed to verify complete operation of the system, requiring a repeat of much of the factory demonstration tests but with the equipment installed at the permanent sites and should include additional tests required to verify field-installed equipment which was not available at the factory.

System Availability Demonstration

At the completion of the Site Demonstration Test, the owner should conduct a System Availability Demonstration test utilizing all equipment, software, and services of the SCADA system in normal day-to-day operations. During the test the system should be required to meet the availability criteria and performance requirements defined in the system specifications.

5.7 Project Delivery Methods for SCADA

There are a number of different project delivery methods for the implementation of SCADA systems. The most common approach is referred to as design-bid-build. In this approach, the owner employs a design consultant to develop a set of bid documents that define the required functionality of the SCADA system. The owner then solicits proposals from qualified contractors. Some agencies use a selection process in which the contractor's proposal and approach are evaluated along with the proposed price. Once selected, the contractor has single source responsibility for the SCADA system implementation. Due to the specialized nature of SCADA projects, often a System Integrator (SI) will perform the work. A SI is a specialized contractor that implements SCADA systems. The SI can fulfill the role of General Contractor or Sub-Contractor depending on the scope of the project.

A variation of the design-bid-build approach involves the system configuration activities. Of course, in the standard approach, the contractor is responsible for all aspects of system development, including system configuration. However, modern SCADA systems utilize easy-to-use, intuitive tools for the development of the system database, graphical displays, control strategies, and reports. Many owners have begun to take advantage of this system flexibility by assigning the SCADA system configuration to a team of their internal resources and staff from the design consultant. This approach allows for much more flexibility during system implementation and provides significant hands-on training for the owner's staff, but can result in higher initial system costs.

An alternative project delivery approach is design-build. In this approach, the owner develops general functional requirements for the SCADA system; this is often considered a 30% design. The project is then awarded to a team which has responsibility for system design and implementation. The design-build approach can sometimes result in a shorter overall project duration.

Chapter 6. Data Validation, Filtration, Aggregation, and Storage

An RTC system usually gets most of its data from a SCADA system. However, there might be more than one SCADA system involved in an RTC system covering a sewer network and other sources of real-time data might be needed to run the RTC system properly. Further, if the RTC system is a part of a reporting and decision support system, then data from sources in addition to SCADA will be needed. Finally, SCADA systems are primarily designed to control production processes and are therefore often not flexible enough to cover the different tasks to be performed by an RTC system for sewer networks. An efficient and cost effective method to overcome these shortcomings is to use a data management and storage system as a part of the RTC system in order to carry out necessary tasks as:

- Data integration from different sources

- Data validation and filtration

- Data storage and aggregation

- Handling of identified events and scheduled tasks (automatic reporting)

- Hosting of the (model-based) RTC algorithm

This chapter focuses on the second and third bullet. However, as incorrect data can cause problems when used in automated RTC systems, data validation has been given special attention in a more thorough description of some available methods. The RTC system usually communicates with a SCADA on: measurements (levels, flows, gate positions….); status information (pumps and valves on/off….); counters (elapsed operation time for pumps….), etc.,

This information is read from the SCADA by the RTC system (typically once a minute). Data from other sources such as, radar weather systems, downstream wastewater treatment plants, remote monitoring stations, etc. can also be collected and included together with the SCADA data, and passed through the same information path as shown in Figure 6-1.

The necessary data are transferred to the RTC algorithm after necessary signal conditioning (validation, filtration, aggregation, etc.). The RTC algorithm can be different for different scenarios, as different control strategies can be necessary to handle different situations. The chosen RTC algorithm provides the setpoints for the controllers that function within the individual control structures and facilities in the sewer system; setpoints are communicated through the SCADA system and control action is implemented at the final control element.

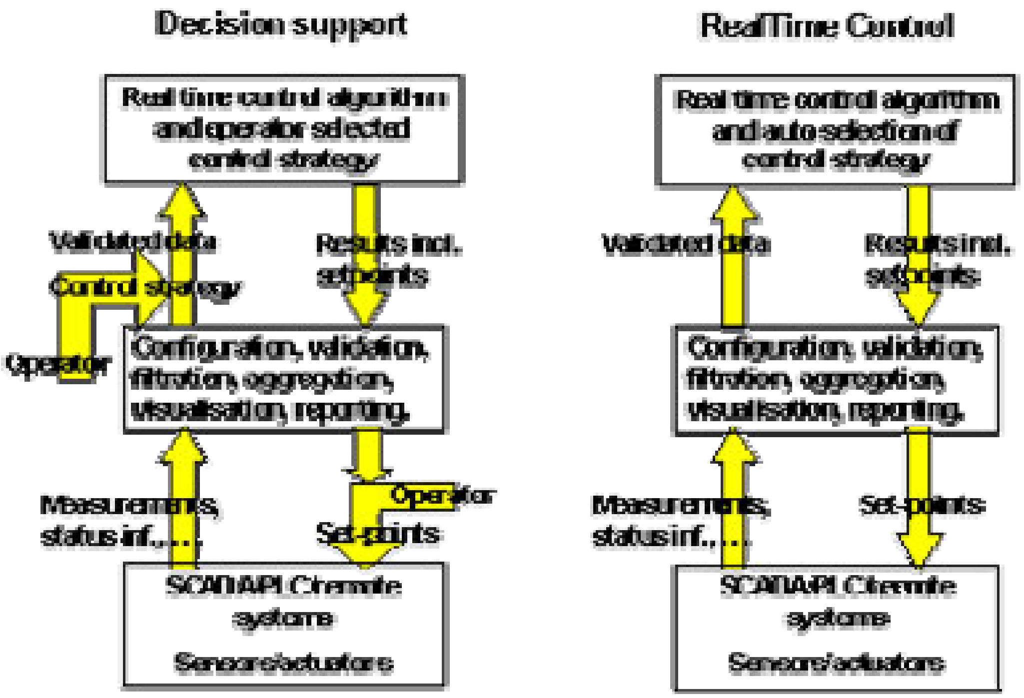


Figure 6-1. Information flow in an RTC system.

As shown in Fig. 6-1, "Decision Support" is an open loop setup. "Real Time Control" is a closed loop setup. The open loop setup requests interaction from an operator, while the closed loop setup relies on automated (programmed) operational rules. As the RTC system reacts directly to its inputs, the quality of the incoming data is critical. Real-time data validation and filtration therefore become one of the important tasks in a well functioning RTC system.

6.1 Data Validation and Filtration

The most common errors in the input data include missing data, measurement values out of range, peaks (outliers) and constant ("frozen") measurement values (indicating that the sensor is out of order). It is possible to check the data for these typical errors using simple methods known as single data validation. However, even if these methods are simple, it is not common that they are implemented directly in PLCs, although the range check might be an exception.

The single data validation methods are applied as part of the interaction between the RTC system and SCADA. One or more methods can be applied as data is read from the SCADA; each method as a result gives a confidence value between 0 and 100 for each data point. If the confidence is lower than a preset threshold, different actions can be taken (avoid using data for control, suspend the control based on the RTC-algorithm and fall back to default control by local control loops, calibrate/repair sensor, etc.).

The single data validation methods are based on the immediate, recent reading, and therefore other methods must also be used to assess the quality of the data in the long term, looking over hours and days (e.g., look for gradual "drift"). These "long term" validation methods are partially based on the same principles as the short term validation methods but are using data from a much longer period of time typically looking days back from the actual time. The long term methods also include additional validation methods to distinguish between instrument drift and a real (actual) gradual change in the process variable. These methods include "cross validation" methods.

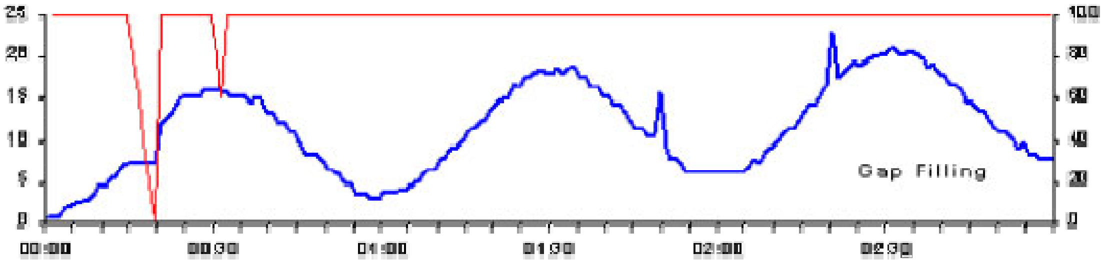
Data validation is an essential step, required before measured data can be used for automated control strategies. In addition to data validation, it might also be necessary to apply *filtering* methods before the validated data can be used in RTC, because even correctly measured data can still include a variation that is too pronounced for closed loop RTC algorithms.

In order to illustrate the single data validation methods, each method is shown in an example based on the same data (Figures 6.2 – 6.6 In all figures, x-axis represents arbitrary time units, the right y-axis is confidence level and the left y-axis is strength of the signals). The data comes from a measurement logged every minute for three hours and showing an hourly variation and a trend. Further, the data has:

- Missing values at 00:15 - 00:20 and 00:30 - 00:32
- Peak values (outliers) at 01:50 and 02:20
- Constant values at 01:55 – 02:05

6.1.1 Gap Filling

Every time a single data point is missing, it has to be considered if a possible control action should use a default option or if it is possible to use an estimate for the missing value and then continue normal operation based on this. Depending on the variability and knowledge of the process measured, several possibilities exist for the estimation of missing data (gap filling). The most simple is to use the value from the last measurement or use the trend from previous values of the measurement. However, if a correlation with other measurements exists or a model is available, better estimates can be obtained.



Measured values: blue; calculated confidence: red. Method adjusted to give zero confidence after five missing values and estimate a value using the previous measured value.

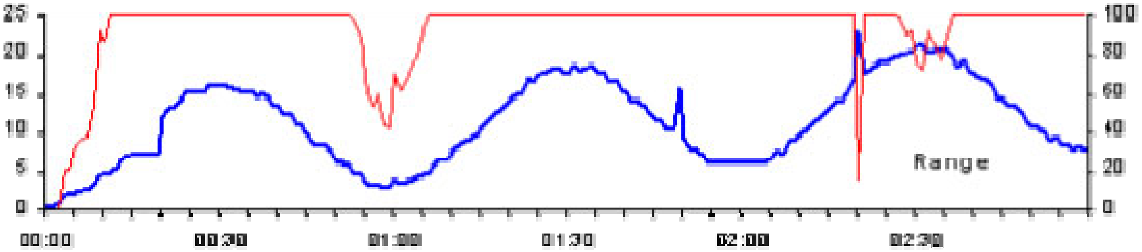
Figure 6-2. "Gap filling" data validation method.

Regardless of what method is used, the confidence in an estimate will be lower than the confidence in the value from a real measurement. Furthermore, confidence will decrease more and more for each consecutive value missing - eventually resulting in zero confidence. How fast confidence reaches zero, and if the decrease in confidence is linear or decreases faster for each value missing, depends on the confidence in the estimates.

6.1.2 Range Check

Values out of range can be related to either the measurement itself or to the expected range of values for the process monitored. The measurement is having a normal working range, where, if properly calibrated, values are believed to be true. This working range should fit the normal variation band of the measurement.

The working range of a sensor is not necessarily the same as the full scale of the sensor. Often, the quality of a measurement is lower at the ends of the full scale, which suggests that confidence in the measurement shall be maximum within the normal working range and decrease gradually to zero through two "warning bands" on each side of the working range. The result of applying these assumptions is shown in Figure 6-3, where the calculated confidence shows unacceptable values in the start of the period, but after a few minutes the values are only triggering a warning. Due to the hourly variation and the drift in the measurement, a warning is again issued after an hour (values too low but might be valid) and after 2.5 h (values too high but might be valid).



Measured values: blue; calculated confidence: red. Method adjusted to accept values in the band from 5 to 20 (confidence = 100) and give zero confidence for values below 1.25 and above 23.75.

Figure 6-3. "Range check" data validation method.

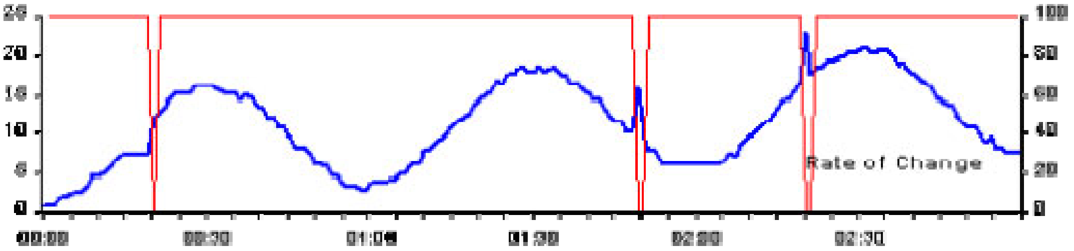
6.1.3 Rate of Change Check

The rate of change in a process variable is an important indicator of the signal quality/reliability. When the rate of change is bigger than the realistic variations in the measurement and/or the noise generated by the sensor, it is usually a clear signal of a disturbance or a problem. The confidence in data that exceeds the feasible (physical, actual) rate of change is normally zero. In such cases, it is often reasonable to accept the previous value (before the disturbance) as a reasonable estimate of the measurement.

Smaller outliers and unexpected peaks in a measurement can also be detected but it can be difficult to distinguish between these when using a simple method. In such cases, confidence can be calculated using a "warning band" similar to the method used for the range check.

The measurement value used in the example varies with approximately 15 units/half h corresponding to 0.5/min, and the random component is not bigger than 1.5/min. Therefore, as long as the numerical difference between two consecutive values is less than two, the values are given a maximum confidence. If the width of the "warning band" is set to 0.5, a numerical difference between two consecutive values has to be bigger than 2.5 before the calculated rate of change is declared as a peak value (peak height greater than 2.5).

Figure 6-4 shows that the peaks can be detected. Also, the shift from estimates to real measurement values at 00:20 is detected, but as this is already known from the gap filling, it can safely be neglected. However, this shows that a sudden shift in measurement values will also be detected by this method.



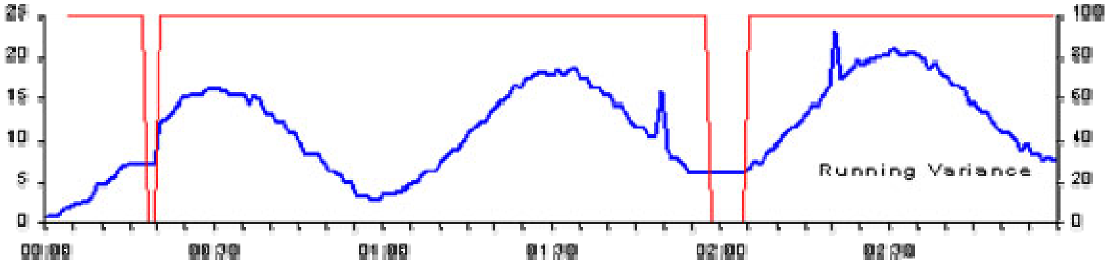
Measured values: blue; calculated confidence: red. Method adjusted to accept peak heights of +/- 2 (confidence = 100) and give zero confidence for peak heights of +/- 2.5.

Figure 6-4. "Rate of change" data validation method.

6.1.4 Running Variance Check

Constant measurement values are typically a result of planned maintenance (automatic calibration) or unexpected (failure) sensor performance, because normally functioning sensing devices always have a small variation in the measurement values. None of the previous methods are able to detect if a sensor fails and "locks" on a fixed measurement value, if this value is within the working range. Therefore, there is a need for a validation method to check the nature of the signal variation. The method should decrease the confidence if the expected variation decreases too much. The confidence will end up with a zero value when the variation has diminished significantly (still allowing for bits to shift in analog to digital converters).

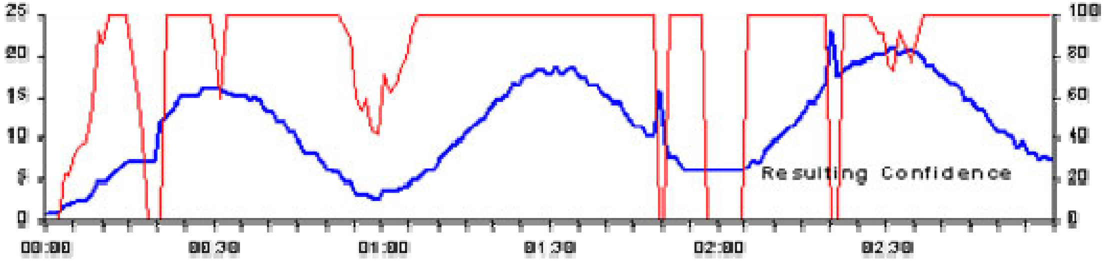
The running variance over 5 min for the measurement used in the example is always higher than 0.05, so the method applies a maximum confidence for a running variance bigger than 0.025 and a minimum confidence for a running variance less than 0.01. Figure 6-5 shows that the constant measurement values around 02:00 are nicely detected together with the estimates used for gap-filling.



Measured values: blue; calculated confidence: red. Method adjusted to use the last 5 measurement values and to accept a variance higher than 0.025 (confidence = 100) and give zero confidence for a variance less

Figure 6-5. "Running variance check" data validation method.than 0.01.

The above methods can be combined and applied at the same time. An overall assessment of the confidence in the measurement value can then be calculated as the minimum of the individual calculated confidence estimates (Figure 6-6). However, as the resulting confidence has focus on the current "snapshot" of sensor performance (here and now), without any comparison to the reference values, these checks will not be able to address the long term drift of the measurement values.



Measured values: blue; calculated confidence: red.

Figure 6-6. Combined method for overall assessment of the confidence in the measurement value.

6.1.5 Checking for Long Term Drift

A known bias in the measurement can be compensated and an unknown bias can be avoided by proper calibration procedures. However, a bias in the measurement value can slowly develop in time, therefore, a validation method detecting long-term drift in the measurement value is needed. Checking for long term drift includes two steps: first detection, and then identification of the cause (trend based on instrument drift, or an actual long-term trend in the measurement).

Detection can be done using two different methods, Expected Mean Check and Acceptable Trend Check, both of them demonstrated below (Figure 6-7 and 6-8) using a measurement having a range of 0 – 100 and logged every 12 min (five times per h). Data from a period of 14 days shows a process variable with a periodic variation of half a day, an expected mean value of approximately 50, and a drift in the measurement starting approximately after a week.

The Expected Mean Check method is based on a calculation of a moving average of the last measured value "n". The moving average is compared to the expected mean value and is allowed to vary within a certain range; the method is therefore a "long term equivalent" of the range check method. It is important that n is chosen in such a way that the moving average is able to accommodate possible periodical variations in the process that is monitored. As shown in Figure 6-7, the expected mean has a value of 50 and the moving average (calculated using the last 60 measurement values) is allowed to vary in the band from 47.5 to 52.5 with warning bands on each side with a width of 2.5.

The Acceptable Trend Check method is based on a calculation of a moving slope. The slope is calculated from the last n value of the moving average calculated as described above. The moving slope is compared to an acceptable trend, and the method is therefore a "long term equivalent" of the rate of change check method. It is important that n is chosen in such a way that the moving slope in fact shows long term drift, and the n for this method is typically 2 - 5 times higher than for Expected Mean Check method.

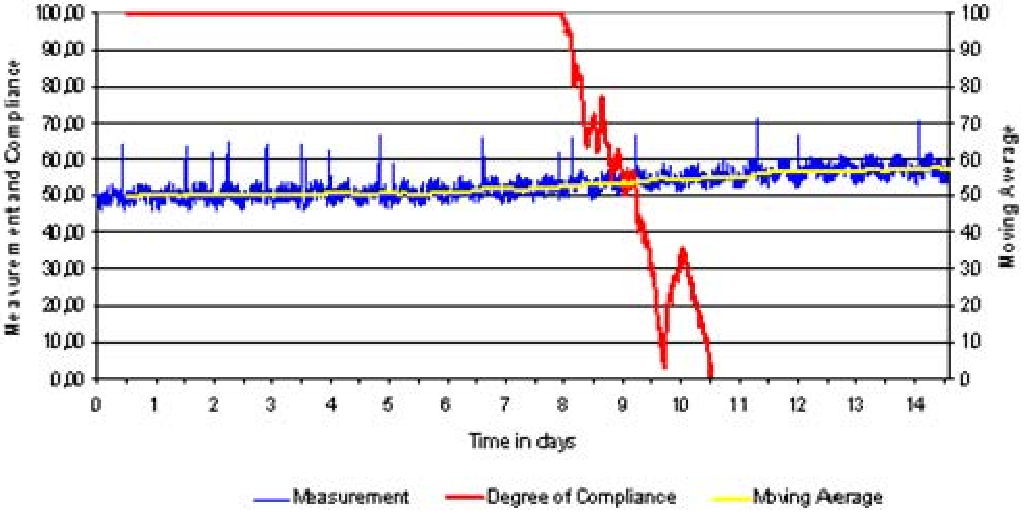


Figure 6-7. Expected mean check method for determining drift in measurement.

As shown in Figure 6-8, the moving slope (calculated using the last 240 measurement values) is allowed to vary in a band from -0.75 to 0.75 with warning bands on each side with a width of 0.25. The drift is detected and a warning given after 7 days based on the moving slope. However, the moving average (Figure 6-7) shows that the resulting bias (or drift in the process variable) is still within acceptable limits. During day 8, the drift becomes unacceptable (Figure 6-8) and the resulting bias increases over the next two days to an unacceptable level (Figure 6-7). After day 13 the drift disappears again but leaves the measurement with an unacceptable bias.

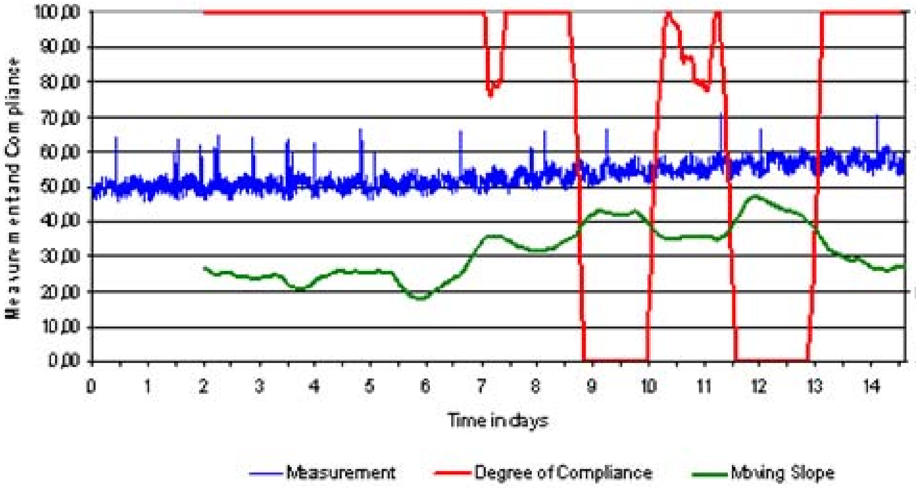


Figure 6-8. Acceptable trend check method for determining drift in measurement.

These methods enable an operator to assess the warnings, and even if both methods works in real time, they are (at least in this example) not so time critical as the single data validation methods. Therefore, actions taken do not necessarily have to be started automatically (even if they could be programmed that way), and the operator can therefore proceed to the next step, which is to determine the cause of the drift. The operator can decide to make a manual measurement (measure a level, analyze a grab sample, etc.) or he can invoke a cross validation method (see next section) and compare the result to the measurement values, and thereby judge if the drift is instrument or process based.

6.1.6 Cross Validation Methods

A cross validation method exploits the possible correlation between measurements and is therefore a multi data validation method. If the measurements are highly correlated, it is possible to build and calibrate a model (simple or complex) describing the relation between two or more measurements. It can be a deterministic or a statistic model, or a combination (known as a grey-box model), and it can have one or more measurements from different sensors as input and one or more of measurement(s) as output. If such a model is running in real time giving a new estimate every time data are logged from different sensors, the estimate can be regarded as a "derived measurement" with the same properties as other measurements. Such an estimate is also known as a software sensor or a virtual sensor.

Some of the more simple examples of software sensors are: a flow sensor based on a level measurement and a flow-depth (Q/H) relationship (one input, one output); a mass sensor based on a flow and a concentration measurement (two inputs, one output); a process rate sensor based on several consecutive measurements of a concentration (at least two inputs, one output); and finally the more complex examples of software sensors which may include real time modeling of the sewer system itself (multiple inputs, multiple outputs).

If a software sensor "measures" the same parameter at the same location as a real sensor, cross validation is quite straightforward because the difference of the two measurements then can be regarded as a new measurement with an expected mean at zero. This new measurement can undergo a range check with narrow limits or directly give an estimate of a bias, which can be followed by the expected mean check. Such a software sensor is also very useful in the case of missing data because the estimate of the measurement then can be used for gap filling.

The simplest cross validation can of course be performed, if an application (for operational security) uses redundant (two or more of the same type of) sensors. Another simple cross validation can be set up in a situation where a flow meter, a level measurement, and a Q/H relation are available.

6.1.7 Data Filtration

Measurements can be rather noisy and fluctuating, which can make them difficult to handle, and difficult to use in calculation of set-points for control. Filtering gives a smoother signal that is better suited for control purposes. However, it has to be remembered that filtering adds to the response time of a measurement. Four of the more commonly used (and simple) filters are described in Table 6-1

Table 6-1. Data Filters Used in Real Time on Measurements

Filter	General expression	Comment
Moving average	$y_t = \sum_{i=0}^{n-1} \frac{1}{n} x_{t-i}$	Also called a rectangular filter. All measurements included are given the same weight. Filters out periodical events with a period equal to the time period covered.
Parzen filter	$y_t = \sum_{i=0}^{n-1} w_{t-i} x_{t-i}$	Also called low-pass filter if weights calculated to decrease with age. Filters out events occurring more often than the time period covered.
Robust filter	$y_t = \frac{1}{n-2} \sum_{i=0}^{n-1} x_{t-i} - x_{\max} - x_{\min}$	Filters out the max and min value in the time period covered and calculates the mean of the rest.
Exponential filter	$y_t = y_{t-1} + a(x_t - y_{t-1})$	An auto regressive filter remembering past measurements according to the factor a. If a=0.5 an abrupt change in a measurement will have reached 97% of its value after five steps.

xt: raw measurement at time t; yt: filtered measurement at time t; n: number of time steps involved.

6.2 Data Storage and Aggregation

The database of an RTC system can be divided into two parts, the static information (that changes less frequently) and the dynamic information. As part of the static information, the database will contain all the configuration information, including user information and configurable properties of the measurements such as:

- Identity name
- Descriptive name
- Location (from location list)
- Method

- Parameter (from parameter list)
- Unit (from unit list)
- Type (from type list)
- Lifetime (how long time measurement values will survive)
- Duration (the period of time a measurement value covers)
- Access permissions (write, edit, append)
- Source identity name (connection information to data source, logging frequency, etc); if empty, data subject to manual input
- Validation parameters

The dynamic information consists of the records logged to configured measurement “channels” in the database. A record should contain the timestamp, duration, value, quality stamp, confidence - where the quality stamp is a more operational way of handling calculated confidences. For example, each measurement could have its own configured quality stamp as shown in Table 6-2.

Table 6-2. Methods for Detection of Long Term Drift

Quality stamp	Confidence level
OK	C >= 90
Estimated	75 =< C < 90
Suspect	50 =< C < 75
Useless	C < 50

The source id could also contain the aggregation information to be applied on measurement in the database selected from the parameters in Table 6-3.

Aggregation is an automatic calculation performed on a measurement within a chosen period in order to reduce the amount of data and at the same time preserve as much information as possible. As for the data validation and filtration, the RTC system needs to be able to aggregate measurements in real time, meaning that aggregation is done periodically, each time when the defined time period for aggregation has elapsed.

Aggregation is frequently used to produce daily values for automatic reporting purposes. An example could be an aggregation of a flow measured in l/s with a logging frequency of one minute into a new measurement with a duration of 24 h (daily flow in m^3/day). The selected time period would be “Day” and the method the “Sum”. Unit conversion should implicitly be given through the properties of the new measurement.

More aggregation procedures can be performed on the same measurement in order to reduce the amount of data without loosing too much of the information. For example, a dynamic one-minute measurement including 1440 values per day can be reduced to four daily values; the daily average, maximum, minimum, and standard deviation. However, detailed analyses of events, calibration of models, etc. will require data with a high frequency. Due to new technology, a data management and storage system can accept large amount of data, e.g., several years of values in minute-based measurements, before the oldest values will be removed by a data diluting service running on the database. Data with a lower frequency will typically "live forever" in the database. High frequency data will normally be available on backups, but as storage capacity becomes cheaper and access times faster, it is easier to have the data a few clicks away and avoid having to restore from a backup.

Table 6-3. Data Filters Used in Real Time on Measurements

Time Period	Aggregation Method
• Hour	• Average
• Day	• Minimum
• Week	• Maximum
• Month	• Standard Deviation
• Year	• Median
• User defined (in minutes)	• Sum
	• Difference
	• Integration
	• Count

Chapter 7. Alternative Configurations/Levels of RTC

There are several ways to categorize control systems and algorithms:

- With respect to *where* the control decisions are made:
    - Local control is executed at a remote site and it does not depend on the communication with the other facilities or other parts of the sewer system.
    - Remote control configuration means that the control actions at a remote site depend on, and are influenced by, input that comes from a different location (most often central control server). Therefore, in case of the communication breakdown, local control can still be operating normally.
- With respect to *who* makes the control decision:
    - Control can be manual (if the operator on site makes the decision)
    - Supervisory (if the operator in the central control room makes the decision on control at a remote site)
    - Automatic (if the control logic and rules and programmed and made without the input of the operator)
- With respect to the *timing of the inputs* that are used for making the control decision:
    - Some control algorithms use only current and past (measured) information in order to make the decisions about control; these algorithms are called reactive, or feedback algorithms.
    - If the control algorithms (also) rely on inputs that are not measured, but are computed as predictions (forecasts) of the future variables (e.g., forecasts of flows, or rainfall), then these algorithms are called predictive algorithms.
- With respect to the scope of their control (*what* is being controlled by the algorithm:
    - Local algorithms control only one site
    - Regional algorithms control several sites
    - System-wide algorithms control all the facilities within the sewer system. Such algorithms are frequently referred to as “global” control algorithms, however, the term system-wide is more appropriate.
- With respect to their inclusion of a mathematical model:

- Control algorithms that include a mathematical model, which must be executed online in order to compute the setpoints and determine the control actions, are called model referenced control algorithms.

- Control algorithms that do not include a mathematical model executed online.

The following paragraphs will describe different options and configurations for RTC of sewer networks, with different levels of complexity and cost, starting from the simpler configurations.

7.1 Local Manual Control

The first level of control is local manual control (Figure 7-1). The operator simply observes the instrument readings at the control site/facility and makes manual adjustments. The only hardware/software (HW/SW) components required for this level of automation is instrumentation and manually operated actuators or controls.

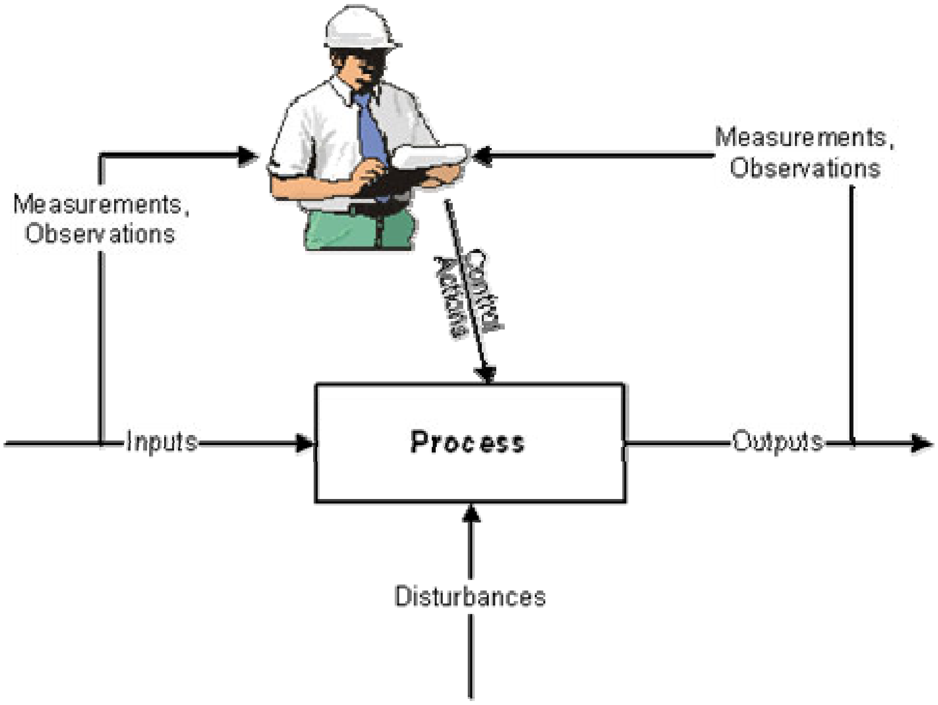


Figure 7-1. Flow diagram of local manual control.

The operator may examine both the outputs of the system (e.g., current flow through a gate) and variables that could be considered inputs (e.g., level upstream of the gate). The operator uses his experience to make adjustments. Since in this case the data acquisition system does not exist, the operator needs to observe the measurements. In some situations, this level of control may be adequate. Experienced operators may sometimes be able to observe and recognize some things that are not routinely captured by sensors (e.g., odor problems, some types of instrument malfunction, or excessive sediment deposits after a rain event).

The possible limitations of local manual control include:

- The presence of the operator is required at the facility to observe the status and implement control actions. This mode of operation is labor intensive for sewer systems that include many different facilities that may need to be controlled.

- The operator can only observe what is happening at this one location and cannot easily assess and consider system-wide conditions.

- Control actions are slow; in case of emergency, it is not possible to react quickly. The actual control actions for a given site are the same either way because the control action is dependent on the gate motor or the pump. However, getting to the site to administer control is slow compared to remote control.

- Since many/most of the stations will be unmanned, the default controls will be static and very conservative; therefore, the sewer network capacity is typically not utilized very efficiently.

For sewer systems that are not very complex and include only a limited (small) number of facilities that can be controlled, local manual control may be adequate. However, many agencies are under financial pressures to reduce and minimize staff levels. Additionally, there may be problems when experienced operating staff leaves or retires. Such organizational factors can adversely affect the ability of the agency to maintain the adequate level of operation by relying only on manual control.

Another potential issue regarding local manual control is that the sewer systems are undergoing slow but continuous changes. Facilities are changed as a result of capital improvement projects or even temporary changes due to maintenance activities. Such changes can impact the way a certain facility or the entire sewer system will "behave" under different conditions and therefore the experience gained in the past may no longer be entirely applicable.

7.2 Local Automatic Control

The next level of control is local automatic control (Figure 7-2). Under local automatic control, the rules and algorithms for controlling the operation of facilities are programmed into the PLCs. The inputs to these programs include the measurements taken locally at the station (e.g., flows, levels, equipment status) and the outputs are the control signals for the local control elements (e.g., gates, pumps) at this station.

This is how most pump stations are normally operated; the level in the wet well is measured and used to make operational decisions and run the pumps. This can be accomplished by placing either analog controllers or digital (programmable logic) controllers (PLCs) into a station. Local automatic control can perform quite well but only the local conditions are considered when control decisions are made.

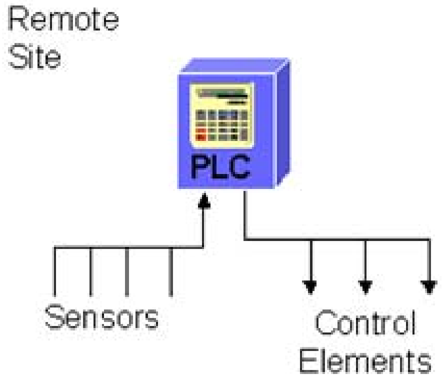


Figure 7-2. Diagram of components of local automatic control.

In the past, before the cost of computers decreased significantly, analog control devices were commonly used for automatic local control. The signals from the sensors were connected directly to an analog control device, and the outputs were wired to the actuators for the control elements. The control settings were difficult to change. In some cases, the analog control equipment remained in the stations even after the PLCs were installed and the PLC interacted with the analog controller. However, it is more common today to connect the PLCs directly to both the sensors (on the input side) and the actuators for the control elements (on the output side).

The possible limitations of local automatic control is that the control strategy implemented at a specific facility can only be based on the conditions at that specific location and does not consider system-wide conditions. Since many/most of the stations will be unmanned, the default controls will be static and very conservative; therefore, the sewer network capacity is typically not utilized very efficiently.

7.3 Control Modes that Require Remote Access

When communications and SCADA are implemented, two more control modes become possible:

- System-wide (or "Global") supervisory control (Figure 7-3). Under this mode, the operator can observe the system-wide conditions from the (often centralized) control console and control any facility in the system remotely.

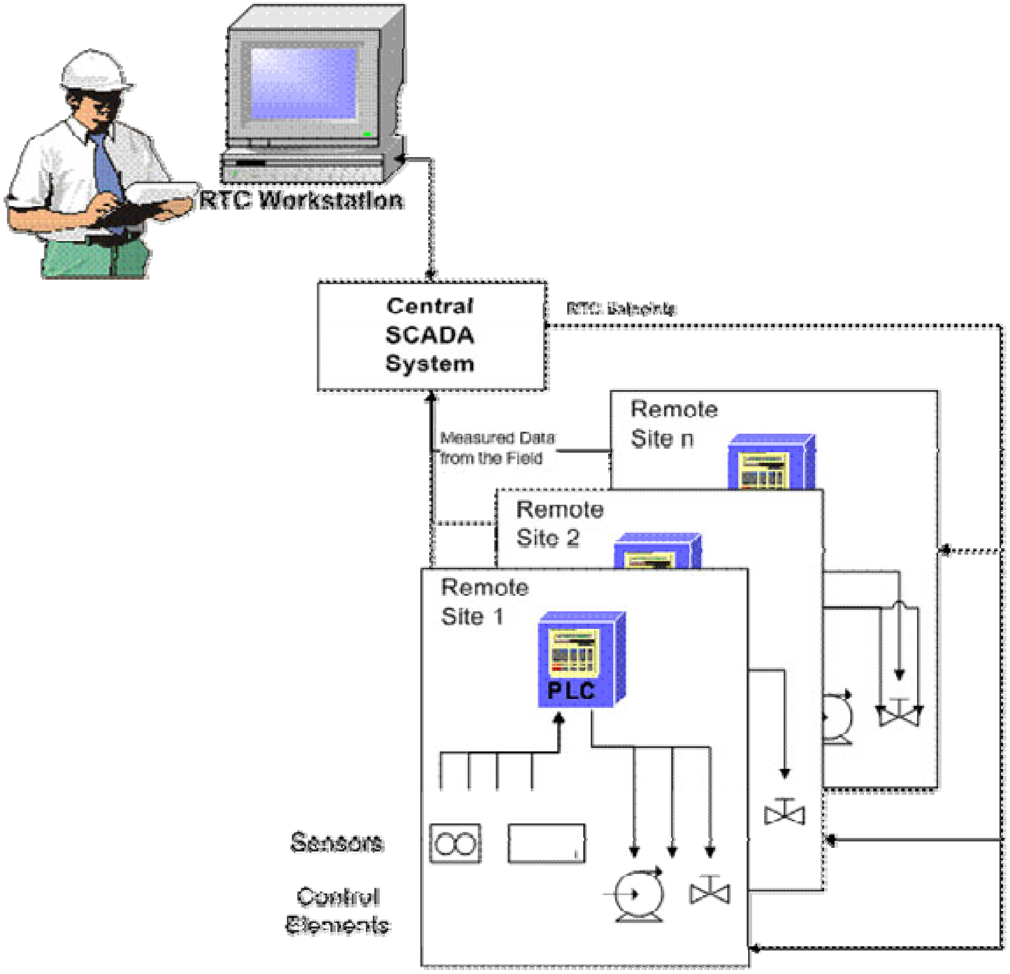


Figure 7-3. Diagram of components of supervisory control.

- Regional control (Figure 7-4). Control algorithms can be set up to control a section or part of the sewer system automatically. This control mode can use remote process variables; for example, the gate at one structure can be controlled using the level signal from somewhere else in the network (not the local level in the same station). This would mean that the rules for operating one or more of the facilities in the region have been programmed and implemented to run automatically on the Central SCADA Server (without requiring operator intervention).

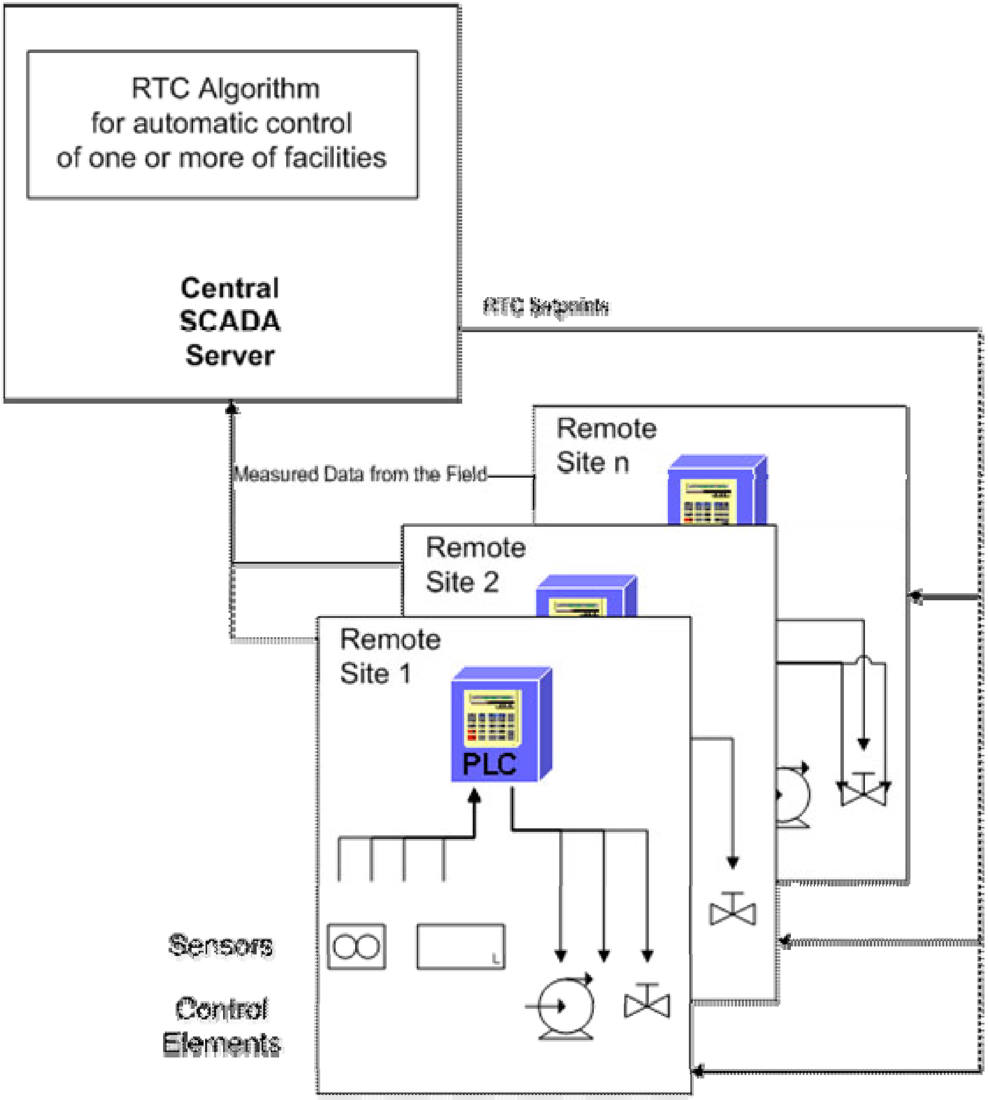


Figure 7-4. Diagram of automatic (remote) regional control.

Both regional control and system-wide supervisory control offer a broad range of useful functionality. System-wide (Global) supervisory control requires not only careful attention from the operator but also a good understanding of the system dynamics. For complex urban networks, determining the most efficient way to operate the facilities can be demanding and requires analysis and planning prior to developing the system design. Regional control may not fully take into account the system-wide conditions because the control logic is based on separate parts of the system and there is no consideration of system-wide conditions.

The next level up is system-wide automatic control (Figure 7-5). This control configuration includes a set of algorithms running on a dedicated RTC server. The algorithms contain rules for system-wide, global control of the network.

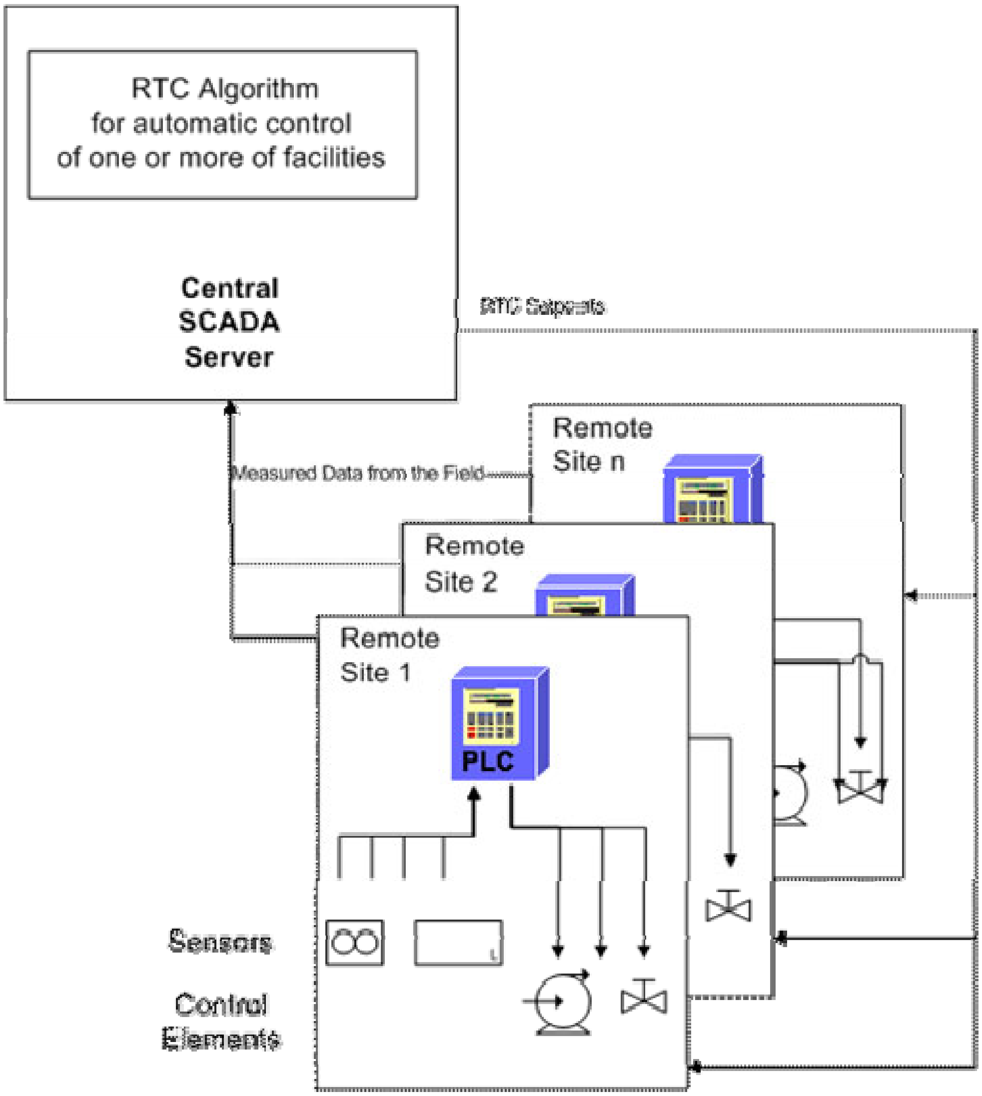


Figure 7-5. Diagram of automatic system-wide global control.

System-wide, global control includes the development and testing of embedded algorithms and logic for the (automatic) operation of the sewer network and the facilities. There are several options for the RTC algorithms; the two main categories of algorithms include:

- Logic based on operating rules. Such logic is referred to as "traceable" or "transparent" because the rules behind the control strategies can be easily discussed with operations staff. The rules of operation can be defined in such a way that everybody involved (including operations staff) has a good understanding of what the rules for different control actions will be under different circumstances.

- Logic based on optimization algorithms that minimize a certain "objective function" that is usually a composite of one or more variables. The RTC based on optimization algorithms must include forecasting (of rainfall or flows) and also demands online models that execute in real time to calculate the state variables for optimization. This control algorithm produces a set of control decisions based on a mathematical procedure that minimizes the objective function. The objective function is a quantified expression of our operational goals and in the process of optimization this function is iteratively evaluated to "find" the strategy that produces the extreme (e.g., minimum) of the function.

In order to evaluate the objective function, optimization will demand advanced knowledge of the rainfall (and the resulting inflows). Therefore, optimization falls into a broader category of *predictive* control methods (Figure 7-6). Forecasts might be obtained in different ways; an example is by using a component that provides forecasts of rainfall. Forecasts would make it possible to implement system-wide, global, predictive control.

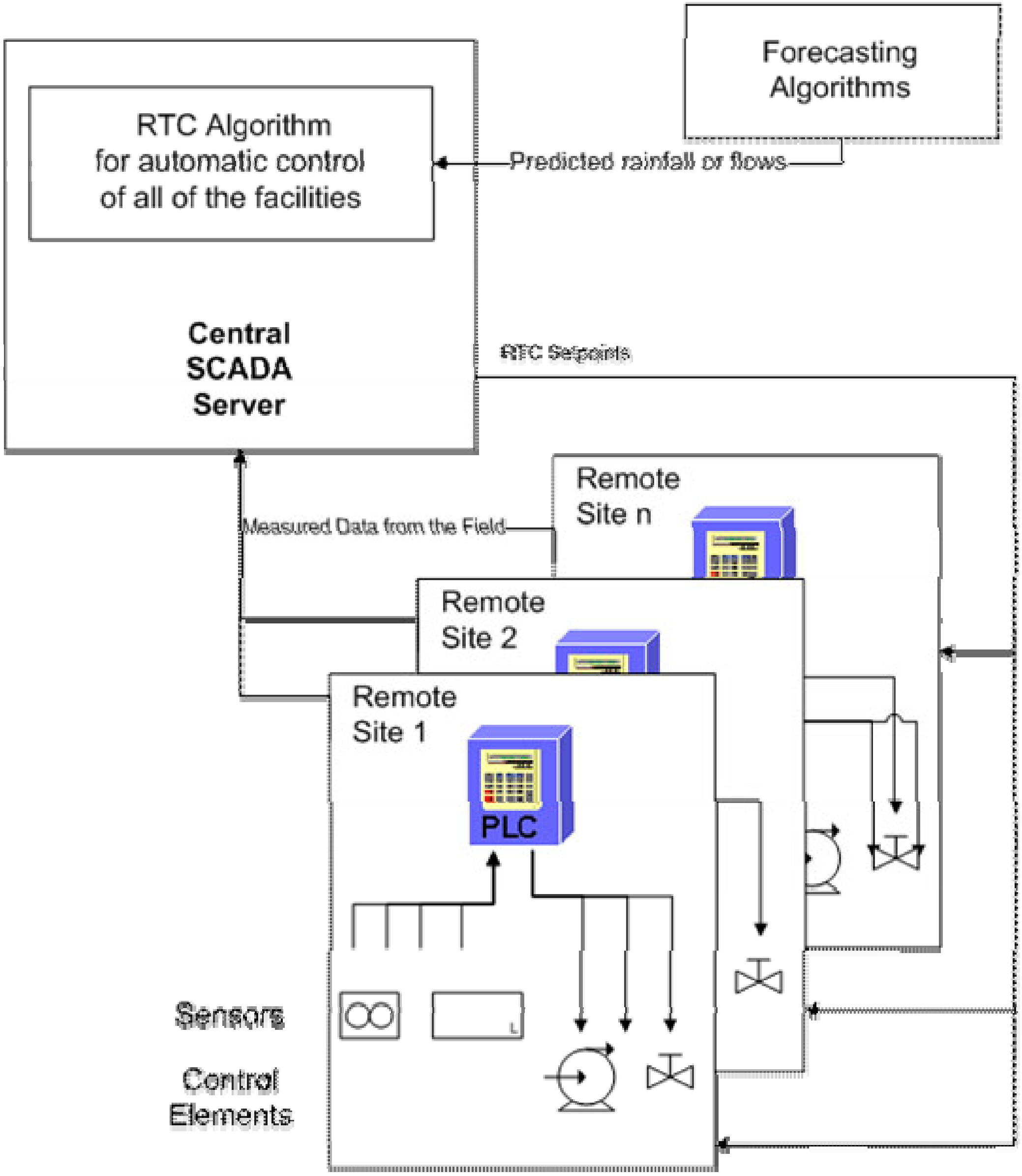


Figure 7-6. Diagram of predictive system-wide ("global") control.

There are some risks associated with using rainfall predictions online, as it is not clear that this technology is at the point where it can be reliably applied. Although some improvements in forecasting rainfall have been made, available methods are not yet at the point of providing reliable and accurate long term (e.g., 12 or 24 h) forecasts for high-intensity (e.g., storms with rainfall exceeding 1 in.) events. Forecasts can be provided by radar systems or using a combination of rainfall gauges and black-box models (such as neural networks).

One specific method for computing the system's control response that has gained high visibility is the linear optimization algorithm. As shown in Figure 7-7, this algorithm requires that a hydraulic model of the network runs online.

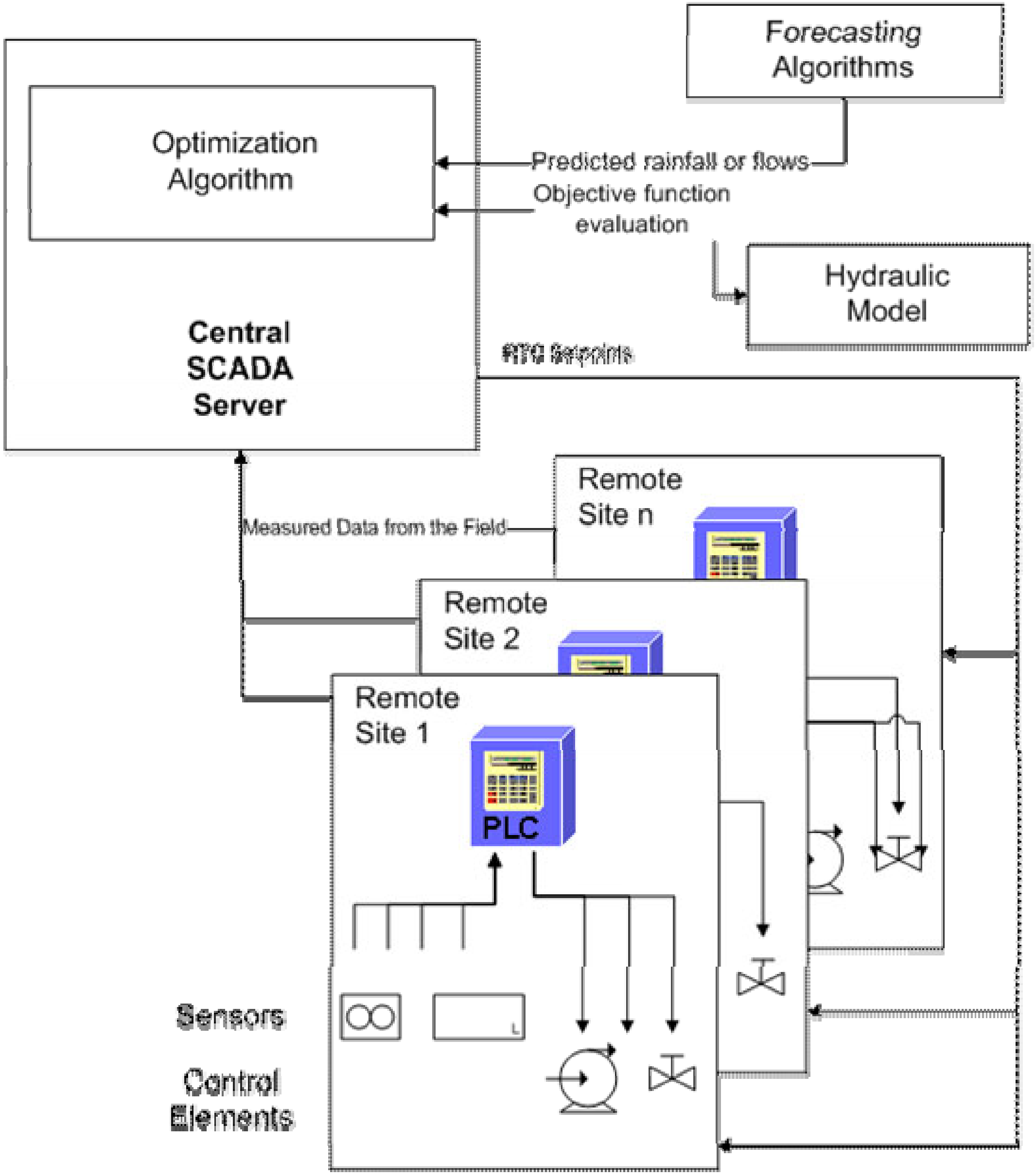


Figure 7-7. Diagram of system-wide ("global") control using linear optimization.

A typical, simplified layout of the components for an implementation of an optimization algorithm within RTC is shown in more detail in Figure 7-8.

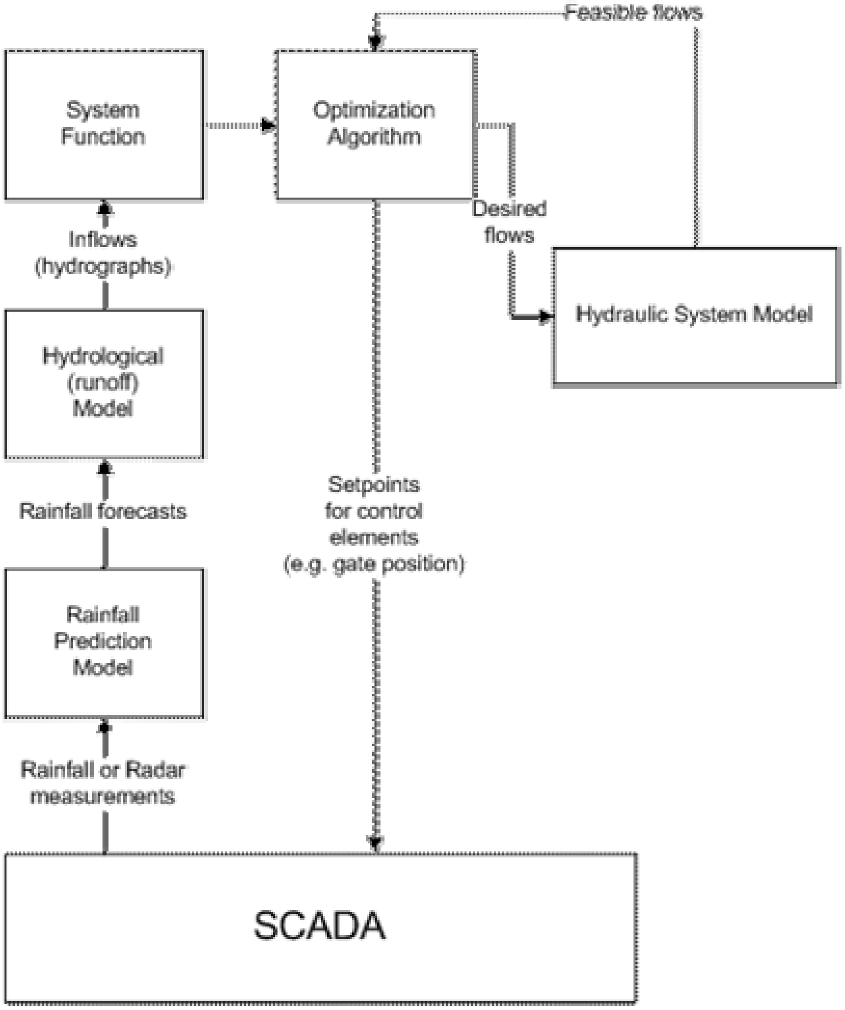


Figure 7-8. Diagram of conceptual layout of optimization in RTC.

As Figure 7-8 demonstrates, this algorithm requires both forecasting and the use of online models for the network. The optimizing "engine" itself is normally an off-the-shelf software package; e.g., in Seattle (King County) and Hamilton (Canada), this component was MINOS package from Stanford University. Referring to Figure 7-8, a typical sequence of computation for online optimization is as follows:

- SCADA system collects the data from the network (e.g., flows, levels, rainfall, radar forecasts, etc.) by "polling" all the remote sites at regularly scheduled intervals. The polling (sampling) interval is normally between one minute and five minutes for a sewer network.

- The module for predicting rainfall reads the process (SCADA) database and computes the precipitation predictions for the specified period of time (called the "prediction horizon"). These predictions can be generated by different systems and algorithms and in some cases may include sophisticated hardware (such as radar) or "black box" algorithms based on historical data (such as time series tools or neural network algorithms). The output from this module is the predicted rainfall for the duration of the prediction horizon.

- The predicted rainfall is provided to the models that can compute the predicted inflows to the network during the prediction horizon. These inflow prediction models can be based on hydrological relationships or other (statistical) models that relate the precipitation to the flows that come from the drainage basins and enter the combined sewer network. The output from this module is the predicted inflows to the sewer network during the prediction horizon.

- The predicted inflows are included in the "system function" that describes the state of the system as it responds to inflows and control decisions. This system representation is connected to the optimization algorithm which tries to minimize the objective function (such as minimize overflows or minimize peak discharge rates).

- As the optimization algorithm searches for the best solution, it needs to compute the system state for each of the alternatives (control settings) that it uses in the search for the optimal scenario. Therefore, it needs to be integrated with the representation of the system that can mimic the behavior of the system and produce the system state. This model of the system is executed online and is often referred to as the "online model."

- The online model can have different characteristics and sometimes simplified (linearized) representations are used because of concerns related to the required computer execution time and stability. In some instances, good results can be achieved by using a simplified hydraulic model that contains only the main trunk lines, interceptors, and controls structures ("skeletonized" version) of the network.

- The optimization algorithm uses the results of the online model to produce a set of desired control actions that are supplied back to the SCADA system (as setpoints) for implementation.

The optimization approach creates a significantly greater demand and expense for maintenance (of models and computer programs) than the rule-based approach. As mentioned previously, the optimization approach requires rainfall prediction.

In summary, with regard to forecasting, it is important to remember that optimization requires that forecasts are provided. Optimization is only one possible way to utilize forecasts for RTC; forecasts can also be used within a rule-based system, where operational rules are adjusted based on the forecasted rainfalls or flows. The best choice of technology and approach depends highly on a number of site-specific factors that must be taken into consideration. It is always prudent, however, to consider the most basic, simplest, and cheapest alternatives first, and then assess the benefits and costs of each additional increment in complexity and cost. A six-year old RTC system in Quebec City shows the specific details of the optimization implementation in that particular application. A very similar optimization method was applied in Seattle (King County) in the mid-1980s.

7.4 Managing Control Modes: Fail Safe Operation

One of the complicating issues about the RTC of sewer networks is that the operational goals change depending on the state of the sewer network. During dry weather, for example, the objective may be to minimize energy consumption, while during wet weather the most important goal may be to avoid overflows. Under all conditions, there are critical constraints such as safe operation, avoiding damage to the equipment, and avoiding flooding. A well designed RTC system needs to effectively manage the different operational objectives and handle the transition between different operational modes in order to provide reliable and efficient operation. An important part of RTC is the management of transitional conditions and operational modes to avoid failure. A reasonable approach to this issue must (at a minimum) address two major categories of risk; failure of equipment, and emergency conditions caused by external factors. Each control/operational level requires that some components of the overall system are functioning properly. Table 7-1 summarizes which components of the overall system have to work properly in order to support different control modes/levels.

Table 7-1. Components Required for Different Control Modes

Control Mode	Instruments	PLCs	SCADA/ communications	Central SCADA server	Active operator input, monitoring	Central RTC server	Rainfall forecasting	OnLine Model
Local Manual Control	X				X			
Local Automatic Control	X	X						
Regional Automatic Control	X	X	X	X				
Supervisory Remote Control	X	X	X		X			
Global Automatic - Rule Based	X	X	X	X		X		
Global Automatic - Optimization	X	X	X	X		X	X	X

Note: Forecasting may be part of rule-based system but is not mandatory.

The fail-safe procedures need to be configured so that they are triggered when the requirements for the current operational mode of the system cannot be met. The fail-safe procedures need to be designed to automatically place the system into the next (lower) mode/level of operation that can be fully supported by the current state of the system components. For example, if the system is operating in the Local Automatic Control mode and the PLCs malfunction or loose power, control would need to revert to Local Manual Control. If the system is operating in Regional Automatic Control, failure of the SCADA system or the central server should automatically trip the system into Local Automatic Control, etc. In case of Global Automatic Predictive control using the optimization algorithm, failure can happen due to problems in any one of the following components:

- Sensors (flow meters, level sensors, rainfall gauges)
- PLC malfunction
- Loss of communication
- SCADA failure
- Central server problems
- Errors or problems with forecasting
- Online model failure or errors

Therefore, even if the ultimate goal is to execute a sophisticated control scheme, such as global predictive optimization, it is a good idea to develop and test the "lower" levels of control that might need to provide backup in case of emergency or component failure. This layered approach can provide the most appropriate level of control for different conditions and helps to manage the overall risks.

The risk management procedures also need to include the ability to deal with emergency conditions that can be detected using the measurements in the field. Special rules can be defined to react to conditions such as, rapidly rising levels in a part of the system. The response can be either an adjustment to the automatic control strategy or a change of operational mode by providing the operator with the Standard Operating Procedure for handling the emergency situation.

Chapter 8. RTC Control Algorithms

An RTC algorithm is a set of rules that determine the control action that will be taken in response to the conditions in the sewer network. The conditions in the network are defined by the levels and flows throughout the network. Levels and flows are often called *system variables* and a "snapshot" of the specific values for system variables at a particular time is often referred to as *system state*. In this section, some of the commonly found RTC algorithms are presented and discussed.

8.1 Local Control Algorithms

Local control algorithms are rules that govern the behavior of a specific control element based on local sensor data and implemented at location of the specific control (remote site).

8.1.1 Primary Controls

Many control elements (e.g., pumps, gates) are controlled using analog controllers. Analog controllers take analog inputs (e.g., levels from a level sensor) and produce output signals that are delivered to the control elements. The control logic is therefore "hardwired" within the electronics of the analog controller and cannot be easily changed. Analog controllers also use discrete measurements (e.g., high-level alarm switches) to start or stop (or open/close) the control elements. The operational logic within analog controllers is usually based on rule curves for starting/stopping pumps or opening/closing gates based on the measurements.

8.1.2 Programmable Logic Controller – Based Controls

PLCs include "industrial grade" processing power and provide the users with a programming environment to define the control rules (algorithms). The most common way to implement local automatic control in sewer system facilities is through using the Proportional Integrated Derivative (PID) feedback (reactive) algorithm that comes standard with most modern PLCs.

As a reactive algorithm, the PID algorithm works by using the difference between the observed (measured) value of the process variable and the desired value of the process variable. The process variable is the variable that we are trying to control; the desired value for this variable is called the *setpoint*. In a pump station, for example, the wet well level may be a process variable and the pump speed (and ON/OFF status) would be controlled to achieve a setpoint (a specific value of the wet well level). The general form of the PID algorithm is:

$$u(t) = u0 + K \bullet [e(t) + \frac{1}{Ti}\int_0^t e(\tau)d\tau + Td \bullet \frac{de(t)}{dt}]$$

Where:

u(t) = controller output at time t

K = controller gain

e(t) = "process error," or difference between process variable and setpoint

Ti = integral time constant

Td = derivative time constant

As can be seen from the above equation, the PID algorithm adjusts the output of the controller in three different ways:

- The Proportional part reacts directly and proportionally to the process error (the difference between the process variable and the setpoint.); the bigger the process error, the stronger the controller reaction.

- The Integral part is used to address, in a way, the history of the process error; i.e., as the process decreases, the proportional reaction is decreased as well. Therefore, the integral portion of the PID controller helps the controller adjust to small but persistent differences between the setpoint and the process variable.

- The Derivative part addresses the direction of the process error and in a way adjusts the controller to the perceived future values of the process error. This component of the PID algorithm is generally intended to speed up the controller and make it more "agile," but in practice it is rarely used because it also can result in unstable behavior of the controller.

The description above is a simplistic, "textbook" explanation of the PID algorithm. Setting up a PID algorithm for optimal performance requires a good understanding of the control theory and an understanding of the underlying process that is being controlled. In practice, algorithms are usually configured based on experience and the algorithm parameters (K, Ti, and Td) are configured for a stable and predictable, rather than optimal, operation. PID is the most common algorithm in process control. It is described in considerable detail in many publications.

8.2 Selection of System-Wide Control Algorithms

A brief summary discussion of several different system-wide control algorithms has already been provided elsewhere in this document. In this section, some general thoughts are presented to facilitate the process of choosing between these different options.

There is no single best choice of algorithm that could be recommended to fit any RTC application. Every RTC application will face site-specific challenges and the choice of the most appropriate algorithm will be influenced by the following factors:

- Size and complexity of the sewer network and the overall hydraulic conditions and dynamics

- Topology of the sewer network and the general flow pattern ("looped" flow with many interconnections or "dendritic" flow pattern without many interconnections)

- Inline storage opportunities. (Are they concentrated in some storage facilities or distributed as inline storage along the sewer network? Where in the network are major storage opportunities located?)

- Organizational issues, including the inhouse expertise and resources available for hydraulic modeling, RTC development and implementation, and for future maintenance/support of RTC

- Budget constraints, both short term and long term

- Overall IT maturity of the organization, status of legacy IT applications (e.g., how stable is the SCADA system?)

- Number, complexity, flexibility, and operational experience with the final control elements (e.g., gates, inflatable dams)

- Organization's experience with instrumentation (e.g., will RTC system use existing instruments or will mostly new instruments need to be installed? How well established are the processes and the funding for maintaining the instruments?)

- Organization's experience with (any type of) RTC of their sewer network (e.g., are local control strategies well established and is there significant experience with using final control elements on the local level? To what extent is their treatment plant run by similar RTC systems?)

- The algorithm may also be impacted by the nature of events that RTC will need to deal with (longer duration, lower intensity events, intense shorter duration events?)

The operational objectives may change depending on the state of the sewer network. During wet weather, the main objective may be to reduce CSOs; during dry weather, the objective may be to save energy (e.g., pumping costs). There may also be a transition period where during the transition from wet to dry flow the objective may be to dewater the storage slowly enough to maximize the total treated volume through the secondary system at the plant. In some cases, therefore, it is not unreasonable to consider different control algorithms for different conditions (e.g., dry weather flow, low intensity event, high intensity event). Some of the specific decisions to be made regarding the system-wide control algorithm may include aspects presented in the following discussion.

8.2.1 Reactive Systems vs. Predictive Systems

Introducing forecasting may improve performance but will add complexity to the algorithm. Forecasts of rainfall deteriorate with the length of the forecasting horizon and forecasts are also less accurate for larger storm events. It is important to remember that rainfall forecasts are not the only way to predict flows/levels in the sewer system. It is also possible to use current measurements (e.g., rainfall and levels in some parts of the network) to forecast levels and flows in the network. For an example of such forecasts, see Heinz and Schultz (2006) (Milwaukee). Since forecasting increases the complexity of the system, benefits over the simpler reactive system should be identified in order to justify the additional complexity and expense.

8.2.2 Automated Rules vs. Optimization

Rule-based systems are transparent and can be easily understood by the operators. Optimization algorithms require forecasts, online models, and the algorithm itself is not readily transparent to the operators. In general, optimization algorithms must be proven to offer sufficient additional operational benefits to justify additional resources for the development, implementation, support, and maintenance. Also, it is important to remember that the word "optimal" is often used in colloquial language with the meaning "the best possible or available." However, in this case "optimal" translates only into one specific mathematical procedure (optimization) and it should not be misunderstood to mean "the best possible" overall approach to this specific problem.

It would be difficult to specify the exact and straightforward generic (non-site specific) selection criteria for choosing the most appropriate algorithm for RTC. Such a decision requires careful consideration of several different factors such as:

- Is the system running "close to full" even during dry weather? In such a case, it will be difficult to obtain benefits from RTC of any kind and additional ("brick and mortar") storage will be required. Using modeling and simulations, different RTC approaches (and algorithms) should be considered as part of the planning and design of new facilities.

- What is the situation with online measurements (e.g. , flows and levels)? Have these sensors been properly maintained in the past? Are there plans in place to maintain them properly in the future? Online measurements are the foundation of the RTC system. An organization that does not have a strong commitment to keeping the online sensors up and running should be very careful when considering automation.

- Is there enough historical data to calibrate the models and provide for a meaningful analysis of system dynamics? Without such data, it will be difficult to build models, and thus assess the impact of different RTC strategies.

- What is the history of communications and SCADA systems in this organization? Have these systems been implemented? Have they been operating reliably? Again, automation should be applied cautiously if there is a history of problems with systems that provide the necessary infrastructure for RTC.

- Does the organization have experience with dynamic ("movable") control elements? One organization discovered that a major control facility (gate) was wired incorrectly: indicators were showing "open" when the gate was actually closed, and "closed" when the gate was actually open. This gate operated this way for years and nobody noticed it. There are obviously risks associated in automating such a facility.

- Is the hydraulic nature of the problem complex? For example, most of the overflows may be concentrated in very few facilities. Therefore, most facilities may not have much of an impact and spending money for their automation may not be effective.

- Will the organization make the financial and organizational commitment to maintaining a complex piece of software?

Rule-based systems are generally more intuitive, less complex, and they introduce a significantly smaller maintenance burden. Clear operational benefits from optimization over rule-based systems should be identified to justify the additional complexity and cost. Since forecasting is part of optimization, there should also be sufficient confidence in the forecasting methods.

Rule-based systems can also be more flexible. Optimization requires that the objective function is (mathematically) formulated. In many cases, such objective function focuses on reduction of overflows. The operational objectives, however, may change depending on the state of the system. During dry weather, for example, the objective may be to save energy. Heuristic rules can easily consider different objectives and their transparent nature makes operator involvement easier.

Chapter 9. Design/development Methodologies for RTC

This chapter addresses the steps in developing an RTC system. Not all systems will include all the phases listed below. The appropriate level of RTC, and the appropriate level of investment into RTC, depends on the specific aspects of each collection system. The steps listed are generic and the activities can also vary in their scope and size.

9.1 Considerations in Planning

The need and proper application of an RTC system is best understood in the context of a plan for how the overall collection system is expected to operate. A System Operations Plan (SOP) defines the operating strategy for the major facilities in the collection system during dry weather and wet weather conditions as well as the transition phases between dry and wet weather. The SOP shows how the existing and future collection system components (including static, local, and remotely controlled facilities) will operate to achieve specific operational objectives. By considering the entire system operations, the need and functional requirements for RTC become more evident and understood. The SOP should be developed and/or updated as part of the design of new sewer facilities that may require real time controls. The SOP will likely identify additional communications and controls that are necessary for system operations and should be implemented along with the new facilities.

An SOP should provide the descriptions, graphics, and supporting information for the following elements:

- Regulatory and performance objectives that are to be achieved by the collection system. Operational objectives include minimizing overflows, minimizing energy consumption, minimizing sediment deposition, and maximizing the volume treated through secondary treatment. Operational objectives are discussed more thoroughly in Section 9.3 below.

- Overall collection system layout including the location of major control facilities such as diversion structures, interceptor conduits, pump stations, and treatment facilities.

- Development and evaluation of various scenarios that have been simulated via a hydraulic model and evaluated according to how well they meet the regulatory and performance objectives.

- Functions of each major control facility during dry weather conditions, transition to wet weather conditions, wet weather conditions, and finally the transition to dry weather conditions.

- Function of the overall integrated system (each component working together) during dry weather conditions, transition to wet weather conditions, wet weather conditions, and finally the transition to dry weather conditions.

- Location and function of the monitoring and communication systems necessary to inform the operators and provide control over the collection system to achieve the operational objectives.

- Recommendations, including expected implementation schedule and costs. Implementation may include a more extensive RTC feasibility study to better define the design requirements of the control system.

9.1.1 Development and Evaluation of Operating Scenarios

As part of the system operations planning process, a variety of operating scenarios should be developed and evaluated to determine the benefits, costs, and impacts of different levels of automation and control at the key facilities. At this point in the process, it is useful to examine each structure and determine if a simple, low-tech solution will sufficiently meet the objectives, and determine if there are significant benefits and capabilities provided by a more sophisticated control system that justify the costs. As applicable, each key structure can be examined for different levels of control:

- Fixed or static controls, such as an orifice and a fixed weir

- Manually variable controls, such as a stop-log weir or a moveable gate

- Automated local controls, in which a gate or pump is controlled based on the local sewer level

- Automated remote (centralized) control, in which gates and pumps are controlled from a central location using remote sensing to determine the state in the sewer at multiple locations and make control decisions based on that current state

- Predictive centralized control, in which decisions for gates and pumps are controlled based on the current state and the hydraulic modeling predictions using rainfall forecasts

Upon reviewing these levels of control for different facilities, the simplest level that will cost-effectively achieve the operational benefits should be selected and recommended for use in the SOP.

While examining each structure or facility, the scenarios should also examine system-based options for achieving the operational objectives. Scenarios containing typical system-based options may include:

- Flow-routing options: Examine different routes for flow to be directed in order to conserve energy consumption (via pumping), maintain scouring velocities through all conduits to minimize sediment deposition, and provide odor control by keeping septic sewage away from populated areas.

- Flow-source options: Examine different strategies to capture flows from specific sources while minimizing flows from other sources. For example, examine different methods to capture priority flows from an SSO source versus a CSO source versus a stormwater source.

- Flow-equalization options: Examine methods to minimize the rate of change in flow to the treatment plant during both dry and wet weather conditions. These would include different flow routes, pump controls, and use of inline and offline storage.

- Dewatering Options: Examine various rates for dewatering stored wet weather flows in order to maximize the total volume of sewage treated through the secondary system while also preventing the formation of septic conditions (odor, H2S, and biological impacts) and preventing unnecessary overflows resulting from back-to-back storms that occur before the storage facilities have been emptied from the previous storm.

When examining the individual structures or the system-based options, the evaluation should include appropriate hydraulic model simulations, evaluation of benefits (compared against operational objectives), estimation of costs, and a decision making process to select and recommend specific controls and operating strategies. Although the final SOP does not need to contain all the documentation from the development and evaluation of scenarios, it must include the recommendations and the basis (justification) for those recommendations. In some cases, automation of a structure may be recommended due to organizational preference and efficiency as opposed to minimum costs in that it may be preferred by an organization to provide remote control of a gate rather than send out an operator on a weekly basis to change the gate setting.

9.1.2 Weather Conditions to be Examined

The SOP will naturally examine the operational strategies for dry weather and wet weather conditions. Each operational objective can typically be classified as either a dry weather objective or a wet weather objective or both. The duration of the dry weather period is typically longer than the wet weather period, yet both last sufficient time to justify close examination of the expected system performance during each condition. It is also important to closely examine the transition phases between the dry and wet conditions because that is where some of the most difficult questions arise. Some of these questions include:

- What system measurement or event triggers the end of the dry weather condition and the start of the wet weather condition? What measurement determines that the wet weather event is over?

- What is the sequence of response actions that should be implemented once a wet weather event is triggered? And when the wet weather event is over?

- How does the prioritization of operational objectives change as the system moves from the dry weather objectives and changes over to the wet weather objectives?

For these reasons, it is important for the SOP to cover at a minimum:

- Dry weather conditions (can be further examined as “summer dry weather” and “winter dry weather” conditions)

- Transition to wet weather conditions

- Wet weather conditions (can be further examined as “wet weather – prior to overflow” and “wet weather – during overflow” and “wet weather – flooding” conditions)

- Transition to dry weather conditions

9.1.3 Considerations for the Project Team and SOP Document

The engineering planners and designers will typically lead the project team assigned to develop the SOP because it is often a component of a larger facilities design that will significantly change the operations of the collection system. However, the targeted audience for the SOPis primarily the operations staff who will be taking control of the collection system once the new facilities are completed. Therefore, it is necessary to have operations staff on the project team, sharing responsibility for developing the plan as well as providing extensive review of the documents. Because of the complexity inherent in the functions of a collection system, it will be necessary to strive for simplicity and clarity in the descriptions of the operation strategy. For example, the operations manager of a 300 MGD POTW required the project team to summarize the operations plan in the basic terms of: “Is it a “Pump First – Store Second” strategy or a “Store First – Pump Second” strategy, or something entirely different?” The project team was able to state it was a “Pump First – Store Second” strategy and went on to describe how each system component supported that overall strategy and how it met the operational objectives.

The SOP will also provide extensive information for the engineering staff charged with designing the RTC infrastructure. The SOP can be used to develop monitoring specifications, PLC and control panel requirements, as well as control narratives for operating each of the major structures. The process for designing the RTC infrastructure is presented next in Section 9.2.

9.2 RTC Infrastructure Design

The foundation of any RTC system includes the instrumentation, online SCADA, and control facilities (e.g., gates, weirs, valves dams). In many cases, the infrastructure that supports an RTC system will exist before RTC is considered or developed. Design practices for the components of this infrastructure are covered in detail in different sources and are beyond the scope of this report. This report focuses on the development and implementation of RTC strategies, assuming that the required infrastructure is in place.

The process for designing RTC usually includes the following stages:

- Feasibility study, to determine whether there are opportunities for RTC to improve the operation of the collection system, including the definition of the operational goals, the development of hydraulic models for the collection system, the analysis of system hydraulics, and preliminary investigations of (the impact of) some potential RTC strategies.

- Detailed analysis of different control strategies and selection (or design) of the most appropriate RTC algorithm, including model simulation and offline testing. Different strategies are simulated using the model results (levels, flows) as inputs and their performance is evaluated using the model results. Strategies are evaluated using the performance metrics discussed in the next section.

- If necessary, design and installation of additional sensors and/or field automation components (PLCs/RTUs).

- Possible upgrades to final control elements (e.g., adding remotely controlled actuators to gates) along with applicable field testing of control elements.

- Development and programming of RTC algorithms.

- Installation of RTC algorithms into the online environment.

- Supervised online testing and training.

- Online startup and implementation of the RTC system.

A brief summary of the key RTC implementation tasks is presented below.

9.3 Defining Operational Goals and Performance Metrics

In many cases, RTC is at first assumed only to be a method for reducing wet weather overflows during heavy rains. However, operators need to deal with many other issues and operational goals are often more broader and more complex than just reduction of wet weather overflows. An important component of a RTC project is to determine the most important operational goals and operating constraints. This should be done in the very early stages of the project, as these goals and constraints will be the foundation for all technical activities. The methodology to determine the operational goals and constraints includes the following:

- Study the operational manuals and documentation on the current operational strategies

- Conduct structured interviews with staff at different levels of the organization

- Examine regulatory requirements and guidelines for new facilities being implemented (i.e., EPA CSO Policy and Guidance, as well as state requirements for implementing CSO facilities)

The result of this research will be a prioritized list of objectives. An example of such a list, from the RTC project at the Milwaukee Metropolitan Sewer District (MMSD) Project Report is as follows:

"The evaluation of different operational alternatives was done within the framework of the stated operational objectives, listed below in the order of importance:

- *Minimize Basement Backups*

- *Minimize Potential for Sanitary Sewer Overflows (SSO)*

- *Minimize Risk of Failure*

- *Minimize the Number of Combined Sewer Overflow (CSO) Events*

- *Maximize Long- term Sustainability*

- *Minimize CSO Volume during CSO Events*

- *Use the Inline Storage System (theMMSD deep storage tunnel) Effectively*

- *Minimize Operating Costs with No Adverse Consequences to Other Objectives"*

"During the objectives definition process, certain elements of system operation were identified as operating constraints rather than objectives. These constraints include:

- *Comply with all requirements of the Wisconsin Pollutant Discharge Elimination System (WPDES) permit.*

- *View the Jones Inland Wastewater Treatment plant (JIWWTP) and South Shore Wastewater Treatment Plant (SSWWTP) treatment capacities as externally defined variable-operating constraints, which will be provided as inputs to the strategy.*

The WPDES permit contains operating requirements for the ISS, which include: The ISS cannot be filled above the crown of the ISS main tunnel (elevation equal to -177.17 feet, MMSD datum) at its upstream terminus. The ISS shall be operated in a manner that ensures a net positive head. Holding time within the ISS should be minimized so that the likelihood of compliance with the net positive head requirement is maximized.

The wastewater influent capacities at the JIWWTP and SSWWTP will be treated as input constraints to the RTC strategy. These wastewater influent capacities are assumed to be available to the strategy at all times. Because capacities can change at any time, for example, if a major treatment unit fails and is taken out of service for repair, the strategy will need to respond accordingly."

Prioritized operational objectives and constraints can serve as a critical guide for the development of the RTC strategy, but are not sufficient. In addition to establishing the goals and the constraints, it is very useful to quantify them by establishing the metrics. An example of metrics, from the same report and linked to the operational objectives listed above, is shown in Table 9-1.

Once the metrics are established, they are used as a basis for comparison between different scenarios, strategies, and operational alternatives. As can be seen from the above example, a number of the objectives listed can be assessed based on simulations; they are included in the hydraulic model results.

Some of the objectives are not linked to hydraulics; for example, from the list above, the operational objective to maximize long term sustainability reflects the desire to implement an RTC system that does not impose an unreasonable maintenance burden after implementation. Such objectives may not have a clear and straightforward metric but are important and need to be considered as well. In this particular case, an RTC design must always consider simpler algorithms before more complex and demanding algorithms.

9.4 Analysis of Hydraulics

In order to effectively plan and implement RTC in a sewerage and stormwater system, it is essential to understand the hydraulics of the network. In this regard, computer models provide the opportunity for well structured analyses and offer a scientific framework for coordinated management and planning of RTC.

Hydraulic models provide two key capabilities; simulations are used to compare different operational scenarios and such analysis also enhances our understanding of the network dynamics and behavior under different conditions. Urban drainage models are used to understand the rather complex interaction between rainfall and network hydraulics. Once the existing conditions have been analyzed and understood, alleviation schemes can be evaluated and the optimal control scheme can be designed and implemented.

Table 9-1. Metrics for Simulation Type

Operational Objective	Metric	Model Analysis Approach
Minimize basement backups	Flag activation frequency	Check maximum water levels at each critical node
Minimize potential for SSOs	Did an SSO occur?	Determine if SS gates close in the result file
Minimize risk of failure	Dependence on mechanical devices	Number of gate and pump activations and hours of pump operation
Minimize number of CSO events	Did a CSO occur?	Determine if CS gates close in the result file
Maximize long-term sustainability	Reproducible strategy development procedure	Not a model outcome
Minimize CSO volume during CSO events	Volume of CSO (MG)	Add discharge at every CS gate to determine total CS volume in the result file
Use the ISS effectively	Volume left in ISS when event ended (MG)	Total ISS volume minus maximum volume stored
Minimize operating costs with no adverse consequences to other objectives	No metric	Not a model outcome

A model is a simplified mathematical representation of the physical system. This representation may be based on a deterministic approach (i.e.,with a fixed relationship that includes known mathematical descriptions of the underlying processes), or it could be stochastic (i.e., involving terms of probability into the model inputs and the interpretation of model results). Models for urban drainage and stormwater are predominantly deterministic models; the text below will refer only to this class of models. Furthermore, deterministic models applied for urban drainage can be roughly classified as physically-based models and conceptual models. Attributing a model to one of these classes depends on the level of mathematical sophistication in the treatment of underlying physical processes in the model. Practically, the models are classified according to the importance of empirical parameters for the models' ability to describe these processes accurately. The reliance on empirical parameters classifies the model as conceptual and emphasizes the need for validation against field measurements. In this context, various hydrological models would belong to the class of conceptual models, while a hydrodynamic network model is an example of a physically-based deterministic model.

Urban drainage models are expected to reproduce behavior of the modeled system with a high level of accuracy. This is usually ensured through the process of parameter calibration and the verification of model results against the measured performance of the real system. Calibration involves adjustment of the model's key parameters, under the objective of minimizing the differences between the model results and the field measurements (e.g. , of water levels). A continuous period or a set of intermittent events used for calibration should preferably include a full range of expected operational conditions in the system. Verification provides a proof that the model generates results within the acceptable error range. A reliable verification should be carried out for a simulation period or intermittent event(s), which are different and independent of those used for the model calibration.

All models must, if possible, be calibrated before application. Conceptual models require more attention in this respect compared to fully deterministic (physically-based) models and the assumptions of the conceptual models must be proven valid. Thus, in urban drainage modeling, focus of model calibration is usually based on correcting and adjusting the parameters in the hydrological models (conceptual), while the deterministic hydrodynamic models of the drainage network typically require just minor adjustments for an accurate performance. However, independent of the applied model type, a good modeling practice recommends thorough model verification before any serious application.

Reliable field measurements in the sewer system and laboratory analysis results are essential for successful model calibration and verification, i.e., for the model application as the whole. Harsh environment in sewers and urban drains (presence of poisonous gases and pathogen microorganisms in confined conduits, aggressive fluids, floating debris), as well as particular hydraulic conditions (alternating free-surface and pressurized flow, rapid flow surges, etc.) require special monitoring equipment and highly trained specialists for achieving good results. Routinely measured variables include water level, flow velocity, flow rate, conductivity, temperature, pH, H_2S, etc. Chemical and biological properties of the water, as well as sediment characteristics, are obtained by manual or automated sampling, followed by laboratory analyses.

The standard of hydrological and hydraulic models today is that they are able to simulate flow though all important parts of a hydrological and hydraulic network. Thus, dynamic hydraulic models can typically describe processes such as surface runoff, infiltration, and the hydraulics of pipes, channels, weirs, gates, pumps, etc. It is outside the scope of this document to provide a detailed description of all of the elements that may be found in an urban drainage system but the text focuses on the description of the flow equation applied to describe the hydraulics in the pipes and channels. Since stability of the model is an important factor in simulating operational changes, it is important that the model can handle all dynamic conditions normally encountered during operation. Models using implicit (as opposed to explicit) methods generally provide a better platform for RTC design and evaluation.

9.5 Offline Analysis of RTC

The planning process of RTC can typically be divided into a number of steps as outlined in Figure 9-1. The first is naturally to formulate the objectives in terms of drainage system functionality, operations, and environmental impact. As a support for any further analysis, a set of statistical performance descriptors, which describe the defined objectives, have to be defined. For example, if the objective is to reduce the CSO overflow, then the descriptor could be the frequency of CSO. Another typical example could be the area of flooding, the load on the treatment plant, pollutant emissions area to the receiving waters, etc.

The development of a hydrological and hydraulic model of a complex urban drainage system for a large city is an elaborate process. This process includes a number of activities, focused on the transformation of the operator’s practices and experiences, raw data set, and other available knowledge about the system (PLC, previous setpoints, etc.) into operational simulation models of the system, capable of reproducing the actual system functionality. The developed models may differ in the area of geographical coverage and the level of modeling detail, all according to the intended purpose. A typical “layout” of the modeling tools for offline evaluation of RTC is shown in Figure 9-2.

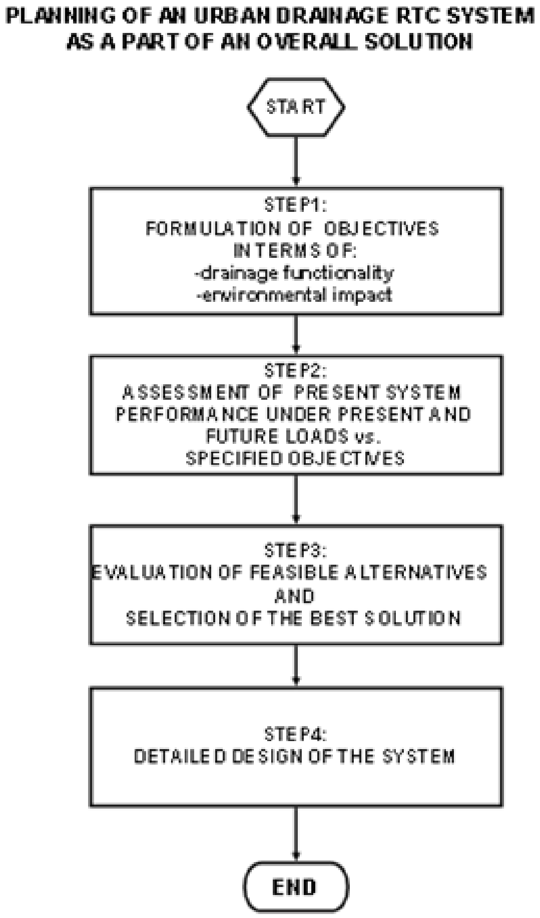


Figure 9-1. Schematic of RTC planning process steps.

Often, the initial task within the context of numerical modeling activities is the development of a reference model of the city’s sewerage and stormwater system. The reference model should comprise the entire sewerage system of the city and should be based on the existing asset database and operating procedures. The reference model should provide a detailed insight into the storm and sewerage system in terms of structural composition, connectivity, specific sites, existing local and system-wide control algorithms, etc. As such, the reference model is used as a reliable foundation for subsequent modeling activities. It is important to insure that data asset analyses and consistency checks must be integral activities of the reference model development. Data consistency and quality are essential conditions for successful model performance. The wastewater asset data obtained from the source database must be examined for inconsistencies and for obvious errors. Any inconsistencies found must be investigated in the field and any survey work deemed necessary in order to provide the missing information must be organized.

The next step in modeling activities is the development of operational models, which will form the foundation for further analysis. The reference model (described above) should be used as the source for this development. Establishment of operational models would often be realized through a series of activities as outlined below, although the actual selection of project activities depends on the specific project characteristic.

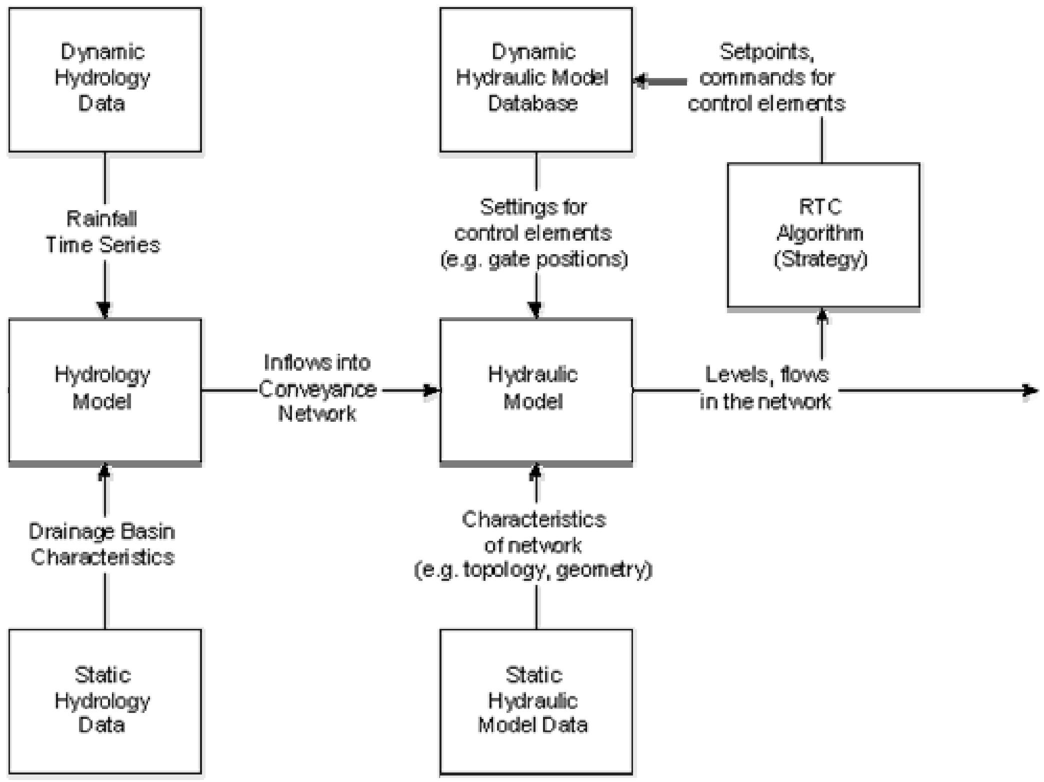


Figure 9-2. Components of offline simulation environment for assessing RTC.

The first activity will typically aim at giving an overview of the hydrology within the total catchment area, and specifying the hydrological load. In some cases, it is important to extend the hydrological description to a model concept that takes into account the direct surface runoff and overland flow, as well as the slow response component caused by infiltration into the sewer system from the surrounding soil. The latter load component depends strongly on the hydrological history, i.e. , on the preceding events. Once the hydrology of the system has been defined and modeled, it is followed by the development of pipe models. The development of the pipe (network) hydraulic model is often separated into several stages, such as:

- Development of main trunk sewer model
- In very large cities it may be advantageous to develop operational sub-models, based on the sub-areas identified within the main trunk model
- Integration of the sub-models into a general operational model

The purpose of the main trunk sewer model is to establish a global hydraulic description of the system. The main trunk sewer model will usually include the following key elements:

- Main trunk sewers and some secondary sewers as identified
- Important storage facilities and elements
- Significant overflow structures located on the trunk sewers
- Significant pumps located on the trunk sewers

In many applications it is fully sufficient to develop a trunk model, while in very large cities it may be necessary to separate the main trunk sewer model into hydraulically independent areas. For each sub-area, a more detailed operational model may be developed. The purpose of these sub-models is to provide an accurate, yet rational, hydrological-hydraulic description of the drainage system functionality in all operational conditions for all individual sub-areas and to enable efficient hydraulic analyses of individual structural and functional upgrades in the area of concern. The appropriate level of modeling detail should be defined in close cooperation with the municipality staff and on the basis of experience from similar projects. Finally, all the different sub-models could be merged into one comprehensive model covering the entire system.

Calibration and verification of computer models is often a very complex and critical step of the model-setup process. The level of confidence in the models, and subsequent recommendations based on the models, is a direct function of how well the models are calibrated and verified. The amount of time required to calibrate the models is dependent on the amount and quality of the monitoring data and the effects of the various assumptions and simplifications regarding the layout and size of the network. For example, the exclusion of many of the minor branches may require addition of compensation storage or capacity.

The confidence level of model outputs will largely depend on the spatial extent of the flow and level monitoring and the magnitude of the rainfall events. A relatively high number of flow monitoring sites would be required to establish the spatial distribution of both wastewater and stormwater sources. The paucity of flow monitoring data within these areas will necessitate assumptions, which will influence the validity of the hydraulic models. Water consumption data for sub-basins should be adopted for calibration of the models for dry weather flow conditions.

Calibration of each model is typically done as follows:

- Calibrate the model to dry weather flow conditions (full diurnal patterns)

- Calibrate the model according to the below mentioned selected type of rain events

- Verify model calibration to other independent wet weather events

The adequacy of the calibration should be consistent with the manner in which the collection system has been represented in the model and the quality and applicability of the measured rainfall and flow data used. The developed models should, at a minimum, be calibrated and verified against:

- A short extreme rain event

- A long term rain event

- Two rain events which show large spatial variation

After the evaluation of the present system performance has been completed, the next step is to select the RTC sites and evaluate different feasible alternatives for RTC strategies.

Review of the potential RTC sites may include both physical condition limitations and hydraulic performance constraints. As outlined in the previous chapters, potential RTC sites are selected with consideration of available storage within the system, uneven loading on the system, and critical diversion (flow-splitting) structures in the system, etc. Physical condition limitations of the RTC sites include, for example, the stability of the pipe bedding to support insystem storage, the structural integrity of the sewer to withstand potential hydraulic surges and prolonged period of surcharge, and adequate space for the installation and maintenance of RTC control devices. It may be necessary to perform site visits to identify potential physical limitations. Often, RTC strategies are designed based on simulation of events. However, long-term continuous simulations are also frequently carried out to confirm the suitability of the RTC scheme and its impact on the long-term system performance.

It is difficult to define a fixed, unique, prescribed list of simulations that should be conducted as part of offline analysis. A brief summary of generic ideas regarding offline RTC analysis is listed below:

- Perform simulation of the existing system (under current control strategy) for a range (light – medium – heavy) of rainfall events. The purpose of these initial simulations is as follows:
    - Establish a reference that any future simulations of potential RTC strategy will be compared to (based on defined operational goals).
    - Identify the “gross” storage limitations of the existing network. For example, if the pipes are close to full all throughout the network even during a small event, the potential for using “existing storage” will be limited.
    - Examine the spatial variability of storage; where is the “available storage volume” located?
    - Examine the distribution of wet weather overflows; are they concentrated around just a few facilities?
    - Examine parts of the model where additional pipes may need to be added to the model; for example, if a conduit connecting to our network is not currently modeled in detail, but it appears that it is significant from the hydraulic point of view, the model may need to be adjusted.
- Prepare simulation runs that include potential “candidate” RTC strategies that will be examined. Every simulation run will build on the lessons learned from the previous simulation. Modelers and engineers can make better progress if they bring experienced operators into this process and discuss the proposed strategies with people who have experience in running the “actual” system.
- Present the operational objectives represented in the models and the results of simulations to the operators and solicit their ideas. Sometimes, people will practical experience will point out why a strategy that looks good “on paper” may not be a good idea and they can provide other ideas that they have developed to address similar operational objectives.
- Always start simulations from simpler, “lower cost” alternatives that would require fewer changes to the existing infrastructure. An example of such progression is presented below:
    - Simulate the network configuration as is and only change the operating rules/strategy for existing control elements
    - Consider simple operating rules first
    - Gradually increase the sophistication of the RTC approach and assess the benefit of each added “layer of complexity” to the RTC approach
    - If additional sensors may improve RTC, add the sensors into the model
    - Consider automating existing facilities (e.g., adding a remotely operated gate actuator)
    - Consider physically upgrading existing facilities (e.g., adding a gate where one does not exist currently)
    - Consider more expensive network modifications (e.g., adding a storage tank)

It is important to always frame these analyses within the context of the costs and the operational goals, as described in Section 9.2.

9.6 RTC Implementation

As is the case with many other types of IT systems, the best methodology for the implementation of a specific RTC system is the one that is based on, and remains focused on, the underlying business needs. The methodology for implementation also needs to recognize the specific issues and conditions of the client organization. This means that we must always focus on the primary user, the operations staff and their needs. Since sewer networks (in different cities) are different from each other, and the business issues and drivers for RTC vary from one municipality to the next, there is no single recipe for RTC implementation. However, there are some general guiding principles that may be applied to most RTC implementations, as follows:

- Phased approach works very well for RTC. It is unwise for an agency that does not have much experience even with basic RTC components (e.g., SCADA systems or instrumentation) to consider moving to sophisticated RTC technology without some carefully planned transition.

- Simple control strategies should always be considered first. The fewer things can go wrong, the more stable RTC will be. Any change towards more sophisticated algorithms, and/or more complex RTC systems, should be incremental and should be considered on its own cost-benefit merits.

- Implementation needs to include carefully planned testing phases, including offline testing, and online startup and testing. Operator training needs to be part of these testing phases.

- It is critically important to involve the users (operators) in the development of RTC as early as possible and to continue that full involvement through implementation. Otherwise, the RTC system may not be embraced and accepted by the users.

- The methodology for implementation needs to recognize the specific issues that each client has. In many cases, obstacles to successful RTC implementation are not technical but political (e.g., users may not accept the system). Therefore, implementation methodology needs to recognize the organizational aspects of the municipality and it should not go “against the cultural grain” of the organization.

For the long-term viability of RTC, it is also essential to develop good documentation both on the “programmer” level and on the “user/operator” level. Although intense training classes (short courses) are very useful, it is best if the users (e.g., operators) can be introduced to the technology throughout the duration of the project, through meetings and workshops, so that they can gradually learn and adopt the RTC technology and tools. A hands-on, one-on-one training program for the operators during system startup is critical to the adoption of the RTC system by the permanent users.

9.7 Hydraulic Analysis Tools for Urban Sewer Networks

Hydraulic models can play different roles in designing and implementing an RTC system. During the RTC design process, hydraulic models are used to simulate different operational scenarios so that different RTC strategies can be compared against each other. Hydraulic models can also be implemented online and embedded into the solution as part of the actual RTC strategy (algorithm). Some hydraulic models are better suited for RTC design or implementation than others. However, the capabilities of hydraulic models that are available in the marketplace change from one product release to the next, so statements regarding specific modeling products that are provided by different vendors would only be valid for a specific period in time. In general, however, there are some features that make the model well suited for RTC, as follows:

- Since operation of control elements to take advantage of the available inline storage will introduce backwater in some cases, it is important that the hydraulic model is based on the dynamic wave solution to the St. Venant equations. It is not necessary nor desirable for the model to simulate rapidly varied flow (transient analysis) such as water hammer effects.

- The hydraulic model should include a dynamic representation of the control structures and the final control elements (e.g., pumps, gates, inflatable dams, etc.). The user should be able to easily configure the operational settings for the control elements so that the model can accurately represent their operation.

- If a hydraulic model is to be incorporated into the online environment as part of the actual RTC algorithm, the model needs to have the ability to dynamically interact with the online environment.

The upfront purchasing and annual maintenance costs to license hydraulic modeling software is often a very small part of the overall budget in an RTC project but selecting an inferior tool can introduce problems and headaches in implementation. Therefore, it makes sense to select a product that has a demonstrated ability (e.g., actual installations) of performing well as part of RTC projects or implemented RTC systems.

Chapter 10. Project Management and Organization

Managing projects is a key function within every municipality. A wealth of information exists regarding general project management. A good place to start the search for the most appropriate reference is the web site (www.pmi.org) of the Project Management Institute.

RTC sometimes has the image of a "complicated computer project" and many municipal managers are concerned about projects that deal with automation and hardware/software components. This is especially true if the projects in question are complex. Complex computer projects have a less-then-perfect performance record overall and have often gone beyond the anticipated budgets or schedules. Most of the projects that a municipality may execute include actually building facilities and are therefore traditional civil engineering ("brick and mortar") projects.

A number of key components in an RTC project are computer programs; therefore, a significant portion of the deliverables is software. When the deliverable is software, traditional project management techniques that are applied to "brick and mortar" projects are not adequate. Rather than looking to traditional project management techniques, it is far better to consider the experience that has been gained from managing software projects.

Management of software projects includes a set of procedures and methodologies that are called Software Development Life Cycle (SDLC). There are different models for SDLC (e.g., waterfall, spiral, rapid development) and they are discussed at great length in IT literature. The key overall objectives that should be addressed within the SDLC include:

- Ensure that the requirements for the project are well defined and documented; requirements should be prepared in such a way that acceptance testing can be easily performed at the end of the project

- Establish testing procedures that will make it possible to identify the issues and problems as early as possible

- Provide effective interaction between domain and IT experts

More recent software development methodologies, along with the increased acceptance of advanced object oriented software development tools and languages, have led to some changes in the approach to the development of functional requirements. There is often no longer an expectation that all aspects of how the application will work can be described in detail in a document before the application development begins.

Overall, the best approach to managing the development of RTC is incremental and iterative. Therefore, RTC projects should be structured in phases and additional layers of complexity should be added only if they are cost justified, preferably after the less complex components of the overall RTC system have been implemented and tested.

Although project management techniques from software development may be used, it should be noted that RTC users may not be computer specialists. The critical success factor in an RTC project is user acceptance; therefore, the project management methodology must include mechanisms for obtaining and maintaining user acceptance. The ***user*** for the RTC system is the operations staff, and therefore they need to take the central role in all aspects of the project. In order to successfully introduce and implement an RTC system for a municipality, it is very important to understand the culture and the tradition of the organization. The understanding of the organizational culture is important in every phase of the project, from the early stages when the funding for the project is being established, to the final stages of startup and implementation.

The reader might wonder what "understanding of the culture" really means in this context. This might sound like a generic, and perhaps vague, phrase that everyone can agree with, but what does it really mean in this practical, specific case of completing an engineering (RTC) project? To answer this question thoroughly and provide some theoretical foundation might require a significant effort that is far beyond this document. However, the following are some practical examples and suggestions based on twenty years of experience dealing with RTC issues in a number of organizations. These thoughts are formatted as questions in first person since these are some of the questions which will need to be considered when approaching an RTC project:

- Where did the idea for the RTC project come from? Did it originate in the operations department, or was it "invented" and "imposed" on the operations by upper management, engineering, or planning? Often, there are tensions between operations and management or engineering and in private the operations folks might feel that the engineering folks do not care or understand what "their real problems are." There is often even a sense of independence and pride with being a "field guy."

- Is there a "project sponsor" for RTC? The project sponsor is a senior manager or a person on executive level, who is interested in RTC. Sometimes, a project sponsor is a visionary, keen to bring in the technology to his organization. While this enthusiasm can provide great benefit and momentum to the project, it is a good idea to find out how the project sponsor defined the RTC, as they promoted the idea within the organization. In other words, some promises may have been made internally even before the request for proposals ever came out. Some of these promises, while well intentioned, may be difficult to achieve. They must all be noted and the expectations of RTC must be understood.

- Is there a "project champion"? A project champion is a technical person who is interested in RTC and is an advocate for it. A project champion has strong technical skills but often does not have decision-making authority; he is hands-on and also keen to see that RTC is successful. It is important to know how the project champion gets along with other people in the organization because it is likely that people will "personalize" the RTC project and sometimes resistance to the project champion may turn into resistance to the project.

- Who is the "go to guy" in operations? In most organizations, there are one or two guys who have been around for many years. When there is an emergency or a question, other people in operations will go to them with questions. It is very important to include these folks in all aspects of an RTC project and also to show them a healthy dose of respect for the knowledge that took twenty or thirty years to gather. The "go-to-guy" can provide a great sounding board as we evaluate different alternatives.

- What is the general attitude towards automation? In one case, upper management in a municipality advertised the automation effort as part of the effort to "de-man the facilities" (even a more favorable interpretation of this term implied loss of jobs). When an RTC engineer appears to interview the operators after such announcements, he might not be met with complete enthusiasm from the operators.

- Have there been some "horror stories" in the past that will make people in operations very cautious? People generally do not like taking risks. If we want them to embrace the RTC project we must convince them that they will not be taking a risk.

- Different organizations have different cultures and different levels of interest or pride in their work. In many cases, the dedication and ingenuity of the people who keep RTC systems running is very impressive. It is a good idea to tour and visit as many facilities as possible. Are they kept clean? If facilities are not cleaned they may not end up being well maintained either.

- What might operations be privately concerned about? It is very unusual for people to bring up their real concerns in meetings, especially if many people are present and if their supervisors or managers are present. They will bring it up one-on-one if they trust the other person. Therefore, it is important to spend time with operators, listen, and earn their trust, before they will be willing to tell us what they really think.

The list above is by no means complete but it illustrates the types of issues that can be considered when we are working on RTC and that fall within the broad term “culture” in an organization. In all of the examples listed above, the words “he” or “guy” are used to describe the organizational issues. This is not meant to be interpreted as an example of exclusionary gender-specific language, but it was simply easier to write this way.

10.1 Long-Term Support and Maintenance

Completing an RTC project is not enough; mechanisms must be in place to keep the system running. Some of the general guidelines regarding long-term maintenance of the RTC system are as follows:

- Simpler RTC systems are easier to maintain. Therefore, increased complexity (of RTC design) must yield sufficient operational benefits to offset these costs and risks.

- Active involvement of the operators and maintenance managers throughout all the phases of the project including the RTC conceptualization, design, and implementation, will increase their understanding of the system and facilitate acceptance and long term viability.

- When the RTC is being designed and developed, there may be a temptation to develop customized (“one of a kind”) software components. Keeping highly customized software to an absolute minimum and maximizing the use of commercial off-the-shelf software components will make maintenance easier.

- If the municipality has internal technical (engineering and IT) staff that has the expertise and the experience to perform majority of the maintenance, this will greatly enhance the chances that the system will keep running in the long term. Hiring such staff is often difficult for many reasons; e.g., caps on the number of employees (“full-time equivalents” or FTEs) in municipalities frequently make this very difficult. Also, compensation levels for people with such skills can be relatively high in the private industry and there may not be a logical “upward mobility” career path for such a person within a municipal organization (public agency).

Some of the recommendations listed above are easier to accomplish for a large agency than for a small agency, because the resources are less readily available in a smaller agency. In all cases, however, the maintenance aspects must be considered early on in the project and need to be reflected in the RTC design.

10.2 Critical Success Factors for RTC

Development and implementation of RTC projects can be a complex task and such endeavor carries certain risks. Risks can be minimized if one pays attention to some key issues or “success factors”:

- Operational staff (the users of the RTC system) must be involved in RTC design, development, and implementation. This involvement needs to start as early as possible and the involvement needs to be active.

- Operational needs, goals, and requirements must be clearly understood and documented because RTC strategies must specifically address these needs. If the agency has a system operations plan, RTC should be addressed along with other operational issues.

- Operational goals must always be the key metric and reference point, along with costs. Technology must remain the means, rather than the end.

- Reliability of the RTC system is very important; it is essential that the system does not break down when people depend on it. For this reason, treatment plant operators and engineers involved with the RTC design will require increased levels of redundancy and safety factors incorporated into the design similar to the plant systems.

- RTC systems will require effort after implementation; this effort includes maintenance and support of all RTC components, including instrumentation, communications, SCADA, and RTC software. This effort must be properly planned and funded.

- Since there is significant need for coordination, it is not wise to push for short schedules and quick implementation. Great pressure for accelerated schedules may jeopardize the overall quality and reliability of the system and adversely affect system acceptance.

The above “success factors”are based on practical experience and observations.

10.3 System Integration and other IT Issues

Throughout the past twenty or thirty years, municipalities have implemented a number of different information systems to address a broad array of different business needs. A typical “landscape” of such applications, likely to be found in a municipality, is shown in Figure 10-1.

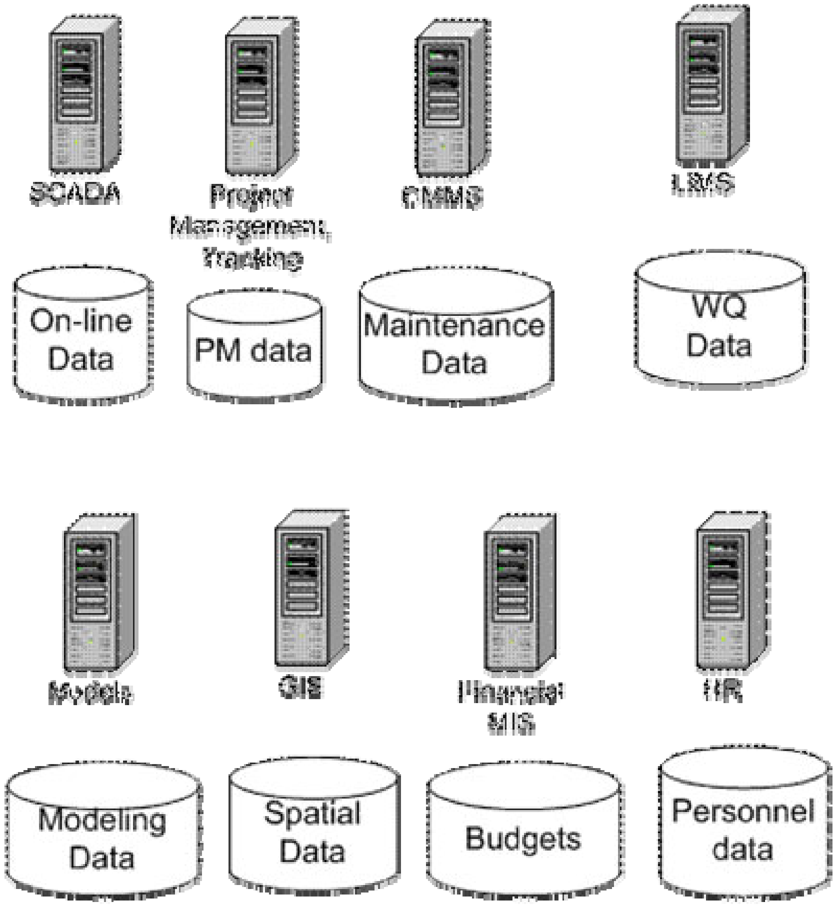


Figure 10-1. Typical applications and associated databases in a large municipality.

As shown, applications include SCADA, Project Management (PM), Computerized Maintenance Management System (CMMS), Laboratory Information Management System (LIMS), mathematical models, Geographic Information System (GIS), and administrative systems such as Financials and Human Resources. Additionally, there could be IT systems to handle inspections, customer information systems, and a number of others.

When a sophisticated RTC system is implemented, it will join the family of applications that already exist and function within the organization. Therefore, it is important that the RTC fits well into the existing overall IT environment. The term “system integration” describes the ability of different computer systems and applications to “work well together.” Systems integration can be implemented on the *data level* or on the *functionality level*. Integration on the data level implies that different applications can exchange or share data; integration on the functionality level implies that the functionality provided by one application may be invoked from a different application.

Issues of computer system integration are especially important if the design of the RTC system will be more complex and advanced, e.g., system-wide RTC that is model-based or includes optimization. In general, it is much better to integrate systems on the data level because the structure of data is relatively stable. A model-based system-wide RTC system, for example, will require that the RTC algorithm is integrated with SCADA (to obtain the measurements from the field and to deliver RTC setpoints) and also connected to the model that represents the hydraulic behavior of the network. Additionally, if results presentation includes maps, at least a connection to a GIS will be needed as well.

Chapter 11. Decision Support for Operators

In discussions about RTC, emphasis is often placed on automated control strategies, where algorithms make decisions about the operation of the system. In many ways, this is a limited view that excludes the role of the operator and ignores some important issues; examples of such issues are:

- Algorithms for reducing wet weather overflows during heavy rainfall are not of much use during the periods when such rain events are absent.

- Operational objectives change depending on the state of the network; RTC could be designed so that it is helpful to operators even during dry conditions, when they deal with emergencies or special conditions caused by equipment failure, or major maintenance or construction activities that impact the network and the facilities.

Therefore, focusing RTC discussion only on automated strategies (algorithms) ignores many other needs that operators may have. One could say that there are two ways to automate a sewer system; automation could make the operator more effective or the goal may be to replace the operator in some decision-making processes. While focus of RTC is usually on the later, decision support systems (DSS) aim for the former. Rather than producing operating decisions through algorithms, DSS aim to help the operator make their own decisions.

The key to helping the operators make better decisions is to provide them with information that will facilitate their decision-making process. Information that could be helpful to operators often exists already, but it may reside in a computer system or application where it is not easily accessible. The central concept of a DSS is system integration. A DSS integrates the information that resides in different parts of the "computer system universe" within an organization and allows the users to view and analyze enterprise-wide data. The benefits of such a system include:

- Information that would otherwise be "hidden" within a single computer system or application, and difficult to access for any but the few users of the primary application, becomes available to users on different levels of the organization. The DSS facilitates information exchange between different functional groups within the organization.

- Analysis that requires information from more than one area or source (e.g., SCADA, LIMS, GIS, models, or CMMS) is greatly facilitated when such diverse data is available through a single access mechanism (often called "portal"). With increased emphasis on holistic approaches to reporting and decision-making, such analytical capabilities provide a direct benefit on the planning (strategic level).

- Some methodologies (e.g., publish-and-subscribe model) for integration can simplify long-term maintenance of links between different computing systems and are preferable to a point-to-point integration directly between different software applications.

- Preferably, DSS can deliver a generic, off-the-shelf tool kit that offers many advantages over one-of-a-kind customized integration solutions developed with only site-specific criteria in mind.

- The implementation of DSS helps coordinate delivery of data by individual primary applications to a broader audience within the organization; DSS development helps establish the guidelines that each application can follow to provide some of its data to users throughout the organization.

- An example of the monetary benefit will be if the capital project implementation can be optimized because some of the projects can be postponed, delayed, or avoided based on more complete analysis.

Overall, the DSS helps obtain value from the previous investments that had been made in different IT systems. Just a few examples of how information could be used on different levels include:

- A sewer network modeler could have access to information about the sediment levels in different branches which normally reside in the inspection database.

- An operator could use a map view (coming from GIS) to observe the history of flooding complaints (from Customer Information System). Using SCADA data for current levels at measuring points and a hydraulic model, a hydraulic profile within a conduit could be presented to the operator. Combined with elevations for different manholes, potential flooding risk could be identified.

- A supervisor could be alerted if a contract (e.g., for sludge hauling) is close to expiring.

- Information could be passed between different applications, run times from SCADA to CMMS, status of work orders from CMMS to operating personnel.

The DSS could have many uses. The examples provided above are just a few of the possible situations where a DSS could add value. Improved access to information can provide a foundation for better decisions .

11.1 Integration of Online Models into DSS and RTC

DSS could be seen as a broader IT framework for management of urban drainage systems and therefore RTC could be seen as a component of an overall DSS. The specific role of RTC within a broader DSS framework would be to provide tools and methods for online functions, addressing a selected objective function (e.g., reducing CSOs).

When mathematical models are integrated into the online RTC environment, they can add valuable analytical capability to the operators. In order to integrate mathematical models into the online environment, at a minimum it is necessary to provide the following:

- A mechanism for the models to extract the online information about the state of the sewer network from the SCADA system

- Tools so that users can configure the interface between the model and “the real world” including setup and “mapping” of SCADA points to the model elements

- Tools and a mechanism for scheduling the automated execution (launch) of the model

- User interfaces for the configuration of scenarios

- User interfaces for presentation of results

With models connected to the online environment, operators can test different operating scenarios using online information.

Bibliography

This report illustrates that developing an RTC system (especially a more complex one) will demand an understanding of several different technical and management areas. The report provides a brief introductory overview of these different aspects in order to give the reader a quick overall view of each aspect. Each of these aspects and technical areas is addressed in many specialized publications, books, and journals. Therefore, a thorough and detailed bibliography would be too large, and potentially disorienting for the intended audience of this report.

In order to expand the view of RTC beyond this report, the reader may want to pursue further, specific knowledge about RTC. One such source is a list of general references regarding different aspects of RTC, listed below. Note that each of these aspects is a broad field of study in itself and it is not possible or practical to provide a complete bibliography. The goal for the list provided below is merely to provide a suggestion for a reasonable starting point into these different aspects of RTC.

For a historical perspective on the application of RTC, the reader is referred to:

Schilling, W. (Ed.) (1989) Real-Time Control of Urban Drainage Systems, The State of the Art. IAWPRC Task Group on Real-Time Control of Urban Drainage Systems, Pergamon Press, London

For a recent reference on the state of the art of RTC:

Schutze, M., Campisano, A., Colas, H., Schilling, W., Vanrolleghem, P. “Real time control of urban wastewater systems – where do we stand today?” Journal of Hydrology 299 (2004) 335-348

For a thorough overview of RTC issues and technologies in the wastewater field:

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

Olsson, G., Nielsen, M., Yuan, Z., Lynggaard-Jensen, A., Steyer, J.P. (2005) Instrumentation, Control, and Automation in Wastewater Systems, IWA Publishing

For an extensive introduction to the mathematics of hydraulic modeling (includes almost 2,000 annotated references):

Miller, W.A, Yevjevich, V. (1975) “Unsteady flow in open channels”, Water Resources Publications, P.O. Box 303, Fort Collins, CO, 80522

For an overview of DSS and the state of the art for DSS in the wastewater industry:

Vitasovic, Z. and Barnett. M. (2004) “Decision Support Systems in Wastewater Facilities”, WERF report, available at WERF web site www.werf.org

For more information on SCADA systems and software development methodologies, the following references are a good start:

Boyer, S.A. (2004) SCADA: Supervisory Control and Data Acquisition, 3rd Edition, ISA (Instrumentation Society of America)

Seffah, A., Gulliksen, J, Desmarais, M.C. (Editors) (2005) Human-Centered Software Engineering – Integrating Usability in the Software Development Lifecycle, Springer Publishing Company, New York, NY

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Hernebring, C., Yde, L., and Magnusson, P. (1999) Regulation of the Sewer System in Helsinborg CSO Reduction by RTC and Model Based Regulation, DHI Software Conference, and June 7-9, 1999

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Akridge A., Bingham B., Carty D., and Colas H. (2006) An Operational Perspective to Real Time Control for Consent Decree Compliance, WEF Collection Systems Specialty Conference, Detroit, August 6-9, 2006

Colas H., Lamarre J., Charron A., and Trieu Duong D.D. (2005) Optimizing the Operation of Large Interceptor Systems in Montreal, WEF Collection Systems Specialty Conference, Boston, July 17-20, 2005

Colas H., Robitaille L., Charron A., Marcoux C., Laverdiere M., and Lessard D. (2005) Application of Real Time Control For CSO And SSO Abatement: Lessons Learned From 6 Years of Operation In Quebec City, ASCE, EWRI Conference, Anchorage, AL, May 15-19, 2005

Maeda, M., Mizushima, H. and Ito, K. (2005) Development of the real-time control (RTC) system for Tokyo sewerage system, Water Science and Technology, Vol 51, No.2 pp 213-220, IWA Publishing, London