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Smart Data Infrastructure for Wet Weather Control and Decision Support

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CONTENTS

Disclaimer ... iv

Acknowledgments ... v

Acronyms and Abbreviations ... vi

Glossary ... vii

1. Introduction ... 1

2. Smart Data Infrastructure ... 2

3. Smart Data Infrastructure and Technologies: Information Inputs ... 4

3.1 Continuous Monitoring ... 4

3.2 Level Monitoring ... 5

3.3 Flow Monitoring ... 6

3.3.1 Physical Flow Monitoring ... 6

3.3.2 Alternative Flow Monitoring Technologies ... 6

3.4 Rainfall Monitoring ... 7

4. Collection System Optimization ... 8

4.1 Capacity Management Operation and Maintenance and I/I Control ... 10

5. Real-Time Control Systems ... 10

5.1 Components of an RTC System ... 12

5.1.1 Supervisory Control and Data Acquisition Systems ... 12

5.2 Real-Time Decision Support Systems ... 13

5.3 Level of Control ... 14

5.4 Guidelines for Applying RTC ... 16

5.5 Key Considerations for RTC Systems ... 17

6. Data Management and Sharing ... 18

6.1 Big Data Management ... 18

6.2 Data Sharing ... 18

6.3 Real-Time Public Notification and Transparency ... 19

7. Data Analytics ... 19

7.1 Data Validation and Filtering ... 20

7.2 Key Performance Indicators ... 21

8. Data Visualization and Decision Support Systems ... 22

9. The Future of Data Gathering Technology for Wet Weather Control and Decision-Making ... 23

10. References ... 25

APPENDIX A: CASE STUDIES

Buffalo, New York: Real Time Control of Inline Storage A-1
Falcon Heights, Minnesota: Predictive Flood Control System A-3
Hawthorne, California: Real-Time Monitoring to Prevent Sewer Overflows A-5
Louisville, Kentucky: Real-Time Control for Integrated Overflow Abatement A-6
Newburgh, New York: Real-Time Control to Monitor Discharges for Reporting/Public Notification A-9
Philadelphia, Pennsylvania: Real-Time Control to Manage Retention Pond Discharge A-10
San Antonio, Texas: Real-Time Control for Cleaning Optimization A-12
San Diego, California: Stormwater Harvesting Augmentation Analysis A-14
South Bend, Indiana: Real-Time Control and Real-Time Decision Support A-16
Washington, DC: Real Time Controls for Rainwater Harvesting and Combined Sewer Overflow Control A-18
Wilmington, Delaware: Real-Time Control to Reduce Combined Sewer Overflow Discharges A-20

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Acronyms and Abbreviations

CFR	Code of Federal Regulations
CMOM	Capacity Management Operation and Maintenance
CPU	Central Processing Unit
CSO	Combined Sewer Overflow
DSS	Decision Support System
EPA	U.S. Environmental Protection Agency
FOG	Fats, Oils, And Grease
GUI	Graphical User Interface
ICS	Industrial Control System
IoT	Internet of Things
I/I	Inflow and Infiltration
IT	Information Technology
KPI	Key Performance Indicator
LTCP	Long-Term Control Plan
MMSD	Milwaukee Metropolitan Sewerage District
MSD	Metropolitan Sewer District (Louisville)
MSDGC	Metropolitan Sewer District of Greater Cincinnati
O&M	Operation and Maintenance
PLC	Programmable Logic Controller
PWD	Philadelphia Water Department
RTC	Real-Time Control
RTDSS	Real-Time Decision Support System
SAWS	San Antonio Water System
SCADA	Supervisory Control and Data Acquisition
SSO	Sanitary Sewer Overflow
WWTP	Wastewater Treatment Plant

Glossary

Agent-Based Control: System with locally interacting components that achieve a coherent global behavior. Through the simple interaction of buying and selling among individual agents, a desirable global effect is achieved, such as fair allocation of resources.

Big Data: Data sets that are so large or complex that traditional data processing application software is inadequate to deal with them.

Cloud: Large-scale, offsite data storage facilities.

EPA SUSTAIN: Framework for the placement of best management practices in urban watersheds.

Gray Infrastructure: Engineering projects that use concrete and steel.

Green Infrastructure: Projects that depend on plants and ecosystem services.

Internet of Things: Process in which hardware is connected to a network (the internet) so that it can better communicate with other systems.

Long-Term Control Plan: Written strategy required by the Clean Water Act for communities with combined sewer systems to reduce and/or eliminate combined sewer overflow discharges in the long term.

Machine Learning: Data analytic method used to devise complex models and algorithms that lend themselves to prediction. This is also known as predictive analytics. There are many algorithms available.

Model Predictive Control: Model-based control strategy that predicts the system response to establish a proper control action. This strategy explicitly uses a mathematical model of the process to generate a sequence of future actions within a finite prediction horizon that minimizes a given cost function.

Real-Time Control: The ability of water infrastructure (valves, weirs, pumps, etc.) to be self-adjusting or remotely adjusted in response to current weather conditions.

Smart Water and Smart Data Infrastructure: The ecosystem of technology tools and solutions focused on the collection, storage, and/or analysis of water-related data.

1. Introduction

Rain and snowmelt (referred to as wet weather conditions) can significantly increase flows at wastewater treatment facilities, creating operational challenges and potentially affecting treatment efficiency, reliability, and control of treatment units at these facilities.

Current approaches to wet weather control rely primarily on gray or green infrastructure, or a combination of the two. In recent years, however, municipalities and utilities have been considering how they can take advantage of technological advances to improve their operations and infrastructure. These advances include:

- Faster computer processing and network speeds, providing ready access to reliable information for informed decisions.
- Smaller, more accurate, and less expensive sensors.
- Low-cost storage of large quantities of data.
- The advent of the "internet of things" (IoT), allowing sensors to be connected over large geographic areas.
- Smaller, higher-capacity batteries and photovoltaics, reducing dependence on permanent hard-wired power sources.
- Wireless transmittal of acquired data, reducing the need for continuous or dial-up hard-wired communications systems.

This document focuses on how municipalities, utilities, and related organizations can use advances in technology to implement "smart data infrastructure" for wet weather control—that is, how they can use advanced monitoring data to support wet weather control and decision-making in real time or near real time. Case studies about communities that have done this across the country are included as appendices and referenced where applicable throughout the report.

What Is in This Document?

This document summarizes key aspects of utility operations where smart data systems can provide significant benefits. It is organized as follows:

Section 2 presents an overview of smart data infrastructure, its relationship with green and gray infrastructure, its benefits, and a general "roadmap" for implementation.

Section 3 describes technologies applied specifically to wastewater collection and stormwater systems and key considerations for selection, design, implementation, and operations and maintenance requirements.

Section 4 describes the use of smart data infrastructure to promote collection system optimization, as well as long-term control plan implementation, modification, and development.

Section 5 discusses the use of real-time control systems to maintain and meet operational objectives.

Section 6 discusses data management, data sharing, and public notification when using smart data systems.

Section 7 describes data analysis in smart data systems, including data validation/filtering and the use of key performance indicators.

Section 8 discusses data visualization and decision support systems.

Section 9 discusses the future of data gathering technology for wet weather control and decision-making.

Appendix A includes 11 case studies about communities across the country that have implemented smart data infrastructure technologies.

2. Smart Data Infrastructure

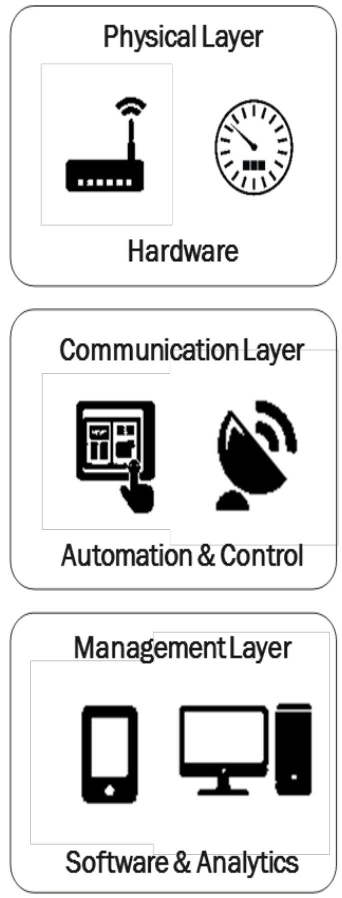
Smart data infrastructure is the integration of emerging and advancing technology to enhance the collection, storage, and/or analysis of water-related data. These solutions can generally be grouped into a framework that consists of hardware, communications, and management systems.

- **Hardware** includes the devices that measure and collect water-related data, such as level meters, flow monitors, valve actuators, and pump-run monitors.
- **Communications** refers to networks, including wireless communications, that migrate data from the hardware to the systems that perform analysis.
- **Management** refers to the software tools and analytical solutions that perform analysis and provide actionable information. It also includes data visualization to give managers real-time information for decision-making and to communicate with the public.

Smart data infrastructure leverages hardware, communication, and management analytics to provide real and tangible benefits to utilities, including:

- Maximizing existing infrastructure and optimizing operations and responses to be proactive, not reactive.
- Providing savings in capital and operational spending.
- Improving asset management and understanding of collection and treatment system performance.
- Improving long-term control plan (LTCP) implementation, modification, and development.
- Meeting regulatory requirements.
- Prioritizing critical assets and future capital planning.
- Providing the ability to better optimize collection system storage capacity to reduce peak flows and the occurrence of overflows.
- Enabling effective customer service and enhancing public notification.

Smart data infrastructure can be used to inform operational decisions that ultimately improve the efficiency, reliability, and lifespan of physical assets (e.g., pipes, pumps, reservoirs, valves). According to Global Water Intelligence Magazine, implementing digital solutions by consolidating monitoring, data analytics, automation, and control could potentially generate up to $320 billion in cost savings from the total expected capital expenditures and operating expenses for different water and wastewater utilities over the five-year, 2016–2020 period (GWI 2016).



The potential cost savings and other factors, such as regulations related to water quality, will likely stimulate the water industry to invest in smart data infrastructure and increasingly adopt the management of data-driven monitoring and control systems in the operation of various combined sewer, separate sewer, and municipal separate storm sewer systems.

In the future, data feeds and cognitive computing could significantly assist system managers by providing near-instantaneous support information for many of the routine and immediate response decisions that must be made in both the municipal and industrial sectors. Transformation may help water and wastewater utilities take advantage of innovations and opportunities in future operation and maintenance (O&M) (see Figure 1).

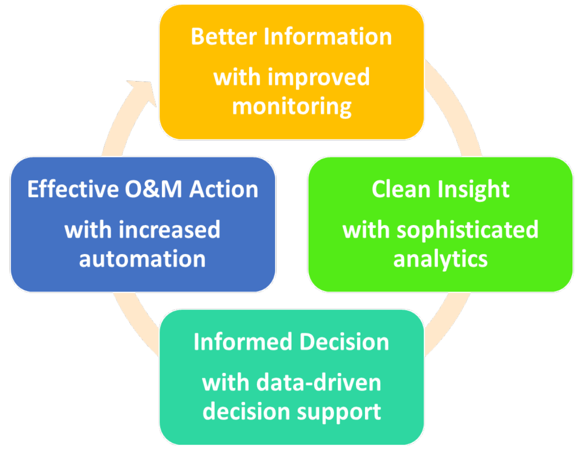


Figure 1. Better information and data can lead to more effective O&M

Roadmap for Implementing Smart Data Infrastructure

There are few, if any, insurmountable technological barriers to implementing the various technologies described in this document. Real-time control technology (Section 5), for example, has been around for nearly 30 years. While its implementation in collection systems remains relatively limited, the effectiveness of real-time control technology has been proven in many successful applications in wastewater treatment plants (U.S. EPA 2006).

When selecting technology and level of complexity, it is important to understand the utility's priorities and needs (e.g., O&M, information technology, security, data usage requirements). It is also important to remember that smart data infrastructure is scalable. Utilities can start small, applying technology that is compatible with the utility's existing capacity to ensure full acceptance and utilization of that technology, then move toward a more comprehensive approach with higher degrees of performance.

Regardless of the size or age of their infrastructure, utilities can benefit from this general roadmap for implementing smart data infrastructure:

1. **Vision for a utility of the future:** Imagine how data, assets, and technology could be leveraged to benefit the utility.
2. **Schedule:** Understand the capacity and timeframe for staff to accept change.
3. **Technology evaluation:** Validate data, prove benefits, and understand delivery.
4. **Detailed planning:** Seek funding and develop an implementation plan.
5. **Phased implementation:** Deploy the technology and associated platform.
6. **Continuous improvement and innovation:** Evaluate phase 1 performance and adapt the planning if necessary.

Key considerations for developing and implementing the roadmap include the following:

- Ensure organizational commitment for staffing and budget needs. There will be initial investment, as well as annual costs associated with the adoption of a technology.
- Communicate to ensure buy-in and support from all levels of management and foster strategic partnerships.
- Establish clear authority, roles, responsibilities, and communication channels.
- Define performance expectations.
- Educate and integrate team members early in the project.
- Provide continuous training and technical support to build the existing workforce's capacity and attract a new generation of workers.

3. Smart Data Infrastructure and Technologies: Information Inputs

Smart data infrastructure can generate highly informative data sets to support wastewater and stormwater collection system decision-making. These data sets help to answer critical questions that allow operators to maximize the effectiveness and efficiency of system operation (Figure 2); however, the usefulness of the data generated relies on accurate and relevant information inputs.

The following sections describe specific strategies and technologies for generating useful wastewater and stormwater collection system data, including key considerations for selection, design, implementation, and O&M. These strategies and technologies include:

- Continuous monitoring (Section 3.1)
- Level monitoring (Section 3.2)
- Flow monitoring (Section 3.3)
- Rainfall monitoring (Section 3.4)

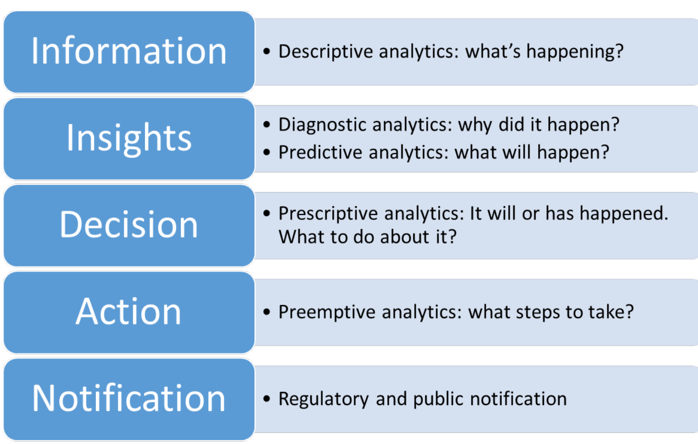


Figure 2. Operational process supported by information inputs

3.1 Continuous Monitoring

Continuous monitoring refers to permanent monitoring systems that report data back to a central system for use. The physical quantities to be monitored in a wastewater and stormwater collection system for proper operation and control are relatively basic and typically consist of flows, water levels, and rainfall conditions for dry and wet weather operations. In addition, equipment (such as pumps, gates, and valves) status needs to be monitored to ensure safe O&M.

Continuous monitoring when combined with proper data analytics and effective visualization can generate significant O&M savings by providing real-time insight into system conditions, which allows operators to prioritize asset management with effective targeted maintenance. Some examples include level trend detections that trigger alarms for equipment maintenance (e.g., cleaning), proactive inflow and infiltration (I/I) risk assessment, and data-driven work scheduling and asset management.

Continuous Monitoring in Practice

Milwaukee Metropolitan Sewerage District (MMSD) is using continuous monitoring to monitor the performance, value, and health of green infrastructure throughout the city. MMSD is monitoring 11 separate sites, including installations in public rights of way, allowing managers to see the combined and individual performance of green roofs and bioretention cells in real time. Every storm is recorded, performance can be reported in aggregate or by event, and the data can be used to fine-tune maintenance intervals and maximize performance.

Key considerations for continuous monitoring of wastewater collection systems include the following:

- The nature of wastewater systems presents a harsh and largely variable environment for monitoring equipment.
- The selection and installation of equipment needs to consider physical and hydraulic conditions, humidity, grit, sedimentation, debris, and corrosion, as well as confined spaces and maintenance access. For example, permanent monitoring equipment should meet explosive zone classifications.
- The advertised measurement accuracy of any sensor may not represent actual performance; as such, it will need to be calibrated/verified.
- Maintenance requirements, as well as hydraulic and physical conditions around the monitoring equipment, should be considered to balance out the increase in cost and complexity to provide accurate measurements. For example, forgoing some level of accuracy by selecting equipment with easier maintenance needs can ensure more reliable readings.

3.2 Level Monitoring

Multiple technologies are used to monitor water level in wastewater infrastructures. The most common types of sensors are pressure transducers, ultrasonic level meters, microwave meters, and capacitive probes. Other discrete devices for specific level detection, such as floating devices and vibrating level sensors, could be used in some cases. The most important criteria for selecting a specific technology will depend on the environment and infrastructure configuration where level must be monitored. More precisely, conditions such as the presence of turbulences and sedimentation in the water or the presence of fats, oils, and grease (FOG); foam; and obstacles in the air space above the monitoring location must be considered to select appropriate technologies.

Pressure transducers need to be submerged in the water where the level must be monitored; they are therefore convenient for applications where sedimentation is not a significant issue. They are typically used where water can be turbulent at the location of measurement. Stilling wells are usually recommended to install pressure probes away from potential debris in the water flow and for easier maintenance.

Ultrasonic level meters are also very common in wastewater applications and consist of installing a probe mounted above the water surface. They are usually preferred whenever space is available above the location where monitoring is needed. Multiple makes and models are available on the market. Ultrasonic sensors are recommended where minimal obstacles, FOG, or foam is present above the surface of the water. The sensor must be mounted far enough from sidewalls to avoid bad readings due to ultrasonic soundwave reflections.

When monitoring space is small or when FOG can be found in the air above the water surface, Doppler **radar microwave meters** are recommended because they use a narrower signal beam that improves the reliability of the measurement.

Capacitive probes are particularly suitable for multi-point water level monitoring and are preferred when a high spatial resolution (of a few millimeters) is necessary (e.g., for a reliable evaluation of stored volumes in big and flat storage facilities). The main advantages of these probes are that the sensors are easy to clean and can handle temperature and pressure variations. However, these sensors can significantly disturb the flow and should not be used in small pipes.

In general, sensors located above the water surface have less O&M, but are subject to corrosion and may experience issues with ice in cold environments.

For locations where monitoring the water level is critical, redundant sensors based on different technologies are recommended. This strategy would consist of using, for example, an ultrasonic meter and a pressure sensor in a storage facility to ensure water level monitoring in all conditions and to maximize the availability of measurements for safe infrastructure operation.

3.3 Flow Monitoring

Operators can use several technologies and methods of flow monitoring to better understand the characteristics of their collection systems.

3.3.1 Physical Flow Monitoring

Typical commercial flow meters available on the market include ultrasonic Doppler devices, acoustic Doppler sensors, transit time effect sensors, and newer technologies such as Doppler radar sensors and laser Doppler meters. Flow meter technology has been developed to fit a variety of applications; submerged and “non-contacting” devices (sensors located above the water surface) are available. Transit time effect technologies consist exclusively of installing one or multiple pairs of probes (a pair includes one transmitter and one receiver) in a crossing path within the water stream. These probes can measure water velocity at different layers in the conduit to compute flow values according to water level and pipe section. Submerged technologies are generally recognized as being more accurate because they can measure the different velocities that can co-exist within a water flow section at the same time, while non-contacting technologies can only measure the velocity from the surface of the water stream.

Practical experiences of wastewater flow monitoring within sewer pipes ranging from 24 inches to 120 inches in diameter and above have shown that submerged flow meter technologies will generally provide measurements with an accuracy from ±10 percent to 20 percent. Non-submerged flow meter technologies will provide flow measurements with an accuracy typically ranging from ±15 percent to 30 percent. The cost for procurement, installation, and maintenance of “non-contacting” devices is lower than submerged technologies. A permanent flow meter installation in sewers typically ranges from $15,000 to $75,000, and can be even higher if significant work is needed for the infrastructures and the electrical utilities. Regular maintenance for cleaning, inspection, and calibration is recommended at least twice a year to keep monitoring reliable and accurate.

3.3.2 Alternative Flow Monitoring Technologies

In some cases, where installing a physical flow meter becomes too complex or expensive, indirect means of flow monitoring can be developed depending on specific hydraulic conditions.

Implementing Monitoring Technology to Improve Operations

The San Antonio Water System (SAWS) recently participated in a study on the use of monitoring to inform cleaning maintenance programs. SAWS equipped 10 high frequency cleanout sites with remote field monitoring units and used analytical software to monitor day-over-day level trend changes and receive messages for trend anomalies. This analysis of the real-time monitoring data detected small but potentially important changes in water levels. These data enabled users to consider actions such as a site inspection or cleaning. Based on the monitoring data, SAWS reduced cleaning frequency by 94 percent in the study areas. Other than a short period in May/June 2016 when nearly 16 inches of rain overwhelmed the SAWS system, there were zero sanitary sewer overflows at the pilot locations.

Level to flow relationship: When pipe flows remain under “free surface flow” conditions, Manning equations can be used to estimate flow (based on water level sensor data) and physical attributes (pipe shape and dimensions, slope, pipe material for the roughness factor) at the level sensor location. However, the flow estimation is invalid when the flow experiences surcharged conditions or backwater effects are present.

Equations of flow under the gate: When modulating gates are used for flow control, gate position and water level data upstream and downstream from the gate can be used to efficiently compute the flow regulated through the gate. The mathematical formula would also consider the gate's hydraulic conditions and physical dimensions, the regulation chamber, and connection pipes. Optimal gate position (i.e., amount of submergence) can vary depending on gate size and flow velocity and must be determined through hydraulic analysis. Based on several facilities' operations using this method, the relative error is under 5 percent during dry flow conditions and around 15 percent in wet weather conditions.

Weir relationship: A common mathematical means of computing flow values uses level monitoring data from a static weir upstream. Specific formulas must be used depending on the shape of the weir, the physical dimensions of the weir (length, width), and the angle of the flow stream according to the weir. This method can provide fairly accurate flow values for weirs under 6 feet in length; weir relationship calculations involve significant uncertainties for longer weirs.

Bending weir relationship: Bending weirs consist of mechanical flap gate devices with pre-determined weights that are designed to maintain a specified water level on the upstream side of the equipment. When inflows cause the upstream level rise, the bending weir reacts by opening to evacuate excess flow. An inclinometer can be installed on the bending weir's flap gate to monitor the angular opening of the mechanical device. Flow can then be estimated using the corresponding flow and weir angle relationship charts provided by the manufacturer.

Flap gate equations: Similar to bending weir relationships, mathematical functions can be developed for computing flows through flap gates. These relationships will require installing an inclinometer on the flap gate and a level meter upstream of the gate. A downstream level meter will also be required for situations where the flap gate can become submerged. Typically, a temporary flow meter calibrates and validates the equation.

Model-based flow computations: Most utilities have developed a calibrated hydrological and hydraulic model (e.g., EPA SWMM 5) to adequately represent their wastewater system. These models are typically used to plan, design, and produce engineering diagnostics. They can be configured for real-time simulations, based on real-time rainfall and level data or forecasted radar rainfall, to provide flow values virtually everywhere within the wastewater collection or stormwater system. A well-calibrated hydraulic model is recognized for providing flow values within an accuracy range from -15 percent to +25 percent (WEF 2011).

3.4 Rainfall Monitoring

A typical rainfall monitoring system deploys a network of spatially located rain gauges that allow for representative measurement of rainfall quantities over a region. As a general rule for guidance, on average, one rain gauge is recommended for every 500 hectares (1,235 acres) of coverage (Campisano et al. 2013), although coverage needs vary depending on local climate and need for predictive accuracy.

Common rain gauges use tipping bucket systems—either optical or mechanical—that count the quantity of rain trapped in a calibrated cylinder. Each bucket tip will count a specific quantity of rain (e.g., 0.005 inch) over a specific time increment.

Such rainfall monitoring can be made available in real time and can be used as inputs to a hydraulic model to compute flow predictions in the sewer collection system. The flow predictions can then be used to determine the time of concentration of the area tributary to the monitoring location. In addition, when combined with radar reflectivity data and rainfall predictions, flow forecasts can be provided with a more accurate level over the entire territory. Generally, rainfall forecasting windows and grid sizes should be proportional to the hydrologic element's longest time of concentration in the tributary collection system where control is desired—e.g., a large combined sewer overflow (CSO). Rainfall forecasts should cover at least two hours ahead.

4. Collection System Optimization

A key benefit of smart data infrastructure is its application in system optimization to maximize existing infrastructure investment and reduce the need for future capital investment. It provides the framework required to optimize the design and O&M of wastewater and stormwater systems by collecting and analyzing large data sets.

There are two types of system optimization. One refers to system improvements that are applied offline (Muleta and Boulos 2007). Some typical examples include raising weirs to reduce overflow discharge, developing best efficiency curves to minimize energy costs and reduce equipment breakdowns, or optimizing the placement of localized stormwater management and green infrastructure control. For example, the EPA SUSTAIN modeling framework uses an optimization approach to identify the least cost and highest benefit solutions to achieve user-defined objectives (U.S. EPA 2009).

The second type of system optimization is applied online to actively manage the operation of wastewater networks and facilities in real time, a process often referred to as "real-time control" (RTC). RTC systems are discussed in greater detail in Section 5 of this document.

Table 1 presents the data used in a smart data infrastructure approach, regardless of optimization type.

Optimizing Collection System Capacity and Performance

The Philadelphia Water Department (PWD) has committed to reducing 7.9 billion gallons of overflows in the city by 2036 through better stormwater runoff management. As part of this effort, PWD, in collaboration with a private corporation, implemented smart data technology to monitor and maximize the performance of an existing stormwater retention basin. The existing basin was retrofitted with technology to monitor basin water level and precipitation, as well as to provide real-time active control to selectively discharge from the basin during optimal times, effectively increasing the useful capacity of the asset.

Table 1. Data Required to Optimize the Design, Operation, and Maintenance of Wastewater and Stormwater Systems

Objective	Cause of Problem	Potential Intervention	Data Required for System Optimization
Eliminate sanitary sewer overflows	• Rainfall-derived I/I • Undersized pipes	• Pipe replacement • I/I mitigation measures	• Level and flow measurements • Sewer and land characteristics • Cost of potential interventions
	• Grease, debris, and sedimentation buildup	• Improved operating procedures • Pipe replacement • Cleaning (pipes streets) • Flushing systems	• Level, velocity, and flow measurements • Camera inspection • Cost of potential interventions
	• Pipe breaks • Leaking manholes • Offset joints	• Repairs • Pipe replacement	• Flow measurements • Camera inspections • Smoke testing • Cost of potential interventions
Minimize operating costs	• High electricity consumption for pumps and gate operation	• Pump replacement • Use of variable frequency drives • Improved set points • Improved controller parameters	• Time-of-use electricity tariffs • Level and flow measurements • Critical elevation for basement and street flooding • Gate, pumps, and actuator characteristics • Cost of potential interventions
Minimize maintenance costs	• High equipment and sensor failure rate	• Repairs • Replacement • Re-localization • Preventive and predictive maintenance • Best efficiency point	• Level and flow measurements • Equipment and sensor history • Equipment inventory and cost • Detailed alarms • Maintenance and calibration history • Cost of potential interventions
	• Sedimentation issues	• Improved operating level • Sewer modification to increase velocities • Flushing devices	• Level and velocity measurements • Camera inspections • Cost of potential interventions
Minimize CSOs	• Rainfall-derived inflow • Undersized facilities (conveyance, storage treatment)	• Upgrade of existing facilities • Addition of green and grey infrastructure • RTC implementation	• Level and flow measurements • Sewer and land characteristics • Operational and physical constraints • Cost of potential interventions
Reduce flooding risks	• Rainfall-derived inflow • Undersized facilities (conveyance, storage)	• Upgrade of existing facilities • Addition of green and grey infrastructure • RTC implementation	• Level and flow measurements • Sewer and land characteristics • Operational and physical constraints • Critical elevation for basement and street flooding • Cost of potential interventions

4.1 Capacity Management Operation and Maintenance and I/I Control

Optimizing the performance of the collection system is the key component in capacity management operation and maintenance (CMOM) programs. CMOM programs combine standard O&M activities with an increased level of data gathering and information management to more effectively operate collection systems. Smart data infrastructure, equipped with the data input tools described in Section 3, can help accomplish this. Successful CMOM programs are used to identify and mediate capacity-related issues in a system, reducing the risk of system failures such as sanitary sewer overflows (SSOs).

CMOM includes I/I control, the process by which unintended clearwater sources (e.g., groundwater and excess stormwater) exceed the design capacity of a collection system, typically due to antiquated, deteriorating, or inadequately maintained infrastructure. Long-term flow and level metering data can be analyzed to determine performance trends over a long period of time. Historical trends of I/I peak flow rates and volumes can be used to identify areas with high rates of I/I, prioritize removal efforts, and evaluate the costs/benefits of those efforts.

Real-time flow rate and level data collection can be used to identify localized capacity limitations, blockages, and sediment accumulation. These data can then inform more proactive management approaches that can reduce overflows in both dry and wet weather conditions. Such approaches help ensure that the collection system capacity is maximized for wastewater conveyance, which is a critical component of all CMOM programs. In addition to direct monitoring, flow rate and level metering data can be used along with asset management data to predict the "unmetered" portions of a collection system and determine other areas at risk of capacity-related issues, such as high I/I.

Facilities can use smart data infrastructure tools—such as real-time metering and information analysis—to understand the different variables that impact collection system capacity and performance. This knowledge would allow utilities to better plan for necessary capital expenditures and optimize system performance for current and future needs.

Using Smart Data Infrastructure and RTC to Reduce CSOs

Louisville Metropolitan Sewer District (MSD) was an early adopter of RTC, applying inline storage since the 1990s and pioneering the application of global optimal and predictive RTC that has been in operation since 2006. The RTC system is key to maximizing the MSD's conveyance, storage, and treatment capacity to reduce CSOs, with consistent operational results capturing more than 1 billion gallons of CSO volume annually. Incorporating RTC into MSD's LTCP has resulted in approximately $200 million in savings compared to traditional methods.

5. Real-Time Control Systems

RTC can be broadly defined as a system that dynamically adjusts facility operations in response to online measurements in the field to maintain and meet operational objectives during both dry and wet weather conditions (U.S. EPA 2006).

Wastewater systems are often purposefully oversized to provide a factor of safety. This extra capacity can provide short-term storage in the conveyance and treatment system when rain falls unevenly across the collection system and varying runoff lag times that introduce stormwater into the system. RTC presents opportunities to optimize full system capacity for both existing and proposed facilities. Potential benefits include receiving water quality protection, energy savings (Tan et al. 1988), flow equalization, reduced flooding, integrated operations, and better facility planning (Gonwa et al. 1993). Real-time or near real-time reporting can also help utilities meet the public notification requirements for CSO and SSO discharges.

A well-designed RTC system can address a number of different operational goals at different times. Examples of operational goals include (U.S. EPA 2006):

- Reducing or eliminating sewer backups and street flooding.
- Reducing or eliminating 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 unplanned (not anticipated) system disturbance, such as major equipment failure or security-related incidents.
- Managing the rate of flow arriving at the wastewater treatment plant.

The application of RTC in a stormwater system is similar to that of a wastewater system. It requires continuous monitoring (e.g., water level, rainfall, weather forecast), control devices (e.g., valves, gates), and data communication to actively manage flows and adapt to changing conditions. If required, temperature, infiltration rate, and water quality parameters (e.g., total suspended solids, nitrogen) can be monitored in real time and integrated into the RTC management strategy. Associated benefits of RTC application in stormwater management include:

- Optimizing the design and sizing of control measures.
- Reducing the frequency of flooding.
- Improving water quality with extended residence time.
- Increasing stormwater harvesting and reuse.
- Adapting to evolving conditions through operation change rather than new infrastructure.
- Providing auditable performance and supporting data from the monitoring system components without additional costs.
- Reducing O&M costs by issuing alerts in real time.

Using RTC to Maximize Capacity and Performance

In 2008, the city of South Bend, Indiana, installed and commissioned a real-time monitoring system of more than 120 sensor locations throughout the city. In 2012, the city and its partners commissioned and distributed a globally optimal RTC system to maximize the capacity and performance of the city's collection system. Since 2012, the city has added additional sensor locations and rain gauges, bringing the total number to 152 sites. It also added automated gates at several stormwater retention basins to better control when and at what rate stormwater is released downstream into the combined system. In the period from 2008 through 2014, South Bend eliminated illicit dry weather overflows and reduced its total CSO volume by roughly 70 percent, or about 1 billion gallons per year.

5.1 Components of an RTC System

Figure 3 presents a typical layout of the components that might be included within an RTC system. Some components are essential for RTC (e.g., sensors, meters), while others may be optional depending on the desired level of control. The components are represented with boxes, and the arrows that connect them indicate the communications and data that are passed on between the components.

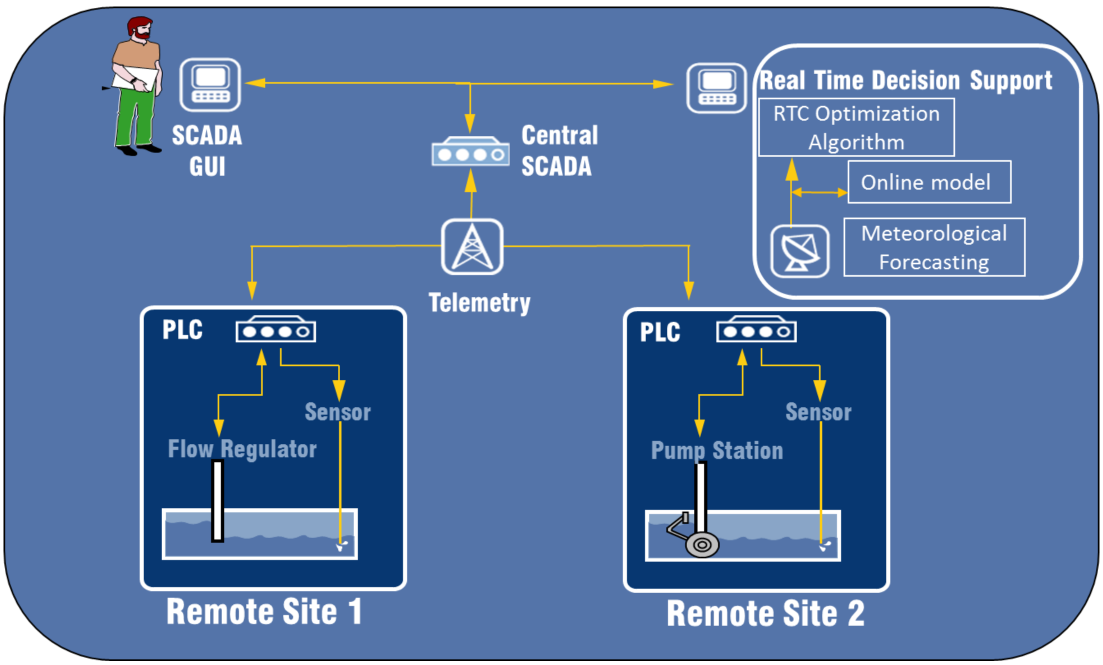


Figure 3. Components of an RTC system

An RTC system, at a minimum, includes sensors that measure the process, control elements that adjust the process, and data communication between them (Schilling 1989). Typical control elements for a wastewater system are regulators, such as pumps (constant or variable speed drives), gates (sluice, radial, sliding, inflatable), and adjustable weirs (bending weir, weir gates).

At each remote site, sensors are connected to the inputs of the local RTC device—in most cases, a programmable logic controller (PLC) or remote terminal unit. The PLC provides outputs (control set points and signals) to the control elements (e.g., gates, pumps) based on the rules embedded (programmed) into the PLC. These rules are feedback algorithms, where action is based on the difference between a set point 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 if the level is too low or increase it if the level is too high. The PLC programs can include set points that are defined locally and receive "remote" set points from a central server.

5.1.1 Supervisory Control and Data Acquisition Systems

Supervisory control and data acquisition (SCADA) systems have become more prevalent in the wastewater industry for collecting and managing monitoring data. SCADA is a control system architecture that uses computers, networked data communications, and graphic user interfaces for high-level process supervisory management. Large SCADA systems have evolved to be increasingly similar in function to distributed control systems, which are widely used for process control at the treatment plants. SCADA system designs have taken full advantage of advances in information technology (IT) to collect, archive, and process large amounts of data.

A SCADA system's fundamental purpose is to communicate data and control commands from a centrally located operator to geographically dispersed remote locations in real time. The communication technology options include telephone-based transmission (used in early SCADA systems due to low cost), fiber-optic cable, radio system, cellular-based communication, wireless internet access, and satellite-based systems.

Designing a SCADA system depends on a wide range of practical considerations, including but not limited to equipment enclosures, environmental conditioning, field interface wiring, system documentation requirements, system testing requirements, IT requirements, and cybersecurity.

As utilities invest in continuous monitoring and SCADA, the generated data must be regarded as an important investment to extract maximum values. According to the U.S. Geological Survey, "poor data quality, redundant data, and lost data can cost organizations 15 percent to 25 percent of their operating budget" (USGS n.d.).

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. The SCADA system is considered the backbone of an RTC system. It includes standard graphical user interface (GUI) tools that operators can access, and it allows them to manually override any remote site control actions at any time. As the needs for real-time or near real-time public notifications rise, centralized data management can facilitate data sharing and enable greater transparency.

RTC and CSO Control

The Metropolitan Sewer District of Greater Cincinnati (MSDGC) has one of the most challenging collection systems in the country to manage during wet weather, as it contains more than 200 CSO points. Together, these overflows discharge over 11 billion gallons of sewage into the Ohio River and its tributaries annually. In 2014, MSDGC began installing sensors throughout its largest watershed. By early 2016, MSDGC had gained both real-time visibility and control of its wastewater system in this watershed and transformed the wastewater collection system into a "smart sewers" network. To date, MSDGC's smart sewer system covers over 150 square miles (approximately half) of its service area, incorporating two major treatment plants, six wet weather storage and treatment facilities, four major interceptor sewers, 164 overflow points, and 32 rain gauges and river level sites. Remote monitoring has improved the maintenance of wet weather facilities and enabled upstream facilities to account for downstream interceptor conditions, increasing overflow capture basin-wide during wet weather.

5.2 Real-Time Decision Support Systems

A real-time decision support system (RTDSS) generally overlays the SCADA system. It is connected to the SCADA database to retrieve system status information. An RTDSS can use a SCADA historian and GUI to program and display system status and trends (e.g., abnormal flow, critical water level alarm) or provide additional dashboards involving data analytics to support O&M decision-making. In an RTC system, an RTDSS performs complex calculations based on information inputs to inform operational decisions and help determine optimal system set points (e.g., flow to be pumped, water level to be maintained in a wet well or pipe length).

Typically, decision support uses advanced computing algorithms that are interactive and multi-objective and often involve using an online model for weather forecasting.

5.3 Level of Control

The RTC system can be automated with a centralized or distributed control technology. The main difference is the control and the input/output subsystems. In distributed control architectures, the number and quality of central processing units (CPUs) is determined by the number of modules. Each module has a controller, and the system usually features a central master PLC. The module PLCs automate their respective areas and usually do not include visualization features.

A central architecture usually features a computer, which deals with all tasks such as input/output connections, PLC, and control. Computing capacity, therefore, must be significantly higher than that of a distributed control technology system. There is only one CPU, which means that only one such spare part is needed. RTC system design criteria drive the selection of a control system platform based on the physical and logical components of the system.

Regardless of the control platform, RTC can be implemented using different levels of control, including local, regional, and global. The levels of control are classified according to progressive increases in complexity, performance, and benefits (Schütze et al. 2004).

These set points can be displayed to the operator for manual control or be sent back to the SCADA system in real time for automated control of remote sites. The algorithms used to determine control logics and set points vary in complexity from simple operating rules to complex mathematical optimization techniques (Garcia-Gutierrez et al. 2014).

Local control, or a local reactive control system, is the simplest form of automatic control. Local control is used to solve specific issues that only require information collected near a regulator and is usually implemented as single-input, single-output feedback loop designed to maintain prescribed set points (e.g., flow or level set points). It is a good solution only if the control objectives pursued can be reached without transferring any information between other remote sites.

Regional control is similar to local control except that a telemetry system is required to exchange data with other remote sites. Regional control can be implemented as a distributed or centralized system built on a SCADA system. Some municipalities design their own decision support system to control the collection system based on the specific constraints and opportunities of each control site. However, the control remains reactive, not predictive. Based on a reactive process, there are limitations in the distances between the control structures and measurements; as such, the operation must remain conservative and suboptimal.

Global control is necessary when the control objectives require strong coordination of the control actions at numerous remote sites on a system-wide level. The set points are usually computed and refreshed periodically (e.g., every five to 15 minutes). The global strategy used to determine the set points includes rule-based and optimization-based techniques (Figure 4). Rule-based control considers possible scenarios that can occur during wastewater system operation and determines appropriate control actions based on experience. The rules are generally easy for operators to implement and understand. However, the quality and the performance of those rules highly depend on the available expert knowledge. For large and complex wastewater systems, the strategy may demand many rules.

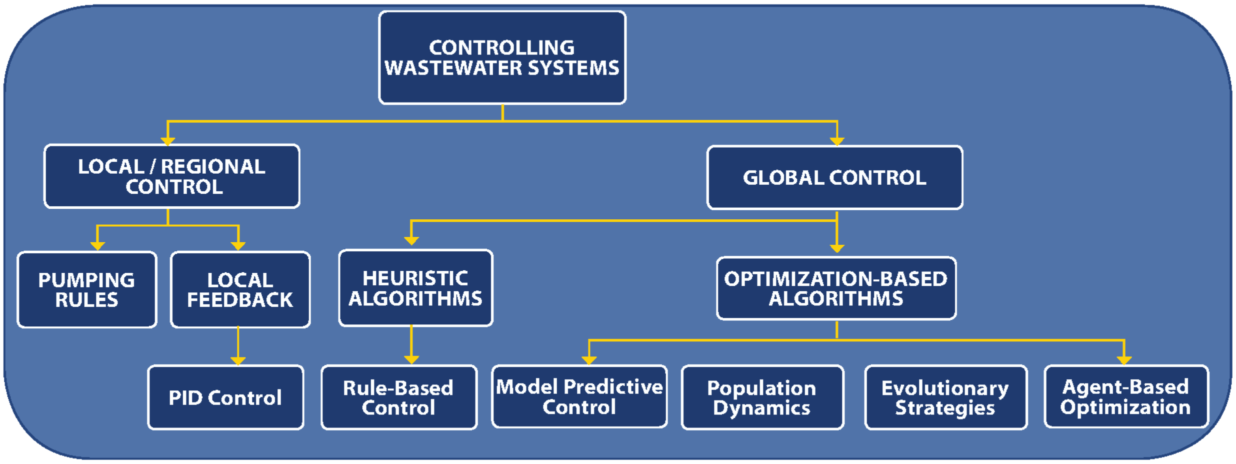


Figure 4. Control strategies for wastewater utilities

Optimization-based strategies involve an optimization problem that represents the desired behavior of the wastewater system. Various algorithms can be used to solve the optimization problem (e.g., model predictive control, agent-based optimization). More detailed descriptions of optimization strategies and mathematical models can be found in Papageorgiou (1988) and Garcia-Gutierrez et al. (2014).

In the last 20 years, model predictive control has been the most extensively used optimization-based strategy. This approach uses a mathematical model of the wastewater system to generate a sequence of future actions—within a finite prediction horizon—that minimizes a cost function (Gelormino and Ricker 1994). Interest in model predictive control is justified by its ability to explicitly express constraints in the system, anticipate future system behavior, and consider non-ideal elements such as delays and disturbances.

Optimizing the collection system requires continuous and strategic adjustment of control devices, as well as predictions of upcoming inflows and their spatial distribution (Cartensen et al. 1998). With proper conditions being monitored, acknowledged, and controlled, a **global RTC system** considers the distribution of flow in the entire system, both in current conditions and in the future. By using a global RTC, a utility has the ability to control flow by opening and closing gates or pumps allows for transfer flow and storage capacity between sites, thus providing the temporary storage and controlled release of significant volumes of wastewater.

Table 2 summarizes which components of the overall system must work properly to support different control modes/levels (U.S. EPA 2006). Notably, forecasting may be part of a rule-based system, but it is not mandatory. A global RTC system often involves a mixture of lower levels of RTC and static controls.

Table 2. 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 control—rule-based	X	X	X	X		X		
Global automatic control—optimization	X	X	X	X		X	X	X

5.4 Guidelines for Applying RTC

In most cases, RTC implementation can offer benefits and improve the performance of urban wastewater or stormwater systems. The costs and extent of these benefits may differ from one system to the next.

The first step in evaluating if RTC is a suitable and viable solution for a utility is to develop criteria for a macroscopic evaluation of RTC potential using a scoring system (Erbe et al. 2007, Schütze et al. 2004). Criteria may include environmental and financial objectives, the topology of the catchment area, collection system characteristics and conditions, operational system behaviors, etc.

The utility may, however, skip the first step if it has already invested in a hydrological and hydraulic model that adequately represents its system and operation and/or has substantial monitoring coverage (which provides good system understanding and condition assessment). The utility can use these existing tools and data in the second step, which involves a preliminary analysis of RTC potential and costs/benefits. The analysis should include a simulation study of a full range of RTC control levels to determine which is the most appropriate; staff interviews with operators, engineers, and other stakeholders; and equipment surveys.

If the various scenarios demonstrate the feasibility and benefits of RTC, the third step involves detailed planning of the RTC system and its implementation, including:

- Detailed planning of control infrastructures.
- Detailed design of control algorithms.
- Risk and failure analysis.
- Detailed design of data infrastructure (or gap analysis if data infrastructure exists).
- Staff training and other organizational planning (i.e., new roles and responsibilities).
- Preparations for obtaining consent by the regulatory authorities.

It is critical to involve operator input from the beginning of the design process. The operators are ultimately responsible for the system operation and performance. Early involvement will ensure that operators' O&M concerns are addressed in the system design and that operators buy in and accept the RTC system.

5.5 Key Considerations for RTC Systems

An RTC system should have robust operation, adequate communication, supervisory manual override, operational confidence, and adaptability (Gonwa et al. 1993, Colas et al. 2004). The system must be designed and configured to ensure a high level of performance under normal conditions and safe operation under downgraded conditions. Its performance should be better than or equal to the system that existed before RTC implementation.

Under all conditions, there are critical constraints, such as operating safely, avoiding equipment damage, and avoiding flooding. A well-designed RTC system must effectively manage different operational objectives and transition between different operational modes to operate reliably and efficiently; at a minimum, it must address externally caused equipment failures and emergency conditions.

The fail-safe procedures must be configured so that they are triggered when the requirements for the system's current operational mode cannot be met. These procedures should automatically place the system into the next (lower) mode/level of operation that can be fully supported. For example, if the system is operating in local automatic control mode and the PLCs malfunction or lose power, it would need to revert to local manual control.

RTC system risk management procedures must include the ability to deal with emergency conditions detected using field measurements.

Special rules can be defined to react to conditions such as rapidly rising levels within the system. The emergency response can be either to adjust the automatic control strategy or change operational mode by giving the operator a standard operating procedure.

Using Smart Data Infrastructure to Promote Resiliency

In response to the historic drought conditions recently experienced in California, the city of San Diego has decided to quantify the potential nexus between stormwater capture and its ongoing effort to reclaim wastewater as a drinking water resource (San Diego currently imports more than 80 percent of its water supply). The city equipped its stormwater control measures with RTCs and assessed them to optimize the management of stormwater storage and release to the reclaimed water system. The simulations suggested that stormwater harvesting could substantially augment local water supplies while complying with stormwater quality regulations.

The reliability of all RTC system components is key to successful implementation. In addition to fail-safe and risk management procedures, system effectiveness can be obtained through the following:

- Proper selection, location, and number of sensors to ensure accurate and adequate measurements.
- Installation of redundant equipment at key locations using different technologies.
- Real-time validation of monitoring data to minimize the amount of low quality data entering the decision-making process.
- Design of safety features, including emergency isolation gates, power supplies, generators, and equipment interlocks specifically designed for safe operation when a critical alarm is activated.
- Preventive and targeted maintenance to ensure equipment availability.
- Stock of replacement pieces for critical infrastructure.

6. Data Management and Sharing

Good data management and sharing can allow operators and control systems to integrate data faster and more effectively. Organized and carefully designed data management systems readily obtain and act on data from various sources, reducing redundancy and the cost of collection system operation.

6.1 Big Data Management

More monitoring requires more data management and storage. To address the challenges of storing, processing, recovering, sharing, and updating large data sets, organizations are finding smarter data management approaches that enable them to effectively corral and optimize their data use.

Some of the best practices for big data management are to reduce the data amount (because the vast majority of big data is either duplicated or synthesized), to virtualize the reuse and storage of the data, and to centralize management of the data set to transform big data into small data (Ashutosh and Savitz 2012).

A smarter data management approach not only allows big data to be backed up far more effectively, but also makes it more easily recoverable and accessible at significantly lower cost. Other benefits include the following:

- Applications require less to process data.
- Data can be better secured because management is centralized, even though access is distributed.
- Data analysis results are more accurate because all copies of data are visible.

6.2 Data Sharing

In addition to the needs of public notification and regulatory reporting (e.g., post-construction performance monitoring, permit compliance), there is a rising need for data sharing among various departments within an organization to improve efficiency and interoperability. Organizations must also be able to securely exchange data with outside administrative domains for transparency and for integrated solutions on city-wide or region-wide scales.

As more data have moved to cloud-based storage, the protection and encryption of off-site data has become more important. While there are still cybersecurity risks, significant improvements have made it much more difficult for outside parties to access critical data and information.

Cybersecurity

The interconnectivity of hardware and data management has increased the need for utilities to plan and manage cybersecurity. Although networking multiple systems provides operational value, it can also expose systems to new data security risks. As utilities move to advanced data storage solutions, addressing cybersecurity will be an essential aspect of master planning activities. Cybersecurity provides insurance to protect utility assets against attacks, outages, and threats, and it reduces the costs of downtime.

Key considerations for data infrastructure and data sharing include the following:

- As organizations become more dependent on cloud-based systems and other internet-based solutions, the importance of a robust, maintainable, and secure network infrastructure becomes critical. Nothing works when the network goes down. Secure, redundant, and scalable internet connections are now required for day-to-day business as essential processing is moved off site.
- Network architecture is increasingly important, and robust, secure solutions must be designed into systems to manage

devices potentially numbering in the thousands, each with multiple data points. Simply using a "firewall" to secure a network is no longer feasible.

- Formerly isolated SCADA/industrial control systems (ICS) are now required to communicate over the internet. To securely realize the vast benefits of cloud computing and the IoT, secure data interconnectivity is essential. Standards have been produced to ensure a high degree of interoperability and security for evolving SCADA/ICS solutions.

Emerging Technologies for Big Data Management

For big data management, all types of data analytics will be more widespread and incorporate more artificial intelligence. Already, machine learning has been applied in predictive analytics for I/I characterization, based on analysis of long-term data trends.

6.3 Real-Time Public Notification and Transparency

Implementation of a smart data infrastructure allows utilities to disseminate relevant and current information to ratepayers and stakeholders. Public notification is becoming the norm for informing interested parties of current utility conditions. While some data must be kept private due to security issues related to protecting treatment processes, some data can be shared to better inform the end user. A common example includes the public notification for current/recent overflow activity to local receiving waters. The real-time notification of overflow activity informs the public that recreational uses may be temporarily compromised, potentially reducing public health issues. Public notification can also include automated notification to the regulating agencies as part of permit requirements.

Real-Time Public Notification with SmartCover™ Systems

The city of Newburgh, New York, replaced its combined sewer telemetry system with a wireless SmartCover™ System. The prior telemetry system used pressure sensors that had to be located beneath the influent channel, in direct contact with the flow and in the combined sewer regulator environment where they would be regularly impacted and damaged or displaced by debris. The new SmartCover™ System's sensors hang from the manhole cover above and do not contact the water, avoiding damage. The new system's wireless satellite connectivity is more reliable than land phone lines at a lower cost. Any computer, tablet, or smartphone with internet access can communicate with the telemetry system, allowing for real-time staff and public notification of CSO events.

7. Data Analytics

Most utilities already generate a substantial amount of process and monitoring data for various purposes. As the amount of data generated each year increases at an exponential rate, it is increasingly critical to convert those data into useful information (Greiner 2011). Technical advancements in complex multidimensional data analysis and data mining can help utilities analyze incredible amounts of data to detect common patterns or learn new things. This can lead to significant operational improvements and dollar savings for wastewater systems.

Big data analytics, a well-established concept, involves analyzing the data collected to discover trends and correlations, uncover hidden patterns and other insights to understand why certain behavior or incidents happened, and then use that insight to predict what will happen. Today's technology and advancements in big data analytics bring speed and efficiency, which enable utilities to analyze large quantities of data and identify insights for immediate decisions (Figure 5).

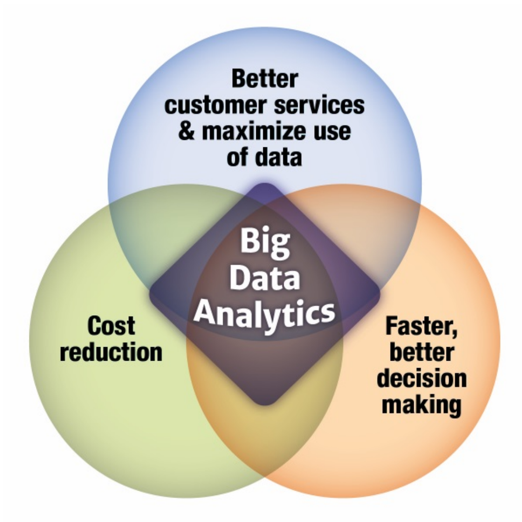


Figure 5. Big data analytics support enhanced decision-making and more effective and less costly operations

Utilities that have already invested heavily in continuous monitoring could use data analytics to get significant value from the data they collect.

There are many data analysis and data mining solutions, which also incorporate data warehousing, database management systems, and online analytical processing.

7.1 Data Validation and Filtering

Data validation is an important consideration for wastewater utilities, particularly for monitoring data within the harsh environment of a wastewater collection system. Raw monitoring data can contain erroneous readings, which could be due to one or a combination of the following:

- Noise (high frequency fluctuations)
- Missing values
- Values out of range
- Outliers (sudden peaks)
- Constant (or frozen) values
- Drifting values (changes in values over a longer period of time)

As the quality of the insights gained from data analytics or the control system's performance will be directly linked to the quality of the data used, raw data collected from the sensors needs to be validated and possibly filtered before being used for further analysis or control purposes. This is an important step to improving the data's reliability.

Emerging Technologies for Data Analytics

The IoT industry trend is to provide more accessibility through cloud computing platforms and open source technologies. The digital platform will streamline the integration of data from various legacy systems and eliminate data duplication and bad data for more effective and powerful data analytics and insight. Cloud-based computing has already been implemented for SCADA system applications and RTC applications.

Data validation can be carried on a single variable (single data validation methods) or by comparing two variables when two or more measures are correlated (cross-validation) (U.S. EPA 2006, Sun et al. 2011).

Single data validation methods include the following:

- **Range validation:** The values that are outside an expected range are flagged as invalid. The expected range is based on the working range of the sensor itself and on the process monitored. For example, a water level in a collection system cannot be lower than the bottom of the chamber where the sensor is located and can seldom exceed ground level.
- **Gap filling:** When data are missing (due to communication failure, sensor automatic

calibration, etc.), it is possible to use an estimate instead. In a real-time context, the last valid value can be used. If correlation exists with other measurements, cross-validation techniques can also be used to produce better estimates (see below). In a post-event analysis, a simple linear interpolation between the values before and after the gap can often be used.

- **Rate of change validation:** If values change at a greater rate than a probable change in measured conditions and sensor noise, then the value is marked as invalid.
- **Running variance validation:** A value is flagged as invalid if the variation over a past value is too small. A frozen value is often due to a sensor failure.
- **Long-term drift:** Expected mean check and acceptable trend check are two methods to detect long-term drift. Once detected, the source of the bias or drift then needs to be identified as it could be caused by sensor drift, as well as a long-term trend of the measured value.

Cross-validation methods are used when it is possible to develop a model or relation between two or more values. The simplest case is where some sensors are redundant and measure the same value or if software can be used to produce another sensor's estimate. A range or rate of change validation can then be carried on the difference between the two values. In more complex cases, the redundancy can come from combining sensor data with a model to produce many estimates of a specific variable (soft sensors or virtual sensors). The data reconciliation technique can then be used to better estimate the variable.

Filtering can be used to reduce the measurement noise inherent to sensor data. The result is smoother and easier to analyze and usually produces better results with control processes.

All RTC system data should be validated in real time. Data validation can be implemented at the local PLC and at the central control station. Whenever possible, data validation processes should take advantage of the correlation between the measurements (i.e., cross-validation methods). At minimum, the data validation algorithms should use sensor alarms and be able to detect missing data, out-of-range values, outliers, and frozen measurements.

7.2 Key Performance Indicators

Developing key performance indicators (KPIs) based on computations of validated data can provide a quick and general understanding of the system's performance. Some of the meaningful KPIs applied for wastewater and stormwater systems include the following:

- **Precipitation frequency:** The average recurrence of rainfall can be assessed using rain gauge readings (NOAA n.d.). Maximum rainfall depth over various durations is calculated and compared to precipitation frequency estimates for the area and precipitation data used for hydraulic model development and calibration.
- **Treated flow:** Maximum flow conveyed to the wastewater treatment plant (WWTP) is compared to the WWTP's treatment capacity. If CSOs or significant retention occur while the treatment capacity is not met, it can signal a suboptimal system or control.
- **Untreated flow:** Estimated or measured overflows from the collection system prior to treatment is compared to total flow treated at the WWTP. This is typically measured as number of overflows and/or the volume of overflows. These values can be compared to those projected or allowed under an approved Long-term Control Plan or NPDES permit to assess system performance and compliance.
- **Partially treated flow:** Estimated or measured volume of wastewater receiving

only partial treatments prior to discharge. These values can be used to assess system performance and compliance.

- **Retention volume:** Maximum stored volume can be presented relative to full capacity. If CSOs occur while the full retention capacity is not met, it can signal a suboptimal system or control.
- **Retention duration:** Exceedingly long durations can lead to odor problems in wastewater storage systems.
- **CSO/SSO volume and duration:** Overflow discharges can be reported to the public in a timely manner.

8. Data Visualization and Decision Support Systems

Data visualization is the presentation of large amounts of complex data using charts or graphs—a quick, easy way to universally convey concepts. It enables data users and decision-makers to visually explore analytics, so they can grasp difficult concepts or identify new patterns. Interactive visualization allows the user to take the concept a step further by using technology to drill down into charts and graphs for more detail, to interactively change the data displayed and how it is processed (SAS n.d.).

Data visualization is a key component of the user interface for any decision support system (DSS). A DSS (also known as decision-making software or DMS) is a computer-based information system that supports business or organizational decision-making activities. DSS has three main functions: information management, data quantification, and model manipulation.

- **Information management** refers to the storage, retrieval, and reporting of information in a structured format convenient to the user.
- **Data quantification** is the process by which large amounts of information are condensed and analytically manipulated into a few core indicators that extract the essence of data.
- **Model manipulation** refers to the construction and resolution of various scenarios to answer, “what if” questions. It includes the processes of model formulation, alternatives generation and solution of the proposed models, often through the use of several operations research/management science approaches (Inc. n.d.). Its main objective is to convert data into usable and actionable knowledge.

There are two main types of DSS tools, one for planning purposes and another for real-time decision support (Hydrology Project n.d.). For wastewater and stormwater applications, DSS is typically structured to allow users to access and analyze monitoring data, run model simulations, and assess the impact of potential decisions by using “what if” scenarios. While the data can be displayed and analyzed in real time to identify areas that need attention or improvement, the appropriate actions can be taken at a later time. For example, DSS can display real-time level data correlating to expected flow behavior. Abnormally high-level data would indicate a potential debris blockage, and the corresponding response decision would be to schedule a maintenance crew to perform a field investigation. However, this action could be optimized with other work orders to improve maintenance efficiency.

An RTDSS allows decision-makers to respond to short-term variations in wastewater and stormwater systems where lead times for decisions vary from a few hours to a few days at most. Typical RTDSS examples include:

- Hydraulic flow diversions
- Storage basins to manage levels or volumes
- CSO or SSO discharge warnings
- Flood forecasting and warnings

See Section 5.2 for additional details on the RTDSS.

Before buying the various computer systems and software needed to create a DSS, utilities should consider (Inc. n.d., WERF 2005):

- Establishing business needs and value for DSS, such as providing guidance for complex operation.
- Evaluating the development of DSS applications using available software, such as spreadsheets, SCADA, or asset management software.
- Integrating information spanning more than just one functional domain into the DSS, as well as support decisions from multiple domains.
- Creating user-friendly DSS for easy viewing and access, as well as allowing users to create scenarios and to simulate and analyze the impacts of different scenarios.
- Ensuring the investment in terms of time and effort to incorporate DSS into daily operations.
- Providing necessary training and knowledge to use DSS effectively.
- Understanding how the DSS is used, such as the limitations or assumptions of the mathematical calculations or processing model used within the DSS.
- Examining other factors, such as future interest rates and new legislation, in the decision-making process.

9. The Future of Data Gathering Technology for Wet Weather Control and Decision-Making

Rapid advancements in data gathering technologies have already led to substantial improvements for real-time operational support and decision-making systems. Future advancements will continue to be made in the following areas:

- Monitoring the frequency, volume, and duration of overflows and discharges within combined and separate sanitary sewer systems.
- Water quality of flows within sewer systems, discharges, and receiving streams; specifically, real-time measurements of bacteria, nutrients, suspended solids, and possibly emerging pollutants.
- Operational data to inform asset management systems and long-term planning.

As these advancements continue, dischargers and regulators will need to adapt to new ways of thinking and embrace the increased role that smart data infrastructure will play in wet weather control and decision support. Dischargers will need to overcome barriers in educating personnel to operate and interact with new technology and systems, as well as adapt to a new culture of enhanced data operations.

New technologies will only be able to maximize end-user benefits if they can be implemented within the framework of regulations.

The advancement and proliferation of new technologies for gathering and analyzing wet weather infrastructure data will lead to the generation of more accurate information and provide for lower-cost operations. With more accurate data, operators will be able to make more informed decisions, increasing efficiency and reducing risks.

Technology advancements will continue to improve our ability to quantify wet weather events and monitor water quality in ways we have never been able to before. In the future, better technology will exist for generating data related to the frequency, volume, and duration of wet weather events. Operators will have increasingly better information to determine the occurrence of wet weather discharges and to calculate the impact of wet weather events on collection system capacity. Better understanding these system characteristics will lead to improved infrastructure design and management, and ultimately the prevention of failures and overflows.

Pollutant sensor technology will also continue to improve, and operators will be able to monitor pollutant impacts on water quality more often and in real time. Operators will also be able to more closely monitor pollutants (such as bacteria) of particular concern to public and environmental health.

Continued improvements in data gathering will increase the effectiveness and reliability of data-informed operations, and ultimately change the pace at which operational decisions can be made, moving increasingly toward real time. Increasing the amount and frequency of reliable data will also enhance asset management programs and promote more informed capital planning. Wet weather system O&M was at one time conducted on a solely reactive basis. As technology and operational strategies have advanced, and more precise and accurate data are more readily available, operators have now shifted their approaches toward preventive and, in some cases, predictive O&M practices.

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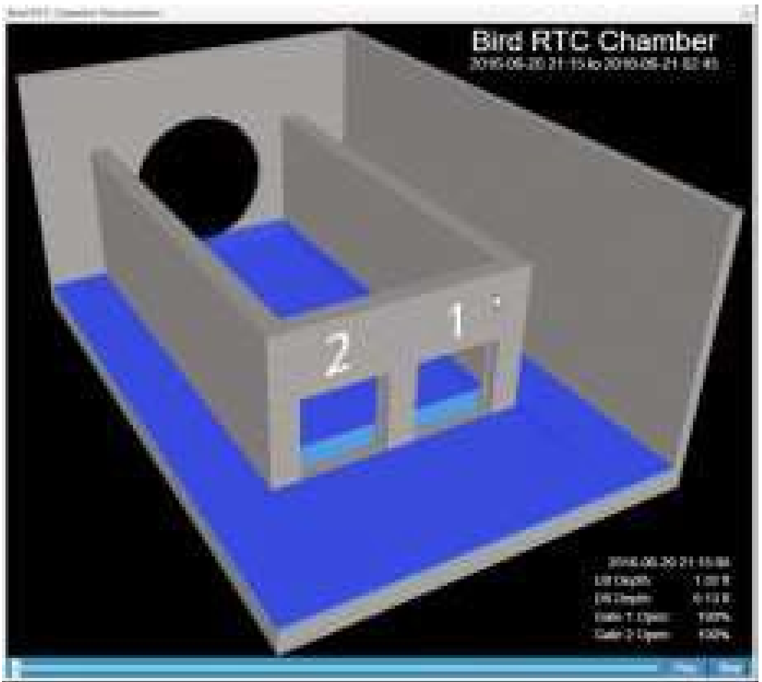
Appendix A
Case Studies

Buffalo, New York:
Real Time Control of Inline Storage



OWNER

Buffalo Sewer Authority

LOCATION

Buffalo, New York

INCEPTION

Commissioned winter 2016; study period March–May 2016

REFERENCES/LINKS

BSA Awarded EPA Environmental Quality Award

www.emnet.net/clients/buffalo-new-york

www.ghd.com/usa

www.arcadis.com

KEY FEATURES

- Reduced combined sewer overflow (CSO) by 13.3 million gallons at two initial RTC sites between March 1 and May 31, 2016.
- Sixteen real-time control (RTC) sites to be established by 2020.
- Expected to reduce CSO by 15 to 20 percent at full capacity.
- $145 million negotiated out of long-term control plan and consent agreement based on modeled outcome of inline storage.

PROJECT DESCRIPTION

Once the 8th largest city in the United States, Buffalo has lost half of its population and most of its industrial base since the 1960s. Before its decline, the city built a massive sewer system to accommodate as many as 750,000 people, but today Buffalo Sewer Authority (BSA) serves just 250,000. This means the collection system has substantial inline storage capacity.

Working with its team of engineers and consultants, BSA identified 16 RTC sites for inline storage and optimal conveyance throughout the city. The sites were chosen for maximum return on investment; from among them, four representative sites were chosen for initial construction. Two of these four sites are now live, while the other two are in design. BSA plans to build and commission all 16 sites by 2020.

The first two inline storage sites, the Bird Avenue RTC and the Lang Avenue RTC, were commissioned in early 2016. Both sites are operated by program logic controllers (PLCs) within BSA's supervisory control and data acquisition (SCADA) system. These PLCs are driven by remote level sensors upstream and downstream of each site, and are presented digitally in the SCADA interface. From March 1 to May 31, 2016, the two sites were studied and tuned to achieve optimal performance. During this period, Lang reduced 4 out of 9 (44 percent) of potential activations, resulting in reduced CSO volume of 1.2 million gallons (64 percent). Bird reduced 14 out of 19 (74 percent) of its potential activations, yielding reduced CSO volume of 12.1 million gallons (64 percent). Both sites were tuned on an ongoing basis, and performance improved with each significant storm during the study period.

Citywide, the program is expected to reduce BSA's CSO volume by 15 to 20 percent, or over 500 million gallons. Based on the modeled outcome of the inline storage program, BSA was able to negotiate $145 million of otherwise needed system improvements out of its long-term control plan and consent agreement with the New York State Department of Environmental Conservation.

Based on the BSA team's experience, the program could yield further operations and maintenance benefits, as well as significant potential for further reductions in overflow volume and activations. As the program develops and all 16 sites are commissioned, the system will benefit substantially from temporal and spatial distribution of rainfall across the urban watershed.

Falcon Heights, Minnesota: Predictive Flood Control System

OWNER
Capitol Region Watershed District
LOCATION
Falcon Heights, Minnesota
INCEPTION
July 2015

KEY FEATURES

- Optimized stormwater management using real-time controls and adaptive logic.
- Doubled flood control capacity of an existing wet pond.
- Reduced risk to nearby residential areas and infrastructure.

PROJECT DESCRIPTION

Curtiss Pond in Falcon Heights, Minnesota, collects runoff from a 38-acre watershed. A playground and residential area surround the pond. Large storms have caused pond overflows and several feet of standing water in the surrounding area, threatening infrastructure and private property. To eliminate this flooding, which poses an imminent safety concern, the Capitol Region Watershed District designed a network of perforated pipes, 10 feet in diameter, to temporarily store and infiltrate the overflow. However, the physical space for the pipe network was limited.

To eliminate the flooding, the District installed an intelligent retention system that uses weather forecast information to predict the amount of runoff from a watershed and prepare the pond to receive the forecasted water. The system autonomously draws down the pond during dry periods, maximizing available capacity in advance of wet weather. This active control allows for a smaller pond design volume while using its full storage capacity to reduce flood risk.

> *"Did you know that innovative technology can automatically check the weather and activate water management structures that protect your neighborhood from flooding? The system will reduce flooding in the park and reduce the risk of damage to surrounding properties."*
>
> **—Capitol Region Watershed District**

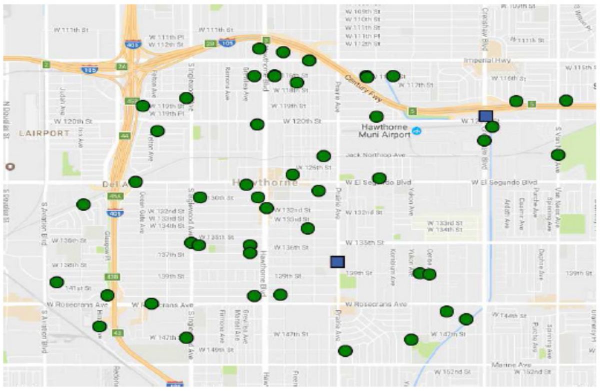
An 8-inch butterfly valve was installed to allow the system to control water draining to the infiltration pipe. The system decreased the storage requirement by 226 feet of pipe, effectively increasing storage volume by 58 percent without changing the project footprint. The system also measures temperature and infiltration rates to improve stormwater management during freezing/thawing cycles.

58% increase in effective storage

132,000 gallons managed

Since deployment in July 2015, the system has successfully collected stormwater runoff from the watershed and prevented the costly flooding of the surrounding area, which limited park use, damaged infrastructure, and created public safety concerns. The system also provides real-time and historical data of site performance. At any time, staff can remotely monitor the system and modify what's happening. This high-efficiency solution has enabled the Capital Region Watershed District to achieve its stormwater management objectives within the constraints of a highly developed urban/suburban area. It also holds potential for expansion to stormwater facilities throughout Falcon Heights to effectively manage storms at the local watershed scale.

Hawthorne, California:
Real-Time Monitoring to Prevent Sewer Overflows



Hawthorne installed 50 SmartCover units in their collection system - about 2.5% of all of their manholes - and virtually eliminated overflows.

OWNER

City of Hawthorne

LOCATION

Hawthorne, California

INCEPTION

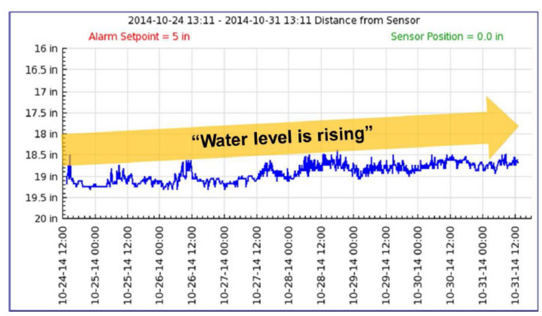
2006

KEY FEATURES

- Real-time control technology provides early warning of pre-flow events.
- Sewer overflows reduced by 99 percent.
- Savings estimated at $2 million in fines and mitigation costs since 2006.

PROJECT DESCRIPTION

The City of Hawthorne operates a small gravity-only sewer system southwest of the LAX airport. This system includes 94 miles of gravity pipeline, no lift stations, no treatment, and just two full-time collection staff. Before 2006, Hawthorne was experiencing about 10 sewer overflows per year in their sanitary sewer collection system. The city estimated that these spills cost them $400,000 annually in fines, cleanup and mitigation costs, and legal costs.



The above graph shows a rise in water level, alerting managers to a potential issue.

In late 2006, the City of Hawthorne positioned 50 real-time remote level monitoring sensors covering 66 of the “hot spots” in the collection system. These systems provide managers real-time early warning of pre-flow events through alarms and through the use of a data analytics tool, used to indicate when pipes were beginning to accumulate dirt; grit; fats, oils, and grease (FOG); or tree roots, thereby changing the daily pattern of water flow in the pipes.

Since the installation of the real-time monitoring system, the City of Hawthorne has experienced only one overflow in its sewer collection system, at a location that was previously unmonitored. This represents a decrease in sewer overflows of 99 percent. Using its two-man crew and the real-time control technology, Hawthorne has been able to virtually eliminate sewer overflows in its collection system, saving more than an estimated $2 million in fines and mitigation costs since 2006.

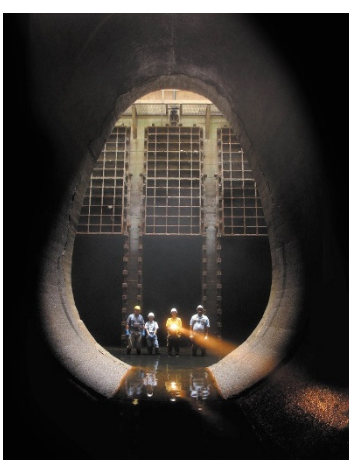
Louisville, Kentucky:
Real-Time Control for Integrated Overflow Abatement

OWNER
Louisville and Jefferson County Metropolitan Sewer District, Louisville, Kentucky
LOCATION
Louisville, Kentucky
INCEPTION
2006
COST
$21M
REFERENCES/LINKS
Angela Akridge, PE, Chief Engineer Louisville & Jefferson County Metropolitan Sewer District 700 West Liberty Street Louisville, KY 40203-1911 Tel.: 502.540.6136

KEY FEATURES

- Enhanced sustainability of sewer systems and improved quality of receiving waters from smart use of real-time control (RTC) technology.
- Maximizes conveyance, storage, and treatment capacity, with consistent operational results of capturing 1 billion gallons of combined sewer overflow (CSO) annually.
- Overall cost savings estimated at $117M from the original CSO long-term control plan (LTCP), a 58% reduction in capital investment.

PROJECT DESCRIPTION



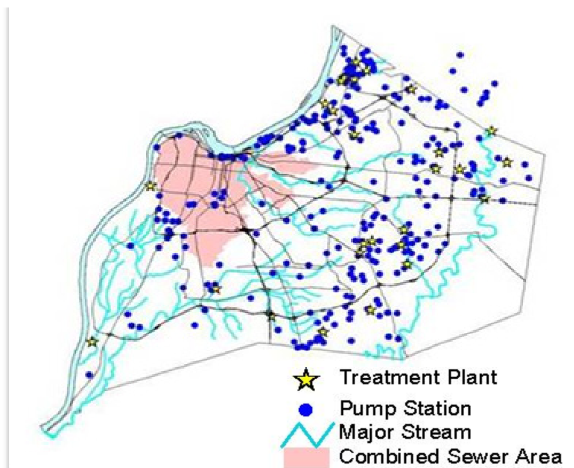
Louisville Metropolitan Sewer District (MSD) operates and maintains a complex wastewater and stormwater system, with more than 3,200 miles of wastewater collection sewer lines, 16 small and regional wastewater treatment plants, over 280 pump stations, and 790 miles of stream water quality monitoring as well as the Ohio River Flood Protection System.

Louisville MSD is one of the nation's early adopters of RTC, applying inline storage since the 1990s and pioneering the application of global optimal and predictive RTC that has been in operation since 2006. The RTC system was a key to maximize the conveyance, storage (inline and office), and treatment capacity to reduce CSO, with consistent operational results of capturing more than 1 billion gallons of CSO annually.

Louisville MSD is mid-way through implementation of a 19-year initiative known as the Integrated Overflow Abatement Plan (IOAP). The vision of the IOAP is to provide a long-term plan to eliminate sanitary sewer overflow (SSO) and other unauthorized discharges and to reduce and mitigate wet weather CSOs in both the combined and separate sewer systems, in an effort to improve water quality in both Louisville Metro streams and the Ohio River.

MSD has a progressive vision for total wastewater system optimization, which includes the control of both inline and offline storage facilities, diversion control within and between the combined and sanitary sewer systems, and maximizing of wastewater treatment throughout the system. RTC is integral to the fulfillment of this vision. Smart use of RTC technology has allowed MSD to enhance the sustainability of their sewer systems while also improving the water quality of receiving waterways.

Technology Description: The global optimal and predictive RTC approach was determined as the most appropriate level of RTC for the Louisville system based on the control objectives and the system hydraulic characteristics. The RTC system includes remote control facilities and a central station. Each remote site includes sensors (flow, level) and a local RTC device (Programmable Logic Controller [PLC] or Remote Terminal Unit [RTU]). Final control elements (e.g., gates, pumps) at each remote control facility 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. Information collected in the field is communicated from the remote stations to the central station via the supervisory control and data acquisition (SCADA) system. The central station manages and coordinates the various modules, including data management and archiving, RTC control algorithms, hydrologic and hydraulic models, and weather forecasting.



As conditions are monitored, acknowledged, and controlled, the RTC system takes into account the distribution of flow in the entire system, both in current conditions and in the future, based on rain forecasts, measurements and sewer simulations in real time. The RTC system provides continuous and strategic adjustment of control devices to optimize flow conveyance, storage, release, and transfer according to the available capacity in the entire system.

Benefit Cost Analysis: The evaluation of RTC feasibility studies of phase 1 implementation identified a relatively low unit cost ranging from \$0.006 to \$0.021 per gallon of CSO reduction per year by maximizing the existing collection and treatment system. This cost is 4 to 10 times lower than traditional approaches of building additional storage. The overall cost savings was estimated at \$117M from the original CSO long-term control plan cost of \$200M (a 58% reduction in capital investment).

Advantages: The RTC technology is scalable and flexible. The global optimal and predictive RTC system involves all levels of control—from static to local to global—to provide system-wide optimization. New control sites can be added and control logics can be modified based on performance monitoring as part of adaptive management. The use of an online model reduces the number of sites and extent of the monitoring network required for system-wide optimization.

Disadvantages: The approach relies on online model and weather forecasting to provide predictions of upcoming inflows and their spatial distribution. This requires the calibration and update of the hydrologic and hydraulic model to represent the wastewater system adequately. The control strategy and decisions need to account for inaccuracy and unpredictability in weather forecasting.

Lessons Learned: Lessons learned from this project include the following:

- The adoption of RTC technology requires organizational commitment and staff buy-in.
- The utility needs to consider operation and maintenance (O&M) issues and constraints when selecting the appropriate level of RTC implementation.
- It is important to involve system operators early in the planning and design, and to identify and communicate roles and responsibilities at every stage, from design, construction, and commissioning to post-construction performance monitoring.
- Development, implementation, and monitoring performance of standard operating procedures and post-event analysis are critical to properly operate, maintain, and improve the RTC system.

RTC Project Cost: RTC program cost is estimated at $21M to date, including retrofit, construction, monitoring, information technology, etc. The current RTC system includes the use of two stormwater retention basins (over 30 million gallons) for CSO control, multiple inline storages, flow diversions, pump stations, as well as the management of Southwestern outfall, which is an egg-shaped tunnel with a diameter ranging from 24 to 27 feet.

"Real Time Control is an important component of MSD's long term plan to mitigate untreated combined sewer overflows into Beargrass Creek and the Ohio River. It is a cost effective management strategy to help sustain the resources of our community."

Future Projects: MSD continues to improve and expand its RTC system as new storage and treatment facilities are constructed under the IOAP.

Training Needs: Web-based training modules on the RTC system were developed and used for continuous training and knowledge transfer. Control site commissioning and start-up provide onsite training opportunities for instrumentation and control (I&C) and O&M staff.

Newburgh, New York: Real-Time Control to Monitor Discharges for Reporting/Public Notification

KEY FEATURES:

- Easier, more reliable, more nimble operations.
- Reduced risk of loss or damage to sensors.
- Reduced cost.

OWNER
City of Newburgh
LOCATION
Newburgh, New York
COST
$78K for 18 units

PROJECT DESCRIPTION

The City of Newburgh replaced its traditional telemetry system with smart controls to provide city staff and the public real-time notification of CSO events and to prepare for increased regulatory requirements for annual reporting and notification.

The City's prior telemetry system used pressure sensors that were required to be located at the bottom of the influent channel, in direct contact with the flow, and in the combined sewer regulator environment. In these locations, the sensors were regularly impacted and damaged or displaced by debris. On numerous occasions under high flow conditions, several entire units were swept away down the CSO and lost at the outfall.

The prior sensors also required expensive calibration equipment and a proprietary consultant to perform the annual calibration of the telemetry system at each installation location. The old telemetry system used a dedicated phone line for each telemetry station, with only a single point of access and control, which was located at the wastewater treatment plant. These hard lines were expensive, had regular loss of communication, and were very difficult or impossible to locate by the utility company when service was required.

With the new telemetry system, all of these problems were avoided. The smart control wireless satellite connectivity proved more reliable than land phone lines, and at a lower cost. Any computer, tablet, or smartphone with internet access can communicate with the telemetry system. There is little calibration needed. When calibration or sensor relocation is required, in-house staff can easily perform the required task with basic tools. The sensors are not in contact with the water, thereby avoiding damage.

Lessons Learned: The new sensors are generally installed hanging from the manhole cover above. At some installation locations, some initial erroneous readings resulted in the discovery that, in some locations within the sewer, plugs of air can cause the sensors to swing. At these locations, a restrained installation of the sensor is required. This has been accomplished in-house with stainless steel angle brackets and associated hardware.

In some sites, initial erroneous readings were caused by low flows with a large distance from the influent channel to the sensor above. This challenge was overcome with the installation of replacement long-range sensors.

Philadelphia, Pennsylvania: Real-Time Control to Manage Retention Pond Discharge

OWNER
Philadelphia Water Department
LOCATION
Philadelphia, Pennsylvania
INCEPTION
2016
COST
Estimated retrofit cost of $53,000 per greened acre

KEY FEATURES

- Retrofit of an existing stormwater management pond with active control technology to increase treatment and reduce wet weather flows.
- Minimization of wet weather discharge for storms up to 2 inches in rainfall depth.
- Integrated system monitoring and reporting capabilities.

PROJECT DESCRIPTION

An existing stormwater management pond (SMP) collecting runoff from 8 acres on private property in the combined sewer area was not meeting Philadelphia Water Department's (PWD's) stormwater management standards. For all areas served by a combined sewer and for which infiltration is infeasible, 100 percent of the runoff from 1.5 inches of rainfall must be routed through an acceptable pollutant-reducing practice and detained in each SMP for no more than 72 hours. Any runoff detained must also be released from the site at a maximum rate of 0.05 cfs per impervious acre. The existing pond was originally designed as an infiltration basin, but does not achieve sufficient infiltration because of errors in the construction process.

A PWD Stormwater Management Incentives Program (SMIP) grant was awarded to fund a facility retrofit to increase treatment and further reduce wet weather flows. The SMP enhancement was achieved through the installation of a continuous monitoring and adaptive control (CMAC) on the existing outlet control structure of the basin. The system includes a level sensor, actuated valve, and integrated software that will provide dynamic control of stormwater storage and discharge above the permanent pool of water in the existing basin.

The stormwater pond contains a permanent pool of 22,500 cubic feet maintained by an outlet structure with a 6-inch orifice. A second, 8-inch orifice is positioned approximately 2 feet above the invert of the lower 6-inch orifice and an overflow weir is positioned approximately 2 feet above the 8-inch orifice. The retrofit involved installing a 6-inch actuated valve on the existing 6-inch orifice, a water level sensor, and the associated communications hardware to connect these to cloud-based control software. The software uses the water level data along with NOAA storm forecasts to determine an optimal valve open percentage based on water quality, storm retention, and flood protection objectives. For this basin, the software was configured to achieve the following logic:

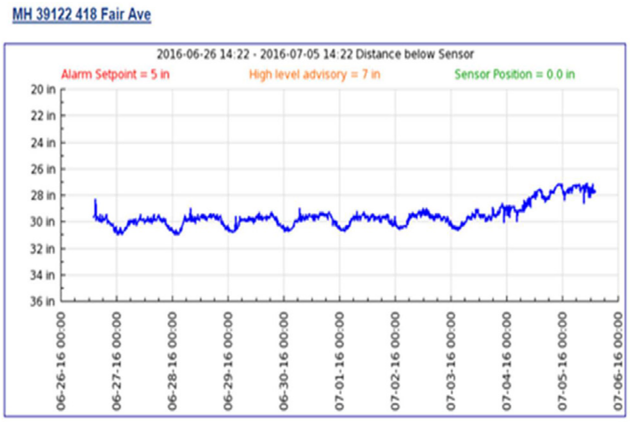
- When a forecasted storm can be fully captured within the basin storage between the permanent pool and the 8-inch orifice, close the 6-inch valve to eliminate wet weather flow.
- After the event, open the valve to release the captured runoff within the 72-hour retention period without exceeding a discharge rate of 0.26 cfs (0.05 cfs per impervious acre).
- When the forecast indicates that an upcoming storm cannot be fully captured, release water at the lowest possible rate to avoid overflowing the riser structure. This logic ensures that the

0.260 cfs target is only exceeded during large events to mitigate high water levels and discharge rates. Post-event, release any captured storm runoff within the 72-hour retention period without exceeding 0.26 cfs target.

The storage volume available above the current permanent pool of water and below the invert of the 8-inch orifice is 38,000 cubic feet. This volume is larger than the runoff generated by the 2-inch storm event (34,000 cubic feet). Therefore, for all rainfall events up to 2 inches, the CMAC basin is able to fully capture the runoff with no discharge to the combined sewer during the wet weather event. After the event, the valve will slowly but continuously adjust (i.e., open further as the driving head drops) to match the target 0.26 cfs rate until the basin returns to its permanent pool elevation.

In addition to meeting the requirements for stormwater retention credits, the retrofit facility still provides safe passage for larger events. The pond depth and outlet structure configuration were not changed from the existing conditions. When the system is fully functioning, the software logic will open the valve as far as is needed to avoid overtopping the outlet structure, up to fully open for very large events. When the valve is fully open, the retrofit and existing conditions peak flow and maximum water surface elevations are identical. If the CMAC system fails to function properly and the 6-inch valve is closed during a large event, modeling shows that the 100-year event is still safely contained within the basin and will not contribute to local flooding. The CMAC system includes fail-safe features that protect the infrastructure in the event of connectivity or physical hardware failures. The retrofit was installed in November 2016 and has been collecting hydraulic data while adaptively managing the pond discharge.

San Antonio, Texas:
Real-Time Control for Cleaning Optimization



Example of a location where the analytic tool indicates a need for cleaning based on water level signature.

OWNER

San Antonio Water System

LOCATION

San Antonio, Texas

INCEPTION

Summer 2015

REFERENCES/LINKS

Jeff Haby, Director, Sewer System Improvements

Tamsen McNarie, Director, Operations Support

KEY FEATURES:

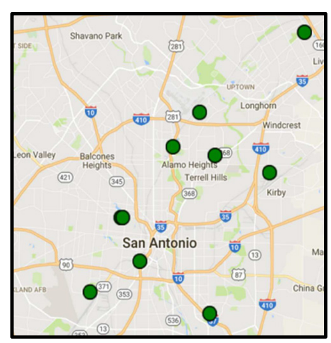
- Decreased cleaning frequency by 94 percent at 10 pilot sites with no increase in spill risk.
- Identified potential savings of $4,000 per location per year.

PROJECT DESCRIPTION

Blockages or flow restrictions in collection systems are a common cause of sewer overflows. Cleaning the collection system pipes can prevent these overflows. High frequency cleanings (HFC) may be necessary where a utility has repeated overflow problems, typically caused by fats, oils, and grease, root intrusion, or debris collection from stormwater runoffs or other sources.

HFC can reduce near-term risk, and the more frequent site visits can yield timely and valuable information about the site. However, HFC can be costly and capital intensive, adds traffic and operational risk to field staff, and increases wear and tear on pipes.

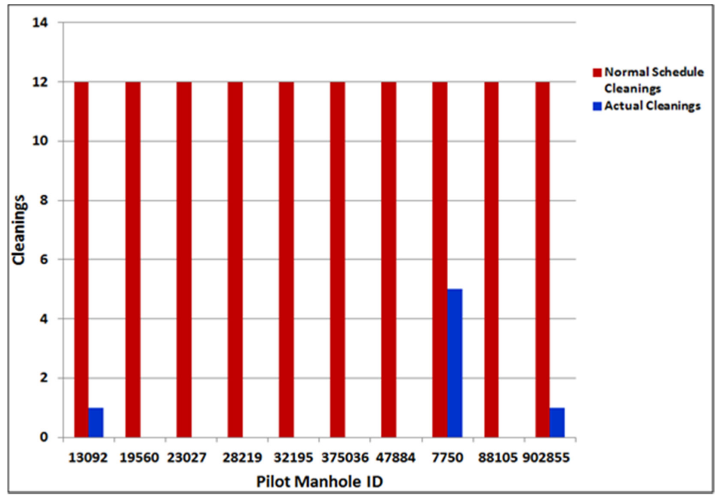
To help reduce overflows and mitigate the disadvantages of HFC, the San Antonio Water System (SAWS) implemented a pilot project at 10 monthly cleaning locations beginning in the summer of 2015. The pilot used a smart control analytic tool, which automatically scans water flow patterns in a location and detects changes that may signify changing pipe conditions upstream or downstream from the monitored location. The system effectively provides real-time continuous pipe condition assessment, allowing SAWS to use data to determine when to clean a sewer pipe segment rather than using a predetermined cleaning schedule.



Location of 10 smart control units for SAWS pilot. SAWS is using more than 300 units for other stressed areas in its svstem.

At the 10 sites monitored, cleaning frequency was decreased by 94 percent, while spill risk decreased due to continuous remote monitoring. With the exception of a period in late May/early June of 2016, when San Antonio experienced 16 inches of rain in a week, overwhelming the SAWS system, there were no spills at monitored sites during the pilot period.

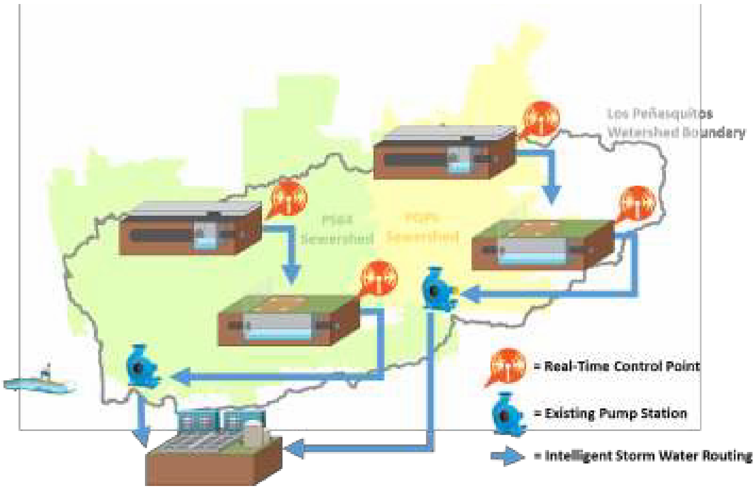
SAWS estimated that, net the costs of the monitoring, use of the system for maintenance optimization can save about $4,000 per monitored location per year for sites currently designated for monthly cleaning.



Cleaning frequency was reduced by 94 percent at 10 pilot locations.

Any mention of trade names or commercial products does not constitute an endorsement or recommendation for use. EPA and its employees do not endorse any products, services or enterprises.

San Diego, California:
Stormwater Harvesting Augmentation Analysis



OWNER

City of San Diego, Stormwater Division

LOCATION

City of San Diego
various locations

INCEPTION

2016

COST

$168,900

REFERENCES/LINKS

Andrea Demich
(858) 541-4348

KEY FEATURES

- Optimized stormwater/wastewater management using real-time controls and adaptive logic.
- Cost savings from program coordination.
- Magnitude of water supply augmentation.
- Water quality benefits.

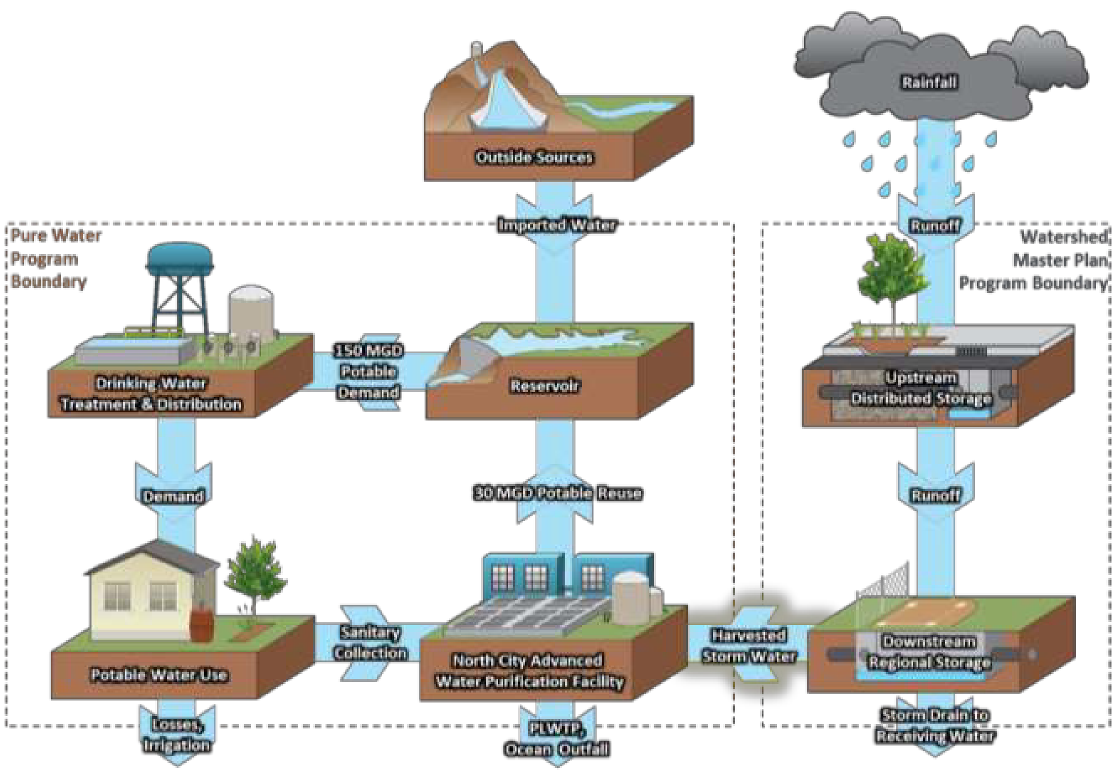
PROJECT DESCRIPTION

California experienced a historic drought with much of the state reaching D4 “exceptional” conditions on the U.S. Drought Monitor. In response, Governor Jerry Brown declared a state of emergency in January 2014 and established the first statewide mandatory water restrictions in March 2015. Concurrently, significant investments in green infrastructure are needed to address water quality impairments throughout Southern California. Despite the apparent synergy, urban stormwater is still underutilized as a water resource in coastal areas and is often conveyed directly to the ocean without beneficial uses. Synergy between drought resiliency planning and water quality protection could be realized if green infrastructure could be optimized to collect, treat, and distribute urban runoff as a supplemental, local water source.

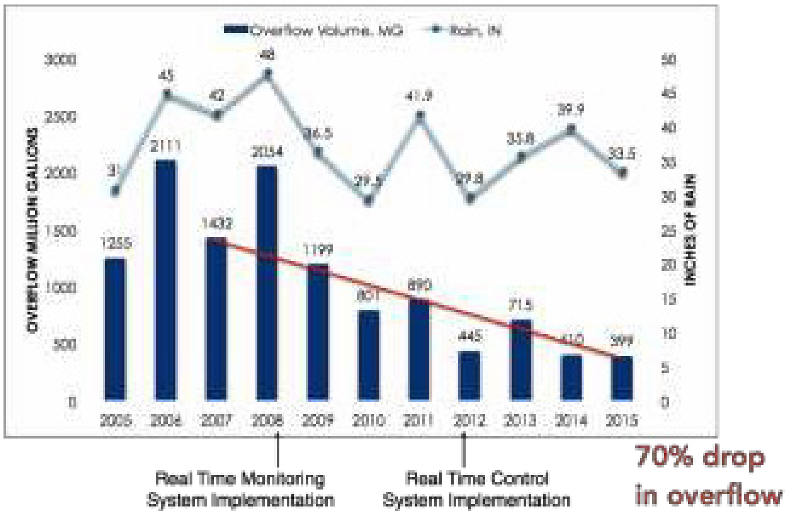
This work explored and quantified the potential nexus between an emerging stormwater capture program and ongoing efforts to reclaim wastewater as a drinking water resource in San Diego, which currently imports over 80 percent of its water supply. The project considered both (1) the need to pursue water independence in response to prolonged droughts, rising imported water costs, and the city’s growing population and (2) the need to plan, construct, and maintain extensive green infrastructure to comply with water quality regulations and flooding issues. As such, it provided valuable data on technological approaches to bolster San Diego’s water resiliency while reducing pollution, flooding, spending, and redundancy.

The analysis first defined treatment plant boundary conditions to determine what additional hydraulic and mass loading (from stormwater) the expanding water reclamation program could accommodate. The team leveraged a calibrated watershed model to predict the loading to the plant from raw stormwater and from effluent from the green infrastructure that will be constructed to address water quality regulations. The team then assessed the cost-effectiveness of methods to convey stormwater to the plant, including using the existing sanitary collection infrastructure and implementing a separate storm drain conveyance. Finally, they assessed upstream stormwater control measures—equipped with real-time controls (RTCs)—to optimize the management of stormwater storage and release to the reclaimed water system. The model included various scales of green infrastructure within the two major sewershed areas served by two existing pump plants. The resulting integrated water management analysis synthesized the benefits, costs, and energy demands of various alternatives to inform data-driven decision-making for municipalities with simultaneous water, wastewater, and stormwater stressors.

Analysis of the coordinated approach to water management hinged on simulating the capabilities of RTCs operated by cloud-based adaptive logic for intelligently managing storage and conveyance of water throughout the collection network (i.e., to reduce stormwater overflow to receiving waters while regulating diverted flow not to exceed the capacity of the treatment plant). This was accomplished using a software package to simulate optimization of control setpoints throughout the sewer network. The software identifies when valves, gates, and pumps should be operated to manage overall system performance in response to forecasted runoff and treatment plant capacity. It is well suited to an application where flows and storage must be actively controlled to enforce certain constraints and multiple objectives must be optimized over a long-term simulation. The analysis demonstrated potential cost savings and co-funding opportunities, as well as solutions to create resilient, low-impact communities. The simulations suggested that stormwater harvesting (enabled by RTCs) could substantially augment local water supplies while complying with stormwater quality regulations.



South Bend, Indiana:
Real-Time Control and Real-Time Decision Support



OWNER

South Bend Department of Public Works

LOCATION

South Bend, Indiana

INCEPTION

2008–present

REFERENCES/LINKS

https://www.southbendin.gov/government/department/public-works

https://www.emnet.net

http://www.greeley-hansen.com

http://pubs.acs.org/doi/abs/10.1021/acs.est.5b05870

KEY FEATURES

- Uses a real-time decision support system (RT-DSS) to maximize conveyance capacity.
- Eliminated illicit dry weather overflows and reduced total combined sewer overflow (CSO) volume by about 70 percent.
- Reduced the potential cost of the city's long-term control plan (LTCP) by an estimated $300-$400 million.

PROJECT DESCRIPTION

Before 2008, South Bend, Indiana had one of the largest CSO discharge volumes per capita in the Great Lakes Watershed. With a population of little over 100,000, South Bend generated annual CSO discharge volumes of 1-2 billion gallons and 25-30 dry weather overflows per year. Had the city simply implemented the prescribed projects in its LTCP, the total cost of mitigating its CSO problem would have totaled roughly $800 million.

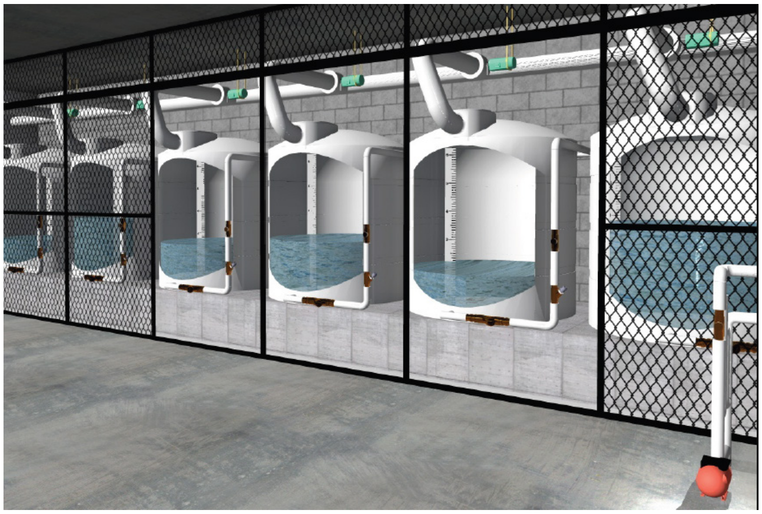
In 2008, the City of South Bend commissioned a real-time monitoring system of more than 120 sensor locations throughout the city. In 2012, after reviewing data from the system and selecting sites accordingly, the City launched a distributed, globally optimal real-time control (RTC) system. The RTC system consists of nine auxiliary throttle lines with valves governed by an agent-based optimization strategy. Distributed computing agents trade available conveyance capacity in real time, similar to a commodities market.

The system provides information to staff throughout the organization through supervisory control and data acquisition (SCADA) screens for the operators, smart phones and tablets for field staff, and customized websites jointly developed with the city's engineering staff. Operations staff can override automated controls and take over valve and gate operation at any time.

Since 2012, the City has added additional sensor locations and rain gauges, bringing the total number to 152 sites. It also added automated gates at several stormwater retention basins to better control the timing and rate of stormwater releases into the combined system.

Maximizing conveyance capacity utilization throughout the Saint Joseph interceptor line was the original objective of the RT-DSS. From 2008 through 2014, South Bend eliminated illicit dry weather overflows in the first 12 months and subsequently reduced its total CSO volume by about 1 billion gallons per year, about 70 percent. This program is estimated to reduce the cost of the city's LTCP by $300-$400 million, nearly 50 percent less than the original $800 million estimate and has already surpassed its original target of a 25 percent reduction in CSOs.

Washington, DC:
Real Time Controls for Rainwater Harvesting and Combined Sewer Overflow Control



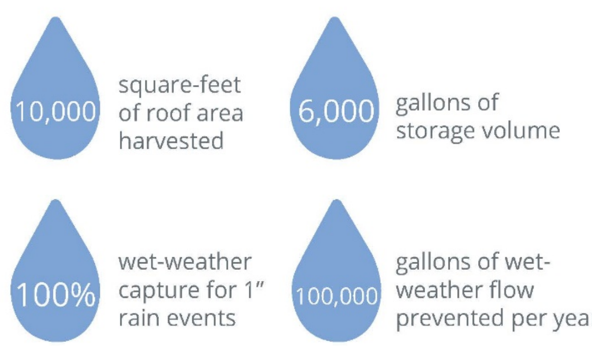
OWNER
U.S. Environmental Protection Agency
LOCATION
Washington, DC
INCEPTION
2014

KEY FEATURES

- Real-time controls to retain water for on-site irrigation and to reduce wet weather discharge to the combined sewer.
- Captures 100 percent of all 1-inch and less rain events, preventing approximately 100,000 gallons of wet weather flow from entering the combined sewer each year.

PROJECT DESCRIPTION

EPA and General Services Administration sought to upgrade an existing 6,000-gallon rainwater harvesting system at EPA headquarters in Washington, D.C. Two competing priorities needed to be addressed: minimizing wet weather discharge while also maintaining water availability for irrigation on site. Uncaptured wet weather flows contributed to the local combined sewer system, increasing the potential for CSOs and poor water quality in the Chesapeake Bay.



To monitor storage volumes and expected storage needs based on weather, the rainwater harvesting system was retrofitted with a continuous monitoring and adaptive control (CMAC) technology. The cloud-based platform automatically monitors the weather forecast and calculates expected runoff volume from future storms. The system then automatically opens the discharge valve in advance of the storm and releases a predicted volume equal to the potential runoff. As the forecast changes, the system adjusts intelligently. Before the storm begins the system closes the valve, capturing rain to refill the cistern. The valve remains closed until another rain event is in the forecast, ensuring that water is available for reuse.

A 1-inch solenoid valve was installed to allow the CMAC technology to control water draining to the combined sewer system. The CMAC technology also monitors discharge flow, irrigation flow, and air temperature and activates a freeze protection system during cold weather. The addition of CMAC technology to the existing rainwater harvesting system eliminated the need to install additional storage volume to meet otherwise competing objectives.

Since deployment in 2014, the advanced rainwater harvesting system at EPA headquarters has proven be a low-cost, high-performance solution for meeting stormwater management goals. The increased data transparency and opportunities for adaptive management can achieve a range of stormwater management objectives.

Wilmington, Delaware:
Real-Time Control to Reduce Combined Sewer Overflow Discharges

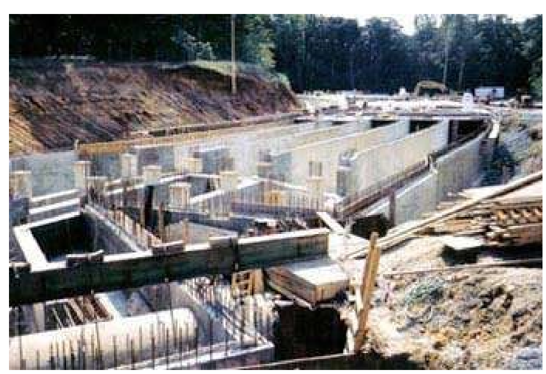
OWNER	City of Wilmington
LOCATION	Wilmington, Delaware
COST	$12M

KEY FEATURES

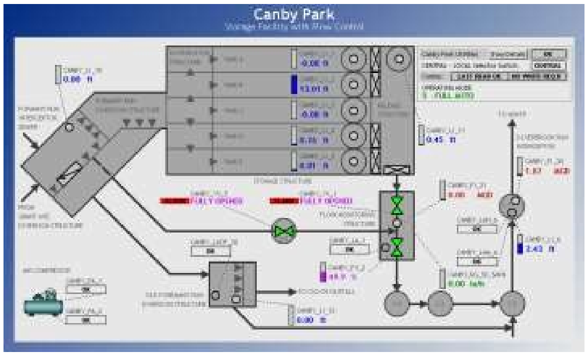
- Anticipated increase of Wilmington's average annual wet weather capture from 50 percent to more than 85 percent.
- Overall cost savings estimated at $87 million from the original CSO long-term control plan (LTCP).
- Fully automated operation, with remote supervision and manual override capacity at all times by treatment plant operators.

PROJECT DESCRIPTION

Since the early 1990s, the City of Wilmington has initiated a series of improvement projects to reduce CSO events and increase the annual average flow intercepted at the wastewater treatment plant. These projects included the upgrade of treatment plant capacity, the construction of the 2.7 million-gallon Canby Park CSO Storage Basin, the elimination of certain CSOs, other specific collection system improvements, and public outreach.



As part of its enhanced long-term control plan (ELTCP), Wilmington implemented a coordinated system-wide real-time control (RTC) solution. The RTC system provides efficient flow management to reduce CSOs along the Brandywine Creek and the Christina River and optimizes the capacity available in the interceptor and pump stations. Overall, the ELTCP will increase the average annual percent capture from 50 percent to more than 85 percent, meeting the CSO control objective via a presumptive approach. Wilmington's green infrastructure program is expected to meet the total maximum daily load (TMDL) objectives by increasing the wet weather capture rate to over 90 percent.



The city has adopted an adaptive management approach whereby site-specific system improvement, such as localized separation and additional green infrastructure, will be determined based on post-construction performance of implemented projects.

The RTC project encompasses the design, retrofitting, and implementation of four flow control stations, the control of Canby Park CSO Storage Basin, the control of the three existing siphons, and the design and implementation of a network of data collection and measuring sites (equipped with flowmeters and rain gauges) for monitoring purposes. All of the local stations are linked to the central station via a telemetry system and automatically managed under a global optimal and predictive RTC approach from the central station, under the supervision of operators. Smart use of RTC technology has allowed the City of Wilmington to significantly reduce overall costs of the LTCP.

Technology description: The RTC system is fully automated, with remote supervision and manual override capacity at all times by treatment plant operators.

The system consists of four major components:

- A monitoring system including level, flow, and rainfall.
- Local control facilities equipped with control elements (gate and pumps), programmable logic controllers (PLC), and remote telemetry units (RTUs) with backup power.
- A supervisory control and data acquisition (SCADA) system for data acquisition of sensor information and control facility status, as well as for communication of control set points.
- A central station which manages and coordinates the various components, including data management and archiving, RTC control algorithms and optimization, hydrologic and hydraulic models, and weather forecasting.

As conditions are monitored, acknowledged, and controlled, Wilmington’s RTC system accounts for current and future flow distribution throughout the system based on rain forecasts, measurements, and sewer simulations in real time. It provides continuous and strategic adjustment of control devices to optimize flow conveyance, storage, release, and transfer according to the available capacity in the entire system.

Cost-benefit analysis: The evaluation of RTC feasibility studies identified a relatively low unit cost of $0.07 per gallon of CSO reduction per year by maximizing the existing collection and treatment system, a cost four times lower than traditional approaches of building additional storage. The overall cost savings is estimated at $87 million from the original CSO LTCP cost of $114 million, for a final LTCP cost of $27 million.

Advantages: The RTC technology is scalable and flexible, and involves all levels of control—from static to local to global—to provide system-wide optimization. Additionally, new control sites can be added and control logics modified based on performance monitoring as part of adaptive management.

The RTC system design and operation takes into account equipment and sensor failures and provides fail-safe control for a robust performance system in real time.

The RTC approach enables the system to meet multiple objectives in a predefined priority order: 1) flood protection, 2) CSO minimization with local priorities, 3) minimal retention time with local priority order, and 4) minimal gate movements.

The use of an online model reduces the number of sites and the extent of the monitoring network required for system-wide optimization. The RTC system provides the city with greatly enhanced capability to monitor, analyze, assess, and report on CSO discharges and collection system performance (capture rate) on an annual basis. This has been useful for reporting to the regulating agency and for integrating adaptive management into LTCP planning.

Disadvantages: The RTC approach relies on an online model and real-time rain gauges to provide predictions of upcoming inflows and their spatial distribution. This requires the calibration and update of the hydrologic and hydraulic model to represent the wastewater system adequately. The control strategy and decisions need to account for inaccuracy in rainfall distributions and real-time monitoring data.

Lessons Learned: The lessons learned from this project include the following:

- The adoption of RTC technology requires organizational commitment and staff buy-in.
- The utility needs to consider O&M issues and constraints when selecting the appropriate level of RTC at the outset.
- It is important to involve system operators early in the planning and design, and to identify and communicate roles and responsibilities at every stage, from design, construction, and commissioning, to post-construction performance monitoring.
- Documentation such as standard operation procedures and post-event analysis is critical to properly operate, maintain, and improve the RTC system.
- Achievement of the anticipated performance was delayed until initially unidentified system collection anomalies were resolved. These included pipes obstructed with up to 50 percent sedimentation or root blockages, and pump station control logic that deviated from the reported operational condition.
- Key to the project has been the City of Wilmington and its designated operator taking ownership of the instrumentation and control (I&C) and SCADA system to maintain equipment and instrumentation in a proactive manner.

RTC Project Cost: The project cost is $12 million, including retrofit, construction, monitoring, information technology, etc. The current RTC system includes the use of one retention basins (2.7 million gallons) for CSO control, an additional 2.0 million gallons of inline storage, the management of three siphons, and the operation of a 135 MGD pumping station.

> *"We'd have to tear up several parks in the city to build more tanks, I'm not a scientist, but we knew there had to be ways to divert the way water flows in pipes. We are among the selected communities that have utilized Real Time Control that makes optimum use of our sewer capacity to manage and minimize overflows. This plan is cheaper, quicker and actually increases the amount of overflow we're trying to catch. The Enhanced LTCP would increase the CSO capture and treatment rate to 87% or higher, reduce CSO control costs by more than $87 million and accelerate implementation by ten years."*
>
> – **Mayor James M. Baker, City of Wilmington, Delaware**