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Smart Data Infrastructure for Wet Weather Control and Decision Support

U.S. Environmental Protection Agency
Office of Wastewater Management

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CONTENTS

APPENDIX A: CASE STUDIES

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Purpose of This Document

This document was originally developed in August 2018 to share how municipalities, utilities, and related organizations can use advanced technologies and monitoring data to support both wet weather control and decision-making in real time or near real time. Advanced wet weather control includes dynamic systems that remotely adjust facility operations in response to evolving field conditions to manage combined sewer overflows, sanitary sewer overflows, sewer backups, street flooding, and stormwater discharges. Technological advancements to support decision-making generally involve a remote monitoring component that communicates the status and condition of the system. This document highlights the technologies currently available and provides case studies to describe some of the possible ways municipalities and utilities implement the technologies. The capabilities of such technologies are broad and continue to expand and evolve over time.

EPA considers this a living document that is continually updated as new technology and case studies emerge. The March 2021 version updated existing case studies with new information and added the following case studies:

- Albany, New York
- Beckley, West Virginia
- Bordeaux, France
- Cincinnati, Ohio
- Fort Wayne, Indiana
- Grand Rapids, Michigan
- Green Bay, Wisconsin
- La Mesa, California
- Ormond Beach, Florida
- Rutland, Vermont
- San Francisco, California

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Acronyms and Abbreviations

BSA	Buffalo Sewer Authority
BSB	Beckley Sanitary Board
cfs	Cubic Feet per Second
CMAC	Continuous Monitoring and Adaptive Control
CMOM	Capacity Management Operation and Maintenance
CPU	Central Processing Unit
CSO	Combined Sewer Overflow
DMS	Decision-Making Software
DSS	Decision Support System
EGLE	Michigan Department of Environment, Great Lakes, and Energy
ELTCP	Enhanced Long-Term Control Plan
EPA	U.S. Environmental Protection Agency
FOG	Fats, Oils, and Grease
GUI	Graphical User Interface
ICS	Industrial Control System
I/I	Inflow and Infiltration
IOAP	Integrated Overflow Abatement Plan
IoT	Internet of Things
IT	Information Technology
KPI	Key Performance Indicator
LTCP	Long-Term Control Plan
LTE-M	Long-Term Evolution Category M
MG	Million Gallons
MGD	Million Gallons per Day
MMSD	Milwaukee Metropolitan Sewerage District
MSD	Metropolitan Sewer District (Louisville or Greater Cincinnati)
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and Maintenance
PID	Proportional, Integral, Derivative
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
SFPUC	San Francisco Public Utilities Commission
SMP	Stormwater Management Pond
SSO	Sanitary Sewer Overflow
STF	Storage and Treatment Facility
VFD	Variable-Frequency Drive
WPCP	Water Pollution Control Plant
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, the system promotes a desirable global effect 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: System that stores data in large-scale, offsite facilities.

Cognitive Computing: Use of computerized models to simulate the human thought process in complex situations where the answers may be ambiguous and uncertain.

EPA SUSTAIN: A decision support system that assists stormwater management professionals with developing and implementing plans for flow and pollution control measures to protect source waters and meet water quality goals.

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: An application of artificial intelligence that provides systems the ability to automatically learn and improve from experience without being explicitly programed.

Manning's Equation: An empirical formula used to estimate the average velocity of a liquid in open channel flow as a function of channel slope, roughness, and shape.

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.

SCADA Historian: A service that collects and stores data from various devices in a supervisory control and data acquisition network.

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.

Time of Concentration: The time required for runoff to travel from the hydraulically most distant point in a watershed to the outlet. The hydraulically most distant point is the point with the longest travel time to the watershed outlet and not necessarily the point with the longest flow distance to the outlet.

1. Introduction

Wet weather—that is, rain and snowmelt—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 mainly on gray or green infrastructure, or a combination of the two. In recent years, however, municipalities and utilities have been considering how they can improve their operations and infrastructure by drawing on recent technological advances. These advances include:

- Faster computer processing and network speeds, providing ready access to reliable information for informed decisions.
- Smaller, more accurate, less expensive sensors.
- Low-cost storage of large quantities of data.
- The advent of the 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 O&M requirements.

Section 4 describes the use of smart data infrastructure to promote collection system optimization, as well as LTCP implementation, modification, and development.

Section 5 discusses the use of RTC 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 KPIs.

Section 8 discusses data visualization and DSS.

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

Appendix A includes 22 case studies about communities across the country that have implemented smart data infrastructure technologies.

2. Smart Data Infrastructure

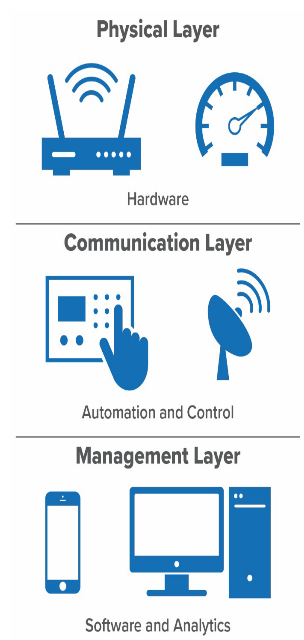
Smart data infrastructure is the integration of emerging and advancing technology to enhance the collection, storage, and/or analysis of water-related data. These solutions can generally be grouped into a framework that consists of hardware, communications, and management systems.

- **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 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 LTCP implementation, modification, and development.
- Meeting regulatory requirements.
- Prioritizing critical assets and future capital planning.
- Providing the ability to 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 save up to $320 billion in total expected capital expenditures and operating expenses for different water and wastewater utilities over the five years from 2016 to 2020 (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 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 help system managers—both municipal and industrial—by providing near-instantaneous support information for many of the routine and immediate response decisions they must make. Transformation may help water and wastewater utilities take advantage of innovations and opportunities in future O&M (see Figure 1).

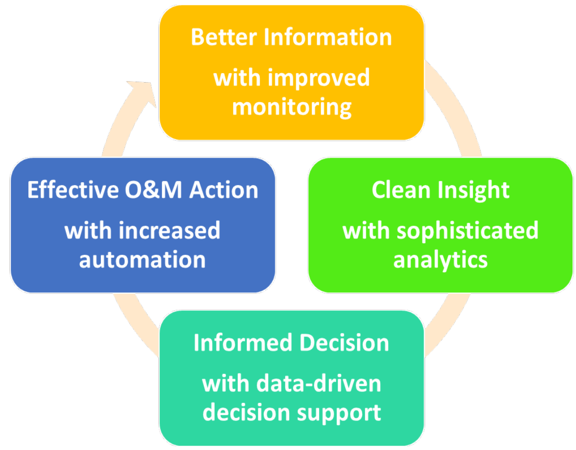


Figure 1. Better information and data can lead to more effective O&M.

Roadmap for Implementing Smart Data Infrastructure

There are few, if any, insurmountable technological barriers to implementing the various technologies described in this document. RTC technology (Section 5), for example, has been around for nearly 30 years. While its implementation in collection systems remains relatively limited, its effectiveness has been proven in many successful applications in WWTPs (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, IT, security, data usage requirements). It is also important to remember that smart data infrastructure is scalable. A utility can start small, applying technology that is compatible with its 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)

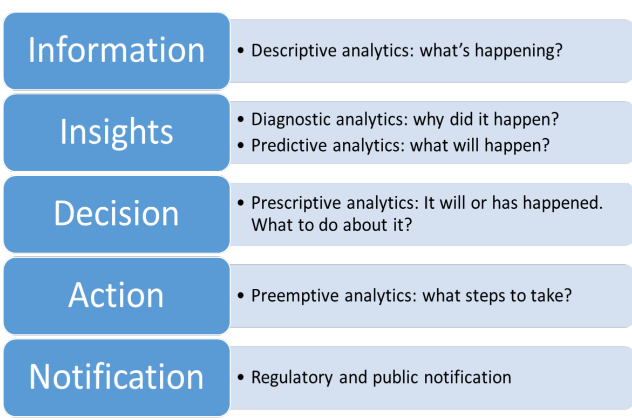


Figure 2. Operational process supported by information inputs.

3.1 Continuous Monitoring

Continuous monitoring uses permanent monitoring systems that report data back to a central system. 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, the status of equipment (such as pumps, gates, and valves) needs to be monitored to ensure safe O&M.

Continuous monitoring, 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. Examples include level trend detections that trigger alarms for equipment maintenance (e.g., cleaning), proactive I/I risk assessment, and data-driven work scheduling and asset management.

Continuous Monitoring in Practice

MMSD is using continuous monitoring to monitor the performance, value, and health of green infrastructure throughout Milwaukee. 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.
- In choosing and installing equipment, operators need 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.
- A sensor's advertised measurement accuracy may not represent its 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, such as floating devices and vibrating level sensors, could be used in some cases. The most important criteria for choosing a specific technology will depend on the environment and infrastructure where water level must be monitored. More precisely, conditions such as turbulence, sedimentation, or FOG in the water; foam; or obstacles in the air space above the monitoring location must be considered.

Pressure transducers need to be submerged in the water where the level must be monitored; they are therefore convenient 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, as a way to install pressure probes away from potential debris in the water flow and for easier maintenance.

Ultrasonic level meters, mounted above the water surface, are also very common in wastewater applications. They are usually preferred when space is available above the monitoring location and minimal obstacles, FOG, or foam are present above the water surface. The sensor must be mounted far enough from sidewalls to avoid bad readings due to soundwave reflections.

When monitoring space is small or FOG is present above the water surface, Doppler **radar microwave meters** are recommended. Their narrower signal beams lead to more reliable measurements under such conditions.

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 large, flat storage facilities. These probes are easy to clean and can handle temperature and pressure variations. However, they can significantly disturb flow and should not be used in small pipes.

In general, sensors above the water surface require 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. For example, using an ultrasonic meter and a pressure sensor in a storage facility would ensure water level monitoring in all conditions.

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. Transit time effect technologies consist exclusively of 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.

Flow meter technology has been developed to fit a variety of applications; submerged and "non-contacting" devices (sensors above the water surface) are available. 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-contacting flow meter technologies will provide flow measurements with an accuracy typically ranging from ±15 percent to 30 percent. Non-contacting devices have lower costs for procurement, installation, and maintenance than submerged technologies. A permanent flow meter installation in sewers typically costs from $15,000 to $75,000, or even more 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 is too complex or expensive, indirect means of flow monitoring can be developed depending on specific hydraulic conditions.

Level to flow relationship: When pipe flows remain under "free surface flow" conditions, Manning's equation 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 pipe is flowing full and under pressure or experiencing backwater effects.

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.

Improving Operations with Monitoring Technology

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. The data enabled users to consider actions such as a site inspection or cleaning. According to the 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 SSOs at the pilot locations.

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 weir's shape, its dimensions (length, width), and the angle of the flow stream according to the weir. This method can provide fairly accurate flow values for weirs under six feet in length; weir relationship calculations involve significant uncertainties for longer weirs.

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

Flap gate equations: As with bending weir relationships, mathematical functions can be developed to compute flows through flap gates. Such a computation requires installing an inclinometer on the flap gate and a level meter upstream of the gate. A downstream level meter will also be needed if the flap gate can become submerged. Typically, a temporary flow meter calibrates and validates the equation.

Model-based flow computations: Most utilities have developed calibrated hydrological and hydraulic models (e.g., EPA SWMM 5) to adequately represent their wastewater systems. 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 provides 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 rain gauges spaced out to allow for representative measurement of rainfall quantities over a region. On average, 1 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 counts a specific quantity of rain (e.g., 0.005 inches) over a specific time increment.

Such rainfall monitoring can be made available in real time and can be used as an input 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, rainfall monitoring can help produce flow forecasts 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 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 the effectiveness of existing infrastructure investments and reduce the need for future capital investment. It provides a framework for optimizing the design and O&M of wastewater and stormwater systems by collecting and analyzing large data sets.

There are two types of system optimization:

- **Offline improvements** (Muleta and Boulos 2007). Examples include raising weirs to reduce overflow discharge, developing best efficiency curves to minimize energy costs and reduce equipment breakdowns, and 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).
- **Online optimization** to actively manage the operation of wastewater networks and facilities in real time, a process often referred to as RTC. RTC systems are discussed in greater detail in Section 5 of this document.

Optimizing Collection System Capacity and Performance

PWD has committed to reducing 7.9 billion gallons of overflows in Philadelphia by 2036 through better stormwater runoff management. As part of this effort, PWD and a private corporation have collaborated to use smart data technology to monitor and maximize the performance of an existing stormwater retention basin. The basin was retrofitted with technology to monitor 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 presents the data used in a smart data infrastructure approach, regardless of optimization type.

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 SSOs	• 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 VFDs • 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 I/I • Undersized facilities (conveyance, storage, treatment)	• Upgrade of existing facilities • Addition of green and gray infrastructure • RTC implementation	• Level and flow measurements • Sewer and land characteristics • Operational and physical constraints • Cost of potential interventions
Reduce flooding risks	• Rainfall-derived I/I • Undersized facilities (conveyance, storage)	• Upgrade of existing facilities • Addition of green and gray 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 CMOM and I/I Control

Optimizing the performance of the collection system is the key component in CMOM programs. CMOM programs combine standard O&M activities with an increased level of data gathering and information management to operate collection systems more effectively. 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 SSOs.

CMOM includes control of I/I, 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. 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. 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 variables that affect 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

The Louisville MSD was an early adopter of RTC, applying inline storage since the 1990s and pioneering 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 about $200 million in savings compared to traditional methods.

5. RTC 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 purposely oversized. This extra capacity can provide short-term storage in the conveyance and treatment system when rain falls unevenly across the collection system and runoff lag times vary. 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 WWTP.

Using RTC to Maximize Capacity and Performance

In 2008, 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 global, 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.

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.

Benefits of using RTC 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.

Figure 3 presents a typical layout of the possible components of 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.

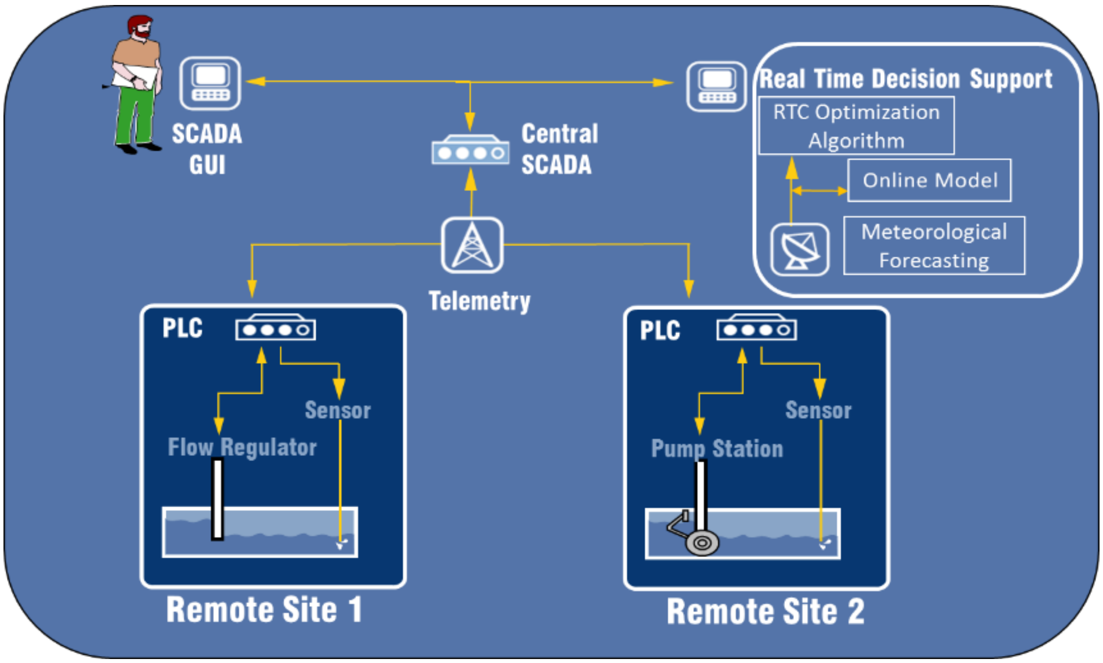


Figure 3. Components of an RTC system.

5.1 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 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 it. These rules are feedback algorithms that base action 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 SCADA Systems

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 GUIs 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 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 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 MSD of Greater Cincinnati 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, MSD began installing sensors throughout its largest watershed. By early 2016, MSD had gained 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, MSD's smart sewer system covers over 150 square miles (about half) of its service area, incorporating 2 major treatment plants, 6 wet weather STFs, 4 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 RTDSS

An 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 CPUs is determined by the number of modules. Each module has a controller, though 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 that 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 local, regional, or global control. The levels of control are classified according to progressive increases in complexity, performance, and benefits (Schütze et al. 2004).

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 a single-input, single-output feedback loop designed to maintain prescribed set points (e.g., flow or level set points). 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). It is a good solution only if the control objectives can be reached without transferring any information between other remote sites.

Regional control is similar to local control except in that a telemetry system exchanges data with other remote sites. Regional control can be implemented as a distributed or centralized system built on a SCADA system. A municipality might design its own DSS to control the collection system based on the specific constraints and opportunities at each control site. However, the control remains reactive, not predictive. This limits 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 5 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 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 depend highly on the available expert knowledge. For large and complex wastewater systems, the strategy may demand many rules.

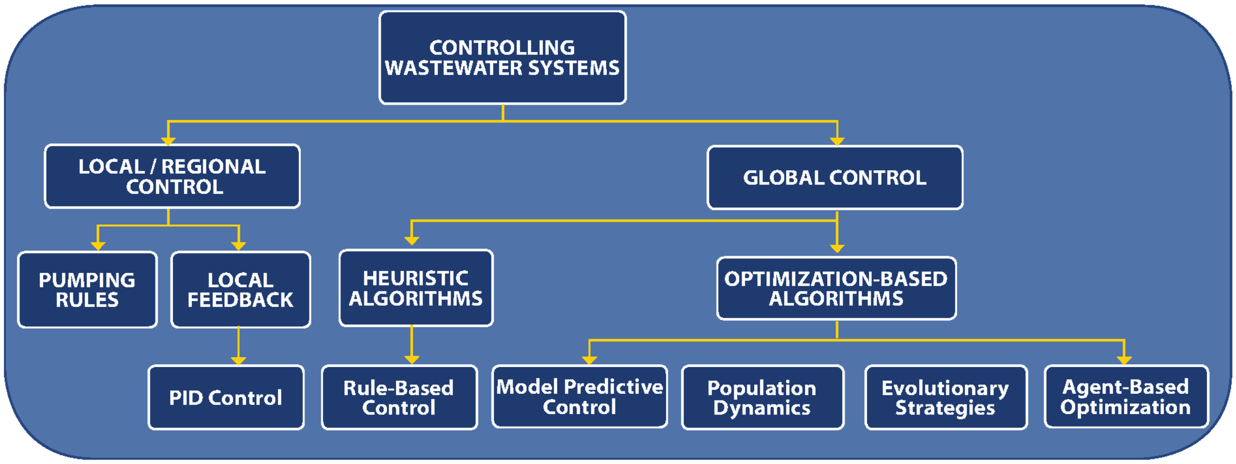


Figure 4. Control strategies for wastewater utilities.

An optimization-based strategy involves 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 under current conditions and in the future. Using a global RTC, a utility can open and close gates or pumps to transfer flows between sites, providing 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 Needed 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 suitable and viable for a utility is to develop criteria for a macroscopic evaluation 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 simulation shows that RTC would be feasible and beneficial, 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 already exists).
- Staff training and other organizational planning (i.e., new roles and responsibilities).
- Preparations for getting consent from 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 the system design addresses their O&M concerns, and that they buy into the 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 failsafe procedures must be configured so that they are triggered when the requirements for the system's current operational mode cannot be met. They 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 failsafe 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 need less computing time 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, 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: 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/ICS must now 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

The City of Newburgh, New York, replaced its combined sewer telemetry system with a wireless 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 debris would regularly damage or displace them. The new 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).

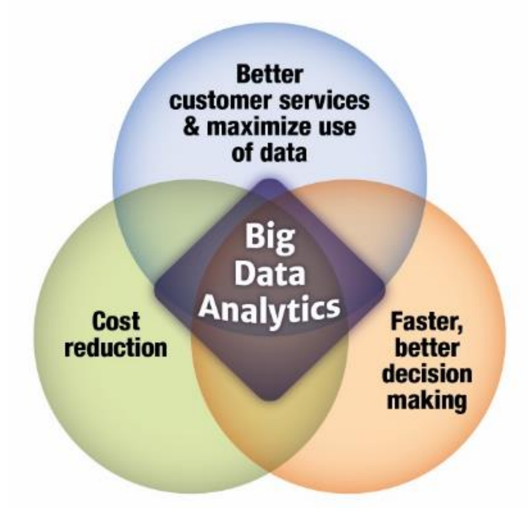


Figure 5. Big data analytics support enhanced decision-making and more effective, less costly operations.

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)

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 from the sensors needs to be validated and possibly filtered before being used for further analysis or control purposes. This is

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.

an important step to improving the data's reliability.

Data validation can be carried out 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 a value changes at a greater rate than a probable change in measured conditions and sensor noise, it 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 bias or drift is detected, its source needs to be identified—it could be caused by sensor drift or be a genuine long-term trend.

Cross-validation methods are used when it is possible to develop a model or relation between two or more values. The simplest cases are where some sensors are redundant and measure the same value or where 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. This produces smoother, easier-to-analyze data and usually leads to 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 KPIs

Developing 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 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 overflow 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 LTCP or NPDES permit to assess system performance and compliance.
- **Partially treated flow:** Estimated or measured volume of wastewater receiving only partial treatment before discharge 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 DSS

Data visualization is the use of charts or graphs to present large amounts of complex data—and thus to convey concepts quickly, easily, and universally. 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 DSS. A DSS (also known as a 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** is 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 information's essence.
- **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 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.

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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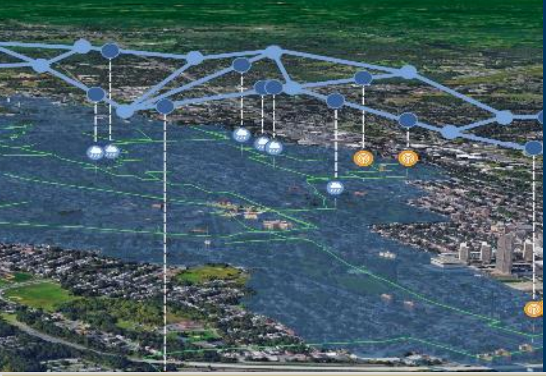
Appendix A
Case Studies



Albany, New York
CSO and Flood Mitigation

OWNER	LOCATION	INCEPTION
City of Albany	**Albany, New York**	**October 2016**

KEY FEATURES

- Wet weather flows reduced 6.5 times more than a traditional passive design would.
- Better understanding of asset condition, performance, and maintenance needs.
- Better pre-event planning and emergency management.

PROJECT DESCRIPTION

> *"As we implement plans for future CSO abatement and flood mitigation projects, we will continue to expand this smart infrastructure network across the city."*
>
> **—Joseph E. Coffey, Jr., P.E.**
> **Commissioner, Albany Water Board**

Beaver Creek District, the largest sewershed in Albany's combined sewer system, discharges over 530 MG of CSOs annually to the Hudson River. The city has invested in capital projects as part of its LTCP to address its CSO and flash flooding issues and mitigate property damage and potential safety hazards. One such project is a smart infrastructure network and a number of interconnected CMAC sites (see Figure 1). The technology has provided the city with increased infrastructure performance, improved resilience, and data-driven operations and planning. Using CMAC, the Albany Water Board reduced wet weather flows by 6.5 times as much as a traditional passive design while only increasing project capital cost by 6.5 percent. With the ability to observe watershed behavior and optimize infrastructure performance, the Albany Water Board is improving stormwater management for the community.

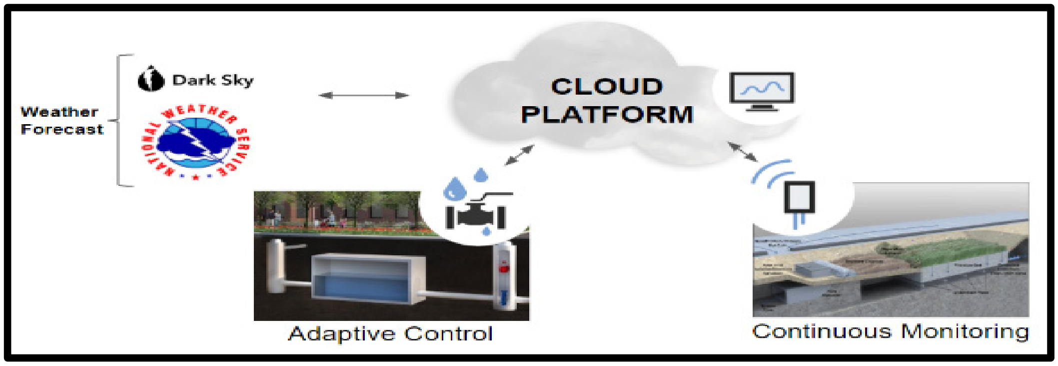


Figure 1. The Albany Water Board uses CMAC to optimize the use of storage throughout the collection system.

In the past, Albany's CSOs, flash flooding, and system surcharging issues caused significant damage and created potential health hazards in both the city and several downstream communities. The Albany Water Board and its design consultants took a progressive approach to these issues, merging innovative technology with traditional gray strategies and green infrastructure practices. At the heart of the solution is a smart infrastructure network, with products that integrate sensors, flow controls, and the weather forecast to optimize discharge rates from stormwater storage infrastructure to the collection system. In addition, the smart infrastructure network:

- Provides the city with visibility into asset condition, performance, and maintenance needs.
- Informs the city about pre-event planning activities and emergency management.
- Provides autonomous control of flows during critical wet weather periods.

The use of digital solutions for data-driven stormwater management has helped Albany improve environmental outcomes, comply with regulatory requirements, and enhance customer service. Strong performance and return on investment have supported Albany's decision to deploy additional monitoring and control sites and grow the interconnected smart watershed—a resilient, data-driven approach to solving the city's most critical stormwater challenges.

The addition of CMAC technology enhanced the storage infrastructure's wet weather performance by 6.5 times as compared to passive control, at a fraction of the cost. Table 1 presents a comparison of cost and performance between the CMAC and passive solutions at three storage sites in the collection system.

Table 1. Cost and Performance Comparison Between the CMAC and Passive Solutions

Description	Hansen		Ryckman		Washington		All	
	Passive	CMAC	Passive	CMAC	Passive	CMAC	Passive	CMAC
Capital cost	$1.35M	$0.1M	$0.750M	$0.1M	$2.50M	$0.1M	$4.60M	$0.3M
Incremental wet weather flow reduction (MG/year)	0.996	2.75	1.31	4.75	7.45	56.1	9.75	63.6
Unit cost ($/gallon/year)	$1.35	$0.04	$0.57	$0.02	$0.34	$0.002	$0.47	$0.005
CMAC incremental capital investment	**7.4%**		**13.3%**		**4.0%**		**6.5%**	
CMAC performance improvement compared to passive control	**2.8x**		**3.6x**		**7.5x**		**6.5x**	

Beckley, West Virginia
Flood Risk Mitigation

OWNER	LOCATION	INCEPTION
Beckley Sanitary Board	**Beckley, West Virginia**	**July 2016**

KEY FEATURES

- Adaptive controls used to optimize an undersized stormwater pond for which few other options were available.
- Downstream flooding potential reduced from four to five events per year to nearly none per year, while deferring millions of dollars of stormwater conveyance upgrades.
- Wet weather flow reduced by 57 percent, compared to 3 percent without adaptive controls.

PROJECT DESCRIPTION

Two urban watersheds converge at the intersection of Robert C. Byrd Drive and Ewart Avenue in Beckley, West Virginia. This has created a longstanding flooding issue: four or five times a year, stormwater overwhelmed the pipe's capacity and flooded five lanes along State Route 16, causing a significant risk to traffic and damaging the road and nearby infrastructure. BSB partnered with state and federal agencies to address the problem.

The cost of upgrading the existing roadway stormwater conveyance system was estimated to exceed $2.5 million. BSB proposed a stormwater retrofit alternative: a detention pond located on existing city-owned property to capture and detain runoff from the Ewart Avenue watershed. This property was relatively small, which meant that the pond's size and passive outlet structure limited the alternative system's capacity to manage all the anticipated runoff from the contributing watershed. Due to these limitations, roadway flooding was only marginally improved. The dry detention structure also had limited function to address state water quality and total maximum daily load requirements that had been instituted due to bank erosion and sedimentation. To improve the performance of the Ewart Avenue stormwater pond, BSB implemented CMAC technology in 2016.

Figure 1. Pre- and post-storm conditions at the Ewart Avenue stormwater pond.

By implementing CMAC at the Ewart Avenue stormwater pond, BSB was able to improve water quality, increase channel protection, and significantly reduce flood risk without building any new downstream stormwater conveyance and management facilities. The pond is conservatively configured to prevent drawdown and to aggressively respond to a broad range of forecasted precipitation events. Figure 1 shows the stormwater pond empty in preparation for a storm and at full capacity after a storm.

BSB used wet weather flow reduction and other environmental metrics to compare CMAC to the passive design. CMAC reduced wet weather flow by 57 percent, versus 3 percent with the passive design. Its average retention time was 32 hours, while the passive design's was 7 hours. Peak flow reduction was 84 percent with CMAC versus 36 percent with the passive design. As Figure 2 shows, retaining more runoff in the pond than the outflow reduced downstream wet weather flow. The annual cost to reduce wet weather flow was estimated to be $0.02 per gallon with CMAC versus $0.36 per gallon with the passive design.

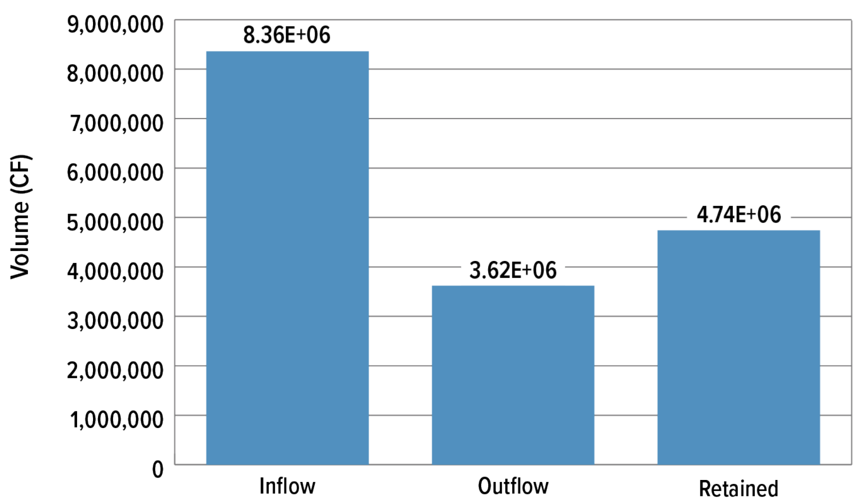


Figure 2. Ewart Avenue stormwater pond performance (data set for all sites, August 2018 to August 2019).

Bordeaux, France
Real-Time Pollution and Flood Control

OWNER	LOCATION	INCEPTION
Bordeaux Métropole	**Bordeaux, France**	**2005**

KEY FEATURES

- 75 percent average reduction of CSO volume.
- 82 percent reduction in CSO frequency.
- 222 million euros ($263 million USD) in capital investment savings.

PROJECT DESCRIPTION

Figure 1. Recreation on the Garonne River in Bordeaux, France.

Bordeaux Métropole services 578 square kilometers (223 square miles) along the Garonne River (shown in Figure 1), including more than 150 open streams. About one-fourth of the habitable area is below the river's high water line, and many floods have occurred since the 1980s. Like many old communities in the United States, Bordeaux mainly has combined sewers that convey both sewage and stormwater—which may be loaded with heavy metals and oil and grease from roadway runoff.

When rainfall exceeds the capacity of the sewer system, CSOs discharge to local waterbodies. To protect the population against flooding and control pollution in receiving waterbodies, namely the Garonne River and Bordeaux Lake, Bordeaux Métropole embarked on an LTCP to implement an intelligent central water management system. The LTCP included the construction of several large stormwater and wastewater storage facilities, tunnel interceptors, and large pumping stations.

In 2013, Bordeaux Métropole began to invest in a capital improvement project plan worth 18 million euros ($21.4 million USD) to integrate RTC into their sewer system. The RTC plan identified three phases for implementation:

1. Offline storage basin capacity of 42,000 cubic meters (11.1 MG) and inline storage capacity of 40,000 cubic meters (10.6 MG). Phase 1 was commissioned in 2012–2014 and has reduced CSO volume by 40 percent annually.

2. 200,600 cubic meters (53 MG) of additional storage in existing retention basins built for flood protection. Phase 2 was commissioned in 2018 and has reduced CSO volume by more than 75 percent annually.
3. Integration of the Garonne River's right shore area with a storage tank volume of 14,300 cubic meters (3.8 MG). Phase 3 is anticipated to be completed by 2022.

Bordeaux Métropole has existing storage reserved for 10-year rainfall events. But rainfall from smaller storms (i.e., storms that occur about once a month) can cause CSOs if not captured. The flood control storage has capacity to reduce CSOs as well, but the two objectives must not conflict—the system needs to stay prepared for flood mitigation in anticipation of intense rain (i.e., dewater storage basins, empty pump station wet wells). This requires a sophisticated RTC system with predictive capabilities. Study results confirmed that optimizing existing facilities before building new infrastructures generated significant environmental and cost benefits. The study found retention capacity for CSO reduction in the existing system's storage basins was 256,900 cubic meters (67.9 MG) and 40,000 cubic meters (10.6 MG) for inline storage.

According to Bordeaux Métropole, the overall implementation of RTC cost 8 million euros ($9.5 million USD) to manage 15 sites, including pump stations and storage facilities, in real time. To achieve equivalent storage using traditional methods would have required building 230,000 cubic meters (60 MG) of storage at a cost of about 222 million euros ($263 million USD). The savings have allowed Bordeaux Métropole to invest in restoring the Garonne River's city shore by converting abandoned storage and old industrial sites to boardwalks, biking trails, and public parks.

The RTC approach did present several challenges:

- It relies on an online model and real-time rain gauges to predict upcoming inflows and their spatial distribution. This requires periodic calibration and updating 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.
- Meteorological forecast data are provided for a period of one hour, while the RTC prediction horizon has to be set at four hours to account for flow conveyance delays. Forecasts beyond the one-hour horizon have to be extrapolated based on a normal curve to correspond with the one-hour prediction horizon.
- The level of water infiltration varies seasonally and based on specific areas. To help mitigate this issue, a specialized external model was developed to feed the RTC optimization algorithm with these varying inputs.

Lessons learned from this project include the following:

- The adoption of RTC technology requires organizational commitment and staff buy-in.
- Hydraulic modeling and system planning are the keys to successful implementation.
- The baseline scenario and rainfall references must be well chosen, as they will be useful during the entire life cycle of the project for performance comparison purposes.
- The utility needs to consider O&M issues and constraints when choosing the level of RTC implementation.
- It is important to involve system operators early in planning and design. It is also important to identify and communicate roles and responsibilities at every stage.
- Documentation such as standard operation procedures and post-event analysis is critical in properly operating, maintaining, and improving an RTC system.

Buffalo, New York
Real-Time Control of Inline Storage

OWNER	LOCATION	INCEPTION
Buffalo Sewer Authority	**Buffalo, New York**	**Commissioned winter 2016; study period March–May 2016**

KEY FEATURES

- CSO volume reduced by 450 MG over 12 months by the first 3 sites—100 MG more than originally projected for the entire project.
- $145 million saved to date from initial enforcement action, due in large part to reductions in CSO activations and volume.
- More sewage captured and treated safely instead of overflowing during wet weather into Buffalo's receiving waters.

PROJECT DESCRIPTION

At the turn of the century, Buffalo was the eighth largest city in the United States, a gateway for commerce and manufacturing due to its early embrace of hydroelectric power from nearby Niagara Falls. To accommodate its projected growth, Buffalo built a state-of-the-art combined sewer system that collected and transmitted sanitary and stormwater flows in a single pipe system to the Buffalo River, Scajaquada Creek, and the Niagara River.

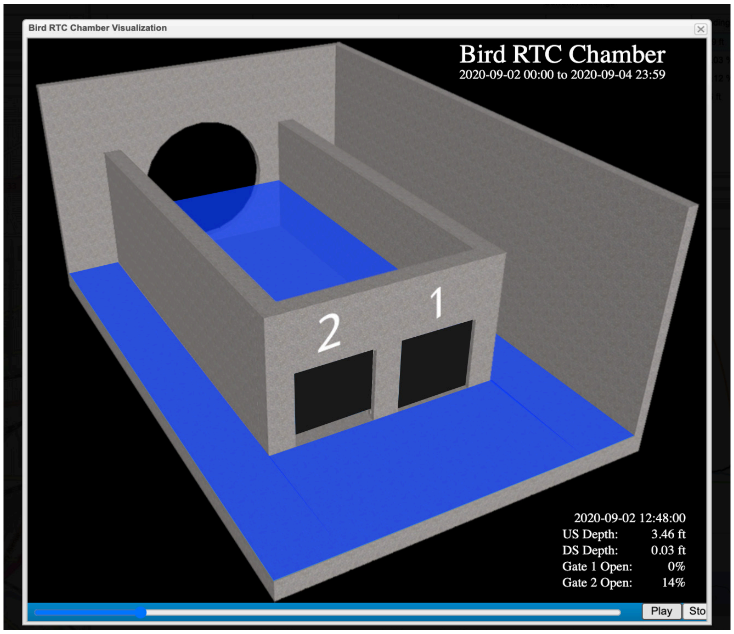
By mid-century, the city added a massive wastewater treatment facility and upgraded its sewer system to accommodate at least 750,000 people. This allowed the city to capture dry weather sewer flows and send them to the plant, but the combined sewer system was still designed to send the vast majority of wet weather flows to the city's receiving waters.

Due to its mid-20th-century sewer design, Buffalo still typically experiences nearly 2 billion gallons of CSOs annually, discharging into its receiving waterways.

As the level of national awareness of the need to protect water resources continued to grow, federal and state regulators began pursuing a consent decree in 2006 requiring further improvements to Buffalo's collection system. Recognizing the generally inadequate stormwater capabilities of the existing combined sewer system, the BSA began to prepare a comprehensive watershed improvement plan with gray, green, and smart sewer solutions. After years of negotiations, the city and its partners came to an agreement; in 2014 BSA received approval of its LTCP for CSO abatement, which had an earlier estimated budget of $525 million. With the city facing limited funds from a reduced taxpayer base, BSA needed an innovative approach to address CSOs.

City officials knew they could not continue operating their collection system the same way they had been since the 1950s, and costly investments in new gray infrastructure like tunnels and storage tanks were equally infeasible. BSA and its contractors began designing and implementing an RTDSS across the city.

The RTDSS strategy focused on building and controlling inline storage vaults to transform Buffalo's massive gravity sewer system into a managed conveyance and storage system. The goal of the RTDSS program is to minimize and/or eliminate CSOs by retrofitting the operational behavior of the existing infrastructure. Sixteen RTDSS sites were identified for inline storage and optimal conveyance throughout the city. These sites were chosen for maximum return on investment; the first 2 sites were selected as a representative sample of all 16. Figure 1 shows a visualization of the Bird RTC Chamber, one of the inline storage vaults in Buffalo's sewer system.



By 2019, four storage sites were live. BSA is working to build and commission most of the rest by the end of 2020. The first 3 sites alone have reduced Buffalo's CSO volume by 450 MG over the 12 months ending June 30, 2019. This nominal volume is already 100 MG more than what was anticipated for all 16 sites according to a typical-year simulation—that is, the BSA RTDSS program could end up reducing CSOs by 3 or 4 times as much as originally projected.

As each wet weather event provides more data, BSA can expect increasing levels of system intelligence, resulting in additional O&M cost reductions as well as further reductions in CSOs. BSA's RTC program is achieving outcomes unpredicted in the original design, with even more sewage than estimated now capable of being safely stored, conveyed, treated, and released to receiving waters as clean water effluent in a wider variety of weather conditions.

BSA was able to present a revised LTCP with a $145 million reduction in budget due to its RTDSS program. The RTDSS retrofits, and additional minimally invasive green and gray infrastructure improvements, will enable critical environmental progress at a far more sustainable cost to residents. The success of BSA's RTDSS program may mean even more capital infrastructure savings in the future as BSA achieves its ongoing environmental, economic, and water equity objectives.

Cincinnati, Ohio
Intelligent Urban Watershed Technology

OWNER	LOCATION	INCEPTION
Metropolitan Sewer District of Greater Cincinnati	Cincinnati, Ohio	2015

KEY FEATURES

- Overflow volumes reduced by 247 MG annually.
- Cost reduced more than 90 percent compared to initial capital work estimated at $38 million.
- CSO mitigation achieved at a price of less than $0.01/gallon.

PROJECT DESCRIPTION

The MSD of Greater Cincinnati serves an Ohio population of more than 850,000 spread out across 290 square miles. Like many large cities, Cincinnati has combined and sanitary sewer systems, some of which were built more than a century ago. Whether by design or due to I/I of stormwater, these systems tend to overflow, discharging untreated sewage into local waterways or flooding streets and basements.

Cincinnati's sewers discharge an average of 11.5 billion gallons of combined sewage every year into the Ohio River and its tributary streams within Cincinnati's urban watershed. In 2002, the U.S. EPA entered into a federal consent decree with MSD, mandating the elimination of SSOs and significant mitigation of CSOs into receiving waterways. Engineers estimated the cost to mitigate the sewer overflows at $3.1 billion, an unacceptable capital expense to pass along to MSD's customers.

Recognizing the generally inadequate stormwater management capabilities of the existing combined sewer system, MSD prepared a comprehensive wet weather improvement plan. MSD knew that full sewer separation and deep tunnel construction are massive capital investments with very low return: they create only episodic benefits during peak flow and are single-use assets with little additional community wealth creation. Instead, MSD sought to use decision intelligence to maximize existing capital assets such as sewer interceptors, STFs, and pump stations—to reduce overflows and gain system-wide benefits through advanced control logic that would optimally operate MSD's urban watershed.

MSD began by focusing on the Mill Creek Interceptor (a major carrier of flows through the MSD service area) and its most upstream asset, the SSO 700 STF. This facility and four other control sites were originally designed to reduce overflow volumes from the constructed outfall at the river. SSO 700 STF has 3.6 MG of storage and a 10 MGD high rate treatment capacity. These assets, combined with the RTC facilities downstream on the Mill Creek Interceptor, provide multiple points to control sewage along the length of the interceptor.

Historically, SSO 700 STF and the RTC facilities have been controlled locally without any coordination between them and other facilities. To cost-effectively increase performance and capacity utilization, MSD implemented a RT-DSS that combines sensors, weather data, and artificial intelligence. The RT-DSS delivers automated, optimized control of existing assets to reduce sewage overflows, maximize storage, and maximize treatment during wet weather.

SSO 700 STF is now controlled based on real-time upstream and downstream conditions, along with real-time feedback on what is happening at two of the downstream RTC facilities (Ross Run and Mitchell Avenue). This allows MSD to use analytics in deciding whether to activate or deactivate high-rate treatment and when to fill or drain tanks. Figure 1 presents the flow analytics application dashboard for the SSO 700 STF.

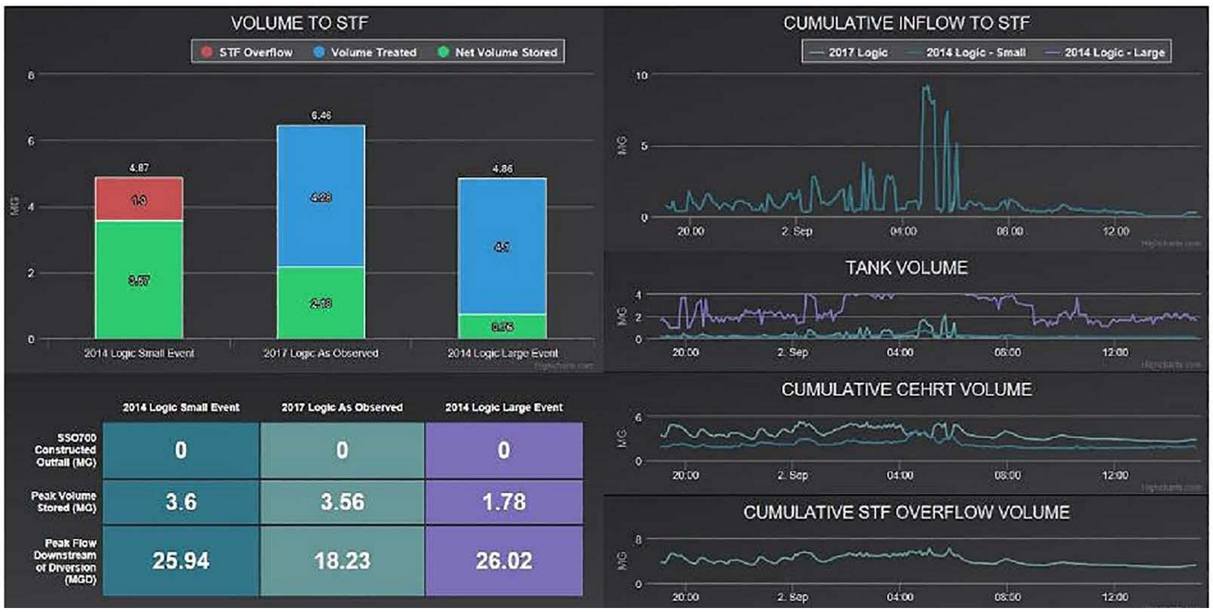


Figure 1. Flow analytics application dashboard for the SSO-700 treatment facility.

The project was an overwhelming success. After MSD implemented the coordinated RTC program, overflow volumes dropped by 247 million gallons annually (based on 2015 rainfall). Implementation of the control system, compared to work estimated to cost more than $38 million, meant a 90 percent cost savings was realized by MSD’s ratepayers. Moreover, CSO mitigation was achieved at a price of less than $0.01/gallon.

This approach enabled MSD to achieve significant reductions in both the capital and operating costs of collecting and treating wastewater in compliance with environmental regulations.

Falcon Heights, Minnesota Predictive Flood Control System

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

KEY FEATURES

- Optimized stormwater management using RTC and adaptive logic.
- Doubled flood control capacity in an existing wet pond.
- Less 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 forecasts 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 design volume while using the pond's 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 eight-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 is happening. This high-efficiency solution has enabled the Capitol 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.

Fort Wayne, Indiana Maximizing Infrastructure Performance to Reduce CSO Volume and Costs

OWNER	LOCATION	INCEPTION
City of Fort Wayne	**Fort Wayne, Indiana**	**2015**

KEY FEATURES

- Smart use of near-real-time flow/depth data to reduce CSOs.
- Flow data and a hydraulic model used to develop an innovative way to capitalize on the difference in timing between combined and sanitary flow.

PROJECT DESCRIPTION

Fort Wayne, Indiana, is located at the junction of the St. Joseph and St. Mary Rivers, which join to form the Maumee River flowing east through Ohio to Lake Erie. The city operates a collection system of both combined and separated sewers along with a 95 MGD WPCP. The system also includes two storage ponds along the Maumee River to store wet weather flow, shown in Figure 1, for later discharge to the WPCP across the river. Wet weather flows reach the ponds through two diversion structures, a high-level passive overflow on the Wayne Street Interceptor and a controllable weir in the St. Joseph Diversion Structure.

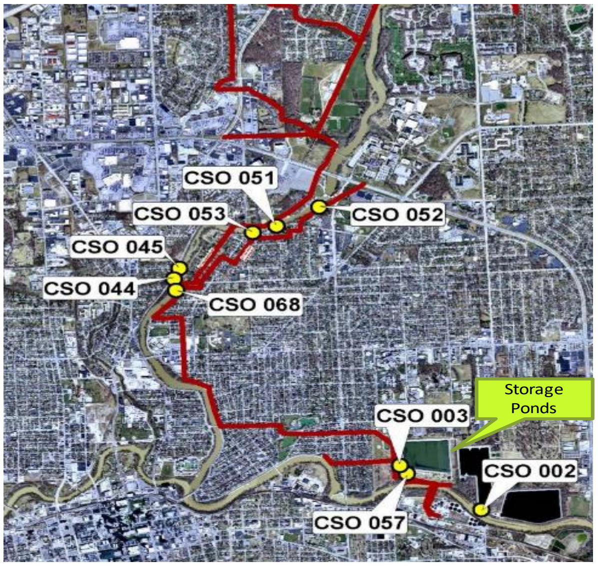


Figure 1. Map of Fort Wayne's combined sewer system and storage ponds.

The city's LTCP, developed pursuant to a consent decree, called for projects estimated at $240 million (2005 dollars). One LTCP project was a collection of satellite STFs along the St. Joseph River in the northern portion of the combined sewer system. St. Joseph CSOs 45, 51, 52, 53, and 68 were all to be controlled using satellite storage or treatment facilities.

The city began a system-wide monitoring program over 2 decades ago, and now has a network of over 100 flow meters, 10 depth-only devices, and 29 rain gauges, all of which feed data to the city's data management platform. The city uses the data to support daily operational decisions, and to manage flood control during high river events. These activities use the data in near real time, with managers viewing the data as needed to support manual adjustments of system control features; managers also use the data offline to maintain calibration of the city's hydraulic model.

The data have also been used to identify opportunities to refine the LTCP. Early on in the LTCP implementation process, the flow data from the St. Joseph Diversion Structure revealed that the downstream CSO response was much faster than the upstream sanitary sewer response and, in many cases, the CSO response was over by the time the sanitary response reached the downstream end of the system.

This observation gave city staff the opportunity to reassess the St. Joseph CSO solution. Comprehensive modeling analyses combined with some innovative design revealed that the city could maximize the benefit of the St. Joseph Diversion Structure to capture the CSO volume without jeopardizing overall system performance. By lowering the diversion weir at the beginning of the storm, the hydraulic grade line in the St. Joseph Diversion Structure drops and its effective capacity increases. That increase in capacity is sufficient to capture the required CSO volume before the sanitary flow from further upstream begins to arrive.

The operating strategy today is to lower the weir at the onset of the storm to capture additional CSO volume in the ponds and raise the weir at the correct time to convey the maximum flow to the WPCP (see Figure 2). This operation must be managed carefully, as the diversion structure hydraulic grade line affects performance at several key locations the system. Therefore, proper implementation of this strategy relies on data feeds from these key locations. Although the majority of this process is controlled manually, it is operated in near real time using the city's data management system dashboard.

One of the keys to near-real-time operation is that the city's network of battery-powered flow meters and depth-only devices can automatically "shift gears" from the normal 6-hour data download frequency to 15 minutes during storm events. Another is that all sensor locations can send data directly to the city's data management system without any intermediary hardware.

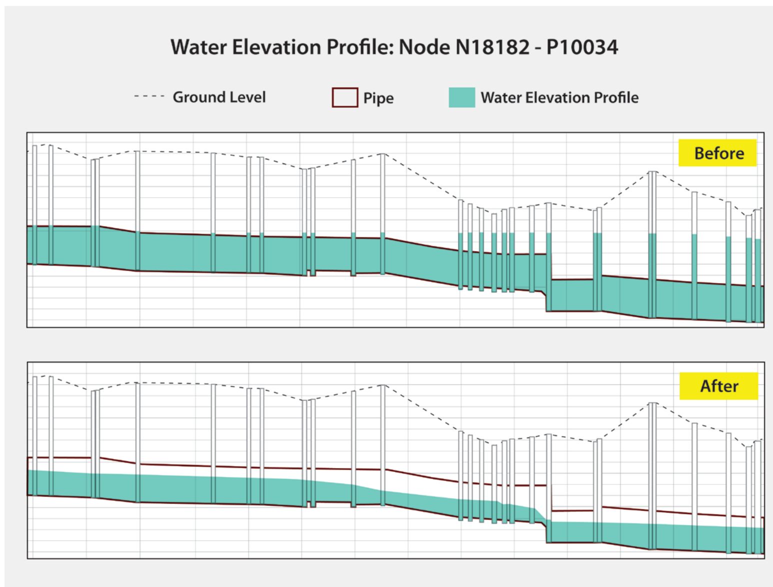


Figure 2. Hydraulic grade line lowered by the St. Joseph control structure, allowing more CSO volume to be stored for treatment.

The original LTCP for the St. Joseph CSO solution called for the expenditure of $23.2 million for storage, disinfection, and other support components. The smart use of near-real-time flow data has allowed the city to eliminate the need for 5 satellite facilities and comply with the consent decree requirements at the St. Joseph CSO outfalls for an expenditure of $5.2 million.

The city's remaining CSOs are being addressed with a storage tunnel and other facilities, and their network of smart flow meters will be used to monitor those facilities and ultimately support a future RTC system.

Grand Rapids, Michigan Mitigating Inflow and Infiltration with Real-Time Control

OWNER	LOCATION	INCEPTION
City of Grand Rapids	Grand Rapids, Michigan	2015

KEY FEATURES

- RTDSS to help the city with sanitary system separation.
- Data showing that the I/I problem could be solved for $30–$50 million as opposed to the original $1 billion estimate.
- Sensor network expanded to more parts of the system.

PROJECT DESCRIPTION

Grand Rapids, Michigan, has garnered accolades in the clean water industry for taking significant proactive steps to improve its sewer system. In the early 1990s, “River City” invested in transforming its collection system from a combined sewer system to separate storm and sanitary sewers. By moving from a single pipe for both stormwater and wastewater conveyance to separate pipes, the city avoided the introduction of sewage into its waterways, reducing overflows and subsequent pollution into the landmark Grand River that flows to Lake Michigan 40 miles downstream.

After nearly 25 years, Grand Rapids finished retrofitting its CSO system to a separate sanitary and stormwater system, completing its LTCP in 2015. But now the city needed to better understand the I/I into these newly separated sanitary sewers to ensure compliance with a mandate from EGLE. This mandate allowed zero overflow events of any kind, except as part of a wet weather event of a magnitude in excess of a 24-hour, 25-year storm.

For compliance purposes, the city needed analytic data to certify performance and understand how the system behaved during a wide variety of wet and dry weather conditions. While gathering this information, the city was also presented with a hydraulic report stating that areas of the community were experiencing excessive surcharging and flooding. The city suspected otherwise, but needed proof to answer regulators: mitigation to eliminate the surcharging and flooding was estimated to cost as much as $1 billion; a capital expense it could ill afford.

To satisfy regulators, Grand Rapids turned to smart data infrastructure to understand how the separate sewers behaved, with the goal of modeling the performance in a computer environment to better predict how the system would perform with less costly improvements to existing infrastructure.

First, the city deployed a sensor network of 90 flow meters and 10 rain gauges to collect real-time data from the sanitary lines. This data was analyzed using an integrated RTDSS, which collected, organized, analyzed, and served the data via dashboards, giving city operators visual cues to understand and regulate the operation of their sewer systems (see Figures 1 and 2). Once built, the model was compared against ongoing sensor data, generating a higher level of system intelligence that is continuously improving with each wet weather event.

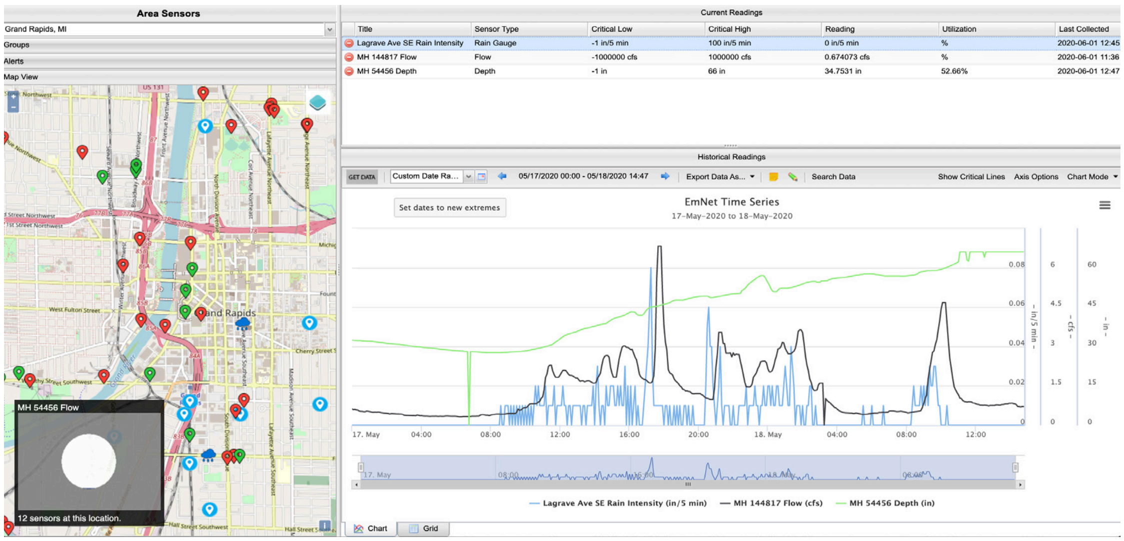


Figure 1. An example of the data collection software, a real-time database and data analytics tool that offers full SCADA integration.

Upon completion of the investigation through the RTDSS, the city demonstrated to EGLE regulators that, by focusing on a few critical areas needing improvement, its I/I problem could be solved for $30–$50 million as opposed to the original $1 billion estimate.

Since implementing the RTDSS solution, Grand Rapids has achieved the performance required by the LTCP and continues working toward final certification with EGLE. Encouraged by those results, it has expanded the RTDSS sensor network by 70 sensors, many of which are now delivering real-time data from the city's stormwater network. Over the next few years, the city will also embark on a multi-phased program to improve sustainability and improve water quality for wildlife and recreational use in the Grand River.

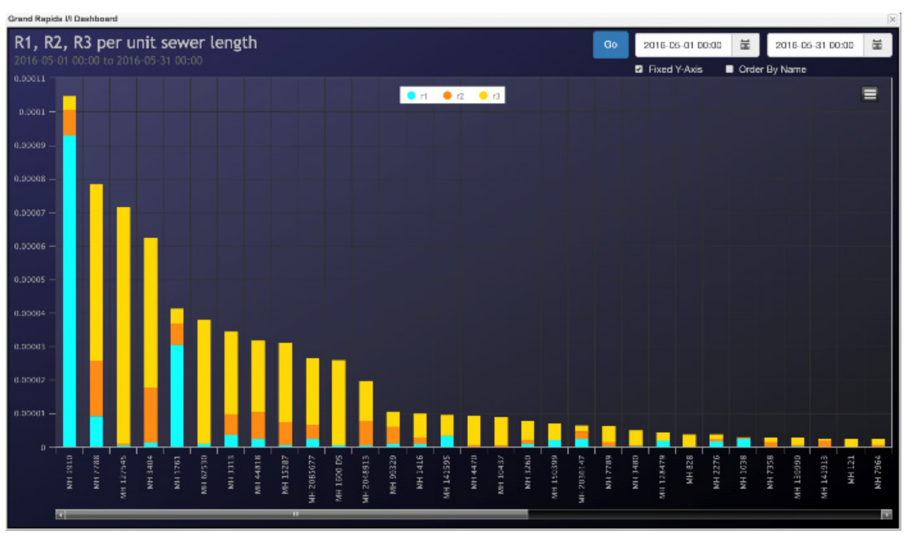


Figure 2. A Grand Rapids I/I analytics dashboard showing the intensity and characterization of their I/I sites.

Green Bay, Wisconsin
Reducing Overflows with Real-Time Monitoring

OWNER	LOCATION	INCEPTION
City of Green Bay	Green Bay, Wisconsin	Fall 2017

KEY FEATURES

- RTC technology using I/I data to prevent sewer spills.
- RTC technology that identifies river level changes to protect bridges from flooding.

PROJECT DESCRIPTION

Since 2016, Green Bay has monitored several manhole locations throughout the city, analyzing the data for a much better understanding of when and where water infiltrates the system during rain events. During heavy rainfall, RTC technology monitors and notifies the city of quickly changing water levels. This monitoring has made it clear that the city would also benefit from information about dynamic water level changes due to infiltration from rivers.

Therefore, in addition to the units at key manhole locations, Green Bay deployed RTC technology to monitor the East River and Fox River. The data help determine how upstream flow and river level changes are affecting downstream flooding in the sewer and stormwater collection systems. In particular, the East River system uses an innovative configuration in which the RTC unit monitors the water level under the Mason Street Bridge (see Figure 1). During significant rainfall events, the bridge-mounted unit plays an important role in identifying river level changes.

Figure 1. During heavy rainfall episodes, RTC technology monitors and notifies the city of rapidly changing water levels at the Mason Street Bridge.

At one point, the East River registered "high" at 74 inches below the sensor and just 7 inches below the bridge.

By monitoring the rapid rise and fall of the East River, combined with data from the Fox River, Green Bay can correlate river level changes with stormwater infiltration into the collection system. The ability to aggregate and analyze storm and river data is helping Green Bay more clearly understand the dynamic relationship between upstream flows and downstream infiltration impacts.

This underground visibility provides valuable I/I water surge data when heavy rainfall hits Green Bay (see Figure 2). Combined with data on quickly rising river levels, the real-time notifications help the city make decisions about allocation of valuable resources in times of urgency.

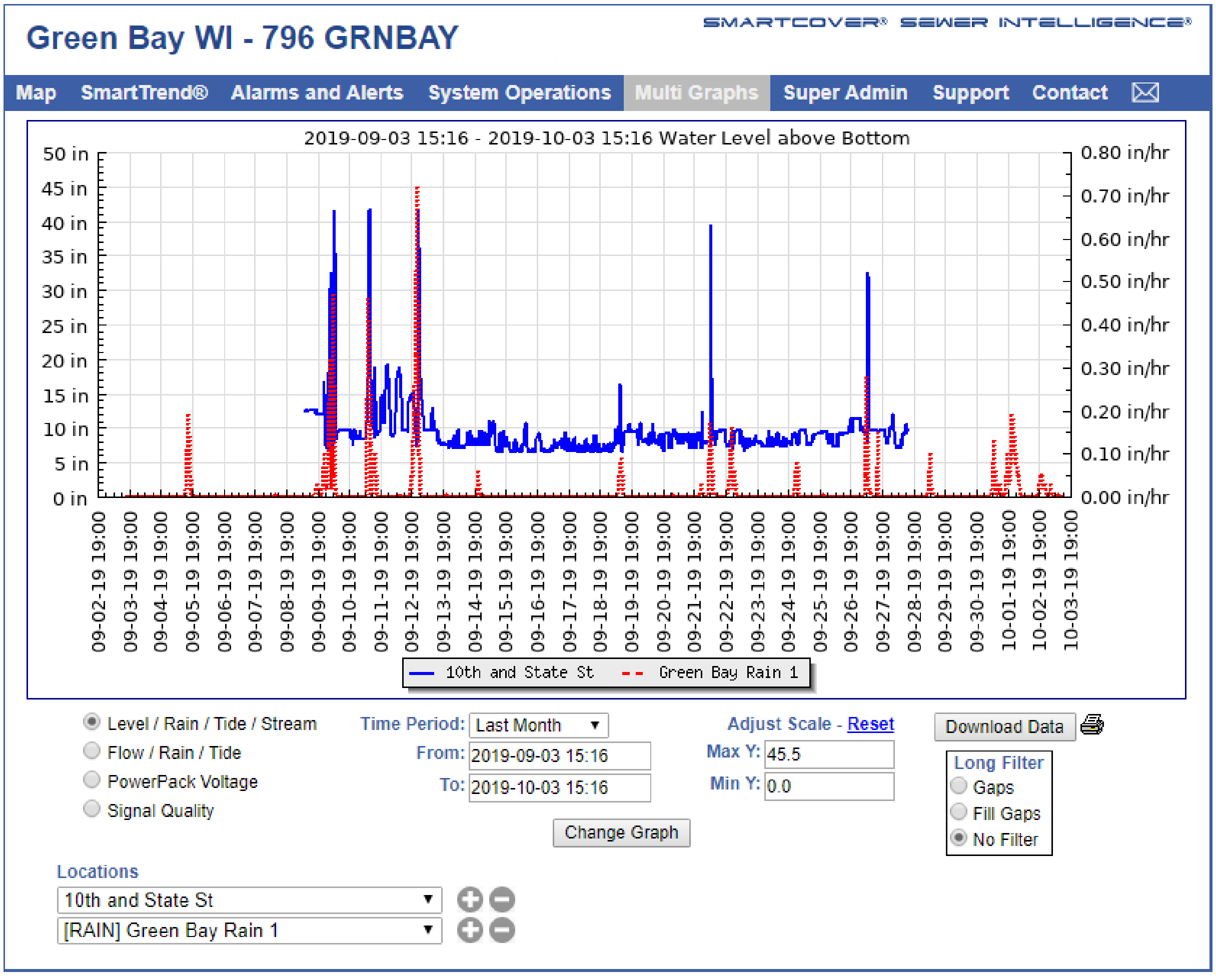


Figure 2. I/I detection displayed by the RTC system.

Hawthorne, California
Real-Time Monitoring to Prevent Sewer Overflows

OWNER	LOCATION	INCEPTION
City of Hawthorne	**Hawthorne, California**	**2006**

KEY FEATURES

- RTC technology that 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 Los Angeles Airport. This system includes 94 miles of gravity pipeline, no lift stations, no treatment, and just 2 full-time collection staff. Before 2006, Hawthorne was experiencing about 10 sewer overflows per year in its sanitary sewer collection system. The city estimated that these spills cost it $400,000 annually in fines, cleanup and mitigation costs, and legal costs.

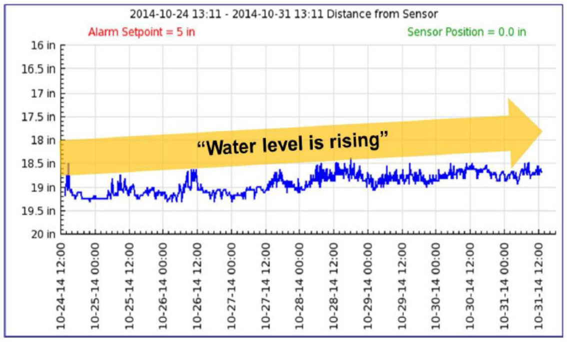


Figure 1. Graph showing a rise in water level, alerting managers to a potential issue.

In late 2006, the city positioned 50 real-time remote level monitoring sensors covering 66 of the “hot spots” in the collection system. These systems give managers real-time early warning of pre-flow events using alarms and a data analytics tool, which indicates when pipes begin to accumulate dirt, grit, FOG, or tree roots, thereby changing the daily pattern of water flow in the pipes (see Figure 1).

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

La Mesa, California
Optimizing Cleaning Maintenance with Smart Monitoring Technology

OWNER	LOCATION	INCEPTION
City of La Mesa	**La Mesa, California**	**2018**

KEY FEATURES

- 10 segments monitored with analytics to determine cleaning frequency.
- Total cleaning reduced by 80 percent with no SSOs.
- Savings of $19,200.

PROJECT DESCRIPTION

La Mesa, located just east of San Diego, employs a highly rigorous cleaning process as part of its preventative maintenance program. The city maintains 153 miles of sanitary sewer and 53 miles of storm pipes. Its maintenance routine includes annually cleaning the entire system and cleaning nearly 100 monthly and quarterly scheduled “hot spots.” A small group of field technicians perform the cleaning, as well as a full range of other tasks to maintain the city’s low SSO track record. The city is committed to further SSO reduction; however, it is challenged by the rigorous cleaning regimen, often juggling staff to meet all maintenance needs.

Seeking a better balance, the city questioned whether many of the high-frequency cleaning segments were being overcleaned and, if reduced, would alleviate maintenance pressures. It lacked data to answer these questions, though.

The city was introduced to a potential solution with real-time, remote segment monitors. This smart technology gathered data, provided redundant SSO alarms, and used predictive software to drive decisions on when to clean based on remote segment-conditions. The city partnered with a supplier and set up a pilot with the following goals:

- Right-size cleaning frequency based on actual segment conditions.
- Enhanced overflow protection.

The city chose 10 segments being cleaned monthly and deployed depth-only monitors with ultrasonic depth, pressure depth, and alignment sensors. Monitors were equipped with advanced, cellular LTE-M communications, important for limiting installation and movement to less than 15 minutes (average). LTE-M enabled antennae to be installed in the manhole without drilling. Cloud-based software collected data and provided continuous access via computers, tablets, and mobile devices.

These systems enabled the city to shift from a schedule-driven process to one driven by segment (site) condition. Maintenance teams were instructed to clean based on segment conditions as illustrated by the hydrograph (Figure 1).

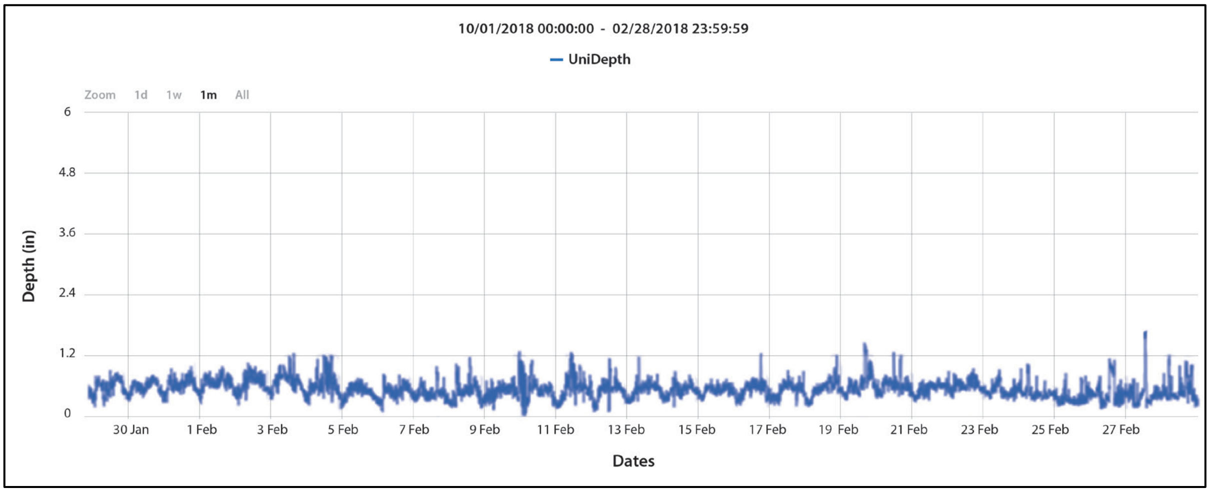


Figure 1: One-month hydrograph showing no necessity to clean.

The results in the first six months revealed that the city had indeed been over-cleaning. Using the schedule-driven process, the 10 segments would have been cleaned 60 times over 6 months. During the pilot and using the site-condition process with smart monitoring, the city cleaned 12 times—an 80 percent reduction. Moreover, during that time, a developing blockage and potential SSO was detected and prevented.

A cost analysis demonstrated that this reduction had a significant productivity savings. The cost per segment cleaned was $400 including such factors as the amortized truck cost, insurance, maintenance, fuel, tools, and consumables and the fully burdened cost of the 2-person crew. Table 1 compares the schedule-driven versus segment (site) condition–driven costs and potential savings for the six-month period.

Table 1. Cost Savings Achieved Through Segment (Site) Condition–Driven Process.

Cost-Savings Analysis	Segments	Months	Cleaning Instances	Cost/Segment	Value
Schedule-Driven (Old Process)	10	6	60	$ 400	$ 24,000
Site Condition-Driven (New, Smart Process)	10	6	12	$ 400	$ 4,800
Reductions (Savings) - Total All Segments			**48**	**$ 400**	**$ 19,200**
Cost of Implementation* - Total Ten Segments					$ 8,360
Net Productivity Savings – Ten Segments					**$ 10,840**
Net Productivity Savings- per Segment					**$ 1,084**

***Equipment, communications, software, installation, training, ongoing field service, warranty**

Outcomes of the process change included the following:

- Productivity savings due to labor reallocation and more work per unit of time. Utilities challenged by labor availability—e.g., hiring constraints, retirements, staff turnover—can effectively fill the gap with technology.
- Addition of continuous SSO monitoring has protected against SSOs. While costs cannot be pre-determined, they would include remediation, regulatory fines, and administration.
- Less use of high-pressure cleaning sprays may extend the asset life by avoiding the deleterious effects on pipes that such cleaning can have.
- Continuous data acquisition from the collection system has been used for other applications, like hydraulic model validation.

Smart technology can enable utilities to optimize their cleaning processes by giving visibility to remote site conditions. The resulting benefits can include increased operations productivity, ongoing SSO prevention, and reduced wear on pipes. Investments to implement smart technology are shown to provide payback well within the first year.

Louisville, Kentucky
Real-Time Control for Integrated Overflow Abatement

OWNER	LOCATION	INCEPTION
Louisville and Jefferson County Metropolitan Sewer District	**Louisville, Kentucky**	**2006**

KEY FEATURES

- More sustainable sewer systems and better quality of receiving waters, thanks to smart use of RTC technology.
- Maximized conveyance, storage, and treatment capacity, consistently capturing 1 billion gallons of CSO annually.
- Overall cost savings estimated at $117 million from the original CSO LTCP, a 58 percent reduction in capital investment.

PROJECT DESCRIPTION

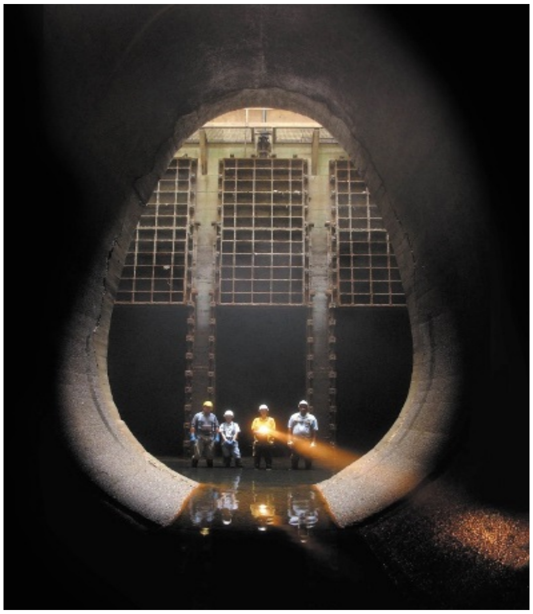


Figure 1. Staff inspecting one of MSD's storage basins.

The Louisville and Jefferson County 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 WWTPs, 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 key to maximizing conveyance, storage (inline and offline; see Figure 1), and treatment capacity to reduce CSO, with consistent operational results of more than 1 billion gallons of CSO captured annually.

Louisville MSD is in the final years of a 19-year initiative known as the IOAP. The vision of the IOAP is to provide a long-term plan to eliminate 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 its sewer systems while also improving the water quality of receiving waterways—shown in Figure 2, along with MSD's combined sewer area.

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 control elements (e.g., gates, pumps) connected to a local PLC. This PLC modulates the control elements based on the rules programmed into it and setpoints computed by a global DSS. Information collected in the field is communicated from the remote stations to the central station via the SCADA system. The central station manages and coordinates the various modules, including data management and archiving, DSS control algorithms, hydrologic and hydraulic models, and weather forecasting.

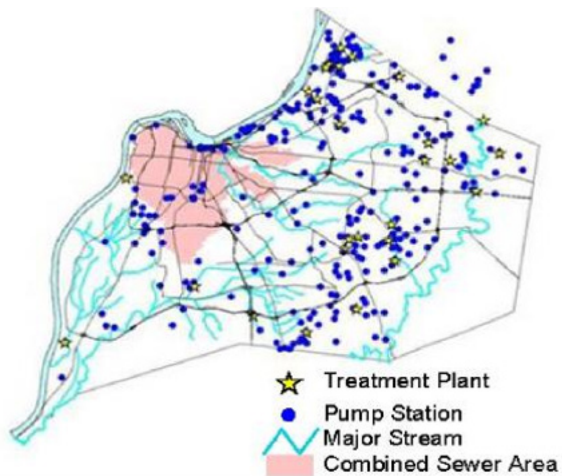


Figure 2. Map of Louisville MSD's combined sewer area.

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

RTC feasibility studies of phase 1 implementation showed that optimizing the existing collection and treatment system would have a relatively low unit cost, ranging from $0.006 to $0.021 per gallon of CSO reduction per year. This cost is 4 to 10 times lower than that of the traditional approach (building more storage). The overall savings was estimated at $117 million from the original CSO LTCP cost of $200 million (a 58 percent reduction in capital investment).

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 were added to the RTC system as the facilities were being built. Moreover, 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.

The RTC approach did present several challenges:

- It relies on online model and weather forecasting to predict upcoming inflows and their spatial distribution. This requires the calibration and updating 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 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 choosing the appropriate level of RTC implementation.
- It is important to involve system operators early in 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 in properly operating, maintaining, and improving an RTC system.

The MSD RTC program's cost is estimated at $21 million, including retrofit, construction, monitoring, IT, etc. The current RTC system includes 2 stormwater retention basins (over 30 MG) for CSO control, multiple inline storages, flow diversions, and pump stations, as well as the management of the southwestern outfall, an egg-shaped tunnel with a diameter ranging from 24 to 27 feet.

"[RTC] is an important component of MSD's long-term plan to mitigate untreated [CSOs] into Beargrass Creek and the Ohio River. It is a cost-effective management strategy to help sustain the resources of our community."

—Angela Akridge
Chief Engineer, Louisville MSD

MSD continues to improve and expand its RTC system as new STFs are constructed under the IOAP.

MSD has developed web-based training modules on the RTC system and used them for continuous training and knowledge transfer. Control site commissioning and startup provide onsite training opportunities for instrumentation and control and O&M staff.

Newburgh, New York
Real-Time Control for CSO Reporting/Public Notification

OWNER	LOCATION	INCEPTION
City of Newburgh	**Newburgh, New York**	**October 2016**

KEY FEATURES

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

PROJECT DESCRIPTION

The City of Newburgh replaced its traditional telemetry system with smart controls, both to give city staff and the public real-time notification of CSO events (see Figure 1) and to prepare for increased regulatory requirements for annual reporting and notification. The city spent around $78,000 for 18 units.

The city's prior telemetry system used pressure sensors that had to be 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 damaged or displaced by debris. Many times, under high flow conditions, several entire units were swept away down the CSO and lost at the outfall.

The prior sensors also needed 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 (at the WWTP). These hard lines were expensive, had regular loss of communication, and were very difficult or impossible for the utility company to find when they needed service.

The new telemetry system resolved all of these problems. The smart control wireless satellite connectivity proved more reliable than land phone lines and cost less. Any computer, tablet, or smartphone with internet access can communicate with the telemetry system. Little calibration is needed; when a sensor does need to be calibrated or moved, in-house staff can easily do so with basic tools. The sensors are not in contact with the water, so they avoid damage.

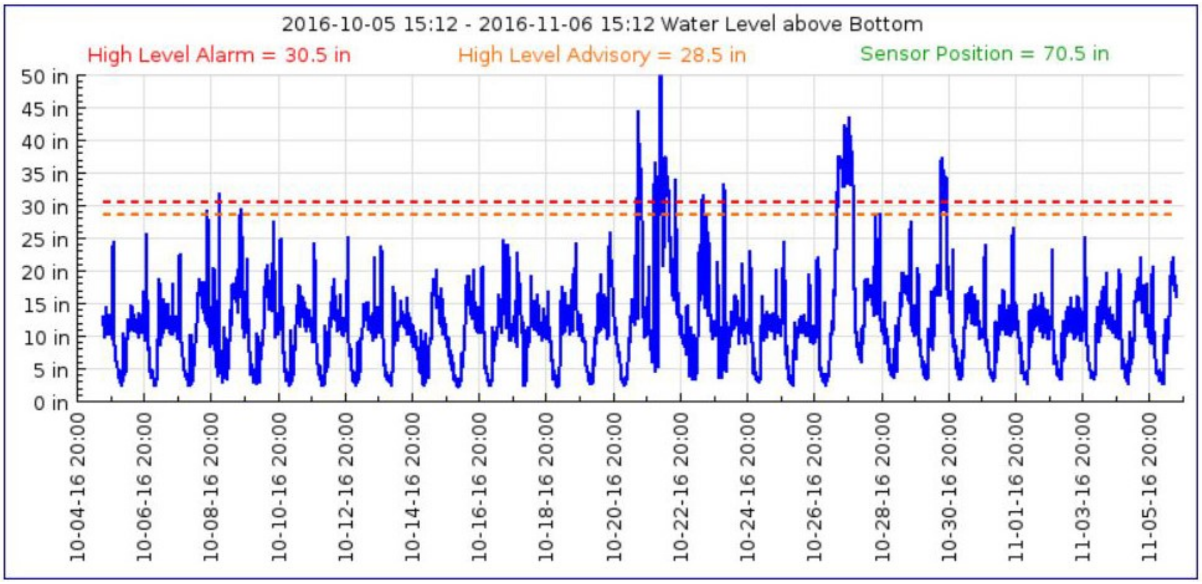


Figure 1. The new system monitors water level above the bottom of the pipe and allows the city to automatically and accurately monitor and report CSO events. Significant rainfall generated stormwater peaks above the red dotted line, which indicates CSO events.

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 needed. 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.

Ormond Beach, Florida
Flood Risk Mitigation—Extreme Events

OWNER	LOCATION	INCEPTION
City of Ormond Beach	**Ormond Beach, Florida**	**February 2017**

KEY FEATURES

- RTC used to convert 70 acre-feet of dead storage into flood management capacity for pre-event drawdown.
- Optimizations to the pump system that mitigated the need for an $8 million upgrade.
- Lakes prevented from reaching flood elevation during 2017's Hurricane Irma.
- Actionable insights for emergency response personnel, improving community resilience.

PROJECT DESCRIPTION

A 2009 storm caused excessive flooding and property damage in Ormond Beach. About 79 structures were affected, and flooding made roads impassable throughout the city's Laurel Creek drainage basin area. With help from the Federal Emergency Management Agency and in coordination with various city departments, an upgrade project was undertaken to address not only the flooding issues but provide the ability to upgrade utilities within the area, enhance park elements, and bring existing roadways up to current city standards.

Figure 1. The Laurel Creek Pump Station is located at an interconnected lake system that provides flood control for the area.

To further minimize the risk of flooding, the city implemented the Laurel Creek Pump Station Additions and Improvements project, which was approved under its Capital Improvements Program. The stormwater pump station is located at an interconnected lake system (comprised of five lakes) and provides flood control for the area (see Figure 1).

As part of this effort to maximize the flood storage potential of the lakes, the city deployed weather-forecast-based CMAC technology. Specifically, CMAC controls two VFD pumps to discharge water from the lakes in advance of a weather event, creating additional storage capacity. A cloud-based software platform collects data from the local weather forecast, four solar-powered water level monitoring stations, and the VFD pumps. Data are processed in real-time, and the cloud platform automatically sends commands via a cellular network to set VFD discharge rates.

The interconnected lake system receives runoff from a 7,680-acre watershed and has a total storage capacity of 250 acre-feet. In preparation for Hurricane Irma, the city used CMAC to discharge about 70 acre-feet of storage from the lake system. Even with the tremendous performance of the lakes' new pump system, there was a total storage increase of 190 acre-feet after pre-event drawdown (see Figure 2). Given that local flooding occurs at a storage volume of 250 acre-feet, the pre-event drawdown prevented flooding of nearby roads and property. Without pre-event drawdown, the lake elevation would have exceeded the flood stage of 5 feet (i.e., a volume of 250 acre-feet). Continuous monitoring before, during, and after Irma's eight-inch rainfall on this basin was also an integral part of the city's emergency operations and further enhanced infrastructure management.

The city estimated that it would have cost $8 million to eliminate flooding by increasing pump capacity with additional pump stations. Instead, the city reduced localized flooding within one year for $200,000 by optimizing its existing system.

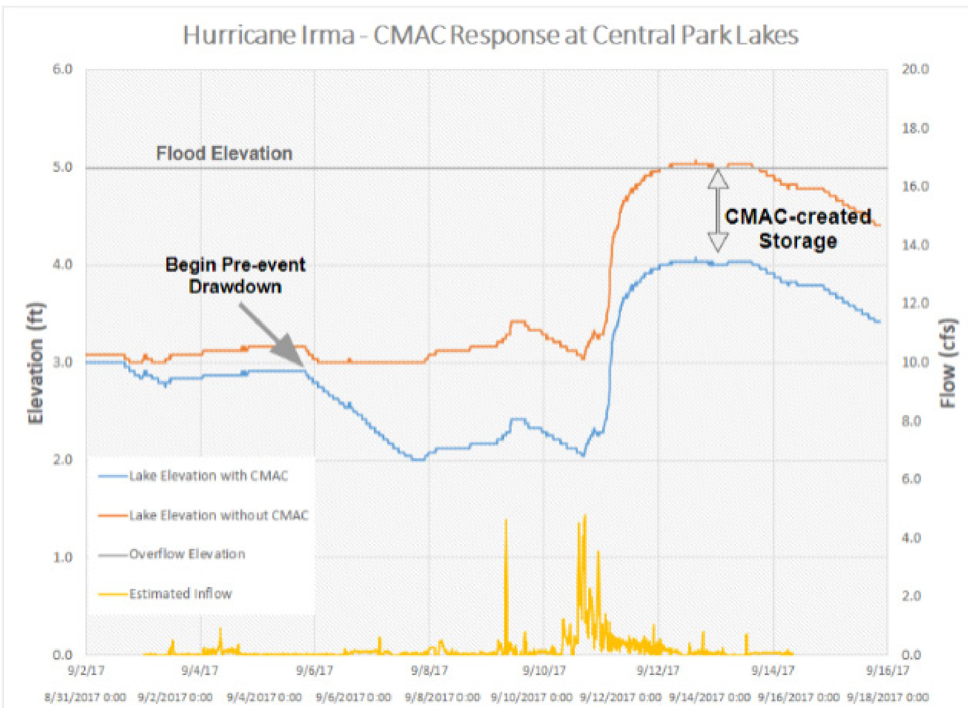


Figure 2. Laurel Creek Pump Station Additions and Improvements project performance during Hurricane Irma.

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

OWNER	LOCATION	INCEPTION
Philadelphia Water Department	**Philadelphia, Pennsylvania**	**2016**

KEY FEATURES

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

PROJECT DESCRIPTION

An existing SMP collecting runoff from eight acres on private property in the combined sewer area was not meeting 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 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 CMAC on the existing outlet control structure of the basin (see Figure 1). 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.

Figure 1. CMAC installation on the existing outlet control structure.

The stormwater pond contains a permanent pool of 22,500 cubic feet maintained by an outlet structure with a 6-inch orifice. A second, eight-inch orifice is positioned about two feet above the invert of the six-inch orifice and an overflow weir is about two feet above the eight-inch orifice. The retrofit involved installing a six-inch actuated valve on the six-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 National Oceanic and Atmospheric Administration 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 eight-inch orifice, close the six-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 0.26 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 the 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 two 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 failsafe 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. Figures 2 and 3 illustrate how the pond's volume and flows after a wet weather event are managed with passive outlet control compared to CMAC.

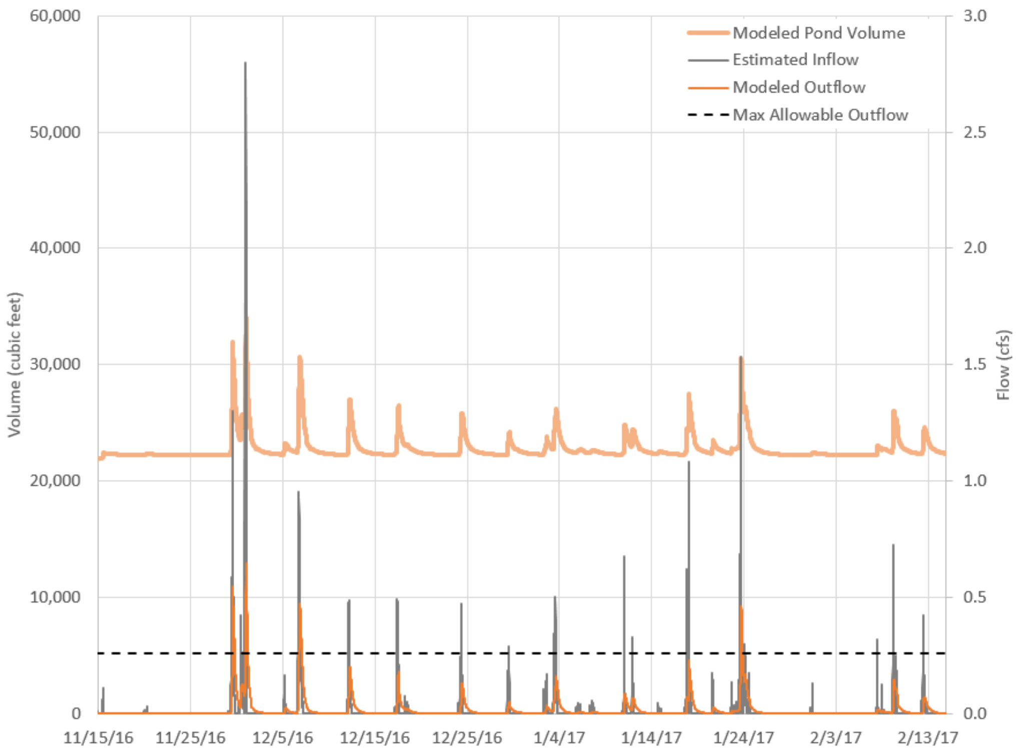


Figure 2. Modeled pond volume and flows with passive outlet control.

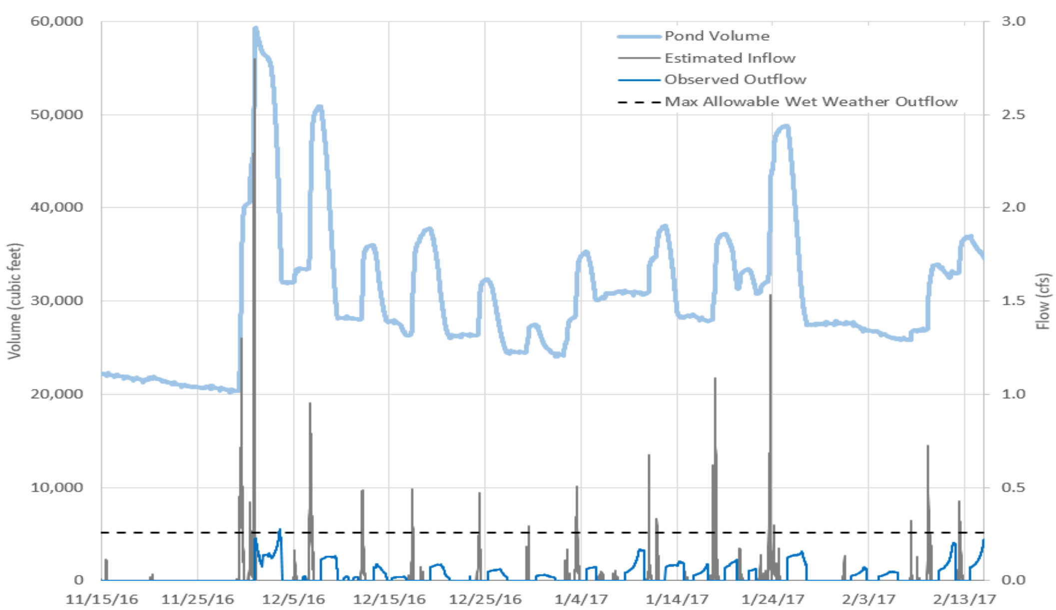


Figure 3. Observed pond volume and flows with CMAC.

Rutland, Vermont
Real-Time Control to Meet Public Notification Requirements

OWNER	LOCATION	INCEPTION
City of Rutland	**Rutland, Vermont**	**July 2017**

KEY FEATURES

- RTC solutions helped the city meet state public notification requirements.
- Easy for non-technical users to visualize the data.

PROJECT DESCRIPTION

Rutland, Vermont, is a small city of about 16,500 residents. It operates a combined sewer system, some of whose sections are more than 100 years old. In the past, the city relied on measuring techniques that involved field crews and site visits, such as reading height markers from a wooden stick, to periodically sample levels in its wastewater system. Although this fulfilled its basic reporting obligations, it clearly did not provide real-time information. It also necessitated frequent field visits, and—being a non-digital method—could not connect with interfaces such as the city's SCADA system. It did not provide the means to predict the development of a CSO, nor could it alert operators to one that was already in progress.

Remedial and proactive engineering work could only be planned on the basis of modeling efforts predicated upon the accuracy of data taken from indirect estimates of water flows. The lack of information from the furthest portions of the collection system from the treatment plant also greatly impeded the city's efforts to address the root problems, inherent in its system design, that were causing the CSOs to happen.

In 2016, the Vermont state legislature enacted law that requires operators to notify the public of overflow events within an hour of discovery. The city saw in the legislation an opportunity to proactively increase the transparency of local government and provide up-to-date information about wastewater management issues to citizens. To comply with the legislation and deliver its planned citizen information initiative, the city realized that it needed to develop an affordable system that could provide real-time level data to its regulators, its customers, and engineers. To this end, the city embarked on a public information initiative that included setting up social media to inform customers of wastewater events including overflows. This provided a user-friendly alternative to the municipality's website.

The city piloted several RTC solutions before choosing a product, in February 2019. Non-technical users could quickly learn how to visualize field data using the web-based data hub. Engineers could integrate the real-time data feed directly into the city's SCADA monitoring and control platform quickly. Members of the public could subscribe to receive live updates about overflows from familiar social platforms.

An additional benefit of the city's RTC solution has been the ability to help draft a hydrologic and hydraulic study, which the city is undertaking to improve the performance of its wastewater network over the long term. Consultants are working with the city to draft a plan that will use the RTC devices to capture extensive data from the field. When complete, the plan will give network operators the ability to accurately predict the development of CSO events. In addition, it will enable the city to undertake a cost-benefit analysis to determine what mix of green infrastructure (aboveground water interception devices), gray infrastructure (underground retention measures), and data infrastructure (flexible state underground devices, such as inflatable weirs, operated based on cues from smart sensors) will yield the best long-term results for minimizing CSO events. As Figure 1 shows, the city is already gathering data on how much Otter Creek backflows into the combined sewer system.

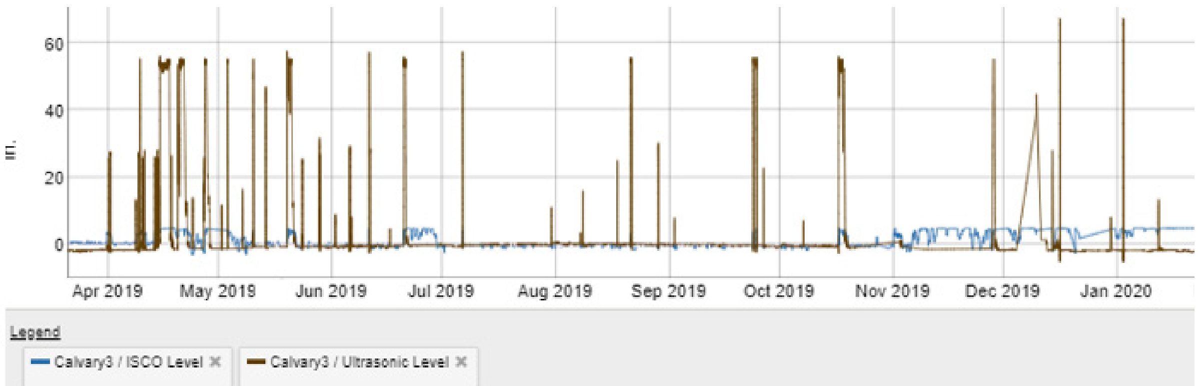


Figure 1. The city uses multiple level sensors to monitor how much Otter Creek backflows into the combined sewer system.

The strategies that the city will put into action, based upon the hydrologic and hydraulic study and the data derived from the RTC installation project, will greatly help it remain compliant with the terms of the Chapter 10 Vermont Statutes Annotated Section 1272 Order ("Regulation of activities causing discharge or affecting significant wetlands"). The order sets out guidance plans for operators who do not currently comply with best practice management guidelines to reduce their overflow rates.

In 2019, total CSO volume for 29 storms was 26.8 MG, with an average duration per event of 3 hours and 21 minutes. The data from the field assets showed that more than 70 percent of the overflows occurred between April and November 2019. The highest recorded discharge was 2.5 cfs, which was reached 10 times during 2019. The city is using the data collected from the monitoring equipment to identify cost-effective collection system modifications it can implement as part of its LTCP. The RTC system has given the city an alternative, convenient way to affordably revolutionize the operation of its network without needing to physically change it.

San Antonio, Texas
Smart Sewers to Fulfill Consent Decrees

OWNER	LOCATION	INCEPTION
San Antonio Water System	**San Antonio Water System**	**Fall 2017**

KEY FEATURES

- 1,246 anticipated cleanings reduced to 65 actual cleanings.
- 95 percent reduction in cleaning frequency at 200 sites.
- No spills.
- Certification of 216 SSO "saves."
- Annual average return on investment of 115 percent.

PROJECT DESCRIPTION

From 2013 to 2015, SAWS tackled an EPA consent decree with an estimated cost of $1 billion. SAWS adopted EPA's CMOM guidelines and instituted high-frequency cleaning for its 110,000 manholes and pipeline segments. Effectively, this meant SAWS established a program of cleaning "high-risk" pipes with potential for overflows and instituted routine cleanings at monthly, bi-monthly, quarterly, semi-annual, and annual frequencies.

To help reduce overflows and mitigate the disadvantages of high-frequency cleaning, SAWS implemented a smart sewer pilot project at 10 monthly cleaning locations from summer 2015 to summer 2016. The pilot used remote sensors that automatically scan water level patterns and issue notification when high levels are detected upstream or downstream from the monitored location. The technology system provides real-time continuous monitoring and trend analysis, allowing SAWS to use data to determine where and when to clean a sewer pipe segment rather than using a predetermined cleaning schedule. The pilot resulted in a 94 percent reduction in cleaning (see Figure 1) and an estimated $4,000 in savings per monitored location.

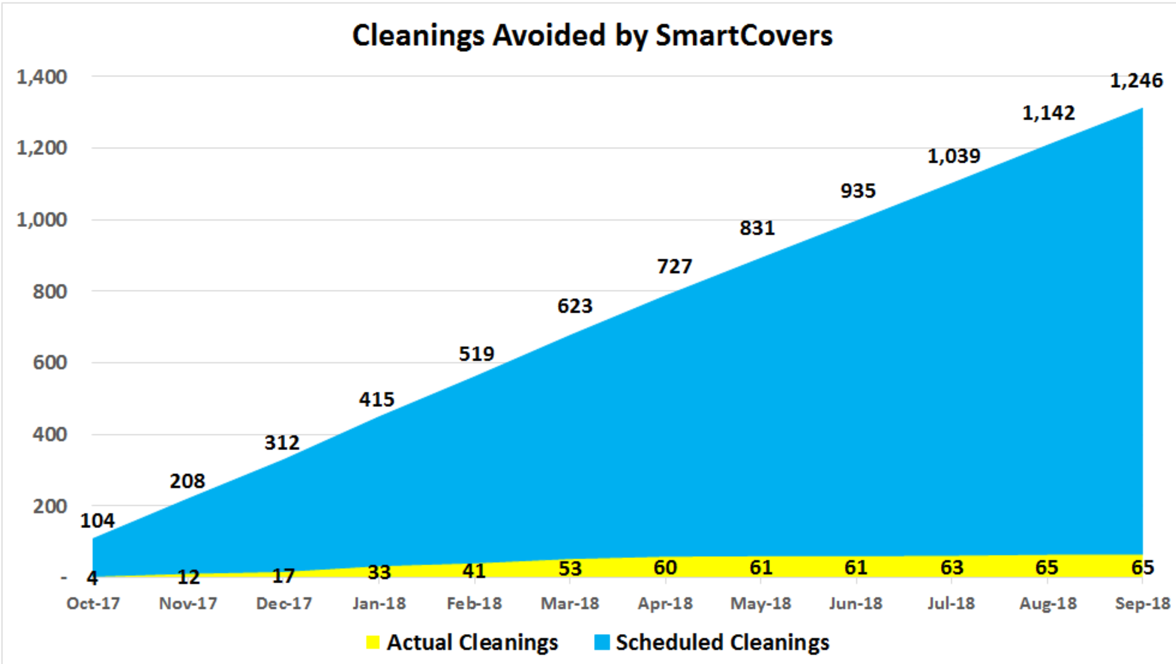


Figure 1. Cleanings avoided with smart data.

In fall 2017, after the success of the pilot program, SAWS deployed another 200 remote monitoring sensors at high-risk sites for regular monthly cleanings. As a conscientious sewer operator, it planned to clean whether the pipes needed cleaning or not. SAWS anticipated nearly 1,300 cleanings at these locations—but with the analysis and the notification system, it ended up needing to clean only 65 sites. SAWS has experienced a 95 percent reduction in cleaning, no SSOs, and a certified 216 SSO "saves," as shown in Figure 2.

Over time, there has been a distinctive paradigm shift from "We always clean this spot just in case" to relying on smart data for more efficient "as-needed" cleaning.

For SAWS, the use of smart data continues to lower cleaning costs while preventing SSOs. And, with its smart sewer solution, SAWS has witnessed fast payoff and excellent return on investment, solved old problems with new technology, extended underground asset lifetime, eased stress on staff, protected lives in the field with no confined space entry, created staff availability for other tasks, lowered pressure on user rates, and significantly decreased operational liabilities.

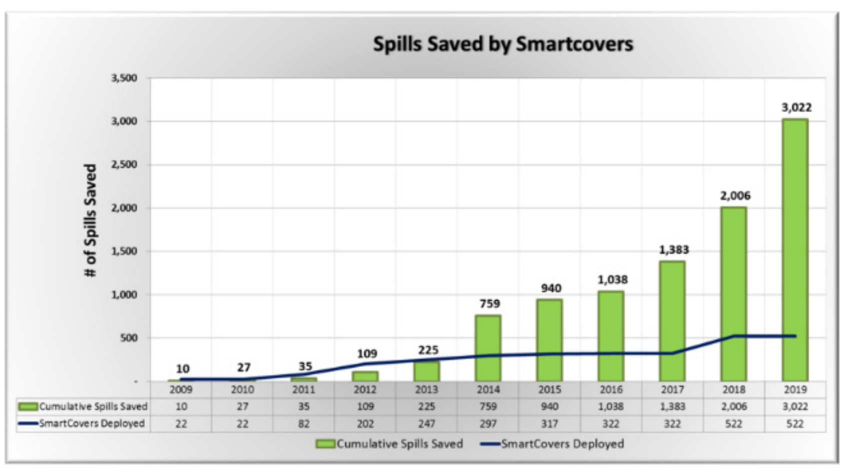


Figure 2. Spills saved using smart data between 2009 and 2019.

San Diego, California Stormwater Harvesting Augmentation Analysis

OWNER	LOCATION	INCEPTION
City of San Diego, Stormwater Division	**City of San Diego**	**2016**

KEY FEATURES

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

PROJECT DESCRIPTION

Starting in 2011, 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. More recently, 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 (see Figure 1), 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 used a calibrated watershed model to predict the loading to the plant from raw stormwater and from effluent from the green infrastructure that would be built 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 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.

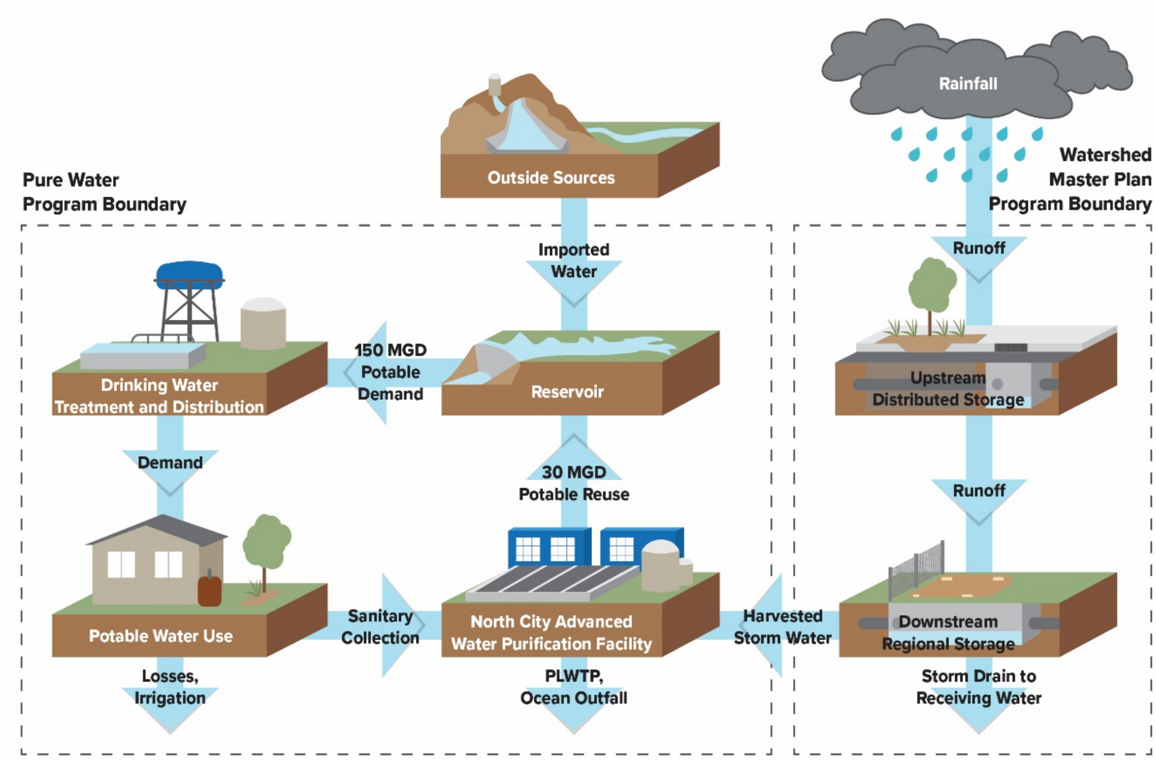


Figure 1. Graphic showing the potential nexus between an emerging stormwater capture program and ongoing efforts to reclaim wastewater as a drinking water resource in San Diego.

San Francisco, California
Real-Time Control to Model Combined Sewer System

OWNER	LOCATION	INCEPTION
San Francisco Public Utilities Commission	**San Francisco, California**	**2017**

KEY FEATURES

- Two-dimensional module that helps characterize the sewer system performance.
- Easy-to-program, easy-to-understand RTC system.
- Less time required for data management and conflict resolution and higher productivity.

PROJECT DESCRIPTION

San Francisco is home to about 880,000 residents and uses a combined sewer system to collect and treat sanitary and stormwater flows. SFPUC owns and operates close to 1,000 miles of sewer mains, 3 treatment facilities, 200 MG of storage, 26 pump stations, and 36 CSO outfalls.

Developing a numerical model for San Francisco's combined sewer system came with several overarching challenges:

- Detailed representation of sanitary and stormwater flows through a large and complex collection network.
- Characterization of overland flow transport through the city's challenging topography.
- Accurate depiction of passive and active control structures' operation.
- Multiple engineers working concurrently to solve the same problem.

To help address these challenges, SFPUC chose a numerical model that has shown remarkable performance in three key areas:

- A two-dimensional module.
- RTC logic.
- Multi-processing capabilities.

The city's combined sewer system is designed to collect and convey flows for a design storm. In extreme storm events, excess stormwater flows may not enter the sewer system and combined sewer flows may exit the sewer system at some locations. In flat topographies, these overland flows might pond in the area until the system regains capacity. However, with San Francisco's famous topography—steep hills, low valleys, and low-lying flat areas—the overland flows often pass over the street surface and either enter back into the sewer system or pond at other low-lying locations. The location where the overland flows originate and the eventual location of re-entry into the system or ponding can be very different.

The two-dimensional module in the city's integrated catchment modeling makes it possible to generate a surface mesh using ground surface elevation data. In extreme storms, when there are overland flows on the ground, the city's integrated catchment modeling enables the two-dimensional module and routes the overland flows by solving the surface flow transport equations for each mesh element.

Allowing the model to mimic the transport of overland flows is extremely helpful to characterize the performance of the sewer system (see Figure 1). The ability to visualize the fate and transport of overland flows with increasing accuracy has given the planners and engineers higher confidence in the model and its use in sewer infrastructure projects.

Figure 1. Overland flows transported on the ground surface, as shown in the two-dimensional module.

Many of the treatment facilities, pump stations, and CSO outfalls convey and treat the flows differently during dry and wet weather. Additionally, during wet weather the operation of some facilities varies depending on the amount of rainfall and the combined sewer flows in the system.

The RTC module allows programming different types of pump stations, gate structures, and valve structures. It also allows programming the set-points for the operation of these facilities. The RTC logic is easy to program and understand and allows a much better representation for simulating the different treatment pathways (i.e., secondary versus primary treatment facility versus CSO outfall) for any storm event.

Several engineers from different locations work on the model, often working to solve the same problem concurrently. The workgroup-based databases and configuration management system have enabled them to work together seamlessly to update the model, develop scenarios for analysis, and generate results using the same network. This has decreased the time needed for database management and conflict resolution and raised team productivity.

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

OWNER	LOCATION	INCEPTION
South Bend Department of Public Works	**South Bend, Indiana**	**2008**

KEY FEATURES

- Illicit dry weather overflows eliminated; total CSO volume reduced by about 70 percent (about 1 billion gallons per year).
- Potential cost of the city's LTCP reduced by an estimated $500 million.
- O&M costs reduced by $1.5 million.
- More than 50 percent decrease in *E. coli* concentration (from the sewer system) in the Saint Joseph River.

PROJECT DESCRIPTION

Before 2008, South Bend had one of the largest CSO discharge volumes per capita in the Great Lakes watershed. With a population of a 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 implemented the prescribed projects in its LTCP, the cost of mitigating its CSO problem would have totaled roughly $800 million.

In 2008, the city commissioned a real-time monitoring system of more than 120 sensor locations throughout the city. In 2012, after reviewing data from the system and choosing sites accordingly, the city launched a distributed, global, optimal 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 SCADA screens for the operators, smartphones 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 of sites to 152. 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 RTDSS. 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 (see Figure 1). The city estimates the program will reduce the cost of the LTCP by $500 million, 63 percent less than the original $800 million estimate; it has already surpassed its original target of a 25 percent reduction in CSOs. *E. coli* concentrations in the Saint Joseph River have dropped by more than 50 percent on average. Overall, this intelligent program allowed South Bend to reduce costly traditional gray infrastructure, while improving system performance and capacity utilization, delivering environmental gains 10 to 15 years ahead of schedule.

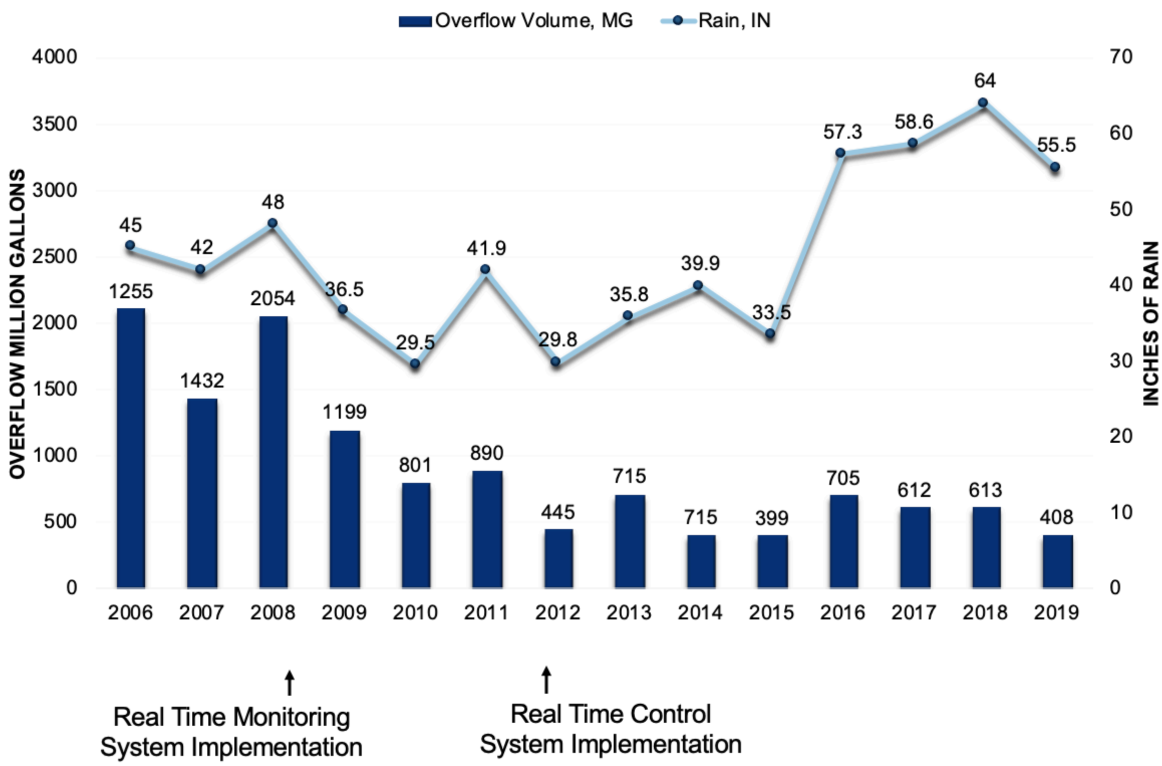


Figure 1. From 2008 through 2014, South Bend eliminated illicit dry weather overflows in the first 12 months and subsequently reduced its total CSO volume by about 1 billion gallons per year, about 70 percent.

Washington, D.C. Real-Time Controls for Rainwater Harvesting and CSOs

OWNER	LOCATION	INCEPTION
U.S. Environmental Protection Agency	**Washington, D.C.**	**2014**

KEY FEATURES

- RTCs that retain water for onsite irrigation and reduce wet weather discharge to the combined sewer.
- 100 percent of all 1-inch (and smaller) rain events captured, preventing about 100,000 gallons of wet weather flow from entering the combined sewer each year.

PROJECT DESCRIPTION

EPA and the 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 and 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 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 stays closed until another rain event is in the forecast, ensuring that water is available for reuse.

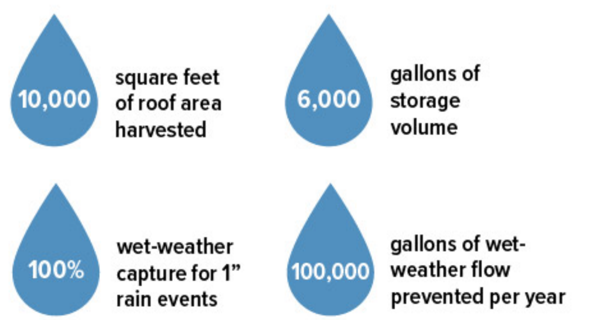


Figure 1. The rainwater harvesting system at EPA Headquarters prevents about 100,000 gallons of wet weather flow from entering the combined sewer each year.

A one-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 to be a low-cost, high-performance solution for meeting stormwater management goals (see Figure 1). The increased data transparency and opportunities for adaptive management can achieve a range of stormwater management objectives. Figure 2 shows how cistern levels are clearly presented to the user for easy storage volume management.

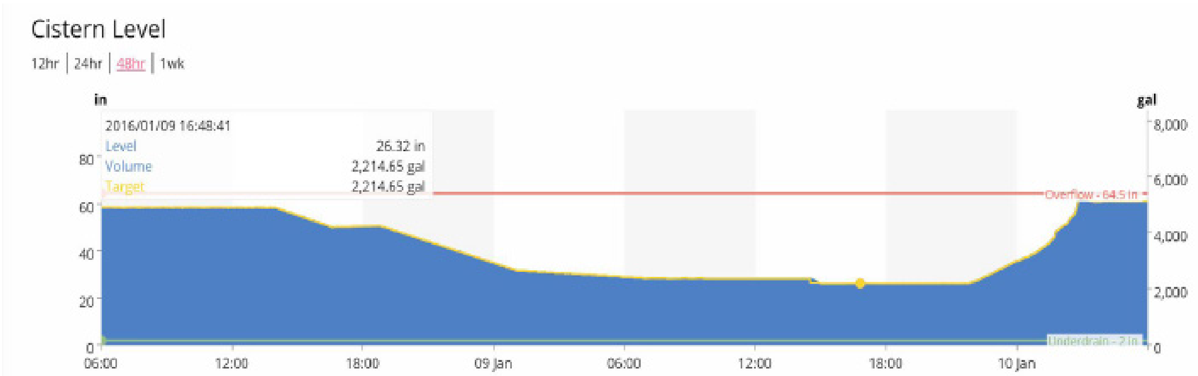


Figure 2. Cistern levels shown in the user interface.

Wilmington, Delaware Real-Time Control to Reduce CSOs

OWNER	LOCATION	INCEPTION
City of Wilmington	**Wilmington, Delaware**	**2011**

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-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 WWTP. These projects included the upgrade of treatment plant capacity, the construction of the 2.7 MG Canby Park CSO Storage Basin (see Figure 1), the elimination of certain CSOs, other specific collection system improvements, and public outreach.

Figure 1. The 2.7 MG Canby Park CSO Storage Basin under construction.

As part of its ELTCP, Wilmington implemented a coordinated system-wide 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 the presumption approach. Wilmington's green infrastructure program is expected to meet the total maximum daily load objectives by increasing the wet weather capture rate to over 90 percent.

The city 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 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 (see Figure 2), under the supervision of operators. Smart use of RTC technology has allowed the City of Wilmington to significantly reduce overall costs of the LTCP.

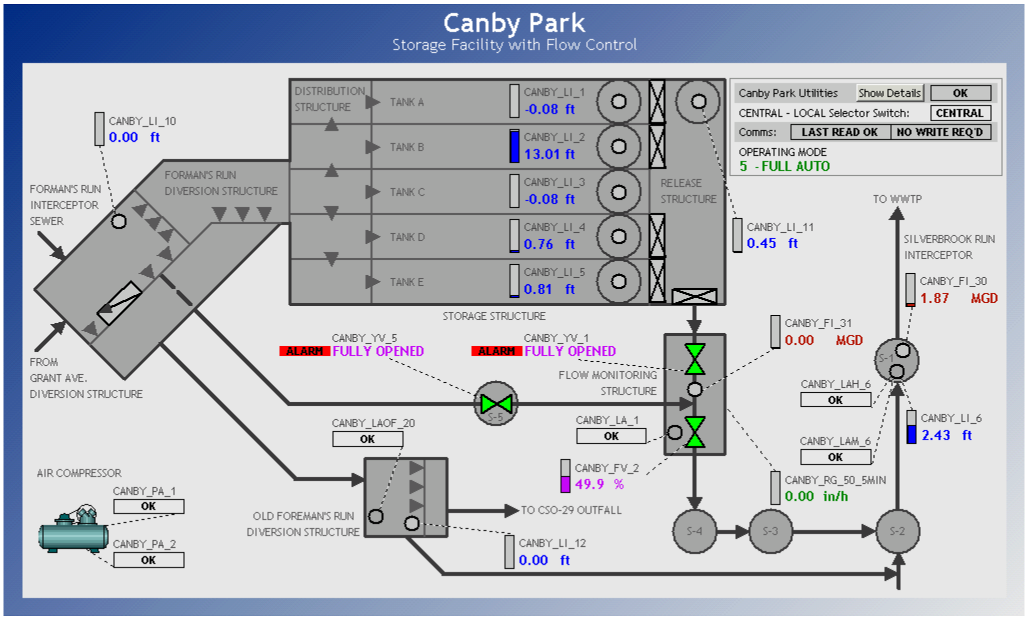


Figure 2. Process flow diagram for the Canby Park CSO Storage Basin.

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

The system has four major components:

- A monitoring system including level, flow, and rainfall.
- Local control facilities equipped with control elements (gate and pumps), PLCs, and remote telemetry units with backup power.
- A SCADA system for data acquisition of sensor information and control facility status, as well as for communication of control set points.
- A central station that 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.

RTC feasibility studies showed that optimizing the existing collection and treatment system would have a relatively low unit cost, $0.07 per gallon of CSO reduction per year. This cost is four times lower than that of the traditional approach (building more storage). The overall savings is estimated at $87 million from the original CSO LTCP cost of $114 million, for a final LTCP cost of $27 million.

The RTC technology is scalable and flexible and 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 modified based on performance monitoring as part of adaptive management.

The RTC system design and operation accounts for equipment and sensor failures and provides failsafe 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 gives the city a 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 agencies and for integrating adaptive management into LTCP planning.

The RTC approach did present several challenges:

- It relies on an online model and real-time rain gauges to predict upcoming inflows and their spatial distribution. This requires the calibration and updating 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.

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 choosing the appropriate level of RTC implementation.
- It is important to involve system operators early in 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 in properly operating, maintaining, and improving an 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, as well as pump station control logic that deviated from the reported operational condition.

"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 [RTC] 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 are 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

- Key to the project has been the City of Wilmington and its designated operator taking ownership of the instrumentation and control and SCADA system to maintain equipment and instrumentation in a proactive manner.

The project cost $12 million, including retrofit, construction, monitoring, IT, etc. The current RTC system includes the use of 1 retention basin (2.7 MG) for CSO control, an additional 2 MG of inline storage, the management of 3 siphons, and the operation of a 135 MGD pumping station.