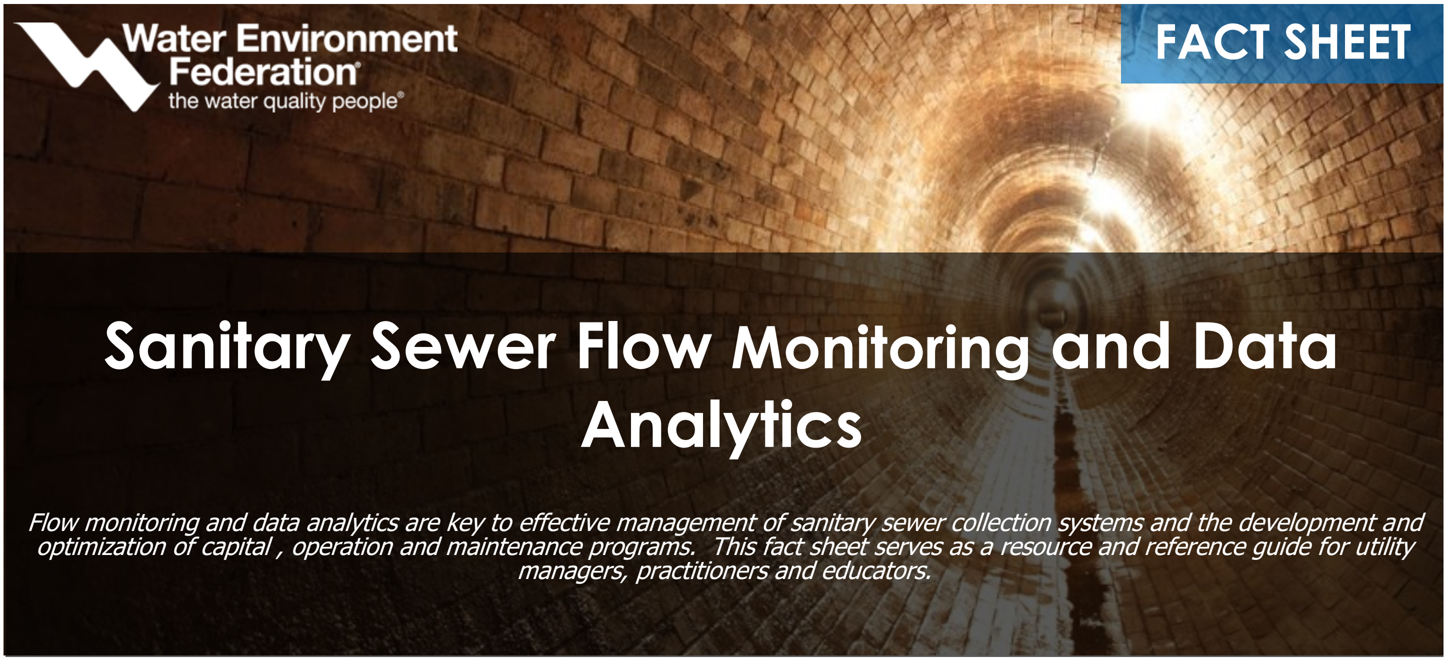

FACT SHEET

Sanitary Sewer Flow Monitoring and Data Analytics

Flow monitoring and data analytics are key to effective management of sanitary sewer collection systems and the development and optimization of capital , operation and maintenance programs. This fact sheet serves as a resource and reference guide for utility managers, practitioners and educators.

Introduction

Flow monitoring is an essential procedure to collect data for evaluating and characterizing wet-weather and dry-weather flow conditions in sanitary sewer collection systems. Real time use of the data for supporting operational decision-making/optimization and in-time maintenance activities has been a growing trend. Over the past three decades, industry practices have evolved in designing flow/rainfall monitoring programs with progressively more effective data analytics that support many business needs:

- rainfall derived infiltration and inflow (RDII) characterization and quantification;
- developing and calibrating hydraulic models; focused sewer condition assessment;
- capacity assessment and overflow baselining; capacity and condition improvements;
- operation and maintenance activities; and in support of actions related to Consent Decrees for many water utilities.

The primary objective of this fact sheet is to summarize industry-wide observations on basics of flow monitoring strategies; data management and analytics; and notable references for developing deeper knowledge.

Flow Monitoring Strategies

A sewer flow and rainfall monitoring program typically involves installing a network of flow meters and rain gauges at strategic locations within the sewer system for a specific duration. Collected data are analyzed to develop flow characteristics under dry- and wet-weather conditions at the meter locations. Industry experiences/observations indicate that successful flow monitoring strategies address the following key considerations.

Establishing clear objectives and expectations: Flow and rainfall monitoring programs should be designed such that they effectively support clear business needs. The most cost-effective way to implement a flow monitoring program is to achieve multiple objectives with a single, properly planned, flow monitoring program. Data collection efforts can be time consuming and expensive. They should be carefully designed to answer specific questions set by business needs with use of tools selected for performing data analytics. The magnitude and details of data collection such as spatial scale, flow meter/rain gauge density, and duration of monitoring vary based on specific project objectives established using a fit-for-purpose approach. It is critical to optimize the time, resources, and costs while balancing the competing and varied business needs.

Permanent vs. Temporary: Permanent monitoring typically occurs at a relatively small number of strategic locations along trunk sewers, upstream of wastewater facilities, and priority sewersheds with known operational problems. These locations will provide necessary long-term data to make operational and capital improvement decisions along with a host of other business needs.

The focus of temporary monitoring at a relatively large number of locations is to provide higher resolution flow data from contributing sewersheds upstream of permanent or long-term monitoring locations on the trunk sewer system. The temporary locations also serve to provide additional data for hydrologic/hydraulic model calibration. These temporary programs are usually undertaken to support the specific objectives of a shorter-term study and/or system assessment in a specific area. Efficacy of temporary flow monitoring design depends on several factors including typical rainfall patterns, seasonal and regional variations in climate and/or environmental factors, tides for coastal communities, and varying system RDII responses.

Timing and Duration of temporary monitoring: Temporary monitoring should be performed during the time of the year where RDII levels are highest. Historical flow records at the wastewater treatment plant and pump stations within the collection system can help determine the months with highest observed RDII and can guide establishing the temporary monitoring program. RDII is more pronounced when the groundwater table and antecedent soil moisture conditions are high. The monitoring program can sometimes be amended with monitoring of groundwater wells to quantify variation in antecedent conditions.

The duration will depend on the precipitation and groundwater characteristics of the region. Generally, a four- to six-month duration under normal precipitation conditions should provide flow characteristics for a range of dry- and wet-weather conditions to support the RDII analysis. The program should include flexibility to shorten or extend the monitoring duration depending on the actual range of RDII responses observed and measured.

Flow monitor placement locations: The density of flow and rain gauge equipment in a monitoring network varies based on the corresponding monitoring objectives. The general locations for flow monitoring typically focus on isolating the flow in each major contributing area. Depending on the specific study circumstances, some may require detailed monitoring of the inflows from upstream sewersheds and the outflows to the downstream trunk sewers.

Some key determining aspects for meter locations include:

- thorough understanding of the system layout and network connectivity with location of flow control/ diversion structures, active SSOs (and their causes if known), and pump station overflows;
- determination of sewershed discharge points to the trunk sewers;
- upstream of known SSOs and flooding locations;
- upstream of pump stations along with pump operating records;
- critical points along the trunk sewer;
- points of major confluence and upstream of interconnection points between parallel trunk sewers; influent lines to treatment plants;
- priority sewersheds with known operational problems.

The site selection process typically includes performing field investigations to review candidate manholes in the general area of each desired monitoring location of interest with a preferred location and several optional locations upstream and downstream. This gives the field crews the latitude to install the meter in the safest manhole that will provide the highest quality data while still fulfilling the set data needs. Factors to be considered include sewer hydraulics; structural conditions of the manhole; access for meter installation; maintenance; data collection; and other safety concerns such as presence of hazardous gases and vehicle traffic.

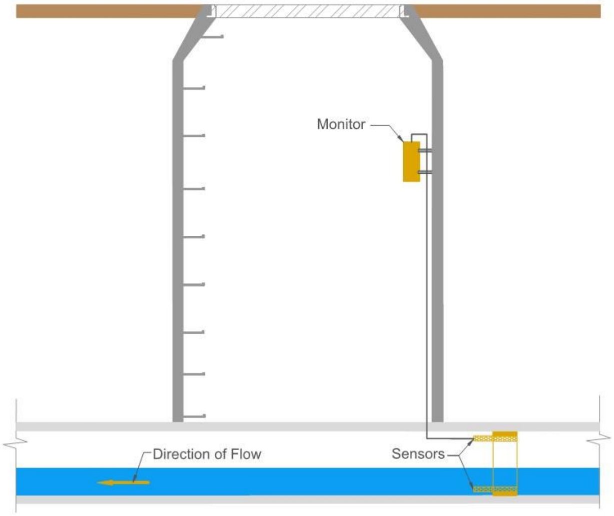

Figure 1: Typical Area-Velocity Monitor Setup
(Image provided by: Barge Design Solutions)

Equipment selection: The objective of the equipment selection is to obtain quality data at selected sites to meet project goals. There are many flow monitoring sensor technologies available, such as ultrasonic; electromagnetic; pressure; bubbler; and float. Newer technologies/ techniques and refinement of existing continue to emerge. Descriptions of the flow monitoring technologies were included in industry references listed at the end of this publication. Figure 1 shows a typical setup for area-velocity sensor and data logging monitor.

Industry best practices point that screening hydraulic conditions at selected sites and determining the most suitable flow monitoring equipment/technology can help obtain the best quality data possible. Hydraulic conditions may include evidence of surcharge; turbulence; number of inlet/outlet pipes; drop connections; and grease accumulation. The flow monitoring manufacturers and/or flow data service providers can guide equipment/ technology selection for each specific flow monitoring site. In some cases, one technology can meet the needs for all locations in a flow monitoring program, while in other cases, several technologies may be needed to match the site hydraulics and program objectives. It is good practice to balance the need for quality data with the program objectives, available technologies and resources.

Equipment Installation, data collection, operation and maintenance: Proper installation and accurate site calibration of equipment is key to collecting accurate data and should be performed by qualified personnel following manufacturer's recommendations and industry standards. It is a good practice to perform a site check three to seven days after the initial installation to confirm the meter performance and site suitability. Based on the initial site observation after installation, adjustments may be necessary and, in some cases, meters may need to be moved to an alternate site.

Subsequently, depending on the data quality observed at the time of installation and/or via telemetry, on-site inspections may need to occur at various frequencies such as weekly, monthly, or quarterly with consideration of the hydraulic conditions as well as the temporary or permanent nature of the monitoring. These site inspections can reduce equipment fouling due to debris and other unforeseen conditions, such as clock errors or battery-life, and will reduce meter down time. A common data collection interval is five minutes, but 10 or 15-minutes and hourly records are also commonly used, depending on established flow monitoring needs and objectives. Five-minute data can always be averaged to hourly or daily, but not the other way. In addition to on-site inspections, data quality should be checked on a weekly basis at a minimum.

Rainfall monitoring and data collection: Reliable rainfall data with the proper resolution is critical for wet-weather flow data analyses. To properly characterize and compare the intensity of rainfall events and resultant wastewater flow reaction, accurate rainfall readings must be obtained on a minimum 15-minute interval, preferably a 5-min interval. The accuracy of precipitation data is typically a function of the equipment, its location, and maintenance. Precision is a function of the type of equipment used. Spatial resolution is a key concern when working with the precipitation data. It has become widely recognized that RDII prediction, and the calibration and application of ever-more precise sewer system models, are significantly hindered by the limitations of precipitation data. These limitations are caused by several factors, including the spatial resolution; poor gauge siting; equipment malfunctions; and data collection/ transformation errors.

Rainfall data is usually available from different sources, such as temporary or permanent rain gauge networks maintained by the utility within the service area and other governmental agencies. If a service area spans several square miles and spatial/temporal variation of rainfall is significant, a combination of spatial estimates of rainfall, based on reflectivity from the nearest National Weather Service (NWS) radar station and point estimates from the local rain gauge network will produce a better estimate of the spatial distribution than either system alone. An area with predominantly convective storm systems may require a higher density of rainfall data than an area with predominantly frontal systems.

Many communities have an established permanent rain gauge network, which can be used to support RDII analyses. It is critical to thoroughly evaluate the performance of the existing rain gauge network at the onset of a flow monitoring program to identify the needs for improvements and to determine if supplemental rainfall monitoring is needed.

Data quantity and quality: Adequate quantity and quality of collected flow and rainfall data are critical to reliably support the RDII analyses and numerous other sewer system management functions. Careful planning of the spatial and temporal extent of this data collection program is a key component of a successful data analysis and subsequent system improvement planning and implementation efforts.

To assure a proper quantity and quality of collected data, the industry practices suggest the following critical actions while the field flow monitoring is in progress:

- perform periodic on-site inspections of all flow meters to minimize data gaps;
- conduct weekly data collection at a minimum;
- perform data quality reviews using continuous flow hydrographs and alert field crew on maintenance needs;
- observe unusual changes in dry-weather flow patterns;
- keep track of the shape of hydrographs and how a meter responds to the relative magnitude of rainfall events, particularly noting characteristic responses in peak flows and volumetric responses and flag any observed inconsistencies in characteristic patterns as the new data is collected/reviewed;
- study/monitor changes in depth vs. velocity scatter plots and take timely actions through meter maintenance/ adjustments as needed.

Data Management and I/I Analytics

Data Management

RDII reduction and management programs are largely data driven programs and flow monitoring programs generate large quantities of data. As such, an effective data management system to consolidate, access, evaluate, and analyze data is critical to the long-term success of any program. Typically, software provided by the flow monitoring equipment vendor includes a basic level of flow and rainfall data management, data quality control, tracking and/or trending of sewer flow characteristics over time, and performing dry- and wet-weather flow analyses. In addition, this software allows utilities to export data to their preferred enterprise asset data management and analytics programs, including customized geographic information systems (GIS) based applications, Computerized Maintenance Management Systems (CMMS) and Supervisory Control and Data Acquisition (SCADA) systems.

Recent trends in flow and rainfall data management include the use of web-based storage/analysis tools offering many options for data review, retrieval and performing basic flow evaluations. Many vendors of monitoring equipment offer these web-based services and a few utilities are developing these in-house capabilities as well. When integrated with telemetry, data can be retrieved on a weekly, daily, near-real-time or on an on-demand basis by the user. This facilitates evaluation of flow measurements in "near-real-time" to support and perform in-time preventive maintenance activities for avoiding sewer spills and for achieving operational optimization. Setting up a web-based service with desired features requires upfront as well as ongoing investments. Data are typically stored in the cloud, or on dedicated website /servers.

Inflow and Infiltration (I/I) Data Analytics

The following key I/I data analytics are practiced in the industry in support of sanitary sewer I/I remediation and sewer management programs:

I/I characterization - A thorough baseline characterization of sanitary sewer flow in dry- and wet-weather conditions is critical for successful RDII reduction/management investments. Although sanitary sewers are designed to convey wastewater with a limited amount of extraneous flow, various and numerous unintended sources of extraneous water entering the pipes can lead to excessive RDII. This undesired condition can be more noticeable after certain threshold precipitation levels occur. This is typically caused by structural deficiencies resulting from system aging, structural failure, lack of proper maintenance, installation of other utilities, ditch cleaning and/or poor construction and design practices. They can include but are not limited to conditions such as broken pipes; storm or drainage system cross-connections – especially, private property sources; streamway infrastructure subject to inundation; leaking joints in the pipes and manhole (MH) structures; perforated MH lids or MHs with pick holes and/or poor sealing; and root infested or broken sewer laterals (See Figure 2). In sanitary sewers, this can lead to excessive I/I.

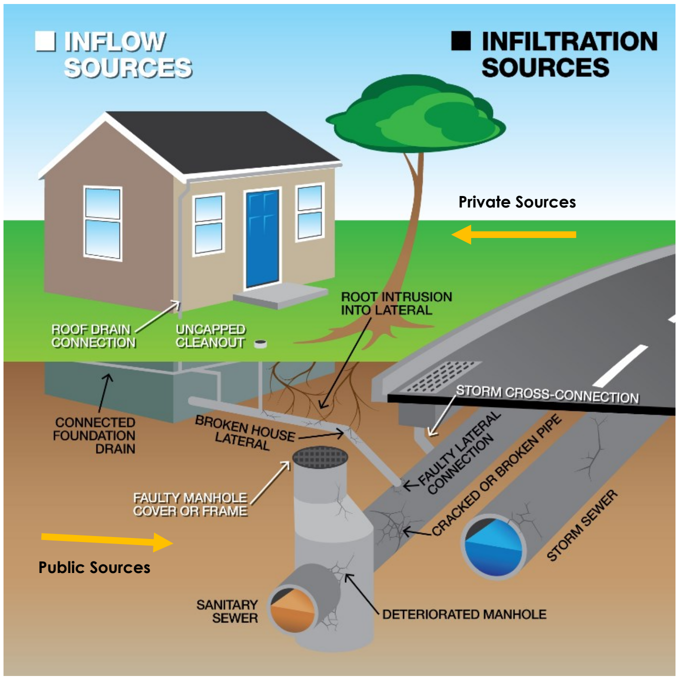

Figure 2: Typical Sources of I/I in Sanitary Sewer Systems (Image from WEF, 2017)

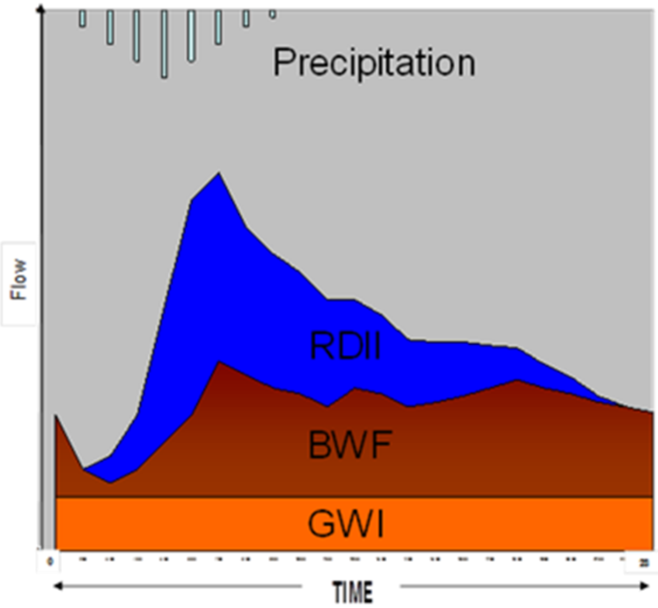

Figure 3: Components of wet-weather wastewater flow during a precipitation event. (US EPA, 2007)

Figure 3 illustrates three distinct components comprising sanitary sewer system flows during a wet-weather event: base wastewater flow (BWF), groundwater infiltration (GWI), and rainfall derived infiltration and inflow (RDII).

BWF, often called base sanitary flow, is the residential, commercial, institutional, and industrial flow discharged to a sanitary sewer system for collection and treatment. BWF normally varies with water use patterns within a service area throughout a 24-hour period. Residential BWF patterns typically exhibit higher flows during the morning and early evening periods and lower flows during the night and early morning hours. BWF patterns can also noticeably vary from weekdays to weekends, and holidays. BWF patterns can be impacted by industrial use that relies heavily on process water (e.g. food processing).

GWI represents the infiltration of groundwater that enters the collection system through leaking pipes, pipe joints, and manhole walls during both dry- and wet-weather conditions. GWI varies throughout the year, often trending higher towards the end of the wet season (or snow melt season in some geographic areas) as groundwater levels and soil moisture levels rise and subside in late summer or after an extended dry period, and some areas may see a decrease during spring bloom.

GWI and BWF together comprise the dry-weather flow (DWF) that occurs in a sanitary sewer system. Because the determination of GWI and BWF components of DWF is not an exact science, various assumptions related to the water consumption return rates and wastewater composition during the early morning hours are typically used to help separate and estimate these flow components.

RDII is the rainfall-derived or wet-weather response component of the total measured hydrograph in a sanitary sewer system during and for a period after a specific rainfall event. In most systems, RDII is the major component of peak wastewater flows and is typically responsible for capacity-related SSO and basement backups. Snow melt may also cause significant RDII flow responses. Levels of RDII can vary in a sewershed from event to event due to antecedent moisture conditions that likely influence the RDII response to a specific rainfall condition.

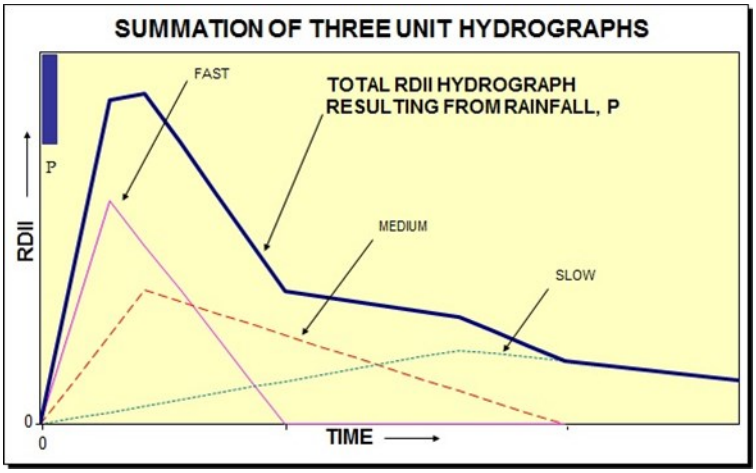

Figure 4: RDII Data Analytics (EPA 2007)

Vendor-provided software or a user's spreadsheet program can help facilitate total RDII estimation, which is performed by subtracting DWF from the total observed flow hydrograph under wet-weather conditions. The real challenge is to develop a RDII understanding that is representative of various rainfall conditions in relation to the pre-event antecedent moisture conditions. Therefore, a system's RDII response must be understood based on multiple rainfall events during the designated flow monitoring period.

Beyond the basic level total RDII estimation, advanced analysis/insights to the RDII hydrographs are needed to develop sewer system hydraulic models for performing capacity assessment and to support focused field investigations for prioritizing sewer condition assessment and define rehabilitation needs. These advanced analyses will help to decompose the RDII hydrographs to characterize fast (inflow), slow (infiltration) and medium (delayed inflow, early infiltration) responses likely with contribution from private property sources (as depicted in Figure 4). Public domain tools such as EPA's Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox allows the users to do this level of comprehensive RDII characterization (known as RTK approach) to support reliable capacity assessment/assurance modeling and to conduct focused field investigations for performing sewer condition assessment. To a degree, this advanced RDII characterization is also offered by some proprietary software from vendors of flow monitoring equipment and sewer modeling software.

Capacity Assessment: The flow monitoring data analytics support the estimation of RDII parameters for application in sanitary sewer collection system hydraulic models. The models are then used to simulate system performance and assess sewer capacity under various operating conditions and meteorological events, which then supports the evaluation of RDII reduction scenarios and hydraulic improvement needs.

Rainfall-RDII simulation modeling techniques vary but generally fall into two broad categories: 1) a physical process approach using rainfall-runoff response algorithms, or 2) an empirical approach simply based on observed rainfall and flow monitoring data to simulate rainfall-RDII response. Selecting a preferred method of estimating RDII responses, and associated hydraulic effects, in sanitary sewer systems depends on the model's intended objectives and preferred technique.

Condition Assessment: RDII characterization data analytics combined with spatial/visual data management/GIS platforms, allow field investigation programs to support reliable condition assessment and subsequent investments in prioritized sewer rehabilitation effort. Proper use of RDII characterization data intelligence improves the cost-effectiveness of time-consuming field investigations and timely return on investment.

The advanced insights provided by RDII analysis and the determination of its characteristic components represented by fast, medium and slow responses is proven to prioritize sub-systems for targeting reduction in inflow, infiltration and private property sources. This discerning approach included in the EPA SSOAP Toolbox allows the deployment of appropriate field investigation techniques and more importantly helps avoid randomness and guess work on expensive and time-consuming field investigations.

Determining efficacy of I/I reduction efforts through pre- and post-remediation I/I assessments: I/I data analytics also provide a basis for re-evaluating characteristic I/I responses within an area of focus before and after RDII reduction efforts to assess the efficacy of the remediation investments. Several practices for pre- and post-remediation efficacy assessment are prevalent in the industry. These practices vary in their level of sophistication, reliability and adaptability to the individual circumstances of a utility.

At a simple level, pre- and post-remediation RDII levels are compared with a known limitation that inherent hydro-geological conditions during pre and post monitoring can influence the comparisons leaving a higher degree of ambiguity. Other techniques in practice add sophistication and rigor to the data analysis by: 1) applying statistical methods that typically use linear and multi-variable regression models; 2) using a combination of flow data analysis and sewer systems model simulations to predict RDII reduction successes; and/or 3) applying more demonstrative process using EPA's control area approach. While an important metric in measuring the success of any program, the selection of a preferred approach and the extent of post-rehabilitation assessment depends on the specific needs of the program; data availability; level of desired sophistication/reliability; and available resources.

Real-time flow assessments to support in-time maintenance and operational optimization: Sanitary sewer system performance optimization is one of the key aspects of the capacity, management, operation, and maintenance (CMOM) program and, as such, is tied to supporting RDII remediation programs. Recent industry trends indicate that many system owners and utilities are eager to adopt technological advances for data driven decision-making that can improve operational efficiencies. These advances include low cost sensors and data storage, connectivity to the internet of things (IoT) for component operation and/or monitoring, faster data communication through advanced wireless networks, and the development of user interface technologies/dashboards. These intelligent sewer platforms integrate key components such as hardware, communications and data management tools that support customized data analytics.

While industry-wide experiences/practices vary, many utilities are reaping benefits from tracking real-time hydraulics performance data at flow/depth meter locations that allow them to make intelligent decisions for real time flow controls towards improving operational efficiency. These practices may involve using intelligent system platforms/dashboards that provide a real-time view on operating conditions; flag operational anomalies; and allow system operators to take preventative measures that can avoid unnecessary sewer spills/overflows as well as maximize the conveyance and treatment of wastewater.

For example, real-time flow/level data monitoring and sewer depth data analytics can lead to early detection of flow backups due to temporary blockages, which can then trigger in-time sewer cleaning to avoid spills/overflows. In addition, the collection of real-time flow/level data in combination with rainfall forecasting and historical operational trends permit the advanced prediction of flow conditions that can lead to better management system flows and wastewater treatment operations. This data, in combination with hydraulic modeling, allows the simulation of a range of hydrologic conditions and can help generate a risk-based understanding of the system performance. As the utility observes real-time developments such as rainfall of a certain volume, actions can be taken based on the simulation results and tolerance for risk at various locations within the system.

Long-term flow trending/profiling: Insights derived from long-term flow and rainfall data analytics are proven to be one of the most critical sewer system management tools to help utilities manage system capacity, understand condition dynamics over time, and adapt to changing conditions. These data analytics are helping utilities monitor and better understand and respond to longer-term changes in sewershed characteristics, condition of aging systems, as well as improved performance through the addition of new sewer assets, asset renewals through I/I reduction/rehabilitation programs, and the implementation of system operational enhancements. Both public domain, commercial and custom developed tools are available to perform flow data analytics for the scope defined by individual utility circumstances. For those utilities with a more advanced digital platform, the long-term data and trending tools are either linked to or integrated into the enterprise-wide asset data management systems.

Evolving Practices: The “state-of-the-art” in flow monitoring practices and data analytical tools/platforms are continuing to evolve as a result of technological advancements by industry-leading equipment manufacturers, increased scale of monitoring and further adaptation of intelligent sewer platforms driven by “big data” integration. It is advised that practitioners stay abreast of these advancements and continually adapt as appropriate.

Acknowledgments

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Additional Resources

This factsheet represents one in a series of complimentary reference documents that WEF is developing with a focus on the topic of infiltration and inflow remediation in sanitary sewer systems. All these publications collectively provide the overall comprehension of various aspects of sanitary sewer system management, including the subject of this fact sheet. The table on the next page provides a list of fact sheets available at the time of issue of this publication.

Additional Resources and Citations	**Related Topics Covered**		
	Monitoring Techniques/ Technologies	**Strategic Planning for Monitoring**	**Data Analysis Techniques/ Analytics**
US EPA. (1975) "Sewer Flow Measurement: A State-of-the Art Assessment" Environmental Protection technology Series, Publication No. EPA-600/2-75-027	✓		
US EPA (1999) Combined Sewer Overflow (CSO) Guidance for Monitoring and Modeling"	✓	✓	✓
US EPA. (2007) "Computer Tools for Sanitary Sewer System Capacity Analysis and Planning.", Publication No. EPA/600/R-07/111		✓	✓
WEF (2009): Existing Sewer Evaluation and Rehabilitation, WEF Manual of Practice FD-6, ASCE Manual and Report on Engineering Practice No. 62, Third Edition	✓	✓	✓
WEF (2011) Prevention and Control of Sewer System Overflows, WEF Manual of Practice No. FD-17, Third Edition	✓	✓	
US EPA (2014) "Guide for Estimating Infiltration and Inflow", EPA New England Water Infrastructure Outreach			✓
US EPA (1991) "Sewer System Infrastructure Analysis and Rehabilitation Handbook", Office of Research and Development, Cincinnati OH, EPA/625/6-91/030		✓	✓
WERF (2003): Reducing Peak Rainfall-Derived Infiltration/Inflow Rates: Case Studies and Protocol; WEFTEC 2004 Session 41 through 50, pp. 485-502, IWA Publishing and Water Environment Federation		✓	✓
WEF (2011) Sanitary Sewers Fact Sheet		✓	
WEF (2017) Sanitary Sewer Systems: Rainfall Derived Infiltration and Inflow (RDII) Modeling Fact Sheet	✓	✓	✓
WEF (2015) Private Property Infiltration and Inflow Fact Sheet	✓	✓	✓
WEF (2017) Sanitary Sewer Rehabilitation Fact Sheet		✓	