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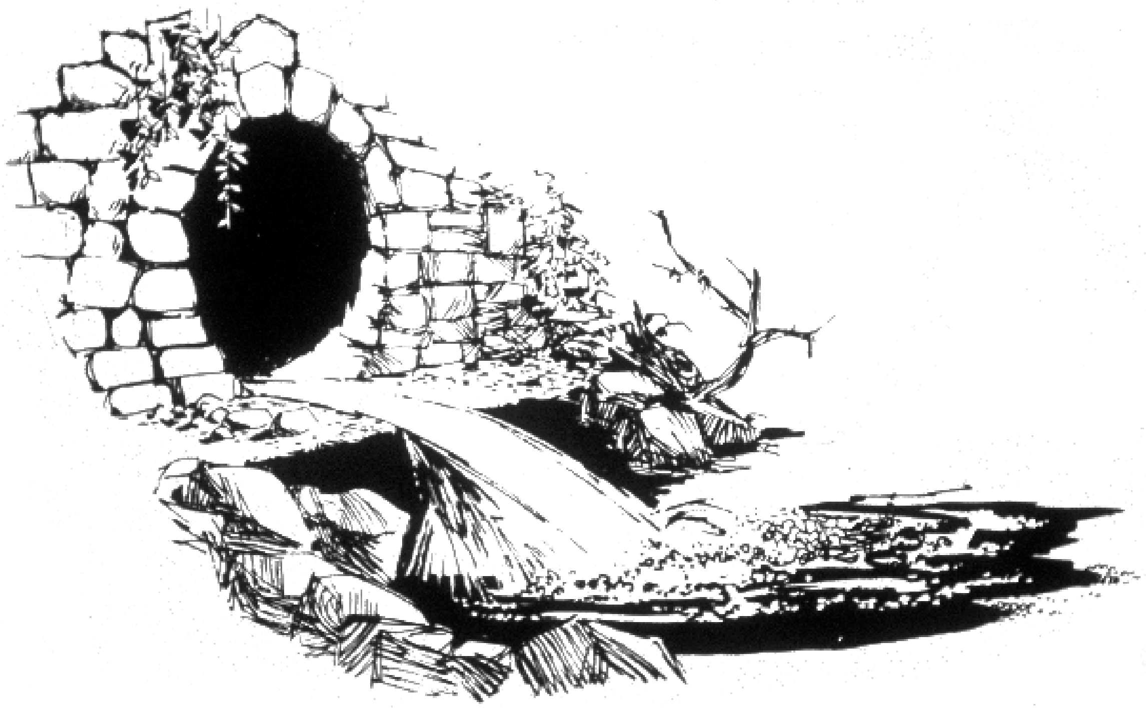
Computer Tools for Sanitary Sewer System Capacity Analysis and Planning



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Computer Tools for Sanitary Sewer System Capacity Analysis and Planning

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Notice

Foreword

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Sally Gutierrez, Director

National Risk Management Research Laboratory

Abstract

A properly designed, operated and maintained sanitary sewer system is meant to collect and convey all of the sewage that flows into it to a wastewater treatment plant. However, occasional unintentional discharges of raw sewage from municipal sanitary sewers – called sanitary sewer overflows (SSOs) – occur in many systems.

Rainfall-derived infiltration and inflow (RDII) into sanitary sewer systems has long been recognized as a major source of operating problems, causing poor performance of many sewer systems. RDII is the main cause of SSOs to customer basements, streets, or nearby streams and can also cause serious operating problems at wastewater treatment facilities. There is a need to develop proven methodologies and computer tools to assist communities in developing SSO control plans that are in line with their projected annual capital budgets and provide flexibility in future improvements.

To accomplish this goal, EPA entered into a cooperative research and development agreement (CRADA) with Camp Dresser & McKee, Inc. (CDM) to develop public-domain software tools to support SSO control planning. These tools, named the Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox, are accompanied by this technical document that describes how to use the Toolbox in analyzing infiltration/inflow, performing capacity analyses of sanitary sewer systems, and developing SSO control plans.

It is the intent of this report to provide the Toolbox users with technical information needed for its effective use for analysis and mitigation of SSO-related problems. The technical report is not intended to serve as the user manual for the SSOAP Toolbox, which is a separate document included with the software package. Instead, it provides an introductory hydrologic approach and identifies a RDII methodology for initial incorporation into the SSOAP Toolbox; an overview of the required sewer system hydraulic analysis; and data collection requirements to support SSO planning and analysis using the SSOAP Toolbox. In addition, the report describes the tools and their functions for performing a sanitary sewer system capacity assessment.

The report also includes a description of the application of EPA's Storm Water Management Model Version 5 (SWMM5) application within the SSOAP Toolbox for assessing the baseline hydraulic conditions of the system and quantifying capacity improvements of various identified improvement scenarios. Guidance is provided for establishing system improvement objectives, screening potential options for improvements, developing improvement scenarios, and using SWMM5 model output to evaluate alternatives. Finally, the report provides a case study that demonstrates how the RDII methodology described in this technical report has been effectively used in SSO planning and analysis.

Table of Contents

List of Tables

List of Figures

Abbreviations and Acronyms

ACO	Administrative Consent Order
BWF	Base Wastewater Flow
CMOM	Capacity, Management, Operation and Maintenance
CSO	Combined Sewer Overflow
DMT	Database Management Tool
DWF	Dry-Weather Flow
FAC	Federal Advisory Committee
FDD	Footing Drain Disconnection
GIS	Geographical Information System
GWI	Groundwater Infiltration
HGL	Hydraulic Grade Line
I/I	Infiltration and Inflow
MDEQ	Michigan Department of Environmental Quality
MG	Million Gallons
MOM	Management, Operation and Maintenance
NPDES	National Pollutant Discharge Elimination System
NWS	National Weather Service
OF	Overflow
O&M	Operations and Maintenance
PSO	Pump Station Overflow
RDI	Rainfall-derived Infiltration
RDII	Rainfall-derived Infiltration and Inflow
RTC	Real Time Control
R,T,K	The R, T, and K parameters in the RTK method for RDII prediction
R-value	Fraction of rainfall volume entering the sewer system as RDII
SCS	U.S. Soil Conservation Service
SSD	SSOAP System Database
SSES	Sewer System Evaluation Survey
SSOAP	Sanitary Sewer Overflow Analysis and Planning
SSO	Sanitary Sewer Overflow
SUH	Synthetic Unit Hydrograph
SWMM	Storm Water Management Model
SWMM5	Storm Water Management Model Version 5
UH	Unit Hydrograph
WERF	Water Environment Research Foundation
WWF	Wet-Weather Flow
WWTP	Wastewater Treatment Plant

Acknowledgements

The authors from Camp Dresser & McKee Inc. (CDM) acknowledge the assistance of EPA Project Officer − Dr. Fu-hsiung (Dennis) Lai and Project Advisor − Mr. Rich Field in successfully executing the Cooperative Research and Development Agreement (CRADA) 216-02. Special thanks are extended to Dr. Lai for his technical participation and valuable suggestions during the development of the SSOAP Toolbox and his detailed review of this report. A significant part of the write-up in Chapter 2 on a literature review of RDII prediction methods was derived from his draft report in support of this CRADA.

Several technical experts within CDM contributed to the preparation of this technical report and the SSOAP Toolbox. CDM's Project Manager/Principal Investigator - Mr. Srini Vallabhaneni has provided oversight and guidance to the team of CDM technical experts and the computer programmers. Mr. Carl Chan provided lead programming support to the tool development. Mr. Ted Burgess provided quality assurance and project advice. In addition, the following CDM technical experts supported the development of the report and SSOAP Toolbox: Mr. Phil Brink, Mr. Terry Meeneghan, Mr. Rod Moeller, Mr. Wayne Miles, Mr. Chuck Moore, Ms. Barbara Moranta, Mr. Ben Sherman, and Mr. Derek Wride. It has been a tremendous effort by each and every one of these individuals in preparing the project work products.

The project team would like to thank the City of Ann Arbor, Michigan, for allowing us to showcase its experiences in SSO analysis and planning. The City's experience demonstrates how the hydrologic and hydraulic methodologies described in this technical report have been effectively used in SSO analysis and planning.

The report content and Toolbox functionality was improved by the review comments of an external technical panel. The project team would like to acknowledge the contribution of five members: Dr. James P. Heaney, University of Florida in Gainesville; Dr. Ken Kerri, California State University at Sacramento; Richard E. Nelson, CH2M HILL; Nancy U. Schultz, CH2M HILL; and Dr. Larry Roesner, Colorado State University.

Chapter 1 Introduction

This technical report accompanies the Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox, a software package developed by Camp Dresser & McKee Inc. (CDM) under a cooperative research and development agreement between between the National Risk Management Research Laboratory of the U.S. Environmental Protection Agency (EPA) and CDM. The SSOAP Toolbox is a suite of computer software tools used to predict rainfall-derived infiltration and inflow (RDII) in sanitary sewer systems and to facilitate capacity analysis of these systems, using EPA Storm Water Management Model Version 5 (SWMM5) (EPA, 2007).

RDII causes operational problems in sanitary sewer systems across the United States. Although sanitary sewer systems are generally designed to accommodate RDII flows during wet weather, these flows often exceed the design allowances. When this occurs, operational problems such as basement floodings, manhole overflows, bypasses to storm sewers and direct discharges to receiving waters from sanitary sewer overflows (SSOs) often result. EPA regards these problems, especially SSOs, as a high priority for corrective action by system owners and operators.

To support the analysis of RDII in sanitary sewer systems and planning of corrective actions to address SSOs, EPA will make the SSOAP Toolbox publicly available free of charge. To those who might find this software package useful, this report provides a technical foundation to understand the intended use of the tool. It also provides an understanding of its underlying technical approach and the role of the software in broader efforts to evaluate sanitary sewer systems and plan improvements. This report is not intended to serve as the user manual for the SSOAP Toolbox, which is included with the software package to be separately released.

1.1 Background and History

A sanitary sewer system is a wastewater collection system, typically owned by a municipality, authority or utility district, which is specifically designed to collect and convey only sanitary wastewater (domestic sewage from homes, and wastewaters from industrial and commercial facilities). Storm water is typically conveyed through a “separate” system. Sanitary sewer systems are not designed to overflow. However, sanitary sewer systems can overflow when the system capacity is exceeded due to wet weather (as a result of RDII), when normal dry-weather flow is blocked for any reason, or when mechanical failures prevent the system from operating properly.

On August 26, 2004, EPA delivered to Congress a report (EPA, 2004) on the impacts and control of combined sewer overflows (CSOs) and SSOs. The report indicates that the occurrence of CSOs and SSOs is widespread, and EPA estimates that between 23,000 and 75,000 SSOs occur each year in the United States, resulting in releases of between 3 billion and 10 billion gallons of untreated wastewater. These events occur throughout the United States and cause or contribute to environmental and human health impacts. Further, the report indicates that there are many existing structural and non-structural technologies that are well-suited for SSO control.

1.2 Regulatory Framework

The 2004 EPA Report to Congress (EPA, 2004) states that: “SSOs that reach waters of the United States are point source discharges, and, like other point source discharges from municipal sanitary sewer systems, are prohibited unless authorized by a National Pollutant Discharge Elimination System (NPDES) permit. Moreover, SSOs, including those that do not reach waters of the United States, may be indicative of improper operation and maintenance of the sewer system, and thus may violate NPDES permit conditions.”

Despite the Clean Water Act prohibition on SSOs cited above, the need for additional regulatory clarification has been suggested, often in the form of an "SSO Rule." To that end, in Fall 1994, EPA initiated a stakeholder process to "address factual and policy issues related to SSOs," and a Federal Advisory Committee (FAC) was formed for this purpose.

In 1995, EPA re-formed the FAC as the Urban Wet Weather Flows Federal Advisory Committee to address SSO issues from a broader water quality perspective. Two subcommittees were established under this committee – one addressed separate storm water issues, and the second addressed SSO issues, which was known as the "SSO Subcommittee."

The SSO Subcommittee held 12 meetings between 1995 and 1999 to discuss SSO policy issues and recommended a number of actions for municipal sanitary sewer collection systems, including development of capacity, management, operation, and maintenance (CMOM) programs and a "closely circumscribed framework for raising a defense for unavoidable discharges."

Since 1999, EPA has focused on SSO problems with compliance assistance and enforcement activities according to the "Compliance and Enforcement Strategy Addressing Combined Sewer Overflows and Sanitary Sewer Overflows," issued April 27, 2000 (EPA, 2000). In addition, EPA was or has been evaluating options for improving NPDES permit requirements for SSOs and municipal sanitary sewer systems.

Although there is no national regulatory program specific to SSOs, a number of EPA regions and state agencies have initiated programs to address SSOs. EPA Region 4's Management, Operation, and Maintenance (MOM) Program is one example, along with state programs such as those in California, Oklahoma, and North Carolina. As these and other programs are implemented, along with updated NPDES permit requirements placed on sanitary sewer systems, it is EPA's intent that the SSOAP Toolbox will become a useful analysis and planning tool for system owners/operators to aid them in addressing SSOs.

1.3 Technical Report Organization

The remaining sections of this document include:

Chapter 2 Hydrologic Approach − An introduction to the sanitary sewer system hydrologic approach, including RDII pathways and mechanisms, and RDII prediction methodologies. This chapter also identifies the initial RDII methodology for incorporation into the SSOAP Toolbox.

Chapter 3 Hydraulic Approach − An overview of sewer system hydraulics and type of sewer hydraulic capacity analysis needed to support SSO analysis and planning.

Chapter 4 Data Collection − A description of data collection needs to support SSO planning and analysis using the SSOAP Toolbox. Guidelines are provided for the collection of information related to system configuration data, and flow and rainfall monitoring data to support RDII analysis and model development.

Chapter 5 Sanitary Sewer System Analysis and Planning (SSOAP) Toolbox − An overview of the SSOAP Toolbox and descriptions of its tools and functions in performing a sanitary sewer system capacity assessment.

Chapter 6 SWMM5 Sewer Flow Routing and Capacity Evaluations − Describes the use of SWMM5 within the SSOAP Toolbox to perform sanitary sewer system capacity assessments. This chapter provides general guidelines on sewer model development and application, and the steps typically used in establishing baseline conditions and performing capacity analysis.

Chapter 7 Development and Analysis of System Improvement Alternatives − Guidance for establishing system improvement objectives, screening potential options for improvements, developing improvement scenarios, and using SWMM5 model output to evaluate alternatives.

Chapter 8 Case Study − Provides a case study that demonstrates how the RDII methodology described in this technical report has been effectively used in SSO planning and analysis.

Chapter 9 References − List of references cited in the report.

Chapter 2 Hydrologic Approach

This chapter provides an overview of sanitary sewer system hydrology and summarizes alternative hydrologic approaches to quantify and characterize the response of sanitary sewer systems to wet weather. Methodologies for RDII prediction and analysis are discussed along with their advantages and disadvantages. This chapter also identifies the specific RDII methodology included in the current version of the SSOAP Toolbox. Finally, a detailed description of the selected RDII methodology is presented.

2.1 Overview of Sanitary Sewer System Hydrology

Sanitary sewer system hydrology is so closely related to urban drainage hydrology that it has effectively become a sub-specialty of what can be termed simply "urban hydrology." Urban hydrology is primarily a study of rainfall runoff in urbanized or urbanizing areas and how much and how often rainfall is captured by a collection system, infiltrates into the soil, or runs off the land surface to receiving waters. Once these questions are answered, engineers turn to the sister science of hydraulics to evaluate resulting water surface elevations and flow velocities − namely, how high water levels will rise, how fast they will flow, and how full sewers will become.

Urban hydrology, as commonly practiced, is an inexact science. It seeks to balance needs for accuracy in making infrastructure decisions against the costs of data collection and continued model calibration. This is also evident with hydrology affecting sanitary sewer collection systems. Therefore, it is important that infrastructure designers have a fundamental understanding of urban hydrology to minimize potential uncertainties and recommend solutions in a cost-effective manner.

Although closely related, the response of a sanitary sewer system to wet-weather conditions differs from that of a storm sewer system. The hydrologic processes for a storm sewer system are more straightforward and understood in which surface runoff creates the predominant response. The hydrologic processes in the sanitary sewer system are not as well understood, nor are they as accurately simulated with the degree of reliability needed for infrastructure improvements. As a result, empirical methods derived from actual flow data are commonly applied to estimate the hydrologic response in the sanitary sewer system, rather than the use of physical processes that are difficult to characterize.

Vallabhaneni et al. (2002) and Wright et al. (2001) discussed various practices in simulating RDII using rainfall-runoff tools. Attempts to simulate the response of a sanitary sewer system to rainfall using rainfall-runoff analysis tools typically yield less reliable results due to inherent differences in the physical process compared with those driving a storm sewer system response. Hence, a customized RDII methodology is developed for analyzing sanitary sewer systems as part of the SSOAP Toolbox.

The three major components of wet-weather wastewater flow into a sanitary system - base wastewater flow (BWF), groundwater infiltration (GWI), and RDII are illustrated in Figure 2-1 and are discussed below.

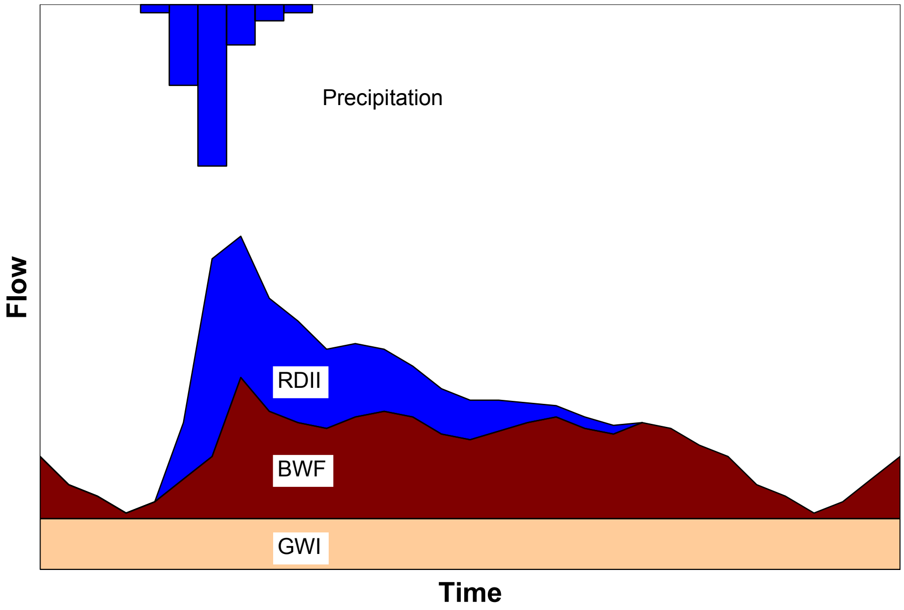


Figure 2-1. Three components of wet-weather wastewater flow.

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 with higher flows during the morning period and lower during the night. In most cases, the average daily BWF is more or less constant during a given day, but varies monthly and seasonally. BWF often represents a significant portion of the flows treated at wastewater treatment facilities.

GWI represents the infiltration of groundwater that enters the collection system through leaking pipes, pipe joints, and manhole walls. GWI varies throughout the year, often trending higher in late winter and spring as groundwater levels and soil moisture levels rise, and subsiding in late summer or after an extended dry period.

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 early morning hours are typically used to help estimate these flows components.

RDII is the rainfall-derived flow response in a sanitary sewer system. In most systems, RDII is the major component of peak wastewater flows and is typically responsible for capacity-related SSO and basement backups. Snowmelt may also cause RDII flows. RDII flows are zero before a rainfall event, increase during the rainfall event, and then decline to zero some time after the rain stops. For cases with less than saturated antecedent moisture conditions, surfaces and soils may take up some of the rainfall early in the event before a response is observed and, if the event is small enough, there may not be a sanitary system response. The maximum amount of rainfall that does not produce a response in the system is termed the "initial abstraction."

Figure 2-2 depicts various pathways of RDII into sanitary sewer systems. "Inflow" is the water that enters the sanitary sewer system directly via depressed manhole lids and frames, downspouts, sump pumps, foundation drains, area way drains and cross-connections with storm sewers. Although direct connections such as downspouts, sump pumps, foundation drains, and areaway drains are no longer common design practices, they still exist and contribute to inflow in many older sanitary systems. Inflow typically occurs shortly after a rainfall starts and stops quickly once it stops. Inflow is typically the major component of the RDII peak flow.

Rainfall-derived infiltration (RDI) refers to rainfall runoff that filters through the soil before entering a sanitary sewer system through damaged pipe sections, leaky joints or poor manhole connections. These defects can occur in both the public right-of-way portions of the sanitary sewer system or in individual service laterals on private property. Infiltration processes typically extend beyond the end of rainfall and takes some time to recede to zero after the storm event. A system may experience a fast RDI response, a slow RDI response, or both.

Figure 2-2. Pathways of infiltration and inflow into sanitary sewer systems.

In areas characterized by soils with high percolation rates, RDI can quickly enter shallow service laterals and sewer system defects, contributing significantly to the peak wet-weather response. RDI is typically the major component of the total RDII volume, especially during periods of high antecedent soil moisture conditions when the recession limb of the wet-weather response can last for several days after the wet-weather event.

The response of a sanitary sewer system is quite complex. Various factors control RDII responses in addition to the rainfall (volume, intensity, and duration) and antecedent moisture conditions, including depth to groundwater, depth to bedrock, land slope, number and size of sewer system defects, type of storm drainage system, soil characteristics, and type of sewer backfill. Further, RDII responses can vary greatly due to spatial rainfall distributions over a sewershed.

2.2 RDII Prediction Methodologies

The ability to estimate RDII flows reliably is critical for developing SSO control plans. The methods presented in this section focus on estimating RDII hydrographs based on flows observed at a point in the sanitary sewer system as monitored by a flow meter. These methods do not require that the number and severity of the defects that allow rainfall runoff to enter the system be determined, though the results can sometimes be used to infer the relative severity of structural defects.

RDII quantification methods require information on the rainfall that fell over the sewershed. The required information varies with specific methodology and may include total rainfall depth, peak intensity, and a complete rainfall hyetograph. The successful application of these methods relies on accurate rainfall and wastewater flow data measurements.

This section also discusses the strengths and weaknesses associated with each RDII prediction method. The goal is to provide an understanding of the available analysis methods and to support the choice of the RDII predictive method(s) for inclusion in the SSOAP Toolbox.

The RDII process and associated data are very much site-specific. No single flow prediction method is likely to be universally applicable. Also, the RDII prediction methods described in this section do not directly account for snow fall and snow melt processes. If analysis of RDII response to snow melt is needed and this is a major concern in defining sewer system improvements, then special procedures may need to be developed to meet project needs. Typically, RDII response to the peak rainfall events establishes the basis for the system improvements rather than snow melt events. In an actual application, however, the objective of the study, as well as the availability of data, time, staff and funding, should be considered when selecting the most appropriate method.

2.2.1 Literature Review Studies

The following summary descriptions of literature review studies and overview of RDII prediction methods are primarily derived from a report prepared by EPA in support of this SSO CRADA that reviewed sewer design practices and RDII flow predictions (Lai, 2007).

A Water Environment Research Foundation (WERF) publication (Bennett et al., 1999) and a conference paper (Schultz et al., 2001) reviewed RDII prediction methods in literature dating back to 1984. Their literature searches included online catalogs at the University of Wisconsin at Milwaukee and Madison. Additional references were identified through contacts with engineering firms and municipal agencies. Forty-two documents were compiled and reviewed in preparing the WERF publication. A detailed discussion on this WERF study is presented in the next section.

In parallel to the 1999 WERF study, Crawford et al. (1999) reviewed three RDII prediction methods: the constant unit rate, rainfall/flow regression, and percent of rainfall volume (R-value). They evaluated merits and limitations of these methods using applications for the City of Salem, Oregon (with a population of about 160,000) and the City and County of Honolulu, Hawaii (population of about 1 million).

Wright et al. (2001) reviewed literature on RDII estimation techniques that have appeared since 1993. They classified the methods into three main groups: the volume-based “rational” method (or R-value method), the unit hydrograph method, and the physical processes modeling method. The paper discussed various unit hydrograph methods, including:

- Synthetic unit hydrograph, in which the shape of the hydrograph is pre-defined
- Data-derived unit hydrograph, which uses multiple regressions to derive the ordinates of a unit hydrograph directly from measured rainfall and RDII flow data
- Conceptually derived unit hydrograph, which uses a system of cascading linear reservoirs.

The 1999 WERF study identified eight broad categories of RDII quantification methods. Three cooperating municipal agencies tested these methods against monitored rainfall-flow data: the Metropolitan Council of Environmental Services, St. Paul, Minnesota; the Bureau of Environmental Services, Portland, Oregon; and the Montgomery Water Works and Sanitary Sewer Board, Montgomery, Alabama. The eight described methodologies were:

1. Constant unit rate method
2. Percentage of rainfall volume (R-value) method

3. Percentage of stream flow method
4. Synthetic unit hydrograph method
5. Probabilistic method
6. Rainfall/flow regression method
7. Synthetic stream flow regression method
8. Methods embedded in hydraulic software

The 1999 WERF study concluded that in practice, any of these RDII prediction methods should be used with the site-specific database of rain and flow observations during both wet and dry periods. However, no one method was likely to be universally applicable because of a variety of site conditions and analysis application needs. The study identified criteria that are used to test the alternative RDII prediction methods using flow and rainfall data supplied by the three cooperating sewer agencies. Specifically, the methods should be able to:

- Predict peak flow for individual storms
- Predict volume for individual storms
- Predict the hydrograph timing, shape, and recession limb
- Predict peak flows for multiple storms
- Predict volume for multiple storms
- Operate on commonly available data

Because the characteristics of the available data vary among the cooperating sewer agencies, the collected data were not applicable to all eight RDII prediction methods considered in 1999 WERF study.

Another important criterion is the adaptability of the analysis and RDII prediction methods to guide rehabilitation programs, and to develop and assess alternative corrective measures. This criterion was not explicitly considered in the 1999 WERF study, but it is included when selecting the RDII methodology to be included in the SSOAP Toolbox.

2.2.2 Overview of RDII Prediction Methodologies

The following section discusses the strengths and weaknesses of each of the alternative RDII prediction methodologies primarily derived from a companion literature review report prepared by EPA in support of this CRADA (Lai, 2007).

The **constant unit rate method** calculates RDII as a constant unit rate based on sewershed characteristics. The unit RDII rates (e.g., gallons per inch of rainfall per acre; gallons per acre land use; gallons per capita; gallons per inch-diameter-mile) from sewersheds are estimated based on flow and rainfall monitoring and sewershed characteristics. RDII is calculated by multiplying RDII unit rates with respective to tributary sewershed characteristics (including area, land use, population, and pipe diameter/length/age) to derive RDII. The constant unit rate method is simple to apply and can help predict RDII volume for unmonitored conditions. However, it is difficult to develop reasonable estimates of unit rate constants, which may vary by storm, antecedent moisture, and season. The method also lacks the capability of developing hydrograph timing and its shape.

Crawford et al. (1999) based their evaluation of the constant unit rate method on data applications for the City of Salem, Oregon, and the City and County of Honolulu, Hawaii. They concluded that peak hourly RDII rates per acre from a five-year storm increase significantly as the average age of sewer pipes increases from 10 to 30 years. To overcome this limitation they suggested that unit RDII rates should increase with the age of the sewer system.

The **constant unit rate method** is suitable for simple applications, such as sizing conveyance facilities for relatively frequent storms, provided there is available rainfall and wastewater flow data from a similar sewershed or sewersheds. If data are not available, precipitation gauges and wastewater flow monitors can be installed with a reasonable level of effort to obtain the needed information.

However, for more complex applications that require multiple storms in multiple sewersheds of varying ages to be analyzed, for the evaluation of major trunk sewer system where the timing causes peak flows to not be additive, or for applications requiring the development and assessment of flow equalization facilities where hydrograph timing and shape are needed, this method is insufficient. It also would not provide adequate information for sewer rehabilitation programs in which sewersheds and predictions of potential RDII flow reduction must be prioritized.

A subset of this method is the method where peak flows are correlated against peak rainfall intensities for observed events. Through this correlation, it may be possible to estimate peak flows of a given return period based on the rainfall frequency. Caution must be used in correlating the return periods of peak rainfall and peak flows. The data will typically be widely scattered due to various factors including antecedent moisture conditions, rainfall distribution, errors in peak flow measurement, and the inability to accurately determine the rainfall intensity over the whole sewershed. Furthermore, unit rates developed for relatively small and frequently occurring storms observed in a typical flow monitoring program cannot be reliably extrapolated to estimate peak flows for infrequently occurring storms such as the two-, five- or 10-year design storms.

The **percentage of rainfall volume (R-value) method** calculates RDII volume as a fixed percentage of the rainfall amount. This method is more adaptable than the constant rate method, in that it accounts for seasonal effects and multiple sewershed types and ages as long as corresponding monitored rainfall and wastewater flow data are available. The R-value is relatively easy to calculate from flow monitoring and rainfall data, and can be used as a guide to determine the relative number and size of RDII defects within a particular sanitary sewer system.

However, this method is unable to estimate peak flows or hydrograph timing and shape. Thus, it should be cautioned when this method is used to calculate the peak flow capacity of sanitary sewer facilities or to model peak flows in sanitary sewer systems. As in the case of all other RDII methodologies, one needs to understand that this method makes simplified assumptions about the complex physical processes that affect RDII volume and the rate at which it enters sanitary sewers.

Regression analysis plots for observed RDII volumes and rainfall depths often show a wide scattering of the data points. Antecedent moisture conditions significantly affect the RDII response to rainfall events. When attempts are made to extrapolate the calculated R-values for frequent storms that are typically occur in monitoring period to an infrequent storm such as a 10-year design storm, even the slightest change in the slope of the regression line can significantly impact the predicted R-value. A monitoring program typically captures flows from low-intensity, low-volume storm events that are less than the one-year return period rainfall volume. Care must be taken when extrapolating these values to estimate flow volumes for high-intensity, high-volume design storm events, such as a five- or 10-year storm.

In using the R-value method to estimate RDII rates for high intensity and less frequent storms, Crawford et al. (1999) cautioned that the R-values should be appropriately tapered to account for the upper limit of peak flows that leaky sewers can take in. This consideration recognizes that there is a limit to the peak flow capacity of inflow connections, leaky manholes, and other sewer system defects. The inflow rate to the system cannot exceed the capacity of the defects. The conveyance capacity of the upstream sewers also limits the observed volumes.

The R-value method is suitable for applications requiring the determination of volume estimates for multiple storms, multiple sewershed types and ages, and seasonal impacts as long as there is corresponding precipitation and wastewater data. This method is also useful in identifying the relative magnitude of infiltration and (through inference) the extent and severity of defects between metered areas. Note that to develop an accurate R-value estimate, only the sewered portion of the flow meter tributary area must be taken into account. When making comparisons of R-values among the metered areas, it is important that a consistent measure of “sewered” area be used in estimating the R-value. This method readily uses existing available rainfall and monitored sewer flow data. If additional monitoring data are needed, supplemental gauges and meters can be installed. Rainfall data can also be supplemented with radar rainfall estimates to better determine the rainfall that fell over the upstream sewershed.

This method is insufficient for sizing conveyance and storage improvements where hydrograph timing, peak flows, and shape are needed.

The **percentage of stream flow method** is similar to the previous rainfall method, but it uses gauged stream flows in nearby watersheds as an independent variable. This method recognizes that stream flows inherently account for the effects of antecedent moisture conditions that influence groundwater levels and resulting GWI in sewers. Therefore, a relationship can be developed between stream flow and sewer flow data. Realistically, the percentage of stream flow method is only applicable for relatively rare cases in which stream gauge data are available in watersheds with basin characteristics similar to the sewersheds being analyzed. Establishing a new stream gauging station is much more demanding and labor intensive than installing a wastewater flow monitor in a sewer. Another problem with this method is that a sewershed may be much smaller than a gauged streamshed, and the scaling factors can produce non-representative analytical results. Again, care should be applied when extrapolating relationships between sewer and stream flow to less frequent rainfall events as the stream has a higher capacity to accept and convey flows than a sanitary sewer system. In addition, where sewer system problems are predominantly driven by the inflow portion of RDII, direct correlation of stream flow and sewer flow data offer limited benefit in characterizing and predicting total RDII.

One variation on this approach is to use a stormwater hydrologic model to simulate stream flows and then correlate these modeled stream flows to the flows observed in the sanitary sewer, as described in the synthetic stream flow regression method.

The **synthetic unit hydrograph method** assumes that RDII in a sewer responding to rainfall can be quantified and characterized via classical unit hydrograph techniques used to analyze storm water runoff in a watershed. The method calculates the RDII hydrograph from a specified unit hydrograph shape that relates RDII to unit precipitation volume, specified time duration and sewershed characteristics. In classic watershed analyses, a unit hydrograph is defined as the direct runoff hydrograph resulting from a unit depth of excess rainfall (e.g., 1 inch or 1 mm, produced by a storm of uniform intensity and specified duration over a watershed). It was first proposed by Sherman (1932) for flood estimation, and has since found wide-ranging applications in surface water hydrology. For surface water applications, unit hydrographs are generally derived from stream flow data and estimates of rainfall excess. The unit hydrograph is applied to the hyetograph of rainfall excess to estimate the surface runoff hydrograph. The method is adapted for sanitary sewershed analyses in which the unit hydrograph is related to the sewer system RDII response to a unit depth of rainfall over the sewershed.

There are three families of unit hydrographs: the synthetic unit hydrograph (SUH), in which the shape of the hydrograph is pre-defined; the data-derived unit hydrograph, which uses multiple regressions to derive the ordinates of a unit hydrograph directly from measured rainfall and RDII flow data; and the conceptually derived unit hydrograph, which uses a system of cascading linear reservoirs.

The simplest SUH has a triangular shape and many formulations, such as that used in SWMM5 (EPA, 2007). Huber and Dickenson (1988) used three unit hydrographs to account for fast, medium, and slow RDII responses. SWMM uses what is known as the RTK curve-fitting method, where R is the fraction of rainfall volume entering the sewer system as RDII during and immediately after the rainfall event, T is the time to peak, and K is the ratio of the time of recession to T. The R, T, K (RTK) method was first developed for an RDII study for the East Bay Municipal Utility District in Oakland, California (Giguere and Riek, 1983). The method, which was included as an option in the SWMM Runoff Block (Huber and Dickenson, 1988), is probably the most popular SUH method due to its applicability to analyze RDII response to rainfall. Since the three unit hydrographs distinctively represent the quantitative contribution of inflow and infiltration to the overall RDII hydrograph, the RTK method can be used to estimate RDII reduction from selected rehabilitation methods by applying a reduction factor to the RDII and GWI hydrographs. The method also provides information on the relative magnitude of rapid infiltration and long-term infiltration in determining the peak flows and total RDII volumes.

The data-derived unit hydrograph (UH) is not based on calibration methods like the RTK method. Instead of beginning with an assumed shape characteristic, the data-derived UH is a linear transform function completely derived from measured data. Namely, it derives the ordinates of a unit hydrograph directly from measured rainfall and RDII flow data using multiple linear regression or linear programming techniques. The goal is to find a vector of unit hydrograph ordinates that minimizes the difference between the time series of measured flow and the estimated flows.

Unit hydrograph methods may also be derived using a system of cascading linear reservoirs where a unit pulse of precipitation is routed through reservoirs characterized by a linear storage-discharge relationship. The cascading reservoir approach provides an important conceptual link between purely empirical methods and physically based conceptual models such as SWMM, which uses the non-linear reservoir approach and the continuity and momentum principles. As with the data-derived UH method, the reservoir parameters use some optimization techniques, such as linear least squares regression or linear programming. The reservoir parameters may be constrained to derive physically realistic values when linear programming is used. Wright et al. (2001) reported that physically unrealistic values (i.e., negative UH ordinates) may be derived from an unconstrained ordinary regression method.

In summary, the unit hydrograph method is suitable for complex sewershed analysis applications requiring multiple storms, multiple sewershed types and ages, and system response hydrograph timing and shape. The method also accounts for the seasonal response of sewer systems to wet-weather conditions as long as corresponding precipitation and wastewater data are available. The method can be used to rank relative sewershed leakiness and prioritize sewer system rehabilitation efforts, and can estimate RDII reduction from selected rehabilitation methods by applying appropriate reduction factors to the RDII and GWI hydrographs. All three unit hydrograph methods can be adapted to a wide range of applications and needs. However, the three methods differ greatly in the quantity of monitored data required and the level of effort and skill needed to apply them.

An analyst can learn to calibrate a series of three triangular unit hydrographs using monitored rainfall and wastewater flow data in a relatively short period of time. However, because the data-derived UH and cascading reservoir methods require larger quantities of monitored data, the analyst must apply multiple linear regression or linear programming techniques. Experience has shown that the additional level of complexity, effort, and cost required by the latter two UH methods typically are not justified by a limited increase in the level of accuracy or precision in the analysis.

With the SUH method, the analyst should exercise care when extrapolating the sewer system RDII response that is determined during a limited flow monitoring period to an unmonitored, large, and infrequent storm, such as a two-, five- or 10-year design storm. Statistical methods complementing the RTK approach are available to extrapolate the RDII response quantified from monitored conditions to unmonitored conditions (natural and synthetic). Vallabhaneni et al. (2002a) reported a successful statistical model with multi-variable regression developed using the results of a RTK analysis for a range of monitored flow conditions. This statistical model was developed based on the observed R-value relationship with event rainfall depth, antecedent one-month precipitation, and GWI. The resulting regression equation was then applied to predict RDII for unmonitored conditions. The statistical model yields reliable results only when the input to the model was consistent with the observed interdependency among the variables during the monitoring conditions. Analysts must ensure that extrapolated R-values take into account the physical reality that there is an upper limit to the peak flows that leaky sewers can accommodate.

The **probabilistic method** uses probability theory to calculate the RDII of a given recurrence interval from long-term records of peak wastewater flows. Various statistical approaches that analyze peak stream flows and rainfall intensities can be used in the statistical analysis of peak wastewater flows. This method is valuable because it is becoming quite common for municipalities to assess sanitary sewer system hydraulic performance using a large and infrequent synthetic storm event, such as a two-, five- or 10-year design storm. While the probabilistic method can predict peak daily RDII flows for large, infrequent storms, the method's accuracy deteriorates rapidly if a long-term dataset in the order of 10 to 25 years is not available. In general, many sanitary sewer systems can not afford to collect monitoring data for such extended periods.

The probabilistic method is well suited for applications that require the characterization and quantification of peak sanitary sewer flow associated with a specific recurrence interval. However, it does not provide flexibility in assessing multiple storms, multiple sewershed types and ages, and seasonal impacts. The method is also not suitable for applications that require hydrograph timing and shape.

The **rainfall/flow regression method** calculates peak RDII flows from rainfall data and provides a means of determining the shape and magnitude of a RDII hydrograph. This regression, expressed as an equation, is derived from rainfall and flow monitoring data in sewers using multiple linear regression methods and considering dry and wet antecedent conditions. Regression equations have stated limits in their parameter ranges and will have even larger errors for sanitary sewersheds that are atypical in construction, slope, age or condition.

Crawford et al. (1999) used regression equations derived from winter data to produce a good match between the monitored and equation predicted hydrographs from other winter storms. However, when they applied the regression equations to summer and early fall storms, they observed large discrepancies between observed and equation predicted flows. To overcome this limitation, they suggested developing a separate series of regressions to represent the seasonal nature of RDII processes. Hence, adequate and representative rainfall and flow data are prerequisites for a successful application of the regression method.

This method provides an alternative to the probabilistic method for projects requiring analysis of sanitary sewer collection systems for specific design storms. It has a greater flexibility for a wider range of applications than the probabilistic method, but it requires the same long-term record of monitored precipitation and wastewater flow to be effective.

In the **synthetic stream flow regression method**, RDII is calculated from synthetic stream flow records and sewershed characteristics using regression equations derived from multiple regression techniques to correlate watershed hydrologic responses to sewer flow responses, specifically infiltration portion of RDII. The synthetic stream flow records typically are generated using calibrated hydrologic simulation models. The 1999 WERF study reported that this method was successfully applied in Milwaukee for sewerage system improvement planning. However, it requires a calibrated watershed runoff model, which often does not exist for many sanitary sewer system improvement projects unless special efforts are invested.

Finally, **methods embedded in publicly or commercially available hydraulic modeling software** use one or more of the prediction methods discussed previously. The most notable is the SWMM program, which incorporates the synthetic unit hydrograph method in its codes. A number of commercial software packages use the SWMM computational engine and therefore use the RTK method. Further, the RTK method has been incorporated into non-SWMM based commercial modeling packages.

Many of the model applications in the sanitary sewer system studies are derived from modeling tools and methods originally developed to simulate stormwater runoff. In many cases, the models used for land surface runoff have been applied to model RDII. As an example, the hydrologic model parameters such as area, width, and roughness are used to simulate flows using kinematic wave procedures as programmed in SWMM and other commercially available models. These models have been used to simulate observed RDII flows. The total runoff area and the runoff capture coefficient can be adjusted to match the observed RDII volumes. The width, slope, and roughness can also be adjusted to calibrate the model to the observed flow pattern. This method is related to the synthetic stream flow method, except that the model parameters are calibrated directly to the observed wastewater flows. One drawback of this method is that it is not possible to conceptually correlate the model parameters to the physical characteristics of the sewers and sewer defects that produce RDII. As with any of the models, caution must be used when extrapolating the models calibrated to frequently occurring observed events to design storms that occur less frequently.

2.2.3 Recommendation of RDII Method for SSOAP Toolbox

From the previously discussed literature review, it can be concluded that there is no single RDII prediction method that is universally applicable. Rainfall and flow observations include a wide variety of site-specific characteristics.

All methods require monitored data to evaluate and validate predictive capabilities. However, the amount of data required varies.

Sewer routing models are used to extrapolate RDII predicted from the limited monitored data to predict flows under future build-out conditions. These models rely on the RDII prediction methods in conjunction with appropriate DWF and GWI projections to develop representative inflow hydrographs at various entries of a sewer system. Hence, the selected RDII prediction method must be amendable for estimating current sewer flows and projecting how sewer flows will change in response to sewer system expansion and aging, and RDII control measures. As stated earlier, the 1999 WERF study concluded that the SUH and rainfall/flow regression methods were preferred for predicting flows for single as well as multiple storm events. The ability of good multiple-storm peak and volume prediction is important in extrapolating data beyond the calibration events for a prolonged period simulation, which is essential for evaluating the effect of RDII on storage and treatment requirements.

Both SUH and rainfall/flow regression methods are empirical methods with parameters calibrated by observed rainfall and sewer flow data. Both have been widely applied and are successful in the RDII source identification and quantification (peak, volume, and time series) in developing a sewer system/treatment improvement plan. The rainfall/flow regression methods will be attractive if there are two or more years of extensive (both temporal and spatial) rainfall and flow data to develop several sets of equations to reflect seasonal influences for dry and wet antecedent and groundwater conditions.

Since regression equations relate the RDII rate to the preceding rainfall amounts corresponding to various time periods (e.g., one hour, two to three hours, four to six hours, seven to 12 hours, 12-24 hours, one to two days, four to seven days, and seven to 15 days) through a series of coefficients, antecedent moisture and groundwater elevations are implicitly embedded in the coefficients determined by the regression analysis. It is difficult to quantify and identify if the RDII problems are caused by inflow, infiltration or both.

On the other hand, the RTK method (one kind of the SUH method) uses up to three triangular unit hydrographs to represent the various ways that precipitation contributes to RDII. The RDII volumes of three unit hydrographs are designated as R_1, R_2 and R_3. A high R_1 value indicates that the RDII is rapidly responding and presumably inflow driven. If more of the total R-value is allocated to R_2 and R_3, this indicates that the RDII is more slowly responding and presumably infiltration driven. This knowledge is useful during a sewer system evaluation survey (SSES) to determine the best SSES approach to use in a particular area, as well as whether a point repair or a comprehensive rehabilitation approach may be more suitable.

The UH approach used in the RTK method is a common method for generating a hydrograph from a rainfall record based on linear response theory. One benefit of using a UH technique to determine rainfall responses in a sewer system is that the technique can analyze RDII flow from storms that have complex patterns of rainfall intensities and durations. The RTK method has been included as an option in SWMM4 and SWMM5, and it has been widely used and proven as a valuable method in separate sanitary sewer system analysis associated with storm events (Giguere and Riek, 1983; CDM et al., 1985; Miles, et al., 1996; Vallabhaneni, et al., 2002a).

In conclusion, the synthetic unit hydrograph method, or RTK method, was selected as the primary hydrologic analysis approach for the SSOAP Toolbox during its initial development. The method is widely used and can analyze and predict RDII in sanitary sewer systems. It has demonstrated flexibilities for a wide range of project needs. As long as corresponding precipitation and wastewater data are available, the method is capable of complex analyses involving peaks and volumes of multiple storms and multiple sewershed types and system ages. The RTK method can account for system response hydrograph timing and shape and seasonable responses of sewer systems to wet-weather conditions. The method can also be used to guide sewer system rehabilitation efforts and estimate the RDII reduction from selected rehabilitation methods.

The probabilistic method and rainfall/flow regression method show promise as supplemental approaches for the future enhancement of the SSOAP Toolbox. These alternatives are well suited for analysis applications requiring the characterization and quantification of sanitary sewer flow associated with a specific recurrence interval event. As long as a sufficient record of rainfall and monitored sewer flow data is available, these methods are viable future options for future SSOAP releases.

2.3 RDII Unit Hydrograph Method

The SSOAP Toolbox uses the RTK method to derive the sanitary sewer system RDII response using the associated rainfall and flow monitoring data. The Toolbox enables users to estimate R,T,K parameters for each rainfall/flow monitoring event and generate corresponding RDII hydrographs. The user has the choice of exporting the RDII hydrographs directly into SWMM5 from the Toolbox or inputting R,T,K values into the SWMM5 input file and generating RDII hydrographs within SWMM5. Alternatively, the user can export the RDII hydrograph from the Toolbox to incorporate into other hydraulic analysis tools. Both SWMM5 and the SSOAP Toolbox have similar computational routines to develop RDII hydrographs using the RTK method. Some commercially available sewer hydraulic modeling programs now allow users to simulate flows using the RTK unit hydrographs, and they can use the RDII hydrograph generation tool in the SSOAP Toolbox.

The RTK method is similar to unit hydrograph methods that are commonly used to simulate flows in storm water runoff analyses. This method is based on fitting three triangular unit hydrographs to an actual RDII hydrograph derived from flow meter data. A unit hydrograph is defined as the flow response that results from one unit of rainfall during one unit of time. Figures 2-3 through 2-5 depict the RTK method and how RDII hydrographs are generated.

Figure 2-3 depicts the triangular unit hydrograph in response to one unit of rainfall over one unit of time. This unit hydrograph is described by the following parameters:

R: the fraction of rainfall volume that enters the sewer system and equals the volume under the hydrograph
T: the time from the onset of rainfall to the peak of the unit hydrograph in hours
K: the ratio of time to recession of the unit hydrograph to the time to peak
A: sewered area
P: rainfall depth over one unit time
Volume: volume of RDII in unit hydrograph
Q_p: peak flow of unit hydrograph

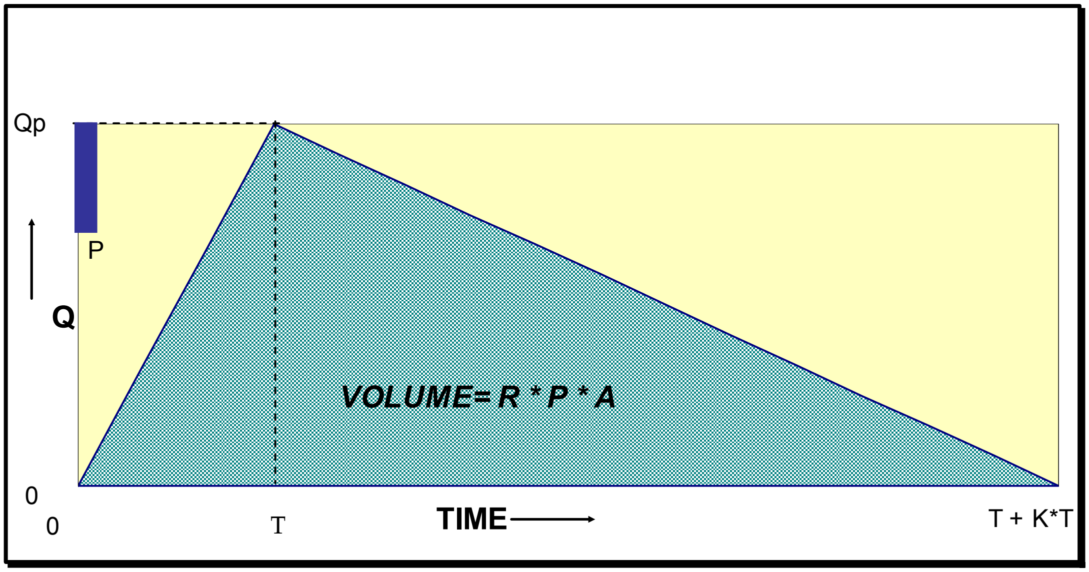


Figure 2-3. Example of a triangular unit hydrograph.

This RTK hydrograph generation method performs has two basic steps, and are illustrated in Figures 2-4 and 2-5. The first step is to define R,T,K parameters in response to one unit of rainfall over one unit of time. Three unit hydrographs are typically used because the shape of an RDII hydrograph is too complex to be well represented by a single unit hydrograph as shown in Figure 2-3. The RDII hydrograph can be generated using less than three sets of R,T,K. However, experience indicates that it often requires three unit hydrographs to adequately represent the various ways that precipitation becomes RDII. The first triangle represents the most rapidly responding inflow component, and has a T of one to three hours. The second triangle includes both rainfall-derived inflow and infiltration, and has a longer T value. The third triangle includes infiltration that may continue long after the storm event has ended and has the longest T value. In this first step, the R,T,K parameters for each of the three triangles are defined for each unit rainfall over one unit time frame. The sum of the R values for each of the three unit hydrographs (i.e., R_1, R_2, and R_3) must equal the total R value for the rainfall event. Figure 2-4 below depicts a summation of three unit hydrographs into a total RDII hydrograph in response to one unit rainfall over one unit time frame.

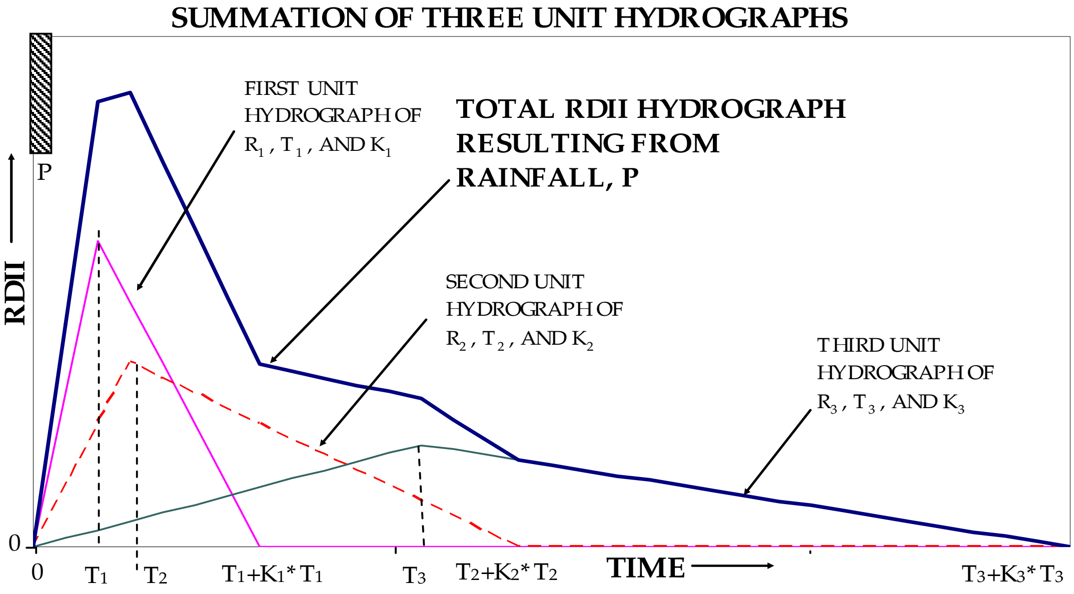


Figure 2-4. Summation of three unit hydrographs.

The unit hydrograph parameters in Figure 2-4 can be described as follows:

T_1, T_2, and T_3: time to the peak of respective unit hydrographs

K_1, K_2, and K_3: recession coefficients of the respective unit hydrographs

$T_1+K_1*T_1$: last time unit of the first unit hydrograph

$T_2+K_2*T_2$: last time unit of the second unit hydrograph

$T_3+K_3*T_3$: last time unit of the third unit hydrograph and the total unit hydrograph

R_1, R_2, and R_3: R-values of respective unit hydrographs; $R = R_1+R_2+R_3$

The second step of the unit hydrograph methodology is to sum all of the RDII unit hydrographs that were developed for each unit of time within a rainfall event to develop a total event RDII hydrograph. Figure 2-5 illustrates the summation of three hydrographs as an example rainfall event. This would represent the hydrograph from a rainfall event lasting three unit time steps. If a rainfall event has rainfall duration is two hours with a 15-minute unit time step, then the hydrograph developed by this method would be the summation of the 24 unit hydrographs that resulted from each 15-minute rainfall increment.

A description of parameters shown in Figure 2-5 is as follows:

P_1, P_2, and P_3: successive rainfall depths over each unit time step

Total Hydrograph: summation of synthetic hydrographs for each unit rainfall

The SSOAP Toolbox automatically sums the unit hydrographs to derive the total RDII hydrograph for a sewershed and selected rainfall events.

The toolbox provides graphical tools and statistical comparisons of predicted and observed peak flows and flow volumes to assist the users in identifying the combination of R, T, and K values that best match the simulated hydrograph with the observed RDII hydrographs. This is accomplished by a curve fitting procedure. In this procedure, the flow monitoring data is first decomposed into the DWF and RDII components. Then the DWF component is subtracted from the total hydrograph to derive the RDII component. The best combination of the R, T, and K values for each of the three triangular unit hydrographs is determined iteratively until the derived RDII hydrograph closely approximates the observed RDII hydrograph.

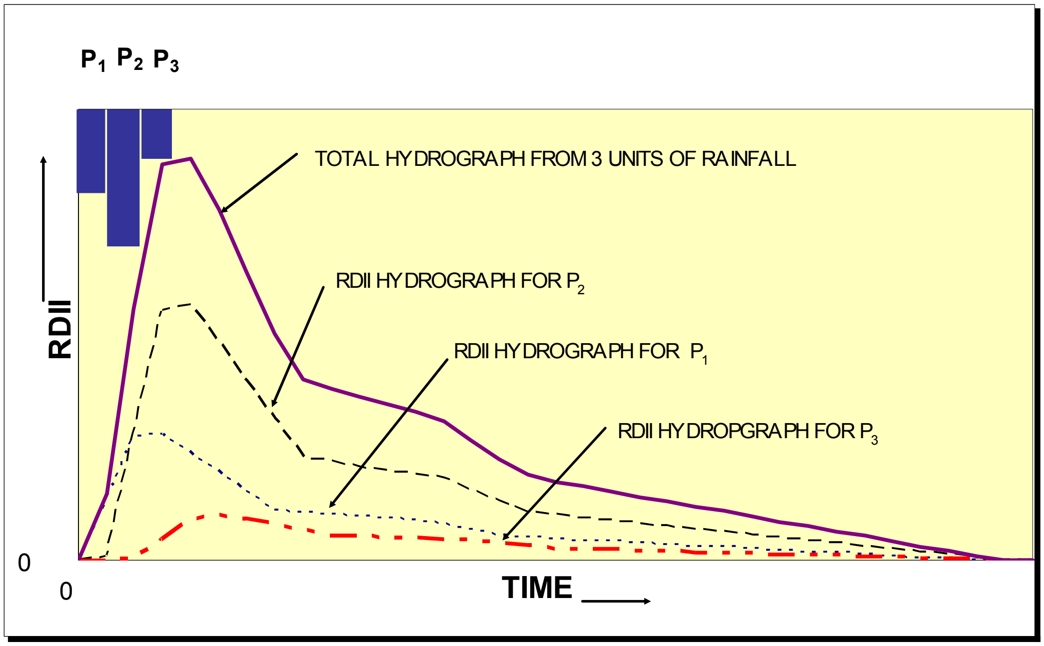


Figure 2-5. Summation of synthetic hydrographs.

Once developed, the RTK unit hydrograph parameters and the rainfall hyetograph of interest can be used to define the RDII inflow hydrograph for sanitary sewer system flow evaluations using hydraulic simulation methods described in Chapter 3.

Chapter 3 Hydraulic Analysis

This chapter provides an overview of sanitary sewer system hydraulics. The SSOAP Toolbox includes linkage to the SWMM5 software to provide the hydraulic analysis function in support of sewer system analysis and planning.

The SSOAP Toolbox functionality is applicable to analyzing wet-weather flow in sanitary sewer systems as opposed to combined sewer or storm sewer systems, for which the wet-weather response mechanisms are very different. However, despite different wet-weather response mechanisms, many of the hydraulic concepts that apply to sanitary sewers also apply to combined and storm sewers.

Because of the closely related nature of the SSOAP Toolbox analytical capabilities and the hydraulics of sewer systems, this chapter is included as background. However, it is only intended to introduce the concepts and provide references to other sources for more detailed information on these topics.

3.1 Overview of Sanitary Sewer System Hydraulics

Sanitary sewer systems are generally constructed as a network of pipe conduits ranging in size from 8 inches in diameter up to 8 ft (or even larger) at the downstream end of large networks. Most systems drain by gravity to the terminus at a wastewater treatment plant. However, where system configuration and topography do not allow for gravity flow conditions, pump stations and force mains are used to deliver flow to the plant or to a point in the system where gravity drainage is available. In some relatively rare cases, such as typically very flat areas and areas where subsurface conditions preclude the use of gravity sewers, pressure systems are used for wastewater collection and transport.

Flow conditions in sanitary sewers vary and are unsteady and non-uniform. During dry-weather conditions, flow in gravity flow portions of sanitary sewer systems generally are designed with the water surface at less than pipe crown, i.e., free-surface flow. This flow may be either sub-critical or super-critical. During wet-weather, flows typically increase, often significantly. Free-surface pipe flow may give way to surcharge flow conditions where pipes are full and under pressure. After the wet-weather event, surcharge flow conditions typically transition back to free-surface flow conditions. The three basic flow regimes – sub-critical, super-critical, and surcharge and the transitions between them – are depicted graphically and described in detail in Yen (1986).

Analyzing surcharge flow conditions is particularly important to SSO planning, as it is typically surcharge conditions that give rise to SSOs and other operational problems in sanitary sewer systems. Also during wet weather, it is common for backwater conditions to develop in sanitary sewers. Backwater conditions often significantly influence the water surface profile in the sewer, which can lead to SSOs and other problems when the water surface rises beyond critical elevations (e.g., SSO weir crests). The analysis of backwater conditions is aided by using steady flow backwater curves to classify backwater surface profiles as mild, steep, critical, horizontal and adverse. A detailed discussion of backwater curves can be found in Chow (1959).

3.2 Analysis Methods: Static, Kinematic, and Dynamic

Flow in sanitary sewer systems is unsteady, but may in some cases and for some purposes be treated as steady flow. However, in most cases the rapid changes in sanitary sewer flows that occur in response to wet weather require dynamic routing rather than static (steady-state) analysis methods.

Dynamic (unsteady flow) analysis may be performed at varying levels of complexity, ranging from relatively simple methods using kinematic wave approximations to those that apply the full dynamic wave (St. Venant) equations for continuity and momentum. Kinematic wave and other simplified forms are derived by dropping terms from the full dynamic wave equation. A complete discussion of the unsteady flow equations can be found in a number of references. One of the most often cited is Lai (1986).

The discharge (conservative) form of the momentum equation is commonly written (Yen, 2004) as:

$$\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{1}{gA}\frac{\partial}{\partial x}\left(\frac{\beta Q^{2}}{A}\right)+\cos\theta\frac{\partial h}{\partial x}-S_{o}+S_{f}=0$$

where:

x = longitudinal direction of sewer

A = flow cross-sectional area normal to x

y = coordinate direction normal to x on a vertical plane

h = depth of flow of the cross-section, measured along y-direction

Q = discharge through A

S_o = channel slope, equal to sin θ

θ = angle between sewer bottom and horizontal plane

S_f = friction slope

g = gravitational acceleration

t = time

β = Boussinesq momentum flux correction coefficient for velocity distribution (Yen, 2004).

The continuity equation can be written as:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0$$

The solution for the full dynamic wave equation is computationally intensive. Because of this, excessive model runtimes have historically been experienced, especially for large pipe systems and for long simulation periods. However, models applying simplified forms of the dynamic wave equation neglect pressure and/or acceleration terms that may be important in some cases. This has created a dilemma for engineers seeking to balance accuracy requirements with practical considerations. A good discussion of the comparative trade-offs between the various simplified forms of the dynamic wave equation can be found in Akan and Yen (1981). Fortunately, the rapid advances in computer technology that have occurred in recent years have significantly reduced the runtimes required for a solution to the full dynamic wave equation, which has greatly facilitated the use of models that apply this approach.

3.3 Pipe Flow Resistance

All forms of the dynamic flow equation retain the friction and gravity terms. The friction term represents the friction slope using a semi-empirical formula, usually Manning's formula, which applies a roughness coefficient (i.e., Manning's n-factor) to compute pipe friction losses.

An accurate definition of the pipe roughness coefficients throughout the modeled sewer network is important to accurately simulate hydraulic conditions. Coefficients vary according to a number of factors, including pipe material and condition. There are a number of references available to help define reasonable values for different pipe materials. Brater and King (1976) provides values that account for pipe conditions.

Grit deposition within the sanitary sewer system influences both the effective pipe roughness coefficient and the actual cross-sectional area of flow. Grit deposition is common in sanitary sewer systems, especially in portions of the network where flow velocities are relatively low, allowing solids to settle.

Because of the difficulty obtaining complete information about grit deposition conditions, which can vary over time, and because pipe roughness cannot be measured directly, hydraulic model calibration efforts typically focus on the pipe roughness coefficient as a key calibration parameter.

3.4 Surcharged Pipe Flow

As previously noted, surcharge conditions can be very important to sanitary sewer system analysis, as surcharging typically is associated with SSOs and other operational problems. Surcharge conditions can be modeled in two ways:

1. Standard closed-conduit algorithms for pressure flow with an incompressible fluid.
2. The use of a hypothetical (extremely narrow) slot at the crown of each surcharged pipe to maintain free surface conditions in the model even when the computed water surface exceeds the pipe crown.

The latter approach, credited to Preissmann (Cunge and Wegner, 1964), simplifies the computational strategy, as it eliminates the need to switch between the St. Venant equation and a surcharge equation. It also eliminates the need to define and test for surcharge criteria, and track the pipes passing the test, to invoke the computational switch from one equation to the other.

There are disadvantages to using the Preissmann slot, which include accuracy problems (dampening of flow peaks) if the slot is too wide and numerical stability problems if the slot is too narrow. Some hydraulic routing models employ one surcharge solution approach or the other, while other models incorporate both and allow the user to define the surcharge solution.

3.5 Hydraulic Analysis of Special Structures and Appurtenances in Sanitary Sewers

There are a number of special structures and appurtenances in sanitary sewer systems that are of particular concern in the hydraulic analysis of these systems. SSOs can occur in the physical system in a number of ways. In some cases, particularly where constructed overflow points exist, the overflow discharges through an orifice or over a weir. In some cases the structure may operate as a weir until the structure itself is surcharged, at which point the structure operates as an orifice. In other cases, the SSO may occur as an overflow discharged through the manhole opening at the ground surface (often known as a flooded manhole). Weirs and orifices are well-described in the literature. A good discussion of weir characteristics can be found in French (1985), while Brater and King (1976) cover both subjects in excellent detail.

Many sanitary sewer systems include pumps and force mains. These structures are generally relatively simple to model, and each sewer modeling software typically has a means for representing the control rules that define the pump operation. In some cases, moveable gates (e.g., sluice gates, inflatable dams), either manual or automatic, are installed in sanitary sewer systems, operation of which can be modeled using control rules. Storage facilities can be represented in most models using a stage-volume (area) relationship.

Chapter 4 Data Collection

4.1 Introduction

This chapter discusses the data requirements to support SSO planning and analysis using the SSOAP Toolbox. One of the primary functions of the Toolbox is to assist users with predicting and estimating RDII. The primary data needs for RDII prediction tools in SSOAP are flow and rainfall data. This chapter focuses on providing guidelines for establishing a flow monitoring and rainfall data collection program. Data such as sewer network attributes, pump stations, treatment plants, and gate operations are also needed for hydraulic modeling using SWMM5 or other sewer models. The data needed for hydraulic modeling are more intensive than the data needed for the RDII prediction tools within the SSOAP Toolbox. More explicit descriptions of the hydraulic modeling data needs are provided in the user manual for the selected hydraulic model, SWMM5 (EPA, 2007).

4.2 Data Requirement for SSO Planning and Analysis

Data collection can be time consuming and expensive and should be carefully defined to meet project objectives and answer specific questions using the SSOAP Toolbox. When planning a data collection, it is important to understand what data are needed and how the SSOAP Toolbox can use this data to provide answers.

The SSOAP Toolbox can be applied to various SSO planning and analysis related activities (e.g., confirming basement flooding reports, determining sewersheds with excessive RDII, and developing SSO elimination plans). The scale and details of data collection depend on project objectives. For example, a municipality that is conducting a macro-level study to determine the relative RDII in different sewersheds within the service area does not require the same level of data collection efforts as one whose primary objective is to conduct a detailed capacity assessment of the system at the individual sewer segment level. In addition, one must consider the practical constraints, such as resources and schedule, in the development of a specific data-collection program.

Data used in the Toolbox to support SSO planning and analysis can be divided into two major types:

1. Sewer system data:
    a. Hydraulic data (e.g., sewer, manholes, pump stations, and other hydraulic components in the sewer system)
    b. Hydrologic/sewershed data (e.g., sewer service area, sewershed delineation)
2. Sewer flow and rainfall data

The ability to predict RDII is the most significant functionality offered in the SSOAP Toolbox to support SSO planning and analysis. The Toolbox utilizes flow and rainfall monitoring data to define an empirical relationship between rainfall and the collection system response. Physical sewer system data are primarily needed for hydraulic modeling using SWMM5 or other commercially available models, which are also briefly discussed in this chapter.

4.3 Sewer System Data

This subsection provides a brief discussion on collecting adequate sewer system data, such as sewersheds, sewer networks, pump stations, and treatment plants. Knowledge of the sewer system configuration is imperative for designing a flow monitoring program, as well as for defining the sewered area which contributes to the RDII hydrologic response.

4.3.1 Physical Sewer System Data

Physical sewer system data, such as sewer segment and manhole attributes, system operational data, and sewer conditions, are needed for hydraulic modeling. The level of detail needed can range from minimal to extensive. Chapter 6 includes a discussion on which factors should be considered when determining the level of detail needed for hydraulic modeling. The level of effort depends on the completeness, organization, and quality of the existing data. In some communities, sewer system information is already available in digital form, such as in a GIS while others in different formats, such as paper records or CAD.

After the physical sewer system data is collected, data reliability should be assessed. The sources of the sewer system data need a thorough review and confirmation. It is common for elevation data to change over the period a sewer system has been constructed because of the use of different vertical reference datum and/or because manhole rim elevations have been raised. The completeness, organization, and quality of the existing data would help estimate the assessment effort and allocate the resources for the data collection.

When information is suspect, effort must be made to ensure data accuracy. This may include efforts such as cross-checking GIS attributes against original as-built drawings, and field investigation. At a minimum, suspect information should be flagged as a source of uncertainty. In some cases, it may be appropriate to apply an estimate of sewer attribute data in locations where some degree of uncertainty is acceptable (e.g., ground elevation from topographic contours may substitute for missing or suspect rim elevation). How suspect information is addressed depends on the significance of the location in question. For example, a small pipe at the upstream end of the system is typically less important than a flow split in a trunk sewer. This data collection effort and refinement serve multiple needs. One is to provide the data required to model the system. Other needs include an accurate and up-to-date description of the sanitary sewer system and GIS or other readily available accurate data on the existing sewers. A more explicit description of the physical sewer data required for the development of a hydraulic model can be found in the user's manual of the selected hydraulic model (e.g., SWMM5 user's manual).

4.3.2 Spatial Sewer System Data

Spatial sewer system data is needed for RDII analysis as well as developing a sewer system model such as using SWMM5. The service area within a community is typically delineated into sub-service areas (i.e., sewersheds) to facilitate information organization and to support day-to-day engineering and operational functions. Typically, many of these communities have GIS- or CAD-based mapping that can be used to develop the service area delineations. These service area delineations must be collected and reviewed. If necessary, the delineations may need to be refined to support the RDII analysis and model development. Chapter 6 provides a detailed discussion on the sewer service area delineation into smaller areas. These delineated small areas are the building blocks of SWMM5 (or other) hydrologic model.

The SSOAP Toolbox requires actual sewered areas within the sewersheds to accurately determine the RDII volume (i.e., R-value). In many cases, service area and sewershed delineation may include areas that are not sewered, such as cemeteries, park land, highway rights-of-way, stream valleys, golf courses, undeveloped areas, or areas on septic systems. The existing GIS mapping may need adjustments by subtracting the unsewered areas to allow a more accurate estimate of R-values required for model input. Chapter 6 also provides additional information on adjusting the collected sewer system spatial information.

In determining the R-value for a metered sewershed, it is important that actual sewered areas are accurately measured. If the sewered area is underestimated, the R-value will be over predicted. On the other hand, if the sewered area is over estimated, the R-value will be under predicted. Accurate and consistent definition of sewered areas allows more meaningful comparison of RDII results. Table 4-1 presents an example that shows the sensitivity of sewered area estimate used on the R-value prediction. This example shows that R-value estimate is directly proportional to the sewered area used for the RDII analysis using SSOAP Toolbox. Hence, the sewer system delineation data must be reviewed thoroughly and adjusted appropriately.

Table 4-1. Sensitivity of Sewer Service Area on R-value Estimates

	Estimate 1	Estimate 2
Sewershed area (acre)	100	300
Rainfall (in.)	1	1
Rainfall Volume (MG)	2.7	8.1
Measured RDII Volume (MG)	0.25	0.25
R-Value	9%	3%

4.4 Sewer Flow and Rainfall Data

This sub-section provides a general guidance on collecting the sewer flow and rainfall data from existing sources and establishing a focused flow monitoring and rainfall collection program to obtain adequate flow and rainfall data. Predicting RDII and hydraulic modeling requires highly reliable flow monitoring and rainfall data. Additional references are available on flow monitoring and rainfall data collection (U.S. EPA, 1999; USEPA, 2005; and Vallabhaneni et al., 2003).

A sewer flow monitoring program typically involves installing a network of meters within the sewer system for a specific duration. Data from these meters are used to develop flow characteristics under dry- and wet-weather conditions at the installed locations.

Rainfall data are usually available from different sources, such as temporary or permanent rain gauge network maintained by the utility within the service area and the nearest National Weather Service (NWS) station or other public agency's rain gauge location. These rainfall sources can be supplemented by the calibrated NWS radar images. The rainfall data support the identification of wet-weather periods to critical input to RDII analysis and sewer system models.

Many communities have invested in flow and rainfall monitoring to support various sewer system management functions either on permanent or temporary basis. These data sources should be reviewed and assessed to verify data adequacy for the RDII and modeling analysis and to determine if additional data is needed.

4.4.1 Flow Monitoring Overview

The flow monitoring program should be designed to meet the broader objectives established for the SSO control planning and analysis. The most cost-effective way to implement a flow monitoring program is to achieve multiple objectives with a single properly planned flow monitoring program. In addition to the broader objectives of SSO control, specific goals established for RDII analysis and sewer system capacity assessment may require refining of the flow monitoring program. The monitoring program, which can be the most costly undertaking in the overall system data collection process, must be tailored to the RDII analysis needs (such as spatial resolution of RDII assessment, number and type of events to monitor, monitoring period, data accuracy) and the modeled system extents (i.e., portion of the service area sewers included in the model and calibrated). Chapter 6 discusses common capacity assessment goals and needs for modeling and RDII analysis.

The following discussion presents primary factors that must be considered in establishing flow monitoring programs.

Permanent vs. temporary

A flow monitoring program can be established as temporary, permanent, or a combination thereof. A temporary flow monitoring program is a "snapshot" of the sewer system over a short duration, typically lasting from weeks to several months or over a longer term lasting one year or longer. More permanent monitoring might be used for determining long-term trends in wastewater flows in major sewer systems or to evaluate before-and-after conditions of a portion of a sewer system for which infrastructure improvements and/or rehabilitation were performed.

The temporary flow monitoring should be established with consideration of historical rainfall patterns and sewer system responses so that the probability of obtaining the most beneficial data is improved. Data from multiple events will improve the ability to assess a range of RDII conditions.

A permanent flow monitoring program offers insight into sewer flow behavior for a wide range of weather and operational conditions over a long period of time. Permanent metering at strategic locations within the collection system is an excellent management tool for the municipality in maintaining and operating collection system and wastewater treatment plants. Permanent metering is often used for flow measurements between jurisdictions and billing purposes. It also provides multiple benefits, including:

1. Historical trends of the flow patterns and overflows/sewer backups/flooding frequency.
2. A sound basis for seasonal variation of RDII response to support developing an effective SSO mitigation plan.
3. The effectiveness or affect of system changes, e.g., sewer rehabilitation, capacity improvements, improved operation practices, and development.

A good flow monitoring strategy must properly select temporary and permanent monitoring locations. Ideal combinations include: temporary monitoring at relatively large number of locations primarily to provide high resolution RDII data from contributing sewersheds upstream of trunk sewer system; and relatively small number of permanent monitoring locations along trunk sewers, upstream of wastewater facilities, and priority sewersheds with known operational problems. In many instances, experience with temporary monitoring helps refine and enhance the permanent metering strategy.

Flow monitoring duration

The duration of a temporary flow monitoring program must be long enough to allow a desired range of dry- and wet-weather flow behavior in the collection system to be determined. The duration will depend on the precipitation characteristics of the region. Generally, a four- to six-month duration under normal precipitation conditions should be adequate to provide flow characteristics for a range of dry- and wet-weather conditions to support the RDII analysis using the SSOAP Toolbox. Where longer-term metering data is available, the uncertainties in the RDII quantification and prediction will be reduced and reliability improved.

Timing of temporary flow monitoring

The temporary monitoring should be conducted during the time of the year where RDII levels are highest. Historical flow records at the wastewater treatment plant 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 inter-event soil moisture are high. Monitoring in the wet season may increase probability of better characterizing the RDII impacts on the sewer flows. Collecting adequate dry-weather data to establish the dry-weather flow conditions is equally important. Beginning the temporary flow monitoring just before the wet season may also help data collection during periods of dry-weather conditions to establish the base flow conditions adequately. Finally, the program should include flexibility to shorten or extend the program depending on the storms and flows captured.

Flow monitoring resources

Planning ahead and securing the required resources is a key for a successful flow monitoring program. Once the general framework for type of monitoring, duration, and the timing for flow monitoring are determined, users must first secure resources (equipment, staffing, and financing). Required field staff must be available for installation, preventative and corrective maintenance, on-site data retrieval, and metering removal activities. Office staff required for regular quality checking of data must be committed to ensure corrective actions are made in a timely manner. With sufficient early planning, proper equipment can be available during the best monitoring periods. Starting the resource planning two to four months ahead of the preferred start day for data collection is a good practice. This lead time allows for securing flow monitoring personnel and equipment, and performing pre-installation activities such as site selection, equipment installation, and confirming that all the meters are installed correctly before starting the data collection.

4.4.2 Flow Monitoring Implementation

Once the general framework for a flow monitoring program is determined, a comprehensive flow monitoring protocol comprised of the following common elements should be developed:

1. General criteria for flow monitoring
2. Site selection
3. Equipment selection
4. Equipment installation and maintenance
5. Data collection and quality control

In general, there are three phases in implementing a flow monitoring program: mobilization, data collection, and demobilization. The mobilization phase includes site selection, equipment selection, installation, and calibration. The data collection phase includes operation and periodic on-site maintenance of the flow monitoring equipment, data collection and data review/quality control. The demobilization phase includes removing the equipment and preparing a report documenting the flow monitoring efforts.

Site selection is critical for successful data collection in any monitoring program. Given the usually limited data obtained during a short-term monitoring program (e.g., a 3 to 4-month period), it is very important to collect high quality data to provide reliable RDII prediction and the model calibration. Vallabhaneni et al. (2003) presented a comprehensive case study of a large-scale flow monitoring program in Metropolitan Sewer District of Greater Cincinnati. They concluded that the rigorous site selection process is imperative to gathering information where it is most needed and gathering information that is of higher quality. This case study also suggested that developing a site rating system based on initial flow data quality is useful in making the final site selections and in helping data users in properly interpreting the data.

The general location for flow monitoring typically focuses on isolating the flow in each major contribution area. Depending on the specific study circumstances, some may require detailed monitoring of the inflows from upstream sewersheds and the outflows to the trunk sewers. The consideration factors for determining the general locations may include:

1. **Thorough understanding of the system layout –** A good understanding of sewer system features is critical to identifying the proper locations for flow monitors. These features include active SSOs, flooding reports, pump stations, pump station overflows, sewer network, and treatment plants.

2. **Determination of sewershed discharge points to the trunk sewers –** The confluence of major tributary sewersheds with trunk sewers provides the primary locations for the flow monitors. These locations are critical for both RDII analysis, and hydraulic model development and calibration.

3. **Upstream of known SSOs and flooding locations –** Monitors should be located upstream of known SSOs or flooding locations to allow determination of RDII. In some cases, SSOs and flooding locations may have tributary areas sufficiently small that monitoring is not required.

4. **Pump Stations –** The RDII prediction tool in the SSOAP Toolbox requires flow data with minimum flow fluctuations. Hence, it is a good practice to avoid locations close to the pump stations. However, for hydraulic modeling purpose, pump stations may need to be monitored if the pump station records and pump operation are not available at the desired resolution. Each pump station records should be reviewed to determine if additional flow monitoring is required.

5. **Trunk sewers –** Flow monitors should be located at critical points along the trunk sewer, including points of major confluence and upstream of interconnection points between parallel trunk sewers. Meters located in series along a trunk sewer where flows must be subtracted to compute flows from the intermediate contributing area should be avoided. The meter error, which can be as great as +/- 20 percent, can surpass the

flow from the incremental area between the meters. This may result in negative or very large RDII and GWI flows for the incremental areas. It is best to place meters on major, or minor, inflow points to the trunk sewer system and avoid meters in series wherever possible.

6. **Treatment plants –** Flow monitors should be located on all influent lines to the treatment plants.

7. **Priority sewersheds –** Flow monitors should be located in the high priority sewersheds with known operational problems.

In addition to the criteria described above, effective use of GIS data, if available, will help identify proper flow monitoring locations.

The final site selection process includes performing field investigations to review candidate manholes for each desired location of interest and select appropriate site for meter installations. Typically, several factors must be considered during these field investigations, including sewer hydraulics, structural conditions of the manhole, access for meter installation, maintenance, data collection, and other safety concerns such as presence of hazardous gas and vehicle traffic. Based on these field investigations and from preliminary data collected for up to one week, final site selection is made. Vallabhaneni et al. (2003) reported detailed procedures for field investigation protocols and the final site selection.

4.4.3 Equipment Selection

The objective of the equipment selection is to obtain the best quality data at selected sites to meet project goals. There are many flow monitoring technologies available, such as ultrasonic sensors, pressure sensors, bubbler sensors, and float sensors. Newer technologies/techniques continue to emerge. Descriptions of the flow monitoring technologies were included in previous literature, such as the EPA's guidance document: "Combined Sewer Overflow Guidance For Monitoring and Modeling" (EPA, 1999) and WEF's Manual of Practice: "Prevention and Control of Sewer System Overflows" (WEF, 1997).

Users should evaluate the hydraulic conditions at selected sites and determine the most suitable flow monitoring equipment/technology to obtain the best quality data possible. Users should consult with the flow monitoring manufacturers and/or flow data service providers when selecting the equipment/technology for each specific flow monitoring site. In some cases, one technology can meet the needs for all locations in a flow monitoring program and in other cases several technologies may be needed to match the system hydraulics. It is a good practice to balance the need for quality data with the available technologies and resources.

4.4.4 Equipment Installation and Maintenance

Proper installation and accurate site calibration of equipment is key to collecting accurate data. Users must adhere to the manufacturer's recommendations and industry standards when installing and calibrating the installed meters. The meter installation must be performed by qualified personnel. The following general procedures would assure the proper meter installation and collect information needed for data processing:

1. Record both the measured and monitor-reported water levels.
2. Adjust level setting of monitor as necessary per manufacturer's recommendations.
3. Record position of probe installation with respect to the bottom of the pipe.
4. Record depth of sediment (if present).
5. Measure the distance upstream from the back of probe to the butt of pipe.
6. Take photographs of the completed installation.

It is a good practice to perform a site check three to seven days after initial installation to confirm the meter performance and site suitability for flow monitoring. Based on the initial site observation after installation, users should make necessary adjustments for the meter installation and, if required, relocate the meter to an alternate site.

Proper maintenance procedures are required to assure consistent meter performance throughout the monitoring duration. These procedures are designed to minimize meter downtime, maintain data quality, and produce reliable data to support the RDII analysis and model calibration.

The frequency of the maintenance visits are based on metering type (temporary vs. permanent) and study objectives. Typically, weekly visits are performed in short-term temporary monitoring program. In some cases, the sites are visited twice in a week when they are concluded to be problematic due to factors such as sediment deposition. Usually, in a permanent monitoring program, monthly or quarterly site visits are made. It is quite common that the permanent metering program has a remote data acquisition system, which allows the checking of meter performance in lieu of frequent site visits. Site visits will include the following activities:

1. Flow data collection.
2. Meter operation check – the real time operating status of a monitor must be checked per manufacturer's recommendations. Typically, level and velocity readings are checked. In addition, other operating parameters such as signal strength, temperature, clock, and battery voltage are also checked, depending on the specific meter technology used. This information should be recorded. Desiccant and batteries should be replaced as required.
3. Installation inspection – the meter probe and all portions of the equipment installation should be visually inspected by entering the manhole or with a remote inspection camera. If necessary, meter installation is adjusted and re-calibrated as needed. It is a good practice to keep a photographic record of the installation inspection. In the case of permanent meters, if required by the manufacturer, they should be removed and recalibrated annually.

4.4.5 Data Collection and Quality Control Using SSOAP

To ensure that the flow monitoring program provides quality data, users should perform periodic on-site inspections of all flow meters as described previously. These site visits can reduce equipment fouling and other unforeseen conditions, such as clock errors, and will reduce meter down time. Data collection should be recorded in a sufficiently fine temporal resolution to meet project needs. A common interval is five minutes, but 10 or 15-minutes and hourly records are also commonly used. Five-minute data can always be averaged to hourly or daily, but not the other way. In addition to on-site inspections, users should perform weekly QA/QC review of the collected data.

Figure 4-1 displays an example from the SSOAP Toolbox data review utility that can be used to assess the quality of the collected flow monitoring data. This Data Review Tool graphic consists of three charts: flow hydrograph with rainfall, flow depth and velocity with rainfall, and depth vs. velocity scatter graph. Users can use the combination of these charts on a weekly basis to review the measured data quality and prompt the field crew if site checks are needed to troubleshoot data inconsistencies or missing data. Once the data collection is complete, this data review tool can assess whether or not data meets the flow monitoring goals. This tool can also determine the portions of the data that are useful in supporting RDII analysis and model development. The following are general guidelines on performing data review using the data review utility.

Data gaps

Flow hydrographs can be used to identify any missing data. Flow meters measure depth and velocity at the desired monitoring location. The flow hydrograph is the product from the measured depth and velocity data. When there is any missing data shown in the flow hydrograph, users can identify the source of the missing flow data (such as depth, velocity, or both) using the depth and velocity data plot. Users may be able to use the available depth/velocity data even if there is missing flow data for certain engineering analysis. In the example shown in Figure 4-1, some velocity readings drop to zero resulting in drops of flow. However, no noteworthy missing data is observed. The analyst may ask the field crew to investigate the causes for these occasional velocity reading drops.

DWF patterns

Flow hydrographs, as well as depth and velocity data plots, can be used to review the consistency of DWF data. The rainfall shown in the flow hydrograph can help users identify the dry-weather periods. Under normal dry conditions, users should observe a similar pattern from the measured flow, depth and velocity data. For example, Figure 4-1 shows that under dry-weather conditions, the depth is consistently near 5-inches, the velocity around 1-1.5 ft/s, and the flow near 0.25 MGD. If a portion of the measured data differs from the normal DWF pattern, analysts should investigate the reason for the data pattern shift. In some cases, DWF patterns may vary because of failed flow monitoring equipment, changes of sewer system flow patterns due to operational changes such as temporary blockages or changes in pump/flow control gate operation in the proximity of the meter. Field investigation and confirmation may be needed to verify the change of measured data pattern. Depending on the duration of the flow monitoring period, longer-term evaluation of data consistency may indicate seasonal variations of the average DWF or monitoring problems from depth sensor's gradual drift.

WWF response

Flow hydrographs and the depth and velocity data plot can also help review the consistency and reliability of the measured data under wet-weather conditions. Analysts should first observe how a meter responds to the rainfall events and note the magnitude of peak flows and shape of hydrographs. A pattern should be found between wet-weather response and the total rainfall. The depth and velocity data plot can also help users gain insight of the sewer system behavior under various wet-weather conditions. Analysts can establish the hydraulic patterns at a specific meter site based on depth and velocity relationships and then look for consistent behavior during various rainfall events. If a portion of the data being reviewed is out of character, the analyst should alert the field crew to investigate.

Depth vs. velocity scattergraphs

The depth-velocity scattergraph is a useful tool to understand the site hydraulic behavior and to assess data consistency and reliability. The depth-velocity scattergraphs can be used to determine if the measured data agrees with the Manning's pipe flow theory. The Manning's theory describes uniform and steady state flows in open channel and points that the depth of flow in an open channel increases as the velocity increases under free flow conditions. Once the pipe goes into surcharge conditions because of capacity limitation at the point of flow measurement or in downstream sewers, this depth to velocity relationship does not hold. The scattergraphs in Figure 4-1 illustrate both depth versus velocity relationships under free and surcharge conditions. In this example the flow monitor is located inside a 12-inch diameter sewer, which shows when the sewer flow is under the capacity, free flow conditions prevail and the meter consistently tracks the depth and velocity relationship. When the flow reaches sewer capacity and cause surcharge conditions (i.e., depth is higher than 12-inch in this example), velocity reduces and another depth-velocity pattern is developed. A scattergraph with uncharacteristic depth and velocity does not always reflect bad meter data and may reflect the actual hydraulic condition at the flow monitoring location. Sewers at capacity constraints, near SSOs, and pump stations will not behave in uniform flow condition, and thus, do not have the similar scattergraphs under free flow conditions shown in Figure 4-1. Sands and Stevens (1995) offered more detailed descriptions of the scattergraphs pattern and how it can be used to gain insight of the sewer system.

At the conclusion of the monitoring period, a final report should be prepared summarizing the efforts. It is a good practice to include the following key elements in the report:

1. Summary of data collection efforts and findings.
2. Map showing flow monitoring locations.
3. Technical summary including descriptions of equipment, Installation notes/records.
4. Calibration and field maintenance records.
5. Hydrographs of five-minute (or other interval) flows and rainfall for the entire monitoring period. In addition, daily, weekly, and monthly summaries of flow depth, velocity, and rates should be developed.
6. Summary of depth-velocity scattergraphs.
7. Data loss and known data limitations.

A well-designed flow monitoring approach will ensure the collection of quality data to successfully apply the RTK approach in the SSOAP Toolbox to predict RDII. Additional information on flow monitoring can be found in the references cited.

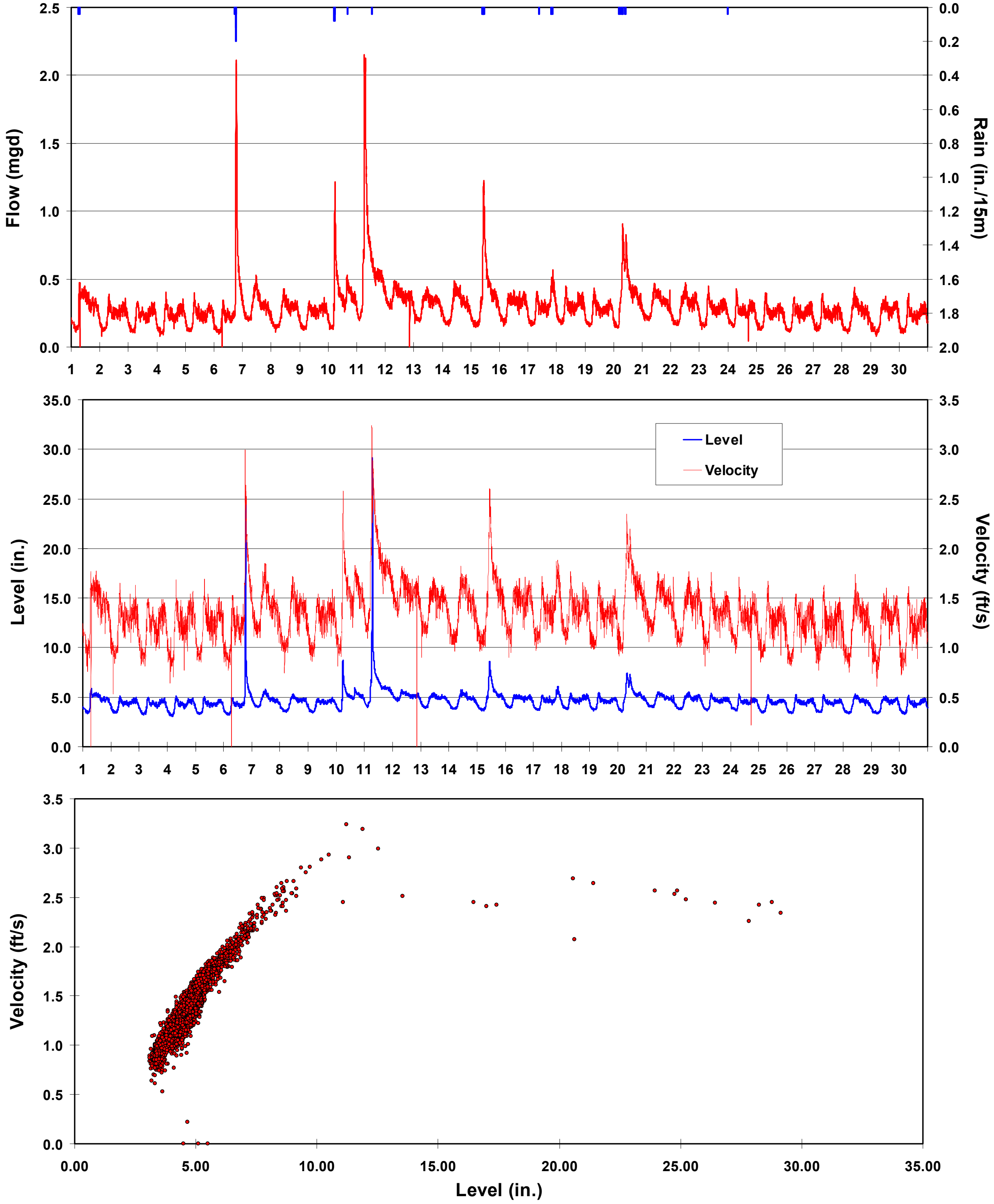


Figure 4-1. Example flow monitoring data review and analysis.

4.5 Rainfall Data

Rainfall monitoring is an integral component in a typical flow monitoring program. The precision, accuracy, and resolution of rainfall data are critical for RDII analyses and sewer modeling. Inadequate rainfall data introduces errors in RDII analyses and model calibration, and hence reduces the overall reliability of the SSOAP Toolbox application.

Many communities have an established permanent rain gauge network, which can be used to support RDII analyses. Available rain gauge data sources should be evaluated to determine if the supplemental rainfall monitoring is needed. The following discussion assesses the data adequacy and methods for collecting the required rainfall data.

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. Accuracy and precision are usually less problematic than resolution when working with the precipitation data. In recent years, it has become widely recognized that RDII prediction, and the calibration and application of ever-more precise sewer system models, is significantly hindered by the limitations of precipitation data resolution. These limitations are caused by several factors, including the spatial resolution, poor gauge sitting, equipment malfunctioning, and data collection/transformation errors.

As a first step, one should determine the performance of the existing rain gauge network to identify the needs for improvements. These improvements may include increasing the rain gauge density to provide adequate coverage for the service area, and modify/replace or relocate the existing rain gauges. It is becoming popular to use the radar technology as a viable means to enhance the spatial coverage of precipitation gauge data, specifically in large communities that span several square miles of area. When the radar technology is used, it is imperative to field verify using the data from the installed gauges..

The location and performance of individual rain gauges should be thoroughly reviewed by qualified personnel. The factors for evaluation include rain gauge spatial distribution, number of gauges and gauge setting. Each site must be visited and site conditions (such as possible obstructions from trees and buildings, wind effects created by surrounding buildings) documented that may adversely affect accurate rainfall measurements. Performance testings should be conducted for each rain gauge to identify any refinement/enhancement necessary to the existing rain gauge network with respect to gauge sitting; spatial coverage and number of gauges; and other relevant changes that will support the data accuracy needs. Vallabhaneni et al. (2002b) presented a case study that described historical data analyses supplemented by various field tests to effectively confirm the rain gauge performance. It is also common practice to follow the manufacturer's recommendation in installing the rain gauges and periodically conduct maintenance and calibration of the equipment.

If a service area spans for several square miles and spatial/temporal variation of rainfall is significant, a combination of aerial estimates of rainfall from radar and point estimates from a rain gauge network will produce a better estimate of the spatial distribution than either system alone. Vallabhaneni et al. (2003) discussed radar-rainfall integration into hydrologic and hydraulic modeling and offered step-by-step approaches. Wride et al. (2003) presented a case study which combines the rain gauges and radar-rainfall technology to improve the characterization of the RDII prediction. They concluded that using only the nearest rain gauge-based analyses can lead to inappropriate R-values. Analysts are strongly encouraged to use the combined knowledge of rainfall characteristics and their potential impacts on the RDII analysis to assess the need for using the radar rainfall technology to supplement the rain gauge network.

In summary, proper flow and rainfall data collection efforts are critical for RDII analyses in sanitary sewer system. Careful planning of the spatial and temporal extent of this data collection program is a key component of a successful SSO analysis and planning efforts.

Chapter 5 Sanitary Sewer Overflow Analysis and Planning Toolbox

5.1 Introduction

This chapter provides an overview of the SSOAP Toolbox, including introductory descriptions of its tools and functions in performing a sanitary sewer system capacity assessment. It is not intended to serve as the user's manual, which is included with the software package.

The SSOAP Toolbox is a suite of computer software tools used to predict RDII in sanitary sewer systems and facilitate capacity analysis. The toolbox includes the option to use SWMM5 for the hydraulic analysis of the sanitary sewer system. The program architecture allows efficient sewer system capacity analysis and planning by a linking of various external data sources, RDII analyses tools and SWMM5. The SSOAP Toolbox is programmed using Borland Delphi® (2006 edition) and operates within the Microsoft Windows® environment.

Figure 5-1 depicts the SSOAP Toolbox organization. There are five tools in the SSOAP Toolbox:

1. Database Management Tool
2. RDII Analysis Tool
3. RDII Hydrograph Generation Tool
4. SSOAP-SWMM 5 Interface Tool
5. SWMM5

The green boxes in Figure 5-1 represent the tools within the SSOAP Toolbox listed above. The grey boxes represent the external data sources for the Toolbox. In addition, the toolbox allows the use of external software tools to perform RDII and hydraulic routing analyses. This chapter provides an overview of the tools within the SSOAP Toolbox.

5.2 Database Management Tool

The purpose of the Database Management Tool (DMT) is to help users manage and organize all data required for performing of RDII analysis and system capacity assessment. DMT also includes useful utilities that help users efficiently perform quality checks of the external data sources and their analysis.

DMT stores and organizes data in a Microsoft Access® database, referred to as the SSOAP System Database (SSD). It serves as the command center and transfers data between the tools in the SSOAP Toolbox. It organizes data in the SSD and serves as a data exchange agent for other tools in the SSOAP Toolbox. As shown in Figure 5-2, the external data sources may include sewer system GIS databases, data from flow monitoring programs, data from rainfall monitoring programs or radar rainfall analyses, and hydraulic modeling analysis results. These external data sources are discussed in greater detail in Section 5.2.1. Since DMT can access SSD directly, the SSOAP users do not require the installation of Microsoft Access® in their computers.

The utilities in DMT perform: (1) rainfall and flow data quality control; (2) data analysis/queries; and, (3) scenario management to support SSO analysis and planning. These functions are often performed using various external, non-integrated tools (e.g., spreadsheets, flow meter software). These tools and capabilities are integrated into the SSOAP Toolbox.

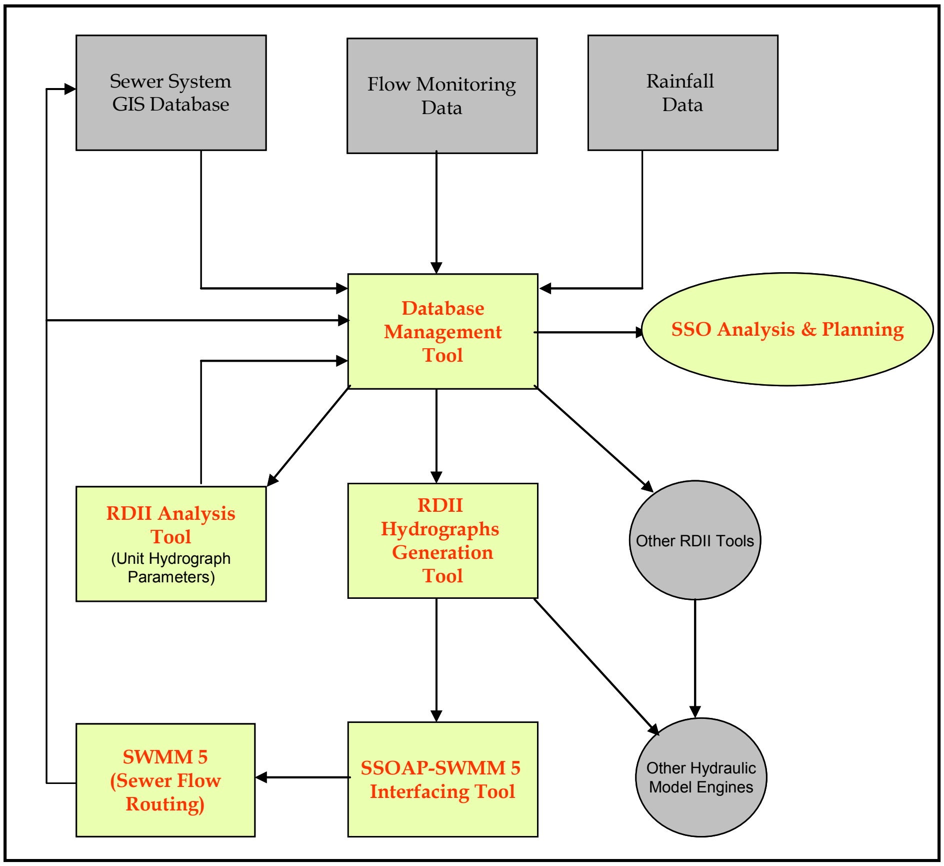


Figure 5-1. Overview of tools within the SSOAP Toolbox.

5.2.1 Interfacing with External Data Sources

DMT manages the import of data from external databases into SSD and also the export of data stored in SSD. Data such as flow monitoring, rainfall, and sewer system characteristics (described in Chapter 4) are stored in SSD using DMT. DMT is specially programmed to support several generic text formats. Users can modify the DMT import function to customize the imported data format. However, in some cases, DMT may not be able to support particular proprietary formats used by flow meter manufacturers. In that case, data may require pre-processing to convert data to standard formats used by the Toolbox prior to importing. In many cases, software provided by flow meter manufacturers may have the ability to export data to one of the standard text formats used by DMT.

Typical data used in the SSOAP Toolbox and their collection methods have been previously described in Chapter 4. How these data are stored and processed is presented below. Examples of importing data is described in the separate user's manual within the SSOAP software.

Flow monitoring data

Users can store a large amount of time-series flow meter data in SSD and manage these data through DMT. Time-series data for a location, including the date, time, and flow, are the minimum flow-related information for predicting RDII using SSOAP. Depth and velocity data can also be stored and utilized to support data quality control as to be described in Section 5.2.3. Users may need to pre-process the flow monitoring data before using DMT to import data as previously described. If the users already have the RDII parameters (i.e., R, T, and K) determined, flow data will not be needed for the RDII analysis.

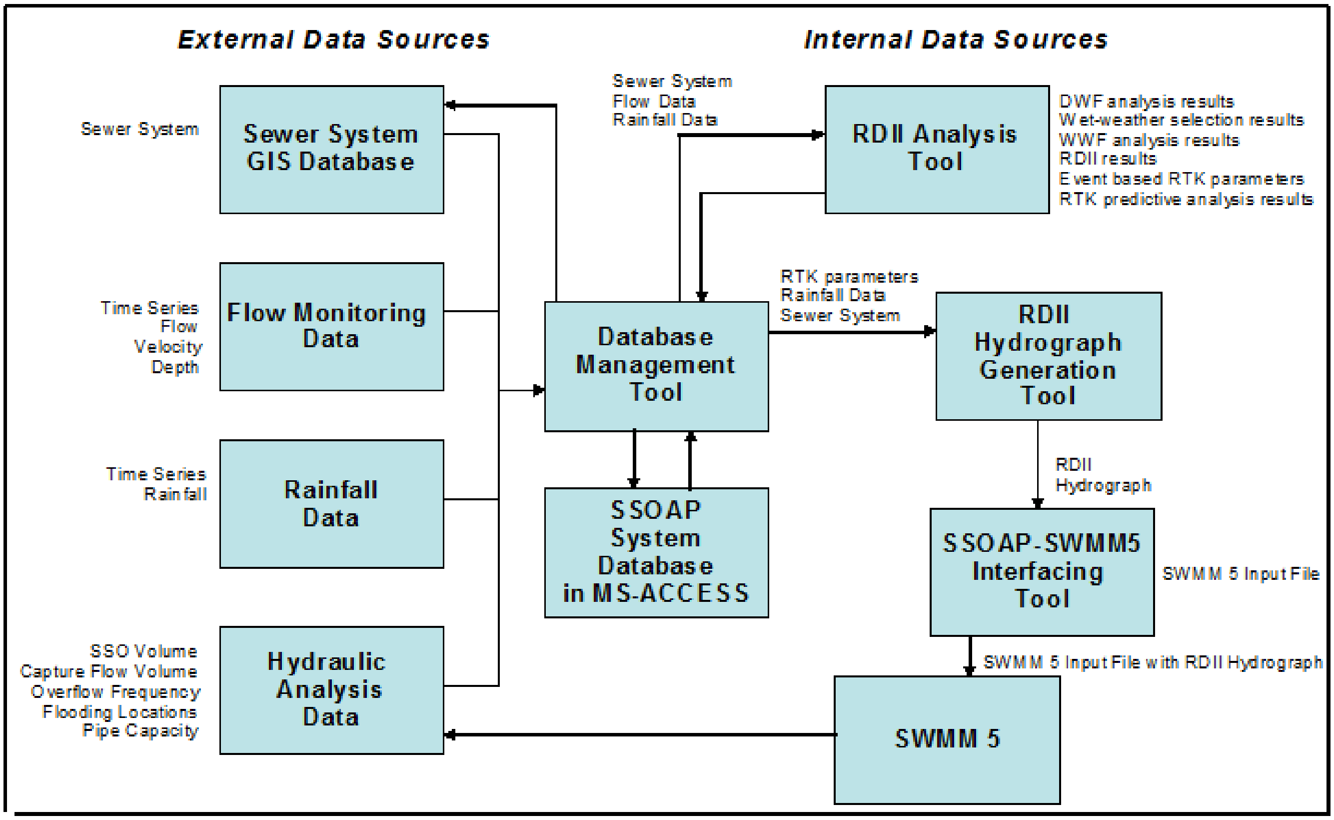


Figure 5-2. External data sources.

Rainfall data
Users can store a large amount of time-series rainfall data either from rainfall gauges or from radar rainfall estimates using SSD and manage these data through DMT. Rainfall data corresponding to the flow monitoring period can be imported as either precipitation volume or intensity. As with the flow monitoring data, rainfall data must include the date, time, and location and amount or intensity. Once stored in the SSD, these data are used for RDII analysis and hydrograph generation. DMT allows custom data formats. As with the flow monitoring data, users may need to pre-process the rainfall data outside of the SSOAP environment. Examples of data custom formats are provided in the user's manual.

Hydraulic analysis data
Hydraulic modeling results such as overflow volumes and frequencies, capture flow volumes, flooding locations, and pipe capacity can be stored in SSD. DMT can be used to directly import a SWMM5 binary output file into SSD. Users can use the scenario manager function in DMT to analyze the SWMM5 result and to support SSO planning and analysis.

DMT also provides options to export data stored in SSD to text files for other sewer system management functions besides capacity assessment. For example, processed flow and rainfall data, and hydraulic simulation results can be exported from SSD to support routine operation and maintenance of a sewer system.

5.2.2 Interacting with Other Tools in the SSOAP Toolbox

DMT can also manage data produced by tools within the SSOAP Toolbox, as described below.

RDII Analysis Tool

DMT exchanges information from and to SSD to perform RDII analysis and store the analysis results. DMT uses information such as flow monitoring, rainfall, and sewer system data from the SSD as input to the RDII Analysis Tool (described in Section 5.3). The RDII analysis results, such as R,T,K parameter values, RDII event start/end time, and DWF and GWI estimates are automatically fed back to SSD and stored.

RDII Hydrograph Generation Tool

DMT provides information stored in SSD such as sewer system data, rainfall and RDII analysis results to the RDII Hydrograph Generation Tool.

5.2.3 DMT Utilities

DMT is equipped with software utilities to perform data quality control, data analysis, and scenario management in support of sanitary sewer system capacity analysis and planning.

Data quality control utility

This utility has three routines to assist users to perform rainfall and flow data review and assess the data usability for RDII analysis:

- Rainfall data review – This routine provides a tabular and graphical (i.e., hyetograph) presentation of the imported rainfall data. In addition, the routine allows a comparison of multiple hyetographs to assess any data inconsistencies and identify data gaps. It summarizes the rainfall data, such as total volume for the period of record, and identifies the largest rainfall event in the record, for each rain gauge. These reviews allow users to assess the overall reliability of the rainfall data before proceeding to the data analysis step.
- Missing flow data analysis – The raw flow data imported into DMT can be reviewed efficiently using this routine to determine missing data. This routine also helps users filter out the missing flow data from the record. It also offers an option to fill in the missing flow data values for small time steps by interpolating them from the recorded values. Note that this method of determining missing flow data for a prolonged period can be unreliable and users should exercise caution.
- Flow data review – This routine offers users a flow data review capability by generating plots from flow data stored in DMT, and data quality and reliability assessment as discussed in Chapter 4. The relationships between measured depth and velocity scatterplots can be generated for selected periods from flow data records. In addition, similar plots can be generated for review of inter-relationships among depth and flow values. Depth and velocity scatterplots can then be used to determine data consistencies and reliability. The scatterplots also help develop knowledge of the sewer system hydraulic behavior at the flow metering locations. The assessment of this flow data review capability within SSOAP offers users an efficient data review tool.

Rainfall data analysis utility

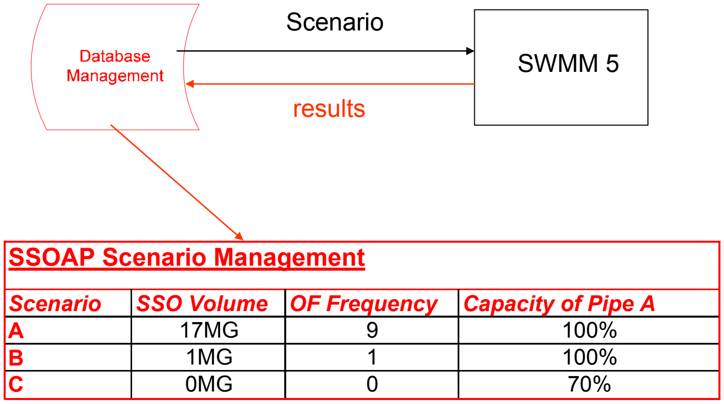
DMT offers this utility for analyzing the imported rainfall data to identify wet-weather events of interest and perform analysis to determine the rainfall characteristic such as the rainfall event start time, rainfall duration, rainfall volume, peak rainfall intensity, and number of dry days prior to each rainfall event. Table 5-1 shows an example of the analysis result. It lists all rainfall events that occurred with relevant characteristics of each event.

Table 5-1. Example of Rainfall Data Analysis Results

Event No.	Start Date/Time	Total Volume (inches)	Duration (hours)	Peak Intensity (inches/hour)	# of Dry Days Prior to Event
1	7-9/2002/ 0630	4.6	4.6	0.3	11.0
2	7-9/2002/1705	0.44	0.9	0.4	0.3
3	7-17/2002/1045	0.24	3.8	0.2	7.7
4	7-19/2002/1835	0.33	1.9	0.3	2.2
5	7-29/2002/1410	0.17	3.8	0.2	9.3

Scenario management utility
The Scenario Management Utility in DMT offers users the ability to organize the sewer system flow routing results from SWMM5. Users can store the modeling results from various model scenarios and apply this utility to compare scenarios to support sewer system evaluations under various precipitation conditions and system configurations. Figure 5-3 provides an example of scenario comparison.

In summary, SSD is a data bank for storing data from flow monitoring, rainfall monitoring, RDII analysis, and SWMM5 modeling. DMT manages data input to and retrieval from SSD. DMT also provides simple utilities that facilitate data review and analysis, and scenario comparisons. Because data is stored in a Microsoft Access database file, users can develop additional custom utilities using Access or other programs to perform more in-depth analysis to meet project-specific needs, without interfering with the core computational routines of SSOAP.



SSOAP Scenario Management

Scenario	SSO Volume	OF Frequency	Capacity of Pipe A
A	17MG	9	100%
B	1MG	1	100%
C	0MG	0	70%

Figure 5-3. Scenario management.

5.3 RDII Analysis Tool

The RDII Analysis Tool implements the RDII unit hydrograph methodology described in Chapter 2. This tool has the ability to support four major analyses:

- DWF analysis
- Wet-weather flow (WWF) analysis
- RTK unit hydrograph curve fitting analysis
- RTK unit hydrograph parameter predictive analysis for unmetered and design precipitation conditions

These analyses are described in the following sections.

5.3.1 DWF Analysis

The RDII Analysis Tool assist users in performing DWF analyses based on flow monitoring and rainfall data. The RDII Analysis Tool helps users select dry-weather days automatically based on flow data and filter out the days with influence of rainfall events. This tool also allows users to automatically select dry-weather days in a graphical environment, and manually add to or remove from the automatically selected days. The RDII Analysis Tool calculates the average DWF from the selected dry-weather days and the average DWF for weekdays and weekend days. Figure 5-4 depicts the results of a DWF analysis indicating weekday and weekend DWF for a sample sewershed.

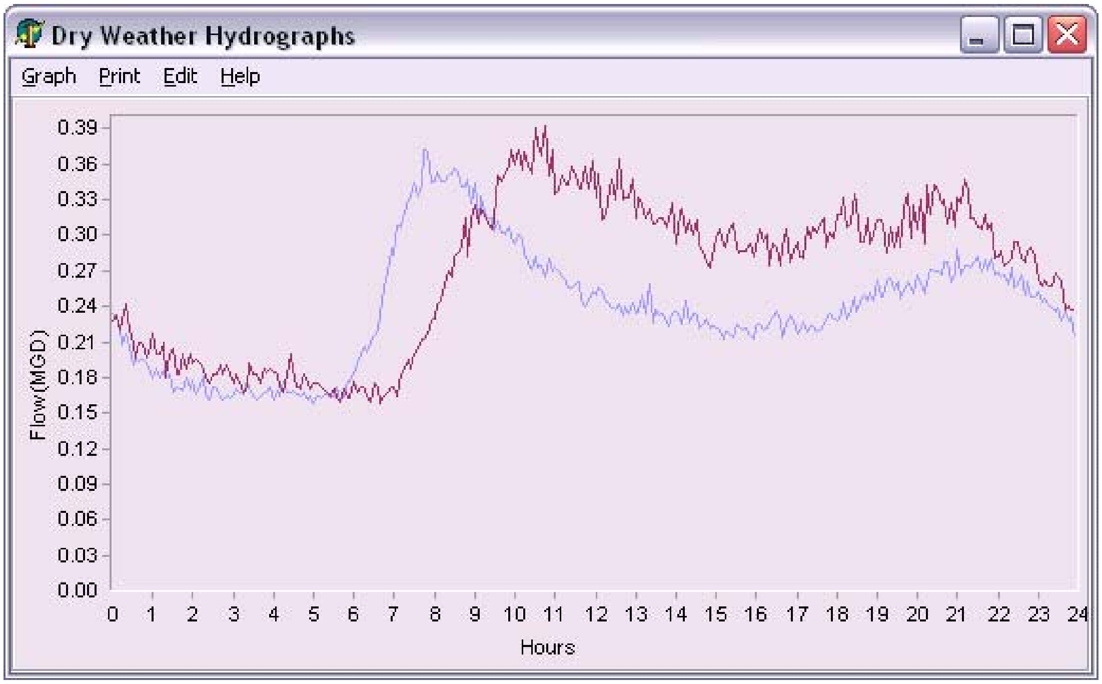


Figure 5-4. DWF hydrograph derived from RDII analysis tool.

5.3.1.1 BWF and DWF Adjustment

The RDII Analysis Tool can address seasonal variations in DWF by accounting for the influence of GWI. The RDII Analysis Tool calculates the difference of the average flow during the given day and the average flow of all DWF days in the period of record. This difference is defined as DWF adjustment in SSOAP Toolbox. The DWF adjustment can be a positive or negative value. This adjustment allows users to set the proper DWF conditions prior to rainfall events to determine the rainfall event specific RDII hydrograph. The user's manual contains an expanded discussion and graphical presentation on the event-specific DWF adjustment.

The RDII Analysis Tool can also decompose DWF into two components: BWF and GWI. For example, when users enter the percentage of the DWF as GWI, the computational routines within the Tool will divide the DWF hydrograph into BWF and GWI.

5.3.2 WWF Analysis

The RDII Analysis Tool offers users various automatic functions to analyze RDII flows. These functions are designed to:

- Identify individual RDII events based on flow monitoring data and rainfall data. The RDII event is defined as the time period during the flow pattern that varies from the DWF because of the influence of RDII. It starts when the rainfall begins and ends when the flow pattern returns back to the pre-rainfall level.
- Summarize the RDII event related data, including:
    - Rainfall (i.e., volume, duration, peak, start time, end time)
    - Flow data (i.e., peak total flow, peak RDII flow, RDII Volume)
    - Percentage of rainfall entering sewer system (i.e., R-value)

The RDII Analysis Tool determines RDII event start and end times by analyzing the RDII flow hydrograph and corresponding rainfall records. Users can also manually define a RDII event or adjust the event automatically. A RDII event is characterized by the peak rate, duration, and volume. These characteristics are needed because users can define threshold limits of RDII events based on a minimum rainfall depth and a minimum peak RDII flow rate. Users can then review and refine the RDII events selected by the tool and use these events for further analyses, including hydrograph decomposition and unit hydrograph curve fitting.

5.3.3 Hydrograph Decomposition and Unit Hydrograph Curve Fitting Analysis

The RDII Analysis Tool uses the RTK unit hydrograph methodology described in Chapter 2 to determine the relationship between rainfall and RDII for each metered sewershed. Parameters in a unit hydrograph are developed through a systematic analysis of measured flow and rainfall. Once developed, these unit hydrograph parameters and rainfall hyetographs are used to define RDII hydrographs for collection system modeling and evaluation using SWMM5 or other hydraulic modeling tools.

The RDII hydrograph of a rainfall event must be first derived using hydrograph decomposition procedures included in the RDII Analysis Tools. Hydrograph decomposition considers a range of parameters, including rainfall depths, sewershed area, antecedent moisture conditions, and groundwater elevations to quantify the individual wastewater flow components in the system.

The RDII Analysis Tool helps users decompose the monitored flow hydrograph automatically and graphically. Figure 5-5 depicts decomposition of the observed flow into DWF and RDII components during a rainfall event. The RDII Analysis Toolbox allows users to adjust the pre-event DWF to change the GWI on a given day compared with the average DWF for the period of record. The RDII flow is the remaining flow after subtraction of adjusted DWF from the observed flow.

After RDII flow hydrograph is defined, the Tool is used to calculate the total R-value, using the rainfall data and sewershed area information.

Users can further decompose the RDII flow using the unit hydrograph approach described in Chapter 2. For each unit rainfall input the RDII Analysis Tool generates unit hydrographs for the corresponding sets of R, T, K, with values defined by the user. Figure 2-4 in Chapter 2 illustrates how the tool generates three unit hydrographs based on the R, T, K parameters for a given unit rainfall input. It also demonstrates that the total RDII unit hydrograph is the summation of three individual unit hydrographs. The three unit hydrographs can be related with fast (first unit hydrograph), medium (second unit hydrograph), and slow (third unit hydrograph) RDII responses typically observed in the sanitary sewer system. In some cases, only one or two unit hydrographs are required to adequately define observed RDII hydrographs.

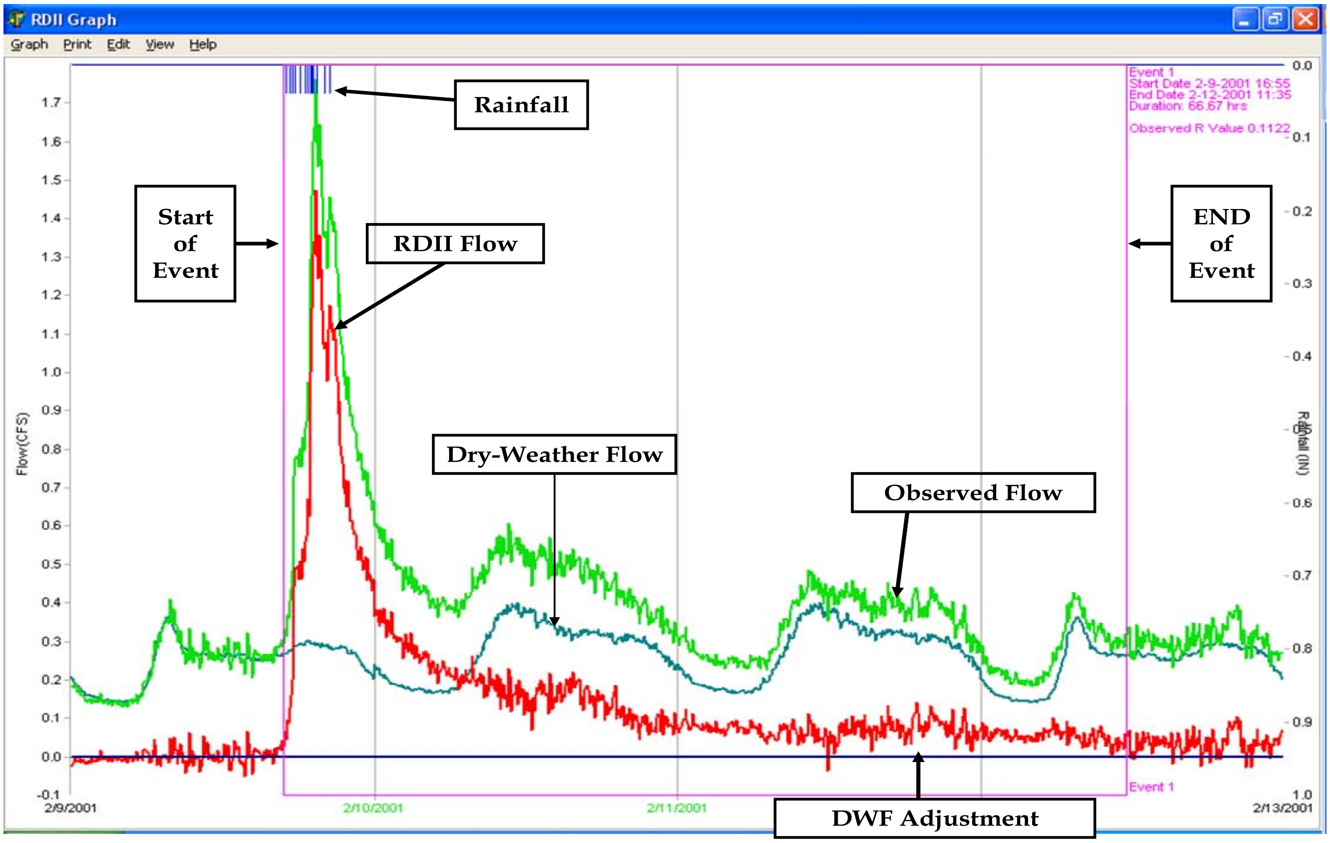


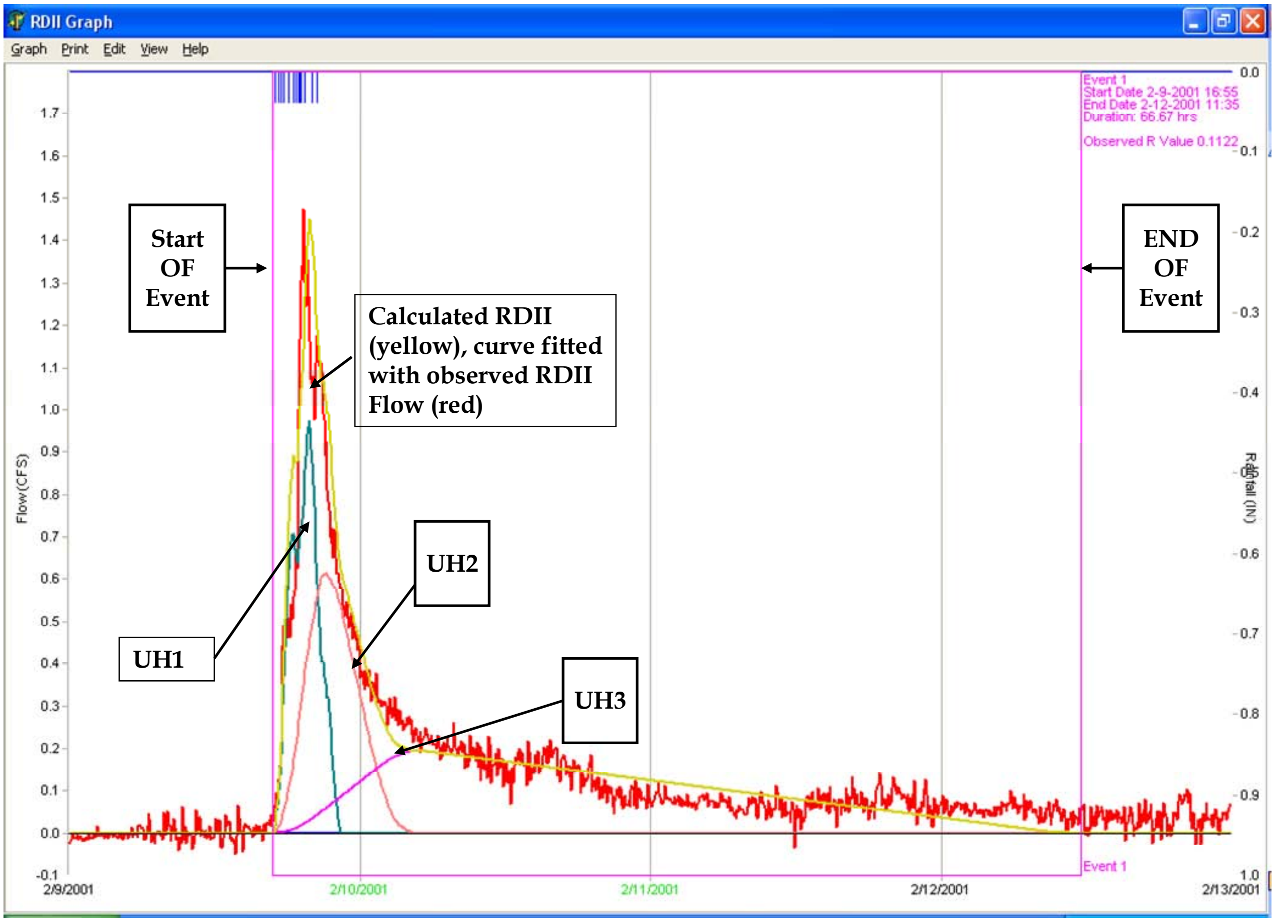
Figure 5-5. Hydrograph decomposition in the RDII Analysis Tool.

R, T, K parameters can be determined by graphically comparing the total RDII hydrographs generated by users' defined R, T, K parameters with the RDII hydrographs from the monitored data. This visual curve fitting is accomplished by iterations. The iteration process continues until a good visual comparison between the calculated RDII hydrograph and the observed RDII hydrograph is achieved. Numerical comparison of total RDII volume with the sum of volume under each of the unit hydrographs will confirm the success of curve fitting. This simple, interactive and visual approach will facilitate determination of the unit hydrograph parameters rather than relying on complicated numerical techniques.

Figure 5-6 shows an example of the hydrograph curve fitting using three unit hydrographs. This analysis can lend understanding of the fast, medium, and slow RDII response in the sewer system tributary to the point of metering. The following general guidelines should be followed in selective the R, T, K parameters to ensure that the calculated RDII hydrograph meets the goal of visual curve fittings:

- Total R value = $R_1 + R_2 + R_3$, if all three unit hydrographs used.
- The T and K parameters should be similar for rainfall events for a given sewershed tributary to the flow monitor since they depend on the geometry and sewer system layout.
- In all cases, $T_1 < T_2 < T_3$
- In most cases, $K_1 < K_2 < K_3$
- The necessity to change T and K significantly for a particular event to match the observed flows is often a sign that the rainfall data being used is not representative of the rainfall that fell over the basin for the event or the system experienced operational challenges resulting in an altered shape of the hydrograph.

- The event specific R-values will vary, generally being higher for wet antecedent moisture conditions and lower for dryer antecedent conditions. Similarly, R-values will typically be higher in a wet season.
- T and K for the three triangular unit hydrograph should generally be within the ranges shown in Table 5-2.



Event 1
Start Date 2-9-2001 16:55
End Date 2-12-2001 11:35
Duration: 66.67 hrs

Observed R Value 0.1122

Figure 5-6. Unit hydrographs curve fitting using the RDII Analysis Tool.

Table 5-2. Ranges of Values for Unit Hydrograph Parameters

Curve	T (hours)	K
1	0.5-2	1-2
2	3-5	2-3
3	5-10	3-7

Once the R, T, K parameters are defined, the RDII Hydrograph Generation Tools would be used to generate RDII hydrographs for selected events from monitoring data, desired design storm events, or continuance multiple events.

5.3.4 Statistical Analysis of RDII Parameters

The R, T, K parameters developed using the RDII Analysis Tool are specific to a rainfall event and observed flow data. These parameters are used to develop the RDII hydrographs for selected monitored events to support calibration of hydraulics of the sewer system model.

When the calibrated hydraulic model is used to perform hydraulic capacity assessment for a non-monitored condition or a design storm, one can estimate the R, T, K parameters condition using statistical methods. The sophistication of these statistical methods varies depending on the quantity of RDII data available. For example, a short-term temporary monitoring program that spans over four months may produce a limited amount of suitable events for RDII analysis compared to a long-term (>1 year) temporary or permanent monitoring. Typically a longer-term monitoring provides more events (samples) to do more sophisticated analysis such as multi-variable regression as compared to a smaller sample set from a short-term monitoring. Vallabhaneni et al. (2003) presented a case study that applied a multi-variable regression method to predict RDII for non-monitored conditions. In addition, long-term monitoring will allow for the development of the seasonal RTK characteristics for the monitored sewershed. A published case study (Loehlein et al, 2004) has a more detailed description on using monthly varied R, T, and K parameters for a RDII study.

The RDII Analysis Tool includes basic statistical analysis functions for developing the correlations between observed precipitation conditions and system RDII responses. The correlation relates RDII responses with several factors such as rainfall characteristics (i.e., depth and intensity) and antecedent moisture conditions. The basic statistical methods included can support application where only limited data is available. It is important that the effects of antecedent moisture conditions are taken into account in deriving the ultimate R,T,K values. When adequate RDII data is available from long-term monitoring, advanced statistical methods such as multi-variable regression can be applied using commercially available statistical packages.

The RDII Analysis Tool is coded to perform the following three basic statistical analyses:

- Median R-value method
- Average R-value method
- Linear regression of R-value method

The RDII predictive analysis provides better results when long-term data are available. The accuracy and applicability of the predicted R,T,K parameters depend on the statistically significant number of wet-weather events available for analyses, the length of the flow monitoring period, the quality of the rainfall and flow data, and the nature of soil moisture conditions that prevailed during the monitoring period.

5.3.4.1 Median R-Value Method

As the name describes, this method selects the median total R-value from all analyzed wet-weather events at a selected flow meter as the representive RDII response. The median total R-value is then broken down into R_1, R_2, and R_3 parameters. The general procedures are:

- Computing the R_1, R_2, and R_3 distribution of all wet-weather events
- Averaging the distributions of all wet-weather events
- Applying the average distribution to the median total R values

Table 5-3 depicts the determination of median R-value, and the distribution of R values using the “median R-value method.”

The tool also determines the remaining RDII parameters (i.e., T and K) by averaging their values for all wet-weather events at a selected flow meter (Table 5-4).

Table 5-3. Example of "Median R-value Method" Application

RDII Analysis Results				**Distribution of**		
R_1	**R_2**	**R_3**	**Total R**	**R_1**	**R_2**	**R_3**
1%	3%	6%	10%	10%	30%	60%
3%	6%	11%	20%	15%	30%	55%
2%	4%	7%	13%	15.4%	30.8%	53.8%
Median Total R-value			13%			
Average R-value Distribution				13.5%	30.3%	56.3%
Representive RDII Response			13%	1.8%	3.9%	7.3%

Table 5-4. Example of RDII Analysis Results

	T_1	**T_2**	**T_3**	**K_1**	**K_2**	**K_3**
Event 1	1.5	4	7	1	2	3
Event 2	2	4.3	7.5	2	3.2	4
Event 3	1.3	3.9	6.7	1	2.3	3
Average	1.6	4.1	7.1	1.3	2.5	3.3

It is important to recognize the limitations of applying median values of R, T, K parameters for a sewershed considering wide variation of RDII responses due to varying rainfall and antecedent moisture conditions. For example, if there were only three rainfall events during a temporary flow monitoring period under a much below-normal precipitation condition, users should be cautious when using any kind of statistical approach discussed in this chapter to determine a statistically representative R-value distribution.

5.3.4.2 Average R-Values Method

Instead of using the median value to determine total R value, the method simply takes the average of all available R-values. The distributions of total R, T, and K values are determined using the same procedures as the median R-value method. Limitations should be recognized in applying the method to a sewershed.

5.3.4.3 Linear Regression Method

This method develops a linear relationship between total R value and total event rainfall depth or other system variables such as rainfall intensity and volume of events occurred a week prior to the currently analyzed wet-weather event. Figure 5-7 shows an example of the linear regression results. The results show that as the total rainfall volume increases, the total R value increases but with a wide variation. The tool determines the correlation using the linear regression method and provides the best fit relationship between total R-value and the total rainfall volume.

Users must be cautious when applying linear regression to predict RDII responses based on limited observed data or when there is a poor correlation of R value with a single variable such as total event rainfall depth. RDII is not dependent on the total rainfall depth alone. Other factors, such as GWI, antecedent moisture, rainfall intensity, and season, may contribute to the variability in the RDII response. As mentioned earlier, users may consider applying multi-variable regression methods available outside of SSOAP to determine the R,T,K parameters for unmetered and design conditions. The SSOAP user's manual provides guidance on how to apply multi-variable regression methods for a determination of R, T, K parameters.

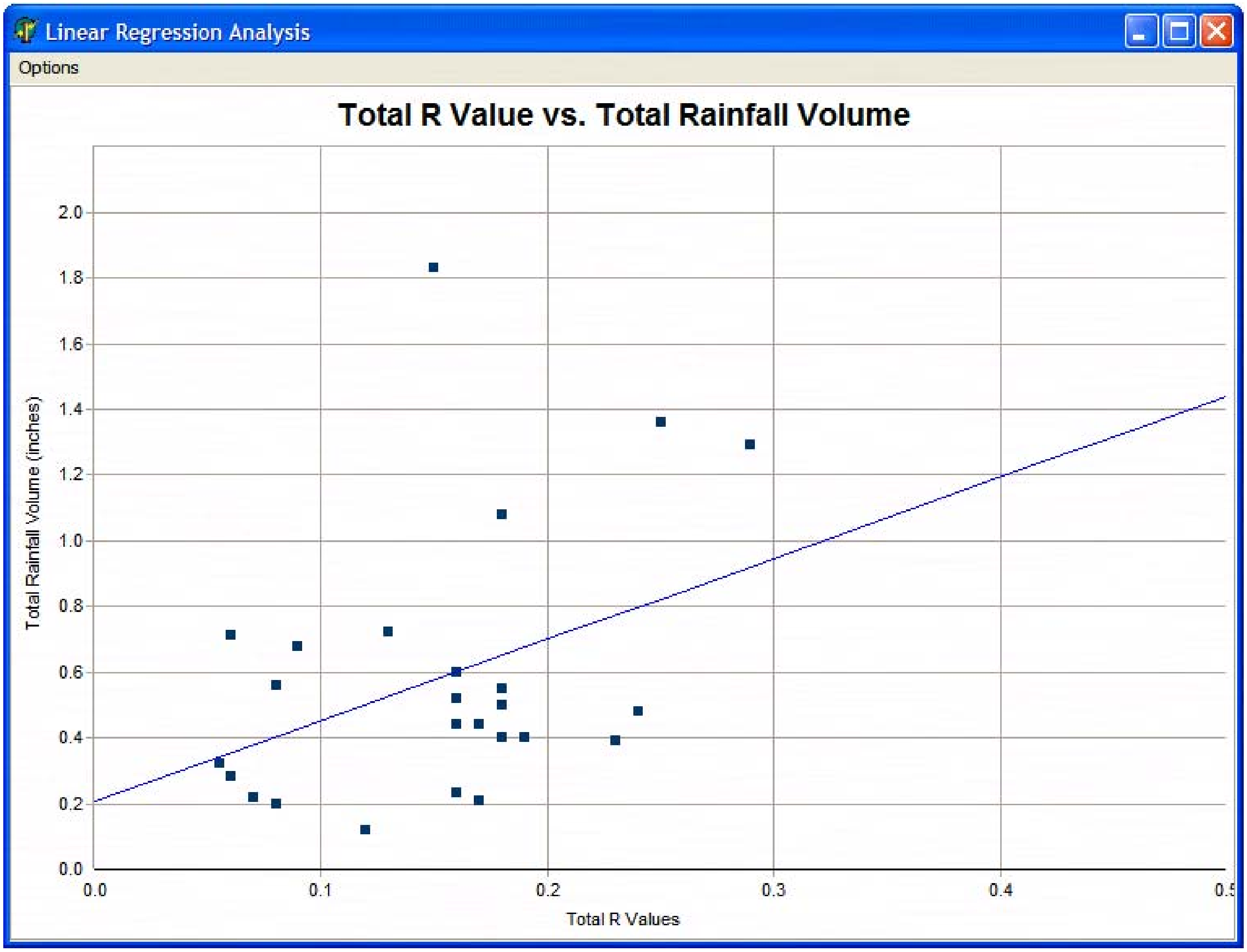


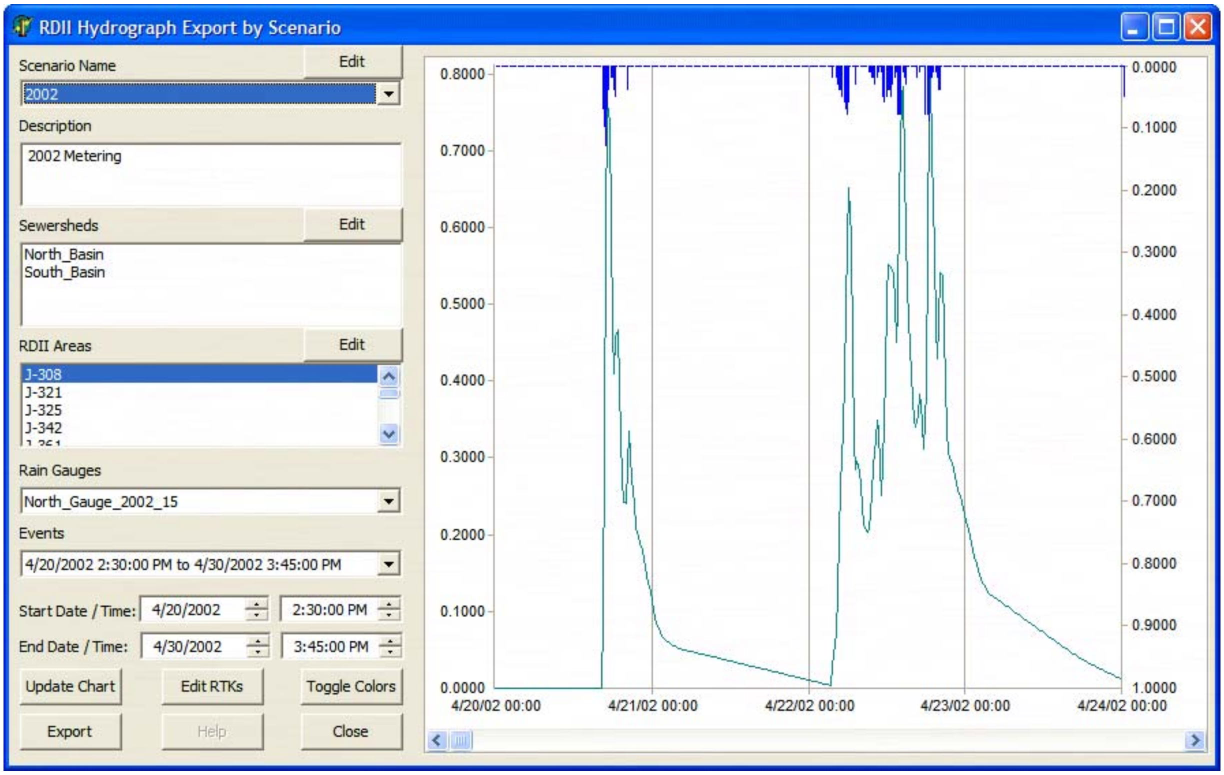
Figure 5-7. Example of a linear regression analysis.

5.4 RDII Hydrograph Generation Tool

This tool generates RDII hydrographs using R,T,K parameters determined by the RDII Analysis Tool using rainfall and sewershed area stored in SSD. To use the tool, users may select:

- Rainfall-event-specific R, T, K parameters from SSD, or
- R, T, K parameters from statistical analysis in RDII Analysis Tool, or
- Parameters derived from other analyses external to the SSOAP Toolbox.

This tool can export RDII hydrograph directly to an external file in SWMM5 or text file. Figure 5-8 shows the user interface of this tool:



Scenario Name: 2002

Description: 2002 Metering

Sewersheds:
North_Basin
South_Basin

RDII Areas:
J-308
J-321
J-325
J-342

Rain Gauges: North_Gauge_2002_15

Events: 4/20/2002 2:30:00 PM to 4/30/2002 3:45:00 PM

Start Date / Time: 4/20/2002 2:30:00 PM

End Date / Time: 4/30/2002 3:45:00 PM

Figure 5-8. User interface of the RDII Analysis Tool.

Within this tool, users can view the RDII hydrograph before exporting the data using the following options:

1. SWMM5 RDII Interface File – A SWMM5 inflow interface file containing RDII and DWF hydrographs.
2. Time-series file in SWMM 5 format – A text file with RDII hydrograph in SWMM 5 [TIMESERIES] format.
3. SWMM5 [RDII] and [Hydrograph] – A portion of SWMM5 input file with the RTK unit hydrograph parameters and sewer system information. The RDII hydrograph will be generated within SWMM5 based on the R,T,K input from the SSOAP Toolbox.
4. Time-series file – A time-series hydrograph in plain text. This format allows users to apply the RDII hydrographs to other hydraulic simulation models and other sewer system management analyses.

After generating the RDII hydrograph file using this tool, users can: (1) go to SWMM5 to arrange these hydrograph files manually before performing sewer routing; or, (2) use the SSOAP-SWMM5 Interface Tool to organize these hydrograph files within SSOAP.

5.5 SSOAP-SWMM5 Interface Tool

The SSOAP-SWMM5 Interface Tool performs three primary functions:

1. Incorporates the hydrographs generated by the RDII Hydrograph Generation Tool into SWMM 5 input files (SWMM5 pre-processing).
2. Performs SWMM5 simulation.
3. Delivers SWMM5 model simulation results to DMT where it organizes the model results in SSD (SWMM5 post-processing).

5.5.1 Pre-processing RDII Hydrographs

The Interface Tool allows users to integrate RDII hydrographs into a SWMM5 input file. The Tool first prompts users to specify the RDII hydrographs and corresponding flow loading locations within the model network and the location of a SWMM5 input file on the computer local hard drive or a network drive. Then the Interface Tool accesses the selected SWMM5 input file for integration of the RDII hydrographs at appropriate locations within the model network.

5.5.2 SWMM5 Simulation

The Interface Tool allows users to run SWMM5 within SSOAP for performing sewer hydraulic routing simulations. This is accomplished by selecting the SWMM5 engine from the SSOAP Toolbox window, and then clicking the appropriate menu option to start the model simulation. The actual SWMM5 model development and improvement are not part of the SSOAP Toolbox development effort. The SWMM5 user manual is the primary reference for the model. Chapter 6 outlines the model and calibration steps and discusses sewer system capacity assessments using model simulations.

5.5.3 Post-processing Model Results

After the SWMM5 model simulation is successfully completed and checked, users then can use the SSOAP-SWMM5 Interface Tool to import the model results into SSD. This interface tool can read a SWMM5 binary output file and extract pertinent data (e.g., flooding/overflow locations) to assess sewer system capacity. DMT will organize these data through scenario management functionalities previously described.

In summary, the SSOAP Toolbox includes a suite of useful tools to assist users in analyzing monitored data for predicting RDII in sanitary sewer systems and in running dynamic flow routing of sewers for the development of needed information that facilitates capacity analysis and planning. Users must have a good understanding of their sewer systems in order to make decisions with the help of the SSOAP Toolbox.

Chapter 6 Sewer System Model Development and Capacity Assessment

6.1 Introduction

This chapter describes the use of SWMM5 within the SSOAP Toolbox environment to perform a sanitary sewer system capacity assessment. References to the SWMM5 user's manual (EPA, 2007) are included throughout the chapter for users needing detailed assistance with model network development, input and output processing, and model execution.

General guidelines are provided on model development and application, and the steps typically used in establishing baseline conditions and performing capacity analysis. The specifics that can be applied to any study depend on many factors, including project objectives, data availability, funding, schedule, and needs and expectations of the stakeholders.

Before discussing the model development and capacity assessment guidelines, it is useful to reiterate the steps required to perform a capacity assessment for a typical sanitary system. These steps are shown in Figure 6-1 and summarized.

1. Define capacity assessment objectives
2. Collect data and review
    a. Review sewer system data/information and develop a data gap analysis to identify data needs to meet the capacity assessment objectives.
    b. Conduct field surveys/investigations to collect sewer system attribute data.
    c. Collect rainfall and flow monitoring data.
3. Develop RDII parameters and hydrographs using the SSOAP Toolbox
    a. Perform rainfall and flow data analysis using the Toolbox to derive RDII parameters and hydrographs.
4. Develop, calibrate, and verify model
    a. Develop a sewer system representation for SWMM5.
    b. Develop DWF model input and perform DWF model calibration.
    c. Select model calibration and verification rainfall events from the flow and rainfall monitoring data.
    d. Perform WWF model calibration and verification for the selected rainfall events.
5. Perform capacity assessment of the existing system
    a. Apply the calibrated model under various DWF and WWF assessment conditions.
    b. Perform assessment based on model simulation results to identify baseline sewer system capacity problems and develop SSO characteristics (frequency, duration, and volume).

Chapters 1 through 5 of this technical report addressed many aspects related to steps 1 through 3 listed above. Model development is described in Section 6.2. Capacity assessment approaches are described in Section 6.3.

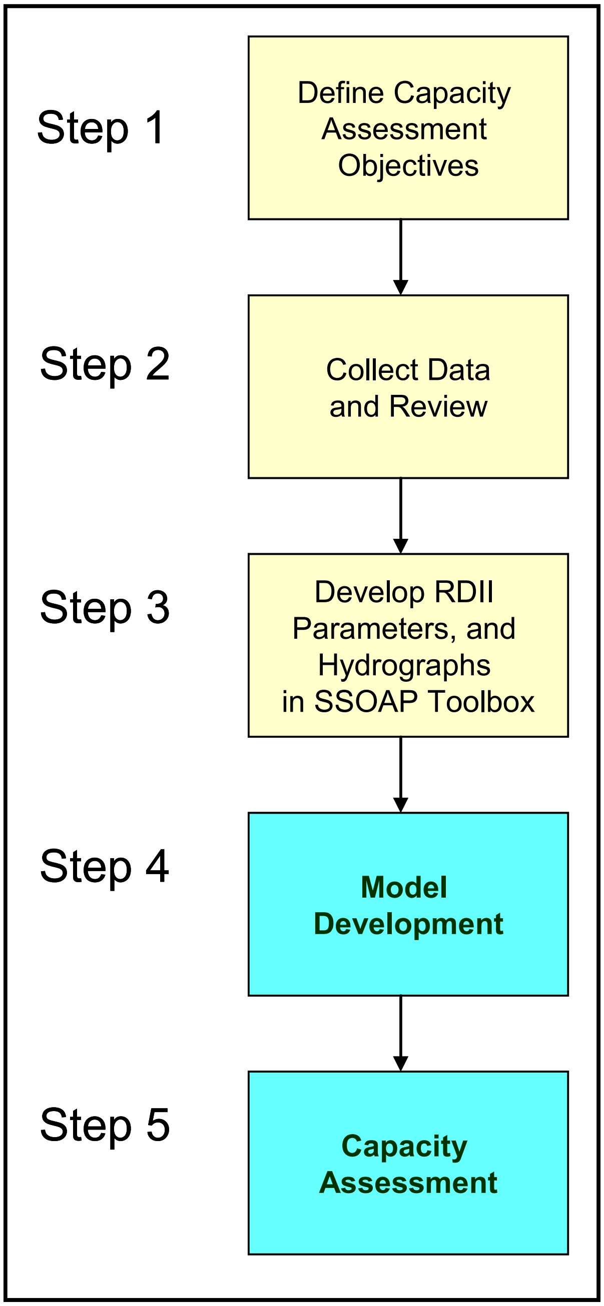


Figure 6-1. Capacity assessment steps for a typical sanitary sewer system.

6.2 Sewer Model Development

A properly developed hydrologic and hydraulic computer model can provide an effective means of evaluating the hydraulic capacity of a sanitary sewer system under DWF and WWF conditions. Model development includes data collection (discussed in Chapter 4), RDII analysis (discussed in Chapter 5), model input development, and model calibration and verification.

Figure 6-2 presents the breakdown of Step 4 of the sewer system capacity assessment steps discussed in Section 6.1.

This figure shows the sequence of activities required to develop model input data, calibrate, and verify a model based on RDII parameters estimated using the SSOAP Toolbox. As illustrated in Figure 6-2, Step 4 contains two components: (1) model input development; and (2) model calibration and verification.

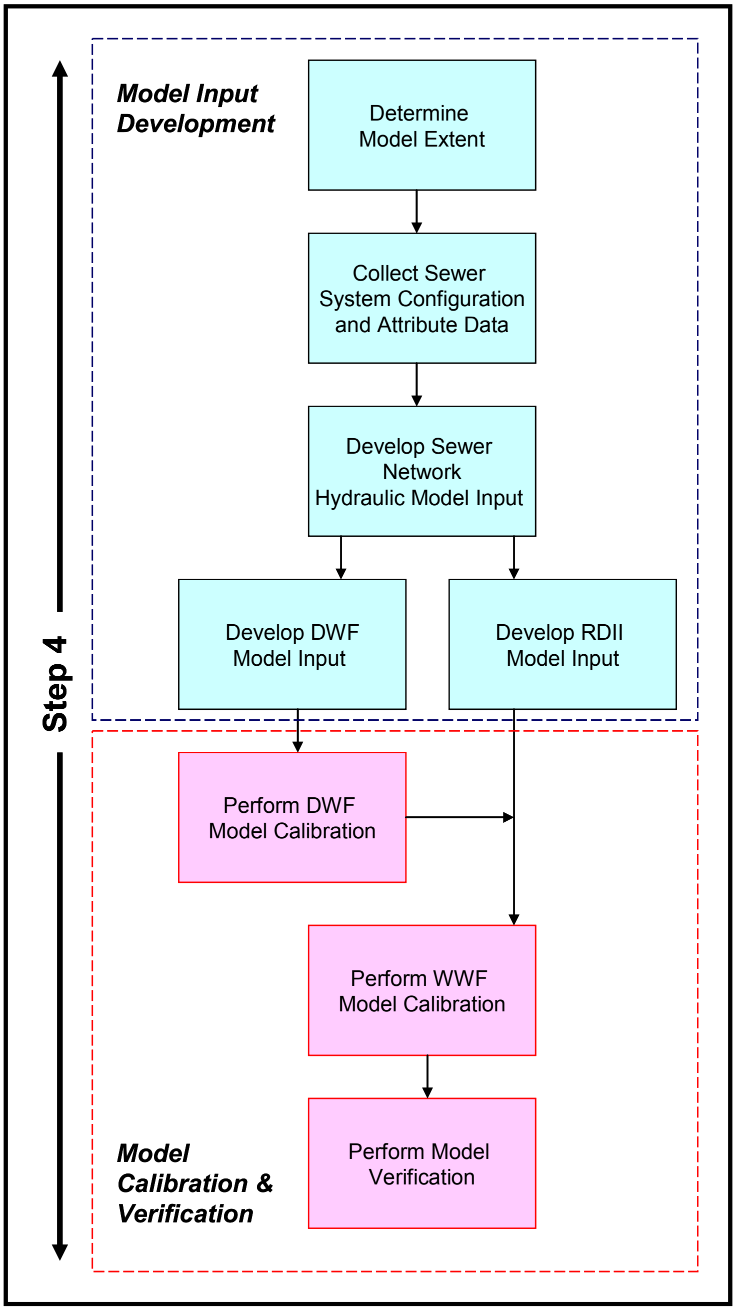


Figure 6-2. Model development, calibration, and verification.

6.2.1 Model Input Development

The goal of model input development is to develop an adequate model in SWMM5 that can fulfill the pre-determined objectives of the capacity assessments (Step 1). The upper part of Figure 6-2 depicts five key procedures in developing a model input for a sanitary sewer network:

- **Determine model extent –** Section 6.2.1.1 discusses how to determine the extent of a sanitary sewer network to fulfill the objectives of the capacity assessment.
- **Collect sewer system configuration and attribute data –** Section 6.2.1.2 describes the collection of sanitary sewer system characteristics and configuration for model development. Chapter 4 provides more in-depth guidelines and discussion on this topic.
- **Develop sanitary sewer network model input –** Section 6.2.1.3 outlines how to develop a sanitary sewer network model input in SWMM5 using the collected sewer system configuration and attribute data. It provides guidance on how to assure more accurate representation of a system's configuration. This section also illustrates ways to identify data inconsistencies and provides examples of data confirmation needs.
- **Develop RDII model input –** Section 6.2.1.4 discusses the hydrologic aspects of a sanitary sewer network. It provides guidance and examples on how to divide the study sanitary sewer service area into sewersheds and sub-sewersheds based on flow monitoring, RDII responses, and points of contribution to the sewer network.
- **Develop DWF model input –** Section 6.2.1.5 presents the two components of DWF: BWF and GWI, as well as suggestions on how to develop DWF data for a study area. In areas with significant projected growth, estimating future DWF is necessary to evaluate the impact of increases in wastewater flows on sewer system capacity.

6.2.1.1 Determine Model Network Extent

The initial step in developing model inputs is to determine the extent of the sanitary sewer network to be modeled. "Model network" refers to the hydraulic representation of a sewer system. Once the project objectives for the study area are defined, one should determine the level of details to be included in the model network extent. The level of details in the model is no longer, as in the past, limited by computer speed and memory. It is now more influenced by the following factors.

1. Capacity assessment objective
2. Size of the sanitary sewer system
3. Model boundary conditions
4. Availability of reliable sewer system data and existing flow monitoring program
5. Funding and schedule

A model network is often selected based on the previously mentioned criteria, but there are cases where some areas of the collection system are modeled in greater detail than other areas due to specific project objectives. For example, if the partial objective is to address customer flooding problems, the model may include a more explicit representation of the sewer system that directly receives the flow from the house or commercial property laterals. The following describes each of the above factors in more details:

Capacity assessment objectives

The objective of the capacity assessment is an important factor when determining the extent of a model network. One should determine what questions need to be answered. For example: what is the hydraulic performance of the entire sanitary system and the occurrence of SSOs? What are the hydraulic constraints in trunk sewers system? Which particular sewer reach has capacity constraints? What causes the sewer backups into basements? Does the existing system have adequate capacity for the anticipated future growth? What is the sewer performance during the dry-weather conditions?

After the study's objective is defined, it is a common practice to select threshold pipe sizes to include in the study. In general, the greater the extent of the model network, the greater its data needs will be and the greater the funds needed to develop the model. Typically, the location of SSOs in a sewershed will determine the upstream model extent. It is recommended that the model extents include sewers known to have SSO baseline characterizations of the system and to develop improvements to address the capacity limits. It must be emphasized that the smaller sized pipes (i.e., 8- and 10-in.-diameter) typically found in the upstream reaches of the system often represent the majority of the sanitary sewer system. Many of these 8- and 10-in. diameter sewers may have more than sufficient capacity and thus do not typically need to be included in the model network as a general rule.

The capacity assessment study often includes sewer performance assessments and consideration of future growth conditions that cause increases in baseflow. In this case, users should consider appropriate model extents within the existing system where future growth is projected to occur.

Collection system size
System sizes and complexity should be considered when determining the model extents. Large and complex systems may need a more focused approach to optimize modeling efforts and resource needs. Phased model development is one way to develop models for larger, more complex systems. In some cases, it may be appropriate to build a "coarse" model, initially, and then refine the model within areas of concern. In other cases, it may be appropriate to subdivide the system study area into separate smaller models that can be constructed sequentially or in parallel by multiple model development teams.

Typically, in large collection systems, the model extents do not include all sewers. The cost of developing a system-wide model increases when smaller diameter pipes are included, and can increase greatly if an electronic database of high quality attributes of the system is not readily available. A typical standard option in modeling the complete system is to include 8- and 10-in. diameter sewers in the modeling network, only in areas of known capacity related problems or otherwise needed to connect the system. On the other hand, the capacity analysis may focus only on trunk sewers. In this case, only larger pipe sizes (15, 18, or 21- in. and larger) are included, which could greatly reduce the modeling effort.

Model boundary conditions
Both upstream and downstream flow boundary conditions should be considered in determining the model extents. Effects from downstream capacity constrictions may impact the evaluations in upstream segments. The model should extend far enough below the area of interest so that the effect of downstream conditions is minimized. Alternatively, the model should terminate at a pump station or other locations where the downstream boundary conditions are known for all simulated conditions. The availability and knowledge of boundary conditions often dictate when and where a modeled sewer system can be divided into multiple models.

Availability of reliable sewer system attribute data and existing flow monitoring program
The amount of reliable system data that is readily available can influence the determination of the extent of the network model. Analysts should consider the magnitude of field investigation and survey work needed when determining the model extent. There may be cases where high quality attribute data exist in an electronic format that may allow inclusion of more sewer network than would otherwise be considered if attributes must be obtained from hard-copy drawings, field investigation, and surveys.

If the existing data from permanent or temporary meters are used for RDII analysis and model calibration, then the model network should include the locations where these meters are. For example, if the meters are located on a major trunk sewer, the model extent becomes coarse and is limited to the trunk sewers. The model network can be expanded upstream of the trunk sewers when flow monitoring data can be collected from the contributing sewershed areas along the trunk sewers. Alternatively, if the detailed existing flow data is available on both trunk sewers and the sewer network within the sewershed areas, the model network can be extended.

Funding and schedule realities
The available funds to perform a collection system capacity assessment study can significantly influence the extent of model development. In some cases, schedule constraints may determine model extents. The more extensive a model, the greater the need for field surveys and flow monitoring effort. In some cases where a high quality of sewer

attribute database is available, the needs of field surveys will be significantly reduced. These field activities are time consuming and cost intensive. Again, phasing the modeling efforts should be considered in large and complex systems. The objectives for the capacity assessment should be balanced with funding and schedule realities.

6.2.1.2 Collect System Configuration and Attribute Data

Once the extent of the sewer system model has been determined, the system configuration and attribute data must be collected from existing sources. Depending on completeness and quality of the existing data, field investigation and survey efforts may be required. In addition, rainfall and flow monitoring efforts may be required to supplement existing data. Chapter 4 describes typical data collection efforts in support of SSO planning and analysis.

6.2.1.3 Develop Sanitary Sewer Model Network

The sanitary sewer system attributes, including connectivity, are compiled as input to SWMM5. The SWMM5 user manual and software tutorial provide step-by-step instructions for developing a model.

In SWMM5, a user can represent the sanitary sewer network in a graphical environment by dragging and dropping the pre-defined sewer system components (e.g., pipes, manholes, pump stations, and weirs) in the software's Study Area Map window. The user can then manually assign attributes to each component with real or approximate coordinates and define the connectivity of the sewer system components. A background image of the service area can be imported to guide the setup of the sewer network.

In addition to SWMM5's network generation capabilities, software developers have created commercial interface products that provide tools to transfer existing sanitary sewer system data needed from a GIS/CAD package directly to the SWMM5 input file format.

Perform quality control of network data

The accuracy of the physical sewer system representation in the model directly impacts the accuracy of the model results. After sewer system attributes and configuration data for SWMM5 are prepared, quality control procedures are essential to assure that the system configuration is accurately represented and identify data inconsistencies and data confirmation needs. Identifying data gaps and resolution early will minimize adverse schedule and budget impacts while assuring the overall quality of the resulting model.

A typical quality check of a model network includes a sewer plan and profile from SWMM5 and a detailed review of other parameters not readily plotted such as pipe roughness, weir configuration, and pump operational settings. The plan views of the model are used to detect any gaps in connectivity data as shown in Figure 6-3.

The profile views help identify questionable sewer system attribute data (e.g., pipe invert, manhole invert and rim elevations) or data gaps as shown in Figure 6-4.

A review of other parameters not readily reviewed in plan or profile should be conducted by querying input data for values that fall outside a reasonable range. For example, the pipe roughness parameter can be sorted and reviewed to identify abnormally high or low values to investigate further if necessary.

When data problems are found, the modeler should first review the GIS and other data sources and attempt to resolve any data transfer problems. If the problem is not related to data transfer, then the problems should be resolved via additional intensive data collection efforts such as map/drawing collection, field survey, and field investigation. In some cases, it may be appropriate to fill in data based on engineering judgment. Missing manhole rim elevations may be estimated by topographic data, if the pipe diameter is inaccurate or missing, the diameter can usually be estimated from the diameters of the upstream and downstream sewers. Records should be kept where data are assumed. If these sections are later determined to be critical for sewer system capacity evaluation, additional field collection efforts should be conducted.

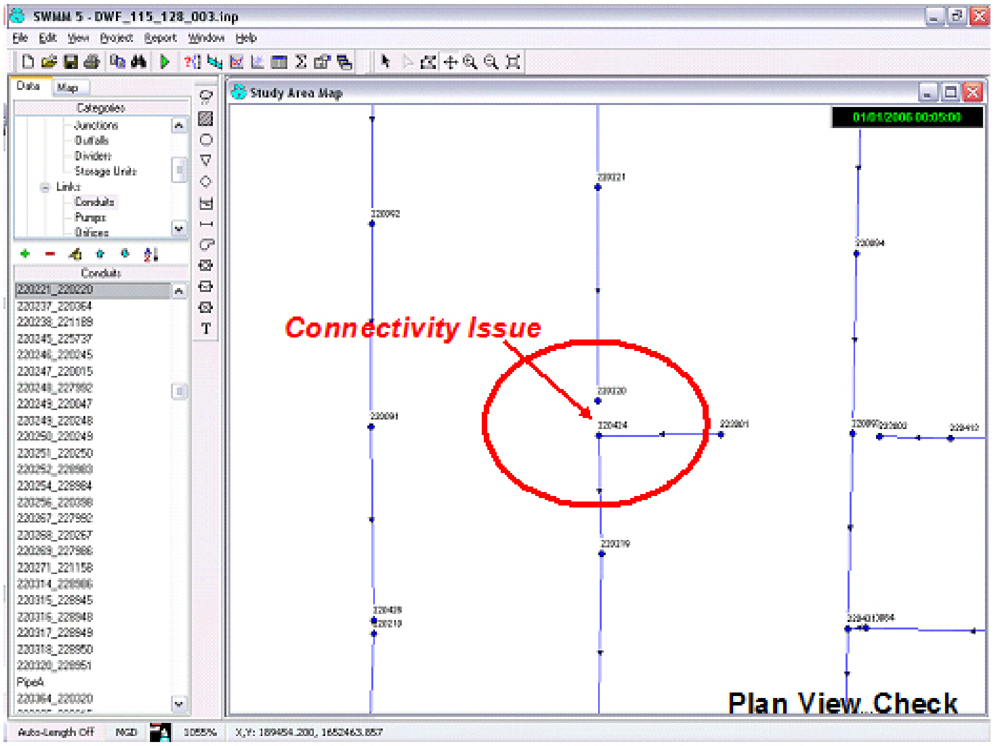


Figure 6-3. Model development plan view connectivity data check.

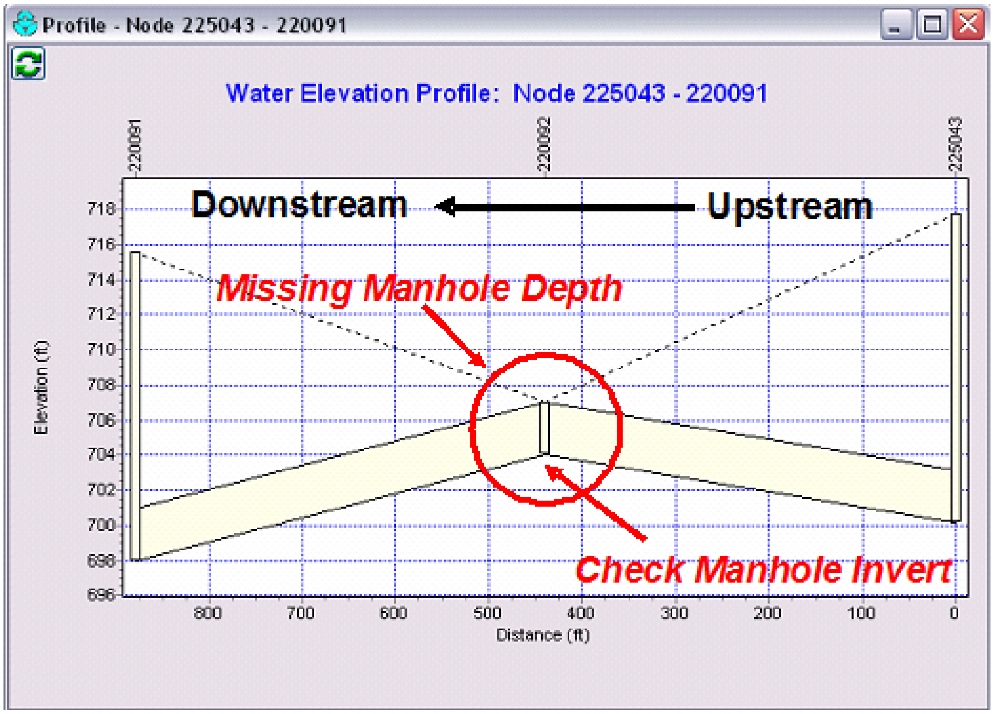


Figure 6-4. Model development sewer profile check.

For large complex models, additional quality control checks may be justified. For example, pipes with adverse (negative) slopes should be identified and verified. Similarly, locations where a larger diameter sewer enters a smaller diameter sewer should be reviewed, as this often identifies inaccurate model data. Other checks can be performed, such as where there are large drops at manholes and where the outgoing sewer invert of a manhole is higher than the influent sewers. Many of the commercially available modeling software include tools to perform these checks automatically.

Other system features may also need to be modeled in addition to the manholes and sewers. These include:

- **Wastewater pumping stations**
- **Control structures** (e.g., weirs, dams or gates used to control the splitting of flows in downstream sewers)

Once the network connectivity is confirmed using SWMM5 plan and profile views and general reasonableness of parameter values, additional quality control checks can be made to assure the flow routing through the model network makes sense in general terms. This is accomplished by performing a model simulation with assumed flow inputs at the upstream flow loading manholes within the model network. If the model simulation is completed successfully and flow balance is preserved, and hydrodynamic profiles in SWMM5 are appropriate, then the model network is ready for the next steps in model development.

6.2.1.4 Develop Sewershed Delineations

The first step in preparing the hydrologic model for a sanitary sewer system is to divide the service area into smaller areas tributary to the flow monitoring locations. This process is called sewershed delineation. The flow monitoring data and rainfall data, described in Chapter 4, and the delineation results, are the three key parameters to determine RDII using the SSOAP Toolbox. Also, these delineated small areas are the building block of the hydrologic model in SWMM5.

The level of delineation depends on the extent of the sanitary sewer network model. In general, a model may contain up to four working levels of delineation:

- **Service Area –** all areas tributary to a wastewater treatment plant (WWWT)
- **Sewershed areas –** subdivisions of a service area, delineating sewers directed to point of treatment or a major trunk sewer
- **Sub-sewershed areas –** subdivisions of a sewershed, delineating sewers directed to second tier points of interest such as metering locations, districts, or SSOs
- **RDII catchment areas –** subdivisions of subsewersheds, delineating sewers directed to model hydraulic loading nodes

These levels of delineation will be used to organize and manage the hydrologic model datasets. Figure 6-7 illustrates the application of these three levels in a single service area.

The sewershed area is the coarsest level of delineation within the service area tributary to a WWTP. The service area can include one or many sewersheds. Figure 6-5 shows the entire service area and sewersheds for a hypothetical sanitary sewer system.

A sewershed may be subdivided into sub-sewersheds. Typically, a sub-sewershed is delineated at flow monitoring locations. Each flow monitor may have different RDII responses. Therefore, the hydrologic modeling work is typically organized at this level.

The sub-sewersheds can be further delineated into RDII catchments, the finest level of delineation. RDII catchments are drainage areas associated with each flow loading point (i.e., manhole) in the modeled sewer network. A sub-

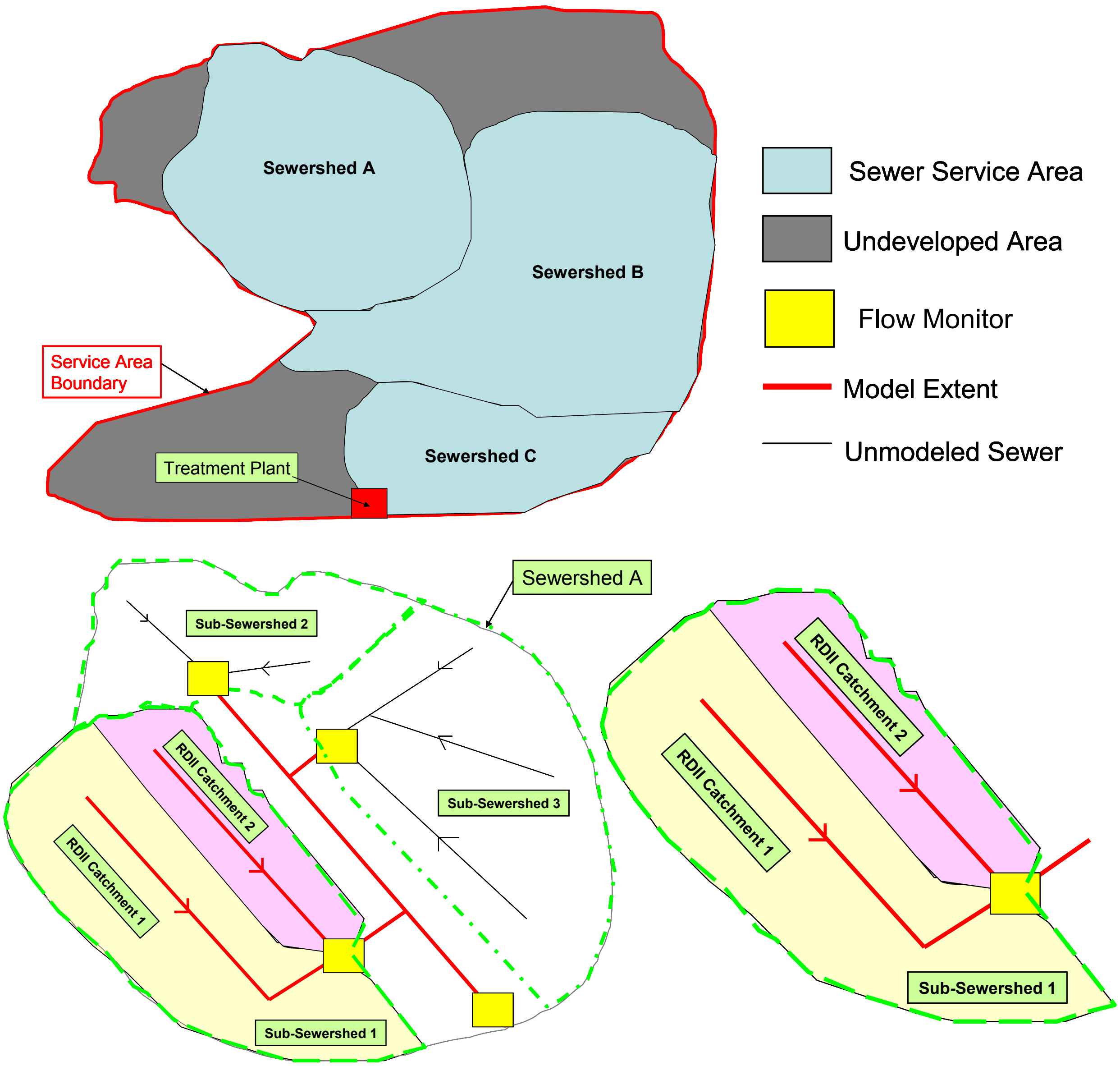


Figure 6-5. Example of service area delineation.

sewershed can contain a number of RDII catchments tributary to the manhole where the flow meter is located.

The delineation will typically be made according to the location of sewers, parcel boundaries and topographic data. In many cases to expedite delineation, the identified RDII catchments, sub-sewersheds, and sewersheds may include areas that are not sewered, such as cemeteries, park land, highway rights-of-way, stream valleys, golf courses, undeveloped areas, or areas on septic systems. Given the delineated area, the sewered area can be determined by subtracting an estimate of the unsewered areas to allow a more accurate estimate of R-values required for model input. For example, GIS procedures can be used to estimate unsewered areas for each RDII catchment based on parcels that are not developed or based on percentages of predominantly sewered versus non-sewered land-use definitions. Alternatively, aerial photography or mapping can be used to subtract large unsewered areas from the sewered area calculation.

6.2.1.5 Develop DWF Components

There are two components of DWF: BWF; and GWI. In many studies, the observed DWFs will be decomposed into these two components. This decomposition process is not exact. Often, various assumptions are required. Typically, DWF, BWF, and GWI are determined from metering data either installed in the collection system or located at wastewater pumping stations or wastewater treatment plants. Alternative procedures can be used to estimate BWF from water consumption or demographic data, but these will typically be adjusted to match the flows observed at these flow meters.

It is often not necessary to separate a DWF into its GWI and BWF components in sanitary sewer system modeling evaluations. The SSOAP toolbox only requires a lumped DWF (GWI and DWF) to determine the RDII flow. However, it is useful to estimate GWI for prioritizing areas with large values for more detailed sewer system evaluations and rehabilitation. Further, understanding GWI contributions lends insight into the seasonal variation observed in DWF. This seasonal variation in DWF used to develop monthly values for input to SWMM5.

While DWF should be accurately determined, DWF is typically a smaller portion of the total peak flows that can be generated in many wastewater collection systems under WWF conditions. Accurately determining the WWF component is typically more critical in performing a successful sanitary sewer system capacity evaluation.

BWF Component

BWF refers to the sanitary flow component, which includes commercial, industrial, and residential flows discharged to the sanitary sewers for treatment. This is sometimes referred to as base sanitary flow. There are many approaches to developing BWF. One approach uses population data, generally derived from land use or census data, together with an assumed unit wastewater flow rate (gallons per day per capita). Flow monitoring data within the system, as well as flow data collected at the WWTP, are then used to define the composite base flow (BWF plus GWI). Finally, the difference between the observed DWF and the computed BWF is attributed to GWI. This procedure normally requires allocating WWTP flows to individual modeled sewersheds, which introduces uncertainty, as the actual BWF from a basin may be very different from the allocated amount. For this reason, other approaches, such as using water-use records with an estimated rate of return, have recently been used more frequently in lieu of population data as a basis for estimation of BWF.

Water use is a more reliable basis for BWF estimates, and the data is generally available at a better resolution. In fact, the resolution is so fine (at individual parcel level) that processing and storing the large datasets has only become feasible recently with the advent of GIS capabilities. As the use of automated meter reading (AMR) becomes more widespread, more detailed water use data will be available, thus further increasing the benefits and accuracy of this approach.

If a water usage method is chosen, the winter-month water use is recommended for estimating the BWF. During winter months, it is expected that only a small percentage of the total water use will be for lawn irrigation. Alternatively, land use and population data may be used to support the DWF input generation. The diurnal flow patterns can then be established using the DWF analysis of the observed flow data at the nearest downstream location. These patterns are then applied to the average BWF from each sub-sewershed and RDII catchment that are estimated based on the average water consumption rates.

Vallabhaneni et al. (2002c) published detailed procedures for using water billing records for DWF model development and calibration. The procedures involved compiling water billing records geographically within the sanitary sewer service area, developing BWF for each RDII catchment based on actual water consumed, and estimating GWI and diurnal variations based on the downstream flow meter data. Water meter data should be reviewed to detect reading errors.

While water use data is one potential source for develping GWI and BWF rates, another approach may be used to obtain the minimum nighttime flows at the permanent or temporary flow meters. All of the minimum nighttime flows are expected to be attributable to GWI. These minimum flows include a nominal and constant BWF.

No matter which approach is used to distribute the DWFs, large sources of wastewater flow, such as from industries, water treatment plants, commercial establishments, should be taken into consideration in distributing the wastewater flows within the upstream sewersheds.

GWI Component

GWI can be estimated from four sources of data described below. Each data source provides increasingly less precise estimates, but covers increasingly larger areas.

1. **Direct GWI measurement –** Flow isolation studies can be used to estimate GWI flows during a nighttime metering when the BWF is small. GWI estimates are developed via direct measurement using temporary weirs installed at the desired sites. Seasonal variations of GWI for the test sites is established and used (together with long-term WWTP or other meter flow records) to project seasonal variations across the entire system. These data can be combined with data from installed pieziometers, which provide long-term groundwater level data within the study area to improve the understanding of these seasonal groundwater variations and their influence on GWI rates.
2. **Inferred GWI measurement –** The network of flow monitors for model calibration provides data that can be used to estimate GWI throughout the system. This can be accomplished in the smaller basin areas where an assumed fraction (usually between 80 and 90 percent in predominantly residential areas) of the minimum diurnal low flows can be attributed primarily to GWI. However, the fraction can go as low as 50 percent depending on the demographics, such as college towns, business districts, and industrial areas.
3. **Water consumption data –** BWF can be estimated as a percentage of water consumption. This percentage is often referred to as the rate of return. The difference between DWF and BSF can be used to compute the GWI flows. The initial BWF estimates are developed by assuming that 80 to 90 percent of the water consumed in a predominant residential area is eventually discharged into the wastewater collection system.
4. **WWTP flow-based estimates –** At the WWTP service area level, GWI is attributed to the difference between observed DWF and the estimated BWF for the service area. WWTP plant influent flow records can be used to develop DWF estimates. In smaller sewer systems this approach can yield better results.

Taken together, the above sources of data will support seasonally adjusted GWI estimates at the modeled-sewershed level.

The estimated BWF, together with appropriate diurnal patterns and GWI estimates, should be used as flow inputs to the model and then calibrated using the observed flow monitoring data during dry periods. The estimated wastewater return rates and GWI are adjusted during the model calibration.

GWI rates determined at a meter will typically be distributed to the upstream sub-sewersheds and RDII catchments based on the sewered area or sewer inch-miles. Sewer inch-miles equal the sum of the sewer length in miles times the sewer diameter in inches for the sewer segments within an RDII catchment or sub-sewershed.

6.2.1.6 Develop RDII Characteristics

Rainfall and flow monitoring data should be analyzed using the SSOAP Toolbox to develop an understanding of the system RDII characteristics for each sewershed/sub-sewershed/catchment. Chapter 5 describes how to perform flow and rainfall analysis, develop R,T,K parameters, and generate RDII hydrographs. The R,T,K values or RDII hydrographs for specific precipitation conditions will then be input into SWMM5 for hydraulic routing.

6.2.2 Model Calibration and Verification

Model calibration and verification is a critical step in ensuring that the model properly simulates the prototype system over a range of storm events under existing conditions. As described in Chapter 4, rainfall and flow data collection programs are critical for a successful model calibration and verification. During a model calibration, the selected rainfall data are used as model input, and the observed flow data are compared with the model simulation results. This is followed by successive applications of the model, during which initial estimates of calibration parameters are adjusted until the simulated results reasonably match the observed data.

A numerical goal for the model calibration should be established to assure that the model simulation results are adequately correlated with the observed flow data. The goal of the model accuracy should be established based on the quality achieved in the flow monitoring data. The factors for consideration include the specific objectives for the capacity assessment, model extents and detail, rainfall data accuracy and precision, the spatial resolution, and data accuracy and precision of the flow monitoring program. In general, a greater degree of model accuracy can be achieved with a detailed model representation of the sewer system, extensive field surveys/investigations, flow monitoring and rainfall monitoring at strategic locations, focused model calibration and verification efforts. This can be very time/cost intensive. The calibration goal must achieve a balance between the capacity assessment objectives and resources and schedule constraints. Flow characteristics, and the shape of flow hydrographs for comparison between the simulated model results and the observed flow data, include peak flow depth, peak flow rate, and volume. It must be emphasized that only reliable portions of observed flow monitoring data should be used in making the correlation analysis.

Model calibration and verification is a three-step process, involving:

1. DWF calibration
2. WWF calibration
3. WWF verification

A brief discussion of these steps follows.

6.2.2.1 DWF Calibration

The purpose of the DWF calibration is to ensure the model is able to properly represent sewer characteristics under existing DWF conditions. This process will also help develop a proper understanding of the sewer network hydraulics without the influence from a rainfall-derived hydrologic response.

Once DWF is routed through the collection system, the simulated DWF hydrographs can be compared with the observed DWF response at each flow meter location. The difference between the observed flow and the computed BWF is attributed to GWI and uncertainties in the wastewater return rates assumed for initial BWF estimates. DWF model calibration involves adjusting the lumped parameter, which includes the initial estimate of wastewater return rates and the magnitude of the GWI component. In addition, minor adjustments may be necessary to improve correlation of the timing of the simulated diurnal flows with the observed DWF data.

Groundwater elevations, and thus GWI rates, may vary considerably over the course of the year in response to seasonal rainfall trends, the growing season, and other factors. The modeler should decide whether a winter/spring high groundwater condition is the desired condition to be simulated. This decision should also consider the selection of the wet-weather rainfall condition that will be simulated as the rainfall frequency statistics for many parts of the country are driven by short-duration, high intensity rainfall events that occur in the summer or fall. Model simulations should not combine GWI rates for one season with rainfall conditions from another season without considering the joint probabilities of these conditions occurring at the same time.

The "Time Series" feature in SWMM5 allows the analyst to view the simulated hydrograph and the observed DWF response. The following calibration metrics should be checked for correlation between the simulated and observed data:

- Peak water depths

- Peak flow rates
- Volume
- Hydrograph shape

Where significant differences occur in the above metrics, the appropriate model parameters should be adjusted while keeping the parameters within an acceptable range. Users should focus on the following elements in DWF calibration.

- Estimates of DWF (BWF and GWI.)
- Manning's roughness coefficient (n-value) and friction loss in the system. This parameter can affect depths of flow in the system and available system capacity.
- Physical system components involving uncertainty (e.g., unknown flow dividers, hydraulic blockage, and sediment.)
- Possible large water dischargers, such as from industries that could affect estimated GWI rates.

Model calibration is an iterative process. The target is to achieve reasonable correlations between the model results and observed data. First, the analysis should match flow depth [or hydraulic grade line (HGL)], then match peak flow and volume, and subsequently go back and confirm that the depth correlation is still valid. Typically, the observed depth data is more reliable than the velocity data which is used to estimate flow rates. In cases where the velocity data is questionable, the model calibration goal can still be achieved by calibrating to the depth data only.

DWF model calibration can be useful in identifying possible system operation problems due to major root intrusion or major sediment deposition in trunk sewers. For example, an unusually high pipe roughness coefficient needed to achieve model calibration is an indication of some blockages in the sewer.

6.2.2.2 WWF Calibration and Verification

The goal of WWF calibration and verification is to ensure the accuracy of the sewer system model in estimating WWF response (i.e., peak HGL, peak flow rates, and surcharge/overflow). Selection of rainfall events that generate a desired range of RDII responses is critical for model calibration and verification. At least two storms from the flow monitoring data should be selected for model calibration and one independent event for verification. Additional events may be necessary in some cases when a higher degree of confidence is needed and adequate time and resources are available. Reliable flow and rain data must be available for as many of the installed flow and rainfall monitors as possible for the selected event.

The storm events selected for WWF calibration will produce sewer-system responses under varying antecedent moisture conditions. Where resources are permitted, continuous rainfall records may be considered for calibration and verification. The storm event selection should also consider the proposed use of the model. If the model will be used to simulate peak flows for a design storm event, then the model calibration should focus on large events as close as possible to the design storm. If, on the other hand, the model is going to be used for continuous simulations to determine peak flows and flow volumes to be stored, then the calibration events should include a range in events.

Model simulation

Once users have identified the WWF calibration events and obtained appropriate RDII hydrographs using the SSOAP Toolbox, they can perform model simulations using SWMM5. (See Chapter 5 and the SSOAP Toolbox user manual for guidance on how to generate RDII input hydrographs and link them to SWMM5.) This section provides guidance on selecting typical model simulation parameters, such as solution technique, simulation time step, and simulation duration. The selection varies depending on a sewer system's configuration and complexity. The following provides three considerations in performing model simulation using SWMM5.

Solution technique – It is recommended that the Dynamic Wave Routing option (full Saint Venant equations) be used for sanitary system modeling to perform capacity assessment that includes surcharge and overflow analysis.

Please refer to Chapter 3 for a discussion of the dynamic wave flow routing option, and to the SWMM5 user manual or online SWMM5 help for specific information on this option. Other solution techniques are discussed in the SWMM5 user manual.

Simulation time step – It is a good general practice to use 5 seconds or less time steps for single event simulation. For complex systems, a smaller time step is usually required to maintain stability during the computations and to achieve continuity errors no more than 2 percent. Users may also use the variable time-step option in SWMM5, where the program will automatically decrease the simulation time step when needed. For simpler system networks, the simulation time step can be larger.

Simulation duration – The model simulation should last long enough to capture the collection system's full response to a rainfall event. The duration is determined based on the sewersheds RDII response characteristics. For a sewer system that exhibits a drawn-out response to rainfall (i.e., prolonged infiltration), simulation duration beyond the last time step of rainfall event may be warranted. In some cases, this could be several hours to days depending on the size of the sewershed. A review of the observed flow data at downstream locations which reflect the flow travel time through the system will provide a basis to estimate the proper simulation duration. For continuous simulation, the duration depends on the rainfall period of record selected and the rainfall distributions at the end of the selected period.

WWF calibration

The model calibration efforts should first include the adjustment of DWF to reflect pre-rainfall event GWI conditions. This adjustment is necessary to establish pre-event specific conditions to allow calibration to the wet-weather response only without introducing error due to DWF temporal variation. This adjustment must be performed because the DWF in the SSOAP Toolbox is determined through averaging the flow rates for multiple dry days during the flow monitoring period. The GWI varies gradually through seasons. Therefore, the DWF before each wet-weather event must be adjusted to reflect the changes in GWI. The variation in GWI is typically of lower magnitude for shorter-term periods (one to four months) and becomes more significant in longer-term (annual and year-to-year.) DWF returns to DWF-calibrated conditions following the wet-weather calibration for use in subsequent analyses. Once appropriate pre-rainfall event antecedent DWF is established, model simulations are performed to calibrate the wet-weather parameters.

Model calibration and verification are performed with SWMM5 for the selected rainfall events using the estimated R, T, and K parameters and RDII hydrographs derived from flow monitoring data. During wet-weather model calibration, the estimated hydraulic characteristics of the sewers such as pipe roughness pump station characteristics and flow diversion structures (such as weirs, dams, orifices) may need additional adjustments beyond refinements through the dry-weather calibration. This is primarily due to the full range of flow rates that occur during wet-weather conditions compared to low flow rates observed during dry weather.

In some cases, when the model extends sufficiently far upstream of the flow meter location with multiple flow loading points, the T and K parameters may need adjustment to account for the flow-travel times from the model flow loading points to the downstream flow meter location where the initial R, T, and K parameters were derived.

Like the DWF calibration, the following calibration parameters are commonly used to compare the simulated and observed data:

- Peak water depths
- Peak flow rates
- Volume
- Hydrograph shape

WWF verification

After the model is adequately calibrated based on the reliable data from the flow monitoring program, rainfall collection program, and understanding of the sewer network system, it must be verified using at least one additional independent rainfall event. To confirm the model parameters, verification can also be performed using a continuous simulation for an extended period with multiple rainfall events. Typically, the extended period can last a few weeks or a few months depending on the data availability. Continuous simulations will ensure that the model can accurately predict the dry- and wet-weather flow under different antecedent moisture conditions, and confirm the model performance under back-to-back wet-weather conditions.

6.3 Capacity Assessment

The framework for the capacity assessment should be consistent with overall SSO control objectives and stakeholder expectations. It is critical to develop capacity assessment goals specific for each study. The sanitary sewer system wet-weather flow management plan requires a sophisticated hydraulic capacity analysis. The flow monitoring data is used for understanding of the system behavior at the point of measurement during the monitoring time period and for calibration of the sewer system hydraulic model. The calibrated model is then applied for selected combinations of precipitation, antecedent moisture, and groundwater conditions to assess the system performance. Through the model application, the sewer system capacity is assessed and the baseline hydraulic conditions are established.

6.3.1 Capacity Assessment Steps

There are two key steps in capacity assessment:

1. Establish specific capacity assessment goals.
2. Determine baseline system hydraulic performance under existing and future projected growth conditions.

6.3.1.1 Capacity Assessment Goals

Capacity assessment goals must be established early in a SSO control analysis and planning. These goals must consider the system's unique configurations, hydraulic capacity challenges, types of overflows, stakeholders' expectations, and socio-economic conditions. Some common goals for capacity assessments include:

1. Identify locations and causes of sewer system hydraulic constraints.
2. Assess pump station hydraulic performance.
3. Assess the WWTP's ability to handle RDII.
4. Assess sewer system hydraulic constraints in the context of inadequate maintenance, hydraulic capacity, and excessive RDII.
5. Assess the performance of the existing system under future population growth scenarios.
6. Assess customer sewer back-ups, manhole-flooding locations, and overflows to waterways.
7. Assess how existing system performance will be improved by currently planned sewer rehabilitation and improvement projects.
8. Define performance expectations.

6.3.1.2 Baseline Hydraulic Performance Assessment

Baseline hydraulic conditions are defined as the DWF and WWF hydraulic responses under the current sanitary sewer system configuration. This baseline assessment provides the basis for a system-wide characterization of the problem, identification of problem areas, and ranking of improvement needs. In addition, baseline conditions are used to measure a municipality's progress in improving system performance as projects are implemented to address the capacity problems.

DWF capacity assessment:

The first step is to perform model simulation with DWF input to assess sewer capacity during peak diurnal flow conditions, identify capacity constraints, and assess GWI impacts on the DWF capacity. Existing sewers are then assessed for the projected future DWF. This assessment will provide insights of the existing sewer network's capability to accommodate future flows from population growth and service area extensions. The goals established for the capacity assessment may require DWF evaluations for a range of future growth conditions (two, five, 10 or 20 years.) Running the model for multiple future growth scenarios allows the development of priorities and implementation schedules for identified projects to address future capacity needs. Table 6-1 shows an example of DWF capacity assessment results. In this example, most of the sewer sections have the ability to perform under existing and up to five-year growth conditions. However, some sections of the system would not have the capacity for the 20-year growth conditions. The whole sewer system is flowing more than half full during the peak DWF under 20-year growth conditions, indicating the potential needs of system improvements 20 years into the future**.**

Table 6-1. Example DWF Capacity Assessment Results under Different Conditions

Interceptor	Pipe Dia. (in.)	Existing DWF Conditions			5-Year Growth DWF Conditions			20-Year Growth DWF Conditions		
		Peak Depth (in.)	Cap. Taken	Cap. Remain	Peak Depth (in.)	Cap. Taken	Cap. Remain	Peak Depth (in.)	Cap. Taken	Cap. Remain
Section 1	36	13	36%	64%	15	42%	58%	20	56%	44%
Section 2	42	17	40%	60%	25	60%	40%	35	83%	17%
Section 3	36	23	64%	36%	28	78%	22%	37	**100%**	**0%**
Section 4	36	19	53%	47%	21	58%	42%	25	69%	31%
Section 5	60	23	38%	62%	29	48%	52%	40	67%	33%
Section 6	60	23	38%	62%	31	52%	48%	62	**100%**	**0%**

WWF capacity assessment

Once the existing sewer system's ability to manage the current and future DWF flows are understood, a WWF capacity assessment can be performed to establish baseline conditions. The WWF capacity assessment should be comprehensive and consistent with the capacity assessment objectives established. A vast number of possibilities exist in defining the assessment scenarios depending on unique problems of a sewer system. The following general scenarios are commonly considered:

1. **WWF capacity assessment with existing DWF during the rainfall/flow monitoring conditions** − This assessment characterizes system behavior during the period of observed flow data and further validates model reliability. If resources are available, conducting continuous simulation for the duration of a monitoring period and assessing the magnitude and recurrence of capacity constraints and resulting surcharge and overflow conditions is recommended. The result is a clear definition of the system WWF capacity under monitored conditions throughout the sewer network modeled.
2. **WWF capacity assessment with future DWF projections with selected rainfall events during the monitoring program −** This assessment provides insight into potential system problems with the existing system configuration if the projected increase in DWF occurs.
3. **WWF capacity assessment with existing DWF and selected design storm conditions** − This assessment applies to an unmonitored design storm (synthetic or natural) and a model with the existing system configuration and existing DWF. In some cases, this may be based on a historic storm with rainfall volume scaled up or down to meet desired design storm intensity or volume. Some studies have used a design storm based on a standard distribution such as the Natural Resources Conservation Service (formerly U.S. Soil Conservation Service -SCS) Type II rainfall distribution. Caution is advised when selecting a design storm. The design storm definition should be consistent with the performance expectations for the individual sewer system. It should be recognized, however, that the simulated peak flows in most cases will not have the same return period as the rainfall event because of the many other conditions that influence peak wastewater flows

(i.e., antecedent moisture conditions, groundwater elevations.)

This scenario establishes the baseline conditions that characterize the sewer system capacity constraints and overflows. For the unmonitored design storm conditions, there are different approaches available for deriving the RDII parameters. Chapter 5 introduces four statistical/regression approaches to determine R,T,K parameters for those conditions.

4. **WWF capacity assessment with existing DWF and selected long-term historical precipitation period –** This assessment allows the user to characterize system behavior over a long-term historical period (in the order of one to 10 years) and a range of rainfall conditions and antecedent moisture conditions. It supports a comprehensive review of average annual system overflow frequency, volume, and duration characteristics. This work will be time-consuming and cost-intensive, but it would yield high confidence in establishing baseline conditions.
5. **WWF capacity assessment with future DWF and selected design storm conditions –** This assessment provides insight into potential system problems with the existing system configuration if the projected increase in DWF occurs under design storm conditions.

Review of model results
The following assessment parameters are usually used to review model results for DWF and WWF capacity assessment simulations. The graphical capabilities is SWMM5 facilitate the system wide assessment of these parameters:

- Sewer capacity use
- Sewer surcharge levels
- Manhole flooding
- Overflows

A sewer surcharge occurs when the HGL is in excess of the sewer's crown elevation and a manhole is flooded is when the HGL is in excess of the manhole ground elevation. It is generally uncommon to experience manhole flooding, sewer back-ups,and overflows under DWF conditions. However, they do occur because of temporary blockages in the system or operational problems *at pump stations and WWTP facilities.*

Sewer capacity use: This is a very common assessment parameter, as sewers are designed to use only a portion of full-pipe capacity under dry-weather conditions. Pipe capacity use can be evaluated based on flow rate and flow depth. The sewer flow capacity use is calculated by the ratio of the simulated peak flow to the design flow of a conduit in percentage. The sewer depth capacity use is calculated by the ratio of the simulated peak depth to the size of the pipe in percentage.

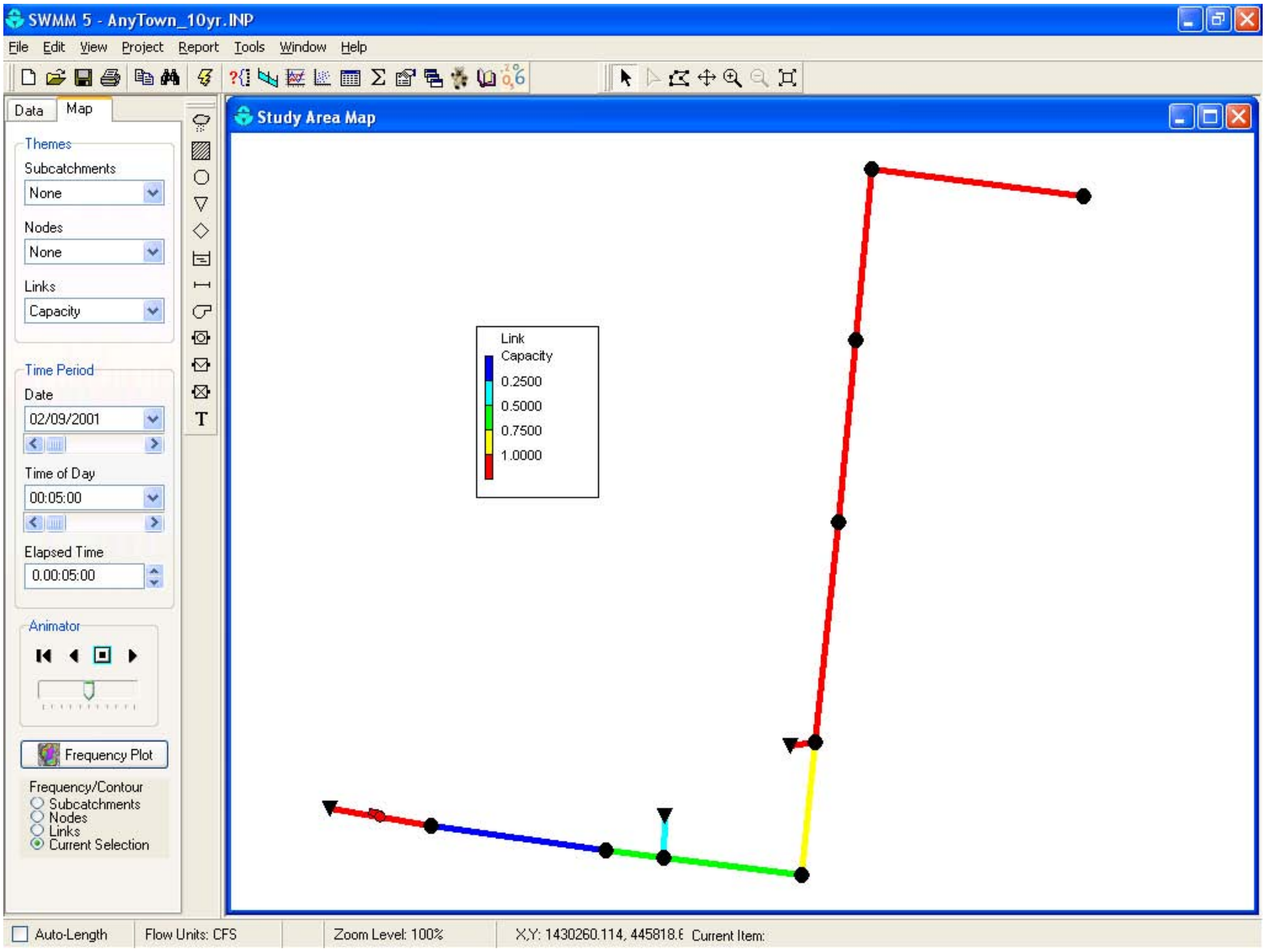
Full-flow sewer capacity based on the pipe slope is conservative in that it does not recognize the fact that many sewer systems can be allowed to surcharge to some degree during infrequent storm events as long as surcharges are not excessive to cause manhole overflows or basement flooding.

Furthermore, the simulated peak flow to design flow ratio can yield some results that do not represent the actual capacity of the pipe segment in question. This is due to the design flow typically being calculated using Manning's equation based on the slope of the pipe segment in question only. There are often cases where a short segment of pipe will have a mild adverse or near-zero slope and result in a very low design flow calculated by Manning's equation which would result in a very high simulated peak flow to design flow ratio. In many of these cases, the actual design capacity to convey flow depends on the conditions upstream and downstream of the pipe segment in question and should be considered for these cases they may not actually be system constraint.

The intervals for the percent capacity can be defined to suit a particular study. A common set of intervals to evaluate system capacity, which is also the default SWMM5 color for each interval, are listed below.

Interval 1:	0-25 percent (blue)
Interval 2:	25-50 percent (light blue)
Interval 3:	50-75 percent (green)
Interval 4:	75-100 percent (yellow)
Interval 5:	>100 percent (red)

SWMM5 allows users to display the system capacity thematic maps. Figure 6-6 depicts such a map. Users can also develop thematic maps illustrating sewer capacity utilization in standard GIS or CAD packages. The red highlighted conduits in Figure 6-6 represent sewers with no capacity left.



Subcatchments: None

Nodes: None

Links: Capacity

Date: 02/09/2001

Time of Day: 00:05:00

Elapsed Time: 0.00:05:00

Frequency/Contour
○ Subcatchments
○ Nodes
○ Links
● Current Selection

☐ Auto-Length | Flow Units: CFS | Zoom Level: 100% | X,Y: 1430260.114, 445818.6 Current Item:

Figure 6-6. SWMM5 thematic map example.

Sewer Surcharge Level: Reviewing sewer surcharge levels is an important step in assessing system hydraulic performance and for investigating basement flooding problems. The SWMM5 simulation results contain data of all conduits/manholes that surcharge including duration and surcharge depth. Table 6-2 shows an example of surcharge summary, showing one manhole flooded and others surcharged. Using the thematic map similar to Figure 6-6, users can present the same information in SWMM5 or in GIS environment.

Table 6-2. Sewer Surcharge and Manhole Flooding Summary

Interceptor	Design Capacity (MGD)	Simulated Peak Depth (in.)	Surcharge Depth (in.)	Manhole Depth (in.)	Capacity Used	Capacity Remain	Duration Surcharged (h)	Notes
Section 1 (36 in.)	51	143	107	143	100%	0%	22	Flooding
Section 2 (42 in.)	31	21	N/A	120	50%	50%	0	N/A
Section 3 (36 in.)	25	42	6	120	100%	0%	9	Surcharged
Section 4 (36 in.)	12	45	9	120	100%	0%	12	Surcharged
Section 5 (60 in.)	41	41	N/A	120	68%	32%	0	N/A
Section 6 (60 in.)	55	50	N/A	120	83%	N/A	0	N/A

Manhole flooding: Manhole flooding is another consideration for assessing the hydraulic performance of a sanitary sewer system. Manhole flooding information is essential when investigating potential street flooding, and overflows to area waterways. Manhole flooding information, such as manhole overflow volume contained in the SWMM5 output, can be extracted for analysis.

Overflows: Overflows from sanitary systems occur in several ways: at previously constructed outfall pipes within the sanitary collection system, at the WWTP, or by overflows to the customer basements via house lateral sewers. A solid understanding of overflow location, frequency, volumes, duration, and causative factors is critical to mitigating overflows. Some communities may have historically constructed SSOs, which are typically represented by an overflow pipe at a manhole that discharges to a receiving water body or storm sewer. SSOs typically have free outfalls but can be influenced by the stage elevations of receiving waters. The receiving water is considered a boundary condition in SWMM5 and it is important to include it in the calibrated sewer system model.

In summary, the steps described above are expected to yield a baseline characterization that fulfills the goals established for the capacity assessment. A properly developed and calibrated hydrologic and hydraulic computer model can provide an effective means to assess the hydraulic capacity of a sanitary sewer system for the existing and future growth conditions. The knowledge gained through the system characterization combined with the SSO control objectives and system model can then be used to screen a range of alternatives to determine a recommended plan that can cost-effectively mitigate SSOs. The resulting WWF management plan can then be integrated into an overall system capital improvement program, as described in Chapter 7.

Chapter 7 Development and Analysis of System Improvement Alternatives

This chapter presents guidelines for developing and analyzing improvement alternatives to mitigate SSOs. Analysis techniques for simulating and developing improvements needed to meet the identified planning criteria are described. These techniques use the various system analysis approaches using the SSOAP Toolbox. A general approach for developing a targeted SSO control plan within funding and schedule constraints is outlined. This chapter also discusses ways to integrate a wet-weather management plan or sewer system improvement plan into a municipality's capital improvement program.

7.1 Establishing Planning Objectives and Improvements Criteria

7.1.1 System Improvement Planning Objectives

The development of system improvements requires an integrated hydrologic and hydraulic analysis of the sewer system of concern, including boundary conditions or limitations from downstream pumping constraints, to gain a comprehensive understanding of existing capacity, DWFs, and WWF responses. The system improvements discussed in this chapter focus primarily on controlling capacity-related SSOs that occur during wet weather. SSOs caused by system operations and maintenance (O&M) are briefly addressed. For more information on O&M related SSOs, useful references include the *Guide for Evaluating Capacity, Management, Operation, and Maintenance (CMOM) Programs at Sanitary Sewer Collection Systems* published by the EPA's Office of Enforcement and Compliance Assurance (EPA, 2002), *Optimizing Operation, Maintenance, and Rehabilitation of Sanitary Sewer Collection Systems* (NEIWPCC, 2003), and *Wastewater Collection Systems Management* (WEF, 1999.) Data regarding sewer system maintenance, sewer surcharging and resulting basement backups, and customer complaints should be reviewed to understand if SSOs are the result of capacity limitations and/or O&M issues such as obstructions and blockages.

Sewer system improvement programs are established, in general, to meet the following capacity-related objectives:

- Provide sufficient transport and treatment capacity for existing and future flows during both dry- and wet-weather conditions.
- Comply with regulatory requirements for capacity assurance and SSO avoidance.
- Meet the level of service expected by customers to avoid system surcharging that may lead to basement or service backups.

These objectives are usually developed in response to system flow conditions identified by the utility through customer interactions, regulatory discussions, and/or their combinations. Increasingly, these capacity objectives are geared to control SSOs in terms of frequency of occurrence, such as no more than once every two, five or 10 years on average.

In addition to the above capacity-related objectives, the following objectives should also be considered during final selection and design of sewer system improvements:

- Control wet-weather effect on operation of system facilities, such as WWTP and pumping stations.
- Provide long-term system structural integrity.

- Control O&M costs.
- Maintain the asset value of the system infrastructure and ensure that they will continue to operate with minimized risk of failure.
- Minimize the effect on the community and environment from construction, odors, and noise.

A systematic evaluation based on system-wide hydrologic and hydraulic modeling has become the main stream approach for developing a good understanding of a sewer system's capacity status, especially when the evaluation is supported by performance data collected through flow and rainfall monitoring and SSES . Utilities throughout the world have used this approach to gain a better understanding of their current conditions and future wastewater collection needs. In turn, such an understanding is essential for making cost-effective, proactive, equitable, and efficient decisions concerning sanitary sewer system improvements.

7.1.2 System Planning Criteria

There are two types of planning criteria in developing and implementing sewer system improvements. The first criterion is to define a threshold of system deficiency based on system model simulations to alert that system improvements are needed. Examples of these criteria include:

- SSOs shall not be predicted to occur during the specified wet-weather planning condition.
- Peak DWF shall use no more than a given percentage of the system capacity (usually 50 to 75 percent, depending on system age and level-of-service expectations.)
- Sewer surcharges shall not exceed a given limit, such as no more than three feet above the crown of the pipe or no less than three feet below the manhole rim elevation.

The second criterion is to define the sizing requirements of new improvements to correct the identified system deficiency. In many cases, regulatory agencies governing sewer system improvements spell out the system design criteria that must be met, such as minimum wet-weather to dry-weather peaking factors or minimum design velocities to maintain solids flushing. Examples of these criteria can be found in the Recommended Standards for Wastewater Facilities, also known as the Ten State Standards (HES, 1997.)

Criteria to size system improvements for facility planning studies are typically based on a combination of future projected DWFs and a maximum frequency of SSO occurrence. Predicted wastewater flows are generated for these conditions using calibrated hydrologic and hydraulic models. Based on these simulations, system improvements are sized to meet identified criteria, which may include the following considerations:

- No system surcharging will occur for the future base wastewater flows (e.g., 20 to 30 years in the future), in combination with a maximum RDII recurrence interval of once every two, five, or 10 years.
- Maximum levels of surcharge will be limited to some criteria for future flows in combination with a less frequent RDII recurrence interval.
- Sewer system overflows will not occur more frequently than a given recurrence interval.
- The selected recurrence interval may change within a sewer system service area depending on the environmental impact of the overflow, and the impact and cost of the facilities required to reduce the frequency.
- Any system storage facilities will not hold wastewater for more than 72 hours and more frequently than once every two, five,or 10 years to control odor production.
- A maximum sustainable wet-weather treatment capacity will not be exceeded for more than 24 hours and more frequently than once every two, five, or 10 years.

These criteria will be system-specific based on customer level-of-service preferences, O&M considerations, and wastewater treatment processes and operations. Therefore, they should be considered prior to developing specific improvement alternatives, as they will influence the size of improvements and thus may influence the outcome of the alternatives analysis.

Alternatively, sensitivity analyses should be performed to identify the facilities required to meet selected levels of service. The cost and impact of these improvements should be evaluated so that informed decisions on the improvements can be made.

7.2 Options for Improving Collection System Performance

Improvement alternatives should account for the impacts of improvements on the whole system, including the impact on downstream facilities and the ability of the treatment facilities to handle the additional flows. System improvement options generally include:

- **Sewer rehabilitation** as a means of increasing existing sewer capacity and/or reducing infiltration and inflow.
- **Equalization storage** to reduce downstream peak flows, including the possible use of real-time controls (RTC) to optimize the use of existing system storage.
- **Increased conveyance capacity** through gravity sewer construction or pump station/force main upgrades.
- **Increased wastewater treatment capacity** through facility expansion, or the use of other wet-weather treatment processes, such as high-rate clarification.

I/I reduction generally relies on rehabilitation of sewer lines and manholes that are often the sources of groundwater or WWFs in sewers. However, in some areas of the country such as Ann Arbor, Michigan (which is described more fully in Chapter 8), footing drains or other private system connections to the sanitary system have been identified as major sources of RDII. In these situations, the contributions of RDII and the cost of removing these connections should be evaluated as an alternative.

Initial evaluations may consider each of these alternatives individually. However, as to be described in Section 7.3, improvement alternatives that combine these improvements to meet system performance objectives should be developed. The final alternatives chosen should meet the utility's level of service objectives and regulatory requirements, as well as budget and time constraints.

Descriptions of each improvement strategy is provided in the following sections, followed by a discussion of the development and evaluation of system-wide alternatives to improve sewer system performance using combinations of these improvements.

7.2.1 Sewer System Rehabilitation

It is typical to perform a focused SSES to determine the scope of sewer rehabilitation required. This often involves a dense flow monitoring network to determine the sources and severity of extraneous flows. The monitoring is generally followed by detailed manhole inspection, close-circuit television inspections, smoke testing, flow isolation, and other techniques to gather adequate information of sewer conditions to guide rehabilitation.

Once an area is identified as a contributor of high RDII and thus designated as a rehabilitation priority, there are three general sewer rehabilitation approaches to proceed:

- Rehabilitate all sewers including service laterals located within the public right-of-way and on private property.
- Rehabilitate only sewers located in public rights-of-way.
- Repair structural defects in pipes and manholes and remove major inflow sources identified.

The first and second approaches are considered "comprehensive rehabilitation." A comprehensive rehabilitation approach consists of rehabilitating every foot of sewer to eliminate all potential points of entry for RDII.

Experience has shown that the greatest cost/benefit ratios can be achieved by comprehensive rehabilitation of those sewersheds area with the greatest level of deterioration. Benefits may be reduced significantly for sewersheds with lower levels of extraneous flow.

The third approach is point rehabilitation, which repairs localized defects identified from inspection and focuses on SSOs resulting from structural and maintenance problems rather than RDII. However, potentials are there to identify some specific defects that are significant sources of RDII. This approach does not include rehabilitating the laterals, and thus is not as effective in reducing RDII as the comprehensive approach.

Because of the time and cost required, and the uncertainty in peak flow reductions provided, sewer system rehabilitation is best used as one part of an overall program that also includes other capacity improvement options, such as relief sewers and pumping station upgrades. However, rehabilitation is an important part of all utilities' ongoing O&M programs to prevent high levels of RDII and to ensure that the sanitary sewer system continues to operate as designed.

When considering rehabilitation, lifecycle costs and benefits should be considered. Sanitary sewer systems continually deteriorate over time. While generally accepted design life for the materials used to construct sewers is on the order of 20 to 30 years, these sewers are called on to provide service for 50 years and longer. While comprehensive rehabilitation approaches previously described have higher initial costs, the collection system is revitalized both structurally and hydraulically, and the service life of the sewers can be extended significantly. A point-repair approach is less costly, but it may not adequately control system deterioration. In addition, migration of infiltration from the repaired defect to defects not addressed by the point repair approach may significantly reduce the effectiveness of this approach in reducing RDII. The potential need for a continuing series of spot repairs may be more costly and less effective than a comprehensive rehabilitation approach. The best approach will vary by systems, and pilot rehabilitation projects that include pre- and post-rehabilitation flow monitoring to determine the RDII reduction success of different approaches within each system are recommended. The validity of these RDII reduction assumptions are critical to the success of the recommended sewer improvements program.

7.2.2 Storage

Flow equalization facilities can reduce SSOs by storing peak flows in excess of sewer capacity. They can effectively reduce localized overflows as well as upstream and downstream overflows (by reducing the hydraulic grade line elevation upstream, and by reducing downstream peak flow rates.) Flow equalization facilities can be constructed within the sewer system, at pump stations and at wastewater treatment plants. Equalization basins sited at plants can also be used for dry-weather diurnal equalization to dampen daily flow fluctuations and improve treatment performance.

Storage is most effective when it is located immediately upstream from the portion of the system with insufficient capacity. For this reason, many existing storage facilities are located at pump stations or treatment plants. The principle of WWF control is relatively simple: flows that exceed the capacity of the downstream facilities are diverted directly to the storage facility. Controlling flows using facilities located far upstream from the flow constraints is often less effective due to time lags and the inflows that enter the system between the facility and the flow constraints.

The key concern in designing a storage facility is to determine its size. The size should account for the range in wet-weather events that affect the system. The storm that produces the largest peak flow may not be a design storm; rather it may be long-duration, low-intensity events that occur back-to-back. Long-term flow monitoring data and/or continuous model simulations using long-term rainfall data are recommended to evaluate system performance when sizing storage.

There are other factors to consider when locating and designing storage facilities, including odor control, solids handling and cleaning the facility after system operation. The operating costs of the facilities must also be considered. Flow equalization analyses usually do not address continuing system deterioration and RDII flow increases over time. As collection systems age and extraneous flows increase, and as DWFs increase due to development, the equalization facility may become undersized. Conversely, if rehabilitation is conducted in the upstream sewers, flow equalization volume required may actually decrease or be eliminated altogether.

Flow equalization storage facilities are designed and operated either on- or off-line, as discussed next.

7.2.2.1 On-Line Flow Equalization Storage
In on-line flow equalization facilities, flow is continuously routed through the storage system during both dry and wet weather. On-line storage can be achieved by replacing a portion of an existing sewer with a larger conduit (pipe, tunnel, or culvert), or by constructing a parallel conduit to provide additional storage capacity. Flows enter and exit the on-line storage system by gravity, and wet-weather storage can be regulated by the downstream hydraulic grade line or by a physical control device. Physical control devices include rate-of-flow control valves, regulators, orifices, and inflatable dams. A low-flow channel may be constructed in the facility to ensure cleansing velocities are maintained during DWF conditions.

7.2.2.2 Off-Line Flow Equalization Storage
Typical off-line flow equalization facilities include equalization basins (either open or covered), above- or below-grade tanks, tunnels, and culverts sized to store peak WWFs that the sewer system cannot accommodate. Flow diversion chambers or pump stations are required to divert peak flows from sewers to a flow equalization tank. A good design and operating practice is to segment the tank into multiple cells and allow it to fill one cell at a time. This approach minimizes the area to be cleaned after a wet-weather event, and can expedite tank draining by gravity or by pumping. The basins can be covered and equipped with odor control systems to reduce the potential public nuisance. Tank mixing systems are also frequently provided (mixers, blowers, pumps) to keep solids in suspension to minimize cleanup effort and odor.

Costs for new flow equalization basins vary significantly depending on the method of tank construction, equalization volume, and site-specific conditions. Construction of an above-ground, open-topped tank typically offers the lowest costs, while a below-ground, covered tank the highest.

Facilities that require pumping of peak flows into the storage tanks would incur the largest cost. Facility costs can be significantly reduced if site conditions allow influent flows to enter via gravity and pumping requirements are limited to effluent flows, since return flow rates can be much smaller than the uncontrolled, storm-induced peaks. The greatest cost efficiencies are achieved if site conditions allow gravity flow for both influents and effluents.

Flow equalization basins require inspection and cleanup after each storm event; routine testing and maintenance; power for wastewater pumping, blowers, and mixers (if applicable); and chemicals for odor control (if applicable.) The annual O&M costs for WWF equalization can vary significantly, depending on volume and number of excess flows.

Tunnels have been successfully used in CSO applications to provide storage during storm events, with subsequent pumping of stored flows to treatment facilities. Tunnels can be constructed in soft ground (shallow tunnels) or deep rock formations. Soft-ground sewer tunnels are commonly constructed by microtunneling, pipe jacking, or installing pipes inside an excavated tunnel (conventional method.) Box culverts can be effectively used for either on- or off-line flow equalization facilities. This option typically entails construction of a below-ground covered culvert aligned so that existing trunk sewers can overflow into it by gravity.

7.2.3 Conveyance
If rehabilitation or source controls are not expected to sufficiently reduce GWI or RDII, an increase in conveyance capacity may be necessary. Increased conveyance capacity by larger or parallel sewers can provide the capacity required for increases in sanitary flows due to population growth or system expansion. It may also prove to be a cost-effective approach to address WWF requirements when combined with other improvement options.

In many cases, enhancement of conveyance capacity can be the least costly alternative in terms of capital and O&M costs. However, potential environmental and community impacts may make this approach impractical, as it will significantly impact the operation of downstream facilities such as pump stations, force mains, interceptor sewers and wastewater treatment plants.

7.2.3.1 Trunk Sewer System Improvements

Trunk sewer system improvements can effectively relieve pipelines prone to surcharging and overflows by increasing sewer capacity. These improvements also have the benefit of providing additional dry-weather wastewater conveyance capacity to accommodate future growth in a service area. Trunk sewer improvement alternatives include: (1) replacement and relief sewers, and (2) sewer pressurization. Because trunk sewer system improvements result in increased downstream wet-weather peak flows, downstream sewer system improvements (additional trunk sewer capacity, plant equalization, and plant improvements) may be required in conjunction with upstream improvements.

Replacement and relief sewers

Replacement and relief sewers convey DWFs that exceed the existing trunk sewer capacity. Relief sewers may be constructed to parallel an existing trunk sewer, or along an independent route designed to bypass hydraulically limited areas. In some cases, relief sewers may also be used to divert flows to another branch of the collection system. They may be designed as on- or off-line systems. On-line relief sewers, which convey both dry- and wet-weather flows, should be designed to ensure that cleansing velocities are maintained to prevent solids deposition, odor, and maintenance problems. In contrast, off-line relief sewers are only used during wet-weather conditions. Flow into off-line relief sewers can be controlled hydraulically via a fixed weir or junction box, or mechanically using a power-operated gate or similar device. In addition to providing additional wet-weather conveyance capacity, relief sewers also provide sewer maintenance flexibility by allowing one sewer line to be removed from service without bypass pumping.

Replacement sewers allow an existing sewer to be abandoned or removed. This approach may be preferable to relief sewer construction if the existing trunk sewer is in poor condition, or if construction easement limitations and/or land acquisition requirements preclude cost-effective relief sewer construction. However, the material costs for replacement sewers are generally higher than those for relief sewers since the replacement sewers are sized larger to offset the loss of capacity served by the existing sewer that will no longer be used. In addition, the need to maintain sewer flow during replacement sewer construction may necessitate special construction procedures (e.g., bypass pumping) that can significantly increase costs.

Sewer pressurization

Sewer pressurization can increase the hydraulic and storage capacity of existing trunk sewers by increasing the hydraulic grade line in the reach until sewers are surcharged. Typically, manholes along the reach are either sealed or raised to allow the sewer to be surcharged during peak wet-weather conditions without flooding.

Sewer pressurization is not a conventional improvement option, and its potential impacts should be carefully considered on a case-by-case basis. The structural integrity and design of the sewer in question must be carefully checked to ensure that it can withstand the increase in pressure. Equally important, the hydraulics should be carefully examined to ensure that the higher water level does not cause sewage backups into homes or other connected systems, and that the backwater does not reduce upstream carrying capacity. If manhole inverts are formed using conventional methods to convey flow from one-half of the pipe depth, then pressurization may not increase hydraulic capacity because of significant entrance and exit losses. To achieve this benefit, the channel must be reconstructed for conveyance of flows that will fill the pipe.

If these considerations are adequately addressed, sewer pressurization can be one of the most cost-effective means of eliminating localized overflows and increasing hydraulic carrying capacity and in-line storage.

7.2.3.2 Pump Station Improvements

Capacity upgrades to existing pump stations or the construction of new pump stations may be required to convey WWFs and prevent overflows upstream of the pump station. A traditional approach would be to parallel the existing force main with a new force main and either retain or abandon the existing force main, depending on its condition. In some cases, this force main can convey increased flow by using pumps with higher discharge heads to overcome the greater friction losses generated by the increased velocities. If the force main receives flow from other pump stations, one must also weigh the impacts of increased system heads on the pumping capacity of the other stations. Also, over time, velocities in excess of 10 ft/s can scour the force main interior, causing premature structural failure.

Another alternative to consider is constructing a new pump station and force main to divert flows from a sewer reach with insufficient capacity to a location that can adequately convey the additional flow. The pump station can be constructed to divert all flows, dry- and wet-weather, from a portion of the sewershed. Alternatively, the pump station can operate intermittently to divert wet-weather flows that exceed the existing downstream conveyance capacity.

7.2.4 Treatment

Pump station and pipe capacity upgrades will produce increased wastewater flows to WWTPs. If these flows exceed the wastewater treatment plant capacity, the flows are temporarily stored in the system until capacity is available, or improvements must be made at the plant to handle the additional flows. The methodology for evaluating treatment plant alternatives is discussed in detail in the 2006 WEF document (WEF, 2006.) To evaluate impacts to a WWTP, analysis must be performed to quantify flows to the WWTP, summarize the service area's characteristics, determine the capacity of the WWTP system and its components, and evaluate the secondary treatment processes.

Alternatives for improving the WWTP's performance during wet weather include on-site storage, in-plant flow re-routing, high-rate treatment processes, blending, and full secondary treatment. Stakeholders should select the best option based on the defined criteria and the cost of each alternative.

7.2.5 Real-Time Control (RTC)

RTC enables wastewater collection systems to capture increased wet-weather flow by: (1) maximizing the use of available in-system storage; (2) maximizing available system conveyance capacity by diverting flow dynamically; and, (3) enhancing control logic for off-line storage. In-system storage reduces conveyance capacity during wet weather and allows flow to back up into and be stored within the otherwise unoccupied pipe. Dynamic flow diversion enables the system's hydraulic conveyance capacity to be fully used during wet weather by shifting flows from overloaded lines to those with capacity. Enhanced control logic at off-line flow equalization facilities allows storage volumes, as well as influent and release rates, to be adjusted based on hydraulic conditions at critical locations along trunk sewers that may be a considerable distance from the storage facilities. Hydraulic models are used to simulate all three RTC strategies described below for increased flow capture and determine which approach or combinations of approaches are most beneficial for system performance improvements.

7.2.5.1 Overview of In-System Storage

In-system storage is the most common objective of RTC in combined sewer systems, but the principles can be applied to sanitary sewer systems in some cases. This approach generally provides greater benefits in larger systems. Since much of the storage capacity is typically used to convey flows, this approach would typically provide relatively small benefits. The ideal condition for its application is whenever the system includes large-diameter sewers that flow partially full during large wet-weather events.

7.2.5.2 Overview of Dynamic Flow Diversion

Branched and parallel interceptor sewers enable a sewer system to employ RTC for dynamic diversion of flows during wet weather. RTC facilities are located at critical system junctions of major trunk sewers, and diversion of flows within the interceptor network is controlled through real-time monitoring of flows and levels (and sometimes precipitation-based predictions of flows) to maximize conveyance capacity. A detailed study using hydraulic analysis models can simulate RTC scenarios and identify RTC opportunities.

7.2.5.3 Overview of Enhanced Control Logic

For many flow equalization facilities, the quantity of flow entering the storage tanks and the release rate to the downstream trunk sewer is determined by local hydraulic conditions. Many control structures are static, such as a fixed side-spillway weir for influent flow and a fixed orifice or pumping rate for effluent flow. System operators can achieve more effective and flexible use of available storage if static controls are replaced with more complex RTCs.

Using variable release rates from flow equalization facilities can adjust decision control logic to seasonal groundwater conditions and/or ensure that storage tanks are emptied as quickly as possible and available for back-to-back storms.

Remote sensors can set the release rates from upstream storage tanks according to the downstream hydraulic conditions and ensure that the hydraulic capacity along critical trunk sewers is fully used at all times. It is very important that system operators are properly educated and trained to meet the challenge of increased complexity in system operations.

7.3 Strategies to Develop Improvement Alternatives

An important principle in developing alternatives is for each alternative to provide the same level of service and the same level of infrastructure renewal. For example, in evaluating a conveyance alternative that increases peak WWFs to the WWTP beyond its existing capacity, some provision for how the flow will be handled at the plant must be included. As an alternative, storage and/or RDII reduction measures may reduce peak flows to the WWTP. To properly compare these alternatives, the conveyance alternative should include either wet-weather storage at the plant and/or increases in the WWTP capacity so the level-of-service of the alternatives is equal.

Given this principle, the following approach to develop improvement alternatives, as illustrated in Figure 7-1, is recommended. The first three alternatives suggested for simulation with the system model are alternatives that completely rely on: (1) conveyance (Alternative A1); (2) storage (Alternative A2); and, (3) I/I reduction (Alternative A3.) While these alternatives may or may not be the practical solutions in meeting the planning criteria, hydraulic model simulation of each of these three alternatives will be useful to develop understandings of the relative benefits of each improvement type in various parts of the system. These alternatives provide the outer boundaries of the triangular universe of possible improvement solutions. The best solution will reside somewhere within this triangular universe, and will likely include a combination of all three improvement alternatives. Guidance in simulating each of these types of improvements follows.

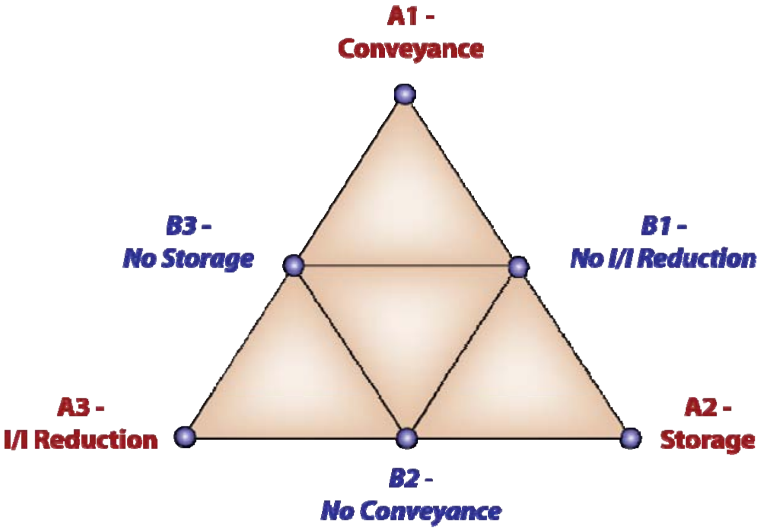


Figure 7-1. Triangular universe of possible wet-weather improvement solutions.

7.3.1 The Conveyance Improvement Alternative

The intent of the conveyance improvement alternative is to determine the sizes of replacement or parallel gravity sewers and/or pump stations and force mains needed to convey all wet-weather flows for the planning storm to the existing treatment facility. If this alternative results in peak WWFs at the wastewater treatment plant that exceeds its existing capacity, then either new storage at the plant or the addition of equalization storage at the plant would be required as part of this alternative. This alternative is typically simulated with the system model assuming that the basic system configuration remains the same. For example, gravity sewers would be installed at the same slopes as the existing system and pump stations would discharge to the same locations as currently used. However, these assumptions may be changed as the alternative is refined.

Pipes can be sized by first routing WWFs through a model system where pipe sizes are increased to a size that is larger than that required to convey flows. Peak WWFs at each modeled pipe may then be exported to a spreadsheet or other design tool to compute replacement and/or parallel pipe sizes needed. In developing cost estimates for this alternative, the condition of the existing sewers should be considered to determine whether a complete replacement, a parallel sewer, or a combination of parallel sewer and rehabilitation of the existing sewer lines is appropriate.

7.3.2 The Storage Improvement Alternative

The storage improvement scenario, in its purist definition, would consist of locating a flow equalization storage facility in the vicinity of every SSO or basement backup. In practicality, storage facilities may be oversized in upstream locations to provide downstream benefits. On the other hand, downstream storage facilities can reduce hydraulic gradelines sufficiently to eliminate upstream surcharging and overflows.

As described in Chapter 6, continuous simulation of sewer system performance over a long-term period of rainfall records that considers the impacts of back-to-back storm events is particularly important when sizing storage facilities. Storage facilities may take several days to drain after a storm event, and subsequent storms may occur during this period. These back-to-back storms may cause more impact on the system than one single event, even if the single event is larger. Hence, continuous simulation is recommended for sizing storage facilities to control WWFs.

Figure 7.2 shows an example of how the result of a continuous simulation is presented for evaluating the benefits of storage facilities. A series of continuous simulations is performed with various sizes of storage to reduce overflow frequency. The results are expressed in terms of an average annual overflow frequency. After a number of simulations that provided results above and below the target annual overflow frequency, the results were plotted and a curve was fit to the points.

In this example, the addition of 7MG of system storage at this location would reduce the predicted annual average overflow frequency to one-half overflows per year, or one overflow every two years.

Similar to the situation discussed in the conveyance improvement alternative, the analyst must consider if any additional improvements are needed to achieve the equal level of service as other improvement alternatives. For example, if a conveyance alternative included replacing an aging trunk sewer that has a history of structural problems, then the storage alternative may require rehabilitation of this trunk sewer. This would be done using a structural liner to provide an equal level of service of the final solution. Including all common improvements needed to provide an equal level of service is an important principle in alternatives analysis. This will allow a reasonable comparison of alternatives, even though the individual components in the selected alternative may be implemented in phases (e.g., the storage facility is constructed in year two of the plan and the trunk sewer is rehabilitated in year 10.)

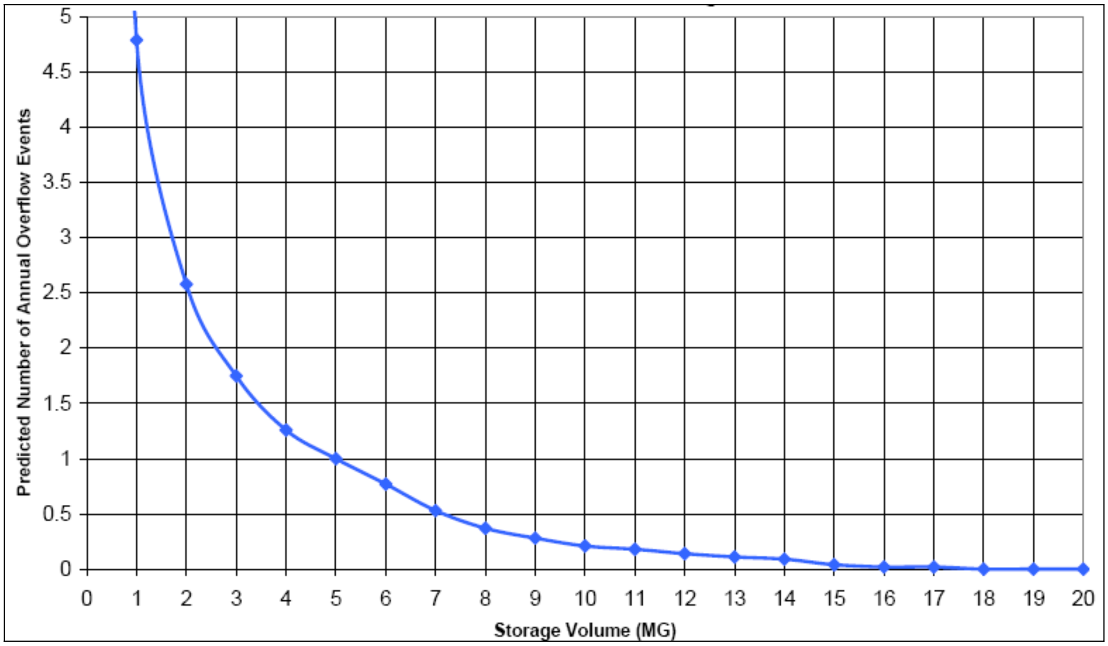


Figure 7-2. Example results showing benefits of storage in reducing overflow frequencies.

7.3.3 The I/I Reduction Improvement Alternative

The I/I reduction improvement alternative would conceptually consist of rehabilitating only the sewers required to reduce I/I sufficiently to eliminate all overflows and/or basement back-ups. This is difficult to determine, especially at the early planning level of a wet-weather improvements program. Therefore, in practicality, the analyst typically must make assumptions of how a rehabilitation program would be implemented. The available flow monitoring and sewer inspection data are generally used to identify sewers where rehabilitation would be effective.

The R-value is a useful parameter in setting priorities for sewer rehabilitation. In the hydrologic system model, each sewershed is assigned an R-value or a range of R-values to represent RDII contributions under various seasonal or antecedent moisture conditions. These R-values are determined from directly available flow monitoring data at a monitored sewershed or from model development and calibration processes for non-monitored sewersheds. The latter would assign R-values from surrogate areas predicted to have similar RDII responses as the monitored sewersheds because of their similarities in characteristics, such as sewer age, construction practices, soils characteristics, and/or maintenance and repair histories. The rehabilitation work would begin in sewersheds that have the highest R-values, and are located upstream from overflows and/or basement backups.

Sewer rehabilitation may be simulated in the hydrologic model by reducing the R-values. Ideally, the analysis can base R-value reductions on system-specific flow monitoring data that is available for other similar areas having undergone rehabilitation and monitoring during pre- and post-rehabilitation conditions. In reality, these data are often not available. If this type of data is not available, the utility must be encouraged to begin a pilot sewer rehabilitation program and collect both pre- and post-sewer rehabilitation flow monitoring data. While reasonable assumptions can be made in planning stages for the purposes of alternatives analysis, actual results can be highly system specific, and assumptions should be validated as early in the program implementation as possible so that the direction of program improvements can be confirmed.

R-values may be reduced in the hydrologic model using a variety of approaches. The following represent the most commonly used methods and assumptions:

- R-values are reduced by a given percentage, usually ranging from 30 to 70 percent. To achieve a higher percentage reduction would require a comprehensive sewer rehabilitation effort, including a program to address RDII from lateral sewers. A comprehensive sewer rehabilitation effort typically consists of rehabilitation of every foot of sewer, every manhole, and lateral connections at a minimum. Unit hydrograph parameters (R_1, R_2, and R_3) may be reduced evenly, or more weight placed on reducing R_1. The available documented results of sewer rehabilitation programs in systems similar in characteristics to the system being analyzed would be helpful in making the determination. Typically, T values and K values in the unit hydrograph model are not changed.
- R-values are reduced from the current value to a target value. Typically, target values may be an R-value of 2 percent, representing the results of a comprehensive sewer rehabilitation program that includes removing private-server RDII contributions. A target of 5 percent may represent the results of a point repair approach aimed at reducing major inflow sources. As before, unit hydrograph parameters may be reduced evenly or more weight placed on reducing R_1; T values and K values are typically not changed.

In analyzing future scenarios, R-values may be increased in some areas to reflect deterioration of sewers. The amount of increase should be judged based on the utility's willingness to commit to an ongoing, annually funded sewer rehabilitation program that targets RDII reduction on a system-wide basis.

The results of the RDII reduction scenario will help determine where in the system wet-weather problems can be addressed with a sewer rehabilitation alternative and where this may not be practical. For example, if wet-weather problems cannot be addressed with RDII reductions of more than 70 percent or to an R-value of 2 percent, then sewer rehabilitation alone is likely not a practical wet-weather improvement solution.

7.3.4 The No RDII Reduction Improvement Alternative

The above discussions of three 'A' alternatives provided good perspectives on the relative benefits of individual conveyance, storage, and RDII reductions in developing an overall improvements strategy. The next three improvement alternatives exclude one of the three major improvements and include a pairing of the other two. The alternatives are referred to as "B" alternatives (see Figure 7-1) and include no RDII reduction alternative (alternative B1), no conveyance alternative (alternative B2) and the no storage alternative (alternative B3.) This combination of alternatives is more commonly practiced by municipalities.

The no RDII reduction alternative is important to consider. This is because measurable RDII reduction in large portions of a sewer system is difficult to achieve in a short period. In addition, there are potentially significant variabilities and uncertainties in the actual quantification of RDII reduction through sewer rehabilitation. Thus, alternatives relying on RDII reduction have some degree of risk in not being successful. Therefore, other alternatives have a higher probability of success in meeting the intended goals in a shorter period.

For this reason, utilities tend to choose conveyance and/or storage as the primary alternatives, to meet a given planning criteria (e.g., controlling wet-weather flows up to a two-year return frequency.) Utilities also include targeted sewer rehabilitation for RDII reduction. If RDII reduction is successful, facilities originally designed will fail less frequently and are able to handle larger storm events.

7.3.5 The No Conveyance Improvement Alternative

The no conveyance improvement alternatives represent a situation where it is difficult to locate or construct new pipelines because of development or environmental issues. Because storage will be a significant part of this alternative, use of continuous simulation for assessing improvements is recommended.

RDII reduction through sewer rehabilitation in strategic sewersheds upstream of the proposed storage facility can reduce the required size. As illustrated in Figure 7-3, sewer rehabilitation in one upstream sewershed reduced the amount of storage required to meet a given overflow return frequency. In this case, a storage facility of approximately 9 MG was required to meet an overflow frequency of 0.5 overflows per year (once every two years), on average. With sewer rehabilitation in one sewershed, assuming that R-value is reduced to 2 percent, the required storage to meet 0.5 overflows per year was reduced to 2.5 MG.

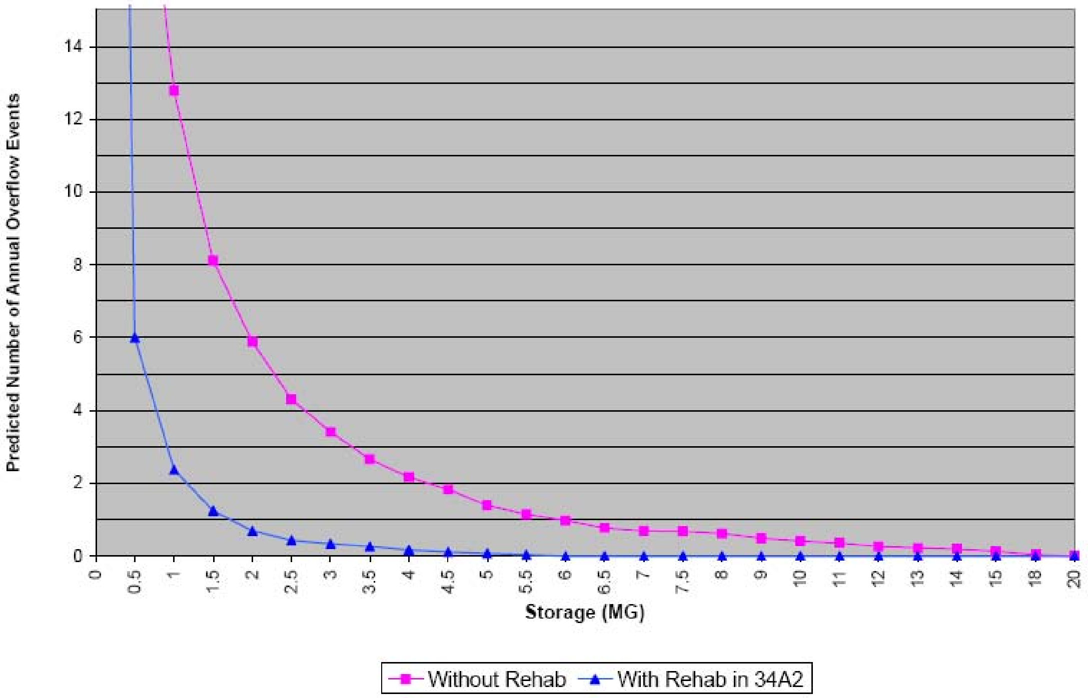


Figure 7-3. Required storage volume with and without sewer rehabilitation.

7.3.6 The No Storage Improvement Alternative

A no storage improvement alternative consideration will help quantify the relative benefits of storage as compared to conveyance and RDII reduction alternatives. In general, for RDII reduction to be cost-effective it must be sufficient to eliminate the need for other conveyance improvements. Usually, developing the cost-effective no storage alternative includes a combination of conveyance and RDII reduction. This would be based on where in the system that each of these improvements was found to be the most cost-effective.

7.3.7 Additional Improvement Alternatives

From the analysis results of the six previously described improvements alternatives, the relative benefits and feasibility of conveyance, storage, and/or RDII reduction throughout the various problem locations of the sewer system can be determined. With this information, an optimized combination of conveyance, storage, and/or RDII reduction alternatives can be developed, considering other cost and non-cost factors.

7.4 Applying the SSOAP Toolbox to Evaluate Improvement Alternatives

The sewer system modeling and the establishment of baseline conditions are critical in identifying and screening potential system improvement alternatives. Combined with system-specific knowledge developed during the baseline characterization under existing and future growth conditions, the applicability of each alternative can be properly assessed. The SSOAP Toolbox is designed to help screen potential alternatives and identify the most promising ones to improve system performance cost-effectively.

SWMM5 is used to evaluate the hydraulic consequences of each scenario. Model input must be changed to reflect the specifics of each alternative. As an example, SWMM5 was applied to a hypothetical community with three sewersheds and a downstream WWTP that experiences system surcharges and overflows. One of the selected scenarios may include the following improvements:

1. Sewershed A: Increase the pump station and downstream force main capacity.
2. Sewershed B: Disconnect the foundation drains to sanitary sewers, rehabilitate the selected manholes and sewers, and construct parallel sewers at selected locations that experience hydraulic bottlenecks.
3. Sewershed C: Construct a storage facility upstream of a pump station to attenuate the peak flow to downstream sewer system.
4. Construct a storage facility at the WWTP to equalize the flows delivered from the collection system prior to discharging to the plant head works.

These facilities are initially sized and refined using the model until the desired system performance is achieved. Quality checks must be performed to assure that the proposed improvements are properly represented in the model network.

The model also provides a means to determine the impact of an upstream system improvement on downstream facilities. For example, constructing a relief sewer or adding pump station capacity may simply transfer the problem to a downstream sewer reach.

For RDII reduction (i.e., sewer rehabilitation and inflow reduction) projects, users must estimate the potential reduction in RDII and reflect that in model input for the R-value, keeping in mind that the R-value is not overly reduced.

SWMM5 model applications may be driven by a design storm or selected continuous precipitation records to evaluate the performance under various conditions. The simulations and their results must be reviewed carefully for accuracy to judge the effectiveness of a given alternative in achieving the performance objective. The model results for each scenario A are then compared with the baseline conditions. Similarly, other potential improvement scenarios can be developed and analyzed.

Model scenarios for various improvements can be developed and tracked using the SSOAP Toolbox. Once all the potential scenarios are analyzed in SWMM5, the results from all the scenarios can be imported to the SSOAP System Database and compared with the baseline conditions. These comparisons can also be performed outside SSOAP using spreadsheets or other means. Chapter 5 and the SSOAP Toolbox User Manual describe the use of this feature.

7.5 Developing a Wet-Weather Management Plan

The ultimate outcome of a sanitary sewer system wet-weather management plan study is a set of system improvements for the municipal planning area that meet the system performance objectives under both current and future flow conditions. These improvements should then be incorporated into the utility's overall capital improvement program. Sewer system owners may need to break the improvements into phases if the plan cannot be implemented as a single project. Project phasing must consider the order and priorities of improvements, so that they do not decrease the level of service. The plan should estimate the costs of the improvements and provide an implementation schedule that considers factors such as funding, permitting, design, bidding, and construction. The future budget may be prepared considering an inflation factor. The assumed inflation factor should be documented so that adjustments may be made when the actual inflation rate differs from the one used.

Wet-weather management plans should incorporate a process to evaluate the full range of improvement alternatives using the categories discussed in this chapter. The evaluation process should include a facilitated workshop process for, at a minimum, representatives from the utility's engineering, operations, management, financial, and customer service divisions. In some cases, it may be appropriate to include other stakeholders: environmental groups, regulators and other customer interests, such as homeowners, commercial interests, and major industrial representatives. This inclusive approach may lead to new and innovative ways of solving problems.

Before convening a broad stakeholders group, it will be necessary to perform system diagnostics and analysis for a full range of planning scenarios to develop practical, effective alternatives for the group's consideration. Stakeholder involvement is beneficial in the development of alternative evaluation criteria (see Figure 7-4), which should be considered in the final selection of alternatives. Examples of such criteria include:

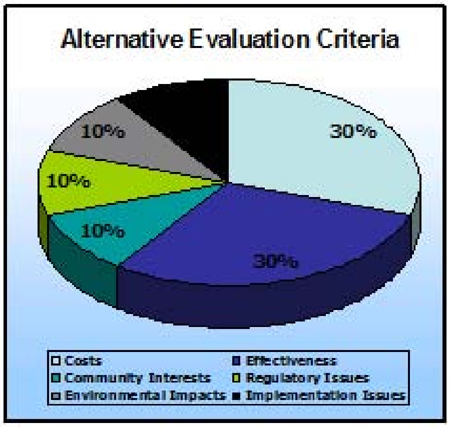


Figure 7-4. Alternative evaluation to involve stakeholders.

- Capital and operational costs
- Effectiveness
- Community interests (e.g., safety, aesthetics, odors, public disruption)
- Environmental impacts
- Reliability of improvements
- Ease of operation and maintained
- Ease of expansion
- Compatibility with regulatory requirements
- Constructability/implementation issues (e.g., utilities and easements)

Evaluation, criteria can be weighted according to stakeholders' input. The following describes the steps commonly used in evaluating alternatives.

Step 1: Determine magnitude of the problem using the SSOAP Toolbox and modeling analyses.
Step 2: Review and screen applicable alternatives.
Step 3: Prepare matrix of feasible scenarios.
Step 4: Use model to determine the level of effort required for each scenario, including their downstream impacts.
Step 5: Estimate cost of each scenario.
Step 6: Determine most cost-effective scenario for the problem area/design storm.
Step 7: Repeat procedure until a series of cost-effective scenarios for varying design storms are developed for each problem area and their costs and benefits are assessed.
Step 8: Consider other non-cost evaluation criteria.
Step 9: Compare and evaluate alternatives.
Step 10: Identify the recommended alternative.

It is important to recognize that interrelationships and differences among problem areas in a sanitary sewer system can be very complex. The most cost-effective solution for a certain area may not address other problem areas. The evaluation process can address this complexity by structuring the alternatives analysis in an iterative process that allows specific problem areas to be revisited in a broader context. This process allows the recommended improvements to be customized to meet unique needs.

One of the most difficult aspects of developing a sanitary sewer improvements plan is the question of sewer rehabilitation benefits. If a sewer system is subject to wet-weather capacity problems, then the reduction in RDII and GWI through sewer rehabilitation should be considered as one element of the overall improvement plan. At issue, however, is the effectiveness of sewer rehabilitation in reducing RDII and GWI, as well as the cost of implementing the rehabilitation. Unfortunately, rehabilitation benefits are highly system-specific and depend on a number of factors, including system age, type of rehabilitation, construction practices, relative importance of private-side RDII and GWI sources, and local economic conditions. Therefore, the best way to understand the benefits of a sewer rehabilitation program is to implement a program and measure its results. This may be accomplished by evaluating the results of past or current sewer rehabilitation work. If that is not available, the planning process may include implementing pilot sewer rehabilitation projects in parallel with other planning activities. At the very least, the municipality should find one or more case studies from other municipalities that have implemented sewer rehabilitation and use their results as assumptions in the planning process until actual local projects can be completed and documented.

Generally, a sewer system capital improvement program needs to include sewer rehabilitation so that the infrastructures may be sustained over a long term. The approach used to perform sewer rehabilitation depends on whether the primary objectives of the rehabilitation are to increase or restore capacity, to reduce RDII and GWI, to correct structural deficiencies, to reduce maintenance costs, or a combination of these objectives. The amount of capital available for sewer rehabilitation will vary considerably by system, but financial analysis methodologies are available to determine the possible return from a given level of investment. This type of analysis stems from the EPA construction grants analysis procedure (EPA, 1975), which compares the cost for performing sewer rehabilitation to the costs of transporting and treating the RDII and GWI entering the system. This method has been updated and enhanced through a recent project by WEF, scheduled for completion in 2008. This WEF study considers the reduced risks and maintenance costs achieved through sewer rehabilitation. Through these analyses, the right combination of sewer rehabilitation and other system improvements, such as capacity upgrades and system storage, can be developed.

Chapter 8 A Case Study – Ann Arbor, Michigan

This chapter provides a case study to demonstrate how the RDII methodology described in this technical report has been effectively used in SSO planning and analysis. This case study serves to illustrate considerable challenges in operating sanitary sewer systems and in planning and analysis for SSO control. More detailed descriptions of the case study and engineering analyses are available in the following references: CDM (2001), Sherman, et al. (2002), Sherman, et al. (2005), Sherman, et al. (2006), and Stonehouse, et al. (2005.)

8.1 Introduction

Controlling SSO and basement backups is important to the City of Ann Arbor, its customers, and its regulators. SSOs are addressed by reducing flows into the system, offsetting any new flow entering the system through a developer mitigation program, and increasing conveyance capacity for strategic reaches of sewer. Inflow from private properties, attributed primarily to footing drains, was determined to be the single largest source of flow under wet-weather conditions. Footing drain flow monitoring provided a greater understanding into the variability and magnitude of this flow. A system-wide model was developed to characterize the hydrology and the collection system hydraulics. This model allowed a system-wide determination of where improvements were needed; prioritization of the footing drain disconnection (FDD) program; and application of a developer mitigation program during which flows from new development are offset by reduced flow in other locations. The approach taken in the City of Ann Arbor is somewhat unique in that:

1. The City recognized that footing drains are a major source of the extraneous flows entering the system and there was real benefit to all users of the system to spend public monies to address the footing drains on private property.
2. The City passed an ordinance requiring that footing drains be disconnected as a legal basis. However, the City's greatest success in compliance was through its public outreach and educational efforts that resulted in an informed and participating citizenry.
3. The City also requires that developers of new projects that would add flow to the sanitary sewer system, offset these flows by reducing existing flows or provide additional capacity to the collection system. The sewer model was reconfigured to specifically represent the development and estimate the additional flow added. Then, flows were removed by disconnecting the appropriate number of footing drains from the collection system at the developer's expense.

Figure 8-1 shows the City's sanitary sewer system and location of its WWTP. The system has the following characteristics:

- Population Served – 114,000
- Tributary Area – 21,900 acres
- Citywide Model – 11,000 pipes (390 miles)
- Base Flow – 19 MGD

SSO occurs during large storm events at the WWTP. Furthermore, precipitation-induced stresses on the sanitary sewer system result in a number of properties experiencing basement backups. A study investigating five areas of concentrated basement backup incidents was performed in 2000 and identified footing drains as a significant contributor to the wet-weather response observed in the sanitary sewer system. In 2003, the City of Ann Arbor, Michigan and the Michigan Department of Environmental Quality (MDEQ) agreed to an Administrative Consent Order (ACO) that serves as the regulatory basis for the City's SSO control program.

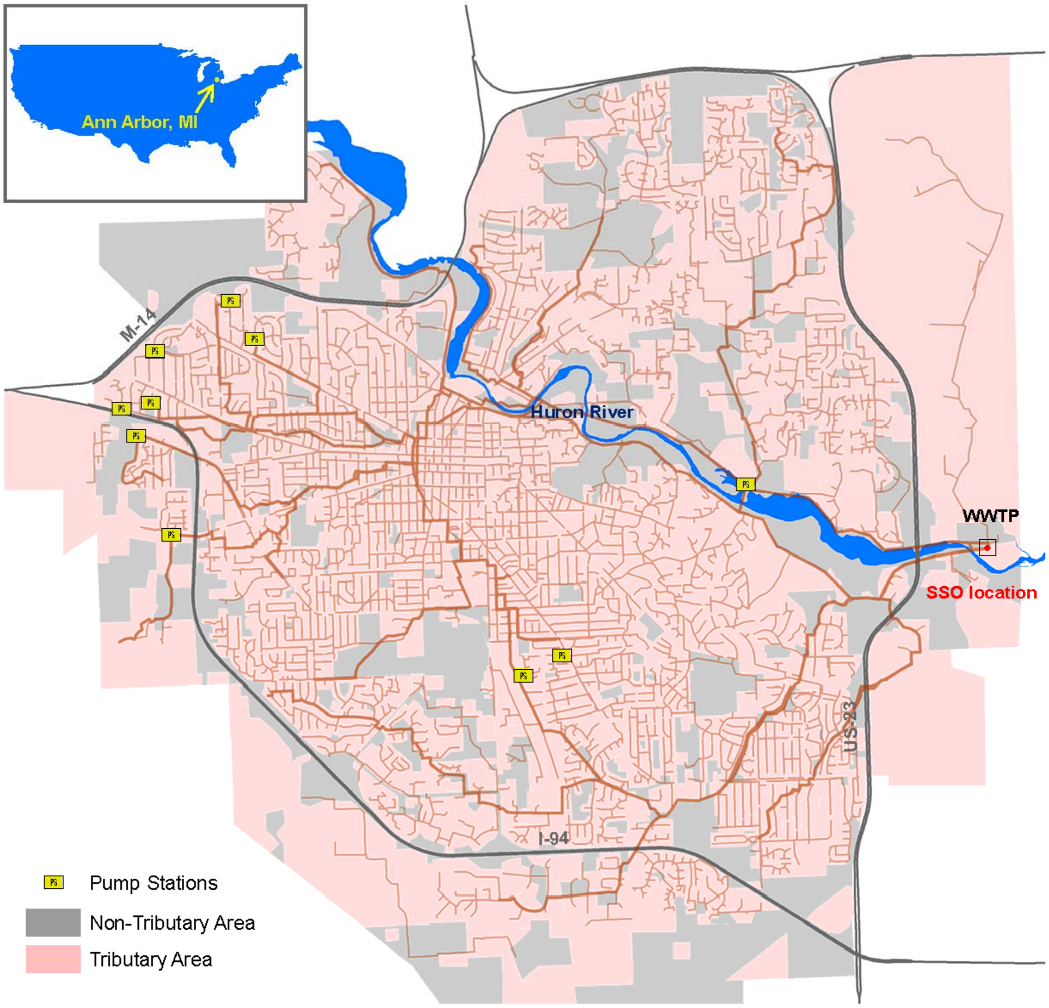


Figure 8-1. Ann Arbor sanitary collection system.

8.2 Hydrology and Hydraulics

The computer model of the City's sanitary sewer system was developed during the third and fourth quarters of 2003. The model helps City staff plan for infrastructure changes and improvements by realistically simulating sewer flows under both existing and future conditions. The model drew information from a GIS database to support development of the hydrologic portion of the model. It also provides collection system attributes to characterize the hydraulic portion of the model. The project team gathered and organized extensive data on the structure of the City's sanitary sewer system. It also collected data on the response of the system, that is, the quantity of flow occurring in its various pipes, and their ability to handle that flow, during dry-weather and storm conditions.

The GIS of the collection system, the DWF data and the wet-weather response information were combined to provide the basis for a computer model of the sanitary sewer system. The modeling software selected for this project was the

SWMM version 4.4h with some minor modifications to array sizes. DHI's Mike SWMM, a commercial package, provided some of the pre- and post-processing functionality. The model has since been converted to SWMM5.

The model development included an initial setup phase, during which connectivity and pipe attributes underwent a thorough review of every profile. Those cases with suspect attributes were investigated further by researching GPS field records (including photos) and where necessary, additional field inspection. DWFs were then incorporated into the model. Finally, wet-weather response parameters were added. These parameters were adjusted to provide a consistent model response during the calibration and validation processes.

8.3 Data Collection

To determine DWF and evaluate the response of the collection system to wet weather, a flow metering network was installed. Flow and water-level data were collected during a six-month period from April to September 2003. The network consisted of 40 flow meters installed throughout the City. Some of these meters were installed to evaluate the response from specific tributary areas, while others were installed in the interceptor sewers to allow overall measurement of flows generated in the areas of the City located north and south of the Huron River.

To understand the water levels in other areas throughout the sanitary collection system, 40 inexpensive peak-stage recorders were also installed to support the six-month monitoring program. At the end of the project, the monitors were left in place to support analysis in the event that a very large storm would occur at a later date. Periodic data were gathered on the peak water elevations reached at these locations to enhance understanding of the wet-weather response of the system. Additionally, a network of 10 tipping bucket rain gauges was used to measure the amount of rainfall to which the collection system was responding. Of these rain gauges, five existed as permanent gauges and five additional gauges were installed (two of which were permanent.) Doppler radar–based information (1 km x 1 km resolution) was used to supplement the rain gauge network with more detailed geographic coverage of rainfall data to support model calibration and verification. Doppler radar-based information (2 km x 2 km resolution) was also obtained for the large June 24-26, 2000 storm event to support analysis of the relatively widespread basement flooding produced by this event.

8.4 Development of System Response Parameters

Collection system response was defined for dry- and wet-weather conditions for dormant and growth seasons. Once the initial framework of the model was established, the next step was to determine typical DWF throughout the City for both dormant and growth seasons. Metering data were analyzed using CDM's Sewer Hydrograph Analysis PackagE (SHAPE) program to establish DWF and RDII days. The SHAPE program allows the decomposition of metered flow into various components, including GWI, BWF, and three unit hydrographs used for defining the shape and volume of the RDII. SHAPE functionality has since been integrated into the SSOAP Toolbox. Measurements of flows at the wastewater treatment plant, supplemented by a comparison to water billing records, provided the initial estimate of DWF. More importantly, they provided a basis on which DWF from metering could be disaggregated to upstream subsewersheds. That is to say that DWFs determined for 40 metering locations were disaggregated to more than 2,600 upstream subsewersheds in proportion to water billing records.

Flow information was also compared to the observed rainfall to determine wet-weather response at each meter location. Response curves created for each meter showed seasonal changes, consistent with previous flow analyses in Ann Arbor and elsewhere. The curves clearly indicated two different seasonal characteristics in the system's response to rainfall, with a marked change from one to the other season. Figure 8-2 illustrates a clear break between seasons occurring in late May 2003. A second transition was not monitored as part of this project but would occur in the fall. These two types of collection system behavior are referred to as the dormant and growth season responses. During the dormant season, with its lack of vegetation, the system responds to wet weather with a significantly greater volume of sewer flow than in the growth season, when vegetation reduces the amount of rainfall entering the collection system. The MDEQ defined growth season from April 1st through October 31st, so for regulatory simulations, parameters were adjusted to appropriately represent these requirements.

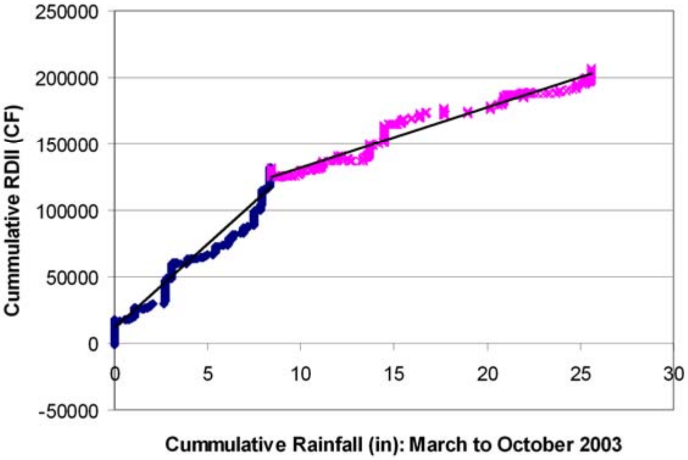


Figure 8-2. Seasonal breakpoint.

The general hydrologic model centers on using the RDII parameters, R, T, and K, for up to three component hydrographs. The T and K parameters are listed in Table 8-1, whereas, the area-weighted average R-values varied from 1.6 to 4 percent for the growth and dormant seasons, respectively. For this work, two component hydrographs were found to be adequate: one defines the more direct response, or inflow; and the other defines the delayed response, or infiltration. The R values quantify the response volume and shape and the T and K parameters further refine the response shape. Another aspect of RDII is illustrated in Figure 8-3, that of the initial abstraction. Initial abstraction is the ability of surfaces and soils to hold water with little or no response observed in the collection system. The maximum initial abstraction (V_0) noted in Figure 8-3 represents the amount of rainfall below which the collection system will not respond if dry antecedent moisture conditions apply. Initial abstraction varies between zero for very wet antecedent moisture conditions and V_o for dry antecedent moisture conditions. The maximum value also varies seasonally with growth season often as much as twice that of dormant. Furthermore, the growth season response volume can be markedly lower than dormant season conditions for the same volume of rainfall. The seasonal variation in initial abstraction and response volume is similar to that observed in many sanitary systems.

Table 8-1. RDII TK Parameterization

Areas Affected	**Footing Drains**		**Component Hydrograph Shape Parameters**			
	Yes	**No**	**T_1**	**K_1**	**T_3**	**K_3**
General Application (except specific areas noted below)	X		2	1.4	5	18.2
General Application (except specific areas noted below)		X	2.4	1	5	18.2
*03B, 17C	X	X	1.2	1	5	18.2
*06A	X	X	5	1	10	8.6
*07A, 07B, 09D	X	X	3	1	5	18.2
*13A	X	X	2	2	8	3

*Areas where flow monitoring data were available but not shown in Figure 8-1.

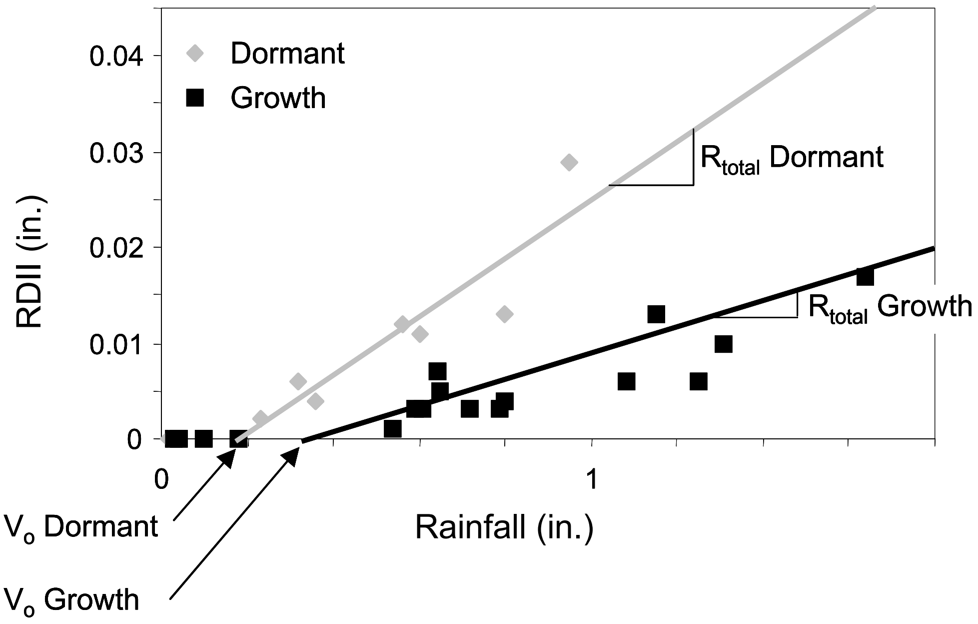


Figure 8-3. Seasonal responses to rainfall relationships.

8.5 Capacity Assessment

Once calibrated, the model was used to analyze Ann Arbor's sanitary sewer system. Several scenarios were created and modeled to determine where the collection system needed improvements. The analyses performed included modeling strategies to prevent SSOs in the Swift Run trunk and assessing the effect of the FDD program to determine when the collection and treatment systems would comply with SSO requirements. Figure 8-4 illustrates surcharging in terms of depth from ground surface to the HGL. High HGL relative to the ground, as determined by the model, coincides well with the locations of basement flooding.

A second part of the modeling analysis work was to review the system from a level-of-service perspective. This effort included simulating two large historical storm events in August 1998 and June 2000, which caused widespread basement backup problems. This analysis resulted in recommendations for system improvements to provide protection to City residents from future similar events. The model allowed various improvements under various FDD program conditions to be evaluated. For example, the model is used to evaluate the effect of new development on the collection system and the effect of removing flows as part of the developer-mitigation requirement.

8.6 SSO Control Program

The City-wide model was used to evaluate the FDD program to reduce RDII in the sanitary sewers. By adjusting the model to account for the number of properties for which FDD has been performed or will be performed in the future, the model helps determine the resulting effects on the wastewater collection system. This capability assists in planning current and future phases of that program.

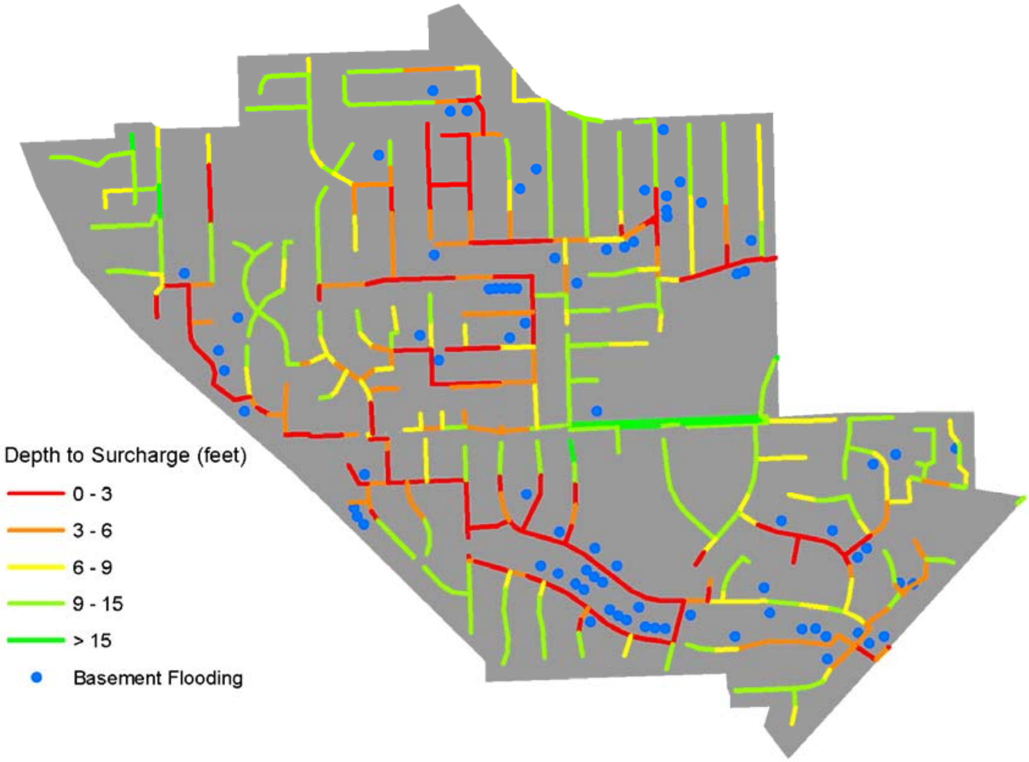


Figure 8-4. System capacity limitations coincide with basement flooding incidents.

To eliminate SSOs, flow must be removed from the sanitary sewer system or the capacity of the system be increased. The requirements for compliance with the ACO include:

- Disconnect footing drains as the primary method of reducing flow. Figures 8-5 and 8-6 show some of the exterior and interior work associated with FDD.
- Monitor a representative sampling of disconnected footing drain flow to confirm the removal of flows from the sanitary sewer system. A hydrograph of footing drain flow is shown in Figure 8-7.
- Monitor sewer flow and model system-wide hydrology and hydraulics to certify that the corrective action plan meets the control objective.
- Implement a mitigation program to offset flow produced by new construction.
- Submit annual report to document compliance with the above requirements.

Figure 8-5 shows work on the curb drain. A curb drain is required in most cases to serve as a collector pipe by which all disconnected footing drains for properties along one side of the street can connect. This curb drain then taps into the existing stormwater system, often at the back-of-curb side of existing catchbasins as shown in Figure 8-5. Figure 8-6 shows a finished sump, to which the footing drain disconnected from the sanitary sewer is reconnected prior to pumping from the basement through a pipe that discharges into the curb drain. Figure 8-6 also shows two persons performing a drawdown test to assess the average pumping rate at one of many locations instrumented with data loggers that record pump ON/OFF cycling. The pumping rate and the ON/OFF data can be used to determine the flow directed to the sump from the footing drains. An example of this footing drain flow is shown in Figure 8-7 and is a useful means of quantifying flows removed at the source, in this case as a response to a storm event. Many footing drains also produce flow under dry-weather conditions, that once removed, also provide a benefit in the form of reduced treatment costs.

Figure 8-5. Curb drains convey disconnected footing drain flow to the storm water system.

Figure 8-6. Testing pumping rate to support monitoring of a disconnected footing drain.

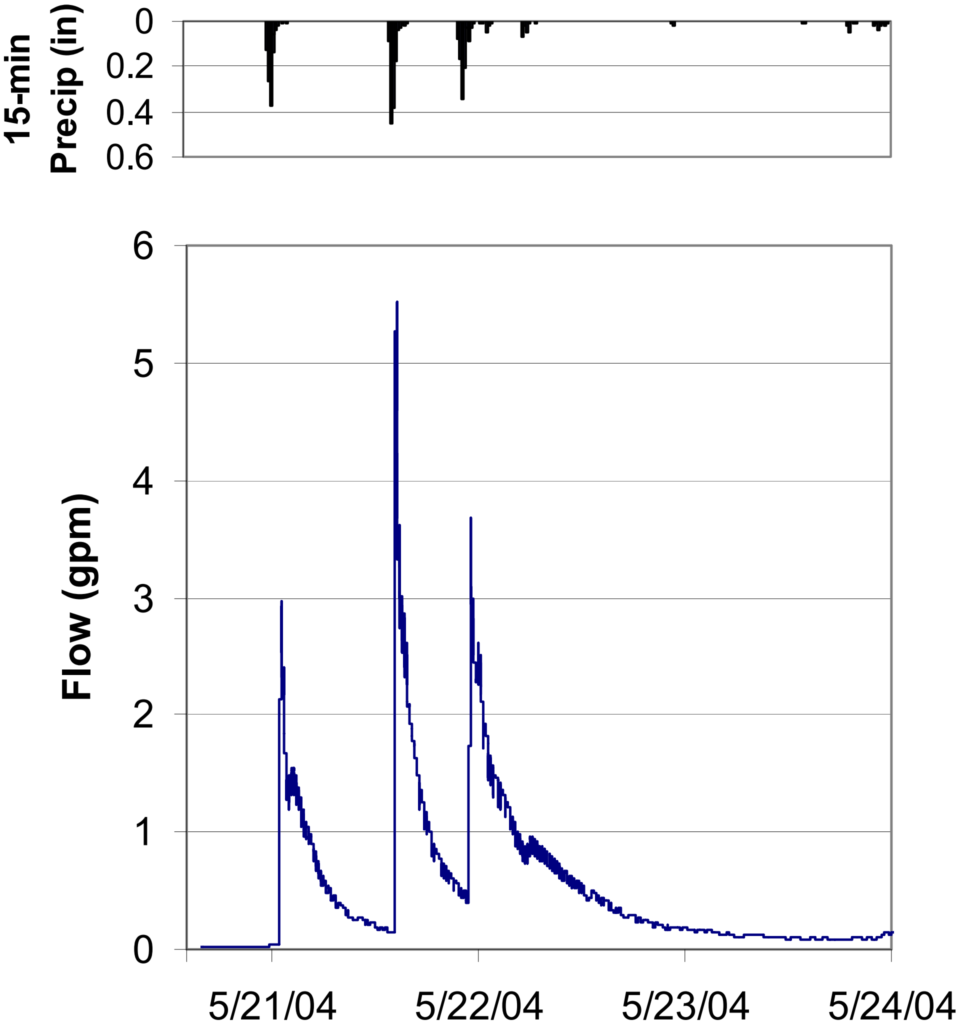


Figure 8-7. Footing drain monitoring provides evidence of flows being removed.

Prioritizing FDDs relied heavily on modeling results. Approximately 1,000 properties have been disconnected. Figure 8-8 illustrates FDD progress. In the areas where the FDD schedule is yet to be determined, there are properties that do not have connected footing drains. These properties are primarily identified by the year constructed or other factors, such as structures on slabs instead of basements.

Many factors influence the prioritization of work. Homes selected for disconnection were based on incident reports, model results, visual surveys for properties at similar elevations, and where curb drain construction made sense for both engineering and cost. The severity of backups and concentrations of effort were also factors. Modeling was used in some areas to confirm that properties were not at risk for basement backup. In general, properties with connected footing drains, which are at risk for basement backup, will have check valves installed. The intent is to ultimately reduce system stresses to the point that the check valves are no longer necessary. Therefore, after focusing on properties at risk for basement backup, footing drain flows will be removed to reduce hydraulic grade line in critical areas.

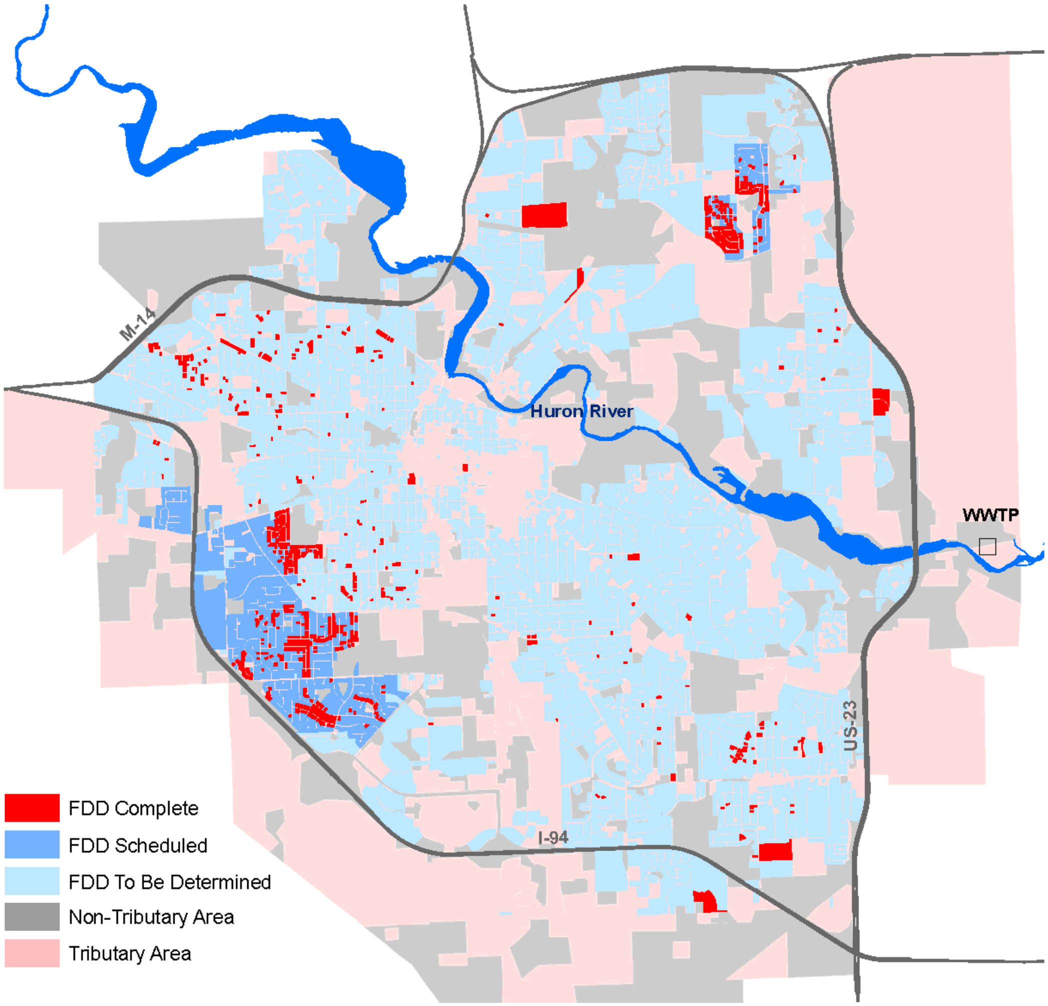


Figure 8-8. Footing drain disconnection progress.

As part of this subsequent phase, the City found that multi-family residential buildings offered the potential to remove footing drain flow at less cost per gallon removed due to a greater length of footing drain (related to building perimeter) per disconnection made. All flow removed has the added benefit of not requiring treatment and further reduces the risk of SSOs at the WWTP.

For large storm events on the order of 3.6 to 3.9 in. during 24 h, estimates based on extrapolating footing drain flow monitoring data suggest approximately 4 gpm peak rate is removed for each FDD on average. With approximately 1,000 disconnections thus far, this equates to between 5 and 6 MGD removed during a large storm event. This is a significant improvement for a system with peak treatment capacity of 29.5 MGD and flow equalization of 16.8 MG. Although less significant, DWF analysis of footing drain flows indicate that there has been approximately 14 MG/year removed from treatment due to base footing drain flow alone. This represents 75 percent of one day's wastewater treatment on a typical DWF day.

In addition to supporting the FDD program, the SSO control program requires that the collection system be managed to ensure improvements are made and that additional development does not exacerbate existing problems. The sanitary sewer system model has been used to identify and support specific infrastructure improvements, including:

- Increased capacity for the Swift Run trunk system.
- Optimized pumping at the Lakewood Pumping Station, including pump upgrades.
- Modeling results were provided in GIS and hardcopy format to the City's planning department to allow consideration of sewer improvements during street repaving and prioritized work. Sewer upgrades are performed concurrently with street repaving efforts where necessary.
- The model is being used to support an ongoing evaluation of flow control between the north and south Huron River interceptors to better optimize system operations to effectively use the existing conveyance capacity.
- Developers are required to mitigate flows added to the collection system by performing FDDs at existing properties. To date, there have been 58 developer projects requiring mitigation of 8.8 MGD based on expected sanitary flow – multiplied by a factor of 4 – to represent potential peak rate added.
- Evaluate impact of University of Michigan football stadium expansion.

8.7 Public Outreach

The City and its residents participated in a joint task force that oversaw the study, the development of the program, and effectiveness of solutions implemented. The task force was the first step in reaching out to the public and involving them in the process. The FDD program included work in five areas in Ann Arbor that have historically experienced basement backups. These areas primarily comprise the most dense sewer network areas shown in Figure 8-8 that lie in the northeast and southwest of the map. For these properties, the facilities located in basements, which include floor drains, laundry, showers, and bathrooms, are being protected from future basement backups using check valves.

As part of construction management services, the program manager scheduled groups of properties to be disconnected each month. The program manager also scheduled group discussions as part of neighborhood meetings (see Figure 8-9), individual meetings with homeowners during preconstruction inspections, reviewed estimates from prequalified contractors, and performed post-construction inspections to ensure that the work met the standards of the City. The public outreach work included periodic presentations to the City Council and weekly video broadcasts on the local cable access channel that explained the need for the program and the required steps for success. In addition, the outreach program consisted of an informational website that explained the project activities, as well as informational materials provided in the reference areas of all of the local libraries.

The work on private properties included installing new sumps in basements, installing check valves, disconnecting the footing drains from the sanitary piping, and installing a sump pump and discharge line. This program also included a flow verification step. For this work, individual sump pump discharges were monitored to better understand the flow volume and peak rates to be expected once these footing drains were disconnected. This information is useful in guiding future implementation phases of the program and providing information to homeowners on the reductions in flows that resulted from performing this disconnection work. Participating property owners rate the program "excellent" year after year based on feedback from a survey provided to owners post-construction.

Figure 8-9. Neighborhood meeting with property owners.

8.8 Summary

A computer model of the entire publicly owned sanitary collection system was developed. The model includes the physical characteristics of the City's sanitary sewers and the wet-weather response characterization for different seasons. The wet-weather response, RDII, was modeled using SWMM and included the R, T, and K parameters for all model tributaries. The model was calibrated and validated with available flow and water-level data. It provides a reasonable estimate of the actual responses expected in the sanitary collection system under a variety of conditions.

The FDD program is underway with approximately 1,000 properties disconnected. This RDII removal program, with work on private property, requires an effective public outreach program to ensure participants are well informed and receptive to the changes needed to address system capacity problems and associated basement backups.

The model was used to determine how the sanitary collection system responds to various storm scenarios, and to understand how the FDD program affects the operation of the system during such storms. The analysis has helped improve the City's understanding of specific deficiencies in its collection system, so that corrections can be made to provide a consistent level of service to all customers.

Moreover, Ann Arbor's City-wide model provides City staff with an ongoing planning tool that can be used to evaluate sewer service for new developments and the impact of such development on the existing system and its customers. It also helps the City develop effective strategies for continued compliance with environmental regulations and policies.

Chapter 9 References

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