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SSOAP Toolbox Enhancements and Case Study

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by

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Abstract

Recognizing the need for tools to support the development of sanitary sewer overflow (SSO) control plans, in October 2009 the U.S. Environmental Protection Agency (EPA) released the first version of the Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox. This first version of the SSOAP Toolbox contained modeling software with five functional tools to assist communities in developing SSO control plans that correspond with communities' projected annual capital budgets and are flexible for future improvements. The SSOAP Toolbox and two related technical reports were developed by EPA and CDM Smith Inc. under a cooperative research and development agreement (CRADA).

During its Aging Water Infrastructure (AWI) research program in 2010, EPA determined the SSOAP Toolbox to be a critical tool for evaluating and prioritizing wastewater collection system infrastructure for improvements, and for assessing the success of sewer rehabilitation activities. Consequently, EPA and CDM Smith enhanced the SSOAP Toolbox with a sixth tool — the Condition Assessment Support Tool — that enables users to develop focused sewer condition assessments and evaluate the success of improvements.

This document describes the Condition Assessment Support Tool and provides a case study to demonstrate how methodologies in the SSOAP toolbox have been effectively used to support wastewater infrastructure improvements. EPA anticipates releasing the second version of the SSOAP Toolbox enhanced with the Condition Assessment Support Tool in the fall of 2012.

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Abbreviations and Acronyms

ADWF	Average Dry-Weather Flow
AWI	Aging Water Infrastructure
CAP	Capacity Assurance Program
CAP/ER	Corrective Action Plan/Engineering Report
CIPP	Cured-in-Place Pipe
CCTV	Close-Circuit Television
CD	Consent Decree
CMOM	Capacity Management, Operation, and Maintenance
CRADA	Cooperative Research and Development Agreement
CSO	Combined Sewer Overflow
DMT	Database Management Tool
DWF	Dry-Weather Flow
EPA	U.S. Environmental Protection Agency
ER	Engineering Report
GIS	Geographical Information System
IA	Initial abstraction parameters used in the RTK method for RDII prediction
K	Ratio of the Time of Rainfall Recession to the Time of Peak
KUB	Knoxville Utilities Board
NPDES	National Pollutant Discharge Elimination System
QA/QC	Quality Assurance/Quality Control
R	Fraction of Rainfall Falling on the Sewered Area that Enters the Sewer System as RDII
RDII	Rainfall-Derived Infiltration and Inflow
R, T, K	The R, T, and K parameters in the RTK method for RDII prediction
SSD	SSOAP Toolbox System Database
SSES	Sewer System Evaluation Survey
SSOAP	Sanitary Sewer Overflow Analysis and Planning
SSO	Sanitary Sewer Overflow
SSOER	SSO Evaluation Report
SWMM	Storm Water Management Model
SWMM5	Storm Water Management Model Version 5
T	The Time to the Peak RDII in Hours
TAZ	Traffic Analysis Zone
TDEC	Tennessee Department of Environment and Conservation

Acknowledgements

The authors from CDM Smith Inc. (CDM Smith) acknowledge the assistance of EPA Project Officer Dr. Ariamalar Selvakumar for her technical participation and detailed review of this report. Special thanks are extended to Dr. Fu-hsiung (Dennis) Lai, a past EPA Project Officer, for his contributions during the initial development of the SSOAP Toolbox and conceptualization of the major enhancements described in this report.

Several technical experts within CDM Smith contributed to the preparation of this technical report and the SSOAP Toolbox enhancements. CDM Smith's Project Manager/Principal Investigator Mr. Srini Vallabhaneni provided oversight and guidance to the team of technical experts and computer programmers. Mr. Carl Chan provided lead programming support with assistance from Mr. Rod Moeller. Mr. Shannon Campbell authored the case study. Mr. Ted Burgess and Mr. Wayne Miles provided project advice. Mr. Ben Sherman provided technical reviews and contributed to the SSOAP Toolbox user's manual. Ms. Jessica McKinney provided technical editing and document development support. Preparing the project work products required a tremendous effort by each and every one of these individuals.

The project team would like to thank the Knoxville Utilities Board (KUB) in Knoxville, Tennessee for allowing us to showcase its experiences in sanitary sewer overflow (SSO) control analysis, planning, and project implementation. The KUB's experience was critical to demonstrate how the enhanced SSOAP Toolbox methodologies are applied to sanitary sewer system evaluations, specifically to prioritize sub-sewersheds for field investigations and to analyze post-rehabilitation flow data to assess rehabilitation effectiveness.

Executive Summary

The U.S. Environmental Protection Agency's (EPA's) Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox (EPA, 2012a) is a public-domain suite of computer software tools to help evaluate the capacity of sanitary sewer systems. The SSOAP Toolbox and two related technical reports were developed by EPA and CDM Smith Inc. under a cooperative research and development agreement (CRADA).

After completion of the CRADA, the EPA contracted CDM Smith to provide SSOAP Toolbox user support and to conduct training workshops for program offices, regions, states, and municipalities nationwide. The SSOAP Toolbox user support included software installation, data input, parameter definitions, software operation, and output interpretations. Periodic minor SSOAP Toolbox software revisions (Versions 1.0.1, 1.0.2, and 1.0.3) have been released based on user feedback. A list of toolbox enhancements with each update is posted on the SSOAP Toolbox download website (EPA, 2012a).

During its Aging Water Infrastructure (AWI) research program in 2010 (EPA, 2010), EPA determined the SSOAP Toolbox to be a critical tool for evaluating and prioritizing wastewater collection system infrastructure for improvements, and for assessing the success of sewer rehabilitation activities. Consequently, EPA and CDM Smith enhanced the SSOAP Toolbox with a sixth tool — the Condition Assessment Support Tool — that enables users to develop focused sewer condition assessments and evaluate the success of completed improvements.

This technical report describes the new Condition Assessment Support Tool and provides a case study that demonstrates how the rainfall-derived infiltration and inflow (RDII) methodology in the SSOAP Toolbox has been effectively used in sewer condition assessment and rehabilitation to support wastewater infrastructure improvements.

The Condition Assessment Support Tool has two primary functions:

1. **Prioritizes Sub-Sewersheds for field Investigations to Support Condition Assessment** – The tool obtains RDII parameters stored in a central database for selected sub-sewersheds and enables graphical and tabular comparisons. This information can be used to prioritize sub-sewershed field investigations and subsequent sewer rehabilitation plans. To accomplish this, a range of RDII parameter is developed, including levels of inflow, infiltration, RDII flow rate/acre, and RDII volume/linear feet of sewer in the sub-sewersheds.

2. **Performs a Pre- and Post- Sewer Rehabilitation RDII Correlation Analysis** – The tool enables graphical and tabular comparison of RDII estimates from two sub-sewersheds (control and rehabilitation) obtained from two different flow monitoring periods (pre-rehabilitation and post-rehabilitation periods). The control sub-sewershed is a sewered area that has not undergone any rehabilitation; is ideally nearby; and, is similar in age, size, land-use, and pipe materials to a sub-sewershed being studied with post-rehabilitation conditions. The control area is used to compare how RDII in pre- and post- rehabilitation periods respond to environmental variations, as a result of system rehabilitation and other improvements. Results can be used to assess the effectiveness of sewer rehabilitation programs.

The case study included in this technical report features the Knoxville Utilities Board (KUB) in Knoxville, Tennessee. KUB's sanitary sewer collection system encompasses more than 64,000 customers, covers approximately 108 square miles (275 km^2) , has more than 1,250 miles (2000 km) of service mains, and is served by four regional wastewater treatment plants, all of which serve a population of nearly 179,000 in the City of Knoxville, Knox County. KUB has been using the RDII methodology in the SSOAP Toolbox for nearly a decade to support planning, operation, and maintenance aspects of its collection system.

The KUB case study illustrates challenges in planning and analysis for SSO control and progressive infrastructure improvements over an extended period. KUB's approach incorporated SSOAP Toolbox methodologies for characterizing RDII to support sewer system capacity and condition assessments. KUB established a mini-basins prioritization system using RDII results for conducting focused field investigations. KUB developed and implemented high priority sewer rehabilitation projects from 2006 through 2010 using RDII assessments coupled with results obtained from field investigations. These projects included cured-in place pipe (CIPP) or line replacement of 151,000 LF (46,000 linear meter) of pipe and rehabilitation of nearly 800 manholes.

Subsequent to rehabilitation projects, KUB compared the RDII results from pre- and post-rehabilitation periods using the same approach employed by the SSOAP's Condition Assessment Support Tool. Based on results obtained from 2006 through 2010, RDII reduction trends varied widely with estimated median reductions of about 51 percent. KUB's sewer condition assessment and rehabilitation efforts are ongoing. RDII reduction trends observed to date will be further substantiated using additional results obtained from ongoing sewer rehabilitation and flow monitoring projects. This continuing cycle of assessment enables KUB to continuously manage its assets improve the reliability of system performance.

Chapter 1: Introduction

This chapter provides the background and history of the Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox (EPA, 2012a), a software package that the U.S. Environmental Protection Agency (EPA) released in October 2009. This chapter also introduces recent enhancements to the SSOAP Toolbox since its original release, and outlines the remaining chapters of this document.

1.1 Background and History

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

Rainfall-derived infiltration and inflow (RDII) causes operational problems in sanitary sewer systems. Although sanitary sewer systems are generally designed to accommodate RDII flows during wet-weather, these flows often exceed the design allowances. EPA places high priority for system owners and operators to correct these problems.

Nationwide, there are more than 19,500 municipal sanitary sewer collection systems serving an estimated 150 million people and about 40,000 SSO events per year. Addressing aging water infrastructure challenges is one of the top national water program priorities, and is one of the top priorities of the U.S. Conference of Mayors. Improving the conditions of aging sewers can reduce infiltration and related SSOs.

The EPA recognized the need to develop methodologies and computer tools to help communities characterize sanitary sewer systems and plan corrective actions to address SSOs. In 2002, the National Risk Management Research Laboratory of the EPA entered into a cooperative research and development agreement (CRADA) with CDM Smith Inc. (CDM Smith) to develop a computer toolbox (i.e., SSOAP Toolbox) and associated technical reports to assist communities in developing SSO mitigation plans. CRADA efforts were completed in 2008 and yielded:

1. Technical Report: Review of Sewer Design Criteria and RDII Prediction Methods, EPA/600/R-08/010, January 2008 (EPA, 2008).

2. Technical Report: Computer Tools for Sanitary Sewer System Capacity Analysis and Planning, EPA/600/R-07/111, October 2007 (EPA, 2007).

3. Software: SSOAP Toolbox, October 2009.

The SSOAP Toolbox can serve as the foundation for wastewater collection system capacity and condition assessments, enabling users to:

- Analyze monitored flow data to predict RDII.
- Prioritize where to inspect, monitor, and assess the performance of rehabilitation activities.
- Help municipalities identify SSO problems and develop a sensible control plan to meet their NPDES permit requirements.

The first version of the SSOAP Toolbox contained a suite of five integrated computer software tools (EPA, 2007) for: Database Management, RDII Analysis, RDII Hydrograph Generation, SSOAP-Storm Water Management Model Version 5 (SWMM5) Interface, and Sewer Flow Routing. The SSOAP Toolbox includes an online user manual and link to relevant technical reports that detail various tools and their functionalities. The SSOAP Toolbox integrates EPA SWMM5 (EPA, 2012b) to perform on hydraulic assessment of the sewer system. In addition, the SSOAP Toolbox allows the use of external software tools to perform RDII and hydraulic routing analyses.

Figure 1-1 shows the overall structure of the SSOAP Toolbox (Version 1.0.3, January 2012) and the flow of data through the analysis and planning process.

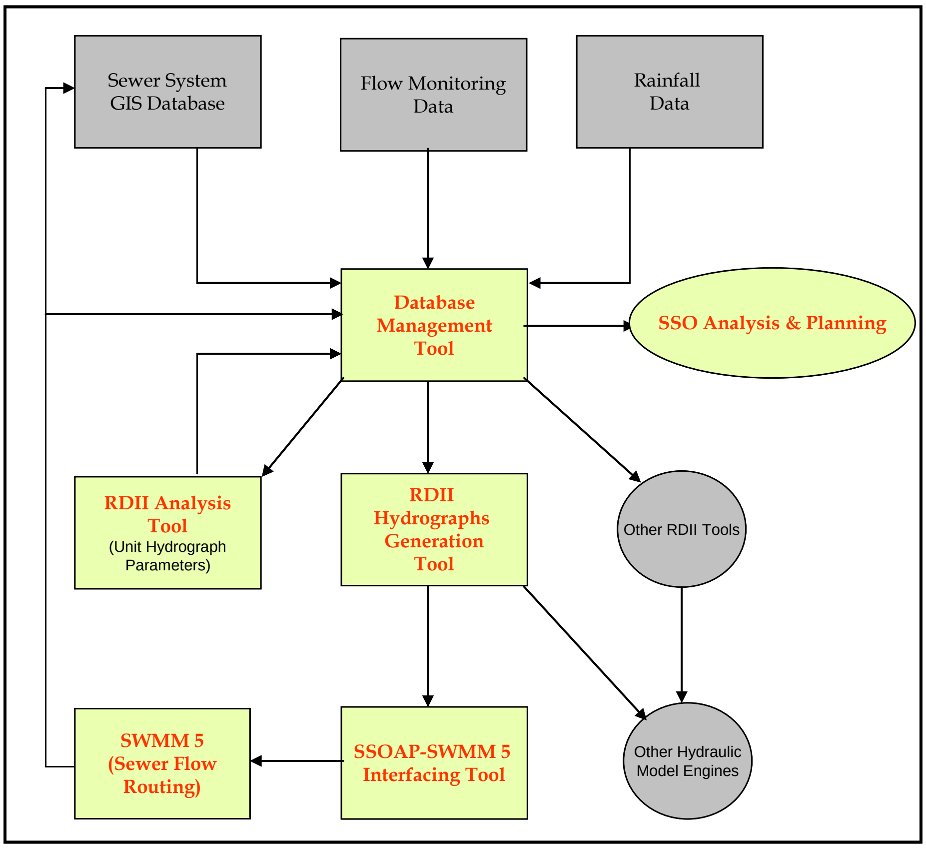

Figure 1-1 – Overview of tools within the first version of the SSOAP Toolbox (Version 1.0.3, January 2012)

The following pages describe the individual components of the first version of SSOAP tools. Full description of these tools and their functions are available in previously published technical report (EPA, 2007) and the online help documentation within the SSOAP Toolbox.

1.1.1 Database Management Tool

The Database Management Tool is the command center of the toolbox. It stores and organizes data using a standard Microsoft Access® database called the SSOAP Toolbox System Database (SSD). This tool interfaces with several external data sources, including sewer system GIS databases, flow monitoring program data, data from rainfall monitoring programs or radar rainfall analyses, and hydraulic modeling analysis results.

1.1.2 RDII Analysis Tool

Based on rainfall flow data collected within the sewer systems, the RDII Analysis Tool evaluates RDII characteristics using a unit hydrograph method, also known as RTK method (EPA, 2008). This method uses three triangular unit (R, T, and K) hydrographs to represent the ways that precipitation contributes to RDII. R represents the fraction of rainfall falling on the sewered area that enters the sewer system as RDII. T is the time to the peak RDII flow in hours, and K is the ratio of the time of recession to the time of peak. The RDII volumes of three unit hydrographs are designated as R1 (fast response), R2 (medium response), and R3 (slow response). The sum of R1, R2, and R3 equals the total R value for the storm event. If more of the total R-value is allocated to R1, this indicates that the RDII is primarily inflow driven. If more of the total R value is allocated to R2 and R3, this indicates that the RDII is primarily infiltration driven.

The RDII Analysis Tool can support four major analyses:

- Dry-weather flow (DWF) to determine base wastewater flow and groundwater infiltration components of wastewater flow.
- Wet-weather flow analysis to determine the RDII hydrograph.
- Unit hydrograph curve fitting analysis to determine RDII unit hydrograph parameters (RTK). This analysis allows adjustment to the initial abstraction (IA) parameters, which can account for antecedent moisture conditions to support continuous model simulation of sanitary sewer systems.
- Statistical analysis of RDII parameters. This analysis uses RTK unit hydrograph parameters that were stored in the Database Management Tool to develop correlations, and helps extrapolate RDII parameters from the correlations found in measured conditions to non-measured or design storm conditions.

1.1.3 RDII Hydrograph Generation Tool

The hydrograph generation tool generates the RDII hydrograph of a sewershed for the selected rainfall events using its physical characteristics (e.g., sewer areas and land uses) stored in the Database Management Tool and the R, T, and K values determined with the RDII Analysis Tool. This tool can provide a visual of the RDII hydrograph generated before exporting the data as input to a sewer routing model. The tool can export RDII hydrographs to SWMM5 or other hydraulic routing engines.

1.1.4 SSOAP-SWMM5 Interface Tool

This tool is designed to organize and incorporate the hydrographs generated by the RDII Hydrograph Generation Tool into the SWMM5 input files. It will then initiate a SWMM5 simulation. After the SWMM5 run, the tool will deliver the SWMM5 simulation results to the Database Management Tool, where the model results will be organized for additional post-processing.

1.1.5 Sewer Flow Routing (SWMM5)

The SSOAP Toolbox uses SWMM5 to perform the actual dynamic flow routing through a sewer network system. It also uses the graphic utility interface capability in SWMM5 (EPA, 2012a and 2012b) to visualize the sewer system responses and to selectively export the output data for further analysis.

1.2 SSOAP Toolbox Enhancements – Addition of Condition Assessment Support Tool

Based on user feedback during the SSOAP Toolbox training workshops during 2009 through 2010 and through technical support activities, minor revisions were made to the SSOAP Toolbox, resulting in the release of Versions 1.0.1, 1.0.2, and 1.0.3 (EPA, 2012a).

During EPA's Aging Water Infrastructure (AWI) research program in 2010 (EPA, 2010), the SSOAP Toolbox was determined to be a critical tool in wastewater collection system analysis, enabling users to analyze monitored flow data to prioritize where to inspect, monitor, and assess the performance of rehabilitation. Consequently, EPA and CDM Smith enhanced the SSOAP Toolbox with a sixth tool — the Condition Assessment Support Tool — that enables users to develop focused sewer condition assessments and evaluations of the success of completed improvements.

Condition assessments of sewers are typically performed by visual examination, which can be time consuming and incur expenses for field investigation technologies [closed-circuit television (CCTV), sonar, laser, ultrasonic, and infrared]. The SSOAP Toolbox's Condition Assessment Support Tool enables users to prioritize areas for field investigation based on RDII prediction methodology. This new tool's uses include:

1. Developing RDII investigation priorities among different sewersheds and sub-sewersheds to facilitate a focused field investigation plan and subsequent sewer rehabilitation plan.

2. Comparing RDII estimates between post-rehabilitation and pre-rehabilitation conditions to better understand rehabilitation effectiveness.

The second version of the SSOAP Toolbox (Version 2.0.0) with the addition of the Condition Assessment Support Tool is anticipated to be released to public in the fall of 2012. Figure 1-2 shows the overall structure of the second version of the SSOAP Toolbox, including the Condition Assessment Support Tool.

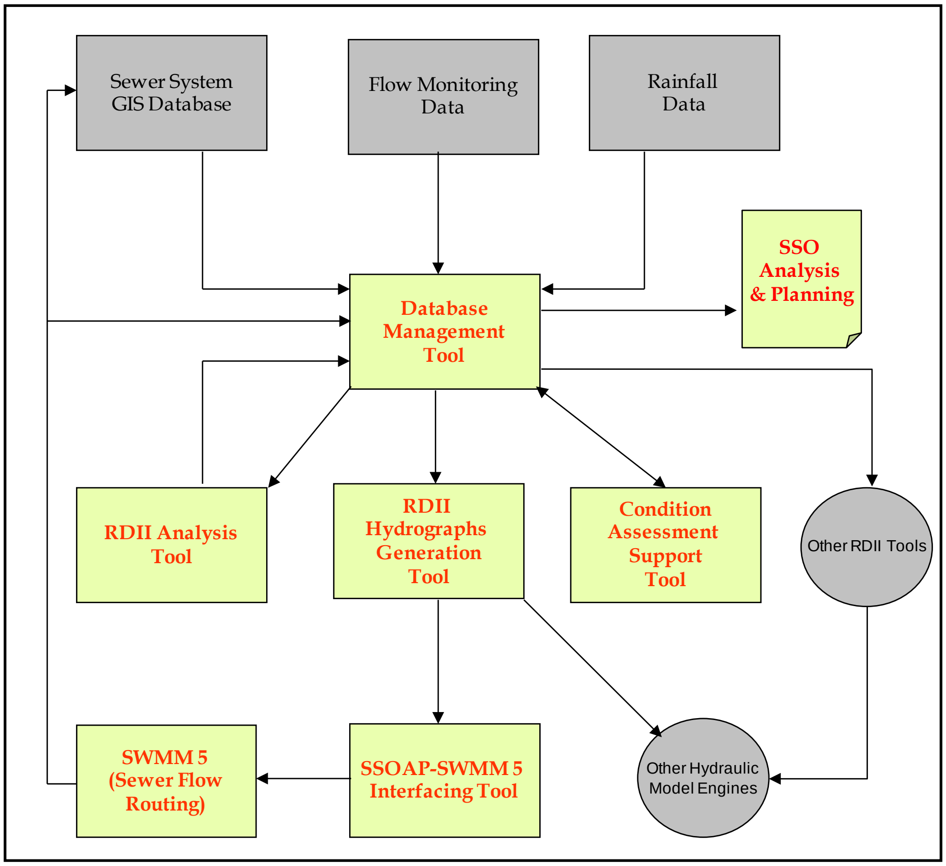

Figure 1-2 – Overview of tools within the SSOAP Toolbox with addition of the Condition Assessment Support Tool (Version 2.0.0, anticipated to be released in the fall of 2012)

1.3 Technical Report Organization

The remaining chapters of this document include:

Chapter 2: Condition Assessment Support Tool Overview − Describes the SSOAP Toolbox's Condition Assessment Support Tool to prioritize sewershed areas for field investigations and to assess the effectiveness of subsequent sewer rehabilitation.

Chapter 3: Case Study – Presents how the Knoxville Utilities Board in Tennessee used the SSOAP Toolbox methodologies to develop a focused condition assessment program and post-rehabilitation performance evaluation of its sewer system.

Chapter 4: References – Provides a list of references cited in the report.

Chapter 2: Condition Assessment Support Tool Overview

2.1 Introduction

The Condition Assessment Support Tool can help users prioritize sewersheds for RDII investigations and assess the subsequent effectiveness of sewer rehabilitation programs. Chapter 1 briefly introduced the Condition Assessment Support Tool along with a description of the other five tools. More details of these five tools are provided in the previously published technical report: Computer Tools for Sanitary Sewer System Capacity Analysis and Planning (EPA, 2007). The online SSOAP Toolbox user's manual also guides users on proper tool usage and provides guidelines for a range of applications (EPA 2012a). This chapter describes the Condition Assessment Support Tool and its capabilities in more detail.

2.2 Primary Functions

The Condition Assessment Support Tool serves two primary functions:

1. Obtains sub-sewersheds' RTK parameters from the Database Management Tool and enables users to compare them via graphics and tables. This information can be used to prioritize sub-sewersheds, design focused field investigations, and subsequent sewer rehabilitation plans.

2. Obtains sub-sewersheds' RTK parameters under pre- and post-rehabilitation conditions from the Database Management Tool and enables users to correlate data via graphics and tables. Users can then assess the effectiveness of sewer rehabilitation programs.

RDII analysis results must be stored in the SSOAP Toolbox database to enable the Condition Assessment Support Tool to function as designed. The Condition Assessment Support Tool allows a number of user-specified criteria to help prioritize sub-sewersheds and correlate pre- and post- sewer rehabilitation RDII parameters.

2.3 Sub-sewershed Prioritization for Condition Assessment Field Investigations

The RDII Analysis Tool can be used to analyze sewer system flow data and develop three unit hydrographs for each sub-sewershed and corresponding RTK values for select wet-weather conditions. Results from these RDII analyses are stored in the Database Management Tool, including R1, R2, R3, and total R-value. Using the spatial distribution of R-values, users can prioritize the tributary areas' condition assessment and subsequent system rehabilitation.

The Condition Assessment Support Tool uses the RDII analysis results stored in the Database Management Tool as the basis to generate information for sub-sewershed prioritization. Users can apply a range of RDII parameters stored in the Database Management Tool, such as Total R, R1, R2, and R3, to prioritize the sub-sewersheds and identify specific types of field investigation needs. Other parameters, such as peak RDII flow rate/sub-sewershed area and RDII volume/length of sewer in sub-sewersheds, can also be used as criteria to assess the priorities.

The following example scenarios are presented to demonstrate the Condition Assessment Support Tool's capability to generate information to help establish sub-sewershed prioritization based on the user's preference.

Example Scenario 1: Sub-sewershed prioritization analysis results based on total RDII: Figure 2-1 shows sub-sewershed prioritization based on RDII in terms of Total R value. Considering that each sub-sewershed is likely to experience a range of Total R values during a flow monitoring period, the SSOAP Toolbox user can select the average or median of the observed R values for this analysis. Alternatively, users can display observed maximum R values for the sub-sewershed prioritization analysis. Figure 2-1 shows an analysis performed with the average Total R value with observed RDII from the same wet-weather events between sub-sewersheds. The analysis shown in Figure 2-1 can guide the user to prioritize RDII investigation and reduction efforts focusing on sub-sewersheds with high average total R-values.

Users may also need to prioritize their investigations and rehabilitation plans based on individual inflow and infiltration components of total RDII data from sub-sewersheds. For example, Figure 2-1 shows sub-sewershed FM18 has the highest RDII compared to other sub-sewersheds, suggesting that FM18 should be the top priority for field investigation. However, more information is needed to determine which type of field investigation (inflow based or infiltration based) should be conducted, which is described in the next scenario.

Example Scenario 2: Sub-sewershed prioritization analysis results based on total RDII and breakdown of inflow and infiltration components (R1, R2, and R3 values): Figure 2-2 extends the analysis shown in Scenario 1, showing sub-sewershed prioritization based on observed RDII in terms of Total R value and distribution of R1, R2, and R3 components. If a sub-sewershed's RDII response is dominated by inflow (R1), conducting extensive internal inspections will likely provide less useful information to design system improvements because the problem is likely be a capacity issue vs. sewer rehabilitation. This example shows that a significant portion of RDII in sub-sewershed FM18 is due to infiltration components (R2 and R3 responses). The condition assessment support tool can use average, median, or maximum R-values for conducting this analysis, similar to Example Scenario 1.

Example Scenario 3: Sub-sewershed prioritization analysis results based on fast response – Inflow dominance (R1 value): The user can select to analyze the sub-sewersheds based on the inflow component (R1), as shown in Figure 2-3. The example analysis presented in Figure 2-3 indicates FM9 had the highest inflow and should have top priority for field investigation, even though it actually had the lowest total RDII compared to other sub-sewersheds.

Example Scenario 4: Sub-sewershed prioritization analysis results based on medium response – foundation/yard drains (R2 value): Figure 2-4 shows how the user can analyze sub-sewersheds based on medium RDII response (R2 values), which typically result from foundation and yard drains discharges. This analysis enables users to determine private property RDII contributions and correction needs, such as footing drain disconnections.

Example Scenario 5: Sub-sewershed prioritization analysis results based on slow response – infiltration dominance (R3 value): The user can perform the prioritization analysis with focus on the infiltration component represented by the R3 value, as shown on Figure 2-5. The results from this analysis help users design field investigation efforts that focus on internal sewer inspections to locate the poor sewer conditions defects that contribute to excessive infiltration.

Example Scenario 6: Sub-sewershed prioritization analysis results based on medium and slow response (R2 plus R3 value): Figure 2-6 shows sub-sewershed prioritization analysis using combined components of medium and slow responses (R2 plus R3). This analysis focuses on an overall infiltration-dominated RDII component, excluding the fast (inflow) response. For sewer systems with nominal medium response, this analysis offers limited value.

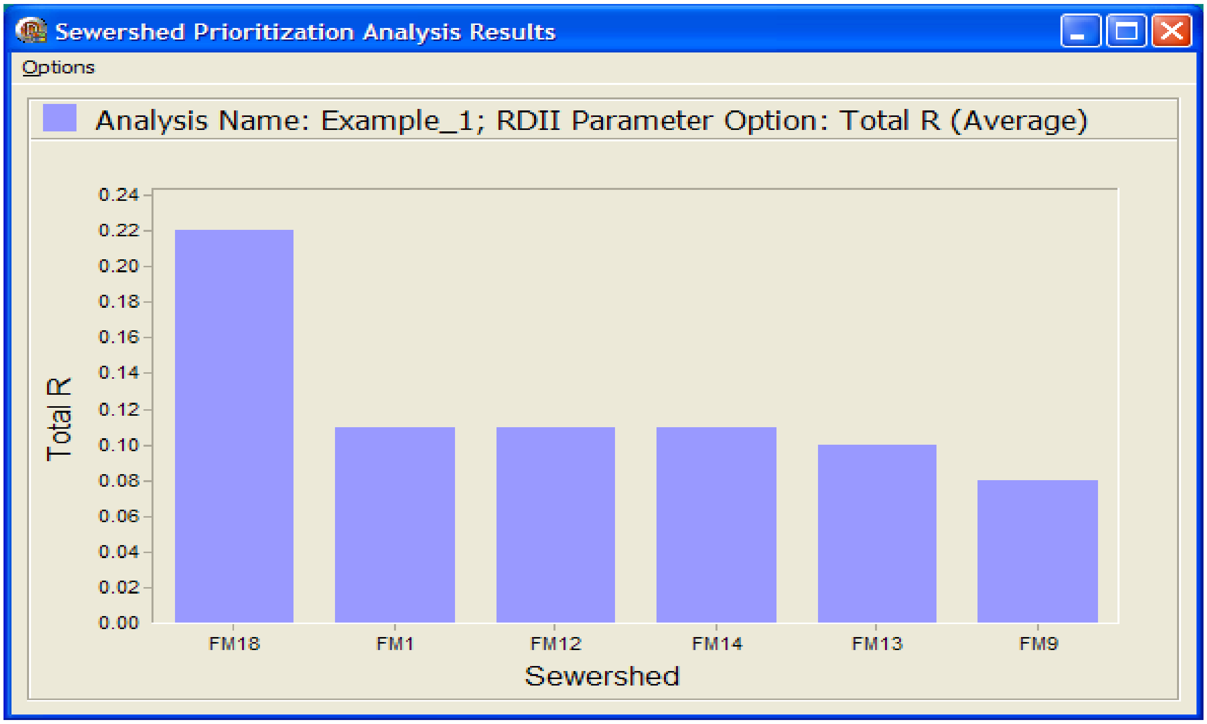

Figure 2-1 – Example Scenario 1 – Sub-sewershed prioritization analysis based on total RDII

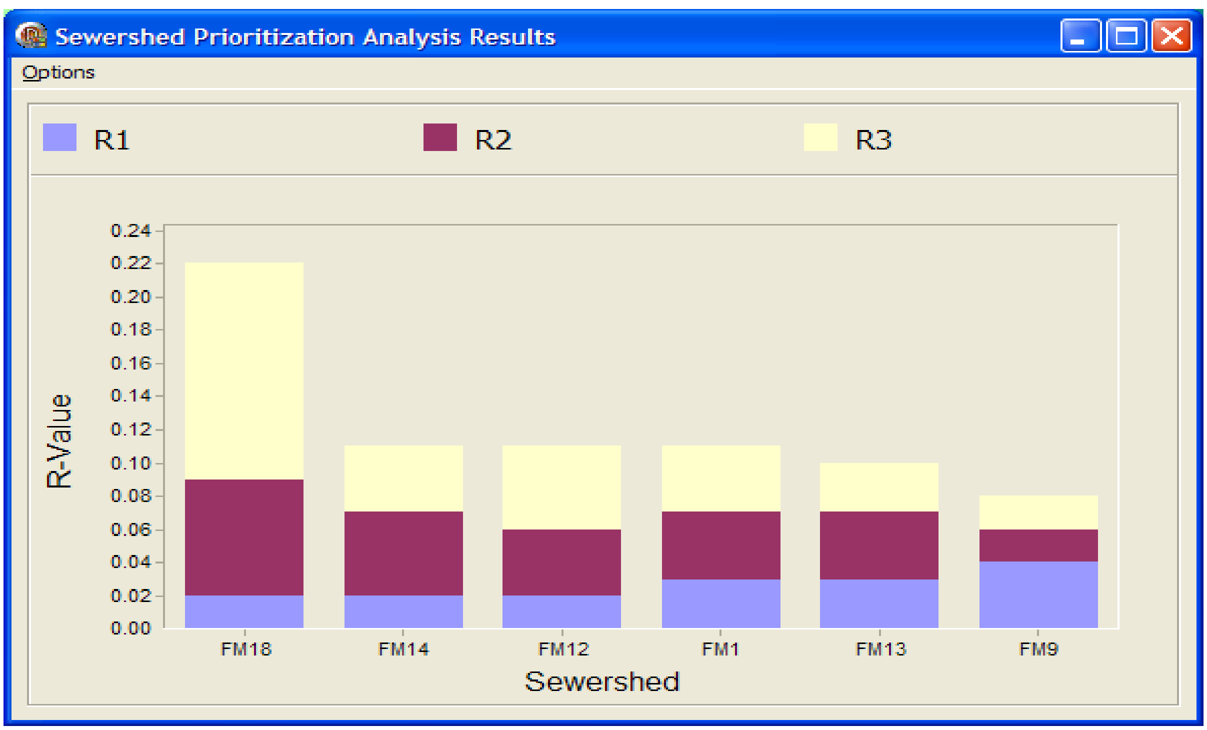

Figure 2-2 – Example Scenario 2 – Sub-sewershed prioritization analysis based on total RDII and breakdown of inflow and infiltration components (R1, R2, and R3 values)

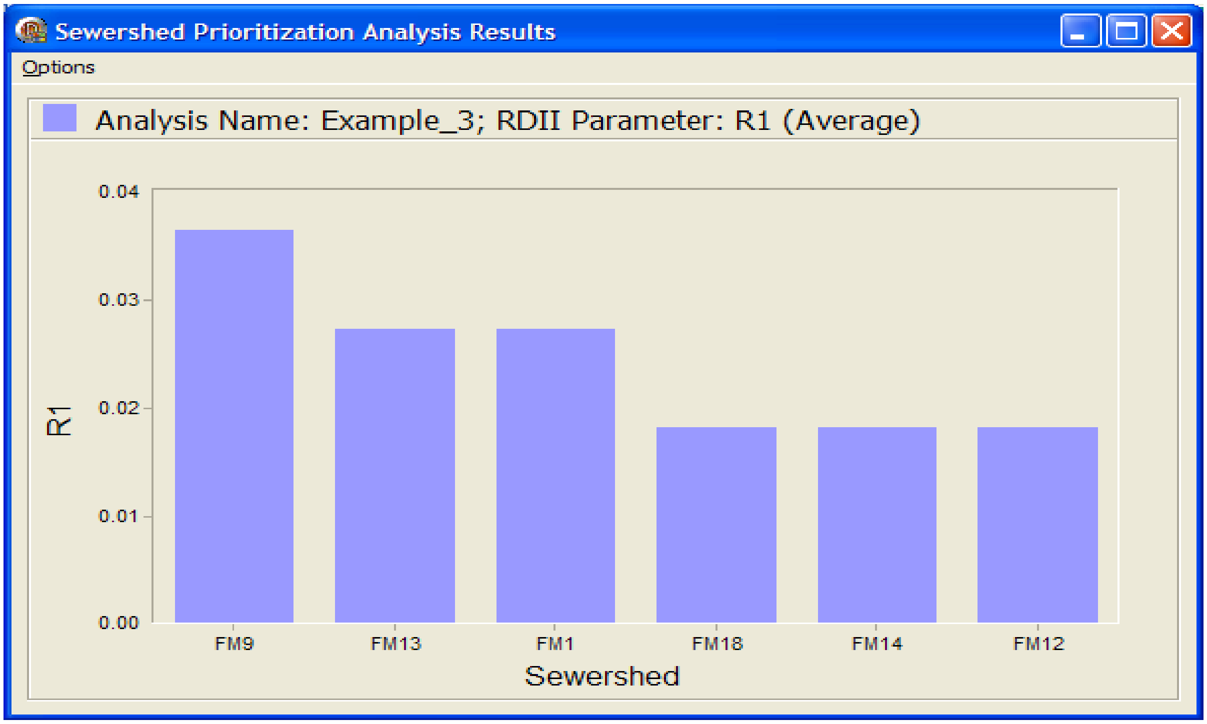

Figure 2-3 – Example Scenario 3 – Sub-sewershed prioritization analysis based on fast response – inflow dominance (R1 value)

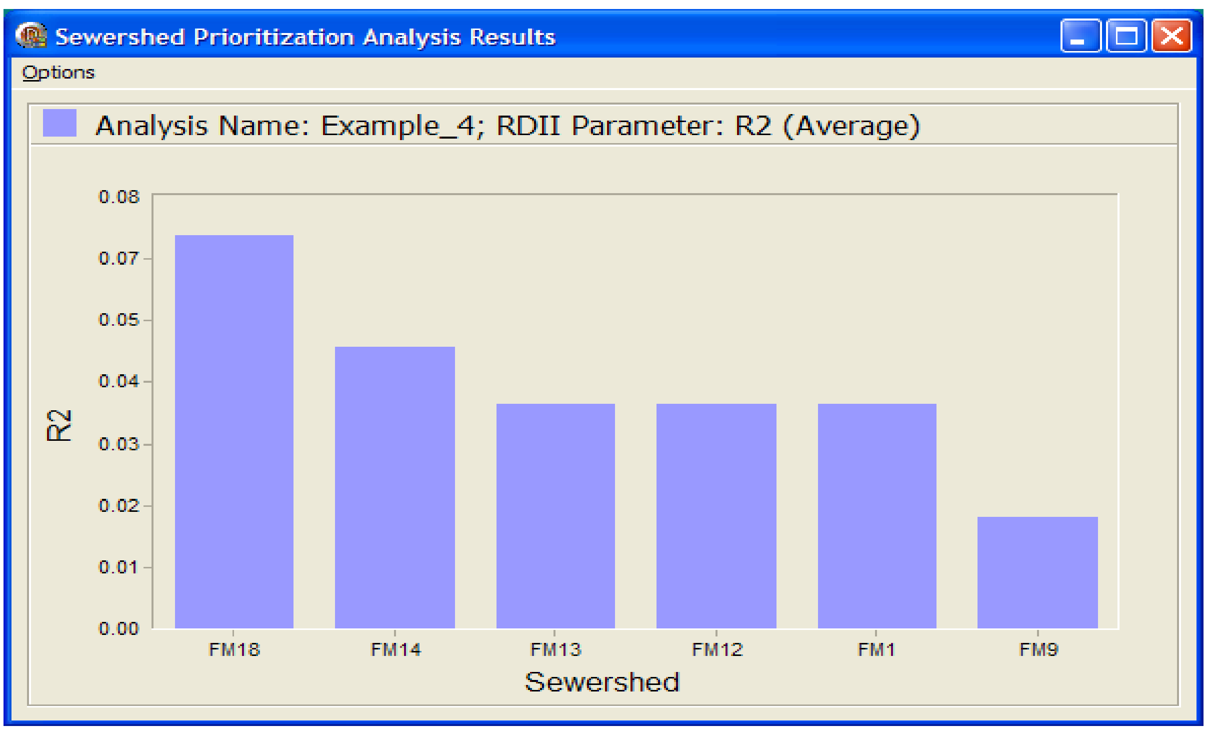

Figure 2-4 – Example Scenario 4 – Sub-sewershed prioritization analysis based on medium response (R2 value)

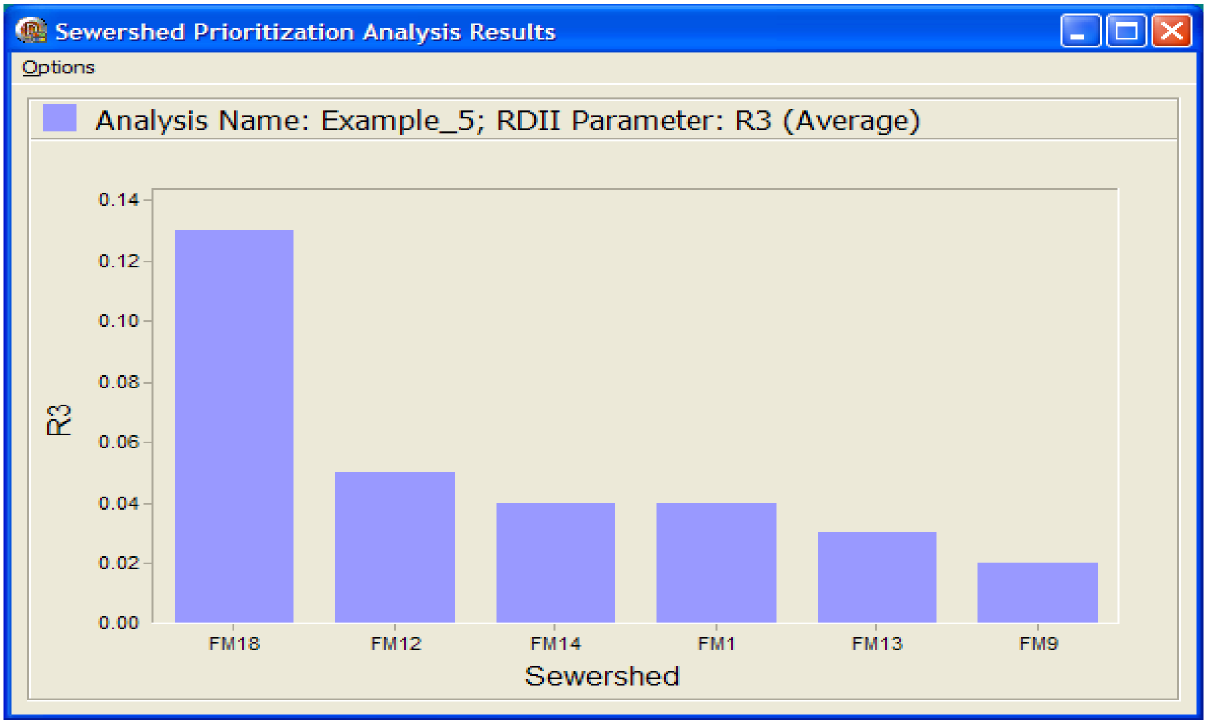

Figure 2-5. Example Scenario 5 – Sub-sewershed prioritization analysis based on slow response – infiltration dominance (R3 value)

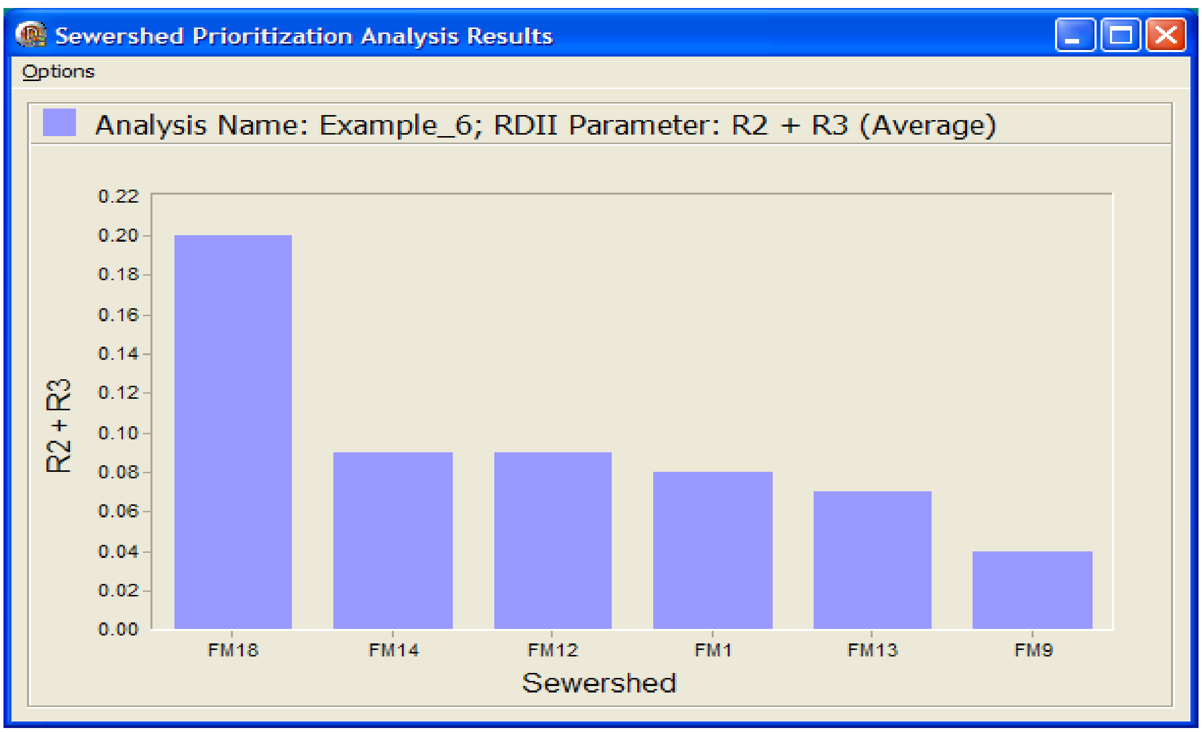

Figure 2-6. Example Scenario 6 – Sub-sewershed prioritization analysis based on medium and slow response (R2 plus R3)

Example Scenario 7: Sub-sewershed prioritization analysis results based on RDII volume per linear feet of sewer): Figure 2-7 presents prioritization analysis with RDII volume/length of sewer in sub-sewersheds as the key parameter. This approach offers a direct correlation of RDII reduction to the length of sewer rehabilitated.

Example Scenario 8: Sub-sewershed prioritization analysis results based on peak RDII flow rate per acre: Figure 2-8 depicts the peak RDII flow rate/sub-sewershed area as the RDII parameter to prioritize sub-sewersheds.

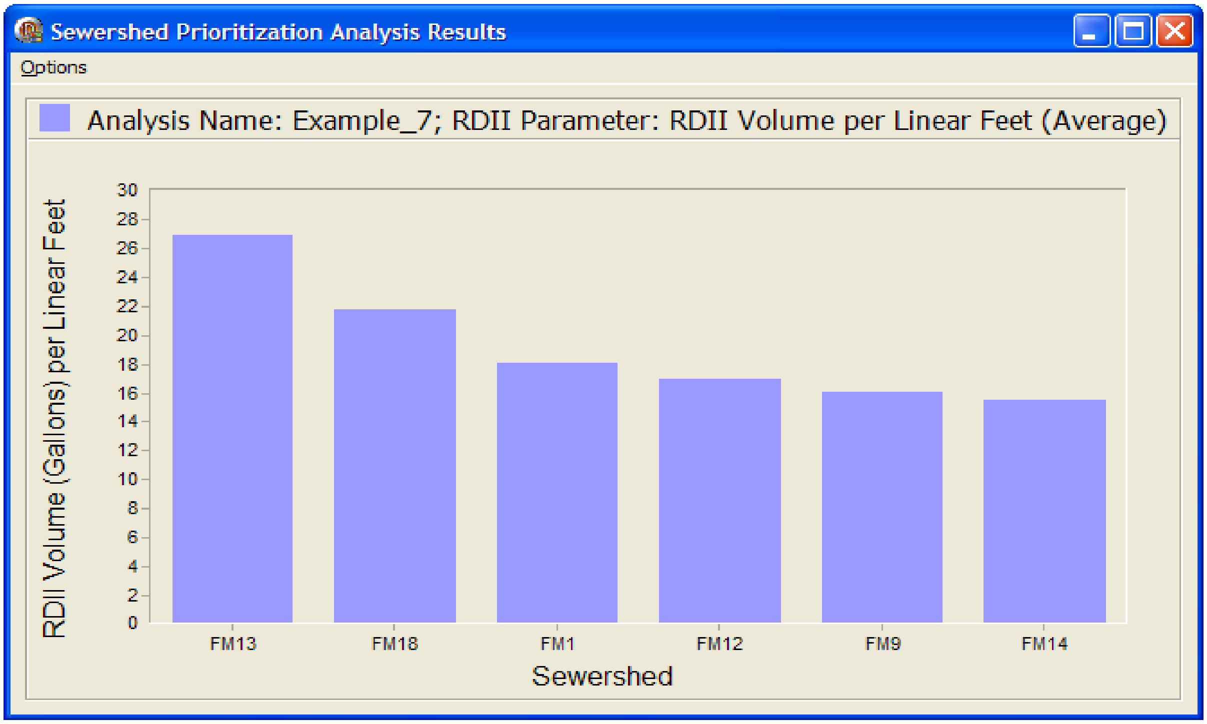

Figure 2-7. Example Scenario 7 – Sub-sewershed prioritization analysis based on RDII volume per linear feet of sewer

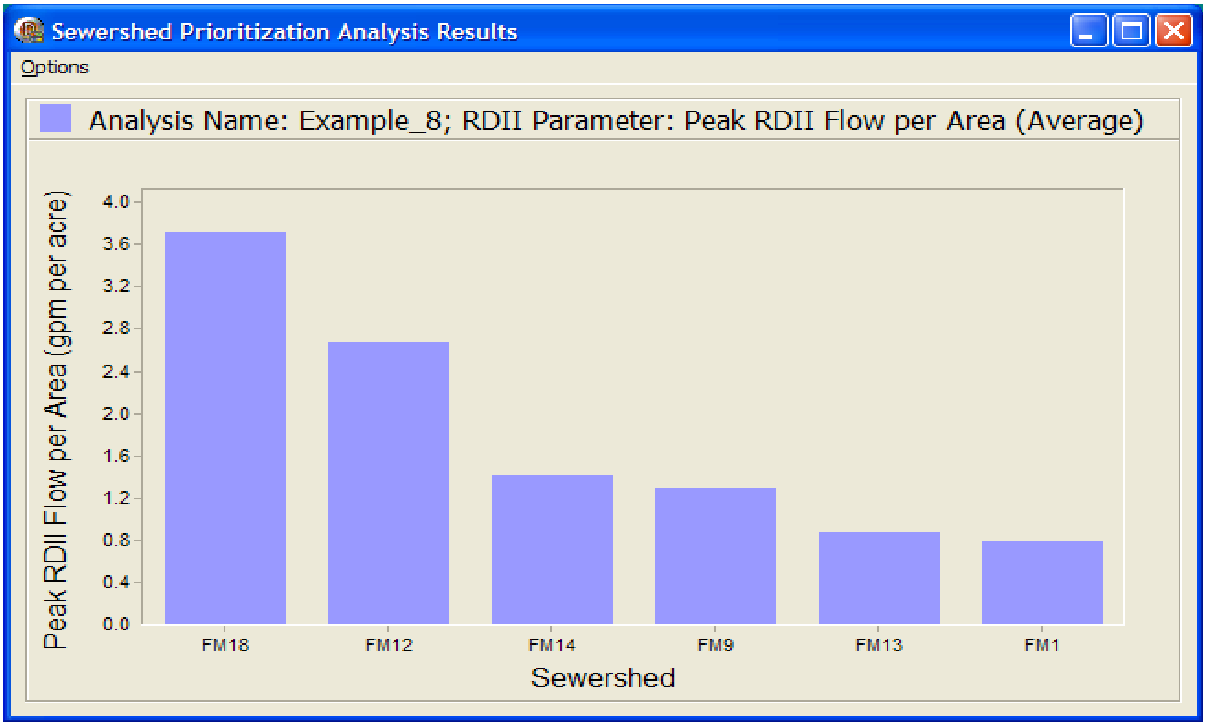

Figure 2-8. Example Scenario 8: Sub-sewershed prioritization analysis based on peak RDII flow rate per area

The analyses shown in examples 1 through 5 help users prioritize sub-sewersheds for further analysis and identify appropriate field investigation techniques. For example, Figure 2-1 (average total-R) shows that sub-sewershed FM18 experiences the highest level of RDII compared to other sewersheds. However, Figure 2-3 (average R1) suggests that there are other sub-sewersheds with more inflow than FM18. Figure 2-6 (average R2 + R3) and Figure 2-4 (average R2) indicate that FM18 has significant infiltration, including foundation and yard drain conditions, which suggests worse sewer conditions. Finally, Figure 2-2 shows the breakdown of R1, R2, and R3, suggesting that the FM18 sewershed should be top priority for field investigation with a focus on sources and quantity of excessive infiltration.

Users can use median values or peak values from the RDII analysis results vs. using average values for the prioritization analyses. In addition, users can display up to three prioritization analyses together for comparison. Figure 2-9 shows three prioritization analyses [total R value (RDII), R1 (inflow), and R2 + R3 (infiltration) combined].

In summary, the Condition Assessment Support Tool is designed to assist the SSOAP Toolbox user to:

- Effectively synthesize data from the RDII database.
- Assess the relative magnitude of inflow and infiltration for each sub-sewershed.
- Establish priorities using a range of RDII parameters.
- Guide users to select appropriate field investigation techniques for sewer condition assessment.

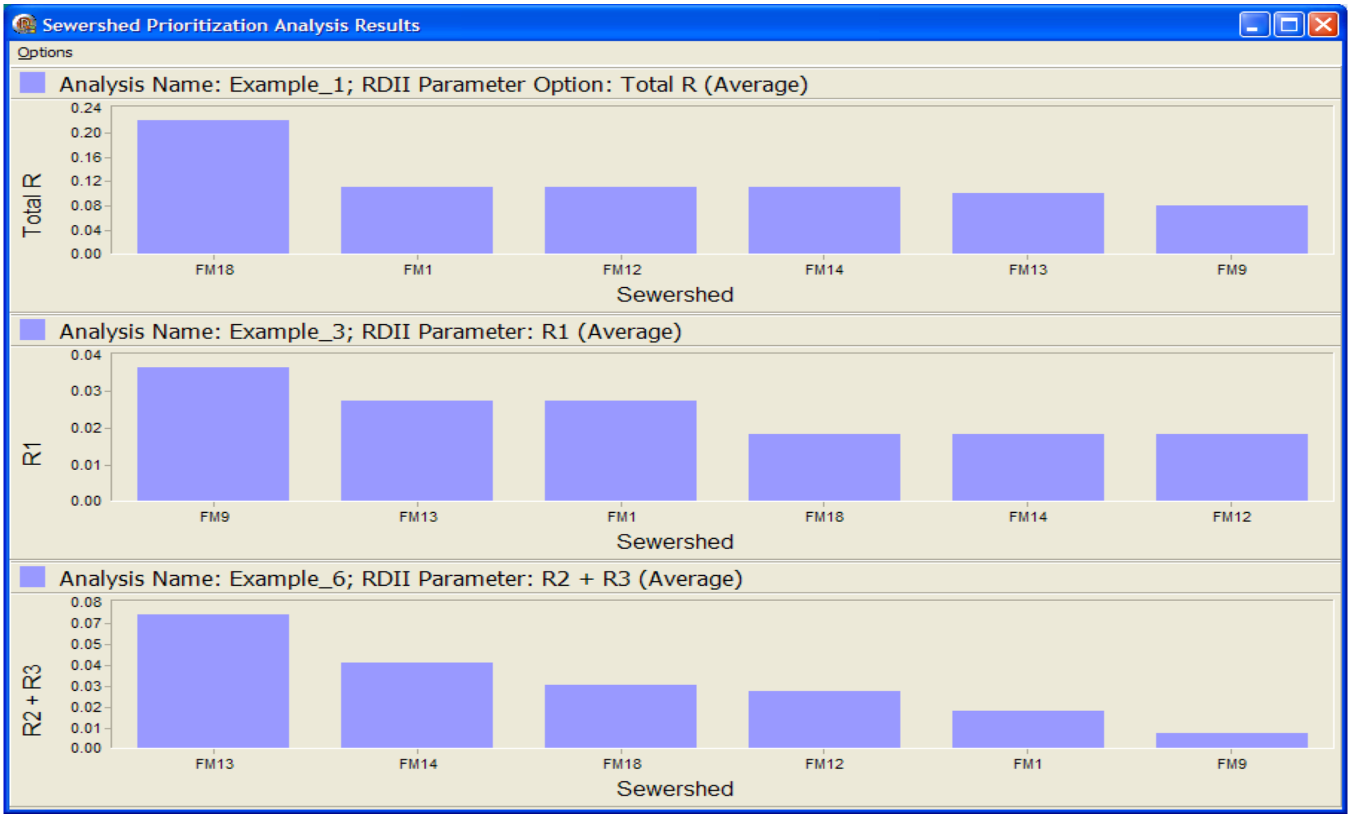

Figure 2-9. Example of using 3 sub-sewershed prioritization analyses to support field investigation decision-making

2.4 Pre- and Post- Sewer Rehabilitation RDII Correlation Analysis

The Condition Assessment Support Tool is also designed to help SSOAP Toolbox users assess the effectiveness of sewer rehabilitation by comparing RDII estimates from two sub-sewersheds (control and rehabilitation) obtained from pre-rehabilitation and post-rehabilitation periods. The control sub-sewershed is a sewered area, ideally nearby, similar in age, size, land-use, and pipe materials to a sub-sewershed being studied with post-rehabilitation conditions. The control area must not have had any rehabilitation work because it will be used to compare how RDII is reduced as a result of system rehabilitation and other improvements.

Figure 2-10 shows the interrelationship between RDII Analysis Results stored in the SSOAP Toolbox database and Condition Assessment Support Tool, and the inputs and outputs for the pre- and post-rehabilitation RDII correlation analysis.

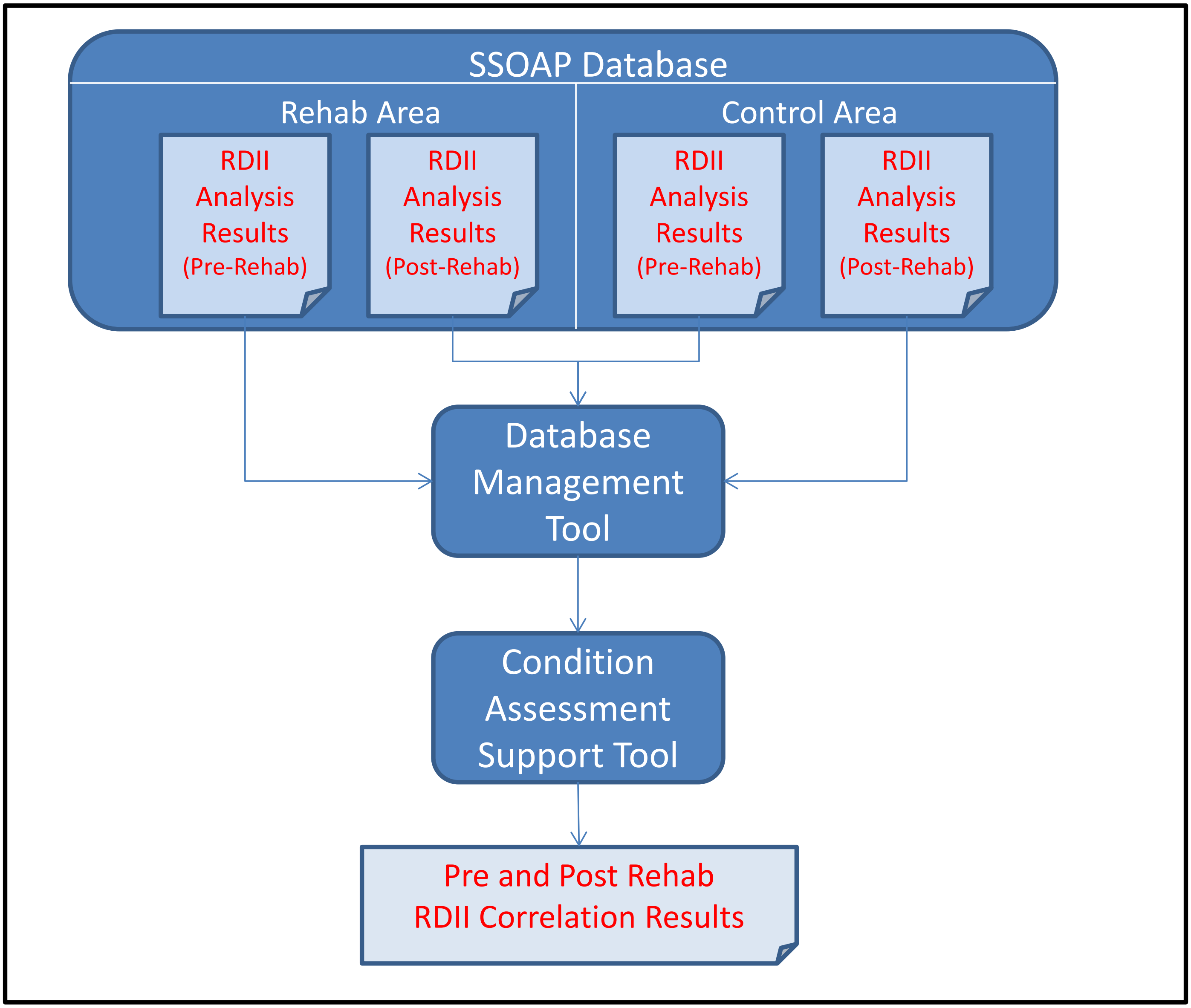

Figure 2-10. Condition Assessment Support Tool: Data process diagram for pre- and post-sewer rehabilitation RDII correlation analysis

The following two conditions must be met to preserve the integrity of pre- and post-rehabilitation RDII correlation analyses:

1. Separate RDII analysis should be conducted, one for flow monitoring periods under pre-rehabilitation conditions, and one for flow monitoring periods under post-rehabilitation conditions.

2. The flow monitoring site should be exactly the same for both pre- and post-rehabilitation flow monitoring periods.

The Condition Assessment Support Tool helps users establish the RDII reduction trends by developing a linear relationship between observed R values in the rehabilitated sub-sewershed and observed R values in the control sub-sewershed under pre- and post-rehabilitation conditions.

SSOAP Toolbox users can use the Condition Assessment Support Tool to establish specific or general RDII reduction trends resulting from a sewer rehabilitation effort. The more data available (e.g., long-term flow monitoring for one year or more vs. short-term monitoring for two to four months), the more reliable the measure of RDII reduction trends with increased statistical significance.

The linear regression methods included in the Condition Assessment Support Tool can help establish general trending of RDII reductions. Users that have the long-term flow meter data and RDII analysis results and would like to study non-linear relationships can export RDII parameters in a tabular format for pre- and post-flow monitoring periods for use in their statistical software package of choice. Future releases of the SSOAP Toolbox may include built-in capacities to support non-linear correlation and trending of RDII reductions based on user feedback and funding availability.

Figures 2-11 and 2-12 show two examples of RDII correlations for pre- and post-rehabilitation conditions for test sub-sewersheds with RDII estimates for respective control sub-sewersheds. This analysis can help users assess RDII reduction trends, accounting for environmental variations between pre- and post-rehabilitation flow monitoring periods.

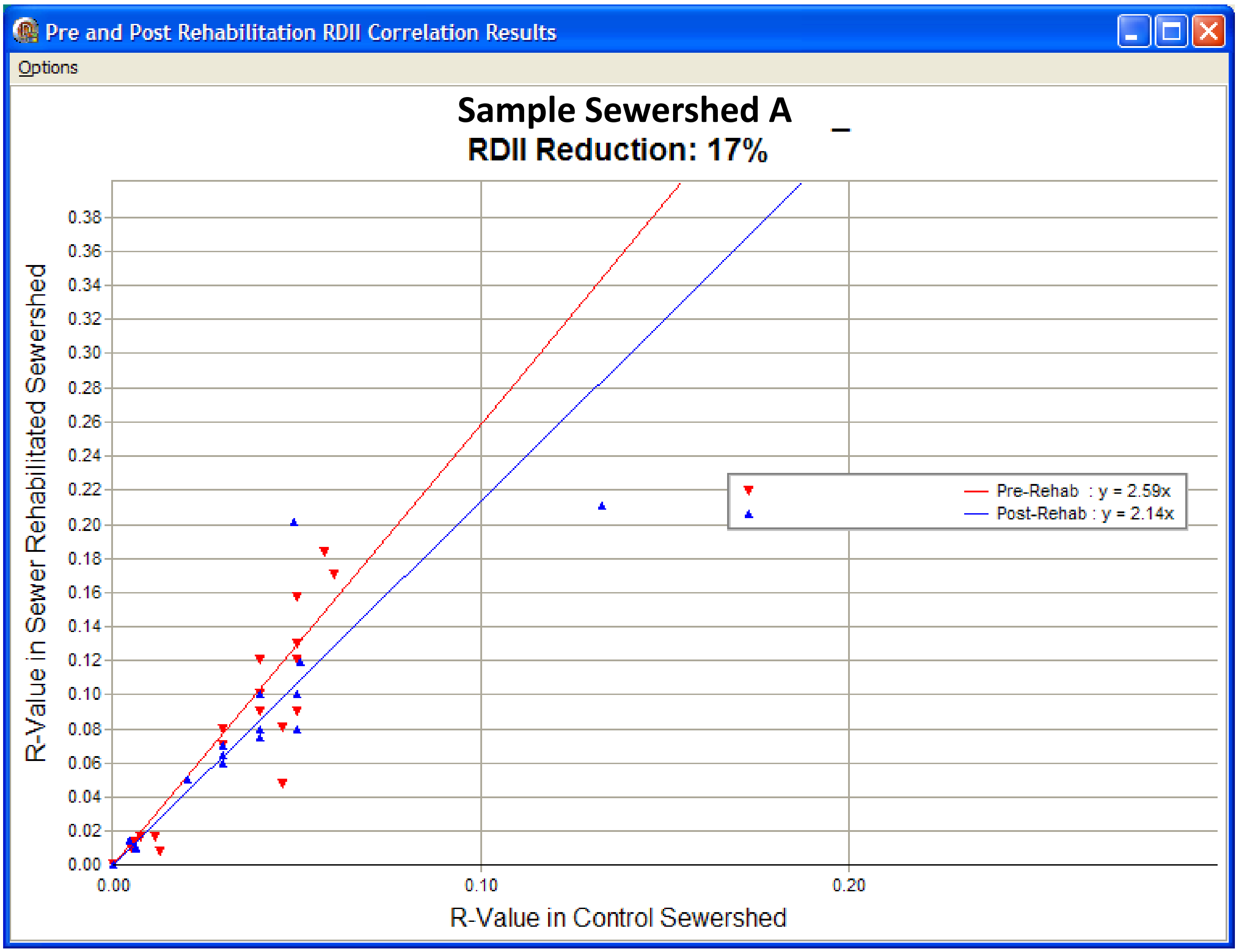

Figure 2-11. Example correlation of RDII between rehabilitation and control sub-sewershed – Example 1

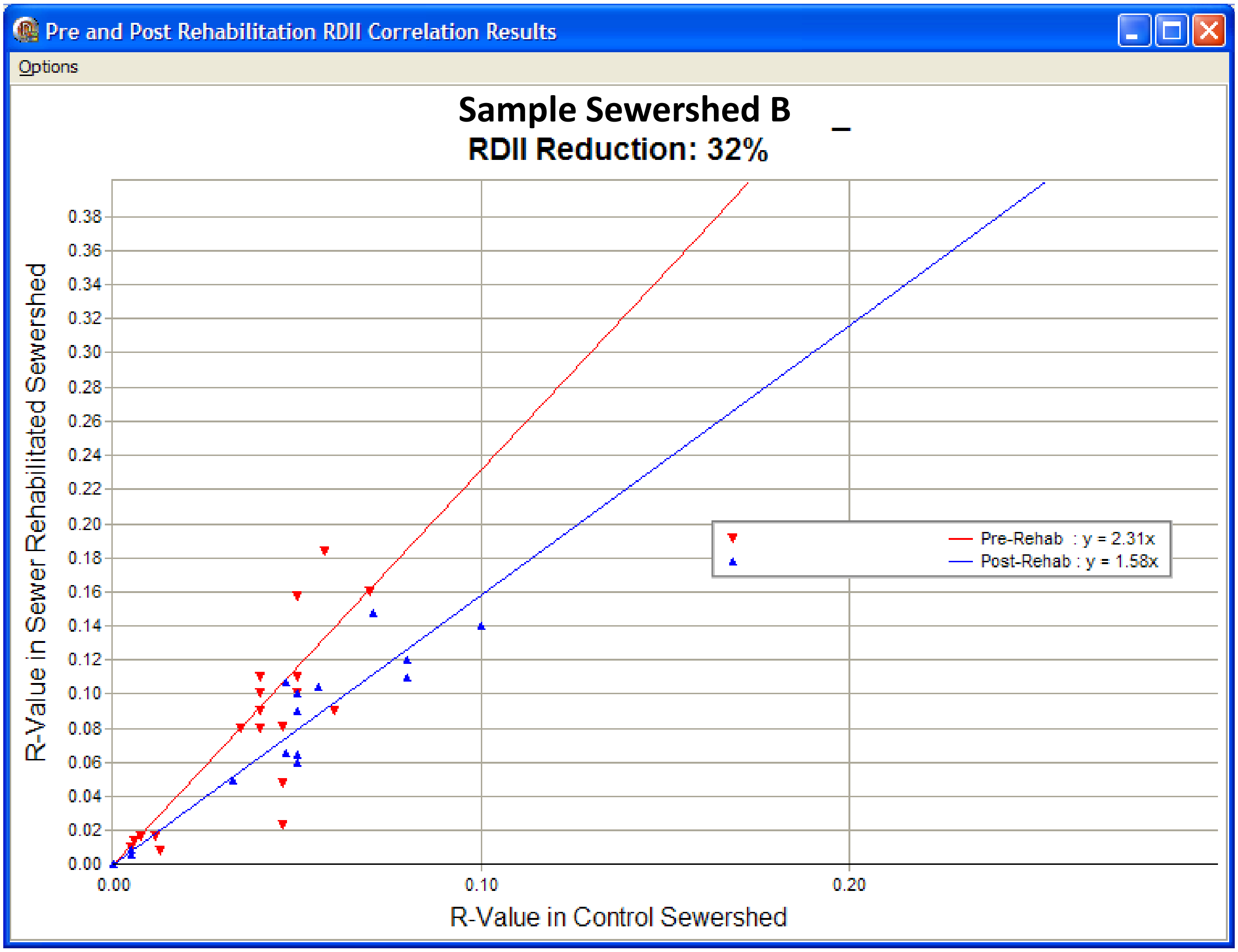

Figure 2-12. Example correlation of RDII between rehabilitation and control sub-sewershed – Example 2

In Figures 2-11 and 2-12, the X-axis represents R-value for the control area and Y-axis represents the rehabilitated area. Each triangle in the figure represents an actual R-value for both control and rehabilitated areas observed during the same wet-weather event during pre- and post-rehabilitation flow monitoring periods. Each line represents a linear regression between the R values of the rehabilitated area and the control area. The RDII reduction trending is estimated by determining the difference in the slopes of the regression lines for pre- and post-rehabilitation conditions.

As shown in Figures 2-11 and 2-12, RDII response in a sewershed can vary significantly under different hydrological conditions. Therefore it is important to obtain a range of rainfall and flow monitoring data to characterize a range of rainfall conditions, antecedent moisture conditions, and RDII responses in the sanitary sewer system. If data are limited, users should be cautious when assessing RDII reduction trends and judging the level of success achieved with completed sewer rehabilitation efforts.

2.5 Summary

The RDII prediction methodology employed in the SSOAP Toolbox offers an effective means to design a focused condition assessment program and maximize the success of field investigation efforts. With the addition of the Condition Assessment Support Tool, the SSOAP Toolbox now offers users a single environment for analyzing RDII, capacity assessment, and monitored flow data to prioritize where to inspect, monitor, and assess the success of rehabilitation activities.

Chapter 3: Case Study − Knoxville, Tennessee

This case study describes how the methodologies implemented in the enhanced SSOAP Toolbox with Condition Assessment Support Tool were applied during a SSO mitigation and wastewater infrastructure improvement program.

3.1 Introduction

Knoxville Utilities Boards (KUB) has been applying the SSOAP Toolbox methodologies for nearly a decade to support planning, operation, and maintenance aspects of its collection system. KUB's sanitary sewer collection system encompasses more than 64,000 customers, covers approximately 108 square miles, has more than 1,250 miles of service mains, and is served by four regional wastewater treatment plants, all of which serve a population of nearly 179,000 in the City of Knoxville/Knox County. Figure 3-1 shows geographic reference to Knoxville, Tennessee.

Figure 3-1. Knoxville, TN location map

Figure 3-2 shows the overall KUB service area and multiple drainage basins, including the First Creek basin, which is the primary example in this case study. Like many sewer utilities, KUB is addressing aging wastewater infrastructure challenges. In February 2005, KUB entered into a Consent Decree (CD) with the U.S. EPA and the Tennessee Department of Environment and Conservation (TDEC) (KUB, 2005b).

KUB's efforts leading up to the CD include an SSO Evaluation Report (SSOER) dated September 2004 (KUB, 2005) and an annual update to this report in April 2005 (KUB, 2005a). The SSOER contains a list of SSOs referred to as the "Long-Term List" that identifies all SSOs that occurred and the associated locations, dates, causes, and volumes.

As part of the CD, KUB submitted the Phase I Corrective Action Plan/Engineering Report (CAP/ER) with the goal of eliminating SSOs on the Long-Term List, including SSOs in the SSOER from 2001 through 2004(KUB, 2005c). Subsequently KUB prepared a Phase II CAP/ERs recommending sewer rehabilitation projects (KUB, 2007). The Phase II CAP/ER was approved by EPA on March 19, 2010, and included SSOs that occurred from 2005 through 2007.

The Phase I CAP/ER was developed using general approaches and analyses included in the SSOAP Toolbox and its predecessor, SHAPE – a sewer hydrograph analyses program – both developed by CDM Smith. From 2006 through 2010, KUB conducted sewer condition assessment and rehabilitation projects in priority mini-basins to reduce RDII throughout its wastewater collection system. Sewer rehabilitation included cured-in-place pipe (CIPP) lining of gravity sewer mains up to and including laterals to private property lines, pipe replacement, manhole rehabilitation, and pipe bursting.

KUB assessed the qualitative and quantitative reductions made in RDII in areas recommended under the CAP/ER Phases I and II by performing pre- and post-rehabilitation flow monitoring and annual rehabilitation analyses from 2006 through 2010. The goal of these studies was to estimate future RDII reductions based on similar rehabilitation in other areas and to update credits taken within a Capacity Assurance Program (CAP) required under the CD. In accordance with the CD, the CAP assesses the peak flow capacity of all major system components (collector sewers, interceptor sewers, pump stations, and treatment plants). Any requests for increased flow to the collection system must be compared to the peak flow capacity of these components. If KUB is unable to certify capacity of the major system components downstream of the proposed flow addition, it may still authorize the additional flow through a system of banked flow credits (based on rehabilitation activities) and other requirements.

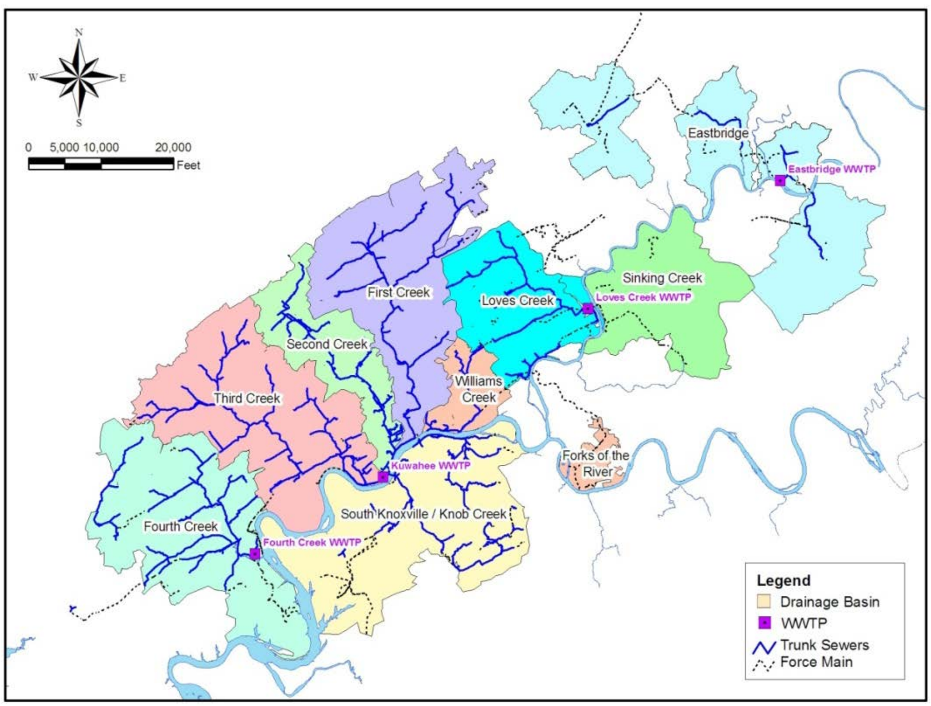

Figure 3-2. Overview of KUB major collection system drainage basins

3.2 Study Area and Approach

KUB's overall CAP efforts can be grouped into three major categories as shown in Figure 3-3. Each category has a distinct focus: data collection and review, RDII analysis, and sewer capacity and condition assessment.

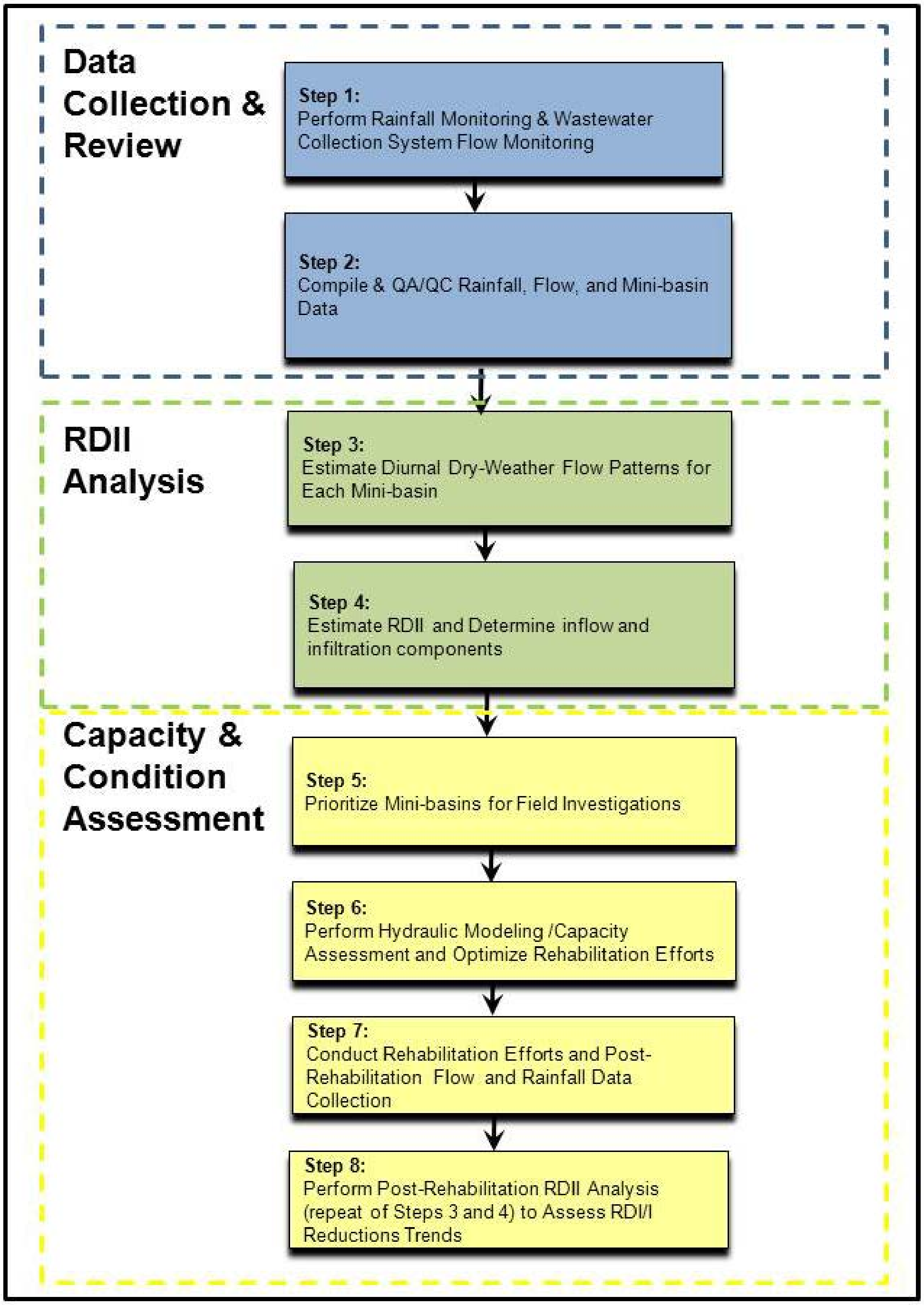

Figure 3-3. Overview of KUB sewer system evaluation process

3.3 Data Collection and Review

KUB's data collection and review efforts can be divided into three components:

- Flow Monitoring Data
- Rainfall Data
- Sub-sewershed Data (mini-basin service area boundaries and acreages)

3.3.1 Flow Monitoring Data

KUB's CD- and CAP-related flow monitoring efforts began in 2003. KUB initiated these flow monitoring efforts to update and compare system-wide flow monitoring results with historic flow data obtained in 1992. The 2003 flow monitoring efforts covered portions of the First Creek (the case study example drainage basin), Second Creek, and South Knoxville/Knob Creek Drainage Basins as depicted in Figure 3-2. These drainage basins were priorities because of higher frequency overflows occurring within the basins in the Fountain City area of First Creek, the Inskip Ball Park in Second Creek, and the Woodson Pump Station area in Knob Creek.

The drainage basins indicated in Figure 3-2 were further divided, based on topography and sewer location, into smaller collection sewer service areas called mini-basins. Upstream mini-basins — areas that are not influenced by other mini-basin areas — became the focus of these initial flow monitoring efforts to isolate and better characterize an area's response to RDII.

Flow monitoring in the first study in spring 2003 included 17 flow monitors in First Creek, seven flow monitors in Second Creek, and eight flow monitors in the Knob Creek area. The First Creek basin was used as an example basin for the prioritization process by which all the drainage basins in this case study were analyzed. This basin served as the main starting point for the collection system analysis.

During the pre-rehabilitation study period, monitored mini-basin areas were marked as "control areas" to be used for comparison purposes to demonstrate RDII reductions/increases accounting for varying environmental conditions. Control areas have not had rehabilitation activities performed during the pre- to post-rehabilitation flow monitoring periods.

In general, flow monitors were placed at system connection points near trunk sewers, in general, to isolate and measure wastewater flows from individual mini-basins. Most locations corresponded to locations of the comprehensive flow monitoring study conducted in 1992.

In the field, flow monitoring locations were screened using field observations and past field notes (for areas being re-monitored) to ensure that quality data could be collected at the proposed sites. If site hydraulics were poor, flow monitoring locations were revised and relocated nearby, where possible.

KUB performed flow monitoring data collection annually from spring 2003 through spring 2010 in all the drainage basins shown in Figure 3-2. Each flow monitoring study used a base 60-day flow monitoring period for data collection. This 60-day period was conducted in the January through March time window, focusing on the historically higher groundwater conditions present in the KUB system. To avoid effects of potential snowfall on monitoring, the time window was revised to occur in late January through late March. The base period was extendable on a week-to-week basis when a particular monitoring period experienced unusual spring precipitation conditions. The goal of this monitoring period was to focus flow monitoring efforts on system capacity when it was more likely impacted by RDII. The temporary flow monitors measured depth and velocity in five-minute increments; this information along with the sewer diameter was used to calculate the flow rate. Readings were measured in 15-minute increments for the permanent flow monitors.

Figure 3-4 depicts these flow and rainfall monitoring locations, which included 395 temporary flow monitors, 35 permanent flow monitors, 146 temporary rain gauges, and eight permanent rain gauges.

Flow monitoring data were quality controlled by reviewing weekly data submittals from the flow monitoring service provider. Data graphs for flow and scatter plots comparing depth and velocity were reviewed to assure data consistency, continuity, and to track flow behavior at each monitor location (i.e., checking for tendencies at the site for backup issues, surcharging conditions, turbulent flows, etc.). The quality assurance/quality control (QA/QC) procedures used were similar to the guidelines presented in the SSOAP Toolbox and the related technical report (EPA, 2007). Flow and rainfall data QA/QC has been critical to assure confidence in any results obtained during the RDII analysis steps.

3.3.2 Rainfall Data

Rainfall data were collected in conjunction with flow monitoring data to later determine the relationship between rainfall volume and the RDII volume. Rain gauge locations (Figure 3-4) were placed throughout the basin to ensure comprehensive coverage. Rainfall amounts from each rain gauge location were compared to one another and to permanent rain gauges in the Knoxville area to verify accuracy. All the temporary rain gauges recorded volumes in increments of 0.01 inches every five minutes. For the permanent rainfall gauges, readings were measured in 15-minute increments.

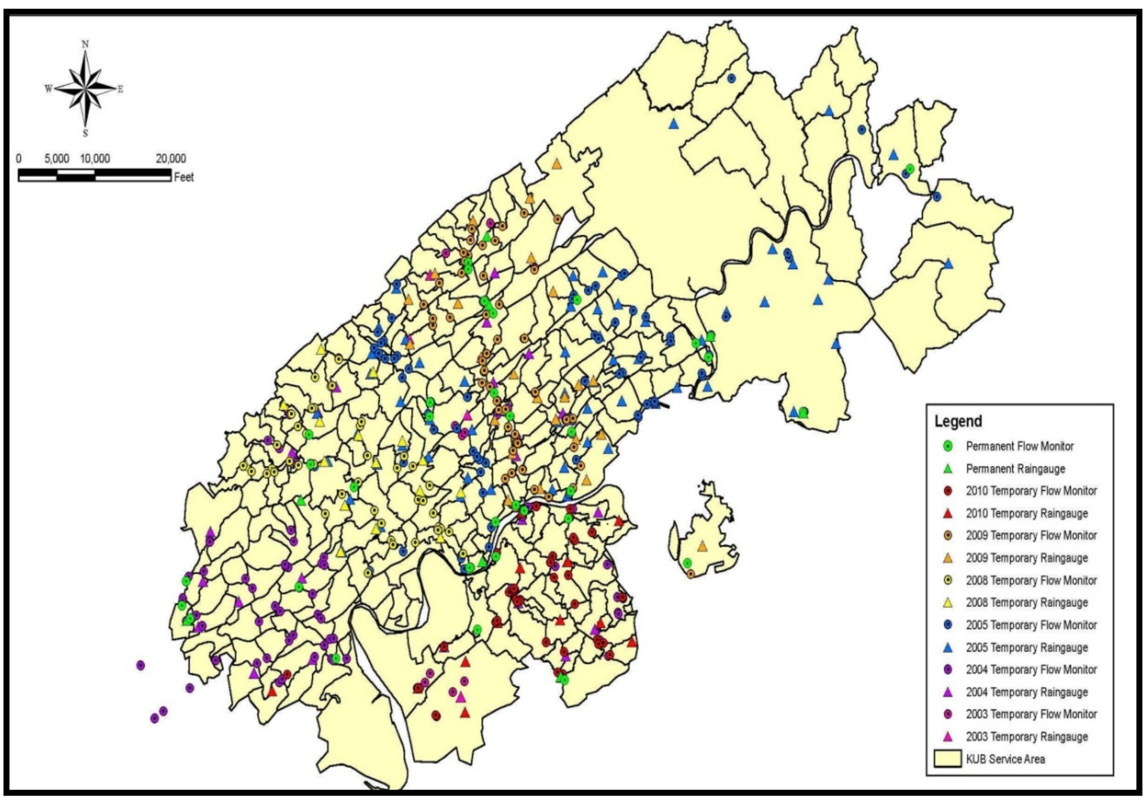

Figure 3-4. KUB flow monitor and rain gauge locations 2003 - 2010

KUB estimated rainfall for each mini-basin using the data collected from rain gauges. KUB used the Thiessen Polygon Method for each monitored area, estimating the amount of rainfall that falls within a given mini-basin for each storm event by performing a weighted average of the rainfall data collected from several nearby rain gauges. A more spatially representative amount of rainfall can be obtained using data from several gauges instead of relying on a single gauge. This method is most often utilized for complicated basins with many mini-basins and rainfall gauges, and was therefore used for the drainage basins within KUB's system.

3.3.3 Sewershed Data (Mini-basin Sewered Areas)

Sewershed area delineation is critical input for RDII analysis. Underestimation of a sewered area can cause an inflated R value. Using KUB's extensive GIS system, aerial photography, and record drawing cataloging system, the team analyzed all flow-monitored mini-basins, including sewered areas upstream. Sewered areas, or sewersheds, were categorized by the complexity of the collection system and the parcels of customers served. Parcels not serviced by a sewer connection (i.e., parks, recreation fields, cemeteries) were omitted. Sewersheds were delineated by flow monitoring location in the SSOAP Toolbox meter management portion of the database.

Figure 3-5 depicts an example of the sewershed vs. the total mini-basin area. The sewershed is indicated with green hatching, representing the acreage that is input for RDII analysis. The overall mini-basin area is represented with the red boundary. The mini-basin area is approximately 25 percent larger than the service area or sewershed area in this example.

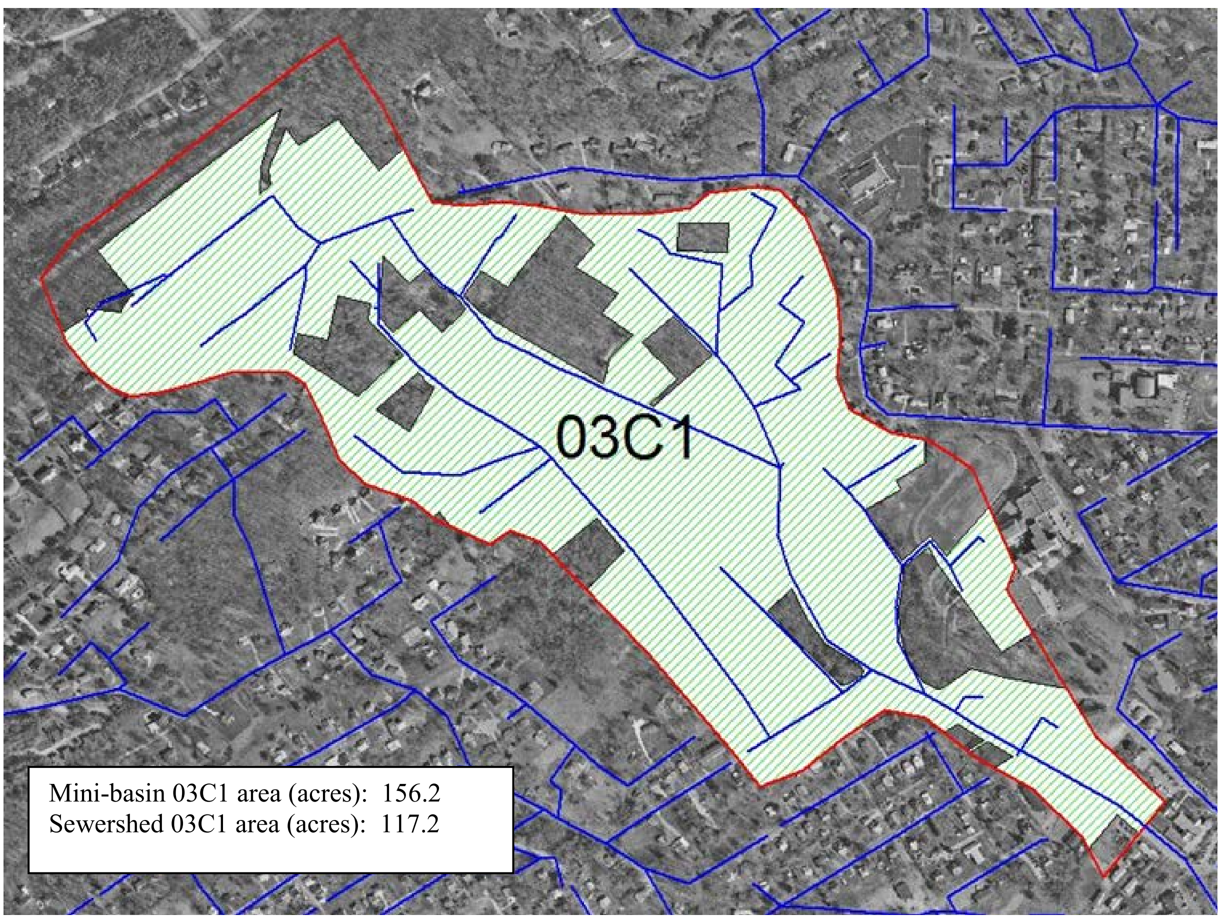

Figure 3-5. Sewershed delineation example

3.4 RDII Analysis

KUB used an approach similar to that described in the EPA technical report (EPA, 2007) to conduct the RDII analysis, featuring two key components:

- Establishing dry-weather flow
- Performing hydrograph decomposition to quantify RDII and estimate individual infiltration and inflow components

3.4.1 Establishing Dry-Weather Flows

One of the main steps in RDII analysis is to establish estimates of dry-weather flows (DWF) and the diurnal dry-weather flow variation recorded at the various mini-basins flow monitors in the study area. DWF is defined as the flow on days when there is no precipitation on record. The diurnal DWF variation is the change in the amount of flow throughout the day as a function of the types of customers in each sewershed.

KUB estimated DWF by averaging dry-weather days from the monitoring data in which there was no recorded rainfall affecting the observed flow. Figure 3-6 contains an example average dry-weather hydrograph for representative weekday and weekend day conditions.

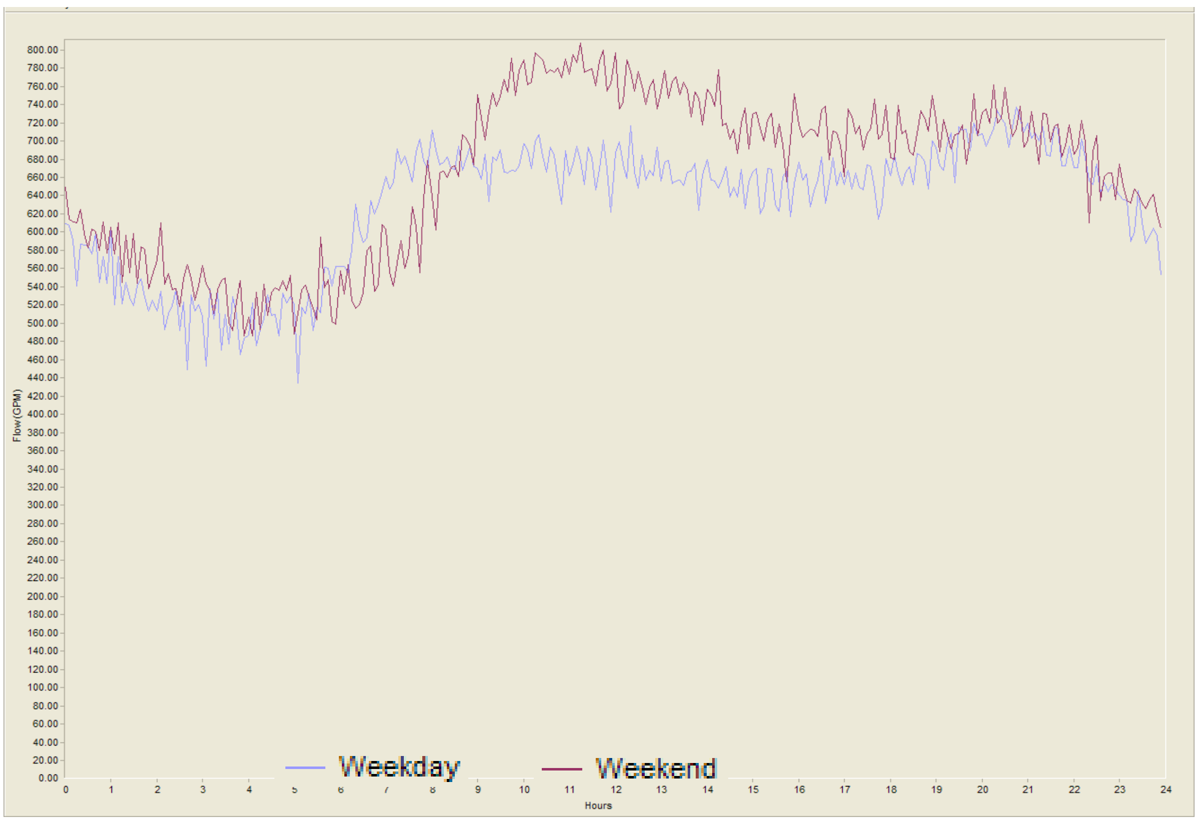

Figure 3-6. Example determination of representative dry-weather hydrograph

3.4.2 Performing Hydrograph Analysis

To determine the RDII component for each storm event, the representative DWF hydrographs are then subtracted from an observed wet-weather hydrograph. This is an important first step in quantifying RDII, estimating the individual infiltration and inflow component, and simulating wet-weather flows in the sewer system using a hydraulic model.

Figure 3-7 presents an example hydrograph analysis for Mini-basin 41C2 located in the South Knoxville/Knob Creek drainage basin. The analysis shows that the RDII flow eventually returns to zero after the rainfall event subsides. In this case, the ADWF for the sewershed is 0.02 mgd (represented with the light blue line). The peak total flow rate recorded during the event was 0.17 mgd (represented with the green line). The difference between the dry-weather hydrograph and the total wet-weather hydrograph reveals that 102,000 gallons of RDII entered the collection system in Mini-basin 41C2 during this 3/12/2010 rainfall event. The second portion of Figure 3-7 depicts the simplified view of the total RDII hydrograph decomposition with fast, medium, and slow response distributions.

Once the hydrograph analysis is completed for each mini-basin, the volume of RDII is compared to the volume of rainfall that fell on the area. The ratio of RDII volume to rainfall volume (which is the inches of rain over the sewershed area) is defined as the R value. The higher the R value, the more inflow and infiltration a sewer system has to convey to the treatment plant. The R value can then be applied to a larger design storm event to estimate the volume of RDII from such a storm event. Figure 3-8 depicts R values from the 2003/2004 flow monitoring study for the First Creek Basin. This figure represents each R value in terms of gallons per linear feet of RDII in each mini-basin. In that First Creek Basin study, R values ranged from 1 percent all the way up to 16.3 percent. KUB also performed similar studies of R values in other drainage basins. Information on the other drainage basins can be found in the Phase I CAP/ER on www.kub.org. The volume of RDII per linear foot of sewer observed was used to prioritize sewersheds for sewer system evaluation and rehabilitation.

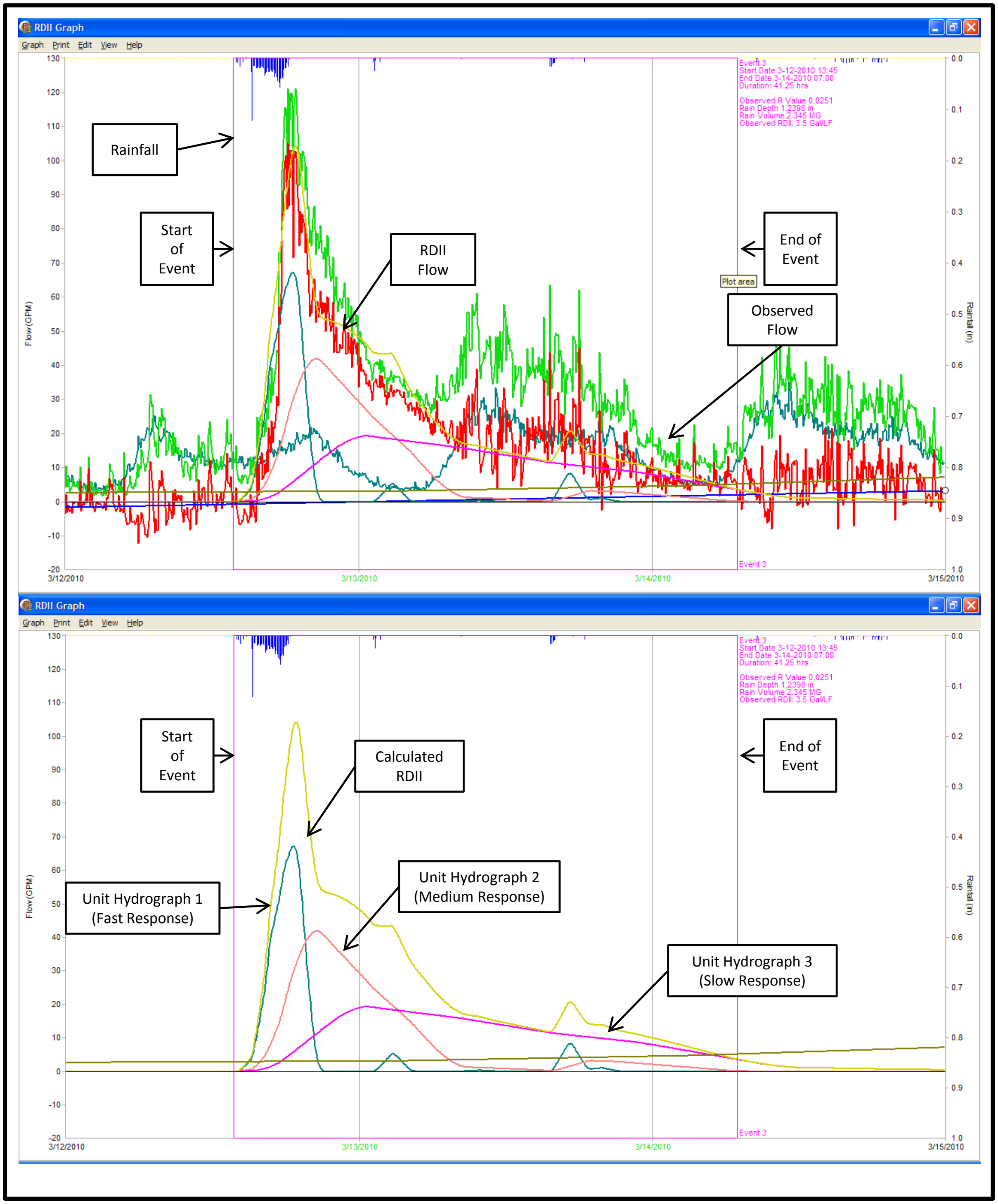

Figure 3-7. Example hydrograph analysis from KUB RDII analyses

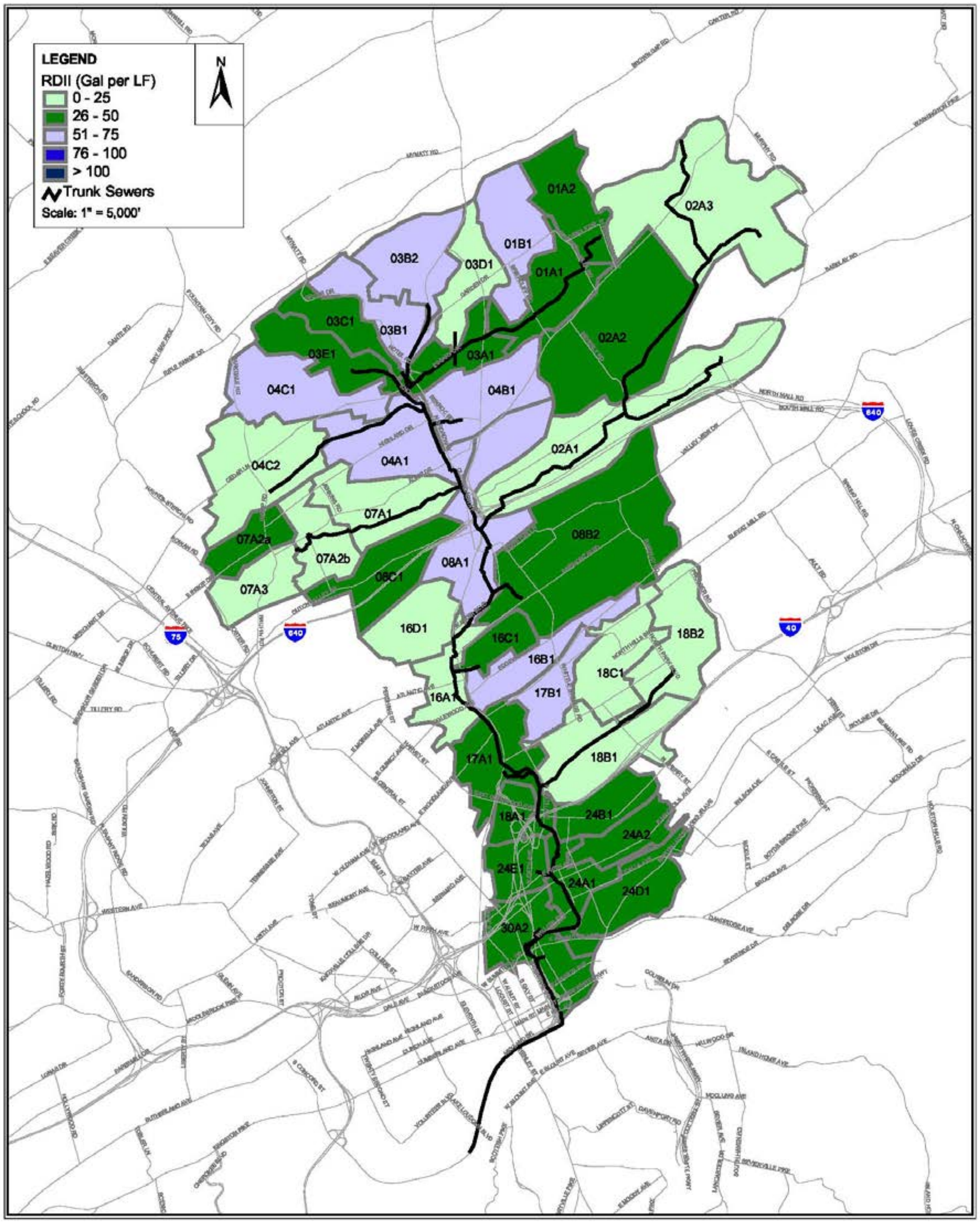

Figure 3-8. First Creek 2003/2004 RDII per linear foot

3.5 Condition Assessment Support – Mini-basin Prioritization

The KUB approach for the most cost-effective means of reducing RDII volumes is to perform focused/targeted sewer system evaluation study (SSES) investigations in areas with high volumes of RDII observed per linear foot of pipe.

After RDII analyses were completed in First Creek, Second Creek, and Knob Creek, KUB compared RDII results and prioritized the mini-basins for focused field investigations. First, KUB prioritized mini-basins for SSES based on the estimated gallons of RDII per linear foot of sewer. The RDII per linear foot of sewer was based on rainfall-weighted R values for each mini-basin from a two-year, spring design storm for the Knoxville area of 2.96 inches over 24 hours. This approach was used knowing that RDII overall would impact not only collection system costs, but traditional treatment and high-rate treatment costs in any improvement cost estimates. By looking at an overall rainfall-weighted R value, mini-basins with a higher potential to reduce these treatment costs could be identified.

Typically the highest rainfall-weighted R value mini-basins also included the highest R1 (inflow) and R2+R3 (infiltration) components of each studied drainage basin. This approach allowed for a larger initial capture of mini-basin candidates for further time-intensive and expensive field studies.

Rainfall-weighted average R values were calculated for each flow monitor based on the R value and total rainfall for each individual storm event. The rainfall-weighted average R value was then calculated by summing the multiple of the total rainfall and the R value for each storm event recorded at a particular meter, and then dividing the sum by the total rainfall during the monitoring period. For instance, given a 1-inch rainfall with an R value of 4 percent and a two-inch rainfall with an R value of 6 percent, the calculation of the rainfall-weighted average R value would be:

$$(1.0 \text{ in.} * 0.04 + 2.0 \text{ in.} * 0.06) \div (1.0 \text{ in.} + 2.0 \text{ in}) = 0.053$$

The result is a rainfall-weighted average R value estimate of 0.053 for this example. This estimate gives a greater weight to the larger storm event and the results are used to estimate the total rainfall entering the collection system in terms of gallons of RDII per linear foot of sewer. This RDII per linear foot parameter was used to prioritize mini-basins for SSES work.

Subsequently, further prioritization of mini-basins was given to “upstream” monitored areas, or flow monitored areas that do not include or have to deduct flows from other monitored areas upstream of them to determine localized flows. Upstream mini-basins are given higher priority for RDII investigations because errors inherent to the flow monitoring process are compounded at downstream meters with large total drainage areas. Specifically, the error can exceed the incremental calculated flow for a downstream mini-basin. Therefore, the accuracy of the calculated flow at the downstream monitor is not as high as for a mini-basin that was directly monitored.

For example, consider Flow Monitor 41A1 near the Neubert Springs Pump Station in the South Knoxville/Knob Creek Basin of KUB’s collection system (Figure 3-9). There were five upstream mini-basins that contributed flow to Mini-basin 41A1 in the 2010 flow monitoring study. The collective average dry-weather weekday flow from the upstream meters was 0.44 mgd and the average dry-weather weekday flow measured at Flow Monitor 41A1 was 0.53 mgd. The difference between these two numbers represents the calculated flow from Mini-basin 41A1 only and is equal to 0.09 mgd. Consider that a very well calibrated meter may have an error of about 5 percent. Five percent of 0.53 mgd, the average dry-weather weekday flow from Meter 41A1, is 0.03 mgd. This error margin alone makes up a substantial portion of the calculated incremental dry-weather flow of 0.09 mgd.

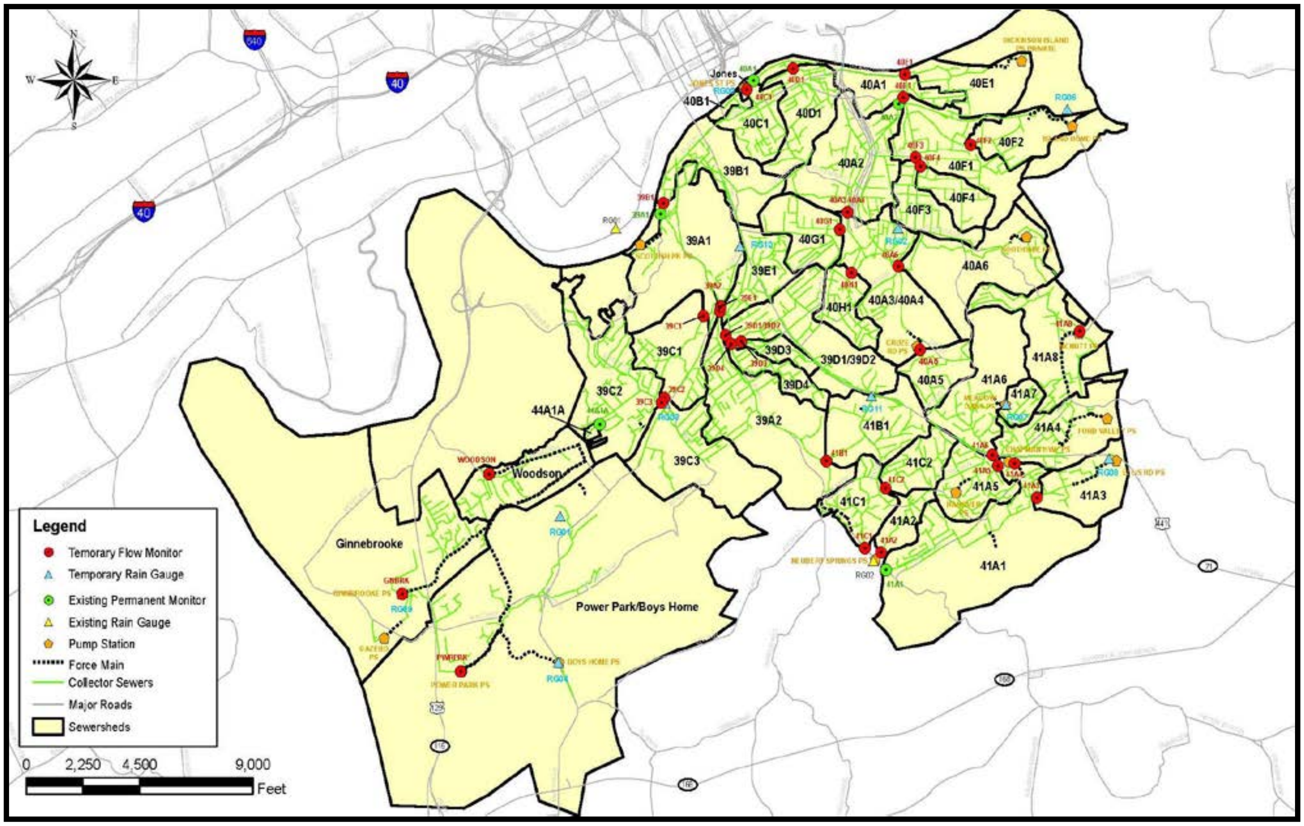

Figure 3-9. South Knoxville monitored sewersheds

This same potential for error also applies to wet-weather flow analyses. In the instance of Flow Monitor 41A1, the flow monitor has to accurately record the sum of all the RDII entering the system from the upstream mini-basins (41A3, 41A4, 41A5, 41A6/41A7, 41A8) as well as the RDII from Mini-basin 41A1. Because Mini-basin 41A1 is 121 acres in comparison to the total upstream area of 563 acres, the portion of RDII entering the system from Mini-basin 41A1 is likely to be approximately equal to the meter error. If the true incremental RDII from Mini-basin 41A1 were low to moderate, it is possible that the sum of the RDII entering the system from upstream areas could equal or exceed the RDII recorded at downstream Monitor 41A1. In this case, the incremental R calculation for Mini-basin 41A1 would yield a negative number and the monitored R value, rather than the negative incremental calculated value, would be used to estimate RDII.

In summary, upstream mini-basins are prioritized over downstream ones in KUB's overall approach. However, downstream flow monitors with high RDII values are evaluated further to determine if the high RDII value can be attributed to RDII from upstream mini-basins. If the upstream areas have low RDII values, then further investigation in the downstream area is warranted, although at a lower priority than the upstream mini-basins recommended for further SSES.

This process of prioritizing mini-basins for SSES created a baseline field of candidate mini-basins for investigation and subsequent rehabilitation. In a 2003 flow monitoring study for the First Creek Basin, KUB listed monitored mini-basins with a rainfall-weighted R value of 50 gallons per linear foot or more of RDII in a priority one category for SSES. A secondary priority category was established in this study for mini-basins with greater than 35 gallons of RDII per linear foot. Both benchmarks were later merged into a single priority system of 40 gallons of RDII per linear foot. This benchmark is program specific and was set to meet the specific KUB circumstances. In KUB's case, when hydraulic models were first used to evaluate impacts to the system based on comprehensive rehabilitation in priority mini-basins (to a goal R value of two percent), the priority one mini-basins above the 50 gallon of RDII per linear foot threshold did not result in the predicted RDII reduction required to satisfy capacity needs. The threshold was then lowered to include all the mini-basins with 40 gallons per linear foot and above to satisfy hydraulic model estimates for capacity needs. These early prioritization efforts in 2003 helped KUB progressively improve and refine the process for projects in subsequent years.

Figure 3-10 shows the prioritization bar graph that was created as a part of the 2003 flow monitoring study using the SSOAP Toolbox. It compares the RDII volume per linear sewer feet between mini-basins in Second Creek. Figure 3-11 shows a more comprehensive comparison of RDII volume per linear sewer between all basins (First Creek, Second Creek, and Knob Creek). Note that figures like Figure 3-11 were developed by compiling SSOAP Toolbox results in an Excel® environment as preferred by KUB.

In that study, Mini-basins 03B1a, 03B2a, and 04B1a in First Creek as well as Mini-basin 15D2 in Second Creek (all part of the 2003 study) were specifically targeted for further SSES investigations. This same analysis was performed on flow monitoring studies from 2004-2010.

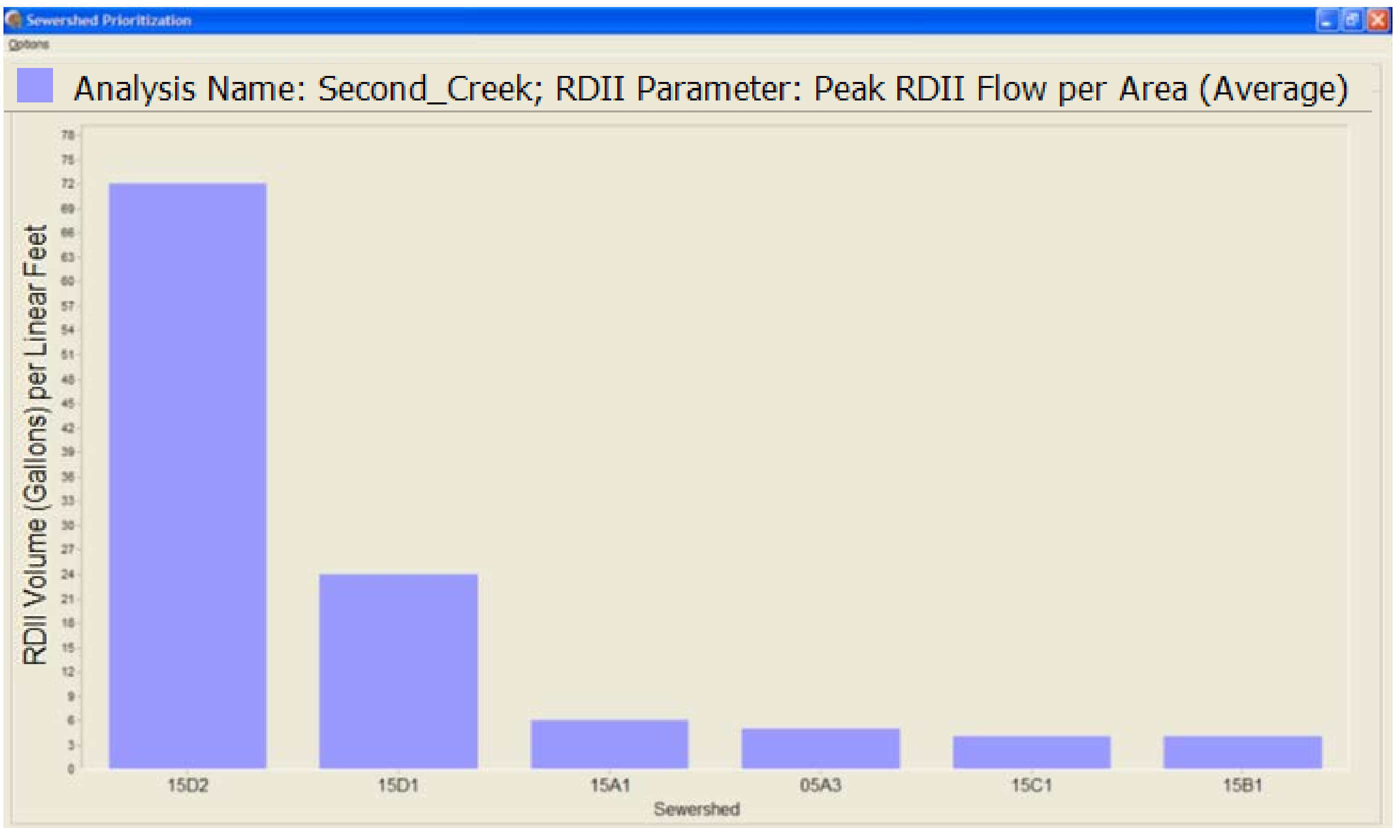

Figure 3-10. Example 2003 field investigation basin prioritization results: Second Creek

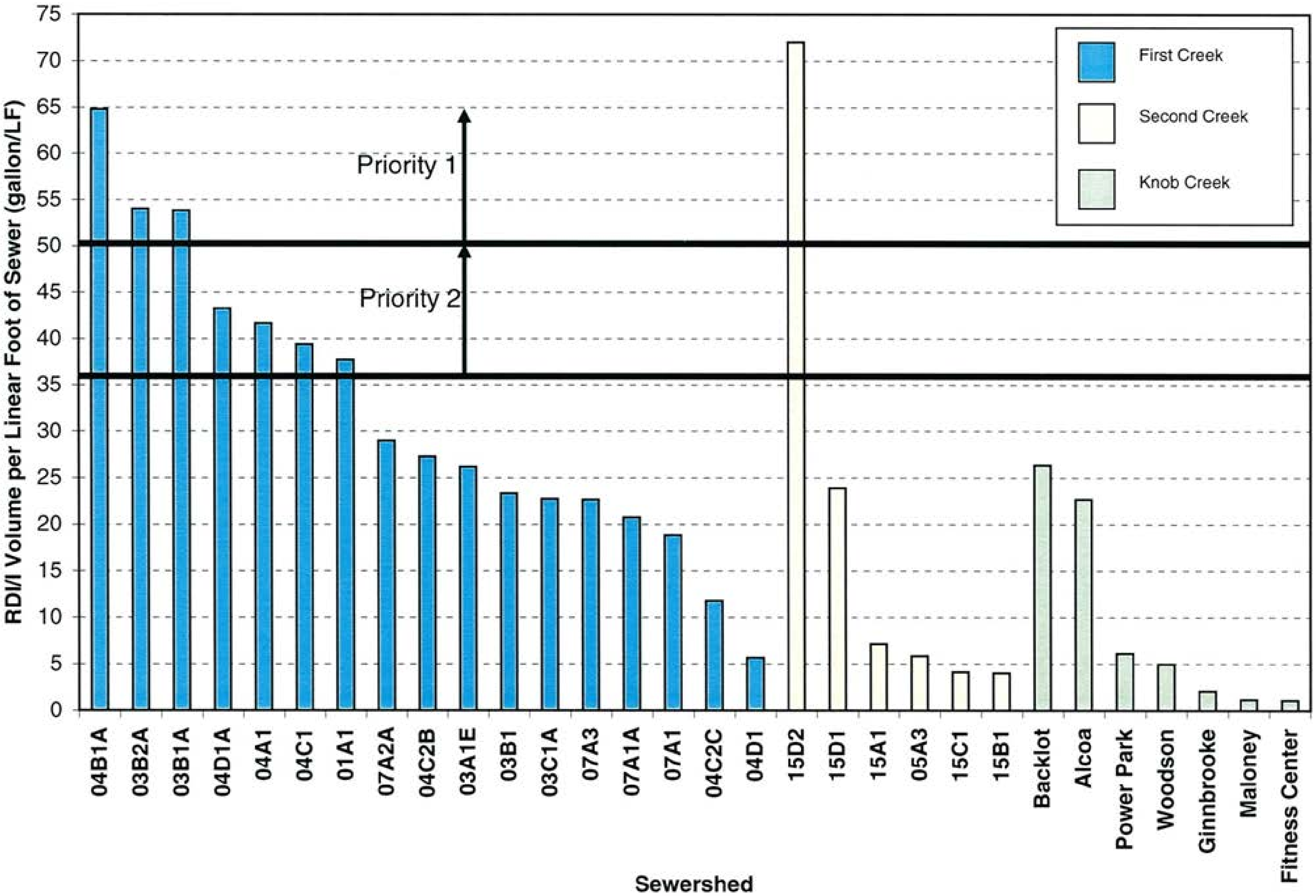

Figure 3-11. Example Field Investigation Basin Prioritization Bar Graph from 2003 First, Second, and South Knoxville/Knob Creek Report

3.6 CAP/ER Improvement Development using Hydraulic Model

This section describes Step 6 of Figure 3-3. The goal for this step was to use hydraulic modeling to assess baseline capacities and to confirm if rehabilitation would significantly reduce RDII. KUB developed extensive mini-basin hydraulic models in the SWMM EXTRAN 4 environment based on the RDII characterization (i.e., RTK) portion of the flow monitoring analyses from data collected from 2003 through 2010.

All collection sewers greater than eight inches were included in each drainage basin's model. The resulting calibrated models were used to evaluate each drainage basin under a two-year, 24-hour design storm during the winter/spring season from December through May. This two-year design storm is based on a 52-year period of rainfall record from the Knoxville Airport rain gauge. Using rainstorm frequency analysis routines within a software program called NetSTORM (CDM Smith, 2012), a two-year, 24-hour winter/spring storm of 2.96 inches for the Knoxville area was developed and subsequently approved by EPA for use in KUB's Consent Decree.

Average DWFs were projected using population estimates developed from Knoxville-Knox County Metropolitan Planning Commission Traffic Analysis Zones (TAZ). The projected flows helped users consider collection system capacity impacts estimated from future population growth.

Basins were modeled under various scenarios to evaluate the effectiveness of alternative improvement combinations with the goal of reducing RDII and addressing SSOERs. Each basin was tested under a baseline of three improvement scenarios under the two-year, design storm condition; namely:

1. Upsize pipes to contain all flows within the crown of the pipe with no mini-basin rehabilitation;
2. Rehabilitate all mini-basins with RDII greater than 40 gallons per linear foot and upsize any pipes that require it to contain flows within the crown of the pipe; and
3. Use wet-weather storage facilities in combination with limited pipe upsizing projects.

Cost estimates were developed for each scenario, keeping in mind the impacts to treatment at the downstream treatment plant. KUB assessed conventional as well as high-rate treatment to handle model-projected increases in flow to the treatment plant.

In the case of the First Creek Basin, modeling scenarios produced a combination of mini-basin rehabilitation, pipe upsizing, and two storage facilities to optimize estimated RDII and SSOER reductions. Initial cost estimates for improvements in the First Creek Basin were estimated to be $68.7 million in August of 2005. Initial estimates of the overall CAP/ER improvement program for all the drainage basins were more than $530 million.

Figure 3-12 illustrates an example end result of the mini-basin prioritization done in the RDII analysis phase along with the collection system modeling scenarios for CAP/ER guidance in the First Creek Basin.

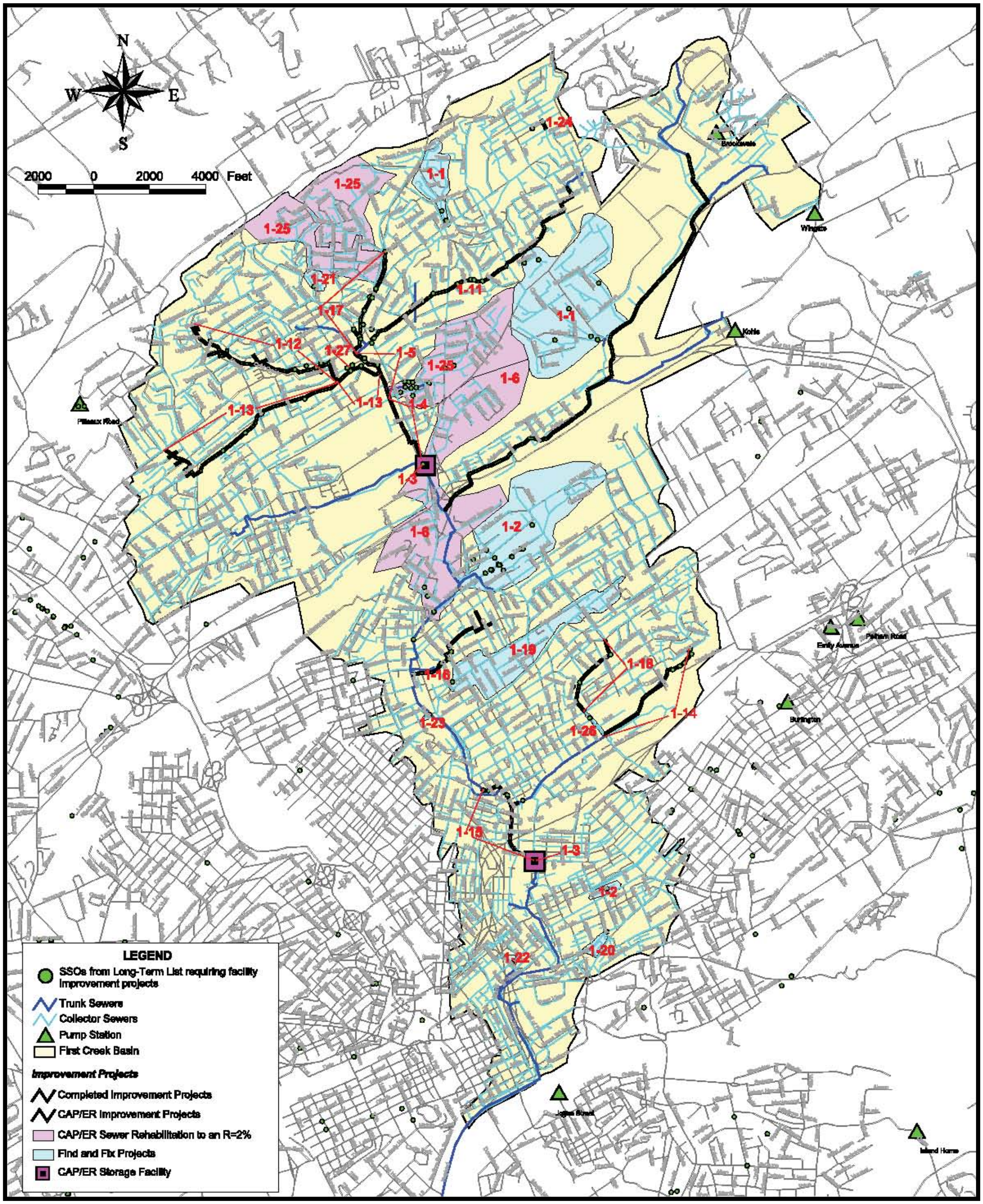

Figure 3-12. First Creek Basin - Phase I CAP/ER facility improvement projects

3.7 Field Investigation, Condition Assessment, and Rehabilitation

This section describes Step 7 of Figure 3-3. Based on results from the RDII analyses undertaken in KUB's flow monitoring program, KUB focused field investigation efforts on mini-basins that exceeded the 40 gallons of RDII per linear foot threshold. Efforts were not limited to just these initial mini-basins, but these areas were the main targets for follow-up system-wide SSES work.

Field investigations in the priority mini-basins included collection system cleaning, smoke testing, and CCTV investigations of collection and main trunk sewer lines. Results from these investigations were then used to recommend the type of rehabilitation needed in each mini-basin area. In areas where CIPP or pipe replacements were utilized, the rehabilitation work included replacement of the lower laterals and installation of clean-out structures on the lower laterals where they had not existed previously. KUB performed CIPP or line replacement on 151,000 lf of pipe from 2006 through 2010. Though CIPP was the main form of rehabilitation undertaken, manhole rehabilitation and replacement were also performed. From 2006 through 2010, manhole rehabilitation at 796 locations was performed.

KUB conducted additional CCTV work on private laterals along the mainline CIPP areas by using push cameras through the clean-out structures up to the connection at the home or business. Any sign of RDII was grounds for KUB to contact the owner and to have the owner make preparations for repair/replacement on the private property lateral. The additional private side lateral CCTV investigations mainly occurred as a result of main line rehabilitation efforts. Additional private lateral CCTV work was also undertaken based on customer service calls and field observations of potential lateral deficiencies.

3.8 Post-Rehabilitation RDII Analysis

After rehabilitation was completed, KUB repeated the Data Collection and Review and RDII Analysis steps (Step 1 through 4 in Figure 3-3).

Following completion of sewer rehabilitation in the mini-basins identified on Figure 3-13, KUB performed post-rehabilitation flow monitoring by drainage basin during the spring of 2006, 2007, 2008, 2009, and 2010 to evaluate the effectiveness of the rehabilitation programs. The results from the rehabilitated mini-basins were compared to flow monitoring results from study control areas (Figure 3-13). The data collection and review methods described earlier for pre-rehabilitation were consistently used for the post-rehabilitation period.

KUB conducted RDII analysis after the data was collected and reviewed for the post-rehabilitation period, as indicated in Steps 3 and 4 of Figure 3-3. These RDII analysis results were subsequently used to conduct RDII Trending Analysis using the approaches included in SSOAP Toolbox's Condition Assessment Support Tool.

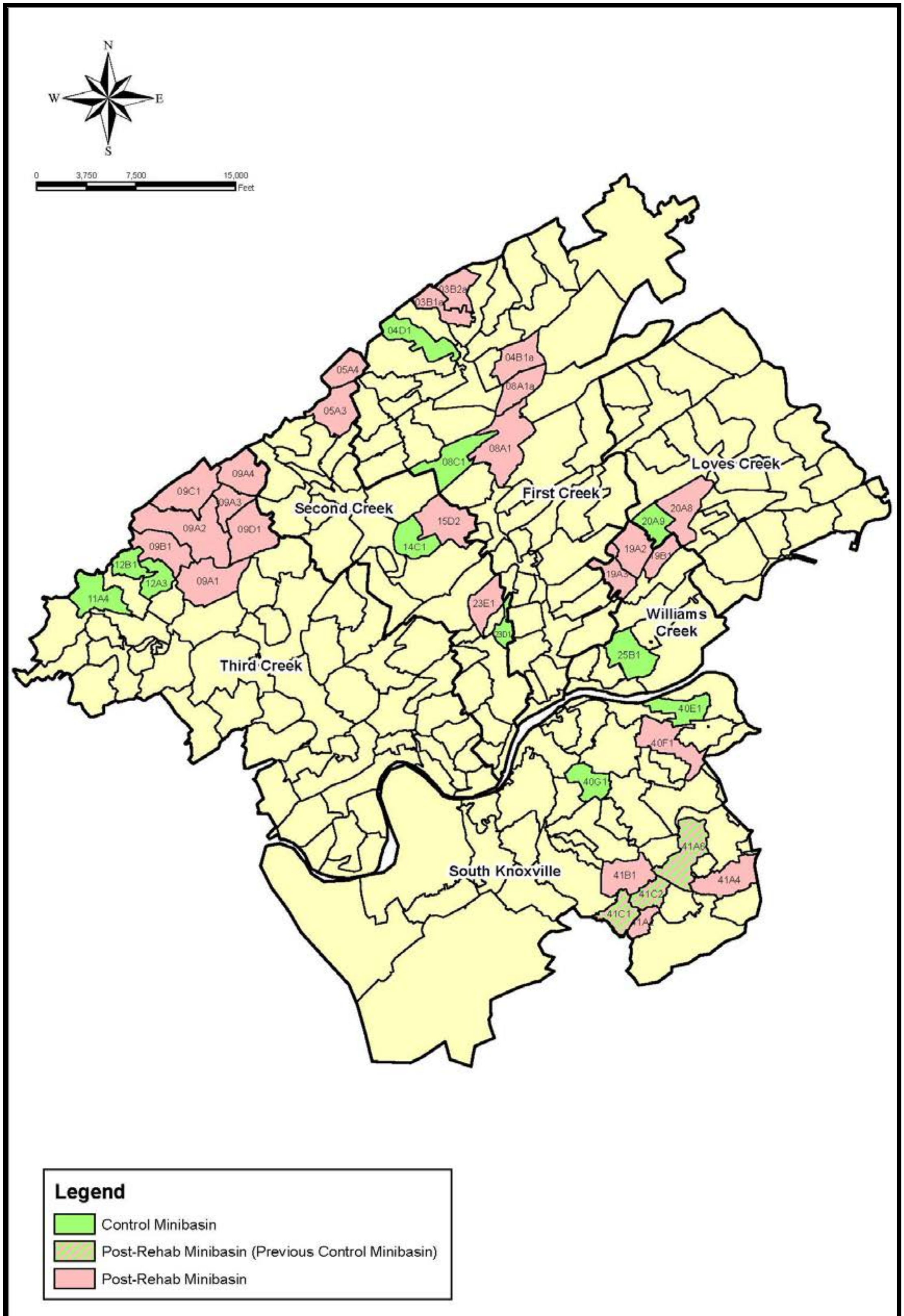

Figure 3-13. Post-rehabilitation flow monitoring locations, including control areas, 2006-2010

3.8.1 Pre- and Post- Rehabilitation RDII Correlation Comparison

KUB used results of the RDII analyses of the pre- and post-rehabilitation periods to estimate trends in RDII reductions using the same approach employed by the Condition Assessment Support Tool. The actions taken by KUB to complete this analysis included:

- Using the Condition Assessment Support Tool used to confirm correlation analysis between pre- and post-rehabilitation RDII results
- Estimating RDII trending
- Synthesizing observed results

Results compiled in this report included five sewer investigations, including two studies undertaken in 2006 and 2007. Both studies assessed the reductions made in RDII based on the mini-basin rehabilitation projects completed just prior to the study dates. In addition to these studies, further mini-basin flow monitoring was conducted in 2008, 2009, and 2010 (see Figure 3-4). Flow monitoring data acquired in the spring of the years 2003, 2004, 2005, and 2006 was used to analyze pre-rehabilitation flow conditions for the study areas previously prioritized for rehabilitation in the Phase 1 CAP/ER.

The rehabilitation of a mini-basin collection system area often addressed a local SSOER or contributed to the elimination of an SSOER downstream. For example, as shown in Figure 3-12, the Mini-basin 04B1a (Project 1-25) was rehabilitated not only to address this prioritized mini-basin's high RDII per linear foot (65 gpd/lf) but also to address multiple downstream SSOERs (indicated as green dot symbols on Figure 3-12).

Once R values were computed for each rainfall event at each flow monitor, a RDII correlation analysis was performed to compare the pre- and post-rehabilitation monitoring results using methodologies included in the SSOAP Toolbox. This correlation is a linear relationship between the R values of the rehabilitated area and the R values of a control area. The linear relationship was established during pre-rehabilitation conditions and post-rehabilitation conditions by performing a linear regression between the R values of the rehabilitated area and control area during each monitoring period. Figure 3-14 presents an example of this analysis for Study Area 08A1a.

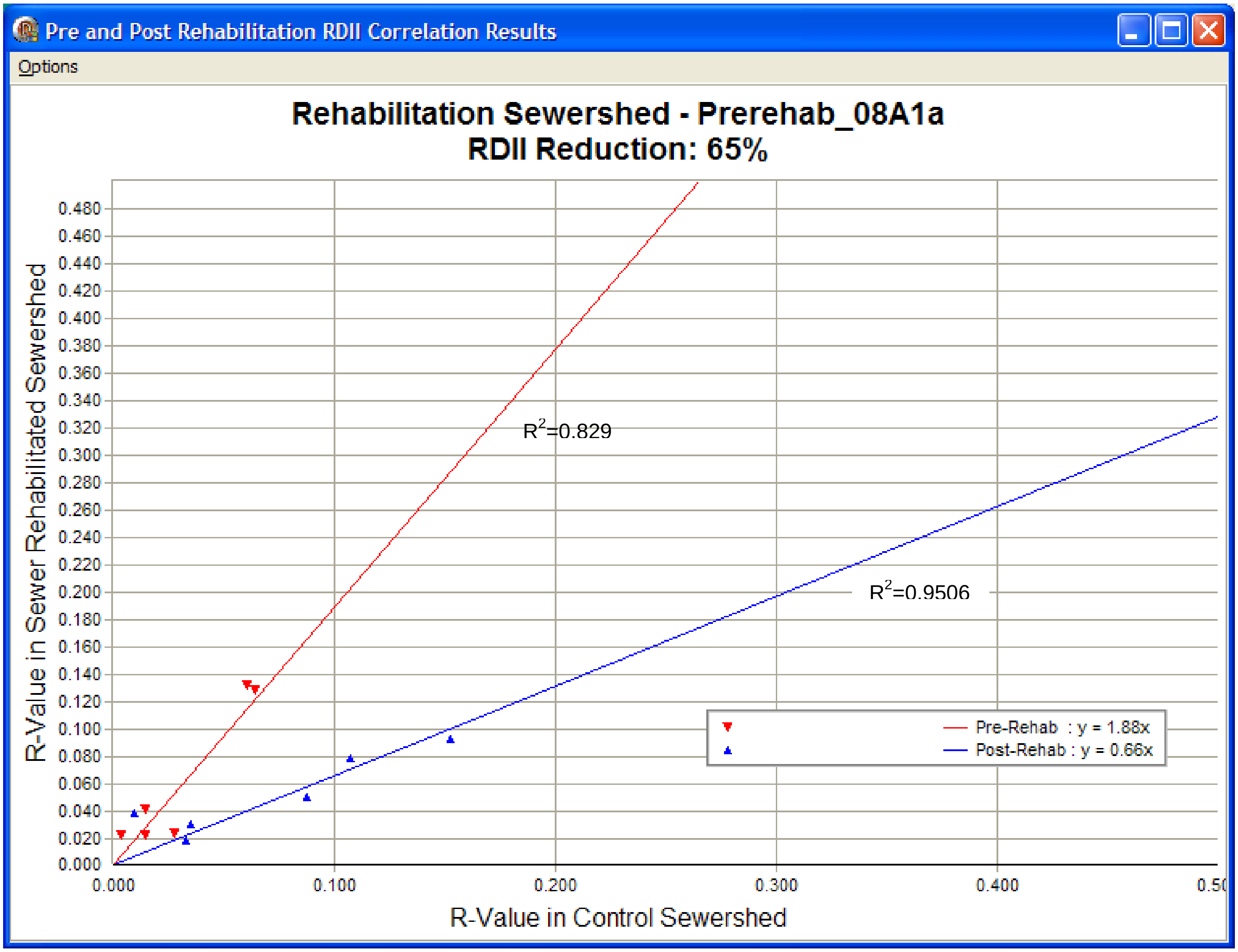

Figure 3-14. Mini-basin 08A1a RDII reduction based on linear regression model

3.8.2 RDII Reduction Estimates

Analysis showed significant RDII reductions for all the study areas with the exception of two areas where flow monitoring issues/collection system operation issues prevented RDII comparisons. In Figure 3-14, the R value for the rehabilitation meter is plotted on the Y axis and the R value for the control meter is on the X axis. Note in this figure the statistical data correlation value R^2. This correlation value reflects how well the individual data points create a highly accurate linear regression line for the data set. In this KUB analysis, values below 0.4 are considered of low data correlation, 0.4 to 0.7 medium correlations, and 0.7 and above high correlation.

For Figure 3-14, the linear regression between the Rehabilitation Area 08A1a and the Control Area 08C1 for the pre-rehabilitation condition produces a regression line with equation y=1.88x. Similarly, a regression of R values between the rehabilitation area and the Control Area 08C1 for post-rehabilitation conditions produces a regression line with the equation of y=0.66x. The regression lines are forced through the point (0,0) to represent where both the control and rehabilitation R values are equal (zero RDII at zero rainfall) creating a common dataset condition. Calculating the difference between the slopes of these lines shows an RDII reduction of 65 percent was achieved. Data correlation was high for both the pre- and post-rehabilitation data sets. In KUB's analyses, the flow monitoring periods focused on the higher groundwater condition spring months in both the pre- and post-rehabilitation flow monitoring periods.

3.8.3 RDII Trending Results

Overall, KUB obtained differing degrees of success in RDII reduction from sewer rehabilitation efforts based on the RDII Trending Analysis. Table 3-1 contains a summary of the RDII trending reductions. All the mini-basins show a reduction in RDII between the pre-rehabilitation and post-rehabilitation monitoring periods with the exception of 05A3/05A4 and 23E1 in the Second Creek drainage basin and 41A4 in the South Knoxville drainage basin. The RDII trending results for Mini-basins 05A3/05A4, 23E1, and 41A4 were skewed due to unexpected field conditions and resulting data reliability issues.

The following is a summary of three major types of results KUB experienced:

Type 1: Confirmation of significant reduction of RDII after sewer rehabilitation

Tables 3-1 through 3-3 shows an example range of RDII trending results between more than 20 mini-basins located in six major drainage basins after sewer rehabilitation work was completed prior to each study year. The analysis showed sewer rehabilitation resulted in a range of 15 percent to 96 percent RDII reduction. These tables also show the data confidence level for each mini-basin by ranking the data correlation between pre-rehabilitation and post-rehabilitation period into low, medium, and high. This data confidence level provides KUB an insight on which mini-basins have a high confidence that RDII reduction has been achieved. For example, in Mini-basin 15D2 in Second Creek (Table 3-2), both pre-rehabilitation and post-rehabilitation data correlation are listed as high giving greater confidence that KUB reduced 47 percent of RDII in that mini-basin, as the study suggested.

Type 2: Inclusive in RDII trending

Data from Mini-basin 05A3/05A4 did not show additional RDII reductions after the 2007 flow monitoring period/sewer rehabilitation. This mini-basin, however, showed poor data correlation with the study control (i.e., RDII events did not overlap well for both the study area and control area for both the pre- and post-rehabilitation study periods.) As a result, the poor correlation skewed post-rehabilitation results into appearing as though no improvements occurred. KUB performed additional flow monitoring in 2012 in an attempt to get better data correlation and was in the process of analyzing the RDII reduction trending at the time of this writing.

Type 3: Insignificant Reduction of RDII after sewer rehabilitation

Table 3-3 also shows examples of RDII trending results for five mini-basins after KUB completed its sewer rehabilitation prior to the 2006 study. Note that the percentage of RDII reduction for Mini-basin 04B1a in First Creek is approximately 15 percent and its data confidence levels are both high in pre-rehabilitation and post-rehabilitation periods. KUB was not satisfied with this 15 percent reduction in this mini-basin and decided to conduct further comprehensive rehabilitation work in the same mini-basin in 2007. As a result, KUB was able to achieve an additional 35 percent reduction after additional comprehensive rehabilitation was completed prior to the 2007 study (see Table 3-2).

Table 3-1. 2009 and 2010 R Reduction Estimates

Drainage Basin	**Williams Creek**	**Williams Creek**	**Williams Creek**	**South Knoxville**	**South Knoxville**	**South Knoxville**
Rehab Area	**19A26**	**19A36**	**19B1**	**41A25**	**41A6 / 41A7**	**41C1 / 41C2**
Control Area	**25B1**	**25B1**	**25B1**	**40G1**	**40G1**	**40G1**
Linear Regression Results						
Pre-Rehab Slope	3.7603	3.6939	3.7663	0.4196	0.6953	1.3161
Post-Rehab Slope	2.3432	1.5366	1.1434	0.1475	0.5225	0.5231
Percent I/I Reduction	38	58	70	NA	25	60
Pre-Rehab Data Correlation	High	Low	High	Low	Low	Low
Post-Rehab Data Correlation	Low	Low	Med.	Med.	Low	Low

Table 3-2. 2007 and 2008 R Reduction Estimates

Table 3-2. 2007 and 2008 R Reduction Estimates

Drainage Basin	First Creek	First Creek	Second Creek	Second Creek	Second Creek	Loves Creek	South Knox.	South Knox.	South Knox.	Third Creek	Third Creek	Third Creek	Third Creek	Third Creek
Rehab Area	04B1a4	08A1a	05A3/ 05A4	15D2	23E12	20A8	40F1	41A4	41B1	09A1	09A2	09A3	09B1	09D1
Control Area	04D1	08C1	14C1	14C1	23D1	20A9	40E1	41C1/ 41C2	41C1/ 41C2	12A3	12A3	11A4	12A3	11A4
Linear Regression Results														
Pre-Rehab. Slope	1.5104	1.8167	0.2349	0.5893	2.324	0.2916	1.2433	0.9589	0.9249	2.0505	2.2082	0.6474	0.5156	1.2487
Post-Rehab. Slope	0.9806	0.6367	0.3289	0.3136	5.8533	0.1874	0.5700	4.0444	0.7323	0.4365	0.7822	0.3067	0.0207	0.6653
Percent I/I Reduction	35%	65%	NA1	47%	NA2	36%	54%	NA3	21%	79%	65%	53%	96%	47%
Pre-Rehab. Data Correlation	Low	High	Low	High	Low	Med.	Med.	High	High	High	High	Low	Low	High
Post-Rehab. Data Correlation	Low	High	Low	High	Low	Med.	High	High	High	Med.	High	High	Low	Med.

Table 3-3. 2006 R Reduction Estimates

Drainage Basin	First Creek	First Creek	First Creek	South Knoxville	South Knoxville
Rehab. Area	03B1a	03B2a	04B1a4	40F1	41B1
Control Area	04D1	04D1	04D1	41C1/41C2	41C1/41C2
Linear Regression Results					
Pre-Rehab. Slope	0.472	0.8618	1.4073	1.078	0.8354
Post-Rehab. Slope	0.2842	0.588	1.2017	0.7837	0.6201
Percent I/I Reduction	40	32	15	27	26
Pre-Rehab. Data Correlation	Low	High	High	High	High
Post-Rehab. Data Correlation	Low	Low	High	High	Low

1) The control meter for this area showed a decrease in R value that skewed the overall data; as a result, the analysis was biased toward no reduction.
2) A cross connection was found coming into 23E1 with an elevated pipe off of the main trunk line with the potential to overflow into 29E1's mini-basin. This explains why there appeared to be no reduction in RDII flows in this mini-basin.
3) Pump station operations upstream appear to have skewed post-rehabilitation results for this study area.
4) 04B1a was studied in 2006 and at that time saw a reduction in R value of 15%. Further rehabilitation was performed in this mini-basin. As a result, total RDII reduction is the sum of the 2006 (15%) and 2007 results (35%)…total reduction 50%.
5) Due to extremely low flow conditions at this site, flow monitoring data pre- and post-rehabilitation made it difficult to determine without a doubt the RDII effects at this location.
6) Mini-basins 19A2 and 19A3 were still in the midst of lateral rehabilitation construction activities during the 2009 flow monitoring study. Since these areas still had more opportunity for RDII reductions and because of construction going on at the time of the study, a non-linear analysis was not applied because these areas were not recommended for overall grouping with rehabilitation results seen to date. It was recommended to omit these 2009 mini-basins results from overall rehabilitation results.

Based on all the post-rehabilitation analyses, KUB concluded that rehabilitation significantly reduced RDII. RDII reductions based on the 2006 through 2010 results varied from 15 percent to 96 percent using the linear regression control method in the SSOAP Toolbox. Given these ranges and the assumption that similar rehabilitation activities occurred in the mini-basins, it would be statistically erroneous to choose just one flow monitor RDII reduction to develop estimates for future reductions.

As a result, progress of the mini-basins as a collective dataset from 2006 through 2010 was considered with a median value chosen as a representative reduction. Focusing on mini-basins that had data correlations in the medium to high range (South Knoxville Mini-basin 40F1, First Creek Mini-basin 08A1a, Second Creek Mini-basin 15D2, Loves Creek Mini-basin 20A8, South Knoxville Mini-basin 40F1, South Knoxville Mini-basin 41B1, Third Creek Mini-basins 09A1, 09A2, 09D1, and Williams Creek Mini-basin19B1), the overall median R value reduction for the linear method was 51 percent. Separate non-linear method analyses were conducted by Dr. Zhiyi Zhang (Zhang, 2008; KUB 2006; KUB 2007). Results from those analyses gave an overall median R value reduction of 57 percent, confirming the results from the linear regression approach used in the SSOAP Toolbox. The median R value has been updated as KUB continues its ongoing post-rehabilitation monitoring efforts.

3.9 Lessons Learned

Many variables affect the post-sewer rehabilitation RDII reductions assessment: fluctuations in year-to-year climate conditions for pre- and post-flow monitoring, quantity and quality of flow data, the extent of rehabilitation performed, the type of rehabilitation, and the effectiveness of SSES studies to pinpoint sources of RDII. The following are some of the main lessons learned through the pre- and post-rehabilitation analysis process:

- **Number of data points available for RDII Trending Analysis is often less than the number of wet-weather events.** An overall data set for analysis is often reduced once corresponding events are finalized. Some individual RDII rainfall events in the pre- and post-rehabilitation analyses did not coincide with the same event at the control meter. This may have been due to spatial variation in rainfall or that the response time at the meter being analyzed and the control meter did not correspond. In some cases, either the control or the study area RDII response would span several rainfall events before returning to average dry-weather flow conditions, making it difficult to compare to other meter data.

- **Reasons for anomalous responses: RDII reduction could be caused by other changes in the collection system other than sewer rehabilitation.** If data trends higher in the post-rehabilitation condition, do not rule out potentially simple reasons such as changes in the collection system or changes in system behavior since pre-rehabilitation RDII analysis. For KUB's Mini-basin 23E1, a previously unknown elevated pipe cross-connection in this system tied into the main trunk line for Second Creek and overwhelmed any potential RDII reductions gained in this mini-basin due to rehabilitation work. The cross-connection allowed for water from the main trunk line to come into Mini-basin 23E1 during significant rainstorm events and greatly skewed flow monitoring results. The skewing was more prominent in the post-rehab flow monitoring conditions. The increased frequency of large storm events in the post-rehabilitation monitoring period likely activated the elevated cross-connection more often than in the pre-rehabilitation condition, adding to monitored flows in the mini-basin.

- **Follow-up work may be required.** KUB had to do follow-up investigations in areas where results did not meet target reductions as experienced in Mini-basin 04B1a within the First Creek Basin. In this mini-basin, the first analysis in 2006 yielded a RDII reduction of 15 percent based on linear regression analysis. These results prompted KUB to do follow-up investigations where additional RDII sources were located and eliminated. KUB achieved an additional 35 percent RDII reduction that occurred in the 2007 study, resulting in a 50 percent total reduction from the original pre-rehabilitation condition. Table 3-1 presents the results of both the initial study and the follow up study for 04B1a.

  The initial post-rehabilitation results may warrant further SSES investigations for potential new sources of RDII. Removal of RDII from one portion of the system may cause RDII to migrate to another portion, or may make previously hidden sources more apparent. Again, in the case of Mini-basin 04B1a, after initial removal of RDII from the system in the 2006 analysis, enough flow was removed to identify more visible patterns resembling sump pump/foundation drain activity.

- **Potential for surface drainage increases.** Any flow denied access to the sanitary collection system will seek a new flow path. After rehabilitation work in the First Creek was performed, notable increases in surface drainage were observed in some mini-basins. It is possible that local reductions in RDII contributed to the immediate increases in the drainage in the Fountain City Park Area. KUB's collection system in the area had been effectively working as both a sanitary and partial storm drainage system prior to rehabilitation.

- **Coordination of construction and flow monitoring efforts needs special attention in scheduling.** Scheduling of flow monitoring is challenging in relation to construction projects. For some mini-basin areas, the rehabilitation work extended into the post-flow monitoring period. As a result, the measurement of the full impact of those efforts was affected. An example of this in the KUB system was when KUB wanted to assess the full impacts of work completed in Williams Creek Mini-basins 19A2 and 19A3. Lateral rehabilitation efforts extended into the flow monitoring study period with substantial portions of each mini-basin still undergoing improvements throughout the flow monitoring study.

- **Locating RDII sources can be challenging.** Some sources, such as directly connected roof drains, are easier to find and eliminate vs. hidden foundation drains or sump pumps on private property. KUB's experience indicated that strange fluctuations in flow monitoring data may help reveal hidden sources of RDII, such as sump pumps and foundation drains. Constant sustained and elevated flow patterns may be indications that a service area has sump pump and foundation drain influences.

- **Climate is not consistent over time.** Because of the nuances in RDII sources and climatology, the reductions seen in RDII can often vary greatly from one mini-basin to another. If the emphasis is placed on reviewing a collective set of mini-basins instead of one individual mini-basin, the results for future planning based on rehabilitation efforts will be better estimated.

3.10 Ongoing and Planned Sewer Condition Assessment Efforts

KUB is continuing its flow monitoring and post-rehabilitation assessments with the next major study in the Loves Creek Drainage Basin in 2012. KUB recently completed extensive rehabilitation work in the northwest portion of this basin to remove RDII and add system capacity in this drainage basin. Rehabilitation efforts undertaken in this drainage basin went beyond the scope of the CAP/ER reports for addressing capacity issues.

KUB continues to monitor its sewer system with temporary flow monitoring studies and a 35 flow monitor, eight rain gauge, permanent network. These efforts add to its ongoing Capacity Management, Operation, and Maintenance (CMOM) efforts to effectively maintain and operate an efficient collection system.

3.11 Summary and Conclusion

Significant efforts were taken to improve KUB's aging collection system. Multi-year flow monitoring data collection, RDII analyses, hydraulic model development and application, field investigations, project design, cost estimating/scheduling, and project implementation and effectiveness assessment have all led to efforts now spanning nearly a decade of work. KUB's overall approach successfully incorporated SSOAP Toolbox methodologies to analyze rainfall and flow monitoring data to perform RDII characterization, capacity assessments using hydraulic models, prioritize mini-basins for extensive field investigations, and to conduct post-rehabilitation flow data analysis to assess rehabilitation effectiveness.

The CAP/ER planning process led to the development of guidance documents that led to collection system and treatment plant improvements estimated at $530 million. Those improvements include gravity main size upgrades, the construction of four wet-weather collection system storage facilities ranging from 3.25 MG up to 9 MG in size, and rehabilitation of targeted mini-basins to reduce RDII, and wet-weather treatment and storage facilities at two wastewater treatment plants.

After compiling the post-rehabilitation results, KUB determined the current overall estimated median R value reductions were 51 percent using the linear regression methodologies currently used in the SSOAP Toolbox. This reduction was further validated by an independent non-linear method that showed a very comparable median R reduction of 57 percent considering inherent flow data uncertainties. KUB is continuing to evaluate its collection system for post-rehabilitation RDII reductions using larger RDII data points derived from the permanent flow meter network and supported by temporary monitoring programs. It has started a temporary flow monitoring study for the spring of 2012 in the Second Creek, Loves Creek, and Eastbridge basins and will perform post-rehabilitation data analyses using the SSOAP Toolbox after the temporary flow monitoring data collection is completed. Results from this upcoming study will be used to further verify/update RDII reduction trends observed to date. This continuing cycle of assessment helps KUB to improve reliability of system performance and continuous management of its assets.

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