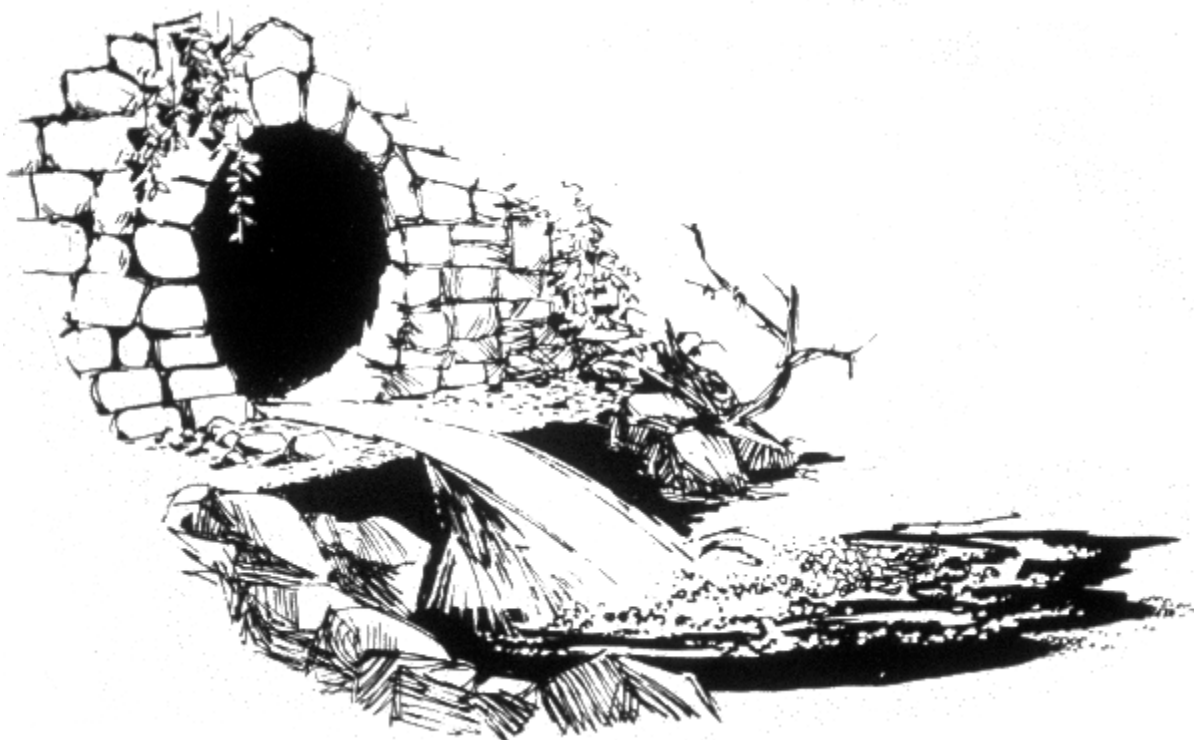**⊕EPA**

Review of Sewer Design Criteria and RDII Prediction Methods

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By

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In support of:

Development of Capacity Analysis Tools and Associated Technical Documents for SSO Control Planning

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Abstract

Rainfall-derived Infiltration and Inflow (RDII) into sanitary sewer systems has long been recognized as a source of operating problems in sewerage systems. RDII is the main cause of sanitary sewer overflows (SSOs) to basements, streets, or nearby streams and can also cause serious operating problems at wastewater treatment facilities. SSOs usually contain high levels of pathogenic microorganisms, suspended solids, toxic pollutants, floatables, nutrients, oxygen-demanding organic components, and oil and grease. There are serious concerns of potential health and environmental risks associated with these discharges.

The Nation's sanitary sewer infrastructure is aging, with some sewers dating back over 100 years. 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. To assist municipalities in developing plans to mitigate SSO problems, the U.S. Environmental Protection Agency (EPA) in 2002 signed a cooperative research and development agreement (CRADA) with Camp Dresser & McKee Inc. (CDM) to develop a public-domain Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox. It contains a suite of computer software tools to facilitate the analysis of RDII and performance of sanitary sewer systems. In addition, the CRADA includes a recently published technical guide (EPA/600/R-07/111) and a SSOAP user's manual being prepared to guide the application of the Toolbox. A beta version of SSOAP is planned to be released to the public in 2008.

This report primarily provides a literature review of the RDII quantification methods (Chapter 4) to support the development of the SSOAP Toolbox under the CRADA. The literature review is centered on the 1999 WERF report in which eight methods are thoroughly assessed using real data from three sewerage agencies. While there is no single RDII method that is universally applicable, the RTK method was chosen to be implemented in the Toolbox as it is probably the most widely accepted one. The method has long been an option in the EPA Storm Water Management Model (SWMM) and is extensively used. Other RDII methods can be included in future expansion of the Toolbox.

Since RDII is closely associated with the structural conditions of sewers and the hydrologic/hydraulic criteria used to design them, Chapters 1 to 3 are included to provide background information. Chapter 1 summarizes the nation's wastewater infrastructure conditions and problems, origins of and problems caused by infiltration and inflow, and EPA regulatory approaches to address the aging systems and SSOs. Chapter 2 presents the components of wastewater flows that form the basis for sanitary sewer design. Historical and current sewer design practices and flow design standards of selected states and local sewerage agencies are described in Chapter 3.

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List of Acronyms and Abbreviations

ASCE	American Society of Civil Engineers
BWF	Base wastewater flow
CDM	Camp Dresser & McKee Inc.
CMOM	Capacity, Management, Operation and Maintenance
CRADA	Cooperation Research and Development Agreement
DWF	Dry-weather flow
EPA	U.S. Environmental Protection Agency
GWI	Groundwater infiltration
I/I	Infiltration/inflow
LP	Linear programming
MCES	Metropolitan Council Environmental Services
NRMRL	National Risk Management Research Laboratory
O&M	Operation and maintenance
POTW	Publicly owned treatment works
RDII	Rainfall-derived infiltration/inflow
RTK	The use of R,T,K parameters in the RTK method for RDII prediction
R-value	Percent of rainfall volume
SSES	Sewer system evaluation survey
SSO	Sanitary sewer overflow
SSOAP	Sanitary Sewer Overflow Analysis and Planning
SUH	Synthetic unit hydrograph
SWMM	EPA Storm Water Management Model
UH	Unit hydrograph
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WWF	Wet-weather flow
WWTP	Wastewater treatment plant

Chapter 1 Introduction

National Wastewater Infrastructure Condition and Problem

Municipal sanitary sewer collection systems play a critical role in protecting public health in our cities and towns. They are designed to convey wastewater from their sources to a wastewater treatment plant (WWTP). Collection systems consist of sewers, pumping stations, force mains, manholes, and all other facilities used to collect wastewater from individual residential, industrial, and commercial sources. The performance of these systems can significantly influence the performance of the WWTP. The 1998 Clean Water Needs Survey (EPA, 2001) identifies more than 19,500 municipal sanitary sewer collection systems nationwide serving an estimated 150 million people and comprising about 500,000 mi of municipally owned pipes in publicly owned systems and probably another 500,000 mi of privately owned pipes that deliver wastewater into these systems. The replacement costs of the nation's sanitary collection systems are estimated to be from 1 to 2 trillion dollars. Another source (NCPWI, 1988) estimates that wastewater treatment and collection systems represent about 10-15% of the total infrastructure values in the United States.

Much of the nation's sanitary sewer infrastructure has been installed over a long time period, with some sewers dating back over 100 yr. An American Society of Civil Engineers (ASCE) study under cooperative agreement with the U.S. Environmental Protection Agency (EPA) (Black & Veatch, 1999) conducted a survey that involved 42 wastewater utilities serving about 26 million people across the continental U.S. of various sizes and population. The survey indicated that the age of collection systems ranged from new to 117 yr, with an average age of 33 yr. About 18% of sewers were built in the last 10 yr, 41% in the last 20 yr, 82% in the last 50 yr, and 98% in the last 100 yr. The average sewer density in this survey is 21 ft of sewer/capita, or about 10 mi/mi^2 of service area.

Older sewers were constructed mainly of vitrified clay, brick, and concrete, while modern sewers were constructed of plastic, ductile iron, steel, and reinforced concrete. A survey conducted for EPA (Arbour and Kerri, 1998) which included 13 sanitary sewer systems indicated that material distribution of gravity sewers are: vitrified clay 61%, plastic of all types 20%, reinforced concrete 7%, unreinforced concrete 7%, and other 5%. Over 50% of force mains use ductile iron. Clay pipes are generally under 915 mm (36 in.) and larger pipes use reinforced concrete to obtain strength especially for resisting vertical loadings. Sewer joints are probably the most susceptible component of a sewer system for infiltration. The joints in older clay sewers were made of cement mortar which may have been initially water-tight and root-resistant, but tend to deteriorate over time because of their rigidity and the potential corrosive conditions associated with hydrogen sulfide.

Infiltration/inflow (I/I) problems have long been the primary focus related to public sewer lines of collection facilities (Lai and Field, 2001). As the integrity of a sewer system starts to deteriorate because of a variety of factors such as old age, traffic load and overburden, poor design, lack of maintenance, the system's ability to transport wastewater to treatment facilities is impaired. Sewer pipeline stoppages and collapses are increasing at a rate of approximately 3% per yr. Roots that puncture and grow inside pipes

cause over 50% of the stoppages, while a combination of roots, corrosion, soil movement, and inadequate construction are the cause of most structural failures (ASCE, 1994). According to a study conducted by the Urban Institute (1981), approximately 50 major main breaks and 500 stoppages occur per 1,600 km/yr (1,000 mi/yr), amounting to an estimated 50,000 breaks and 500,000 stoppages annually in the nation. Deterioration of joint materials, force main pressure surges, disturbance by construction or direct tapping, and seismic activity also contribute to collection line failures. These problems result in approximately 75% of the nation's piping systems functioning at 50% of capacity or less (ASCE, 1994).

Problems Caused by I/I

Besides stoppages and collapses, the problems caused by aging and deteriorating collection systems include excessive I/I that robs capacity in a sanitary sewer system and negatively affects operation of the entire sewerage system. This I/I problem eventually comes to the attention of the general public in the form of sewer overflows, sewer backups, equipment failures, facility expansion needs, permit violations, and increases in operating costs and user fees.

I/I can greatly increase flows and cause unnecessary burdens on the treatment plant and contribute to sanitary sewer overflows (SSOs). SSOs are untreated sewage overflows from sanitary sewer collection systems to streets, private property, basements, and receiving waters. SSOs occur when flows exceed the capacity of a sewer and sewers surcharge. Usually, SSOs are most prevalent during and immediately after wet weather when flows are high due to I/I. In addition to I/I, contributing factors to SSOs include sewer blockages from root intrusion, grease build-up, sedimentation, and debris, all of which are not wet weather related. SSOs usually contain high levels of pathogenic microorganisms, suspended solids, toxic pollutants, floatables, nutrients, oxygen-demanding organic components, and oil and grease. SSO effects are many, including: (1) closing of beach and recreational areas; (2) prevention of fishing and shellfish harvesting; (3) public health risks associated with raw sewage in roadways, drainage ditches, basements, and surface waters; (4) inhibition of potential development from sewer connection moratoriums; and (5) financial liability of a community from public relation problems. In San Diego, CA, SSOs threatened drinking water supplies, creating the potential for serious adverse public health impact (Golden, 1996).

Available data indicate that essentially all large collection systems experience periodic SSOs and between one-third and two-thirds of the nation's sanitary sewer systems have problems with SSOs or peak flows at the WWTP. It is estimated that there are about 40,000 SSO events per yr nationwide. The national cost estimate to mitigate SSOs for the next 20-yr period is $164 billion (2007 dollars) to attain almost zero overflows per yr per municipality and about $119 billion and $96 billion (2007 dollars), respectively, to attain one and two overflows per yr per municipality (EPA, 1996a).

Causes of I/I

I/I is caused by stormwater and groundwater entry into faults in the sewer system. The causes of I/I are not the same. Infiltration is the water entering a sewer system and service connections from the ground through defective pipes, pipe joints, damaged house lateral connections, or manhole walls. Infiltration most often is related to a high groundwater table that is observed during a wet season or in response to a severe storm. Because sewers are underground, signs of accelerated deterioration and capacity limitations are not readily apparent until there is a major failure. Sewer pipe failures start with cracking, lateral deflection, crown sag and offset joints, as well as deteriorated mortar and exposed reinforcing caused by hydrogen sulfide corrosion. Factors that can contribute to deterioration and lead to structural failure include the size of defect, soil type, trench bedding characteristics, sewer hydraulic regime, sewer sedimentation, root intrusion, groundwater level and fluctuation, internal and external corrosion, method

of construction, and loading on a sewer. When a defect is present, outside water may breach the sewer wall and soil can enter with it. Loss of soil and reduced side support eventually causes sewer collapse by a random event adjacent to the area, such as a near-by excavation, storm events, or traffic loads.

The production and release of hydrogen sulfide (H_2S) gas in sewers contributes to the destruction of sewer pipes and manholes. The process begins with the biological reduction of sulfate by the anaerobic slime layer residing on pipe and sewer sediment surfaces below the water in a sewer pipe. The anoxic bacteria utilize the oxygen in the sulfate ion as an electron acceptor in the metabolic processes. The resulting sulfide ion is transformed into H_2S gas after picking up two hydrogen ions from wastewater. Once released to the sewer atmosphere, aerobic bacteria (Thiobacillus) which reside on sewer walls and surfaces above the water line consume the H_2S gas and secrete sulfuric acid (H_2SO4). In severe instances, the pH of the pipe can reach as low as 0.5. This will cause severe damage to unprotected sewer surfaces and may eventually result in the total failure of the pipe (Fan et al., 2000; Fan et al., 2001, Fan et al., 2003).

Inflow is the water discharged into a sewer system and service connections from various sources, e.g., roof leaders, sumps, yard and area drains, foundation drains, cooling water discharges, manhole covers, cross connections from storm sewers and combined sewers, catchbasins, surface runoff, street washwater, or drainage. All of these inflows, mostly associated with building connections, are usually unauthorized. They can contribute as much as 70 to 80% of the I/I load (Field and Struzeski, 1972). Public sewers and private building sewer connections are both becoming older and are subject to I/I. However, house connection sewers may be in worse conditions because they are ignored and receive little or no maintenance and inspection. WEF (1999) performed an in-depth study using questionnaires to gather information on wastewater collection systems, private building sewer connections, and the way municipalities are addressing I/I problems. A vast majority (83%) of those sewer agencies surveyed have aggressive programs to detect illegal or unauthorized connections and, once detected, most would exercise their authority through enforceable regulations to remove them. I/I associated with private building sewer connections are either caused by the property owner's intention to prevent property from water damage, such as illegal sump pump connections, or by causes (e.g., cracked or broken lines) that are beyond the control of property owners. A small sump can pump as much as 50,000 gal/d and can have a significant, cumulative effect when considered along with the high number of sump pumps in a sewer system.

Once the infiltrated and inflow waters are combined within the sewer system, their net effect is the same: robbed sewer capacities and usurped capacities of system facilities such as pumping, treatment, and overflow regulators.

EPA Approach

Cost-effective I/I Control
For about two decades, from the early 1970s to the late 1980s, the impetus for sewer infrastructure work in a municipality was dictated by the Federal Water Pollution Control Act Amendments of 1972 which focused on publicly owned treatment works (POTW) and their discharges. It required all applicants for federal construction grants for POTW to verify that sewer systems discharging into POTW were not subject to "excessive I/I," which is the quantity of I/I that can be economically eliminated from a sewer system by rehabilitation. In other words, the Act required potential grantees to compare the cost of sewer rehabilitation (including replacement) with the cost of transportation to and treatment at a POTW. Sewer systems determined to have "excessive I/I" were eligible for rehabilitation in the construction grant while systems with "non-excessive I/I" were not. Cesareo and Field (1975) described the procedures to perform

a cost-effectiveness analysis of I/I control of a sewer system as it is related to transport and treatment.

From 1978-1989, the total outlay of construction grant funds required for the identification of sewer I/I problems was about $2 billion (EPA, 1991). These costs included costs for preliminary I/I analysis or a detailed sewer system evaluation survey. The total cost associated with replacement and/or major rehabilitation of existing sewer systems was about $1.8 billion. Major rehabilitation was defined as extensive repair of existing sewers on the verge of collapse, structurally unsound, or beyond the scope of normal maintenance programs.

In the early 1990s, as much of the Nation's collection system infrastructure continued to age and deteriorate, there was a growing concern over the health and environmental risks of SSOs. In response, EPA organized a National SSO Policy Workgroup in 1993 to institute and implement a national SSO control policy. In 1995, EPA sponsored a National Conference on SSOs which resulted in many important papers on SSO control (EPA, 1996b). In May 1999, EPA was directed to develop and issue a strong national regulation in one year to prevent SSOs from contaminating our Nation's beaches and jeopardizing the health of our Nation's families. But after an extended review of the draft Rule by various EPA regional offices and stakeholder organizations, the Rule is currently on hold. Though its official release status is unclear, its major component, namely, the Capacity, Management, Operation and Maintenance (CMOM) program, has been adopted as a good operation and maintenance tool by the SSO communities.

Proposed SSO Rule
The proposed SSO Rule will consist of the following components that are proposed to be included in all National Pollutant Discharge Elimination System (NPDES) permit requirements for POTW served by sanitary sewer collection systems:

1) Capacity, Management, Operation and Maintenance (CMOM) program for municipal sanitary sewer collection systems
2) Prohibition on municipal sanitary sewer system discharges
3) Reporting, recordkeeping, and public notification requirements for municipal sanitary sewer collection and SSOs
4) Remote treatment facilities

The parts of the proposed SSO Rule that are likely to require substantial engineering analysis efforts are contained in the CMOM program. This program requires that a NPDES permittee must:

1) Properly operate and maintain all parts of the collection system
2) Provide adequate capacity to convey base and peak flows for all parts of the collection system
3) Take all feasible steps to stop and mitigate the impact of SSOs
4) Provide public notification of overflow events

Requirement (1) of the CMOM program specifies that municipalities conduct inflow elimination or reduction, cost-effective sewer rehabilitation, and collection system inspection with associated clean out and repair. As building connection lateral sewers contribute as much as 70 to 80% of I/I, a significant amount of I/I will not be abated even after proper operation and maintenance (O&M) and rehabilitation of street sewers. This remaining I/I would be included in meeting CMOM requirements (2) and (3), which require municipalities to develop a capacity assurance plan to convey peak wet-weather flows (WWF) and a plan to mitigate SSOs. To develop a capacity assurance plan, it is necessary to know the flow conveyance capacity at various parts of the collection system under normal dry-weather and "stressed"

wet-weather conditions. To capture the system response to the dynamic nature of WWF generation and baseflow variations, a systemwide hydraulic evaluation using dynamic models (e.g., EXTRAN in SWMM4 [Roesner et al., 1988]) would be advantageous and often necessary for identifying the causes of the SSO problem to allow the development and evaluation of the most cost-effective engineering solutions (Lai et al., 2000; Lai et al., 2001).

Cooperative Research and Development Agreement
To assist SSO communities in developing SSO mitigation plans, EPA signed a cooperative research and development agreement (CRADA) in 2002 with Camp Dresser & McKee Inc (CDM) to develop a public domain computer analysis and modeling toolbox. The Toolbox is named Sanitary Sewer Overflow Analysis and Planning (SSOAP).   It contains a suite of computer software tools to facilitate the analysis of rainfall-derived infiltration/inflow (RDII) and performance of sanitary sewer systems.   It is designed to provide technical support for complying with the "C" for Capacity in the CMOM program.   In addition, a reference document and a SSOAP user's manual to guide the application of the Toolbox for performing capacity analysis of a sanitary sewer system and developing SSO control plans will be prepared as part of the CRADA.

Chapter 2 Components of Wastewater Flows for Sanitary Sewer Design

Sanitary sewers are constructed primarily to collect and transport the wastewater of a community to a treatment facility before eventual disposal to a receiving water body. Traditionally, two main criteria in the design of a sanitary sewer are to carry the peak discharge for which it is designed and to transport suspended materials to prevent deposition in the sewer (ASCE, 1982). Wastewater flows for design of sanitary sewers can be divided into two categories: (1) base wastewater flow (BWF) component associated with flows during dry-weather periods, and (2) extraneous flow component associated with flows from wet-weather events.

The BWF component primarily includes sanitary flow contribution from residential, commercial, industrial, and institutional users. BWF rates typically vary throughout the day, with the peak flow generally occurring during the morning hours. It also includes some amount of groundwater infiltration (GWI), particularly in areas where groundwater table is high.

Extraneous water enters the sewer system during wet-weather periods through cracks and open joints in sewer mains, manholes, and building laterals, as well as through direct connections between storm drains and sanitary sewer and from illegal drainage connections on private property. These extraneous flows, termed RDII, can cause significant increases in peak flows in the system. In designing sanitary sewer systems, an engineer must estimate the current and future BWF and RDII to insure that sewers have adequate conveyance capacities for the determined design horizon.

Estimation of wastewater flows involves determining the amount of each of the wastewater flow components (BWF, GWI, and RDII), as well as the time variations of flow associated with each component.

Base Wastewater Flow (BWF)

Sanitary Flow Contribution
Sanitary flows are largely a function of population, population density, water consumption, and land uses. Hence, sanitary flow estimation usually involves a study of existing and projected land uses and demographic data, and water consumption from which to estimate per capita daily water consumption. The per capita wastewater flows are usually expressed as percentages (or "return ratio") of per capita water consumptions. The "return ratios" for residential and non-residential uses may vary. These ratios can be determined from a careful analysis of a long-term (e.g., a full year) monitored sewer flow data and water consumption data taking into consideration of groundwater infiltration flows. In estimating probable future per capita wastewater contributions, changes in indoor and outdoor water use habits from the growing water conservation ethic and associated requirements should be considered.   Special consideration needs to be given to industrial contributions as the rates vary with the type, size, and operation of the industry. Furthermore, peak discharges may be the result of flows contributed over a short operation time of the industry. Flows important to the design of sanitary sewers are daily minimum and maximum, daily average, and peak flow. Peak flows estimated for the end of the design period

usually determine the desired hydraulic capacities of sanitary sewers, pumps, and some treatment plant conduits (ASCE, 1982).

Groundwater Infiltration (GWI)

GWI refers to that portion of wastewater embedded in the monitored dry-weather flow (DWF) data at a sewage pump station or a treatment facility. The rate of GWI depends on the number and size of defects within a sewer and the hydraulic head available and hence is greater in wet spring high groundwater table season than in other seasons. As sewer pipes age and deteriorate, GWI is expected to increase in amount and scope. GWI problems can be particularly severe in areas where sewer systems are installed below the groundwater table. This unwanted flow results in the need for larger sewerage and increased O&M costs for pumping and treatment. Hence, in the design of sewers, it is customary to include a rate of about 1,000 gal/acre·d, some to require as high as 2,000 gal/acre·d (ASCE, 1982).

GWI rates can vary a great deal in a sewer system and local flow monitoring data are needed for determination of GWI rates that meaningfully reflect the gross site-specific conditions. If permanent monitoring stations do not already exist, temporary monitoring stations are installed for flow data collection. The best time for flow monitoring for BWF and GWI determinations would be in early spring when groundwater table is high and outdoor water uses are low. During this time, wastewater from a residential area may be assumed to be the same as the billed water use and the GWI can be calculated as the difference between the measured DWF and the wastewater flow determined from the billed water use.

Rainfall-Derived Infiltration/Inflow (RDII)

RDII is that portion of a sewer flow hydrograph above the normal dry-weather base flow pattern. It is a sewer flow response to rainfall or snowmelt in a sewershed. The term of "I/I" probably first appeared in the 1960s. Prior to that time, the main focus was the determination of "infiltration" in DWF. "Inflow," referred to as the "stormwater" contribution, was recognized but was only casually addressed (ASCE, 1962; HES, 1968). With the influx of federal money and enforcement of federal requirements in mid-1970s, the amount of "I/I" data surged as did the interest of flow prediction of RDII from monitoring data particularly since late 1980s.

RDII has long been recognized as a major factor in the sizing of sewer pipes and treatment plants. It was found by tests that as much as 150 gal/min may leak through a manhole cover as stormwater inflow (Rawn, 1936). With manholes placed 300 to 500 ft apart, this would amount to 3.5 to 2.0 Mgal/mi·d of sewer pipe (Babbitt, 1947). It was recognized in the early 20th century that improper connections of roof drains, street inlets, and foundation and cellar drains to sanitary sewers, in combination with poor quality of house lateral construction, depleted the reserved sewer capacities that were usually built-in for the future growth of an area. These unwanted entries of stormwater to sanitary sewers were considered a "misuse" or "abuse" of the system that should be "prohibited" (Metcalf & Eddy, 1928).

The amount of this extraneous water had never been adequately reported in general terms because of the difficulty in quantifying the flows accurately. To cope with this problem in the early design of sewers, various provisions for design flow rates were adopted by various State's Board of Health. For example, the Illinois State Board used 300 to 350 gal/d for each person to be served. The Missouri State Board specified the use of per capita flows ranging from 500 to 1,000 gal/d depending upon infiltration, anticipated stormwater connections, and possible future development (Babbit, 1947). For the design of the sanitary sewer system for the Beargrass Interceptor District in Louisville, KY, the maximum sewage rates of 875, 500, and 400 gal/capita·d were used respectively for areas draining 10, 250, and 1000 acres (Metcalf & Eddy, 1928). These rates included GWI of about 2,000 gal/acre·d. Earlier, the design flows for the City's sewers were based on a per capita flow rate of about 300 gal/d.

Flow monitoring data such as from the City of Houston, TX shows that wet-weather peaking factors (peak WWF to average DWF ratio) of 30 are commonly recorded, and factors reaching 50 have been recorded in individual basins (Jenq et al., 1996). Hence, better flow prediction methods with parameters calibrated with site-specific data must be used to insure that sewers are provided with adequate conveyance capacity throughout the design life of the system. A reliable estimate of RDII is critical in developing an effective and cost-effective plan to control SSOs.

Chapter 3 Past and Current Sewer Design Practices to Provide Capacities for I/I

Historical Practices

Human beings have built sewers since 3500 BC (Babylonian time) but these sewers (in the form of open ditches) were initially built for drainage of stormwater away from populated areas (Schladweiler, 2001). As time passed, people began to realize the need of getting human wastes away from their home. Storm water drainage pipes were the most convenient means of resolving the problems. Smaller connector pipes were built from home to transport waste via these storm sewers to streams and rivers. The original storm sewers then became combined sewers. While combined sewers continued to be built until about the 1940s, people began to understand in the mid-1800s (Dr. Snow of England) that "filth", when mixed with their water supply, often resulted in disease (cholera outbreak) and death. Later, Dr. Louis Pasteur discovered that germs convey disease (Schladweiler, 2001). Since then, cities and municipalities in Europe and the United States began installing public sewer and treatment systems to address health and aesthetic concerns. A lot of "standards" for design and maintenance of sewers set in late 1800s through early 1900s are basically still in use today. The changes since then are primarily in pipe materials and installation methods, and better tools for monitoring and detection of sewer defects and for maintenance. For instance, J. W. Bazalgette, Chief Engineer of the Metropolitan Commission of Sewers (of London) in and around 1852 adopted a mean velocity of 2.2 ft/s as the sewer design velocity for preventing siltation in intercepting and outfall sewers running half full (Metcalf and Eddy, 1928). This is still considered a good design practice today. Metcalf and Eddy (1928) had a detailed historical count of earlier engineering practices.

Current Practices

The "Ten-State" Standards (1997 Edition)
The design of new sewer systems must conform with state and local regulations that provide minimum design standards, acceptable methods for estimating peak design flow, and minimum design criteria to ensure that flow is conveyed through the system with enough velocity to scour out materials that settle in pipes during periods of low flows. In 1947, 10 states (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, New York, Ohio, Pennsylvania, and Wisconsin) in the Great Lakes-Upper Mississippi River region formed a committee to review existing design standards for sewage works and published joint standards in 1951. Several revisions were made since and the 2004 edition is the latest. While the earlier editions used per capita daily contributions for estimating sewer design flows that include I/I (400 gal/capita·d for laterals, 250 gal/capita·d for trunks and outfall sewers, and 3.5 times of average DWF for interceptors), the more recent edition of the "Ten-State" standards (HES, 1997) uses less numerical and more qualitative design criteria.

The Standards state that wastewater collection systems are to be sized based on an average of 100 gal/capita·d plus that from industrial plants and major institutional and commercial facilities. The 100 gal/capita·d figure is assumed to cover "normal" infiltration but an additional allowance should be made

where conditions are unfavorable, such as when rain water from roofs, streets, and other areas, and groundwater from foundation drains cannot be fully eliminated from the system. In determining the peak wastewater flow that includes normal infiltration for design, the 100 gal/capita·d is multiplied by a peaking factor (peak hourly/design average) computed from a formula that relates to the square root of population in thousands developed by Harmon (1918) from flow data in Toledo, OH. For the new sewers serving existing development, the "Ten-State" Standards, without indicating how, caution that the likelihood of I/I contributions from existing service lines and non-wastewater connections to those service lines shall be site-specifically evaluated and quantified. Many states and municipalities in the nation, whether or not in the Great Lake-Mississippi River region, make a reference to the "Ten-State" Standards in the approval of plans for new sewer systems or modifications to existing ones.

State and Local Design Requirements

Table 3-1 presents a summary of selected state and local design standards for sizing of new sanitary sewers and rehabilitation of existing ones. The table is prepared from the Rules and Regulations of the respective states and local communities cited and from the available references (Parsons Engineering Science, 2000; Mauro, 2001)

Table 3-1 shows that states and local municipalities use two distinctly different criteria for granting construction permits of new sanitary sewers and for reviewing control plans to mitigate SSOs in existing sewer systems. For design of new collection sewers, the prevalent practice is to use the Ten States Standards or similar, which use standard engineering peaking factor to account for I/I. Massachusetts uses the criteria in TR-16 (NEIWPCC, 1998) that provides guides to develop per capita flow, reasonable amounts of I/I, and appropriate peaking factors. Oregon uses similar methods but, instead of allowing a minimum infiltration of 250-500 gal/in.dia·mi·d of sewer pipe as in Massachusetts, the infiltration amount is limited to a maximum of 2,000 gal/acre·d in order to limit the treatment capacity required. New Jersey provides an elaborate table showing average flow rates for various types of establishments and measurement units. New sewers are to be sized to carry twice the average flow rate at half full. No additional provisions of I/I are required in computing the average flow.

EPA had proposed a SSO Rule to mitigate SSO problems associated with existing sanitary sewer systems. The CMOM program in the Rule emphasizes O&M and capacity assurance of all system components, and is widely accepted by states and sanitary sewer communities. States prevailingly regulate SSO activities through their respective but generally similar SSO policies, and the policies are enforced through NPDES permits. The driving forces to eliminate or reduce SSOs are from environmental and health concerns. The target is to achieve the desired performance of no overflow in the entire existing system that includes collection sewers and treatment facilities. In other words, the focus is on the collection and treatment system as a whole rather than the individual sewer lines. Hence different performance criteria are used.

The engineering approaches practiced by states and local municipalities are similar. The "rainfall method," that uses "design" storms, is generally used to perform the hydraulic analysis of a system for developing sewer rehabilitation and SSO mitigation plans. This reflects an understanding that the prime culprit of SSO problems is the RDII associated with severe wet-weather events. However, the return frequency of the design storms required by states for system analysis varies, as does the levels of risk management. Massachusetts requires an I/I removal study if infiltration exceeds 4,000 gal/in.dia·mi·d or I/I from 1-yr, 6-hr storm exceeds sewer carrying capacities in segments of the sewer system. To abate potential bacteria pollution, Oregon prohibits SSO in winter time from a storm event equal to or less than the 5-yr, 24-hr duration storm, and in summer months, from the storms equal to or less than the 10-yr, 24-hr storms. Michigan adopts a more aggressive criterion that requires the sanitary sewer system to retain the flow generated from a 25-yr, 24-hr storm event, or 3.9 in. of rain in a 24-hr period. One common

requirement among the states is that all states require the collection of flow and rainfall monitoring data and use of a hydraulic model for sewer system evaluation and identification of rehabilitation locations.

Table 3-1. Summary of State and Local Standards for Sizing of Sanitary Sewers

State/ Municipality	Design Flows/Peaking Factors for New Sewers (construction permits)	Wet-weather Performance Criteria for Existing System w/SSO	Remarks
Illinois	Use Ten States Standards	Design storm not specified as SSO not allowed	- Use water pollution control permit processes to require compliance reporting and cost-effectiveness to enforce case-by-case compliance of no SSO - Sewer ban enforced when 2 SSOs occur in 5 years
Oregon	- Use 50-100 gal/capita·d for domestic flows, peaking factors 1.8 – 4.0, and allow a maximum of 2,000 gal/acre·d for infiltration	- Use "rainfall method" to derive baseline flow rates from STP flow data to project future design flow rates Detailed guidelines provided. - No overflow allowed from: Winter (Jan-May) – 5-yr, 24-hr event (effective 2010) Summer(Jun-Dec) – 10-yr, 24-hr event	Systems currently experiencing SSO due to I/I are usually subject to enforcement action and must prepare and submit plans to assure compliance by 2010, earlier if sensitive receiving streams are involved
North Carolina	- Generally follow Ten States Standards with the minimum peak flow at 2.5 of the average daily flow - Infiltration/exfiltration rate not to exceed 100 gal/in.dia·mi·d (200 gal/in.dia·mi·d in Ten States Standards)	Design storm not specified as SSO is not allowed	- To complete issuing first time holistic collection system permits by 2005 - Use operation/maintenance based permit to enforce individual compliance of system performance
Michigan	Use Ten States Standards	The State SSO policy requires sewer correction actions based on 25-yr, 24-hr storm or 3.9 in. of rainfall	Equivalent to less than one overflow per 10 years period
Kentucky	Use Ten States Standards	- Design storm not specified as SSO is not permitted - Trickle I/I study when	- SSO communities are required to develop a SSO plan and schedule (guidelines provided) to eliminate overflows

State/ Municipality	Design Flows/Peaking Factors for New Sewers (construction permits)	Wet-weather Performance Criteria for Existing System w/SSO	Remarks
		annual ave. daily flow > 120 gal/capita·d or 24-hr flow > 275 gal/capita·d at STP	- if failed, enforce through moratorium on sewer extension and connection and consent decree
Massachusetts	Use TR-16 "Guides for the Design of Wastewater Treatment Works"	Sewer design based on peak hourly sewage rate plus I/I based on 1-yr, 6-hr storm	Cost-effectiveness I/I removal study is required if infiltration exceeds 4,000 gal/in.dia·mi·d or inflow from 1-yr, 6-hr exceeds carrying capacity in segments of the sewer system
Minnesoda	Use Ten States Standards	- All bypasses are regulated by permit and are prohibited - Trickle I/I study when average daily flow > 120 gal/capita·d or peak flow > 275 gal/capita·d at STP	- Require to follow bypass notification procedures and take timely corrective action - Failure will result in enforcement actions including monetary penalties
New Jersey	- Use the projected design flow rates (I/I included) specified for various types of establishments and facilities in N.J.A.C.7:14A-23.3 - Sewers to be sized to carry twice the projected flow at half full	- Design storm not specified - Use 80% permitted treatment capacity as a threshold for requiring the development of I/I reduction plan	Like other states, permitting tools (sewer connection ban, penalties) are used to enforce compliance of capacity assurance and prevention of system overloading causing permit violation
Cincinnati, OH	- Use 100 gal/capita·d to compute the average sewage flow - Peaking factors decreasing from 4.0 to 3.3 for population increasing from 750 to 5,000 - Additional I/I allowance of 1000 gal/acre·d added to the peak flow	- Design capacity is based on flow monitoring and model-projected peak flow rate from a design storm - Design flow comprised of BWF, GWI, and RDII - BWF is the greater of peak diurnal flow projected or monitored - GWI is the greater of observed or projected one-year max. rate - RDII based on SCS Type II rainfall distribution assuming full build out conditions	Like many other SSO communities, the sewer rehabilitation program was developed in response to directive from Ohio State DEP to eliminate SSOs as dictated in the NPDES permit that prohibits SSOs

Chapter 4 RDII Prediction Methods

Introduction

A reliable estimate of RDII is critical in the development of a cost-effective SSO control plan. This chapter provides a summary of selected literature articles and reports that review and evaluate RDII prediction methods.   The RDII prediction method that is included in this phase of CRADA effort will be presented. It should be kept in mind that RDII is very much site-specific. No single method is likely to be universally applicable. The goal is to select and implement one RDII prediction method that is most likely to be accepted and used by practicing engineers. Other methods can be included later outside this CRADA by independent software providers.

Unit Hydrograph

A unit hydrograph is defined as the direct runoff hydrograph resulting from unit depth of excess rainfall, say, 1 in. or 1mm, produced by a storm of uniform intensity and specified duration over a watershed. It was first proposed by Sherman for flood estimation and has since found wide-ranging application for the estimation of actual floods where a hydrograph is required. Unit hydrographs are generally derived from streamflow data and estimates of rainfall excess. The unit hydrograph is applied to the hyetograph of rainfall excess to estimate the surface runoff hydrograph. A flood hydrograph is a combination of the surface runoff hydrograph and baseflow.

Literature Review

WERF Report (1999)
A Water Environment Research Foundation (WERF) publication (Bennett et al., 1999) and a conference paper (Schultz et al., 2001) provided an expanded review of RDII prediction methods in the literature going back to 1984. Their literature search included online catalogs at the University of Wisconsin at Milwaukee and Madison. Additional references were identified through contacts with engineering firms and municipal agencies. A total of 42 documents was compiled and reviewed.

Eight broad categories of RDII quantification methods were identified and three cooperating municipal agencies were involved in testing these methods against the monitored rainfall-flow data. The three agencies are the Metropolitan Council Environmental Services, St. Paul, MN; Bureau of Environmental Services, Portland, OR; and the Montgomery Water Works and Sanitary Sewer Board, Montgomery, AL. The eight categories are:

1) The constant unit rate method
2) The percentage of rainfall volume (R-value) method
3) The percentage of stream flow method
4) The synthetic unit hydrograph (SUH) method

5) The probabilistic method
6) The rainfall/sewer flow regression method
7) The synthetic stream flow regression method
8) Methods embedded in hydraulic software

The **constant unit rate method** calculates RDII as a fixed constant (e.g., gal/acre·in.rainfall) multiplied by measurements of tributary sewershed characteristics (e.g., area, land use, population, pipe diameter, pipe length, and pipe age). The **percentage of rainfall volume (R-value) method** calculates RDII volume as a fixed percentage of the rainfall amount. The **percentage of streamflow method** is similar to the previous rainfall method, but it uses streamflows in nearby watersheds as an independent variable. This method recognizes that streamflows inherently account for the effects of antecedent moisture conditions that consequently influence the groundwater levels. A relationship can be developed between sewer flow and streamflow data.

The **SUH method** assumes that RDII in a sewer responding to rainfall is similar to stormwater runoff in a watershed and calculates RDII hydrograph from a specified "unit" hydrograph shape that relates RDII to unit precipitation volume and specified time duration, and sewershed characteristics. The simplest synthetic unit hydrograph has a triangular shape and many formulations like that in EPA's Storm Water Management Model (SWMM) (Huber and Dickenson.1988; EPA 2006) use multiple unit hydrographs to account for fast, medium and slow RDII responses. **Probabilistic method** calculates RDII of a given recurrence interval from long-term sewer flow records using probability theory. The method establishes the relationship of peak RDII flow to recurrence interval. **Rainfall/sewer flow regression method** calculates peak RDII flows from rainfall data through a relationship between rainfall and RDII flows. 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.

In the **synthetic streamflow regression method**, RDII is calculated from synthetic streamflow records and sewershed characters using regression equations derived from multiple regression techniques to correlate hydrologic responses to sewer flow responses. The synthetic streamflow records can be generated by calibrated hydrologic simulation models. Finally, **methods embedded in publicly or commercially available hydraulic software** uses one or more of the previous seven prediction methods discussed above. The most notable one is probably the EPA's SWMM that programs the synthetic unit hydrograph method into the codes.

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 due to a variety of site conditions and analysis application needs. The study identified criteria (listed below) to test the alternative RDII prediction methods using flow and rainfall data supplied by the three previously identified cooperating sewer agencies. Specifically, the methods should be able to:

1) Predict peak flows for individual storms
2) Predict volume for individual storms
3) Predict the hydrograph timing, shape, recession limb
4) Predict peak flows for multiple storms
5) Predict volume for multiple storms
6) Operate on commonly available data

The 1999 WERF study also concluded that the SUH and rainfall/sewer flow regression methods were the

most accurate at predicting peak flows and event volumes both for single storm event and multiple storm events. While the probabilistic method can be accurate for predicting peak daily RDII flows, it will require long-term data.

The constant unit rate method is simple to apply and can provide a good prediction of the event volume of a single storm. But it is difficult to develop reasonable estimates of unit rate constants, which may vary temporally, for all storm events. Percent of streamflow methods are only good for rare cases where stream gauge data are available in watersheds with similar basin characteristics as the sewersheds being analyzed. Besides, a sewershed is usually smaller than a watershed. The synthetic streamflow regression method was successfully applied in Milwaukee for sewerage system improvement planning. The prerequisite for applying this method is the availability of a calibrated watershed runoff model which, more often than not, does not exist for the case at hand.

The WERF study emphasized that, in an actual application, the objective, intent, and purpose of the studies as well as the availability of data, time, and staff should be considered in selecting the most appropriate flow estimation method.

Review by Crawford, et al. (1999)

Crawford et al. (1999) focused their review on three RDII prediction methods: constant unit rate, rainfall/flow regression, and percent of rainfall volume (R-value). The merits and limitations of these methods were evaluated from applications to two collections of the City of Salem, Oregon (with a population of about 160,000) and the City and County of Honolulu, Hawaii serving a population of about 1,000,000. They concluded from the data that peak hourly RDII rates per acre from a 5-yr storm increase significantly as the average age of sewer pipes increases from 10 to 30 yrs. Hence, use of a single rate for new sewer areas is easily proved not to be realistic. To overcome this limitation, they suggest that unit RDII rates should appropriately increase with the age of the sewer system.

The regression method provided a means of determining the shape and magnitude of a RDII hydrograph. Crawford et al. (1999) were able to use the regression equations derived from data under winter conditions to get a good match between the monitored and simulated hydrographs from other winter storms. However, when they applied the regression equations to summer and early fall storms, large discrepancies between observed and simulated flows were noted. To overcome this limitation, they suggest that a separate series of regressions should be developed to represent the seasonal nature of the rainfall-I/I processes. Hence, adequate and representative rainfall and flow data are pre-requisite for a successful application of regression method.

In applying the "R-Value" method to estimating RDII rates for greater intensity and less frequent storms than that used to derive the "R" value, Crawford et al. (1999) cautioned that the "R" values should be appropriately tapered to account for the upper limit of peak flows that the leaky sewers can take in. This is to recognize that there is a limit to the ability of the flow connections, leaky manholes, and damaged laterals to take in water.

Review by Wright et al. (2001)

Wright et al. (2001) reviewed literature of RDII estimation techniques that appeared since 1993. The methods are grossly classified into three groups: volume-based "Rational" method (or R-value method), unit hydrograph method, and physical processes modeling method. The volume-based method does not provide temporal information that is needed for sewer conveyance capacity assessment. Like the volume-based method, the unit hydrograph methods are empirical methods based on observations of rainfall and flow. The paper discusses various unit hydrograph methods, including: the SUH where the shape of the

hydrograph is pre-defined; the data-derived unit hydrograph using multiple regressions to directly derive the ordinates of a unit hydrograph from measured rainfall and RDII flow data; and, the conceptually-derived unit hydrograph using a system of cascading linear reservoirs.

The so-called "RTK method", included as an option in SWMM Runoff Block (Huber and Dickenson, 1988), is probably the most popular SUH method. This method uses three triangular hydrographs to estimate the wide range of response times associated with the effect of fast inflow and slower GWI. The R parameter is the fraction of rainfall volume entering the sewer system as RDII, T is the time to peak, and K is the ratio of time of recession to T. Since the three unit hydrographs distinctively represent the quantitative contribution of inflow and infiltration to the overall RDII hydrograph, the paper stated that 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.

Data-derived unit hydrograph (UH) derives the ordinates of a unit hydrograph directly from measured rainfall and RDII flow data using multiple linear regression or linear programming techniques and is not based on calibration methods like the "RTK method." Instead of beginning with an assumed shape characteristic as the "RTK method," the data-derived UH is a linear transform function completely derived from measured data. The goal is to find a vector of unit hydrograph ordinates that minimize the difference between the time series of measured flow and the estimated flows. The paper summarized two approaches in determining RDII responses. One approach is a regression on the time series of measured rainfall and flow and is often labeled in the literature as "the Regression Method." The other approach estimates unit hydrograph ordinates using optimization techniques such as unconstrained or constrained least squares regression or a liner programming technique. Wright et al. (2001) proved that the "the Regression Method" is exactly equivalent to the traditional unit hydrograph analysis.

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 provided an important conceptual link between purely empirical methods and more physically based conceptual models, like SWMM which uses the non-linear reservoir approach and the continuity and momentum principles. As with the data-derived UH method, the reservoir parameters are found using some optimization techniques such as linear least squares regression or linear programming (LP) technique. The reservoir parameters may be constrained to derive physically realistic values when LP is used. But physically unrealistic values (i.e., negative UH ordinates) may be derived when an unconstrained ordinary regression method is used.

The physically based model advocated by Wright et al. (2001) is the SWMM Runoff Block with modifications by Kadota and Djebbar (1998). The primary modification included the use of water elevation in a sewer pipe instead of pipe invert elevation to better represent the driving head of groundwater for computing the rate of infiltration entering. They also promoted the use of effective RDII contributing area as a parameter to quantify RDII reductions for pipeline and manhole rehabilitation. RDII rates and volumes are conceptualized as coming from an effective area. With these modifications, SWMM, a physically based model, will have physical parameters that can be used to reflect the reduction of RDII associated with the extent of sewer rehabilitation work completed.

Recommended RDII Prediction Method for SSOAP

From the above literature review, it can be concluded that no single RDII prediction method is universally applicable due to a wide variety of site-specific database of rain and flow observations during both wet and dry periods. All methods require monitored data to evaluate and validate their predictive capabilities but the amount of data required varies. If flow data are not available, but sewershed data (e.g., area, land

use, population, and sewer pipe length) are, the constant unit rate method (e.g., gal/acre) may apply for estimating peak I/I rates for sewer design. On the other hand, the probabilistic method will require long-term flow data to perform meaningful frequency analysis for deriving the relationship of peak RDII flow rates or event volumes to recurrence interval. For other methods, flow data of a few months duration are usually sufficient. But when daily flow data are used, several years of data are needed to obtain a good RDII prediction (Bennett et al., 1999).

A flow monitoring program in a sanitary sewer system can never monitor flow under future sewershed and sewer conditions. Sewer routing models are needed to expand the limited monitored data to existing and future build-out conditions where no data are available. 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 in all parts of a sewer system 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 SUH and rainfall/flow regression methods were preferred for predicting flows for single as well as multiple storm events. Good multiple-storm peak and volume prediction is important in extrapolating data beyond the calibration events for a prolonged period simulation to evaluate the effect of RDII on storage and treatment.

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) for the development of sewer system/treatment improvement plans. The rainfall/flow regression methods will be attractive if there are at least two 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 only relate the RDII rate to the preceding rainfall amounts corresponding to various time periods (e.g., 1 hr, 2-3 hrs, 4-6 hrs, 7-12 hrs, 12-24 hrs, 1-2 d, 4-7 d, and 7-15 d) 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 the individual contributing flow components and identify if the RDII problems are caused by inflow, infiltration or both. A quantitative knowledge of flow contributing sources would help identify SSO control options.

On the other hand, the RTK method, one kind of the SUH method, uses 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 primarily inflow driven. If more of the total R-value is allocated to R_2 and R_3, this indicates that the RDII is primarily infiltration driven. This knowledge is useful during a sewer system evaluation survey (SSES) to determine the best SSES approach to use in an area and whether a point repair or a comprehensive rehabilitation approach is 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 be applied to 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 has been widely used and proven to be a valuable method in separate sanitary sewer system analysis associated with storm events.

The RTK method was developed by CDM staff members (Giguere and Riek, 1983; CDM et al., 1985; Miles, et al., 1996; Vallabhaneni, et al., 2002). It has been used on sewer system master planning projects throughout the country by CDM engineers and client staff members since the mid-1980s. This CRADA

is intended for CDM to share their rich and long experience in applying the RTK method for SSO analysis and control planning. Hence, the SSOAP Toolbox will initially incorporate the RTK method only. Other RDII prediction methods may be included in future effort to expand SSOAP by EPA or private sectors.

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