A Toolbox for Sanitary Sewer Overflow Analysis and Planning (SSOAP) and Applications

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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 these systems. RDII is the main cause of sanitary sewer overflows (SSOs) to basements, streets, or nearby streams and the resulting high flows can also cause serious operating problems at wastewater treatment facilities. To assist municipalities in developing plans to mitigate SSO problems, the U.S. Environmental Protection Agency signed a cooperative research and development agreement (CRADA) with Camp Dresser & McKee, Inc. to develop a public-domain Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox. In addition, the CRADA will prepare a technical document and a SSOAP user's manual to guide the application of the SSOAP Toolbox for performing capacity analysis of a sanitary sewer system and developing SSO control plans. The Toolbox will be ready soon for beta testing by the public. The SSOAP and the RDII methodology in performing capacity analyses of sanitary sewer systems and developing SSO control plans will be described in this paper.

KEYWORDS

Sanitary sewers, infiltration/inflow, flow monitoring, unit hydrograph, SWMM model.

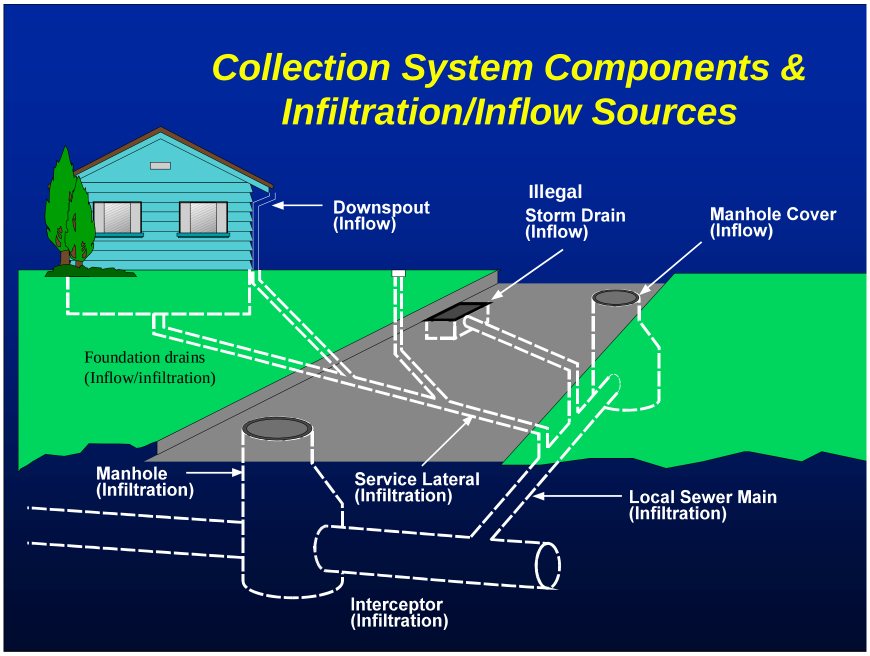
INTRODUCTION

Municipal sanitary sewer collection systems play a critical role in protecting public health in our municipalities. They are designed to convey wastewater from their sources to a wastewater treatment plant (WWTP). Collection systems consist of house service laterals, 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) identified more than 19,500 municipal sanitary sewer collection systems nationwide serving an estimated 150 million people and comprising about 800,000 km (500,000 mi) of municipally owned pipes in publicly owned systems and probably another 800,000 km (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.

Sanitary sewers are designed to collect and transport the wastewater of a community to a treatment facility before eventual disposal to a receiving water body. Much of the nation's sanitary sewer infrastructure has been installed over a long time period, with some sewers being over 100 years old. 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, and lack of maintenance, the system's ability to transport wastewater to treatment facilities is impaired. Sewer stoppages and collapses are increasing at a rate of approximately 3% per year. Roots that penetrate 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 jointing 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).

Infiltration/inflow (I/I) problems have long been the primary focus related to sewer lines (Lai and Field, 2001). Besides structural failures, the problems caused by aging and deteriorating collection systems include excessive I/I that rob capacity and negatively affect 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, higher operating costs, and higher user fees. Figure 1 shows the collection system components and various pathways of I/I into sanitary sewer systems.

Figure 1 - Pathways of Infiltration and Inflow into Sanitary Sewer Systems



Available data indicates that essentially all collection systems experience periodic sanitary sewer overflows (SSOs) and between one-third and two-thirds of the nation's sanitary sewer systems have problems with SSOs or excessive peak flows at the WWTP. SSOs are untreated sewage overflows from sanitary sewer collection systems to streets, private property, basements, and receiving waters. It is estimated that there are about 40,000 SSO events per year nationwide. The national cost estimate to mitigate SSOs for the next 20-yr period was estimated to be $108 billion (1994 dollars) to attain zero overflows per year (EPA, 1996) and about $78 billion and $63 billion, respectively, to attain one and two overflows per year (EPA, 1998).

THE PROPOSED SSO RULE

Because of concerns of potential health and environmental risks associated with poor performance of many of these systems, the U.S. Environmental Protection Agency (EPA) has proposed a SSO Rule to add control and mitigation of SSOs to the existing National Pollutant Discharge Elimination System (NPDES) permit requirements. The proposed Rule includes a Capacity, Management, Operation, and Maintenance (CMOM) program for collection and treatment systems. Though not yet formally adopted, CMOM is being widely accepted as good practice by many municipalities.

The proposed SSO Rule requires the following components in the NPDES permit requirements for publicly owned treatment works (POTW) served by sanitary sewer collection systems:

1) 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 requires substantial engineering analysis 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) by which municipalities must 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 system-wide hydraulic evaluation using dynamic models (e.g., EXTRAN in SWMM4 [Roesner *et al*., 1988] or its equivalent in SWMM5) 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 and McKee (CDM) to develop a public domain computer analysis and modeling toolbox. The Toolbox is named **SSO A**nalysis and **P**lanning (**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 technical 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..

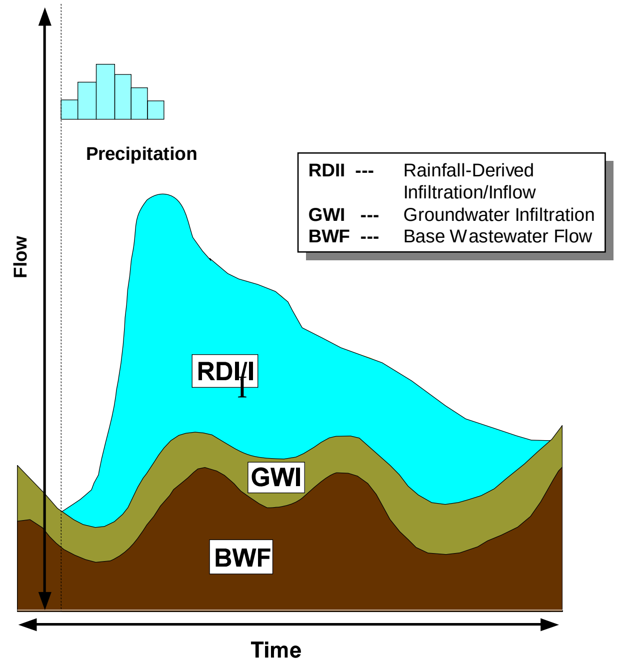
COMPONENTS OF WASTERWATER FLOWS FOR SANITARY SEWER ANALYSIS AND DESIGN

Wastewater flows for analysis and design of sanitary sewers can be divided into three categories: (1) base wastewater flow (BWF) associated with the sanitary flow contribution; (2) groundwater infiltration (GWI) associated with flows infiltrated during during dry weather periods; and, (3) extraneous flow associated with flows from wet weather events. The BWF component primarily includes the 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. GWI can be significant, particularly in areas where the groundwater level is high. GWI and BWF together comprise the dry weather flow (DWF) that occurs in the sanitary sewer system.

Extraneous flows are waters that enter the sewer system during wet weather periods through cracks, openings, and open joints in sewer mains, manholes, and building laterals, as well as through direct connections between storm drains and sanitary sewers and from illegal drainage connections on private property. These extraneous flows, usually termed RDII, can cause significant increases in peak flows in the system.

Figure 2 shows the three components (BWF, GWI, and RDII) of wastewater flow as would be monitored at a sewer during wet weather. Estimation of wastewater flows involves determining the amount of each of the wastewater flow components, as well as the time variations of flow associated with each component.

Figure 2 - Three Components of Wet weather Wastewater Flow



BWF

BWF is the residential, commercial, and industrial flow discharged to the sanitary sewer system for collection and treatment. Residential flows are 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 long-term (year) monitored sewer flow data and water consumption data taking into consideration the flow contribution of groundwater infiltration. In estimating probable future per capita wastewater contributions, changes in indoor and outdoor water use habits from growing water conservation 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. In design of sewers, peak flows estimated for the end of the design period usually determine the hydraulic capacities of sanitary sewers, pumps, and treatment plants (ASCE, 1982).

GWI

GWI refers to that portion of wastewater embedded in the monitored DWF data within a collection system or at 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 a wet spring when a high groundwater table would prevail. As sewer pipes age and deteriorate, GWI is expected to increase in intensity and points of entry. GWI problems can be particularly severe in areas where sewer systems are installed below groundwater. This unwanted flow results in the need for larger sewerage and increased O&M costs for pumping and treatment.

GWI rates can vary a great deal in a sewer system. Local monitoring flow 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 stations need to be installed for flow data collection. The best time for flow monitoring for BWF and GWI determinations would be in early spring when the groundwater table is high and outdoor water uses are low. During this time, residential wastewater 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.

RDII

RDII is that portion of a sewer flow hydrograph above the normal DWF flow pattern. It is a sewer flow response to rainfall or snowmelt in a sewershed. The term "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. In the early 20th century, the U.S. recognized that improper connections of roof drains, street inlets, and foundation and cellar drains to sanitary sewers, in combination with the 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 RDII 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 Board of Health departments. For example, the Illinois State Board used 1.1 to 1.3 m^3/d (300 to 350 gal/d) for each person to be served. The Missouri State Board specified the use of per capita flows ranging from 1.9 to 3.8 m^3/d (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 3310, 1890, and 1510 L/capita/d (875, 500, and 400 gal/capita/d) were used respectively for areas draining 4, 100, and 400 ha (10, 250, and 1000 acres) (Metcalf & Eddy, 1928). These rates included a GWI of about 18,700 L/ha/d (2,000 gal/acre/d). Earlier, the design flows for the City's sewers were based on a per capita flow rate of about 1.1 m^3/d (300 gal/d).
Flow monitoring data such as from the City of Houston, TX showed that a wet weather peaking factor (peak WWF to average DWF ratio) of 30 were commonly recorded, and factors reaching 50 had 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.

RDII PREDICTION METHODS

A Water Environment Research Foundation (WERF) study (Bennett *et al.*, 1999) evaluated eight broad categories of RDII prediction methods. The eight described methodologies were:

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

The **constant unit rate method** calculates RDII volume as a fixed constant (e.g., gal/in. rainfall/acre) multiplied by measurements of tributary sewershed characteristics (e.g., area, land use, population, and pipe diameter/length/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 anticipates that streamflows inherently account for the effects of antecedent moisture conditions and consequently influence the groundwater levels. It relies on the development of a relationship between sewer flow and streamflow data.

The **synthetic unit hydrograph method** assumes that RDII in a sewer responding to rainfall is similar to stormwater runoff in a watershed. It calculates the RDII hydrograph from a specified "unit" hydrograph shape that relates RDII to unit precipitation volume and specified duration, and sewershed characteristics. The simplest synthetic unit hydrograph has a triangular shape and many formulations such as 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. The **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. The **rainfall/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 characteristics 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 which programs the synthetic unit hydrograph method into the codes.

The 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 cooperating sewer agencies. The three agencies are the Metropolitan Council Environmental Services (MCES), St. Paul, MN; Bureau of Environmental Services (BES), Portland, OR; and the Montgomery Water Works and Sanitary Sewer Board (MWWSSB), Montgomery, AL. 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

Because the characteristics of the available data varied among the cooperating sewer agencies, the collected data were not applicable to all eight RDII prediction methods considered in the WERF study. The report concluded that the synthetic unit hydrograph (SUH) and rainfall/flow regression were the two most accurate methods for predicting peak flows and event volumes for single as well as multiple storm events. The ability of a good multiple storm peak and volume prediction is important in extrapolating data beyond the calibration events for a prolonged period simulation that is needed for evaluating the effect of RDII on storage and treatment of wastewater flows.

The RTK method, as used in SWMM Version 4 (Huber and Dickenson 1988) and Version 5 (SWMM5) (EPA 2006), is probably the most popular SUH method. This 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.

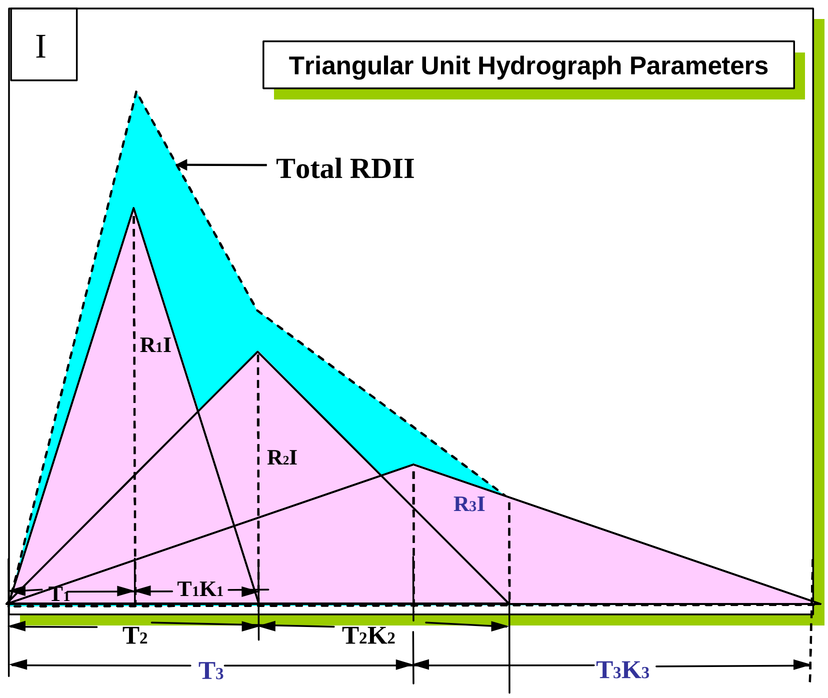
The RTK method was developed by CDM staff members (Giguere and Riek, 1983; CDM *et al*., 1985; Miles *et al*., 1996; Vallabhaneni *et al*., 2002). It has been used on sewer system master planning projects throughout the country by CDM engineers and client staff members since the mid-1980s. The CRADA with CDM is partially intended for CDM to share their 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 the future effort to expand the SSOAP Toolbox by EPA or the private sector.

The RTK Method

This RTK method is based on fitting up to three triangular unit hydrographs to an observed RDII hydrograph derived from site-specific flow monitoring data. A unit hydrograph is defined as the flow response that results from one inch of rainfall for a specified time period. Three unit hydrographs are used because the shape of a RDII hydrograph derived from flow data is usually too complex to be adequately represented by a single triangular hydrograph.

As shown in Figure 3, the shape of each of the three unit hydrographs is defined by three parameters: R, T, and K. 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 sum of the R values for each of the three unit hydrographs (R_1, R_2, R_3) equals the total R value for the storm event which represents the total fraction of rainfall over the sewershed that entered the sewer system.

Figure 3 – The RTK Method Parameters

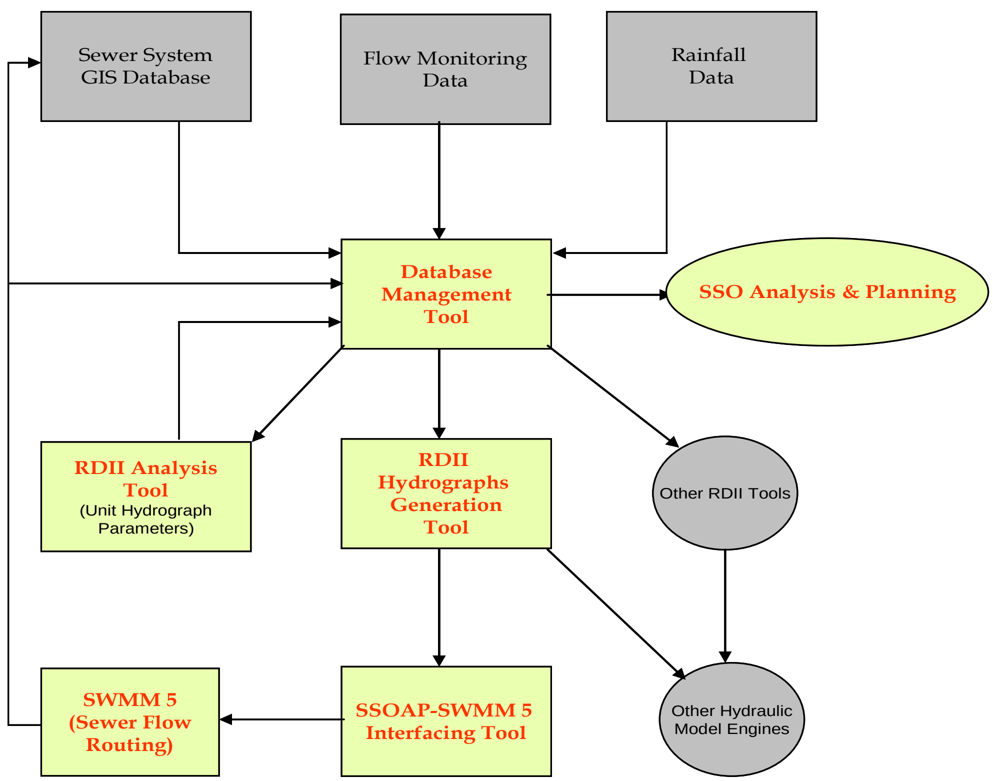


The first triangular unit hydrograph (R_1) represents the most rapidly responding flow component. It generally has a T of 0.5 to 2.0 and a K value of 1.0 to 2.0. The second triangular unit hydrograph (R_2) can be thought of as including both rainfall-derived inflow and infiltration. It has a longer T value of 3 to 5 and a K value of 2.0 to 3.0. The third triangular unit hydrograph (R_3) includes infiltration that may continue long after the storm event has ended. It has the longest T value in the range of 10 to 15 and a K value of 3.0 to 7.0. The sum of R_1, R_2, and R_3 must equal the total R value of the sewershed in response to one unit of rainfall shown in Figure 3 as "I". After the R, T, and K values for three unit triangular hydrographs are determined for a sewershed, the total RDII hydrograph of the sewershed for other storms can then be derived by summing all three RDII hydrographs considering the appropriate ordinates and time lags. The challenge is to find the combination of R, T, and K values for each of three triangles that results in a hydrograph that best match the peak and shape of RDII hydrographs from the flow monitoring data.

OVERVIEW OF THE SSOAP TOOLBOX

Figure 4 shows the overall structure of the SSOAP Toolbox. The SSOAP Toolbox integrates an existing database of a sanitary sewer system and contains five functional tools for: Database Management, RDII Analysis, RDII Hydrograph Generation, SSOAP-SWMM5 Interface, and Sewer Flow Routing (SWMM5). These tools are shown in green in the figure, which describes

Figure 4 – System Flow Chart of SSOAP



flow of data through the analysis and planning process using the SSOAP Toolbox. The individual components of SSOAP tools are described below.

Database Management Tool

The Database Management Tool (DMT) serves as the command center of the toolbox. It stores and organizes data using a standard Microsoft Access® database called SSOAP System

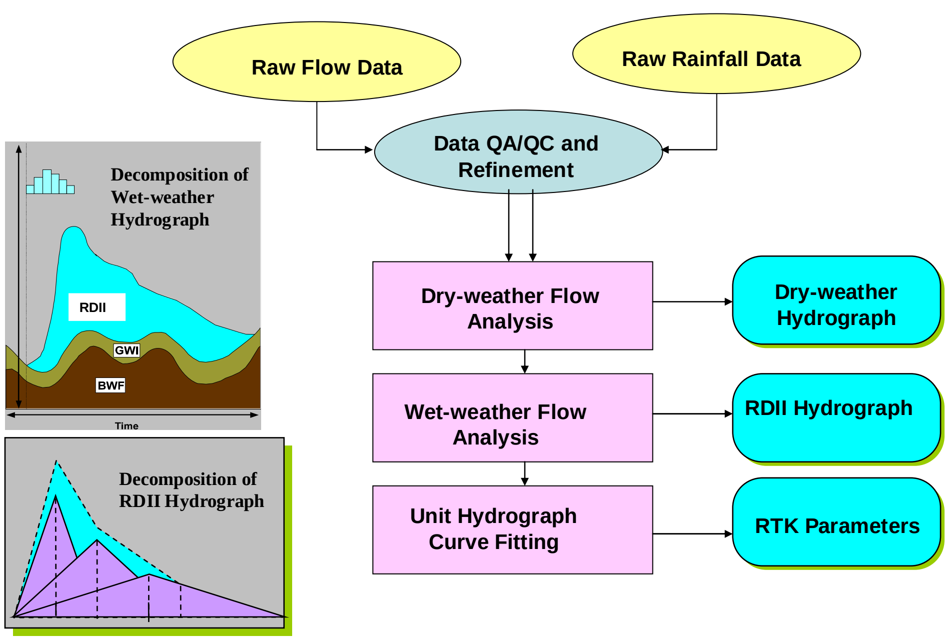
Database (SSD). The DMT organizes data in the SSD, provides interface with several external data sources, and manages the import of data from external databases into the SSD and export of data from it. The external data sources may include sewer system GIS databases, data from flow monitoring programs, data from rainfall monitoring programs or radar rainfall analyses, and hydraulic modeling analysis results. The other primary functions of the DMT are to provide an interface with other tools in the Toolbox and manage data produced by them.

To facilitate the data management function, the DMT has included three additional utilities: (1) a software to perform rainfall and flow data quality control; (2) a rainfall data analysis utility to identify wet weather events of interest and perform rainfall analysis to determine rainfall volume, peak rainfall intensity, and antecedent moisture conditions; and (3) a scenario management utility to support sanitary sewer system capacity analysis and planning. The integration of these additional utilities in the Toolbox improves the efficiency and results of comprehensive data reviews.

RDII Analysis Tool

The RDII Analysis Tool allows users to perform the wastewater hydrograph decomposition and determine up to three sets of RDII parameters (R, T, K) in the RTK method, as previously described. Figure 5 presents the overall approaches used. Decomposition of the flow data into each of the major wastewater components is essential for identifying the sources of flow in the system and for developing an understanding of the system RDII characteristics.

Figure 5 – Flow Chart of the Analyses Performed by the RDII Analysis Tool



The RDII Analysis Tool performs four major analyses:

Dry weather flow analysis – to evaluate the complete record of flow and rainfall monitoring data; isolate the typical dry and wet weather periods, with definition of characteristic sanitary flow components; assess seasonal dry weather infiltration rates; and develop average dry weather flow patterns for weekdays and weekends. The end result of this DWF analysis is the characterization of representative weekday and weekend DWF hydrographs at each metered station which will be used to perform wet weather flow analysis. As previously stated, DWF is the sum of BWF and GWI.

The DWF analysis also includes a determination of individual BWF and GWI components for assessing the impact of GWI on system conveyance and treatment capacities. This is accomplished by identifying the minimum nightly monitored flow for a day, usually occurring during the early morning hours. In residential areas, the experience indicates that about 10% of this nightly minimum flow is attributable to wastewater, with the remaining flow to GWI. This tool allows users to vary the percent of wastewater in nightly minimum flow. The BWF hydrograph is derived by subtracting each day's GWI from the DWF hydrograph for that day.

Wet weather flow analysis – to determine the RDII hydrograph for a storm event by subtracting the DWF hydrograph and GWI adjustment flow from the total monitored hydrograph (BWF plus GWI plus RDII). The GWI rates prior to a rainfall event usually need adjustment to account for seasonal variations. These seasonal adjustments are based on the assumption that the difference between monitored flows and the computed DWF hydrograph should be approximately zero before and after a storm event being evaluated. The tool helps users to perform analyses to determine, for each RDII event:

1) Rainfall (i.e., volume, duration, peak, start time, end time)
2) Flow data (i.e., peak flow, peak RDII flow, RDII volume)
3) Percentage of rainfall entering sewer system as RDII (i.e., total R)

The RDII Analysis Tool determines the starting and ending times of a RDII event by analyzing the RDII flow hydrograph and corresponding rainfall records that meet the user-defined conditions of an RDII event. These conditions may include peak RDII rates, durations, and rainfall volume. For instance, the user can define threshold limits for an RDII event based on a minimum rainfall depth or a minimum peak RDII flow rate. Then the users review the RDII events selected by the tool and perform decomposition and curve fitting. The RDII peak flows and volumes will help users understand the general magnitude of RDII response in the system. The R values data will help prioritize the sewersheds within a service area in managing and reducing RDII.

Unit hydrograph curve fitting analysis – to determine R, T, K values through a systematic analysis of measured flow and rainfall for each metering location. The goal of the unit hydrograph curve fitting process is to adjust the R, T, K parameters for each event analyzed so that, when these values are applied to the monitored precipitation data, the simulated RDII reasonably matches the monitored flow. Users can develop up to three unit hydrographs to decompose the total RDII hydrograph to reflect fast, medium, and slow RDII responses in a sanitary sewer system. The RDII Analysis Tool provides a graphic environment for users to perform visual curve fitting by a trial and error method. A successful determination of R, T, K values is obtained when the computed RDII hydrograph is visually correct with the RDII hydrograph derived from the monitored data. During the process, the R, T, K values are expected to vary from event to event, generally being higher for wet antecedent moisture conditions and lower for dry conditions.

***Statistical analysis of RDII parameters* –** to allow users to perform predictive analysis of R, T, K unit hydrograph parameters to extrapolate from measured conditions to non-measured or design conditions. This tool will have the ability to perform a statistical analysis of the R, T, K parameters stored in the SSD to develop correlations between the observed precipitation conditions and the system RDII response, specifically the R value. The statistical model relates the R value to the selected parameters, i.e., rainfall volume, antecedent 1-month rainfall volume, and GWI. The later two parameters represent the antecedent moisture conditions. Three statistical methods (median R value method, average R value method, and linear regression method) are incorporated in SSOAP to assist the users. Other methods, e.g., multi-variable regression methods outside of SSOAP, may also be used.

RDII Hydrograph Generation Tool

This tool generates the RDII hydrograph of a sewershed for the selected rainfall events using its physical characteristics (e.g., sewer areas and land uses) data stored in the SSD and the R, T, K values determined by the RDII Analysis Tool. Within this tool, the users can view the RDII hydrograph generated before exporting the data as input to a sewer routing model. This tool will have the ability to export RDII hydrographs to other hydraulic routing engines in addition to SWMM5.

SSOAP-SWMM5 Interface Tool

The SSOAP-SWMM5 Interface Tool is designed to assist users in organizing and incorporating the hydrographs generated by the RDII Hydrograph Generation Tool into the SWMM 5 input files. It will initiate a SWMM5 simulation. After the SWMM5 run, the tool will deliver the SWMM5 simulation results to the DMT, where the model results will be organized in the SSD for additional post-processing.

SWMM5

While other sewer routing models may be linked to the DMT and used, 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 to visualize the sewer system responses and selectively exports the output data for further analysis.

EXAMPLE APPLICATIONS OF APPROACHES USED IN SSOAP

The development of the SSOAP Toolbox is near completion and will soon be under testing before it is released for public beta testing in the fall of 2007. Hence, there has been no real application yet of the SSOAP Toolbox at this time. However, the integration approaches and uses of the RTK method for the quantification and prediction of RDII flows have been successfully applied in the real world. A brief summary for each of the three available publications is given below to show the successful application of the general approaches used in developing the SSOAP Toolbox to perform SSO analysis and planning.

Mark Loehlein *et al*.(2005) described the effort to control SSO problems for the Allegheny County Sanitary Authority (ALCOSAN) and its member municipalities surrounding Pittsburgh, PA. This case study highlights the application of the RTK methodology to quantify and predict RDII in sanitary sewer systems and the use of monthly varied RTK values for the continuous hydraulic model simulations using SWMM. This case study demonstrated how the approaches similarly used in the SSOAP Toolbox were successfully applied, including flow/rain data review, DWF evaluation, WWF evaluation, RTK parameters analysis, sewer flow routing, and analysis of modeling results.

Vallabhaneni *et al*.(2002) provided a case study on the evaluation of SSO related problems for the Metropolitan Sewer District of Greater Cincinnati, Ohio. This case study also used the RTK method for RDII quantification and SWMM modeling to evaluate alternatives for mitigating SSOs and water-in-basement problems in a pilot sewershed area. The Cincinnati case study highlighted the success of quantifying RDII response for a range of monitored precipitation conditions and the use of statistical approaches to predict RDII response for unmonitored conditions.

Similarly, Lai *et al.* (2001) described a case study application of similar approaches as in SSOAP for the SSO control planning study for the County of Henrico County, VA. The study used various tools for performing data management, wastewater decomposition, estimating GWI rates from monitored data, determining R, T, K values, generation of RDII hydrographs, interface with SWMM4, sewer flow routing using SWMM4, and post-processing of modeling outputs for identification of system deficiencies and options for system improvement. The integration of these tools at that time was specifically customized for the project at hand and was not designed for general application as is intended in the current SSOAP Toolbox.

TECHNICAL PANEL REVIEW OF SSOAP

A technical panel comprised of five experts in SSO-related engineering and modeling issues was convened in October, 2006 to review the tools contained in the SSOAP Toolbox. These experts were from the engineering profession and academia. They strongly agreed on the usefulness of the Toolbox to engineers in mid-size regional consulting firms and large national firms, as well as academicians. The tool would help sewer agencies evaluate and develop effective solutions to wet weather performance problems in collection systems. Besides the computerized RTK parameter determination and RDII hydrograph development and SWMM5 interface, the panel agreed that the RDII Analysis Tool can be a great data analysis tool. It allows engineers to gain insights into sewer system behaviors, particularly the source and relative magnitude of inflow and infiltration, through the analysis of monitored data prior to complex modeling efforts.

The panel members also agreed that there is no other tool currently available that can perform the functions of the SSOAP Toolbox. The tools in the Toolbox would simplify the analyses for the novices and expedite the analyses for the experienced users. However, they strongly recommended inserting a disclaimer in the Toolbox that it is intended for users with appropriate education and training in hydrologic and hydraulic principles and background on sanitary sewer systems. There were concerns that the Toolbox might be inappropriately used by unqualified users, especially considering the likelihood that user-friendly interface could make one believe that the Toolbox would be easy to use. The panel members were satisfied that the Toolbox has the ability to export the RDII hydrographs into a spreadsheet program, which can then be integrated into hydraulic models other than SWMM5.

The Toolbox will be released to the public free of charge and open-coded.

DISCLAIMER

Any opinions expressed in this paper are those of the author(s) and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

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