FACT SHEET

Water Environment Federation
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Sanitary Sewer Systems: Rainfall Derived Infiltration and Inflow (RDII) Modeling

RDII simulation models are commonly used as one of the key tools in characterizing system wet weather response, evaluating needs, and predicting performance within I/I reduction and remediation programs. This fact sheet serves as a resource and reference guide for utility managers, practitioners and educators.

What is RDII?

Rainfall derived infiltration and inflow (RDII) of extraneous stormwater and groundwater to sanitary sewers can unduly affect the capacity and operation of collection and treatment systems. In many cases, excessive RDII can be a significant cause of sanitary sewer overflows (SSOs) and basement backups. Many utilities are investing significant resources on reducing RDII through sewer rehabilitation/replacement and private property efforts to eliminate sources of RDII. Utilities also are constructing additional infrastructure assets to assure adequate system capacity.

Application of sound and defensible RDII estimation methods is critical for RDII simulation modeling. These models need to support infiltration and inflow (I/I) reduction and remediation programs that will effectively mitigate SSOs.

This fact sheet summarizes the basics of using RDII simulation models and estimation tools in establishing I/I reduction and remediation programs. This fact sheet will provide utility managers, practitioners and educators an overview of key considerations and published reference materials currently available. The authors' observations, based on their national expertise are provided as they relate to recent trends and evolving practices for RDII modeling within their own practices and the industry in general.

What are RDII models?

RDII simulation models use simplified mathematical representations of complex systems and dynamic processes, which are depicted in Figure 1.

RDII models require appropriate inputs and intricate computational algorithms to achieve intended analysis objectives. The typical RDII sources within a sanitary sewer system (as illustrated in Figure 1) contribute extraneous flow in multiple and complicated pathways. This makes RDII quantification challenging and adds a high degree of uncertainty. This uncertainty comes from spatial and temporal factors as outlined later.

RDII quantification can be improved by collecting flow and rainfall monitoring data and observing system performance during various meteorological conditions. RDII quantification also requires a good determination of the system's physical characteristics to help understand and interpret observed data.

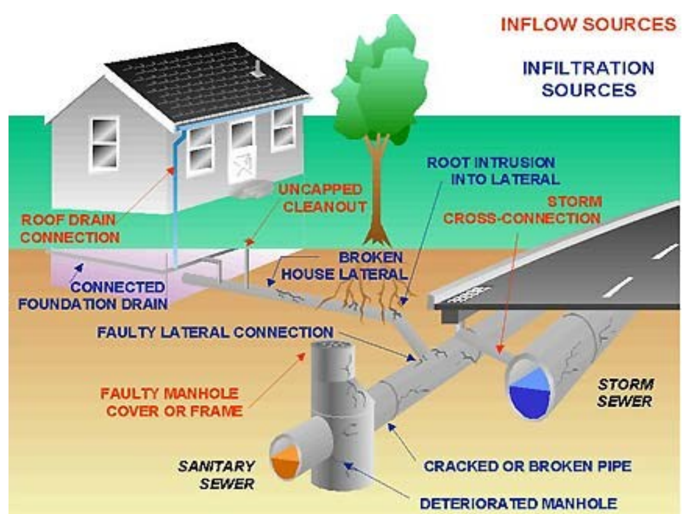

Figure 1: Typical sources of I/I in sanitary sewer systems. (Adapted from WE&RF, 2003)

Figure 2 (pg. 2) shows that sanitary sewer system flows under wet weather conditions are comprised of three distinct components:

- a rate of groundwater infiltration (GWI) component related to antecedent moisture conditions preceding wet weather events,
- a base wastewater flow (BWF) component, and
- rainfall derived infiltration and inflow (RDII).

GWI and BWF can be derived from monitoring data collected in the field and well defined for representation in models. Once an RDII simulation model is developed, calibrated, and validated it can predict the expected response for different events throughout the system. Once these steps are completed, the RDII model becomes a highly effective tool in the decision-making process for I/I reduction and remediation programs.

RDII estimation methods

The Water Environment & Reuse Foundation, (WE&RF, 1999) provided an expanded review of RDII quantification methods in the literature looking back to as early as 1984. WE&RF grouped the methods into eight broad categories that included both deterministic and probabilistic methods. Empirically based deterministic simulation models are used most commonly in practice, as they can provide reliable results with a limited amount of data. Probabilistic and regression based models, on the other hand, require long monitoring periods to provide a credible understanding of the system performance under different storm conditions.

The U.S. Environmental Protection Agency (EPA) did a follow up study to review the commonly used RDII quantification methods in 2008 (US EPA 2008). EPA concluded the following:

- No single RDII prediction method from the eight broad methods could be universally applicable due to the wide variety of site-specific rain and flow observations during both wet and dry periods experienced across the U.S.
- All methods require monitored data be collected to evaluate and validate their predictive capabilities but the amount of data required varies.
- Selecting a preferred method of estimating RDII responses, and associated hydraulic effects, in sanitary sewer systems depends on the model's intended role within the program as well as its ability to predict multi-storm peak flows and volumes. This latter point is a key consideration in extrapolating data beyond calibration events; application of a model beyond a high-level planning tool; and for evaluating RDII effects on conveyance, storage, and treatment systems.

EPA also concluded that the Synthetic Unit Hydrograph approach, which employs an empirical approach to representing catchment area`s response based on site-specific flow monitoring data and experience, has been widely used and is a proven approach. EPA has incorporated this approach in its initial version of the Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox. This toolbox was developed to estimate RDII parameters and provide inputs to hydraulic models that can then simulate RDII through sewer systems. EPA also recommends the regression approach, which requires long-term monitoring data to develop a representation of RDII.

Based on the WE&RF (1999) reference, Table 1 (pg. 3) provides a general description of five RDII estimation methods most commonly used in current (i.e. 2016) practice as key decision-making tools within an I/I reduction and remediation program.

The WE&RF (1999) reference further discusses the applicability and the limitations specific to each method. This includes the following:

- Some methods require more data than can be assembled reasonably.
- Some methods are independent of rainfall, and, hence, cannot address the effects of more — or less — intense rainfall.
- Several methods cannot predict responses under changed physical conditions.
- Most methods depend greatly on measured flow response to rainfall; thus, they require support of multiple assumptions if used to model 'non-monitored' locations or storms.
- Most methods assume groundwater infiltration is either minimal or constant. This is not the case in sewer systems that experience significant seasonal variations in wet weather effects, which occurs in most collection systems east of the Mississippi.
- Many methods are applicable to isolated storms and do not accurately reflect the effect of sequential storms or long-term periods.

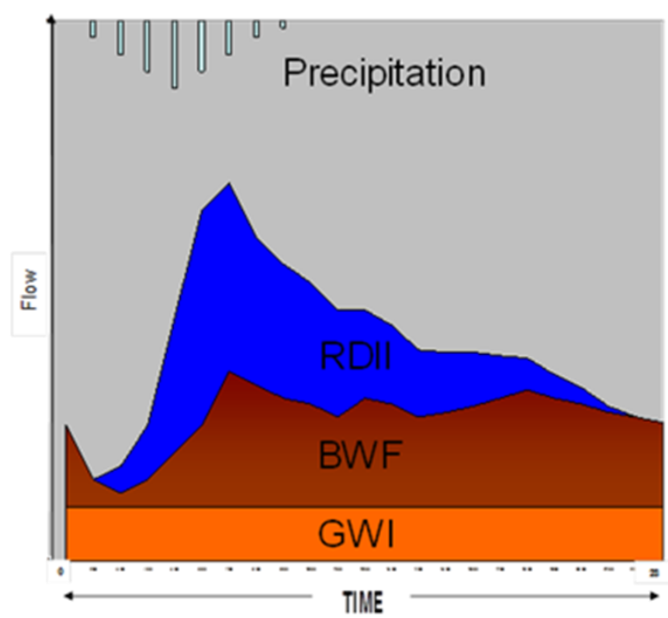

Figure 2: Components of wet-weather wastewater flow during a precipitation event. (US EPA, 2007)

RDII methodology	Description
Constant unit rate	Constant unit rate (flow rate or volume) applied uniformly over a sewershed (i.e. defined catchment or study area serviced by sewers). Unit rates are derived based on site-specific monitoring data and measurable sewershed characteristics (e.g., gallons per acre of sewershed area; gallons per inch-mile diameter of pipe; gallons per capita)
Percentage of rainfall volume (R-factor)	Ratio of the volume of RDII to the rainfall volume that is falling on the area observed by the flow monitor, determined for a number of storm events.
Multiple linear regression (rainfall / flow regression)	Uses multiple linear regression methods to derive a relationship between rainfall data and monitored RDII response.
Synthetic unit hydrograph (e.g. linear and quasi-linear unit hydrographs)	Conceptualizes the RDII response to rainfall volume and duration in a similar manner to hydrologic/runoff response from a basin, where the shape of the RDII hydrograph is a function of basin characteristics. Multiple unit hydrograph shapes and types can be applied to represent a variety of sources and timings of RDII responses (i.e. direct and indirect sources of infiltration and inflow).
Hydrologic (surface runoff) modeling routines	Conceptualizes the RDII responses as surface runoff inputs to the collection system, and uses surface runoff routines commonly available in current in hydrologic models to represent direct inflows and rapid responses within the piped systems. Also, surface runoff hydrographs are generated for curve fitting the observed infiltration responses.

Table 1: RDII estimation methodologies (Adapted from WE&RF, 1999)

The techniques used in the application of the methods listed in Table 1 have evolved since their earlier introduction in practice. This is further discussed at the end of this document. Currently, there are many public-domain and commercially available computer packages that have implemented or can incorporate listed RDII estimation techniques within the software platforms offered. Many of these software packages offer productivity tools such as a link with geographic information system (GIS) asset databases, supervisory control and data acquisition (SCADA) data with rainfall and system flows, and other data sources used to streamline the model development tasks.

Why RDII simulation models?

In many sanitary systems, RDII is problematic as it is the major component of wastewater flows observed under wet weather conditions. In northern climates, systems also may experience RDII type responses from snowmelt. The extent of these sources and their corresponding contributions vary greatly between systems and specific events.

Practitioners have several data sources to help characterize and understand the conveyance system operating conditions and the capacity challenges of the collection system during wet weather events. These include flow monitoring, closed circuit television (CCTV) investigations/field inspections, recorded observations of overflows or basement backups, and maintenance records. These collected data only provide information on system operating conditions and/or performance limitations at the specific location or during a specific time period that a flow or field survey was conducted. Extending the understanding of the system operating condition to other locations and understanding its performance limitations under different event conditions requires an extrapolation tool.

An RDII simulation model, based on hydrologic and hydraulic principles, is the commonly used tool. These models incorporate information gained through investigation to help utility managers better understand and quantify the extent of RDII and the effect on collection system hydraulics as an overall system. The RDII model can effectively be employed to assess effects on system performance and operational risks; evaluate effectiveness and operational costs of various remedial solutions; and demonstrate projected and on-going effectiveness of an I/I reduction and remediation program as remedial measures are implemented.

Application of RDII models in wet-weather programs

Key applications of the calibrated-validated RDII model include the following:

Understanding baseline conditions. Since a hydraulic model can interpolate between the points where the system flows are metered and field investigations are conducted, the RDII model provides practitioners a sewer analysis tool that can assist them in characterizing RDII sources, the magnitude of the RDII response, and the hydraulic effects throughout the system. The models also can extrapolate results by simulating systemwide RDII responses under environmental and system configurations that were different from those observed or that existed during the field investigations. These differences include different rainfall events, antecedent soil moisture, and system operating conditions. The existing condition model can set a baseline condition from which the evaluation of alternatives and the assessment of program effectiveness can be conducted.

Planning for future conditions. RDII models are effective as tools to plan for evolving environmental and system conditions. The system may be assessed to consider projected future growth, planned system upgrades or capital improvement programs, potential climate change effects, operational modifications, and future development needs. Evaluation of alternative scenarios and environmental conditions under future conditions provides a basis to assess the validity and long-term effectiveness of the I/I reduction and remediation program.

Implementation planning and effectiveness monitoring. RDII models can be developed to reflect overall I/I remediation plans and can estimate expected results at various stages of implementation. With the ability to regularly update and revalidate the RDII model as part of a post-rehabilitation monitoring program, the RDII model becomes a key tool in the monitoring of the program effectiveness. The model can provide valuable data that may direct future program efforts toward better/adaptive solutions and improved cost-effectiveness.

Model considerations and limitations

While models are valuable tools in sewer system management, experienced practitioners recognize that RDII models are limited by inherent assumptions and conceptual representations of complex processes. One key consideration is the selection and application of proper RDII methods and modeling tools tailored to system conditions and modeling objectives.

The selection of an appropriate modeling tool for the job at hand is key to the success of any I/I reduction and remediation program that seeks to apply models for purposes that go beyond high level planning assessments and existing condition assessments. For example, constant unit rate or volumetric methods may be appropriate for screening-level assessments of capacity constraints. However, more advanced hydrologic and hydraulic modeling methods are necessary to support an analysis where storage and flow routing effects are important and system performance for various event conditions is to be defined with a greater level of accuracy. Within these more advanced modeling methods, various techniques to better represent system performance under multiple-event conditions and over long-term simulations continue to evolve as discussed in the Evolving Practices section below.

Regardless of the RDII method selected, extrapolations to larger storms than those observed in the model calibration monitoring period or to portions of the sewer system upstream of the flow monitoring locations will have greater uncertainty that should be recognized in the interpretation of model results. Key considerations when evaluating the usefulness of a model to evaluate the effectiveness of remedial solutions include data-record length and calibration needs, the ability to project results under different physical and environmental conditions than calibrated, and transportability of the model to the representation of other similar areas.

Another limitation of sewer system models is the risk of software or data obsolescence. Within a long-term program, practitioners have to recognize the need to maintain the model. This need reflects both system changes/improvements and updating to evolving software technology. A million-dollar investment in a modeling tool will lose value gradually if the model is not updated and transferred to new software versions periodically. A long-term program should include periodic reviews of model performance and staff training needs, and, as required updates of the model to ensure its continued value as an effective tool within the program.

Evolving practices

Along with advancements in long-term data collection and management have come recent innovations in RDII modeling. These innovations have been focused largely on the improvement of techniques for defining and relating established model RDII parameters under a range of environmental and physical conditions over long periods of time on a continuous basis. A literature search will reveal a few case studies describing these evolving practices. These case studies include but are not limited to the following:

- The use of long-term (e.g., seasonal, annual and multiyear) continuous simulation approaches rather than traditional single event simulations to evaluate the collection system performance and potential improvements.
- Modeling RDII response by physical representation of the underground processes of infiltration through the soil and as contributions from the groundwater table or by accounting for seasonal effects in soil moisture. These approaches better support long-term simulations of RDII.

- The use of stochastic methods to represent variations in RDII response under changing conditions. The technique is used to define calibration parameters for initial rainfall losses, groundwater infiltration, and soil moisture recovery rates required to support long-term simulations.
- The use of advanced genetic algorithm methods to assist in calibrating optimized RDII parameter sets from the monitored data.

The "state-of-the-art" in RDII modeling practice continues to evolve as a result of affordable long-term flow data, technological advancements in "big data" management, and information exchange amongst practitioners and researchers. It is advised that practitioners stay abreast of these advancements and continually adapt as appropriate.

Acknowledgments

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Additional Resources

Resource	Description
SSOAP Toolbox Enhancements and Case Study (Publication No. EPA/600/R-12/690) https://www.epa.gov/water-research/sanitary-sewer-overflow-analysis-and-planning-ssoap-toolbox	The 2012 SSOAP toolbox created by the U.S. Environmental Protection Agency is a suite of computer software tools used for the quantification of RDII and help capacity analysis and condition assessment of sanitary sewer systems. This toolbox includes EPA's Storm Water Management Model Version 5 (SWMM5) for performing dynamic routing of flows through the sanitary sewer systems.
Review of Sewer Design Criteria and RDII Prediction Methods (Publication No. EPA/600/R-08/010) https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1008BP3.TXT	The 2008 evaluation included a holistic review of wet-weather peak flow design criteria for sanitary sewers used in different jurisdictions, and current practices at the time for predicting RDII in sanitary sewers.
Computer Tools for Sanitary Sewer System Capacity Analysis and Planning (Publication No. EPA/600/R-07/111) https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1008BBP.TXT	The 2008 report provided an overview of sanitary sewer hydrology, with a focus on the unit hydrograph method that was incorporated into the SSOAP toolbox. Guidance for data collection to support SSOAP toolbox analysis is also provided. A case study for sanitary sewer capacity assessment is also provided.
Prevention and Control of Sewer System Overflows (WEF Manual of Practice No. FD-17 Chapter 5, section 4.4) http://stormwater.wef.org/2012/01/wef-manual-of-practice-fd17-prevention-and-control-of-sewer-system-overflows/	This resource provides information necessary to help managers and engineers understand and analyze an overflow problem and offers guidance on finding the most efficient, feasible, and cost-effective strategies to reduce or eliminate such overflows. This authoritative volume also serves as a planning guide for developing long-term control plans for combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs).
Existing Sewer Evaluation and Rehabilitation (WEF Manual of Practice FD-6, ASCE Manual and Report on Engineering Practice No. 62, Third Edition) https://www.e-wef.org/Default.aspx?TabID=251&productId=5302	A detailed manual intended to support development of a comprehensive sewer system evaluation and rehabilitation program. This manual includes field data collection, structural evaluation, capacity evaluation, RDII source detection, and rehabilitation technology selection.
Using Flow Prediction Technologies to Control Sanitary Sewer Overflows (WE&RF Project 97-CTS-8) https://www.werf.org/a/ka/Search/ResearchProfile.aspx?ReportId=97-CTS-8	This report provides tools to appropriate RDII flow projection methodologies to help control sanitary sewer overflows and wet weather in general. Criteria needed to the appropriate RDII analysis method are examined. The report contains case studies from three diverse metropolitan areas.
Reducing Peak Rainfall-Derived Infiltration/Inflow Rates: Case Studies and Protocol; (IWA Publishing, WE&RF Project 99WWF8) http://www.iwapublishing.com/books/9781843396529/reducing-peak-rdii-flow-rates-case-studies-and-protocol	This research project examined construction projects that successfully reduced Rainfall Dependent Infiltration/Inflow (RDII). The projects examined include both those that successfully reduced RDII and those that did not. The protocol provides methods for communities who are preparing to perform similar work to examine and utilize the results of any RDII removal project.