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Rainfall Derived Inflow and Infiltration Modeling Approaches

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When designing and rehabilitating sanitary sewers, there are various methods available for estimating and predicting the impacts of inflow and infiltration on sanitary sewer systems. Each method presents challenges that need to be addressed so that rehabilitation options and designs can accommodate the conditions that the best available data suggest. This chapter provides an introduction to rainfall derived inflow and infiltration (RDII), an overview of the methods available for estimating RDII, a discussion of the challenges posed by the three most commonly used methods, and potential responses to these challenges.

8.1 Review of Analysis Methods

8.1.1 RDII in Sewer Design

Rainfall derived inflow and infiltration are problematic in most sanitary sewer systems. RDII is present to some extent in all sewers, but only when it is in small amounts relative to total sewer flows is it a background concern. The Ontario Centre for Municipal Best Practices (OCMBP) studied the rates of inflow and infiltration across Ontario and found that data are often compared on a municipal scale, which masks variability among catchments (OCMBP, 2008). DeCoite et al. (1981) examined a sewershed in California using comprehensive flow monitoring to identify inflow and infiltration sources. They found that the upstream area size for each monitored sewershed affects the accuracy of pinpointing problem locations, with larger subsystems appearing to have a uniformly high or low RDII.

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The OCMBP study also noted that care should be taken when comparing data from different years because of the dependence of RDII on rainfall. A drop in RDII during a dry year following a wet year should not necessarily be considered an improvement. Finally, the annual cost of treating RDII estimated by the Ontario Municipal Benchmarking Initiative for municipalities ranged from $121 000 to $16 000 000, based on survey responses (OCMBP, 2008). Reducing RDII is an important step in controlling known annual costs. If estimated inaccurately, RDII may lead to unnecessarily increasing the size of future capital projects.

There is disagreement over the contribution of each component of RDII. Bishop et al. (1987) claimed that inflows represent less than 10% peak flow while Vallabhaneni et al. (2008) stated that inflows are the major contribution of RDII to peak flow. It is possible that in some systems with more direct connections inflow is more significant, and in other systems, where roof leaders and foundation drains are not connected to sanitary sewers, inflow is less significant. It would be useful to understand how and why inflow prevalence varies from location to location.

In design, RDII estimation tools should provide appropriate estimates for sanitary sewer design allowance for inflow and infiltration, but this allowance is frequently exceeded by extraneous flows (Vallabhaneni et al., 2008). The ten state standards presented by Lai (2008) could shed some light on this. The present standard has changed from a quantitative specific unit rate to more qualitative measures because of the site specific nature of RDII (Lai, 2008). Municipalities in Ontario have maintained quantitative specific unit rates, and each municipality or region has their own sewer design manuals that provide constant unit rates of infiltration and inflow allowances. A selection of these rates is listed in Table 8.1 below.

Table 8.1 Ontario infiltration rates.

Municipality	Infiltration Allowance (m^3/ha/d)
City of Brockville (n.d.)	24.2
City of Kingston (2004)	12.1
City of London (2005)	8.6
City of Toronto (2009)	22.5
Region of Durham (2010)	22.5
Region of Peel (2009)	17.3

The constant unit rates in Table 8.1 can only predict site specific RDII by accident because they cannot account for actual site characteristics. Part of the reason for keeping constant unit rates is that design manuals are meant to clearly define requirements, and the manuals were all developed using the same tools with limited predictive power available for RDII estimation.

8.1.2 RDII Estimation Techniques

There are seven categories of RDII estimation techniques, most of which are implemented in software. These categories are listed in Schultz et al. (2001) in their summary of Bennett et al. (1999), a Water Environment Research Foundation report that discusses flow prediction technologies. These categories are as follows:

1. Constant unit rates;
2. R-value;
3. Percentage of stream flow;
4. Recurrence interval;
5. Synthetic stream flow regression;
6. Rainfall/flow regression; and
7. Synthetic unit hydrograph.

A brief explanation of each method is presented in the following paragraphs. In evaluating these methods, the ability to predict multi-storm peaks and multi-storm volumes is important for extrapolating data beyond calibration events, and also for evaluating RDII effects on storage and treatment systems (Lai, 2008).

Constant Unit Rate Method

Constant unit rates, like those presented in Table 8.1, are applied uniformly over a catchment or study area. Bennett et al. (1999) described constant unit rates as being system specific and their applicability to another system should be verified before being used for design. A constant unit rate is developed by normalizing RDII volume with rainfall or by a physical sewer characteristic, which is seen to provide better results (as discussed below). It is recommended that the unit rate be adjusted upwards to account for known system characteristics, such as pipe age, pipe material or backfill material, in order to avoid underestimation for small to medium events (Crawford et al., 1999). Other limitations that need to be considered when using the constant unit rate method are that catchment characteristics are only included by how they affect RDII volume. Individual characteristics are not accounted for in calculating unit rates.

The Bureau of Environmental Services (BES) in Portland, Oregon found that there was less variation in the unit rate when it was expressed in terms of a sewer's physical characteristics (Bennett et al., 1999). Among the characteristics examined the number of manholes was found to be the most representative, followed in decreasing order by length of pipe, inch diameter mile of sewer, sewershed area, and number of service laterals. As a conservative estimate, the constant unit rate has been viewed as acceptable (Schultz et al., 2001). However, excessively over-designed systems pose problems not present in appropriately sized ones, such as the deposition of solids due to low flow velocities (USEPA, 2007).

R-value Method

The R-value method, also called the percentage of rainfall method, represents RDII as a fixed percentage of rainfall volume, and is usually calculated on a per storm basis. R-values are determined for rainfall events larger than 25 mm, and results are sensitive to variations in dry weather flow (DWF) and groundwater infiltration (GWI) estimates (Crawford et al., 1999). Vallabhaneni et al. (2007) noted that event specific R-values vary because the method does not account for antecedent moisture conditions (AMCs). Wright et al. (2001) suggested that an average or median R-value from a monthly series may be more stable for use in estimation and design.

The R-values must be used carefully to ensure that the application is consistent with derivation assumptions, which is difficult as the assumptions are frequently not clearly documented (Bennett et al., 1999). The R-value method is not useful for peak flow estimation because it only provides a volume estimate (Merrill et al., 2003).

Percentage of Streamflow Method

The percentage of streamflow method represents RDII as a percentage of measured streamflow. To calibrate this method, the sewershed where flow monitoring data are available should be within the watershed containing the gauged stream. Schultz et al. (2001) suggested that using streamflow records overcomes the instability in the R-value method because they account for antecedent moisture conditions. Application of this method requires the assumption that the underlying soil conditions of the sewershed are similar to those near the stream, and that sewer conditions are similar to the monitored area when applying calculated values to unmonitored sewersheds (Crawford et al., 1999).

Recurrence Interval Method

The recurrence interval method uses flow monitoring data to analyze RDII peak flows and volumes (Crawford et al., 1999). Similar to determining streamflow recurrence intervals, this method requires long term data to allow reasonable conclusions to be drawn (Bennett et al., 1999). The method can be useful for comparing basins, but when physical conditions have changed within an individual basin, predicting RDII becomes difficult or impossible (Bennett et al., 1999).

Synthetic Streamflow Regression Method

A synthetic streamflow regression is a predictive equation used for watersheds for which there are inadequate measured streamflow records. It is based on synthetic streamflow and basin characteristics with the goal of relating sewer response and stream hydrologic response to rainfall (Bennett et al., 1999). The method allows RDII estimation for a sewershed inside or outside of the gauged watershed that shares similar characteristics (e.g. soil type, dimensions), but it is unclear from the literature whether the accuracy of such estimates has been studied (Bennett et al., 1999).

Rainfall/Flow Regression Method

Zhang (2005) developed a time series model to address the lack of statistical validity in many of the RDII estimation methods presented in Bennett et al. (1999). The model estimates RDII using unmodified flow monitoring data and rainfall data. Ideally, this model would also incorporate groundwater level fluctuations, but such data are not readily available so groundwater is represented by a time varying term. Zhang (2005) finds that a time varying term is representative of groundwater fluctuations because groundwater level does not vary greatly during periods of a few months. However, Zhang (2005) notes that groundwater level data should be used if it is available. The model allows for statistical comparison of pre- and post-rehabilitation RDII to determine if a statistically significant reduction has occurred.

Zhang (2007) improved on the work of Zhang (2005) by introducing the assumption that each rainfall event produces a unique RDII effect. The previous work assumed that the RDII effect of each event was the same. Autoregressive errors are included to determine if RDII reduction occurs in independent data series, which negates the problem that reduction has little meaning if RDII cannot be reliably measured. The model works for a terminal sewershed, but many sewers to be modeled are in series so additional work is required on a method to separate flows between basins or in a sewer network. Zhang (2007) noted that forecasting is important in design and rehabilitation; the model lays a foundation for forecasting.

Synthetic Unit Hydrograph Method

Synthetic unit hydrographs are developed for catchments where limited or no rainfall, streamflow or sewer flow data are available. RDII modeling is usually performed using a combination of a quasi-linear hydrograph and a Nash unit hydrograph, or using the RTK method. The former uses the quasi-linear hydrograph to account for the inflow and the Nash unit hydrograph (UH) to account for infiltration, while the latter uses a combination of three triangular unit hydrographs. A limitation of the quasi-linear hydrograph–Nash UH method is that it can only be used for discrete events whereas the RTK method can be used with continuous simulation (Bennett et al., 1999).

Given that the ideal implementation of RDII modeling is with long term data, the focus is the RTK method, which is the primary RDII method in the United States Environmental Protection Agency's (USEPA) stormwater management model (SWMM) in the Runoff Block (Huber and Dickenson, 1988). Three sets of RTK parameters can be defined for each month in SWMM; one for each of the short term inflow, intermediate term inflow, and long term infiltration unit hydrographs (Rossman, 2004). Each of the three unit hydrographs has three parameters:

R, the fraction of rainfall volume that enters the sewer system;
T, the time from the onset of rainfall to the peak of the UH in hours; and
K, the ratio of time to recession of the UH to the time to peak.

Calibration of the RTK parameters is done using rainfall and corresponding flow monitoring data. A rough estimate of the total R-value is found by dividing total rainfall volume by wet weather flow volume first. Next, calibration is done by plotting wet weather flow, as depth against time, together with the RTK model generated hydrographs, and then manually adjusting *R*, *T* and *K* values to achieve the best fit.

In SWMM versions 4 and 5, RDII can be represented using either the RTK method or an RDII time series (Vallabhaneni et al., 2008). When using RDII time series as an input, the time series is pre-processed information and therefore must be updated whenever the rainfall input is altered. However, the RTK method output can be calculated within the model using rainfall as its input. The RTK method parameters do not necessarily need to be changed when rainfall input changes. RTK parameters are entered as a unit hydrograph and associated with nodes where RDII is present.

8.2 Analysis Challenges

8.2.1 Introduction to Challenges

There are several challenges to using the RDII estimation methods, including record length, antecedent moisture conditions and calibration. Above all of these challenges is an unwillingness, legally enforced or otherwise, to share data about RDII estimation. Many municipalities perform RDII estimation and analysis, but few are willing or able to share the results of their analysis outside of anonymous aggregated studies (OCMBP, 2008). This makes obtaining data to perform comparison between methods difficult and has resulted in relatively few comparisons. It is also the reason further analysis of individual methods is not considered in this chapter (Bennett et al., 1999; Johnston et al., 2005; Wright et al., 2001).

8.2.2 Record Length

According to several studies (e.g. Bennett et al., 1999; Crawford et al., 1999; Wright et al., 2001), the three most commonly used methods amongst the seven outlined above are the constant unit rate, R-value and RTK methods. Each of these methods poses challenges for practical use.

As an example, a challenge that applies to all seven categories of methods is with respect to the use of flow monitoring records as input. Most of these techniques do not explicitly consider what is an appropriate record length. The literature suggests many appropriate record lengths:

- a minimum of 1 y, but a 4 month period including the spring season can provide a reasonable basis (Vallabhaneni et al., 2002);
- 1 month or 2 month but with a high risk of incorrectly estimating RDII (Kurz et al., 2002);
- a minimum of 42 d at 15 min recording intervals for a 400 parameter regression model (Zhang, 2005); and
- at least 1 y (Loehlein et al., 2005).

The variation between what is considered reasonable by these sources is wide, but longer is not always better. Knowledge of changes in the sewershed and sewer system are important when considering the quality of a flow monitoring record.

As mentioned, one study, by Kurz et al. (2002), concluded that relying on short term or uncalibrated temporary monitoring poses a high risk of incorrectly estimating RDII. One solution presented to overcome this problem is to have a permanent network supplemented by temporary monitoring that can be normalized by the permanent network (Kurz et al., 2002).

As with other aspects of water resources engineering, record length will be a problem because the basis of design is stochastically occurring rainfall and the resulting RDII should be stochastically determined. The importance of addressing this issue is in considering its implications for each site rather than having a universally applicable rule.

8.2.3 Constant Unit Rate Method Challenges

The constant unit rates are used in design manuals across Canada and the challenge is that a calculated rate applies exclusively to the system for which it was developed (Bennett et al., 1999). However, design manuals suggest using a single rate over multiple catchments that are contained within municipal boundaries, even when these catchments have different physical characteristics.

If constant unit rates are to be used in this context, specifying rates for each catchment or subcatchment could address this challenge by accounting for differing responses resulting from soil, vegetative cover and other factors. Additional consideration is needed for projects that cross sewershed boundaries where characteristics may change.

8.2.4 R-value Method Challenges

Antecedent Moisture Conditions

Two challenges for the R-value method are accounting for AMCs and sensitivity to how flow is divided. Calibrating the R-values in practice does not always account for antecedent moisture conditions because R-values are commonly calculated on an event basis. Omitting AMCs removes a direct influence over the amount of runoff and infiltration resulting from a given rainfall.

Bishop et al. (1987) examined inflow and infiltration on a regional scale to identify problem areas and develop a correction plan. This study found that soil moisture can have a major impact on the magnitude of inflow and infiltration. Overcoming this challenge is not simple because there are no methods that directly measure AMCs.

Division of Flow Components

Separating the components of flow is an important element of analysis. How the components are separated remains unresolved because groundwater does not influence all sites equally and the DWF pattern can be inconsistent. Despite the variability of groundwater and DWF, some studies have suggested specific divisions. It is common for GWI to be set equal to 90% of average minimum daily flow. GWI is treated as relatively constant during each season (Vallabhaneni et al., 2008).

Once groundwater infiltration is set then the average DWF pattern can be determined from the monitored flow data. Finally, it is possible to determine wet weather flow contributions by subtracting DWF and GWI. It is possible for specific flow separation decisions to strongly influence RDII estimation depending on the magnitudes of each component.

8.2.5 RTK Method Challenges

Challenges with the RTK method include the lack of accounting for AMCs, difficulty in calibrating the nine parameters, and the lack of relation to catchment characteristics. These are discussed in the following paragraphs.

Antecedent Moisture Conditions

AMCs are generally omitted from the RTK method calibration, just as they are for the R-value method although there are a few calibration techniques that make an effort to account for AMCs. Loehlein et al. (2005) let RTK parameters vary from event to event with larger values for higher antecedent moisture conditions and lower values for lower AMCs. However, to use all of these calibrated RTK events in SWMM, it is necessary either to average individual storms into one composite set of RTK values or to average the storms for each individual month to develop a set of monthly-varying RTK parameters (Loehlein et al., 2005). Within SWMM it is possible to define initial abstraction values for each of the three RTK triangular hydrographs. However, adding maximum abstraction depth, recovery rate and initial depth for each of the three hydrographs gives another nine parameters that require calibration.

Calibration

The second challenge, calibration, has been examined extensively (Bennett et al., 1999; Loehlein et al., 2005; Gheith, 2010), and the methods proposed include using brute force, regression models and genetic algorithms. In the BES case study, mentioned above, it took approximately 20 h per monitoring location to calibrate the nine RTK parameters to achieve the best fit (Bennett et al., 1999).

An example of a calibration technique that accounts for AMCs is presented in Gheith (2010), where an approach to calibrating the RTK method for continuous simulation that takes into account the variability of initial abstraction (I_a) was developed The author used Equation 8.1 to examine four possible calibration combinations of the two unknowns R-value, R, and initial abstraction, I_a, which can be fixed or variable in a calibration process. The proposed approach is selected after a review of continuous calibration methodologies. It obtains a constant R-value by calibrating with an event that follows a larger event, such that the initial abstraction can be assumed to be zero. The equation used is as follows:

$$R = \frac{RDII_{volume}}{A_{serviced}\left(i_{total\ rain} - I_a\right)} \tag{8.1}$$

where:

$RDII_{volume}$ = total RDII volume determined from gauge data (mm/ha or in./acre),
$A_{serviced}$ = service area being examined (ha or acre),
$i_{total\ rain}$ = total rainfall volume determined from gauge data (mm or in.), and

I_a = initial abstraction at the beginning of a storm event (mm or in.).

Both of the above described techniques are time consuming. The USEPA has developed the sanitary sewer overflow analysis and planning toolbox (SSOAP), a tool to automate most steps of the calibration and reduce the time required to fit parameters. It is a relatively new tool designed to help characterize RDII from rainfall records and sewer flow monitoring data. SSOAP shares some functions with Camp Dresser & McKee, Inc.'s (CDM) SHAPE utilities programs as described in Vallabhaneni et al. (2002).

SSOAP was developed to rationalize RDII design criteria and facilitate selection of RTK parameters. It uses the RTK synthetic unit hydrograph method developed by CDM staff to characterize RDII (Vallabhaneni et al., 2008). Other estimation methods can be added to the program in the future.

Part of the calibration challenge is that comparisons between the techniques are few, so the relative usefulness and ease of use of each technique is unclear. In evaluating any RDII estimation method, a comparison with SSOAP may be useful to judge the relative effectiveness of each method. A further understanding of SSOAP functions is necessary as it was released recently (in January 2010) and has yet to build up a body of applications.

Parameters and Physical Characteristics

Another challenge is that there is seldom any relationship between any of the nine RTK parameters and the physical characteristics of the catchment being modeled. This may be a small problem for modeling existing sewer systems where monitoring data exist, but it prevents the RTK method from being used effectively as a predictive model to inform system design. Without an understanding of which physical characteristics are most important to selecting the RTK parameters, it is difficult to assess whether the catchment of interest for design shares the same characteristics with another catchment with known RTK parameters.

One way of addressing this challenge is to adapt the technique used to calibrate the RTK parameters in such a way as to take into account the sewershed and sewer characteristics. This change may also result in a better tool that could be useful for analysis of existing sewers and for design of new ones.

8.3 Future Work

One approach that is being explored to address some of the challenges discussed is developing models based on probability distribution transformation theory, which was first applied to water resources by Eagleson (1972). This is accomplished by basing models on rainfall characteristic frequency distributions and developing rainfall–RDII transformations. This section discusses the conceptual basis for two such modeling approaches.

8.3.1 RTK Based Model Conceptualization

In the process of developing a rainfall–RDII transformation, it is important to have a conceptualization that is supported by current methods and available data. The RTK method is commonly used and it is used as the basis for this conceptualization. For this conceptualization, the RTK method's T and K parameters are used to define the time bases of three simplified rectangular hydrographs and R-values are used to define the hydrographs' areas. With area and time base defined, peak flow rate for each hydrograph is fixed. Representing the individual RDII flow components with rectangular hydrographs may reduce the peak flow rate projection of each component individually, but may still provide an acceptable estimate of overall peak flow.

8.3.2 Separate Inflow and Infiltration Models

This second formulation is more loosely based on the RTK method. It begins with the assumption that the inflow and infiltration processes can be modeled separately from one another. This assumption is supported by published values for RTK time parameters that show the general relationship that times to peak of the first two hydrographs (T_1 and T_2) are much less than the time to peak of the third hydrograph (T_3). Similarly, the total combined duration of the first two hydrographs is less than that of the third hydrograph.

A case study presented in Bennett et al. (1999) from BES suggests that the range of T_3 values spans from 12 h to 132 h while the range for T_1 and T_2 is between 5 h and 25 h. Figure 8.1 shows the distribution of values from the five locations listed in the BES case study.

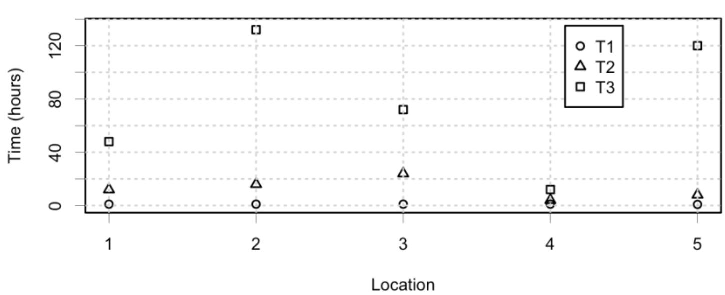

Figure 8.1 RTK UH time to peak values (adapted from Bennett et al., 1999).

The total duration of each hydrograph is calculated using $T_n(1 + K_n)$, where n = 1, 2 and 3. The total durations are distributed similarly to t ime to peak values. Figure 8.2 shows the ranges of the total durations at the five BES case study locations.

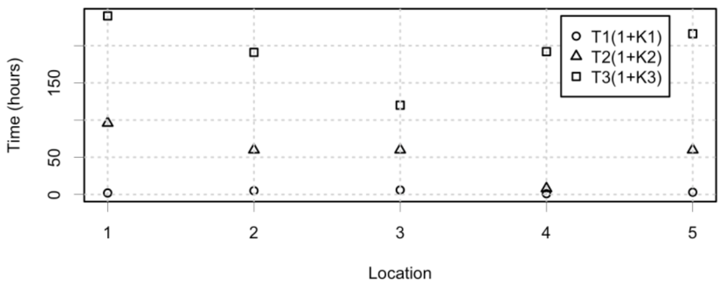

Figure 8.2 RTK UH total duration values (adapted from Bennett et al., 1999).

8.4 Conclusions

This chapter presents the seven categories of RDII estimation methods and discusses challenges associated with methods in these categories. The challenges that apply to all categories are adequate lengths of flow monitoring records and how flow records are separated into their components. To address difficulties with analysing flow monitoring data, it is important to consider the end goal of the analysis and in turn determine the sensitivity to flow monitoring challenges.

The challenges presented when applying three most commonly used methods are examined. The constant unit rate method, like all methods, needs to be evaluated for its applicability to the catchment being investigated. A challenge for both the R-value and RTK methods is how AMCs are considered during calibration. The RTK method has further challenges with calibration and with relating its parameters to physical catchment characteristics. Calibration can be a time consuming process even when automated tools are used. The lack of relationship between the RTK parameters and physical characteristics limits the applicability of the method when flow monitoring is lacking.

Further work is in progress to develop a screening level tool to estimate RDII, and explore possible relationships between the RTK parameters and physical characteristics. The screening tool is based on derived probability distribution theory and employs rainfall characteristic frequency distributions to account for stochastic rainfall. Further details of future work can be obtained by request in the primary author's MASc thesis (Mikalson, 2011).

It is clear that the response to each challenge presented is different with some needing to be dealt with on a case by case basis and others needing changes to how sewershed characteristics and rainfall frequency based estimation are included in modeling. Addressing these challenges should make the outcomes better when employing the estimation methods, and lead to better engineering decisions in the long term.

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