

## A Detailed Procedure for Separating RDII Stages and Generating a Single Set of RTK Hydrographs for Continuous Simulation

Hazem Gheith

This chapter presents a step-by-step procedure for performing continuous calibration of the rain dependent inflow and infiltration (RDII) process using the RTK method in SWMM. The procedure starts with the separation of the observed RDII hydrograph into its three distinct stages; inflow, delayed inflow and groundwater infiltration. The separation approach relies on identifying the distinct difference in the time frame of each RDII stage. The discontinuities in the slope of the flow hydrograph reveal the peak and terminal recession times for each of the three stages. These stages are then simulated in SWMM using the RTK unit hydrograph method. A single set of RTK parameters for each RDII stage is calculated using rainfall volume, duration and start and peak times, and the time for flow routing through the collection system network. A combination of precipitation, depression storage recovery rate, and the calculated single set of the RTK parameters can then be used to calculate RDII response in continuous simulation of hydrology and hydraulics models.

This chapter details a secondary, but essential, step towards calculating a single set of RDII parameters for continuous calibration. The primary step (Gheith, 2010) was a procedure for calculating the total  $R$  value that is only a function of the internal factors affecting the RDII process.

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## 11.1 Overview of the RDII Process

### 11.1.1 RDII Stages

There are several ways that RDII can enter a collection system. The varying means and methods have a definite impact on how the RDII response is noted within the system. For example, perforated manhole lids, illicit direct storm pipe connections, floor drains and downspout connections will result in an immediate inflow response within a collection system (within minutes), while damaged manholes, nearby storm sewer leaks, and damaged lateral connections result in a delayed inflow response within the collection system (minutes to hours). A detailed overview of RDII simulation methodologies is presented by Vallabhaneni et al. (2007) and Lai (2008). The RTK method is widely used in SWMM. The RTK unit hydrograph was first introduced in the SWMM Runoff block by Huber and Dickenson (1988). The immediate inflow response is represented in the SWMM RTK method by a narrow, high peak unit hydrograph triangle, known as the first triangle. The delayed inflow response is represented by a broad, middle peak response unit hydrograph triangle, known as the second triangle.

A third extended period of RDII response, noted in each collection system as the infiltration stage, results from the rise of the GWT around the collection system. Groundwater enters the sanitary system through damaged joints and cracks in the pipes. This is represented in the SWMM RTK method by a broader time to peak flow and a small peak flow response unit hydrograph, known as the third triangle. This slow RDII response can reach its peak in hours, but will usually recede in a time span of days.

### 11.1.2 External and Internal Factors Causing RDII

Runoff is the excess rain after all initial abstractions are subtracted from the precipitation. RDII represents the percentage of runoff that enters the sanitary collection system during and after the storm event. The volume and shape of the RDII hydrograph are functions of external and internal factors with respect to the collection system. External factors are those factors that reduce and delay the precipitation before the runoff arrives at the sanitary collection system, and include runoff routing path, surface abstraction (e.g. vegetation, surface ponds), evaporation, and infiltration. The internal factors are related to the physical conditions of the collection system.

Both factors play an important role in determining what, if any, RDII enters the system. In tight systems, with no defects (e.g. no cracks, dislocated joints, or perforated manhole lids), no RDII should take place. If the sanitary

collection system has defects a percentage of the runoff that will arrive at the vicinity of the collection system will permeate into the sanitary system as RDII. The volume of RDII that enters a collection system depends on the size and number of these internal defects. The shape of the RDII hydrograph depends mostly on external factors related to the dimension of the sewershed, which controls the travel time of the runoff before it arrives at the collection system, and partially on internal factors related to the location and configuration of any system defects.

The RDII hydrograph volume varies between sanitary collection systems, based predominately on the number and size of the collection system defects (internal factors). For new collection systems, there should be few internal defects and RDII is expected to be small when compared to the normal dry weather flow (DWF) conditions. As the collection system gets older, soil movement, root intrusion, structural failure, poor construction, and the erosion process can cause cracks in the pipes and damage at the joints and manholes. RDII will increase as these defects increase.

Several internal and external factors can contribute to causing one of the three RDII stages to dominate the extraneous flow contribution to the collection system. In sewersheds experiencing extended wet periods with high GWT or excessive rainfall conditions, there will be a greater infiltration response, represented in SWMM by a larger  $R_3$ . In dense residential areas with multiple lateral connections, the delayed inflow response will likely be dominant, represented by larger  $R_2$ . In older developments where downspouts and floor drains might be directly connected to the sanitary collection system, the first inflow stage could be dominant, represented by larger  $R_1$ .

The RDII hydrograph also varies between collection systems because of external factors. These include the climatic conditions and the surface and subsurface conditions. For example, at times when the groundwater table (GWT) is far below the collection system, groundwater infiltration into the collection system will be minimal. This is because much of the infiltrated precipitation will fill larger subsurface layers before the GWT rises enough to reach the collection system elevation. This is represented by a large initial abstraction before calculation of the volume of the third RDII stage. Here the RDII hydrograph will be dominated by the first and second RDII stages. Runoff varies according to the precipitation and climatic conditions, while the  $R$  percentage is constant (a function of the number and size of defects).

### 11.1.3 Hindrances to a Complete Physically Based RDII Calculation

It is difficult to determine RDII stages through physically based calculations, since the internal factors causing the RDII process (the number and level of

defects) cannot be accurately quantified. Currently, the most widely utilized method to determine the collection system defects which affect the RDII response is through comprehensive and costly inspection and televising activities. This method provides good information on the system condition, but it does not provide enough information to determine the expected RDII response. For example, collection systems are televised and inspected during DWF conditions, which prohibits the inspector from fully understanding how much RDII could enter the collection system through the system defects under wet weather or saturated soil conditions. Also, during wet weather and saturated conditions, collection system defects act as submerged orifices, making flow a function of the defect shape and size and the orifice friction loss. At this time, there are no documented studies detailing such flow conditions through defects. Due to the difficulty in determining internal factors and how they impact RDII response, hydrology model simulations are still dependent on the flow monitoring hydrograph to quantify the percentage of runoff that enters into the sanitary collection system as RDII.

#### 11.1.4 Approaches to Calculating SWMM RTK Parameters

Correct representation of the RDII sources in SWMM simulation is important in order to allow for an accurate assessment of RDII reduction alternatives. For any one monitored RDII event, there can be an unlimited number of combinations for the nine parameters describing the three unit hydrograph triangles to represent the RDII hydrograph. A common practice for determining the RTK parameters for continuous calibration is to use trial and error until a best fit RTK set for one monitored RDII event is calculated. This set is then tested and manipulated to minimize the collective errors in peak RDII flow or volume for several RDII events. In some practices several RTK sets are calculated from several monitored RDII events for a sewershed and a median or average set is then used as the representative set for that particular system. The ability of hydrology models constructed using this method of RTK development to accurately simulate the collection system response in a continuous simulation becomes unpredictable (Gheith, 2010). These models are often used to evaluate potential system responses to improvements such as rehabilitation and replacement. This inherent limitation could lead to flawed improvement recommendations.

A more appropriate approach is to calculate a set of RTK parameters that are functions only of the internal defects of the system. This set will be constant for each sub-sewershed of the collection system and will allow for a direct RDII level comparison between the RDII for different sub-sewersheds, since the RTK set for each sub-sewershed is independent of the

climatic, land use or soil conditions, and is only dependent on the internal collection system defects.

## 11.2 Representation of the RDII Process

An observed flow hydrograph downstream of a separate sanitary collection system is a combination of three major flow sources: base wastewater flow (i.e. the waste stream from returned daily water usage of residential, commercial and industrial users), groundwater infiltration that takes place in dry weather periods, and RDII. Figure 11.1 shows that the components of sanitary flow are base groundwater infiltration (GWI), in addition to the base wastewater sewage flow (BWWF). Both GWI and BWWF add up to form the DWF component. RDII is the wet weather flow component. The focus of this chapter is on calibrating and simulating the RDII component of the flow hydrograph. In separate sanitary collection systems, the RDII component is a representation of the precipitation over the upstream portion of the collection system that enters the collection system directly through illicit storm connections, and indirectly through system defects. In SWMM simulations, the hydrology of the RDII process is simplified by assuming that the flow enters the collection system as a flow hydrograph at the upstream nodes (man-holes). This hydrograph is calculated at each time step from the runoff and multiplied by a unit hydrograph. In this chapter, and to facilitate a better presentation of the proposed approach for simulating the RDII process in SWMM, four conceptual representations of the RDII process are explained below, given in increasing order of complexity.

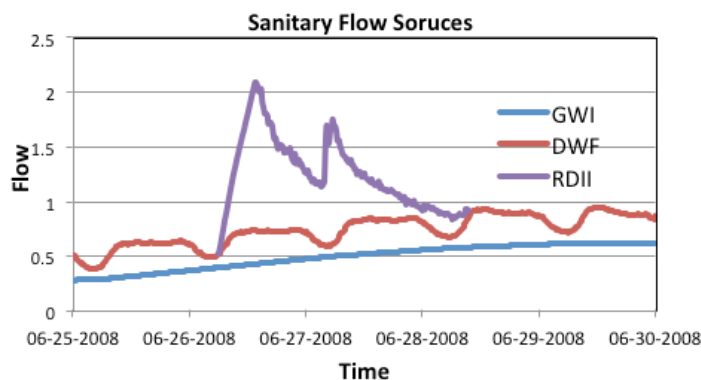


Figure 11.1 Sanitary flow sources: dry and wet weather components.

### 11.2.1 RDII Response from a Rainfall Input at a Point

For this first conceptual representation, a simple hydrology model is built to calculate the RDII response time and volume expected from a unit depth of rain that travels on or through the soil surface and arrives at one specific pipe segment, as shown in Figure 11.2. To calibrate the hydrology model, it is assumed that a flow meter which monitors the volume and arrival time of the generated RDII is placed at the outlet end of the pipe segment. The hydrology model can then be used to calculate the RDII response from the rain conditions without the need for a flow monitor at the outlet point.

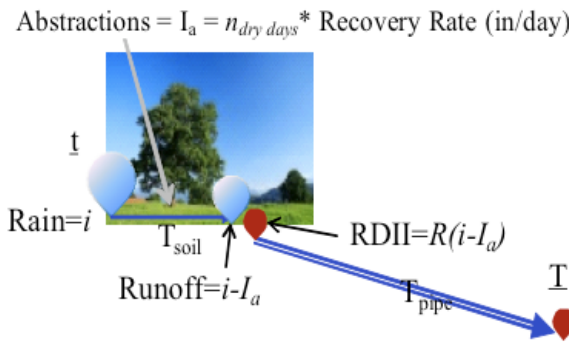


Figure 11.2 Conceptual representation of the RDII process from one drop of rain volume. (Underlined time variables represent an absolute time, while non-underlined time variables represent travel times in hours.)

As presented in Figure 11.2, the rain  $i$  observed at time  $\underline{t}$  will travel through the soil and as surface overland flow in time  $T_{soil}$  to arrive at the collection system. Some of the rain will be lost to wet the soil and to transpiration, and the remaining runoff depth will be  $(i - I_a)$  where  $I_a$  is the initial abstraction, which is a function of both the number of dry days since the last rain event and the rate at which the system is drying out per day (daily storage recovery rate,  $Rec$ ). Depending on the surface and subsurface soil conditions, the initial abstraction could have a maximum abstraction value. It is also important to note that in some cases the initial abstraction can be greater than the rainfall. In this case, there will be no runoff.

In sanitary systems not all runoff enters the collection system. Only a percentage  $R$ , a function of the size and number of defects in the sanitary collection system, of the runoff will enter the collection system. For tight systems with no defects,  $R$  is zero. If cracks and defects exist, the RDII vol-

ume entering the pipe segment will be equal to  $R*(i - I_a)$ . The RDII will then travel through the pipe  $T_{pipe}$  to arrive at the flow meter at an observed time  $\underline{T}$ .

The above representation can be put on a timeline presentation as shown in Figure 11.3 and Equations 11.1 and 11.2. The rain drop time  $\underline{t}$  is obtained from the rain gauge. The observed RDII response time at the flow meter  $\underline{T}$  is known from the flow meter data. The travel time in the pipe can be calculated using the pipe length and the flow velocity as observed by the flow meter. The time the drop of rain takes to travel through the soil to arrive at the collection system  $T_{soil}$ , can then be calculated using Equation 11.1.

$$\underline{T} - \underline{t} = T_{soil} + T_{pipe} \quad (11.1)$$

$$RDII = R*(i - I_a) = R*(i - n_{dry} * Rec) \quad (11.2)$$

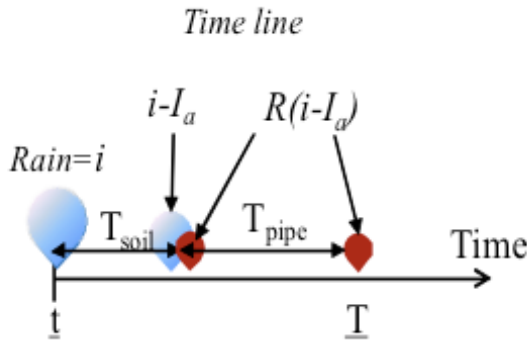


Figure 11.3 Timeline presentation of RDII process from a one drop of rain at a point.

In Equation 11.2,  $i$  is known from the rain gauge and  $RDII$  is known from the flow meter. Equation 11.2 includes two unknowns,  $R$  and  $I_a$ .  $I_a$  is a function of the number of dry days ( $n_{dry}$ ) and the storage recovery rate ( $Rec$ ) as explained above. In order to overcome the difficulty of solving one equation for two unknowns, parameters of the hydrology model should first be built using a storm event where the sewershed is almost completely wet, for which  $I_a$  can safely be assumed to be zero (Gheith, 2010). In this case, Equation 11.2 can be used to calculate  $R$ . Another observed event can then be used, knowing the number of dry days before the event, to calculate the storage recovery rate. If the storage recovery rate changes seasonally or monthly, other observed events can be used to calculate the recovery rate in each season or month. In this case, SWMM will adjust the application of Equation 11.2 for each month based on the user defined monthly  $Rec$  values.

Equations 11.1 and 11.2 can then be used to calculate RDII response time and volume in other storm events where only rain data is available and flow monitoring data is not available. In this case, the RDII response time  $\underline{T}$  can be calculated using Equation 11.1 since  $\underline{t}$  is known from the rain gauge;  $T_{soil}$  is calculated during the model calibration and is assumed constant since sewershed land use and soil features are held constant; and  $T_{pipe}$  can be calculated from the hydraulics of the collection system. Similarly, RDII volume can be calculated from Equation 11.2 since  $R$  and  $Rec$  are calculated during the model calibration and  $i$  and  $n_{dry}$  are known from the rain gauge data.

### 11.2.2 One Rainfall Time Step Evenly Distributed over a Sewershed

In this second case, it is assumed that there is an evenly distributed rainfall over one time step throughout the sewershed, as shown in Figure 11.4. The rainfall will travel overland or infiltrate into the soil for later collection at an inlet point in the collection system. Assume that a flow meter is placed at the outlet point of the collection system to observe the RDII. Different rain amounts during different time steps will have different travel times on or through the soil, based on the distance to the collection system inflow point. To simplify the representation of the runoff process as it arrives at the inlet point, the closest runoff volume will be small and will arrive first. As runoff from more distant areas arrives at the inlet point, the runoff volume will increase, starting from the small value and building up to a maximum value. As more distant runoff arrives and attenuates due to travel over and through the soil, the RDII starts to recede until the contribution of the most distant point of the sewershed is collected.

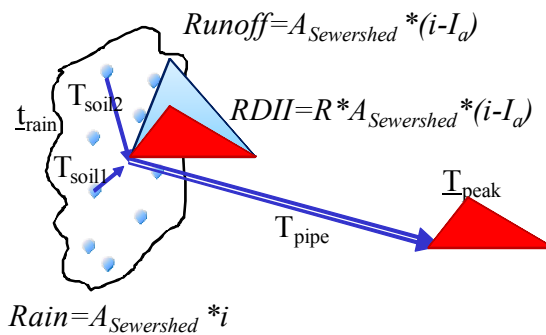


Figure 11.4 Conceptual representation of RDII process from rainfall in one time step, evenly distributed over the sewershed.



In the SWMM RTK unit hydrograph method, rainfall is assumed to be evenly distributed over the sanitary sewershed, and the runoff and RDII response at the inlet point are simplified and represented by a triangular shape as shown in Figure 11.4. Total rainfall volume will be  $(I * A_{sewershed})$  where  $I$  is the depth of the precipitation and  $A_{sewershed}$  is the serviced area of the sewershed. Due to initial abstraction, the runoff arriving at the inlet point will be less than the rain by the abstraction value. Furthermore, not all runoff arriving at the inlet point will enter the collection system as RDII. Only a percentage  $R$  of the runoff will enter the collection system as RDII (the darker triangle shown in Figure 11.4). The RDII triangle will then travel through the pipe to the outlet point, where it is measured by a flow meter.

The RDII is presented on the timeline as shown in Figure 11.5. Notice that the duration of the RDII hydrograph is equal to the base of the RDII triangle as observed by the flow meter at the outlet.  $T_o$  is the time the RDII hydrograph was first observed at the flow meter,  $T_{peak}$  is the time the RDII response is at its highest, and  $T_{final}$  is the time that the observed RDII response ended.

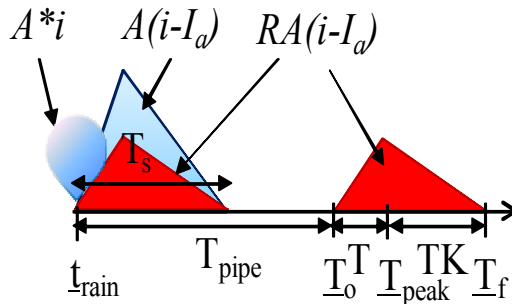


Figure 11.5 Timeline representation of RDII process from a one rain time step over a sewershed of an area  $A$ .

Equations 11.3, 11.4 and 11.5 can then be used to calculate the three triangle parameters  $R$ ,  $T$  and  $K$ . In Equation 11.3, the RDII hydrograph travel time inside the collection system,  $T_{pipe}$ , can be calculated by knowing the pipe length, and the average velocity from the flow meter. Knowing the time of rain  $t_{rain}$  from the rain gauge and the time of peak RDII response  $T_{peak}$  from the observed RDII hydrograph at the flow meter at the outlet, the time it takes for the rising limb of the RDII triangle,  $T$ , can then be calculated. Knowing the peak and final times of the RDII triangle, from the flow meter, and  $T$  from Equation 11.3, the parameter  $K$  can be calculated from Equation 11.4. Finally, knowing the base of the RDII triangle and the peak flow of the triangle, from the observed hydrograph at the flow meter, the RDII volume

is known and  $R$  can be calculated using Equation 11.5. Similarly to the previous representation, and to avoid having two unknowns in equation 11.5, the calculation process should first be done for a situation in which the sewershed is saturated and  $I_a$  is zero. Other events can then be used to calculate the recovery rate.

$$T_{peak} - t_{rain} = T + T_{pipe} \quad (11.3)$$

$$T_{final} - T_{peak} = T * K \quad (11.4)$$

$$RDII = R * A * (i - I_a) = R * (i - n_{dry} * Rec) \quad (11.5)$$

For SWMM simulation, the user defines the unit hydrograph parameters that are applied to the runoff at the inlet point, as shown in Figure 11.6.

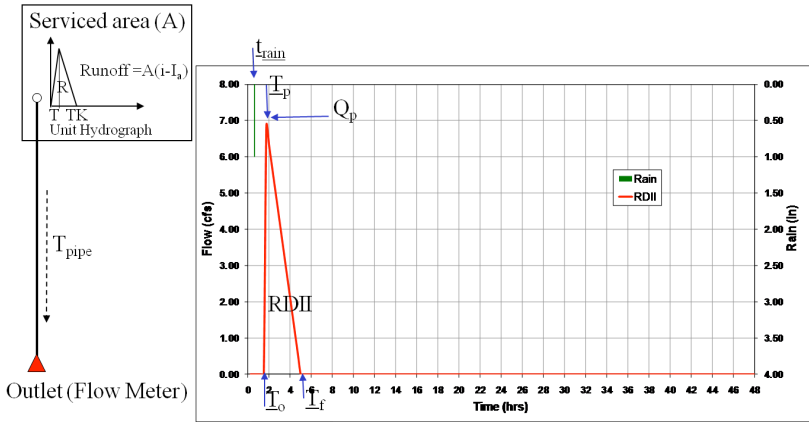


Figure 11.6 Calculating the unit hydrograph parameters  $R$ ,  $T$  and  $K$  due to one rainfall time step.

The unit hydrograph is a triangle with a time base of  $T + KT$  and area equal to  $R$ . If the serviced area is  $A_{serviced}$  and the initial abstraction is  $I_a$ , then the runoff is  $A * (i - I_a)$  and RDII volume will be  $R * A * (i - I_a)$ . As shown in the graph, knowing the response at the flow meter and the average time it takes for the flow to travel through the pipe, the three unit hydrograph parameters can be calculated as described in Equations 11.6, 11.7 and 11.8. The RDII volume will be  $0.5 * (T_f - T_o) * Q_p$ , where  $Q_p$  is the observed peak flow. The initial RDII response time  $T_o$  can be replaced with  $t_{rain} + T_{pipe}$ . This replacement is useful in later steps when calculating RDII from non-monitored wet weather flow events. Notice that for simplicity, the hydrograph attenuation in the pipe segment is assumed negligible. The  $R$ ,  $T$  and  $K$  parameters can then be calculated as:

$$R = \frac{RDII \text{ Volume}}{A * (i - I_a)} = \frac{1/2 (T_f - (t_{rain} + T_{pipe})) * Q_p}{A * (i - n_{dry} * Rec)} \quad (11.6)$$

$$T = T_{peak} - t_{rain} - T_{pipe} \quad (11.7)$$

$$K = \frac{T_{final} - t_{rain} - T_{pipe} - T}{T} \quad (11.8)$$

### 11.2.3 Several Rainfall Time Steps Distributed over a Sewershed

In this third case, assume that the RDII response is due to several rainfall time steps that are each evenly distributed over the sewershed. The total rainfall depth is  $i_{total}$  and the rainfall duration is  $d_r$ . Each rainfall time step will contribute a portion of the RDII response. At each step, the generated runoff will be multiplied by a unit hydrograph as shown in Figure 11.7. The total base time span of the RDII as it enters the inlet point of the collection system will be  $T + TK + d_r$  and the RDII volume will be  $R * A * (i_{total} - I_a)$ .

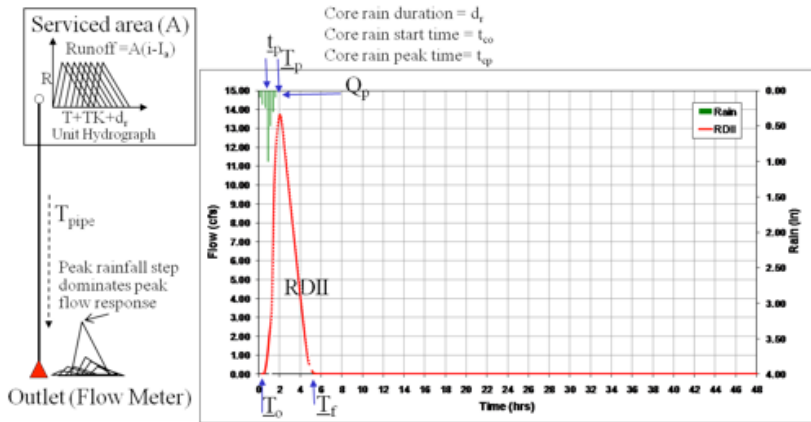


Figure 11.7 Calculating the unit hydrograph parameters  $R$ ,  $T$  and  $K$  using observed hydrograph and routing time due to several rainfall time steps.

Assume that one rainfall time step or a core portion of the rainfall event dominates the intensity of the event. This is typically characteristic of summer thunder storms in the Midwest climate. In these types of storms most of the rainfall volume precipitates within a few time steps. In a rainfall event in the Midwest climate monitored in 5 min time steps, a summer storm will

start with rainfall volume  $<0.02$  in. (0.51 mm)/time step for few time steps. The rain intensity then rises to higher values for few time steps. The few time steps with the higher rainfall values dominant the RDII response. The rainfall then recedes again to  $<0.02$  in. (0.51 mm) for few more time steps before rainfall stops. As presented in Figure 11.7 above the start time of the dominant rainfall portion of the event is  $t_{co}$  and the time of the peak rainfall time step is  $t_{cp}$ . The rising slope of the RDII response will be close to the slope of the RDII triangle from the dominant high intensity rainfall time step, as shown in Figure 11.7. If the flow hydrograph response is known from the flow meter at the outlet point, then the SWMM RDII parameters  $R$ ,  $T$  and  $K$  can be calculated from the following equations:

$$R = \frac{RDII Volume}{A * (i_{total} - I_a)} \approx \frac{\frac{1}{2}(T_{final} - (t_{cp} + T_{pipe})) * Q_p}{A * (i_{total} - n_{dry} * Rec)} \quad (11.9)$$

$$T = T_{peak} - t_{cp} - T_{pipe} \quad (11.10)$$

$$K = \frac{T_{final} - t_{co} - T_{pipe} - T - d_r}{T} \quad (11.11)$$

#### 11.2.4 Several Rainfall Time Steps over Several Sub-Sewersheds

In this case, there is more than one pipe segment in the network and more than one inlet manhole is assumed to receive RDII as shown in Figure 11.8.

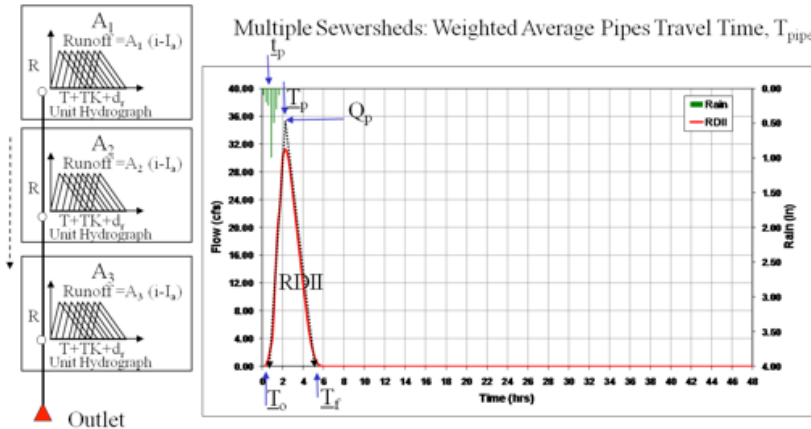


Figure 11.8 Calculating the unit hydrograph parameters  $R$ ,  $T$  and  $K$  for RDII from several rainfall time steps and several sub-sewersheds. In the presented example, assume RDII from three sub-sewersheds are discharging into the collection system at three receiving manholes.

For this representation greater attenuation is expected in the observed RDII response at the flow meter, as a result of the varying travel times expected for RDII to reach each inlet manhole and as the RDII is routed throughout the collection system. The only difference from the conditions of the previous case is that the travel time  $T_{pipe}$  through the pipe network should be replaced by an area weighted average:

$$T_{pipe} = \frac{A_1 T_{pipe1} + A_2 T_{pipe2} + A_3 T_{pipe3}}{A_1 + A_2 + A_3} \quad (11.12)$$

Equations 11.9, 11.10 and 11.11 will then stay the same.

## 11.3 Calculating RDII for Multiple Stages

All four representations described above were for the simple case of a single RDII stage. In field conditions, the RDII process is more complicated because of the different types of system defects and varying sources of RDII. The SWMM RTK unit hydrograph module allows the use of up to three unit hydrograph triangles with different time spans and peaks. Splitting the RDII hydrograph and calculating the RDII parameters for this more complex condition will be discussed in this section.

### 11.3.1 Characteristics of each RDII Stage

A typical flow hydrograph in a collection system during an RDII event will look like the one presented in Figure 11.9.

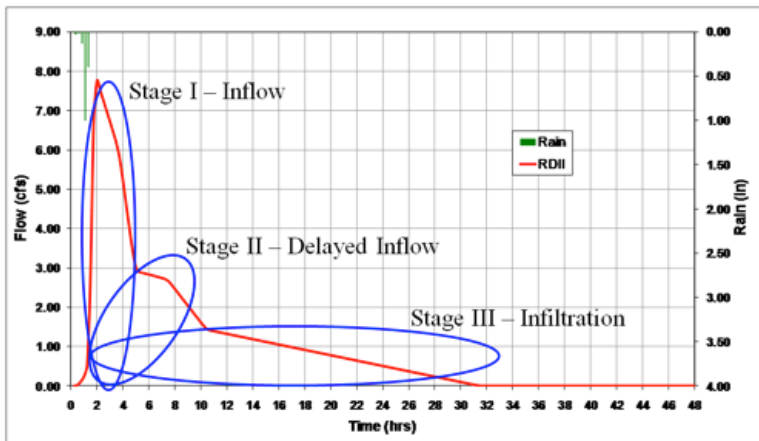


Figure 11.9 RDII stages.

Due to the wide range of RDII sources and collection system defects, there is a subjective nature to isolating these stages explicitly. A simplified approach groups the sources of RDII in accordance with the time spans of the various RDII processes. This approach is commensurate with RTK unit hydrograph theory that splits the RDII process into three stages: inflow stage, delayed inflow stage, and infiltration stage. Each stage has its own deterministic input parameters. The validity of this approach is confirmed by its common application in projects nationwide. Exceptions may arise in uniquely monitored sewersheds, but they are rare enough to be considered outside the norm.

### *RDII Stage 1 Inflow*

This stage represents RDII entering the collection system through illicit direct storm connections, downspout connections, floor drains, and displaced or perforated sanitary manhole lids. The general characteristics are:

- it starts within a few minutes of the start time of the rain event;
- in most cases, the initial abstraction is small;
- it ceases a few minutes after the rain event;
- the hydrograph shape from this stage is usually a sharp peak since it represents direct runoff from impervious areas in the collection system; and
- if it exists, it usually dominates the RDII peak response.

### *RDII Stage 2 Delayed Inflow*

This stage represents RDII entering the collection system through foundation drains, near-surface damaged pipes (e.g. lateral connections), damaged manhole castings, and leaks from pressured storm pipe trenches to sanitary pipes. It has been observed from several Infiltration/Inflow (I/I) studies that the largest portion of I/I seen in public sewers is observed in sanitary sewers that are in the vicinity of, and parallel to, a storm collection system (City of Columbus, 2009). The general characteristics of the delayed inflow stage are:

- it starts within a few hours of the start time of the rain event;
- it ceases a few hours after the rain event; and
- it usually dominates peak RDII in cases where inflow from direct connections is small.

### *RDII Stage 3 Infiltration*

This stage represents the RDII entering the collection system as infiltration from the rising GWT surrounding the collection system. The infiltration en-

ters the collection system through damaged joints and cracked pipes in the main collectors and interceptors. The general characteristics are:

- it starts and peaks several hours after the start of the rain event;
- it ceases days after the rain event;
- the time frame depends on several factors, including the vertical location of the GWT, which varies greatly depending on the climate and local hydrology; and
- based on the subsurface strata, the GWT could remain at high levels for an extended period (seasons) (it is important to differentiate between the RDII infiltration stage due to the immediate storm event versus the seasonal nature of groundwater infiltration that takes place during DWF).

11.3.2 Splitting an RDII Flow Hydrograph into Three RDII Stages

Based on the general characteristics of the three RDII stages presented in the previous section, some general conclusions can be applied to an observed RDII hydrograph. For example, Figure 11.10 presents a synthetic RDII hydrograph generated from a rainfall that has several time steps, a drainage basin that has several sub-sewersheds and a collection system with multiple input locations.

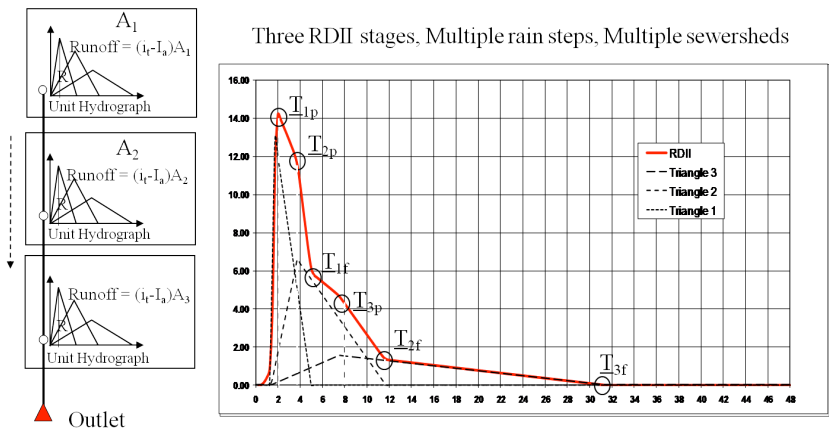


Figure 11.10 Splitting RDII Stages from an RDII flow hydrograph resulting from several rainfall time steps over several sub-sewersheds.

Figure 11.10 presents the RDII response from each stage separately, then the three stages are added together to represent the total RDII hydrograph. The following conclusions can be drawn from the hydrograph presented in Figure 11.10:

- the slope of the rising limb of the hydrograph is highly influenced by the rising limb of the first stage of the RDII process;
- the slope of the tail portion of the recession limb of the hydrograph can be attributed to the third stage of the RDII process; and
- the points at which the rate of change of flow (hydrograph slope) is discontinuous correspond to either a peak or an end of one of the RDII stages:
  - if the discontinuity leads to a smaller rate of change of flow (steeper slope), the time stamp of the discontinuity indicates a peak of one of the stages (see  $T_{1p}$ ,  $T_{2p}$  and  $T_{3p}$  in Figure 11.10); and
  - if the discontinuity leads to a larger rate of change of flow (shallower slope), the time stamp of the discontinuity indicates an end of one of the RDII stages (see  $T_{1f}$ ,  $T_{2f}$  and  $T_{3f}$  in Figure 11.10).

It is very common that the characteristics of the RDII hydrograph replicate the conceptual RDII hydrograph presented in Figure 11.10. The peak flow time stamp for the first RDII stage,  $T_{1p}$ , will usually correspond to the peak time of the RDII hydrograph as shown in Figure 11.10. Similarly,  $T_{3f}$  for the third RDII stage can be identified from the RDII hydrograph point at which RDII drops to zero at the end of the RDII response. The remaining four time stamps,  $T_{2p}$ ,  $T_{3p}$ ,  $T_{1f}$ , and  $T_{2f}$  can be located using the RDII hydrograph by tracking the most distinct discontinuity as illustrated in Figure 11.10.

Knowing the peak and final times of each RDII stage will allow separation of the RDII hydrograph into its three RDII stages. This can be achieved by starting with separating the third RDII stage since its recession limb is not affected by the other two RDII stages. Equations 11.9, 11.10 and 11.11 can then be used to calculate the  $R_k$ ,  $T_k$  and  $K_k$  ( $k = 1, 2, 3$ ) parameters needed to simulate each of the three RDII stages. In these equations, rain information ( $t_{co}$ ,  $t_{cp}$ ,  $d_r$  and  $i_{total}$ ) will be obtained from the rain gauge data. The total serviced area and length of the pipes for averaging  $T_{pipe}$  can be obtained from GIS layers. The RDII stage characteristics  $T_{p1}$ ,  $T_{p2}$ ,  $T_{p3}$ ,  $T_{f1}$ ,  $T_{f2}$ ,  $T_{f3}$ ,  $Q_{p1}$ ,  $Q_{p2}$  and  $Q_{p3}$  are obtained from the flow hydrograph by tracking the discontinuities as explained above.



### 11.3.3 Simulating RDII stages in Continuous Simulation

The calibrated SWMM RTK parameters for each RDII stage can then be used to simulate RDII in continuous simulation. These parameters are used in SWMM to calculate the flow input hydrographs at each model node defined to receive RDII. At each time step  $\Delta t$ , the volume of each of the three RDII hydrograph from each sub-sewershed will be calculated as follows:

$$RDIIvolume_{k,\Delta t} = R_k * A_{Served-sub} * (i_{\Delta t} - n_{dry} * Rec_k) \quad (11.13)$$

where:

$(RDII\ volume)_{k,\Delta t}$  = triangle  $k$  volume (corresponding to the RDII stage  $k$ ) calculated at each time step  $\Delta t$ ,

$R_k$  = percentage of runoff (excess rain) for each RDII stage that will enter the collection system at each model node defined to receive RDII (constant per monitored sewershed since they are a function of the size and number of collection system defects, which are not storm specific),

$A_{Served-sub}$  = serviced portion of the sanitary sub-sewershed area upstream of the flow meter (this user-defined value is obtained using GIS or aerial maps and knowledge of the sanitary servicing provided by both public and private sewers),

$i_{\Delta t}$  = depth of the precipitation portion during each model time step (if the rainfall time step is larger than the model time step, SWMM divides the rain time step as an integer multiple of the model time step),

$n_{dry}$  = the number of dry days since the last rainfall event, and

$Rec_k$  = storage recovery rate parameter for each RDII stage. SWMM allows the user to define different  $Rec_k$  for each month.

In Equation 11.13, the available abstraction at the beginning of the event for each RDII stage is calculated using the stage recovery rate  $Rec_k$ . The total initial abstraction for each RDII stage at the start of each storm event is calculated by SWMM in continuous simulation based on the number of dry days since the previous rainfall event multiplied by the storage recovery rate per day as defined by the user. The RDII volume for each of the RDII stages is calculated only after the accumulated rainfall time step is greater than the initial abstraction. SWMM then applies the  $T_k$  and  $K_k$  parameters to the calculated RDII volumes to shape the three RDII stages at the inflow points.

The calculated flow hydrographs at the identified inflow manholes are routed through the collection system network. The simulated flow hydrograph at the flow meter location can then be compared against the observed hydrograph to confirm the calculations for the RDII parameters.

## 11.4 Calibration Event Selection Procedure

### 11.4.1 Antecedent Moisture Condition Considerations

The calculation methodology presented in this chapter favours the practice that defines the  $R$  value as a constant function of the system defects, and the initial abstraction  $I_a$  as a variable function of the antecedent moisture condition (Gheith, 2010). This practice is appropriate for continuous simulation because it is representative of true field conditions. This is due to the fact that the  $R$  value is defined as the percentage of runoff volume that enters the system through the collection system defects. These defects are not seasonal nor are they event related. On the other hand, the value for  $I_a$  is variable and based on climatic conditions through the user defined storage recovery rate during dry periods and due to the seasonal variability as defined by the user. Parameters that are different from one season to another are storage recovery rate and maximum storage. Seasonally, the recovery rate is expected to change based on vegetation, temperature, wind speed, radiation, humidity and other possible climatic effects. Also, it is expected that the maximum basin storage will change seasonally based on the GWT elevation and vegetation. That is why the initial storage is highly variable and difficult to calculate. Ignoring it could also mislead any attempt to correlate to RDII. Figure 11.11 is a representation of the climatic conditions affecting  $I_a$ .

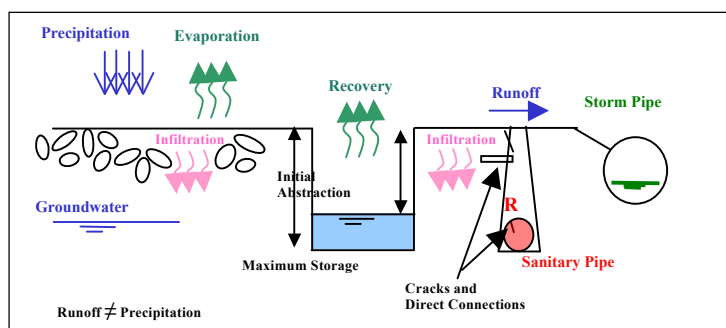


Figure 11.11 Conceptual representation of storage recovery between storm events.

A portion of the precipitation is lost due to ground wetting, infiltration, evaporation, transpiration, and other types of water storage or losses. The recovered storage before any event (initial abstraction) could be anywhere between zero and the maximum basin storage volume as described in Equations 11.14 and 11.15. As a result, in most wet weather events runoff does not equal precipitation. The initial abstraction varies between zero at completely saturated conditions (no available storage) to a maximum value of  $S_{max}$  after prolonged dry weather conditions.  $S_{max}$  is a user defined parameter which is a function of sewershed topography, slope, subsurface soil type and GWT elevation.

$$I_n = n_{drydays} * \text{recovery rate} \quad (11.14)$$

where:

$$S_{max} \geq I_a \geq 0 \quad (11.15)$$

Figure 11.12 represents a saturated soil condition that can take place when there are back-to-back storms. If the system reaches a completely saturated condition during one storm event and another storm event occurs shortly thereafter, precipitation from the second storm will almost entirely become runoff. This is due to the fact that at this condition  $I_a$  can safely be assumed as zero in Equation 11.9. In this case,  $R$  can be calculated easily using Equation 11.9.

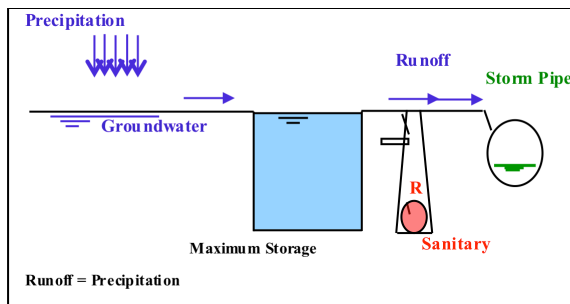


Figure 11.12 Representation of saturated condition:  $I_a$  is almost zero.

#### 11.4.2 Preferred Storm Event for Continuous Calibration

It is important to select a suitable initial calibration storm for the continuous calibration procedure. A good selection of an initial storm event would lead to the best fit RDII parameters without the need to repeat the process in many events. There are two considerations to define a good initial calibration event. The first consideration is that the event-specific parameters can

be ignored without affecting the calculation of the remaining parameters that are constant between the events. As explained previously, parameters that are event-specific are the initial abstraction and the number of dry days. The second consideration is that the storm event should be dominated by high intensity rainfall time steps. This will facilitate the application of the procedure presented in this chapter.

In the Midwest climate, the first consideration can be achieved by using storms that take place in the winter season, in which the GWT is high and temperature is low. The recovery rate will be very small and the initial abstraction term in Equation 11.13 will be minimal. As shown in Table 11.1, the difficulty associated with winter storms is that, in the Midwest climate, rainfall is usually of low intensity and is usually associated with freezing rain or snow melt conditions. On the other hand, summer storms are usually characterized by high intensity rainfall. The difficulty is that the storage recovery rate in the summer season is high and initial abstraction varies greatly, depending on temperature and other climatic conditions and on the number of dry days before each event.

A storm that will meet both considerations would be a summer storm that is shortly preceded by another storm. The first storm will bring the watershed to saturated conditions. The short period before the start of the second storm will result in a minimal initial abstraction. It is recommended to increase the  $R$  values by 5% to 10% to accommodate the small initial abstraction value between the two summer storms. Note that the procedure detailed in this chapter does not require that the second storm, which will be used to calculate the RDII stages and parameters, be a large recurrence frequency storm. In contrast, it is better to avoid storms with attenuation in the flow hydrograph due to possible downstream backups, capacity limitations within the monitored portion of the collection system, and upstream overflows or flooded manholes. Examples of such storms may be found in Table 1.4 of Gheith (2010).

Table 11.1 Possible storm for initial calibration step.

| Storm Type   | Advantages  | C  |
|--|---|--|
| Winter storm                                       | Minimum $I_a$ effects                                       | Low intensity<br>Freezing rain<br>Snowmelt<br>$I_a$ is maximum |
| Summer storm (preceded by long dry weather period) | Sharp short rain<br>High Intensity                          |  |
| Summer storm (preceded shortly by another storm)   | Sharp short rain<br>High Intensity<br>Minimum $I_a$ effects | $R$ values could be affected by the preceding storm event      |

## 11.5 Conclusions

This chapter presented a step by step approach for splitting the observed RDII hydrograph from a flow meter record into the three distinct stages of RDII: inflow, delayed inflow, and groundwater infiltration. This approach depends on the idea that certain dominating stages of the RDII process take place at different time frames during the RDII process. The discontinuities in the rate of change of the flow (slope of the flow hydrograph) are used to define the peak and end of each RDII stage. These stages of RDII can then be simulated in SWMM using the RTK triangle unit hydrograph procedure, replacing the need for a trial and error approach. A step by step procedure is demonstrated to calculate a set of RTK parameters needed for continuous simulation.

The approach allows for a more reliable system evaluation which will lead to better selection and prioritization of the RDII remediation actions. The distinct and careful calculation of each of the three RDII stages using the proposed calculation procedure allows for better decisions on the impact of RDII reduction plans. For example, if point source defect or illegal connections exist in the field, it will be clearly presented in the inflow unit hydrograph through  $R_I$ ,  $T_I$  and  $K_I$ . The effect of eliminating this RDII source can easily be applied in the calibrated model by reducing the contribution of the first triangle only. The benefit of lining or replacing all lateral connections can usually be better evaluated by eliminating the RDII pathways that are represented by the second triangle. Similarly, the effect of lining all collectors and interceptors to evaluate the effect of reducing infiltration can be tested by reducing the contribution from the RDII pathways that are represented by the third triangle in the calibrated model.

## References

- City of Columbus Department of Public Utilities, Division of Sewage and Drainage, 2009. West Fifth I/I Study Report.
- Gheith, H. 2010. "A Stepped Approach to Generating a Single Set of RTK Parameters for Continuous Calibration." *Journal of Water Management Modeling* R236-01. doi: 10.14796/JWMM.R236-01.
- Huber, W. and Dickinson, R., 1988. Storm Water Management Model Version 4, User's Manual, EPA/600/3 88/001a (NTIS PB88 236641/AS). Athens, GA: USEPA.
- Lai, F., 2008. Review of Sewer Design Criteria and RDII Prediction Methods, EPA/600/R-08/010. USEPA.
- Vallabhaneni, S., Chan, C. and Burgess, E., 2007. Computer Tools for Sanitary Sewer System Capacity Analysis and Planning, EPA/600/R-07/111. USEPA.

