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Comparison of RDII Unit Hydrograph Approaches for Continuous Simulation using SWMM 5

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Continuous simulation of collection systems allows the modeler to quantify the frequencies of overflows, runtimes of pumps, utilization and dewatering durations of storage, and other important characteristics of wet-weather system performance. SWMM 5 uses the RTK unit hydrograph approach to calculate rainfall derived inflow and infiltration (RDII). SWMM 5 allows up to eighteen empirically derived unit hydrograph parameters which may be varied monthly. These parameters can be used in different ways through various emphases and parameter combinations including omission of some of the parameters (Gheith, 2009). In some cases similar accuracy can be attained in a particular objective measure, such as peak flow, when using another approach. A consistent approach is recommended to facilitate more equitable comparisons between modeled sanitary sewer service areas, both in terms of the parameters used and the simulation results produced.

Using available flow monitoring data from the Sewer System Capacity Model Update 2006 project for the City of Columbus, Ohio, wet weather flow responses were analyzed seasonally (dormant and growth seasons). A sample flow meter basin was selected and several RDII unit hydrograph approaches were compared using the flow and rainfall data selected for a 16 month period. The analysis indicated that seasonally varied RTK with monthly varied initial abstraction parameters (D_{max}, D_{rec} and D_0) provide the best simulation results for both large and small storms. However, seasonally-

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varied RTK with seasonally varied initial abstraction parameters (D_{max}, D_{rec} and D_0) may be more appropriate with limited monitoring data to support planning solutions. This chapter first compares different approaches in terms of the accuracy of the model calibration results, and then further discusses the alternative approach when data availability is limited.

12.1 Introduction

Continuous simulation of collection system hydrology and hydraulics has become more practical and desirable over the past decade (Yeboah and Heineman, 2004). Compared to single event simulation, continuous simulation can more correctly represent the antecedent conditions by incorporating processes of both dry weather periods and wet weather periods. Continuous simulation modeling has been applied to various aspects of collection system planning, design and management, especially for combined sewer overflow (CSO) long term control plans, sanitary sewer overflow (SSO) controls, and storage and pump facility applications in sanitary sewer system.

The unit hydrograph approach is one the most popular empirical approaches to simulated rainfall derived inflow and infiltration (EPA, 2008). As public domain software, EPA SWMM 5 has been widely used for continuous hydrology modeling with the unit hydrograph approach (Yeboah and Heineman, 2004). Prior to SWMM 5, the SWMM 4 unit hydrograph approach had eighteen empirical parameters and twelve month applications in the RUNOFF block, which could simulate RDII continuously. The continuous flow generated from the RUNOFF block could further be input to the TRANSPORT block and then the EXTRAN block for flow routing (TenBroek et al., 1998). SWMM 4 RUNOFF generated flow/hydrology could also be loaded as input to NetSTORM software for continuous simulation modeling. Earlier version of SWMM 5 (through build 5.0.009) excluded all the IA parameters from the unit hydrograph method. Starting from SWMM 5 build 5.0.010, IA parameters were partially reinstated, and since build 5.0.015, SWMM 5 can define up to eighteen empirically derived unit hydrograph parameters on a monthly basis to calculate RDII. Given sufficiently accurate monitored data, these parameters can be used in different ways to achieve similar calibration results. However, monitored data are often limited and short term, so the user will need to choose the best approach for the specific applications.

12.2 Approaches of Continuous Hydrology Simulations

12.2.1 Study Area

As part of the Sewer System Capacity Model Update 2006 project for City of Columbus (Ohio), over 100 flow meters were installed and continuously monitored for sixteen months from January 2008 to May 2009. Meter basin SC-MI-12 (460 acres, 186 ha, separate sewer system and residential dominant land use) was selected to compare the different approaches of continuous simulation.

12.2.2 Various RDII Approaches

RDII flow can be affected by various factors, such as vegetation coverage, groundwater table, temperature, and evaporation rate. These factors are also influenced by the season of the year. For instance, without applying IA parameters, basin SC-MI-12 showed total R (percentage of rainfall entering the system) ranging from 4% to 26% within the monitoring period. The primary reasons for the wide range of total R are seasonal changes and antecedent moisture condition changes within season. The other (secondary) differences can be storm characteristics and when certain I/I pathways are utilized.

To better represent the physical system using a model, it is important to understand how the RDII response varies throughout the year. Figure 12.1 demonstrates a significant seasonal variation of RDII response. X-axis is the cumulative rainfall from Jan. 20th, 2008 to May 20th, 2009. Y-axis is the cumulative response during the same period. The cumulative response and rainfall are calculated by Equations 12.1 and 12.2.

$$Cr_n = \frac{\sum_{t=1}^{n}(Q_t - Q_{\min})}{A} \times 12 \tag{12.1}$$

$$CP_n = \sum_{t=1}^{n} P_t \tag{12.2}$$

where

Q_t = daily flow volume at day t (ft^3),
Q_{min} = minimum daily flow volume during the period (ft^3),
n = total number of days prior to day t,
A = total tributary area (ft^2), and
P_t = daily rainfall at day t (inch).

The number 12 is a dimensionless unit conversion factor (feet to inches). Q_{min} does not vary with season for this specific monitored basin due to the residential land use.

As seen in Figure 12.1, the slopes of the fitted straight lines indicate the altitude of the wet weather flow responses to rainfall. It appears that during the months of December through April, wet weather flow responses are much higher than during the months of May through November with same amount of rainfall. The season December to April is defined as the dormant season and the season May to November is defined as the growth season. The breakpoint at which RDII seasons change may vary depending on the year considered. Therefore, the longer the record, the greater the understanding of when breakpoints are most likely to occur.

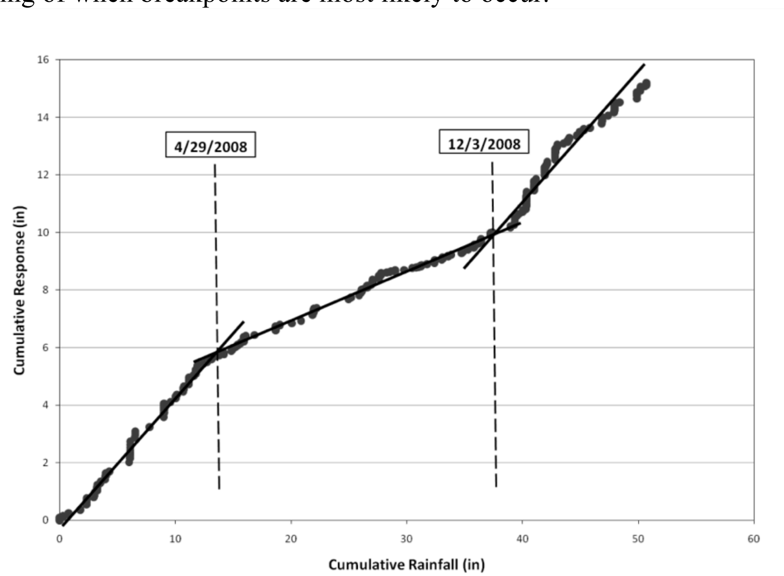

Figure 12.1 Seasonal variation of RDII response.

In SWMM 5, RDII flow can be simulated by unit hydrograph approach using up to eighteen parameters (EPA, 2009) on a monthly basis. Three sets of unit hydrographs define the short term, intermediate term and long term response of inflow and infiltration. Each of the three unit hydrographs includes six parameter, R, T, K, D_{max}, D_{rec} and D_0 (EPA 2009). The first three parameters are used to define the shape of the unit hydrograph and the last three parameters are used to represent the antecedent conditions and simulate initial abstraction (IA, the amount of rainfall that does not produce any I/I response). The definitions of these parameters are:

R = the fraction of rainfall volume that becomes inflow/infiltration (%),

T = the time from the onset of rainfall to the peak of unit hydrograph (hrs),

K = the ratio of the time to recession of the unit hydrograph to the time to peak,

D_{max} = the maximum possible depth of initial abstraction (inch); it is the maximum storage available for initial abstraction,

D_{rec} = the recovery rate at which stored initial abstraction is depleted during dry periods (inch/day), and

D_0 = the initial depth of stored initial abstraction (inch); it is the storage being utilized at the beginning of the simulation.

In practice, the eighteen parameters can be adjusted differently to produce more or less accurate model calibration results. The possible approaches are:

1. Fixed RTK without IA;
2. Fixed RTK with variable IA;
3. Variable RTK without IA; and
4. Variable RTK with variable IA.

Approach 1 is the least preferred approach because RDII response varies season by season, storm by storm both through the influence of variable antecedent moisture conditions and storm characteristics. Approach 2 has been studied by others (e.g. Gheith, 2009); this chapter focuses on comparing approaches 2, 3 and 4 with seasonal and monthly variations of the parameters.

Table 12.1 lists the variations of the unit hydrograph parameters in the models for comparison purposes. The models are first calibrated to a dormant season storm with the highest or longest RDII response. Then the same T and K are applied to all the twelve months. Further, growth season Rs are developed for model 1 to calibrate to the highest or longest RDII response within the growth season. Finally, IA parameters are developed for model 2 and model 3. As listed in Table 12.1, Dormant RTKs are the same in all the models and Growth *RTK*s are the same in all the models applied. Dormant IAs (D_{max}, D_{rec} and D_0) are the same parameters used in all the models applied and same as Growth IAs (D_{max}, D_{rec} and D_0).

Table 12.1 Models with different UH parameters.

	Model 1	Model 2	Model 3
RTK	Dormant RTK Growth RTK	Dormant RTK	Dormant RTK Growth RTK
IA	No IA	Dormant IA Growth IA	Dormant IA Growth IA

During the monitoring period, significant hydrologic conditions were noted in March and June of 2008. Substantial snow melting occurred during March 2008; although this month produced the highest wet weather response, the amount of snow melting could not be accurately quantified. Therefore March 2008 is not selected to represent dormant season RTK. Rainfall >25 y recurrence rainfall occurred during June 2008; therefore storms in June 2008 are not selected to represent the growth season RTK. The February 5th 2008 storm appears to have the highest RDII response (highest total *R*) with two peaks. The highest peak of the RDII response occurred on February 6th, 2008 with saturated antecedent conditions (Peak 2, Figure 12.2). Therefore, the highest peak of the RDII response caused by February 5th, 2008 storm is selected to represent dormant season with zero initial abstraction, and the dormant season RTK without IA is developed to match to the second peak (Peak 2, Figure 12.2). As indicated in Figure 12.2, model 1 overestimates the peak and volume for smaller storms. For February 12th, 2008 storm, model 1 overestimates the peak over 120%, while model 2 and model 3 overestimate peak by 60%.

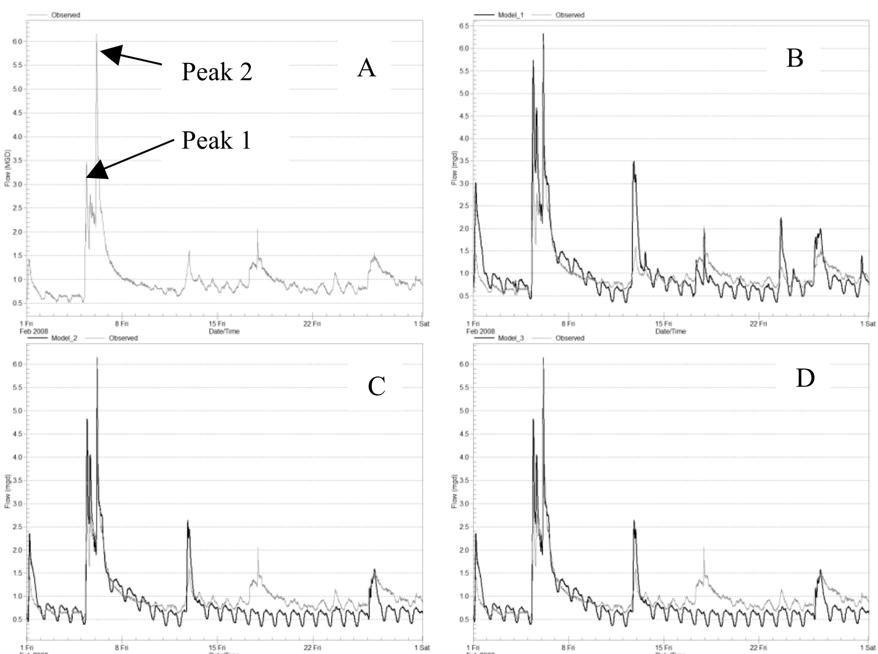

Figure 12.2 Calibration results of model 1, model 2 and model 3 for Feb. 2008 (dormant season): A Observed data; B Model 1 vs Observed; C Model 2 vs Observed; D Model 3 vs Observed.

For model 1 and model 3, growth season RTK is developed to calibrate against November 15th, 2008 storm. This storm also produces multiple peaks in the RDII responses and the highest peak occurs with wet antecedent condition. As seen in Figure 12.3, for two smaller storms, November 7th and November 24th model 1 overestimates the peaks by over 50%, while model 2 overestimates by less than 10%. Model 3 overestimates the peak of November 7th by 3%, but underestimates the peak of November 24th by 20%. The total volume of model 2 and model 3 are 3% and 5% less than the observed volume, respectively. Figure 12.4 shows the calibration results for another growth season month (September, 2008). Model 1, model 2 and model 3 overestimate the highest peak (September 5th, 2008) by 38%, 68% and 23% respectively.

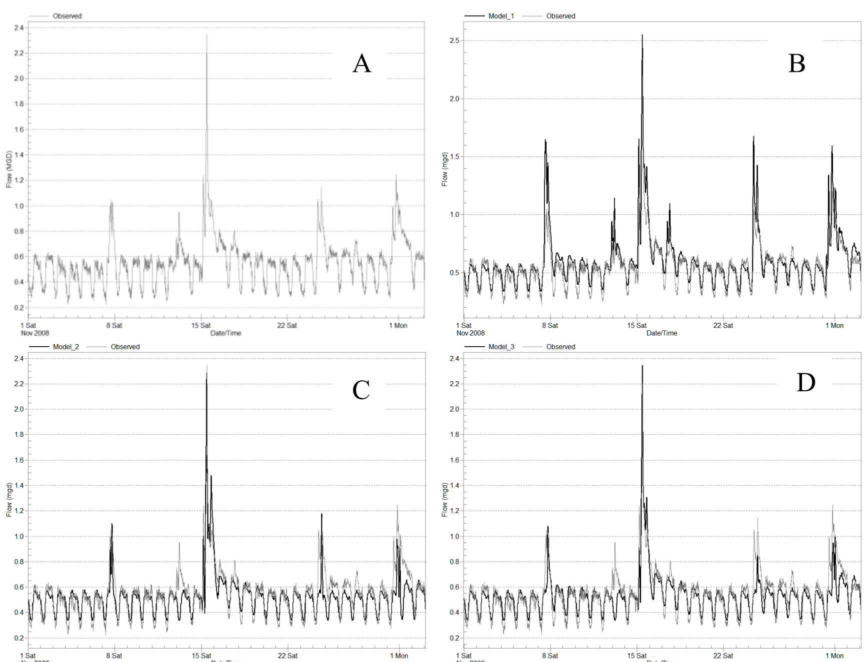

Figure 12.3 Calibration results of model 1, model 2 and model 3 for Nov. 2008 (growth season): A Observed data; B Model 1 vs Observed; C Model 2 vs Observed; D Model 3 vs Observed.

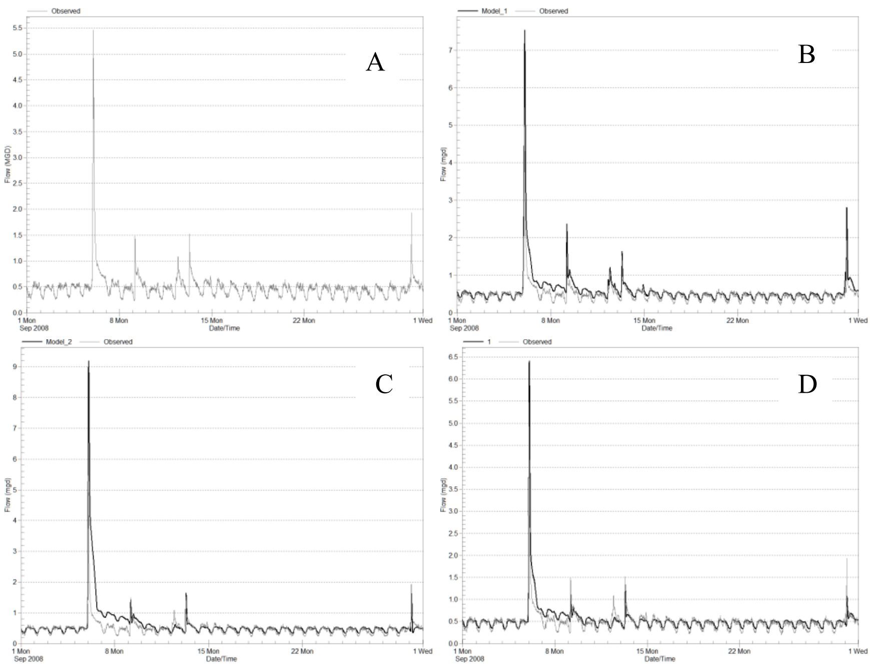

Figure 12.4 Calibration results of model 1, model 2 and model 3 for September 2008 (growth season): A Observed data; B Model 1 vs Observed; C Model 2 vs Observed; D Model 3 vs Observed.

Within 2008 (excluding March and June), for meter basin SC-MI-12, a total of twenty storms produced a RDII response at least twice as much as the dry weather peak flow (peak observed flow rate >2 MGD). Simulation results of those twenty storms are represented in Figure 12.5. The diagonal line of the scatter plots shows the perfect match of simulated results to observed data and the two dash lines indicate the ± 15% error margin. Figure 12.5 demonstrates that model produces better continuous calibration results with IA parameters (model 2 and model 3). In addition, model performs continuous simulation better with seasonal varied RTK (model 3) than fixed RTK (model 2).

To further improve the simulation results, 2 extra models (model 4 and model 5) are developed to consider monthly varied parameters. Model 3 is selected and compared to model 4 and model 5 and the unit hydrograph parameters are summarized in Table 12.2.

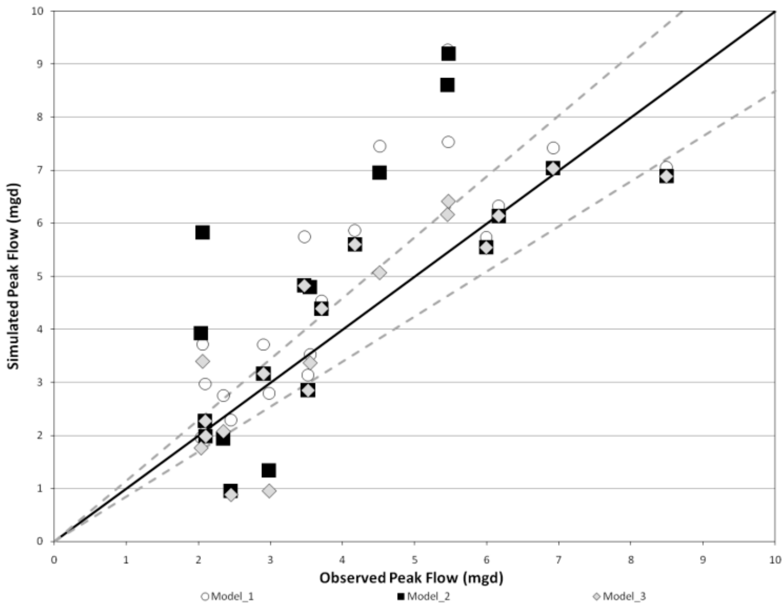

Figure 12.5 Scatter plots of peak flow calibration results of model 1, model 2 and model 3 for twenty storms in 2008.

Table 12.2 Additional models with different UH parameters.

	Model 3	Model 4	Model 5
RTK	Dormant RTK Growth RTK	Dormant RTK	Dormant RTK Growth RTK
IA	Dormant IA Growth IA	Monthly IA	Monthly IA

As seen in Figures 12.6, 12.7, 12.8 and Table 12.3, model performs continuous simulation better with seasonal varied RTK and monthly varied IA (model 5) than Fixed RTK and monthly varied IA (model 4) in terms of matching peak flow rate to the observed peak. However, both model 4 and model 5 show better calibration results than model 3 for both large (peak ≥4 MGD) and small storms (peak <4 MGD) (Table 12.3).

Table 12.3 Summary of storms with simulated peak rates within/outside ±15% from the observed peak flow for all models; large storms are defined as peak flow ≥4MGD (8 storms) and small storms are defined as peak flow <4 MGD (12 storms).

	Model 1	Model 2	Model 3	Model 4	Model 5
Total No. Storms	20	20	20	20	20
No. Storms within ±15%	9	6	11	10	12
No. Large Storms within ±15%	3	3	5	6	6
No. Small Storms within ±15%	6	3	6	4	6
No. Large Storms outside ±15%	5	5	3	2	2
No. Small Storms outside ±15%	7	9	6	8	6

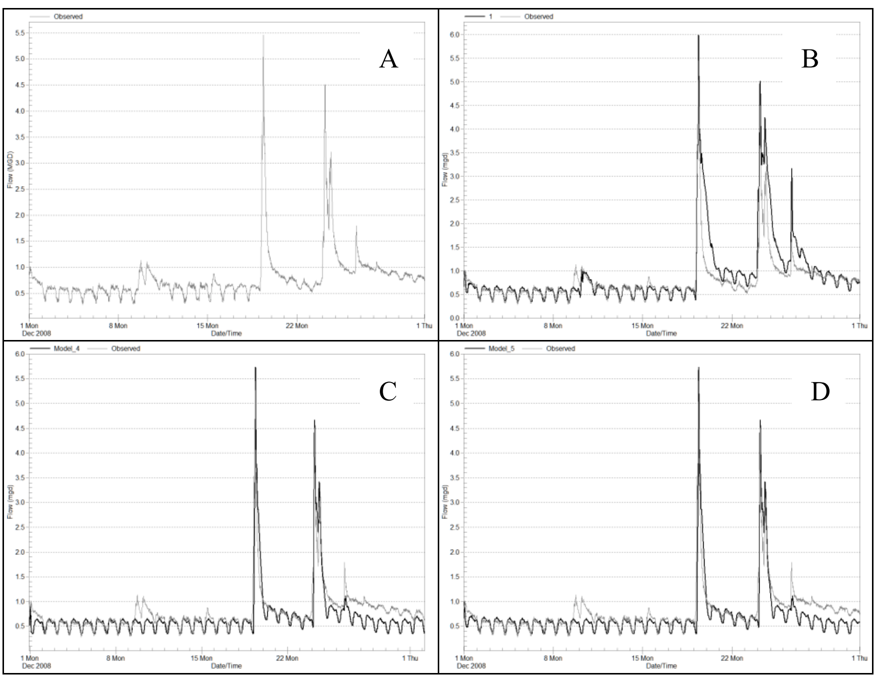

Figure 12.6 Calibration results of model 3, model 4 and model 5 for December 2008: A Observed data; B Model 1 vs Observed; C Model 2 vs Observed; D Model 3 vs Observed.

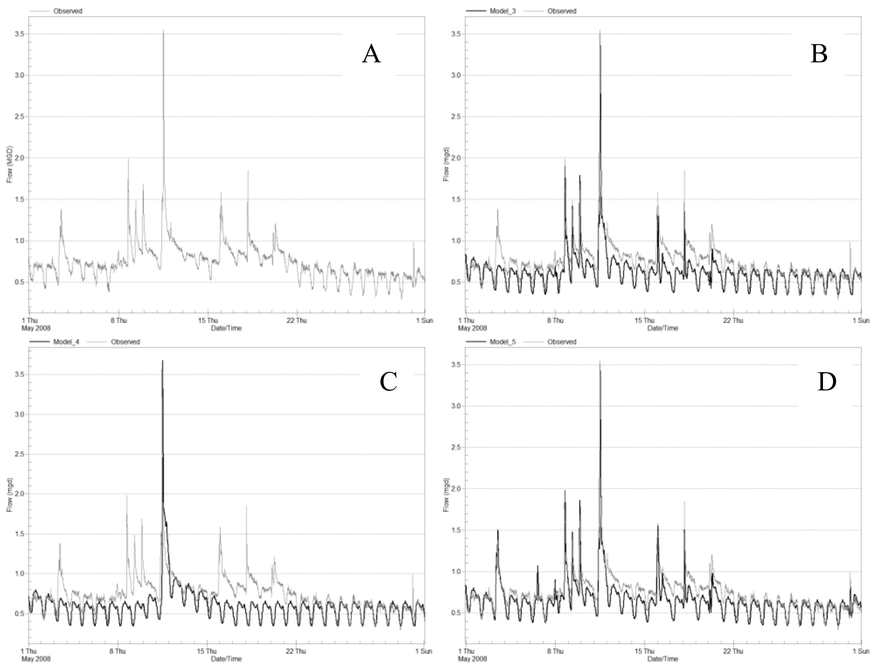

Figure 12.7 Calibration results of model 3, model 4 and model 5 for May, 2008: A Observed data; B Model 1 vs Observed; C Model 2 vs Observed; D Model 3 vs Observed.

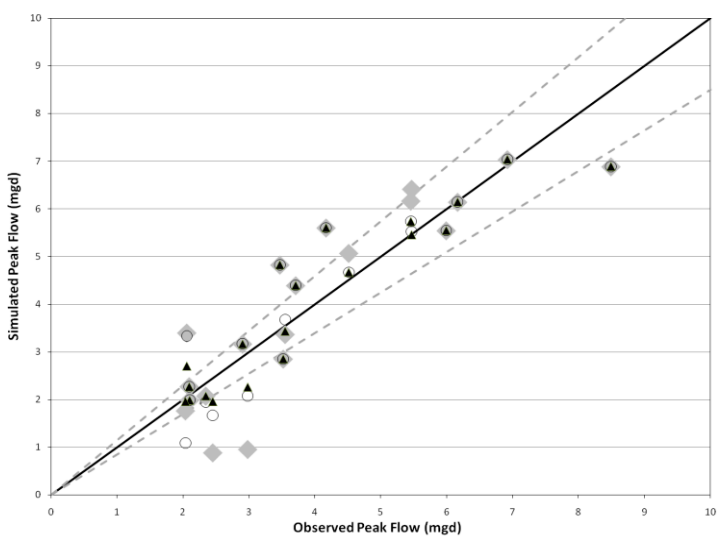

Figure 12.8 Scatter plots of peak flow calibration results of model 3, model 4 and model 5 for twenty storms in 2008.

The above modeling results indicate seasonal RTK with monthly IA (model 5) produces the best calibration results. However, the user needs to be aware of the limitation of this approach. This approach assumes that the one-year of observed data can well represent the typical year condition. It is well known that year-to-year variation factors such as rainfall, groundwater level and temperature can influence RDII. Seasonal RDII may also vary because of the influence of these factors (i.e. the seasonal breakpoints shown in Figure 12.1 may occur at different times in other years). Therefore, long term (multiple years) observed data are necessary to develop statistically representative monthly IA parameters. The monthly IA parameters developed with single year observations are less likely to be representative of monthly variation given the small number of storm events within a given month. On the other hand, seasonal RTK with seasonal IA (model 3) produces relatively good agreement to the observation for the larger storms (Figure 12.8 and Table 12.3). For model 3, the simulation results outside of the ± 15% range of the error margin are more associated with smaller storms. In engineering practice, the moderate to large storms are more likely to be used as design criteria and tend to be the key drivers for solutions. However, pump runtimes or the ability to dewater storage facilities may be influenced by smaller storms. In that case, the modeler may need to understand the significance of this uncertainty by evaluating model sensitivity to expected variation in specific parameters.

12.3 Conclusions

The various approaches of continuous simulation can produce more or less accurate calibration results. Seasonal RTK with monthly IA parameters (model 5) appears to perform the best in terms of matching both peak and volume for wide ranges of rainfall and RDII response. However, this approach requires multiple years of continuous monitoring which may not be cost effective. Alternatively, a model with seasonal RTK and seasonal IA performs (model 3) very well for moderate to large RDII responses, but this approach should be applied carefully if smaller RDII responses need to be taken into account.

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