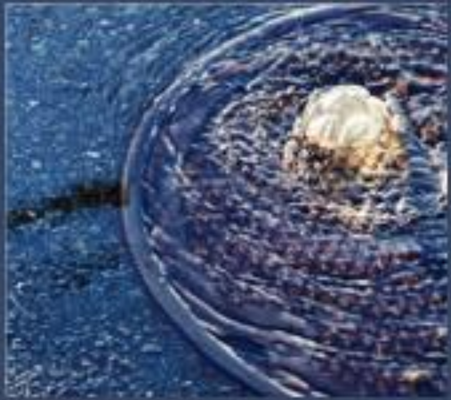
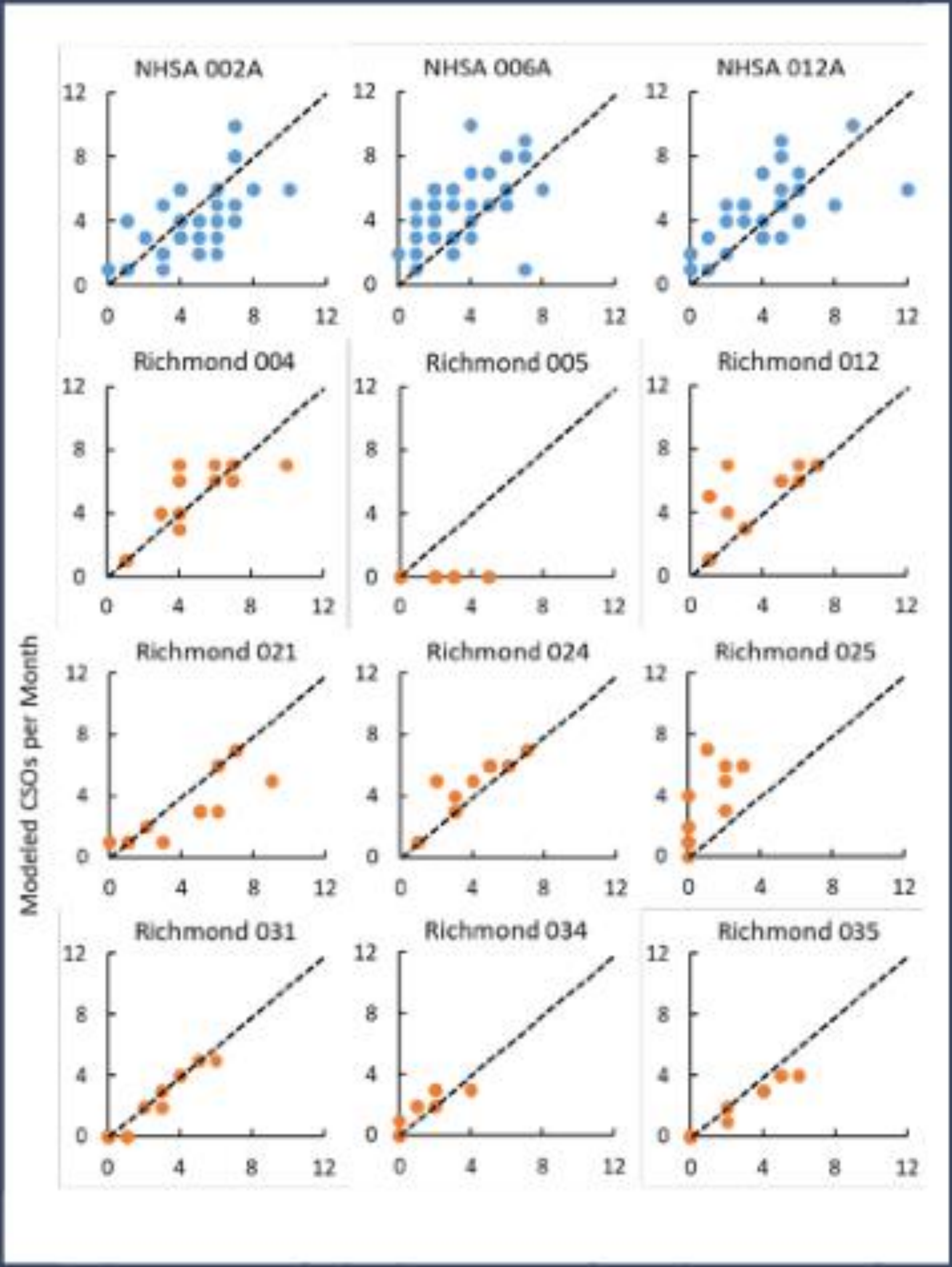
Combined Sewer Overflow (CSO) Model Validation Study





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Disclaimer

The U.S. Environmental Protection Agency (EPA) has designed the Combined Sewer Overflow (CSO) Model for Small Communities as a tool to help small CSO communities reasonably estimate CSO volume and occurrence. EPA is not mandating the use of this model under the 1994 CSO Control Policy or the use of the presumption approach under the 1994 CSO Control Policy. This document is not itself a regulation, nor is it legally enforceable. Rather, it provides a guide to the CSO Model that communities may use in analyzing combined sewer systems and reasonably evaluating the presumption approach criteria to design or estimate sewer overflow volume and/or occurrence. Communities, small or otherwise, might find the model useful and should consult with their National Pollutant Discharge Elimination System permitting authorities to determine whether it is appropriate for them to use the CSO Model for Small Communities. Any mention of trade names, manufacturers, or products in this document does not imply an endorsement by the United States Government or EPA.

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Abbreviations

CSO	combined sewer overflow
CSS	combined sewer system
DCIA	directly connected impervious area
EPA	United States Environmental Protection Agency
HWU	Henderson Water Utility
in.	inches
LTCP	long-term control plan
MG	million gallons
MGD	million gallons per day
min	minute
NHSA	North Hudson Sewerage Authority
NPDES	National Pollutant Discharge Elimination System
t_c	time of concentration

Overview

The Combined Sewer Overflow (CSO) Model for Small Communities (hereafter referred to as the "CSO Model") is a spreadsheet-based planning tool for small communities that want a simple approach to estimating a CSO occurrence, as well as treated or untreated CSO volume over a 24-hour period, and have limited resources to invest in more advanced CSO monitoring and modeling. The CSO Model may also be used to estimate the CSO controls, either green or gray, needed to meet the presumption approach criteria (i) or (ii) in designing a CSO long-term control plan (LTCP). The CSO Model is designed for small CSO communities that have relatively simple combined sewer systems (CSSs). However, large CSO communities, with populations of greater than 75,000, might find the CSO Model useful if they need to update their existing models, or as a first step before using more expensive models. CSO communities that have many CSO outfalls and complex systems can also use the CSO Model by breaking down their CSS into sub-sewersheds based on receiving waterbodies and sewer infrastructure.

The CSO Model is based on a modified version of the Rational Method with a computational timestep of 15 minutes. Runoff response depends on sub-sewershed impervious area and time of concentration (t_c). Routing is performed using minimal, straightforward input, including dry weather flow definition, presence of green or gray volume controls, and regulator capacity. For additional information about the model itself, see the CSO Model User Guide.

As part of model development, the U.S. Environmental Protection Agency (EPA) performed a validation study to evaluate the CSO Model and determine changes to improve its accuracy and usability. For the validation study, EPA used data from six communities, 28 individual sub-sewersheds with CSSs, and 2,302 CSO events. Given the variety of data types available for model validation, EPA used multiple approaches divided into two major phases of testing to evaluate different aspects of the CSO Model. The first phase of testing used a preliminary version of the CSO Model to test its major components, such as its timestep and its use of percent imperviousness as a runoff coefficient. The second phase of testing used the final version of the model, also referred to as the Revised CSO Model, which EPA revised based on findings from the first round of testing. The main objectives of the second phase of testing were to provide an evaluation of the level of accuracy that could be expected of the final CSO Model and to illustrate different ways in which the CSO Model could be used.

Validation Study Partners

EPA worked with six partner communities for this validation study, including:

- Elisabeth, New Jersey
- Henderson Water Utility, Kentucky
- North Hudson Sewerage Authority, New Jersey
- Omaha, Nebraska
- Richmond, Virginia
- Saco, Maine

This document summarizes data compilation, model validation, and model improvements in the following eight sections:

1. System Characterization and Monitoring Data
2. Effect of Timestep Aggregation on Observed Data
3. Effect of Timestep Aggregation on CSO Model Output
4. Accuracy of the Modified Rational Method in Quantifying Stormwater Runoff
5. Revised CSO Model—Runoff
6. Revised CSO Model—Overflow
7. Model Validation Conclusions
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System Characterization and Monitoring Data

Six CSO communities, which range in size and complexity, provided EPA with system characterization information and flow monitoring data. EPA worked with community staff and their contractors to identify individual sub-sewersheds that had sufficient monitoring data to be suitable for validating the CSO Model. EPA designed the CSO Model to simulate overflows from smaller systems (ideally less than 100 acres) with low complexity (e.g., minimal interconnections with other sub-sewersheds, simple routing, no tailwater effects). In total, EPA selected 28 sub-sewersheds across the six communities for various validation steps depending on the types of data provided. Test sub-sewersheds range in size from 12 to 493 acres, with a median and average size of 88 and 146 acres, respectively.

Table 1 summarizes system parameters of each sub-sewershed, including measurements in million gallons (MG) and million gallons per day (MGD).

Table 1. Characterization of CSO systems used for CSO Model validation.

Sub-sewershed/ CSO ID	Sub-basin area (acres)	Average impervious surface (%)	CSO hydraulic control capacity (MGD)	Total CSO volume control (MG)	Dry weather flow rate (MGD)
EPA Region 1: Saco, Maine					
001	18	69%	11.4	0	1.107
EPA Region 2: Elizabeth, New Jersey[a]					
001	439	58%	4.16	0.32	1.37
031	59.5	68%	3.00	0	0.24
036	210	46%	6.62	0	1.06
039	245	69%	21.5	0	0.70
040	34.9	63%	2	0	0.24
EPA Region 2: North Hudson Sewerage Authority, New Jersey					
002A (H1)	276	69%	0.1	0	0.16
006A (H5)	151	98%	2.4	0	0.67
012A (18PS)	85.9	47%	1.3	0	0.030
015A (W5)	36.9	80%	1	0	0.035
EPA Region 3: Richmond, Virginia[b]					
004	91.6	22%	1.4	0	0.22
005	11.8	31%	7.5	0	0.02
012	90.0	17%	1.3	0	0.17
014	394	36%	60	0	0.87
021	493	30%	20	0	0.26
024	197	14%	2.5	0	0.23
025	65.7	21%	2.4	0	0.18
026	101	15%	1.6	0	0.15
031	176	21%	13	0	0.35
034	63.0	35%	12.8	0	0.42
035	30.9	32%	5.2	0	0.16
039	174	22%	1.9	0	0.38

Sub-sewershed/ CSO ID	Sub-basin area (acres)	Average impervious surface (%)	CSO hydraulic control capacity (MGD)	Total CSO volume control (MG)	Dry weather flow rate (MGD)
EPA Region 4: Henderson Water Utility, Kentucky[c]					
003 - Ragan St.	347	20%	2.7	0	1.39
004 - Jackson St.	43.4	38%	5.6	0	0.17
007 - Powell St.	27	26%	3.4	0	0.11
EPA Region 7: Omaha, Nebraska[d]					
110	72.0	50%	Inflow only	NA	0.055
114	80.3	25%	Inflow only	NA	0.039
203	70.5	44%	Inflow only	NA	0.14

[a] Hydraulic control capacity is inferred from maximum observed regulator flow, or the difference between observed inflow and overflow. Dry weather flow is calculated as the average regulator flow for time steps in which no rain had occurred for at least three hours.

[b] Contractor provided impervious surface in the form of directly connected impervious area (DCIA). Therefore, EPA made no corrections for larger sub-catchments.

[c] CSO hydraulic control capacity is estimated based on values provided in the 2009 LTCP and known up-sizing of pipes to 18 inches. Dry weather flow is estimated using sub-basin acres provided by Henderson Water Utility's contractor and the method used in the 2009 LTCP, which allocated peak dry weather flow of 11.5 MGD to sub-basins by area. Average dry weather flow is assumed to be 50 percent of peak dry weather flow.

[d] Dry weather flow calculated as sum of 1) inflow and infiltration, 2) sanitary flow, and 3) commercial/industrial flow, as provided by contractors in Omaha, Nebraska.

EPA determined model inputs for the test sub-sewersheds using a variety of approaches that depended on the type of data provided by each community. In some cases, communities provided model inputs directly, whereas other communities provided spatial data and system reports that were used to define model inputs. In addition to files provided directly by the communities, the following resources—with URLs provided where available—were used for various aspects of system characterization:

- City of Elizabeth System Characterization Report (Mott MacDonald, 2019).
- North Hudson Sewerage Authority Selection and Implementation of Alternatives for the Adams Street Wastewater Treatment Plant (Jacobs Engineering Group, 2020).
- Richmond VA Wastewater Utility Website (City of Richmond, 2022).
- Henderson Water Utility Long Term Control Plan webpage and report (HWU and Strand Associates, Inc., 2009).
- City of Omaha Long Term Control Plan (City of Omaha, 2014).

EPA obtained CSO hydraulic control capacity (i.e., regulator capacity) directly from community personnel when possible. For many sub-sewersheds, these data were not available and EPA either estimated regulator capacity from design drawings or inferred it through analyzing the monitoring data. Similarly, when not provided directly, EPA estimated dry weather flow rate from design reports or calculated it from the monitoring data by averaging data for total inflow during periods three hours before or three hours after any recorded rainfall.

In addition to the basic characterization data provided in Table 1, EPA needed sewer network layout and elevation data to calculate t_c within the CSO Model. When not provided directly, EPA used network layouts in shapefile format, as well as publicly available digital elevation models, to identify the longest flow path length, upstream elevation, and downstream elevation. Table 2 presents these data.

Table 2. t_c inputs.

Sub-sewershed/CSO ID	Length of longest flow path (feet)	Elevation at upstream end of main flow path (feet)	Elevation at downstream end of main flow path (feet)	Slope (%)	t_c (hour)
EPA Region 1: Saco, Maine					
001	<1000	NA		2–4%	0.25
EPA Region 2: Elizabeth, New Jersey					
001	7281	33.6	10.9	0.3%	1
031	4644	28.6	12.5	0.3%	0.75
036	4725	41.9	24.1	0.4%	0.75
039	5798	29.2	11.5	0.3%	1
040	2928	21.1	7.9	0.5%	0.5
EPA Region 2: North Hudson Sewerage Authority, New Jersey					
002A (H1)	8269	Topography indicates minimal slope; no data available on subsurface pipes. Assume 0.5% slope.		0.5%	1
006A (H5)	5018			0.5%	0.75
012A (18PS)	4671			0.5%	0.75
015A (W5)	2660			0.5%	0.25
EPA Region 3: Richmond, Virginia					
004	t_c estimated directly by contractor to Richmond, VA.				0.25
005					0.25
012					0.25
014					0.5
021					0.5
024					0.25
025					0.25
026					0.25
031					0.25
034					0.25
035					0.25
039					0.25
EPA Region 4: Henderson Water Utility, Kentucky					
003	8925	367	354	0.5%	1
004	4536	426	354	1.6%	0.5
007	2217	423	354	3.1%	0.25
EPA Region 7: Omaha, Nebraska					
110	4524	1168	968	4.4%	0.5
114	6590	1204	958	3.7%	0.75
203	5167	1242	1100	2.7%	0.5

Communities also provided rainfall and flow monitoring data in a range of formats and temporal resolutions. Accordingly, EPA performed different types of model validations for each community, supported by the available data. For example, Elizabeth, New Jersey, provided data on continuous rainfall, runoff, and overflow time series. EPA used this data to compare modeled hydrographs to observed hydrographs at multiple points within a single sub-sewershed, allowing for detailed evaluation of runoff response and overflow hydrographs produced by the CSO Model. In addition, North Hudson Sewerage Authority (NHSA) provided data on rainfall and the number of CSO events per month, which allowed for an evaluation of the CSO Model's ability to predict the presence or absence of a CSO event from three years of historic rainfall patterns. Table 3 provides a characterization of the monitoring data available from each community, as well as the number of individual storm events used for validation purposes.

Table 3. Characterization of storm events used for CSO Model validation.

Community	Number of basins	Number of events	Rainfall per event (in.)	Rainfall data description	Runoff data description	Overflow data description
Saco, ME	1	22	0.31–4.3	15-minute timestep/ per event	N/A	Event size (MG) and magnitude (MGD)
Elizabeth, NJ	5	7	0.31–1.9	5-minute timestep/ continuous time series	5-minute timestep/ continuous time series	5-minute timestep/ continuous time series
North Hudson Sewerage Authority, NJ	4	259	0.1–3.1	15-minute timestep/ continuous time series	N/A	Number of overflows per month
Richmond, VA	12	79	0.1–2.2	15-minute timestep/ continuous time series	N/A	15-minute timestep/ continuous time series
Henderson Water Utility, KY	3	78	0.05–2.3	15-minute timestep/ continuous time series	N/A	5-minute timestep/ continuous time series
Omaha, NE	3	9	0.13–1.6	60-minute timestep/ continuous time series	15-minute timestep/ continuous time series	N/A

Effect of Timestep Aggregation on Observed Data

CSO events, especially in small communities, can be caused by fast, intense storms that often last under one hour. Models that average rainfall and runoff response over an hour or longer may underestimate short-term events, or peak flows, which can ultimately lead to an underestimation of CSO volumes. Conversely, many communities do not have access to rainfall data that are recorded more often than every 15 minutes, or even every hour. For the CSO Model, it is therefore important to incorporate a simulation timestep that balances model accuracy with data availability.

To test how the timestep can produce sufficiently accurate flow data, EPA reproduced the original data at different levels of aggregation using Elizabeth and Omaha as test cases. Elizabeth sub-sewersheds provided data at a five-minute timestep, so EPA produced 15- and 60-minute aggregations. Omaha sub-sewersheds provided data at a 15-minute timestep, so EPA only produced 60-minute aggregations. Figure 1 illustrates a selection of these comparisons.

Results in Figure 1 demonstrate how data displayed on a 60-minute timestep can reduce peak flows by up to 50 percent. The top tile, from sub-sewershed 114 in Omaha, clearly illustrates the difference between 15-minute and 60-minute levels of aggregation. Results from sub-sewersheds 031 and 036 in Elizabeth show that differences between a five-minute and 15-minute timestep are minimal, most likely because the t_c for each of these sub-sewersheds is greater than 15 minutes. These conclusions were generally consistent across all sub-sewersheds and events.

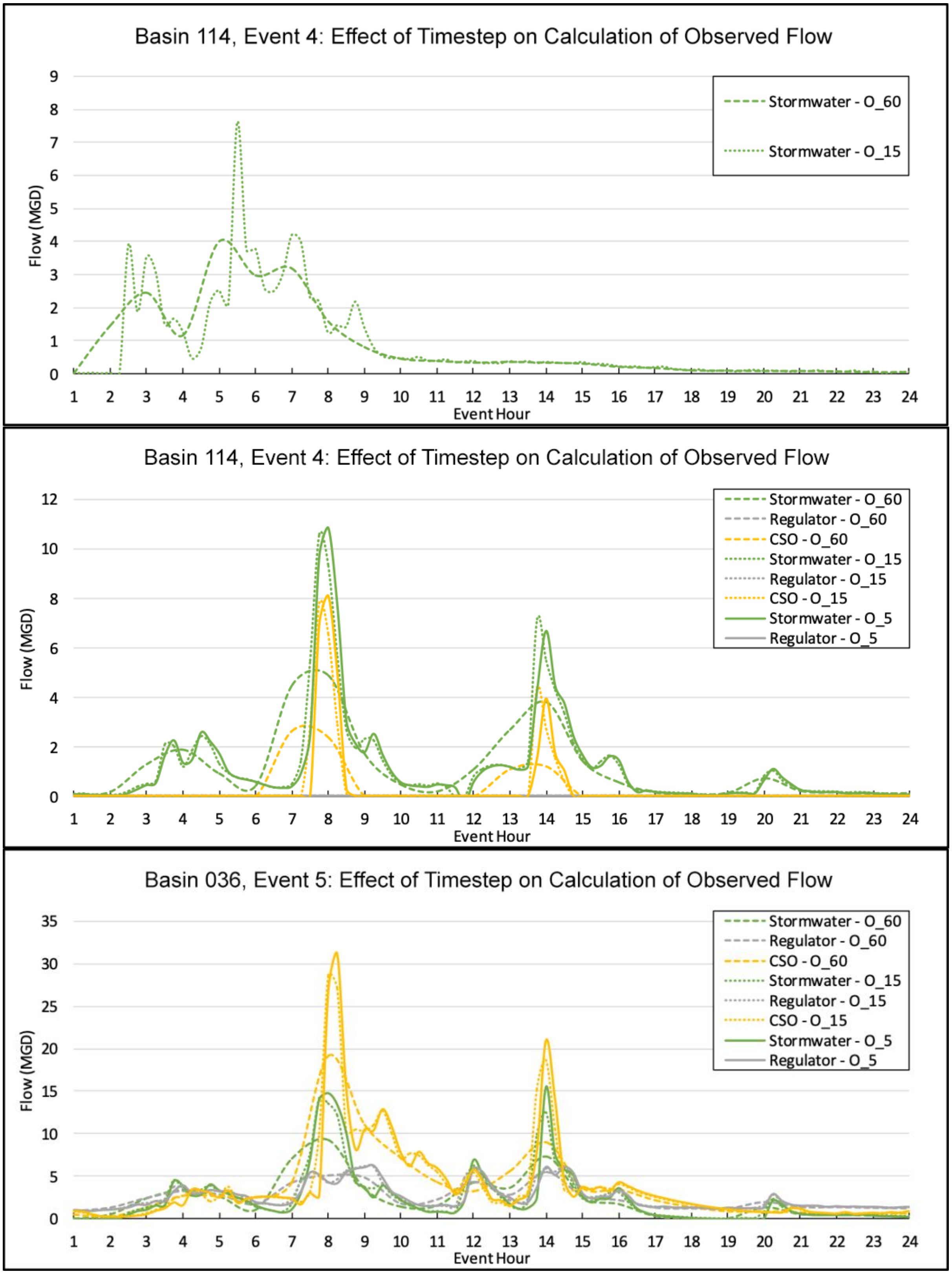

Figure 1. Example illustrations showing effect of timestep on observed flow calculation.

Effect of Timestep Aggregation on CSO Model Output

Based on the results described above, EPA created a revised version of the CSO Model using a 15-minute timestep and compared it with model output that used a 60-minute timestep, again using Elizabeth and Omaha as test communities. EPA ran each version for each Elizabeth sub-sewershed listed in Table 1 and the associated events listed in Table 3. EPA only simulated Omaha sub-sewersheds using a 15-minute timestep. For Elizabeth sub-sewershed simulations, EPA aggregated the original five-minute rainfall data to 15-minute averages. For Omaha sub-sewershed simulations, EPA distributed the original 60-minute rainfall data evenly across each 15-minute interval of each simulation hour. In other words, for an observed record of 0.1 inches over one hour, EPA used a model input of 0.025 inches per 15 minutes instead.

Figure 2 illustrates results for the same sub-sewershed and event combinations used in Figure 1. In the legend, “M” and “O” are used to denote modeled and observed, respectively. For sub-sewershed 114, observed results are at a 15-minute timestep, while observed results for sub-sewersheds 031 and 036 are at a five-minute timestep.

Again, results show that simulation on a 60-minute timestep results in a significant loss of detail in terms of peak flow rate prediction. Results from sub-sewersheds 031 and 036 show that by decreasing the model timestep from 60 minutes (M_60) to 15 minutes (M_15), the ability to reproduce the timing of the peak flows is improved. In other words, the timing of runoff response appears to be as dependent on model timestep as on t_c.

Although reducing the timestep from 60 to 15 minutes improves the detail and timing of model outputs, model accuracy still has limitations. First, the top tile in Figure 2 shows that although model timestep improves runoff response detail, certain hydrograph peaks are not reproduced due to differences between the resolution of rainfall data input (hourly) and actual rainfall variability. The ability to reproduce any fluctuations in flow due to fluctuations in rainfall at less than an hourly timestep is limited by using an hourly average rainfall input.

Next, results from sub-sewershed 036, which is 210 acres in size, show that even with a 15-minute timestep, peak flows are overestimated, sometimes by a factor of two or more. Conversely, results from sub-sewershed 031, which is just 60 acres, are reasonably accurate. A qualitative review of results across other simulations shows the same pattern, whereby simulation results for larger sub-sewersheds (e.g., greater than 100 acres) are much higher than observed results. This difference is due to the interaction of impervious area, sewershed size, and runoff response, and is evaluated quantitatively in the next section.

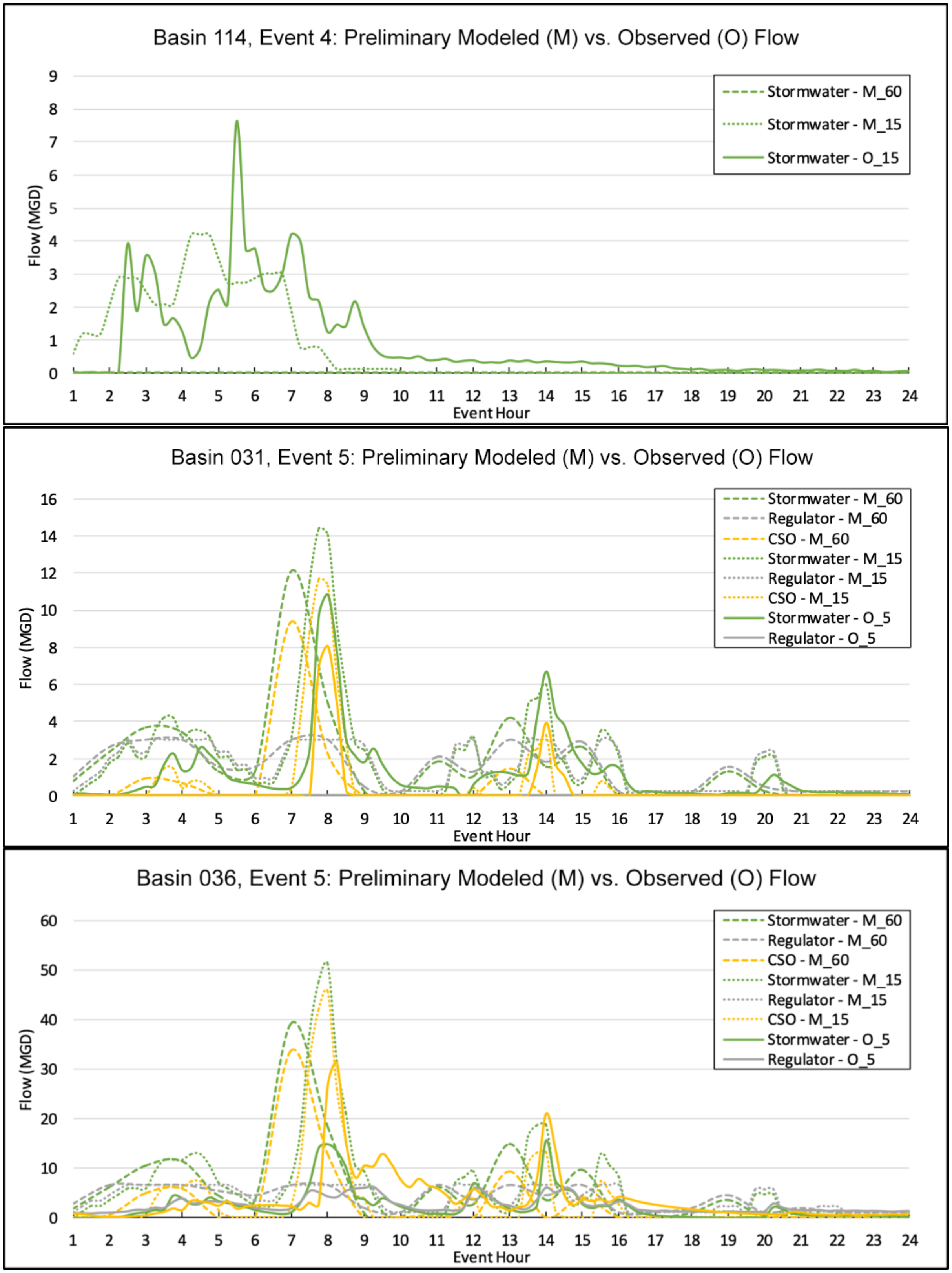

Figure 2. Example illustrations of preliminary results using hourly (M_60) and 15-minute (M_15) models.

Accuracy of the Modified Rational Method in Quantifying Stormwater Runoff

EPA designed the CSO Model to quantify the CSO volume that results from a given storm event. While depicting realistic hydrographs is an important factor, CSO volume is the main model output. As shown above, however, there are instances where the 15-minute timestep still appears to be over- or under-predicting stormwater runoff, which directly affects the model’s ability to quantify CSOs. Because CSOs are so closely related to wet weather flow, EPA first evaluated the accuracy of the modified Rational Method in quantifying stormwater runoff in detail. Again, EPA used data from Elizabeth and Omaha, the two communities that provided runoff data (Table 3).

The Rational Method is not recommended for larger basins. Often, stormwater practitioners cite 200 acres as a hard cutoff, though the actual cutoff can be much smaller and variable depending on the desired degree of accuracy and site-specific conditions (Thompson, 2006). In addition, the appropriateness of impervious area alone as a runoff coefficient surrogate is questionable at larger scales. To evaluate the predictive power of the modified Rational Method across all available monitoring records, EPA aggregated total flow volume and peak flow rate over each 24-hour simulation period and compared to modeled results. Linear regressions were fitted through each sub-sewershed data set, using observed data as the predictor. Equations for each data set help show the degree to which volumes or flow rates are overpredicted (slope >1, assuming an intercept of 0) or underpredicted (slope <1, assuming an intercept of 0).

Figure 3 shows 15-minute modeled results plotted against observed results. Results are separated according to sub-sewershed size and total volume or peak flow rate. The tiles on the left show results for sub-sewersheds smaller than 100 acres, while the tiles on the right show results for sub-sewersheds larger than 100 acres. The top two tiles display 24-hour volume totals, while the bottom two tiles display peak flow rates observed over the 24-hour simulation period.

For sub-sewersheds smaller than 100 acres, slopes for total runoff volume (top left) range from 0.5 to 1.4, with an average of 0.9. Sub-sewershed 040, which has the smallest slope but largest intercept, is tidally influenced. This tidal influence has a noticeable effect on flow records, especially for smaller events, as higher tailwaters limit the ability of pipe networks to convey stormwater. Figure 3 illustrates this effect, with smaller events being relatively more overpredicted than what was observed, resulting in a larger intercept and flatter slope than would be expected without tidewater effects.

For sub-sewersheds greater than 100 acres, slopes for total runoff volume (top right) range from 1.4 to 2.9, with an average of 2.1. In other words, the CSO Model overpredicted runoff volume for these sub-sewersheds by an average factor of approximately two. In larger watersheds, a directly connected impervious area (DCIA) is often a more appropriate indicator of runoff-generating potential than total impervious area (Sutherland, 1995). However, DCIA is more complex than impervious area, as it refers to impervious areas directly connected to stormwater drainage infrastructure, and can therefore be hard to measure at the landscape scale. A set of equations exists to calculate DCIA from impervious area, referred to as the “Sutherland Equations” (Sutherland, 1995). For high-density land uses, the equations predict DCIA to range from 25 to 40 percent of total impervious area. As a rough approximation, if DCIA of sub-sewersheds 001, 036, and 039 were 40 percent of the current impervious area and used as model input instead of the values shown in Table 1, the average slope of the resulting regressions would likely be closer to 1.

Peak flow rate results, as the bottom two tiles of Figure 3 illustrate, are similar to total volumes but with greater variability, especially for smaller sub-sewersheds (bottom left). The slopes for sub-sewersheds 110 (0.2), 114 (0.5), and 203 (0.1) are all well below 1, indicating considerable underprediction of peak flow. However, these simulations use average hourly rainfall data, which dampens sub-hourly fluctuations in actual rainfall patterns and limits the ability of the revised CSO Model to capture that variability. This effect is illustrated for the M_15 series in the top tile of Figure 2, where—despite having a shorter model timestep—peak flows were still underpredicted by about half (7.6 MGD observed, 4.2 MGD modeled), owing to the use of hourly rainfall. By comparison, observed and modeled total volumes for that same event were closer (0.81 MG observed, 0.72 MG modeled).

Figure 3 also shows that, in almost all cases, linear regressions result in positive y-intercepts due the current version of the CSO Model not including initial abstraction, or the initial volume of water that must be “abstracted” before runoff is generated. Initial abstraction is the result of factors like vegetation interception and small depressional storages (e.g., parking lot puddles) scattered throughout a watershed. Based on the results in Figure 3, initial abstraction has an appreciable effect on modeled flow rates, particularly for small events. EPA compiled the results separately to determine initial abstraction by regressing observed runoff depth (inches) to observed rainfall depth (inches) for each sub-sewershed. Intercepts of the resulting linear regression equations provide an estimation of initial abstraction across the events considered. For the sub-sewersheds included in this study, initial abstraction ranged from 0.1 to 0.19 inches, with an average of 0.14 inches.

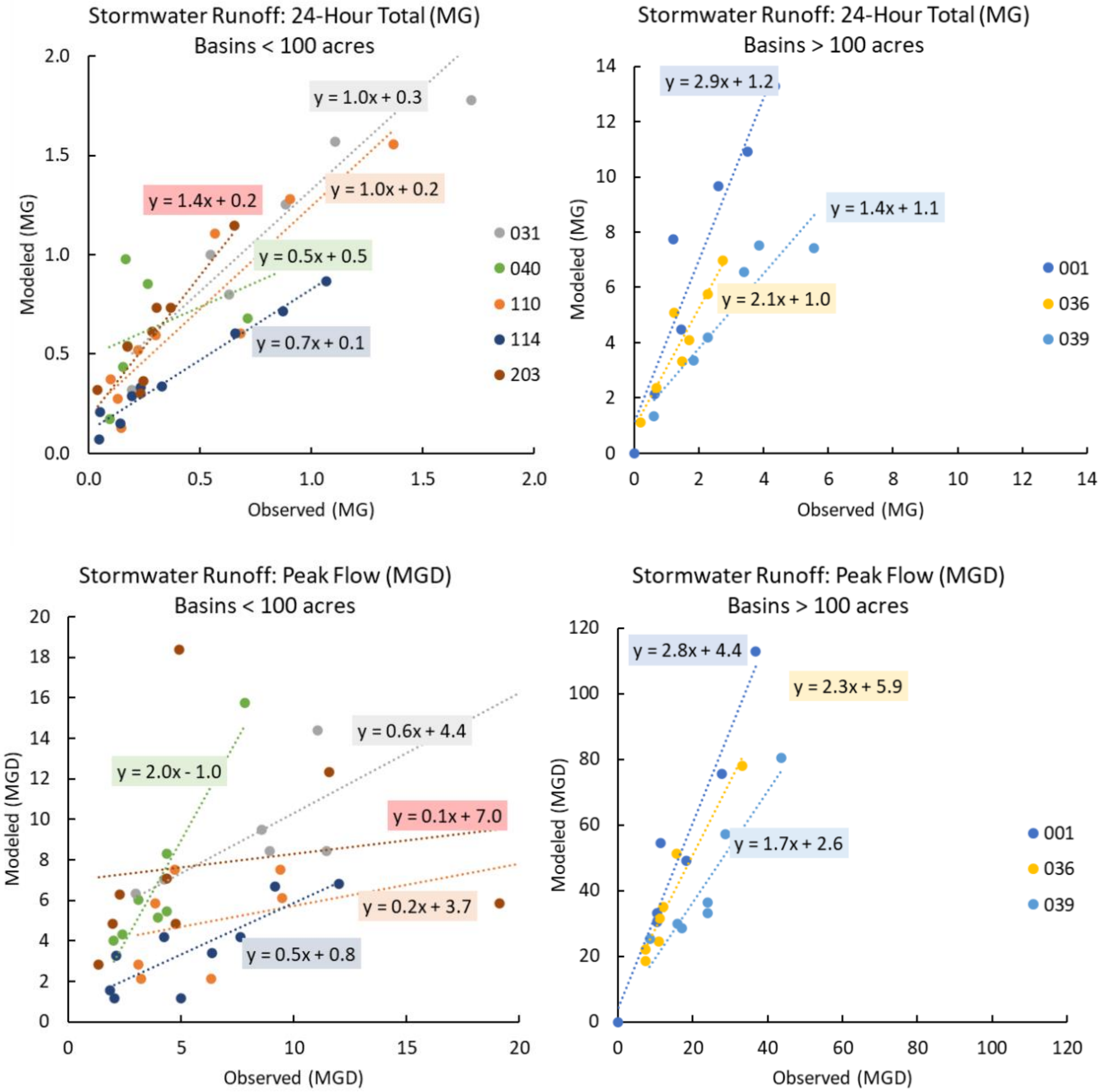

Figure 3. Summary of modeled (15-minute) versus observed runoff for Elizabeth and Omaha sub-sewersheds.

Revised CSO Model—Runoff

Based on the results presented above, the 15-minute model was further updated to address identified shortcomings. The revised CSO Model includes the following updates relative to the original CSO Model:

- Simulation timestep of 15 minutes, reduced from 60 minutes.
- Ability to use hourly or 15-minute rainfall time series as input.
- Recommendation that sub-sewersheds greater than 100 acres use a value of “0.5*impervious area” as model input.
- Incorporation of initial abstraction, set at a default of 0.1 inches, with the ability to enter a custom value when known.
    - Within the revised CSO Model, initial abstraction modifies the rainfall time series so the first 0.1 inches (or other, if custom value is used) of rainfall is effectively removed.

Figure 4 illustrates results for the same sub-sewershed and event combinations used in Figure 1 and Figure 2. The leading edge of the first hydrograph peak shows the effect of incorporating initial abstraction. For each simulation, initial abstraction results in a more realistic lag between rainfall and runoff initiation. In each case (and across other simulations not shown), the observed lag is greater than the modeled lag, indicating that actual initial abstraction may be greater than 0.1 inches. Additionally, qualitative review of event hydrographs shows that initial abstraction may be “recharged” multiple times within a 24-hour time period. In other words, the storage that contributes to initial abstraction (e.g., interception, small depressional storages) can dry out in less than 24 hours. However, this is a highly variable process and depends on local weather conditions such as temperature and humidity. The CSO Model assumes that initial abstraction only occurs once during each simulation period as input of additional weather data and is beyond the scope of the CSO Model.

The bottom tile of Figure 4 contains a comparison of the 15-minute timestep (M_15) and revised model (M_15_imp), which shows the effect of using “0.5*impervious area” as input for sub-sewersheds greater than 100 acres. As shown, this input achieves much better agreement between revised (M_15_imp) and observed (O_5) runoff results.

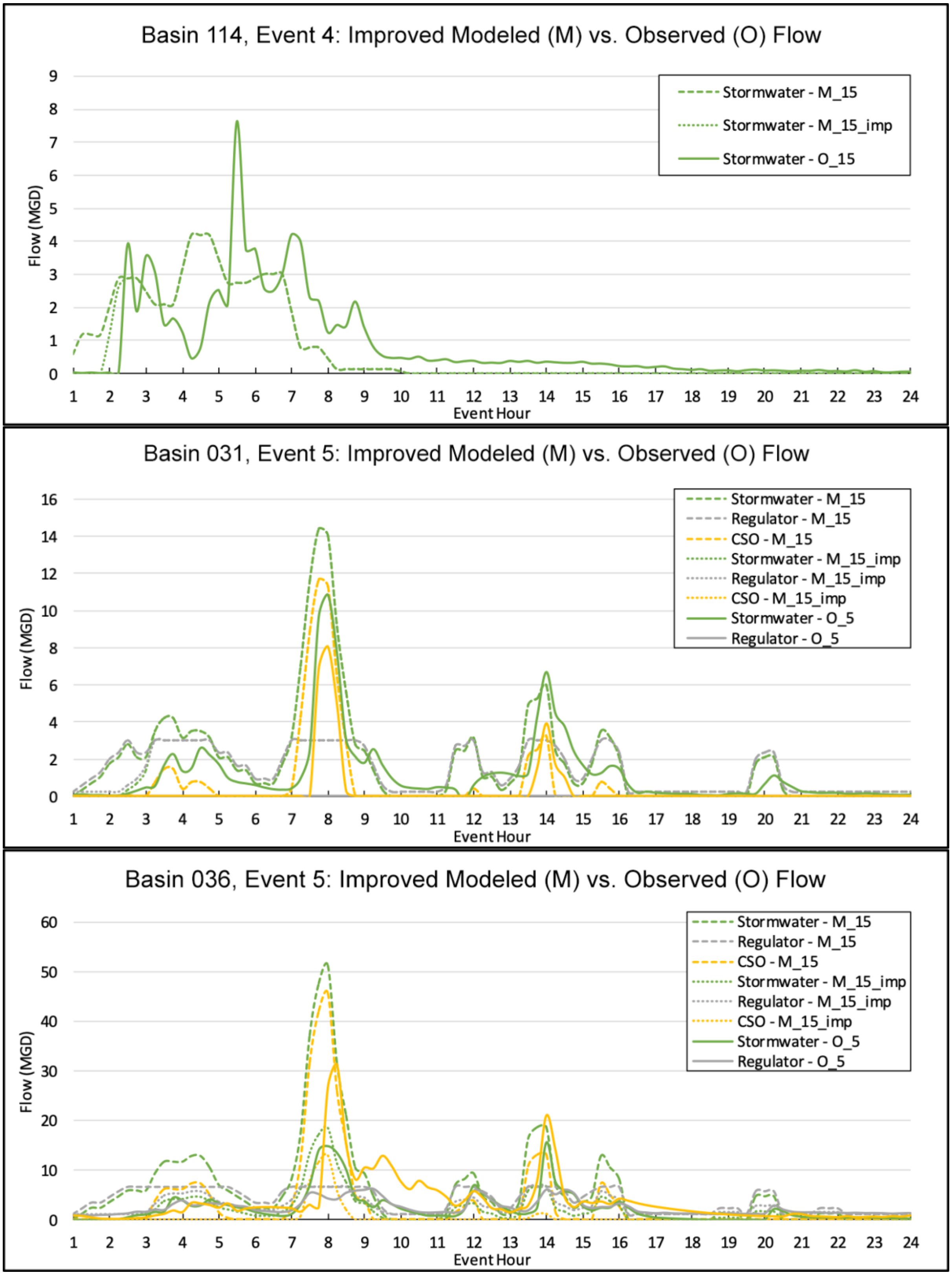

Figure 4. Example illustrations of 15-minute (M_15) and revised (M_15_Imp) model results.

Figure 5 shows revised CSO Model results for runoff plotted against observed results for all monitoring events, similar to Figure 3. Table 4 compares regression statistics, including slope and y-intercept, between revised CSO Model results (i.e., 15-minute timestep, initial abstraction of 0.1 inches, and 0.5*impervious area for basins >100 acres) and 15-minute CSO Model results. As summarized in Table 4, the adjustments made to the 15-minute CSO Model, including incorporating initial abstraction and modifying impervious area input for large sub-sewersheds, results in improved accuracy.

Incorporating initial abstraction reduced the average y-intercept from 0.65 to 0.25 for total volume regressions and from 3.0 to 0.94 for peak flow rate regressions. These values suggest that using a default initial abstraction of 0.1 inches is a significant improvement, but may still be an underestimation. Incorporating a modified impervious area input for larger sub-sewersheds reduced the average slope from 1.4 to 0.87 for total volume regressions and from 1.4 to 0.95 for peak flow rate regressions.

Table 4. Comparison of the 15-minute and revised CSO Model results for the prediction of stormwater runoff.

Sub-basin ID	Number of events	Sub-basin area (acres)	Initial abstraction (in.)[a]	Total volume				Peak flow rate			
				Slope		Intercept		Slope		Intercept	
				15-min	Revised	15-min	Revised	15-min	Revised	15 min	Revised
Elizabeth, New Jersey											
001	7	439	0.14	2.9	1.4	1.2	0.38	2.8	1.4	4.4	0.85
031	7	59.5	0.14	1.0	1.0	0.31	0.20	0.59	0.64	4.4	3.6
036	7	210	0.13	2.1	0.77	0.95	0.21	2.3	0.83	5.9	1.6
039	7	245	0.12	1.4	0.69	1.1	0.33	1.7	0.95	2.6	-1.66
040[b]	7	34.9	-0.015	0.50	0.50	0.49	0.43	2.0	2.1	-1.0	-1.9
Omaha, Nebraska											
110[c]	9	72.0	0.18	1.0	1.0	0.21	0.11	0.21	0.21	3.7	3.5
114[c]	9	80.3	0.19	0.71	0.71	0.11	0.059	0.51	0.53	0.76	0.56
203[c]	9	70.5	0.10	1.4	1.4	0.18	0.10	0.13	0.13	6.7	6.7
			Average:	**1.4**	**0.87**	**0.62**	**0.25**	**1.4**	**0.95**	**3.0**	**0.94**

[a] Calculated from regression of observed runoff volume to observed rainfall volume.
[b] Observed data was tidally influenced.
[c] Hourly rainfall data.

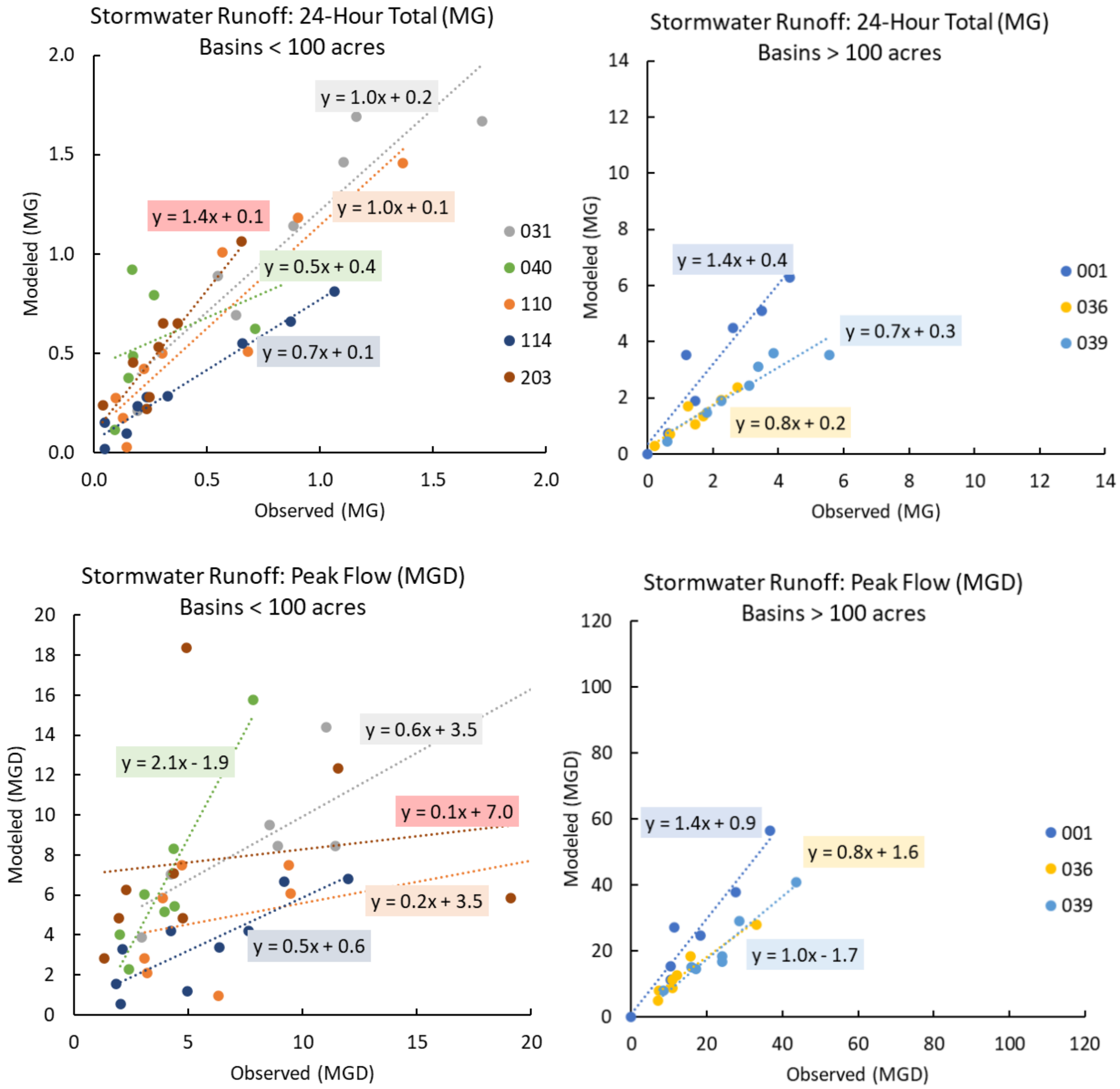

Figure 5. Summary of modeled (revised CSO Model) versus observed runoff results for Elizabeth and Omaha sub-sewersheds.

Revised CSO Model—CSO

Using the revised CSO Model, EPA compared model predictions to observations using two main approaches that depend on the type of data provided by the test communities. The different approaches also demonstrate the different ways that the CSO Model may be used, including:

- **Predicting CSO occurrence:** For communities with minimal knowledge of their combined sewer system, simply knowing whether a CSO occurred for a given storm can be helpful. Here, we ran the CSO Model using a full year of rainfall data for Richmond, Virginia, and Henderson Water Utility (HWU) in Kentucky, as well as three years of rainfall data for NHSA in New Jersey (for a total of 2,218 individual simulations), to evaluate the ability of the CSO Model to predict the number of events that would occur during a given month.
- **Predicting CSO volume (MG) and peak flow rate (MGD):** Using the model as a typical community would use it, we ran simulations of 21 sub-sewersheds across four communities (for a total of 1,239 simulations) to evaluate the ability of the CSO Model to predict the total volume and peak flow rate of a CSO event.

Predicting CSO Occurrence

The communities of NHSA, Richmond, and HWU each provided EPA with continuous time series rainfall data and some measure of CSO occurrence, including either outfall flow time series data or monthly overflow reports. To simulate monthly events, EPA ran the CSO Model for all sub-sewersheds on days when the total rainfall exceeded 0.1 inches, which is equivalent to the default initial abstraction.

For each community, EPA ran multiple rounds of simulations using different inputs for initial abstraction and impervious surface area based on the preliminary findings discussed earlier in this report. For NHSA and HWU, results of these iterations showed better agreement between modeled and observed results when using an initial abstraction value of 0.2 inches instead of 0.1 inches. In comparison, for Richmond, a value of 0.1 inches resulted in better agreement between modeled and observed results when considering monthly events, total CSO volume, and peak flow. Therefore, EPA updated the guidance for this model to recommend a range of 0.1 to 0.2 inches, with a minimum default of 0.1 inches.

Impervious surface area was also varied for sub-sewersheds greater than 100 acres, which include 002A (69 percent impervious) and 006A (98 percent impervious) from NHSA, as well as 003 (20 percent impervious) from HWU. Several Richmond sub-sewersheds were greater than 100 acres; however, the sewershed characterization data were already in terms of DCIA, so they did not require correction. Simulation results showed that for NHSA sub-basins 002A and 006A, using the full impervious area resulted in a significant overprediction of CSO events, while using a value of “0.5*impervious area” resulted in a much better agreement. For HWU sub-sewershed 003, the correction of “0.5*impervious area” actually resulted in an underprediction of CSO occurrence. Although drawn from a small sample size, EPA suggests that the “0.5*impervious area” correction is more suitable for sewersheds with an initial percent impervious greater than 20 percent. EPA has also updated guidance for this model input accordingly, and recommended caution when using the correction for large sewersheds with low initial impervious area.

Table 5 summarizes and Figure 6 illustrates the results of the CSO occurrence testing for NHSA, Richmond, and HWU.

The data provided in Table 5 summarize the results in terms of residuals, which refer to the deviation of individual modeled results from observed data. Residuals are described for the full period of record of each sub-sewershed. The period of record bias quantifies the average deviation and the direction of that deviation over all simulation events. For example, for NHSA sub-sewershed 002A, a bias of -0.47 events means that over the 36-month simulation period for that sub-sewershed, which included 259 individual events, the CSO Model predicts an average number of monthly events that is 0.47 events less than the actual average of 4.5 events per month. The average residual, in comparison, is the average of the absolute value of all monthly residuals and can be interpreted as the average monthly deviation. Using NHSA sub-sewershed 002A as an example again, an average residual of 1.5 events per month means that over the period of record, the CSO Model predicts the number of monthly events to within an average range of 1.5 events above or below the actual value. Across the 19 sub-sewersheds and 2,218 individual simulations, the CSO Model output results in an average period of record bias of 0.26 events per month (or +8 percent compared to the average 3.11 events per month) and an average monthly residual of 1.12 events per month (or 36 percent of the average 3.11 events per month). The overall positive bias indicates that the CSO Model is slightly conservative, in that it tends to estimate more overflows per month than are observed.

Table 5. Comparison of modeled (revised CSO Model) to observed CSO events per month for NHSA, Richmond, and HWU.

Sub-basin/ CSO ID	Number of events[a]	Number of months	Sub-basin area (acres)	Initial abstraction (in.)	Average events per month	Events per month residuals	
						Period of record bias (events/month)[c]	Average residual (events/month)[d]
EPA Region 2: North Hudson Sewerage Authority, New Jersey							
002A (H1)	259	36	276	0.2	4.5	-0.47	1.5
006A (H5)	259	36	151	0.2	3.3	1.4	2.1
012A (18PS)	259	36	85.9	0.2	4.1	0.44	1.6
015A (W5)	259	36	36.9	0.2	4.2	0.53	1.5
EPA Region 3: Richmond, Virginia							
004	79	12	91.6	0.1	5.2	0.17	1.0
005	79	12	11.8	0.1	1.8	-1.8	1.8
012	79	12	90.0	0.1	4.0	1.2	1.2
014	79	12	394	0.1	1.1	0.0	0.33
021	79	12	493	0.1	4.3	-1.0	1.2
024	79	12	197	0.1	4.1	0.58	0.58
025	79	12	65.7	0.1	0.8	2.3	2.3
026	79	12	101	0.1	2.9	1.7	1.7
031	79	12	176	0.1	2.0	-0.25	0.25
034	79	12	63.0	0.1	0.8	0.25	0.42
035	79	12	30.9	0.1	1.8	-0.42	0.42
039	79	12	174	0.1	4.8	1.0	1.0
EPA Region 4: Henderson Water Utility, Kentucky							
003	78	12	347	0.2	5.0	-0.33	0.50
004	78	12	43.4	0.2	1.3	0.42	0.75
007	78	12	27	0.2	3.1	-0.75	1.25
				Average:	**3.11**	**0.26**	**1.12**

[a] Number of simulated events based on rainfall amounts that cause one or more outfalls to overflow.

[b] Refers to the observed average events per month. For NHSA, EPA determined these values from monthly NPDES monitoring data from 2017–2019, obtained for Facility ID NJ0026085 from https://echo.epa.gov/. EPA calculated observed events from Richmond and HWU based on flow records provided to EPA from each community.

[c] Calculated as the average of all monthly residuals.

[d] Calculated as the average of the absolute value of all monthly residuals.

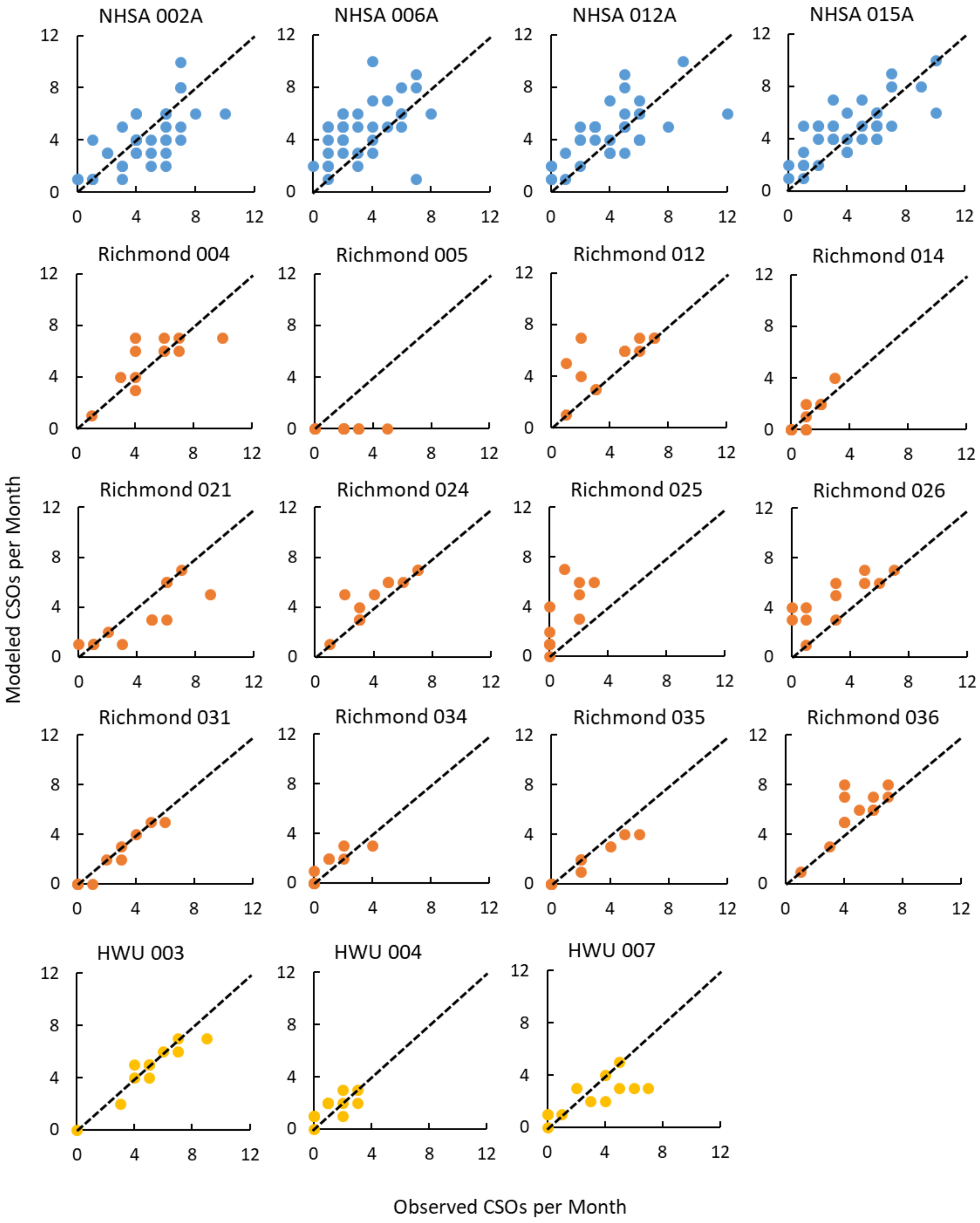

Figure 6. Summary of modeled (revised CSO Model) versus observed monthly CSO events for NHSA, Richmond, and HWU. The x- and y-axes for each plot range from 0–12 events per month, so that the dashed line represents a 1:1 slope, or perfect agreement.

Predicting Event Volume and Peak Flow Rate

The communities of Saco, Maine; Elizabeth, New Jersey; Richmond, Virginia; and HWU in Kentucky each provided EPA with sufficient rainfall and overflow time series data to compare CSO Model output to observed CSO volumes and peak flow rates for individual events. To simulate each event, EPA ran the CSO Model for all days in which a CSO occurred (Saco and Elizabeth) or all days in which the daily rainfall exceeded 0.1 inch (Richmond and HWU).

Similar to the prediction of monthly events, multiple rounds of simulations were run using different inputs for initial abstraction and impervious surface area based on the preliminary findings discussed earlier in this report (see discussion on page 19). The determination of final model inputs for each community is provided in Table 6.

The comparison of modeled to observed CSO volumes and peak flow rates are described in Table 6 and illustrated in Figure 7. For each metric (total volume in terms of MG or peak flow rate in terms of MGD), results are described in the same way as the runoff results presented in Table 4, where values of slope and intercept can be used to characterize the general deviation of CSO Model results from observed characteristics.

Given the intentional simplicity of the CSO Model and the difficulty of reproducing complex flow regimes that dictate CSO characteristics (e.g., assuming a static value for regulator capacity), the data described in Table 6 and illustrated in Figure 7 have considerable variability. For example, slopes of total volume plots for each sub-sewershed range from 0.13 (Saco 001) to 8.6 (HWU 004), which translates to an underestimation of event volume of 87 percent to an overestimation of nearly nine times what was observed. However, these extreme examples highlight what are likely unique scenarios.

First, Saco sub-sewershed 001 is one of the smallest systems evaluated (18 acres), yet has one of the highest regulator capacities (11.4 MGD), suggesting a highly “flashy” system where rainfall is converted to short but intense flows through the sewer system. The 0.74 slope of the peak flow rate regression is much closer to 1, meaning that peak flow rates are less underestimated than CSO volumes. The difference between the 0.13 and 0.74 slopes suggests that although the CSO Model can reasonably predict peak CSO flow rate, it does not capture the sustained high flow rate that exists in this sub-sewershed. Although the underprediction of total volume is not ideal, the ability for a screening tool to predict the occurrence of a CSO, which is more dependent on the ability to reliably predict peak flows, still provides value.

At the other end of the spectrum is HWU sub-sewershed 004. Based on conversations with HWU personnel, their community’s CSO outfalls are mostly within a single corridor that runs along the Ohio River, and all regulators are simple 18-inch drop pipes, meaning that when the capacity of the 18-inch pipe is exceeded, a CSO occurs. This description would seem to imply that all regulators function similarly. However, as shown in Table 6, predictions of total volume from HWU sub-sewersheds 003 and 007 result in slopes of 0.9 and 0.92, respectively, which is much closer to 1 than the slope of 8.6 from HWU sub-sewershed 004. In other words, there appear to be nuances in sub-sewershed 004 that result in far less CSO volume than predicted by the CSO Model. These nuances could be due to unaccounted storage capacity in the conveyance system or complex flow regimes that unintentionally limit peak flows within the system.

The presence of these hidden complexities is further evidenced by flow records from three other sub-sewersheds in the HWU system: 005 (Towles Street), 008 (Washington Street), and 009 (First Street) that were not included in this evaluation due to the presence of only one CSO event between all three sub-sewersheds over the entire 12-month period of record. Irregular flow observations such as these further reinforce the conclusion that the CSO Model’s effectiveness as a screening tool can be greatly improved by coupling the model with basic field monitoring techniques, such as chalking at a CSO outfall as a means of determining whether a CSO occurred (see Section 3.1.3 of EPA’s CSO Guidance for Monitoring and Modeling for additional discussion of simple field monitoring techniques).

Despite cases where complex systems resulted in poor predictive performance of the CSO Model, the CSO Model behaves reasonably well when judged by the average slopes and intercepts determined across all 21 sub-sewersheds included in Table 6 and illustrated in Figure 7. For the prediction of CSO volume, regressions of modeled to observed results yield an average slope of 1.29 and an average intercept of 0.05. These results suggest that, on average, the CSO Model slightly overpredicts total CSO volume (based on a slope >1) and, for very small events, may predict the occurrence of a CSO event when there was no CSO (based on a small intercept >0). In terms of peak flow, the resulting average slope of 0.91 suggests that the CSO Model slightly underpredicts larger peak flows (based on a slope <1), while the peak flow intercept of 1.08 implies that, for small events, the CSO Model overpredicts peak flows and may predict the occurrence of a CSO event when there was no CSO.

Table 6. Comparison of modeled and observed CSO event total volume (MG) and peak flow rate (MGD) for Saco, Elizabeth, Richmond, and HWU.

Sub-basin/CSO ID	Number of events[a]	Sub-basin area (acres)	Initial abstraction (in.)[b]	Total volume		Peak flow rate	
				Slope	Intercept	Slope	Intercept
EPA Region 1: Saco, Maine							
001	22	18	0.1	0.13	0.03	0.74	0.76
EPA Region 2: Elizabeth, New Jersey							
001	7	439	0.1	1.1	0.36	1.4	0.87
031	7	59.5	0.1	1.2	0.21	0.62	2.9
036	7	210	0.1	0.23	-0.27	0.28	0.51
039	7	245	0.1	1.5	-0.03	1.6	0.54
040	7	34.9	0.1	3.1	0.14	1.8	2.2
EPA Region 3: Richmond, Virginia							
004	79	91.6	0.1	0.49	0.04	0.64	0.98
005	79	11.8	0.1	Model results indicate 0 overflow.			
012	79	90.0	0.1	0.40	0.04	0.58	0.87
014	79	394	0.1	0.79	0.01	0.79	1.2
021	79	493	0.1	0.39	0.11	0.58	0.82
024	79	197	0.1	0.35	0.07	0.45	2.1
025	79	65.7	0.1	0.96	0.03	0.92	1.5
026	79	101	0.1	0.82	0.03	0.71	0.74
031	79	176	0.1	0.60	0.02	0.67	0.40
034	79	63.0	0.1	1.8	0.01	1.3	0.83
035	79	30.9	0.1	0.89	0.00	0.74	0.17
039	79	174	0.1	0.70	0.08	0.75	1.5
EPA Region 4: Henderson Water Utility, Kentucky							
003 - Ragan St.	78	347	0.2	0.90	0.22	1.14	2.3
004 - Jackson St.	78	43.4	0.2	8.6	0.00	2.1	0.16
007 - Powell St.	78	27	0.2	0.92	0.00	0.36	0.17
Average:				**1.29**	**0.05**	**0.91**	**1.08**

[a] Number of simulated events based on rainfall amounts that cause one or more outfalls to overflow.

[b] Initial simulations run with values ranging from 0.1 to 0.2 inches to determine the most suitable input based on the agreement between modeled and observed results. Values shown here resulted in the best agreement.

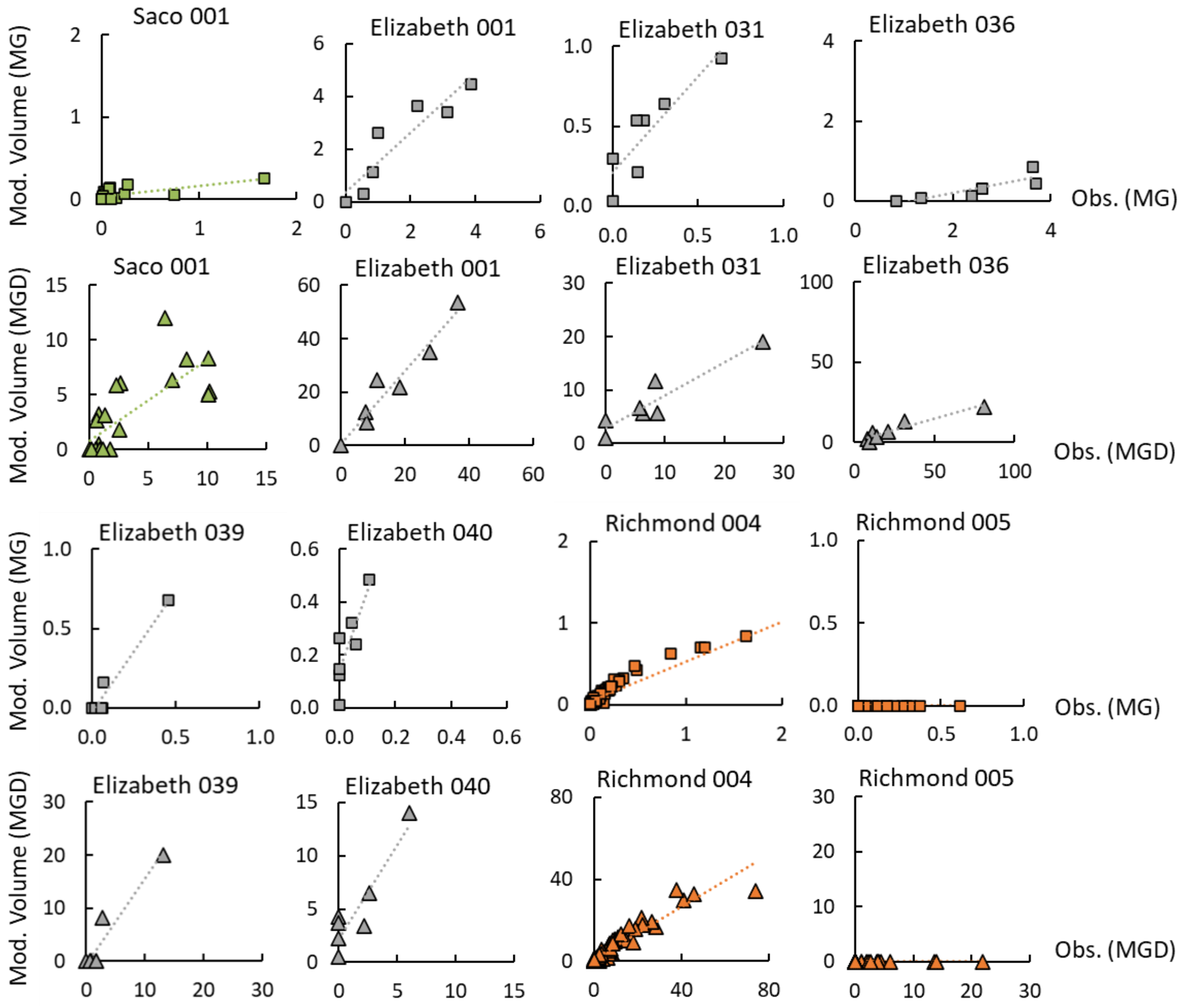

Figure 7. Summary of modeled (revised CSO Model) versus observed monthly CSO events for Saco, Elizabeth, Richmond, and HWU. Model results are presented on the y-axis and observed results on the x-axis. Total event volume plots are illustrated with squares and peak flow rate plots are illustrated with triangles.

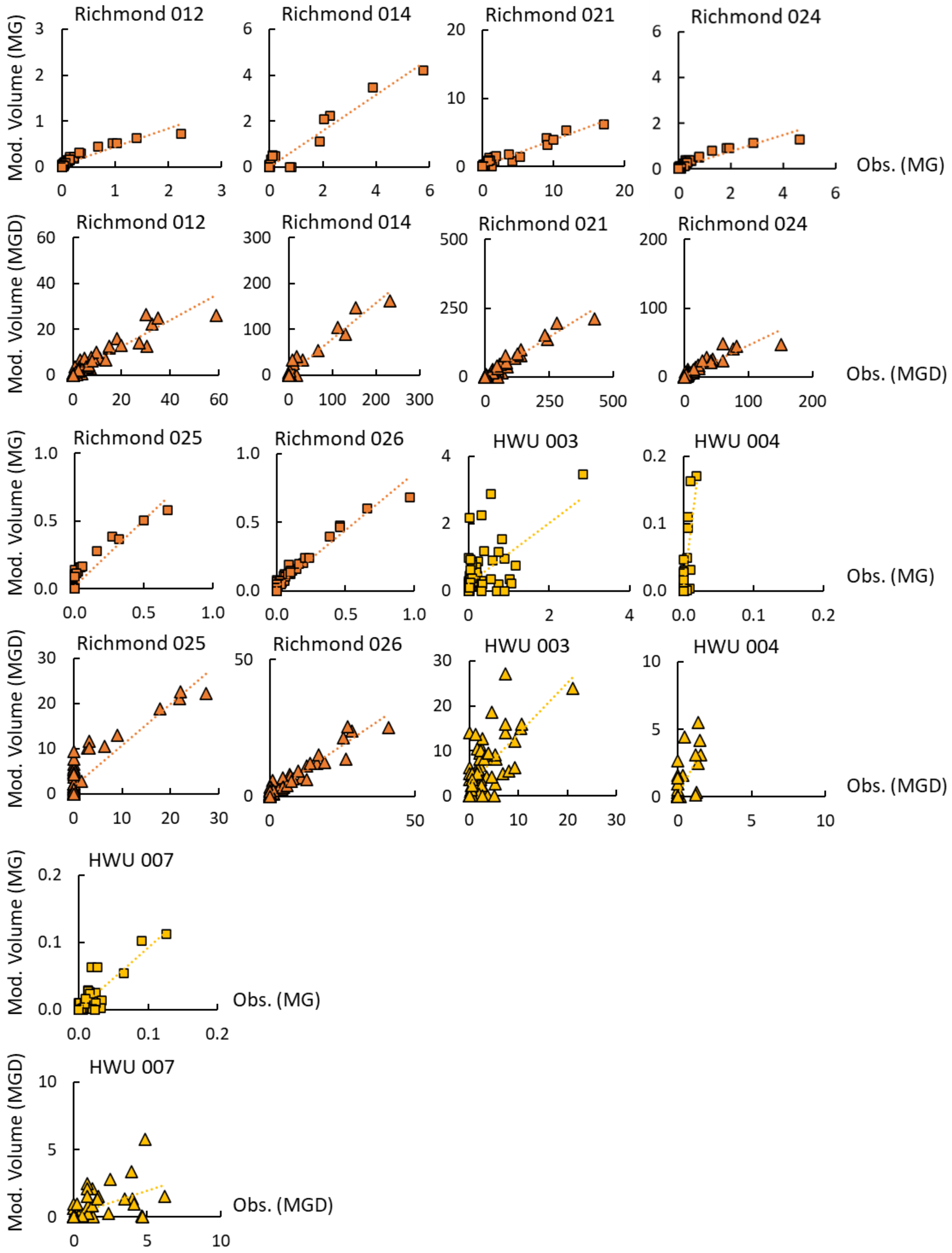

Figure 7 (Continued). Summary of modeled (revised CSO Model) versus observed monthly CSO events. Model results are presented on the y-axis, observed results on the x-axis. Total event volume plots are illustrated with squares and peak flow rate plots are illustrated with triangles.

The range of slopes, particularly for total volume regressions, is wider for CSO regressions (Table 6) than runoff regressions (Table 4), which illustrates a limitation of the revised CSO Model in its ability to capture realistic hydraulic control capacities. The revised CSO Model uses a single input for hydraulic control capacity, which is mainly dependent on regulator capacity, and calculations assume all incoming flow up to that capacity diverted to the interceptor. However, not only is this capacity difficult to accurately predict, but it is variable across a range of incoming flows and responds more as a rating curve than a single rate. While CSO Model input for regular capacity could be modified to include a rating curve, this may also present a usability challenge as the intended user is not expected to have access to the type of detailed monitoring or modeling data necessary to define an accurate rating curve.

Model Validation Conclusions

Results presented above yield several conclusions that EPA used to improve CSO Model accuracy. These conclusions include:

- Aggregating five-minute time series to a 15-minute timestep causes minimal loss of detail, while aggregating to a 60-minute timestep causes significant loss of detail.
- Decreasing the CSO Model timestep from 60 minutes to 15 minutes greatly improves the accuracy of peak flow prediction and improves runoff response timing.
- The resolution of rainfall data has a large effect on the ability to accurately simulate peak flows, especially for smaller sub-sewersheds.
    - EPA recommends using rainfall data collected at a 15-minute interval or shorter.
- Using impervious area as a runoff coefficient, the CSO Model overpredicts stormwater runoff volume for sub-sewersheds larger than 100 acres by a factor of approximately two, unless the percent imperviousness of the sub-sewershed is 20 percent or less.
- Initial abstraction is an important term, even for simulation of larger storm events. A value of 0.1 to 0.2 inches is recommended based on validation results.
- The CSO Model predicts runoff volumes and rates better than CSO volumes and rates, owing to the difficulty in estimating a system's hydraulic control, or regulator, capacity.
- Despite a variable ability to predict CSO volumes and flow rates, the CSO Model performs well in its ability to evaluate the presence or absence of a CSO event.
- Combined with simple, low-cost field monitoring techniques, the CSO Model can serve as a powerful screening-level tool to help communities better understand their combined sewer systems and reduce the need to monitor every rain event.

Based on these conclusions, EPA made the following improvements to the CSO Model:

- The model timestep has been reduced from 60 minutes to 15 minutes.
- The user guide instructions for obtaining rainfall data have been updated to reflect a recommendation that 15-minute data be obtained wherever possible.
- An initial abstraction term has been incorporated, set at a default of 0.1 inches with the ability to update based on local conditions.
- Text in the user guide has been added to recommend the following: For larger sub-sewersheds (generally greater than 100 acres), the model tends to overpredict peak runoff flow rates and total runoff volumes (and CSOs by extension) when using total percent impervious area as a model input. This overprediction is likely due to the influence of directly connected and disconnected impervious surfaces—as discussed in EPA's factsheet on Estimating Change in Impervious Area (IA) and Directly Connected Impervious Areas (DCIA) for Massachusetts Small MS4 Permit—especially as drainage areas increase in size. If modeling larger sub-sewersheds, EPA therefore encourages the user to use the model input for percent imperviousness as a calibration parameter, reducing the value until reasonable results are obtained. Based on general model validation performed by EPA, a reduction of percent imperviousness by up to 50 percent was found to better predict runoff rates and volumes for larger sub-sewersheds.

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