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Modeling Impacts of Combined Sewer Overflows in SWMM in Cleveland, Ohio

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MODELING IMPACTS OF COMBINED SEWER OVERFLOWS IN SWMM IN CLEVELAND, OHIO

By

Zoe A. Miller

A Report

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This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Environmental Engineering.

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Abstract

Despite its legacy of pollution, the City of Cleveland, Ohio, has historically been at the forefront of water quality management. Today, the Northeast Ohio Regional Sewer District (NEORSD), which serves the Greater Cleveland area, is following a consent decree with the State of Ohio to minimize combined sewer overflows (CSOs), along with implementing an integrated Clean Water Act planning study to prioritize infrastructure improvements with a broader view of water quality objectives. This report summarizes an urban watershed modeling effort to support the integrated planning (IP) process. Specifically, the development, calibration, and validation of the EPA Stormwater Management Model (SWMM) for the NEORSD area is presented, followed by an application of the model under both uniform and spatially distributed rainfall inputs. Results show the importance of using spatially variable inputs for urban watershed modeling studies over large areas. Based on this work, several recommendations for future research are made, including expanding the scope of the simulations performed to all SWMM models used in the IP modeling to gain a deeper understanding of how distributed versus uniform rainfall impacts the total loads to Lake Erie; testing the SWMM models with fixed, free and time-variable downstream boundaries to understand how well SWMM can model the stream-lake interaction (backwater and reverse flow); and simulating loads into Lake Erie using rainfall scenarios that account for climate change.

Chapter 1: Introduction

Cleveland, on the southern shores of Lake Erie, has endured a number of embarrassing nicknames including "mistake on the lake." Like other rust belt cities on the shores of the Great Lakes, Cleveland has observed industrial decline and population loss following World War II. Despite being home to the infamous Cuyahoga River, which caught on fire multiple times leading up to one famous fire in 1969, Cleveland is now a city making stringent efforts to clean up its waterways and improve the overall health of rivers and Lake Erie, in large part in response to a Consent Decree, or legal settlement that was made to address Combined Sewer Overflows (CSOs).

According to the U.S. Environmental Protection Agency (EPA), "Combined sewer systems are sewers that are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe" (http://water.epa.gov/polwaste/npdes/cso/). Combined systems typically convey polluted water to wastewater treatment plants where the water is treated and then discharged back into the environment. During large rain events, however, wastewater treatment plants cannot accommodate such large volumes of water, and untreated water is conveyed in overflow pipes and discharged into natural waterways, adversely affecting the environment and posing a threat to public health. These wet weather events and outfalls are also referred to as combined sewer overflows (CSOs). In 2012, the American Society of Civil Engineering issued a policy statement that condemned the future construction of combined systems due to their detrimental effects on "environmental and health risks" from overflows (ASCE, 2012).

While combined systems are no longer an acceptable technology, they were widely constructed in cities around the turn of the 20th century. At that time, when cities were rapidly expanding, cities were turning away from cesspools because of increasing population density, the manual labor required to maintain cesspools, and environmental health concerns. Urban areas had to decide which type of sewer system they would replace cesspools with: combined or separate systems. At the time, combined sewer systems were ideal because they provided a solution for both wastewater and stormwater at minimum cost, and there was little awareness of receiving water quality.

Today, CSOs remain a persistent threat to water quality, particularly in "rust belt" cities which have faced a period of industrial decline. For example, in 2014, the Great Lakes Basin had 1,482 reported untreated CSO events, and 824 of those were in Ohio; however, five communities did not have available data (EPA 2016). It is estimated that in 2014 Ohio discharged 3,200 MG of untreated CSO volume and 400 MG of treated CSO volume, where treated CSOs have undergone a minimum level of treatment (EPA 2016).

Within the Greater Cleveland Area, there are over 100 CSO locations, discharging into the Cuyahoga River, other rivers and streams, and directly into Lake Erie. The Northeast Ohio Regional Sewer District (NEORSD) currently manages wet weather flows (stormwater and wastewater) in the Greater Cleveland Area and is responsible for reducing CSO and other pollutant discharges in order to comply with the Clean Water Act. In 2010, a Consent Decree was settled between the NEORSD and the Ohio Environmental Protection Agency (EPA) and U.S. EPA, stating that the NEORSD must spend $3 billion dollars on infrastructure and other programs to reduce the CSO discharges going into the natural water bodies. Many other cities across the U.S., such as Boston, MA (MWRA 2012), Philadelphia, PA (PWD 2009) and Washington DC (DCWSA 2002), have programs underway to eliminate or reduce CSO problems.

This research seeks to apply a suite of mathematical models linking collection system models, which model CSO overflows, to stream models to generate pollutant loads into Lake Erie under existing and alternative conditions for assessment and planning for the Consent Decree. The NEORSD has used the EPA Stormwater Management Model (SWMM), a mechanistic rainfall-runoff model which has been widely used to model urban watersheds. Other locations where SWMM has been applied include Philadelphia, PA (Hung et al. 2016), Cincinnati, OH (Mancipe-Munoz et al. 2014), Buffalo, NY (Irvine et al. 2005), and Satander, Spain (Temprano et al. 2006). SWMM has the capability of modeling CSOs and other point sources, as well as non-point source pollution loads to specified outlet points (Rossman et al. 2009; James et al., 2010; Gironas et al, 2010)

The objectives of this SWMM modeling study are to develop urban watershed models that integrate point-source discharges, including CSO events, with non-point source loads for three pollutants of concern (POCs)--bacteria, ammonia nitrogen, and phosphorus--and apply the models in the evaluation of integrated Clean Water Act planning alternatives. The models will generate pollutant loads at watershed outlet points that serve as inputs to a Lake Erie hydrodynamic model, which in turn will compute socioecological impacts such as beach closings and nutrient concentration exceedances.

This report summarizes the watershed modeling effort. Following a discussion of the development, calibration, and validation of SWMM models for the NEORSD area (Chapter 2), the use of spatially variable rainfall data is illustrated for two case study watersheds under existing and Consent Decree conditions (Chapter 3). A summary and recommendations for future research are presented in the closing chapter (Chapter 4).

Chapter 2: SWMM Model Development and Calibration

This chapter presents urban watershed models developed using SWMM to integrate point-source discharges, such as CSOs, and non-point source loads for three pollutants of concern (POCs) identified by NEORSD: *E.coli*, phosphorus and ammonia. The models were to be set up for continuous simulations of the summer beach season to ultimately generate time-variable loads to be used as inputs to a Lake Erie hydrodynamic model. This chapter summarizes the SWMM model set-up, calibration and validation. SWMM models were built upon pre-existing SWMM 4.4 models that required updates and improvements to be used for continuous simulations that would model existing conditions.

The NEORSD previously commissioned the Regional Intercommunity Drainage Evaluation (RIDE) study to evaluate storm drainage issues throughout various communities in the service area (Aldrich et al., 2005). Principal goals of the study were to offer solutions to local stormwater drainage problems and collect data needed for a regional stormwater management process. One result of the RIDE study was a set of SWMM (version 4.4) models that were used to model the hydrology and hydraulics of various subwatersheds throughout the NEORSD area. These models were initialized and calibrated for simulation of design storms of various intensities and durations (e.g., 2-year, 24-hour storm). For this study, the SWMM models were updated to version 5 using an online converter (USEPA, 2005). The software PCSWMM, developed by Computational Hydraulics International (CHI) (www.computationalhydraulics.com), was then used to make appropriate adjustments to the models through a graphical interface and geospatial mapping tools (Fig 1).

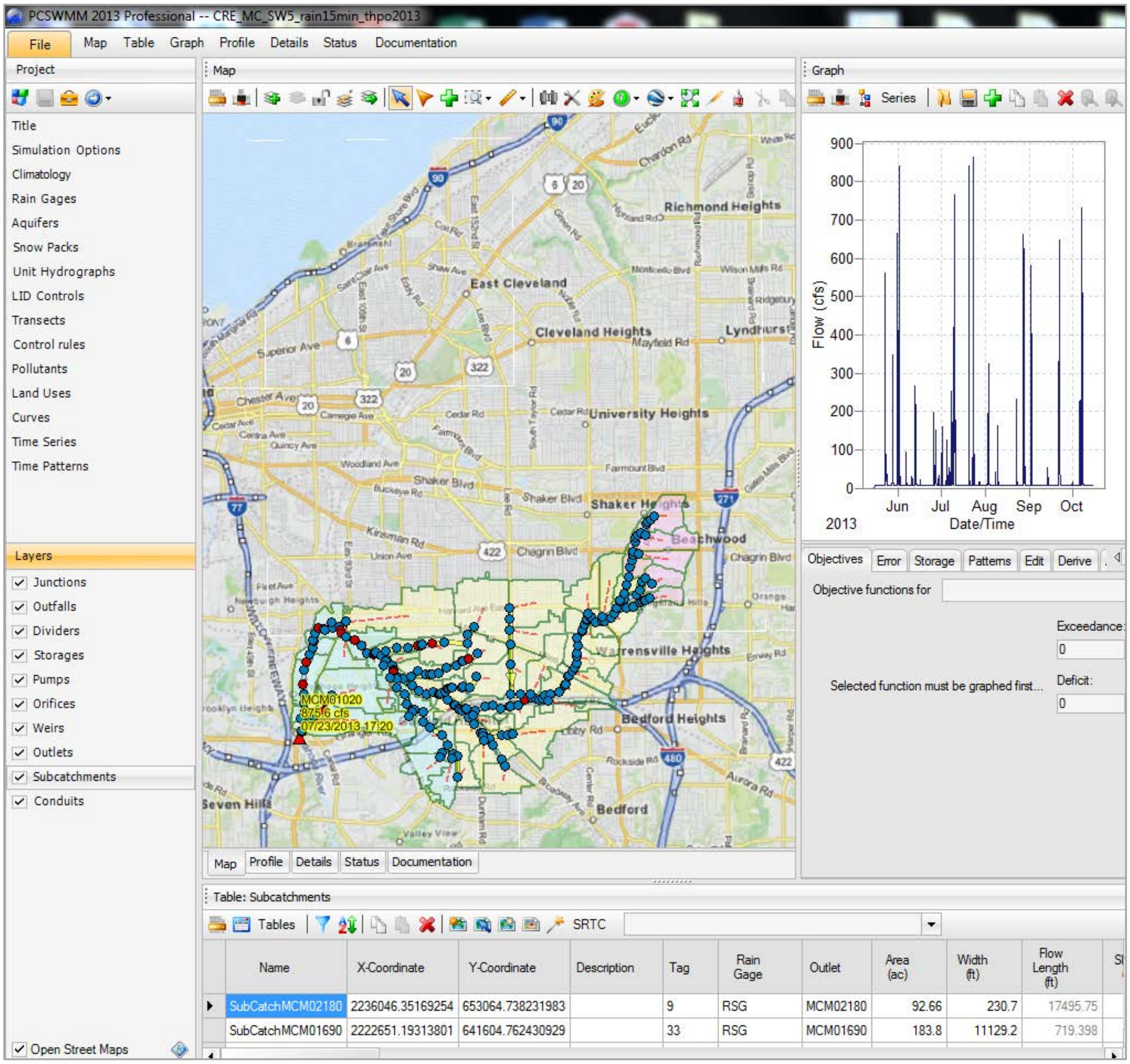

Figure 1. Snapshot of the PCSWMM interface. A majority of the features in EPA SWMM are present in the PCSWMM interface. Features unique to PCSWMM include the background street map, advanced time series plotting, a calibration tool, and geospatial rendering of the SWMM model nodes, links and polygons (https://www.pcswmm.com/).

The first step before making appropriate adjustments to the models was to ensure that the conversion from SWMM 4.4 to 5 was done successfully. This was done by comparing the outflow volumes for the 2-yr design storm. The results were found to match closely, generally within 10%, with the differences attributed to updated numerical methods in SWMM5 and uncertainty in the definition (lack of documentation) of event simulation length. A series of adjustments were then made to the SWMM5 models to represent continuous (e.g., seasonal) water quantity and quality simulations of existing infrastructure and proposed alternatives, as discussed below. Table 1 summarizes the SWMM models required for the scope of this integrated Clean Water Act planning study.

Table 1. SWMM models, watershed area, and CSO count

Model Name	Model Source	SWMM Subcatchment Area(mi^2)	NEORSD CSOs
Abram Creek	RIDE SWMM 4.4	9.12	0
Big Creek	RIDE SWMM 4.4	21.81	18
Cuyahoga River	Other	2.97	33
Doan Brook	Other SWMM 5	5.52	16
Dugway Brook	RIDE SWMM 4.4	6.32	2
Euclid Creek	RIDE SWMM 4.4	22.14	3
Green Creek	RIDE SWMM 4.4	0.63	2
Mill Creek	RIDE SWMM 4.4	8.36	21
Nine Mile	RIDE SWMM 4.4	5.21	2
Rocky River	Other	20.73	6
West Creek	RIDE SWMM 4.4	13.98	1
SWMM Total			**104**

In addition to SWMM models used in the RIDE study, the NEORSD has used a suite of collection system models (CSM) developed in the software Infoworks-CS by Innovyze (www.innovyze.com/products/infoworks_cs/). These models represent the combined collection system areas throughout the NEORSD service area (e.g., Metcalf & Eddy, 2002). The baseline CSM models have the capability of generating hourly CSO time series, in addition to other flows that discharge into the receiving waters, including sanitary sewer overflows (SSOs) and flows labeled additional stormwater (ASW). Further, the CSM models represent flows to wastewater treatment plants (WWTP), along with WWTP treated effluents and bypasses. In this study, CSOs, SSOs, and ASW were represented by CSM outputs, which served as time series inputs to the SWMM models. NEORSD data was used to represent the WWTP treated effluent and bypass discharges when available. For consistency, the CSM models used the same NEORSD rain gages as the SWMM5 models to account for the spatial and temporal distribution of rainfall. Any overlap between the CSM and SWMM subcatchments was addressed by rerouting SWMM subcatchments to dummy nodes so that stormwater was not accounted for twice, as further discussed below.

SWMM5 Model Set-Up and Data Integration

The SWMM5 models represent subcatchment hydrology and flow in stream networks. Runoff is modeled based on rainfall inputs and either the Horton or Green-Ampt infiltration methods. Stream discharge includes runoff, various point-source inputs (e.g., CSOs), and baseflow, and is modeled using the dynamic wave equations with either fixed or free boundary conditions. Sixteen NEORSD rain gages were used in the SWMM models in this study, and each SWMM5 model uses two to five rain gages as inputs to account for spatial rainfall variability.

Baseflow Estimation

For continuous simulations, baseflow needed to be added to the models, since the original models used in the RIDE study did not represent dry weather flow. A visual baseflow separation method was applied to summer (June through August) measured daily flows at nine USGS gaging stations (see Table 2) located within the NEORSD area. For each gage and each month, an average baseflow per unit area was calculated, and the values were found to be reasonably consistent (Fig. 2). Using these values, each subcatchment area was assigned a summer baseflow, represented as a constant flow entering the stream network at the subcatchment outlet node.

Table 2. USGS streamflow gages used to estimate baseflow in SWMM5 model subcatchments

USGS Gage ID	Gage Name	Drainage Area (mi2)	June 3-Year Average	July 3-Year Average	August 3-Year Average
412141081412100	West Creek at Pleasant Valley Road near Parma OH	1.10	**0.10**	**0.10**	**0.10**
04201506	Abram Creek at Middleburg Heights OH	1.45	**0.11**	**0.08**	**0.13**
412325081415500	West Creek at Ridgewood Road at Parma OH	3.87	**1.95**	**1.00**	**0.63**
04201515	Abram Creek at Brook Park OH	5.12	**0.15**	**0.15**	**0.25**
04201526	Abram Creek at Kolthoff Drive at Brook Park OH	8.12	**1.50**	**1.95**	**1.15**
412453081395500	West Creek at Brooklyn Heights OH	9.23	**3.00**	**2.50**	**2.25**
04208460	Mill Creek at Garfield Hts OH	17.90	**6.67**	**7.17**	**6.17**
412624081450700	East Branch Big Creek at Brooklyn OH	19.20	**5.00**	**7.00**	**9.00**
04208700	Euclid Creek at Cleveland OH	23.10	**7.50**	**6.67**	**6.17**

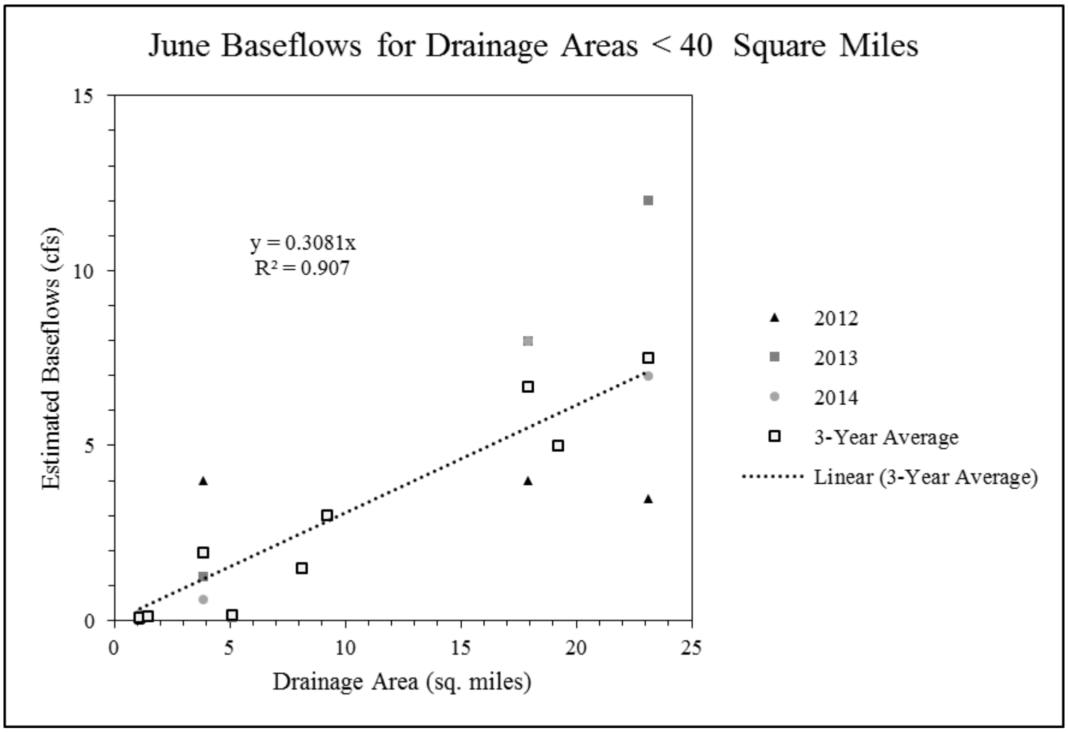

Figure 2. Estimated baseflow for each drainage area for three years, including the 3-year average.

Point Sources and Land Use

The next adjustment to the SWMM5 models was to represent point-source discharges, including CSOs, SSOs (separate and common trench), additional stormwater flows (ASWs), and illicit discharges (ILLDs). Prior to integrating these point sources as time series inputs, a check needed to be done to ensure that stormwater volumes accounted for in the collection system models (CSMs) were not also accounted for in the SWMM models. This required the subcatchments in the SWMM5 and CSM models to be geospatially represented so that overlapping areas could be identified. Although there is some uncertainty in the model subcatchment delineations and area attributes, the accuracy was deemed sufficient for identification of overlapping areas. If a subcatchment in the SWMM5 model was found to overlap significantly with one or more CSM subcatchments, then the SWMM5 subcatchment was rerouted to a dummy outlet. As a result of this step, volumes of stormwater that were rerouted to a dummy outlet would be accounted for as flows to the WWTPs, CSO time series, or ASW time series at CSO outfalls. Use of dummy outlets allowed all subcatchments to remain in the SWMM5 models, for the purposes of documentation and flexibility in future modeling studies.

The point-source discharges all have identified locations within the stream networks and are modeled with a direct time series, Q. The total volume modeled under existing conditions is shown in Figure 3 and the modeled changed under the Consent Decree in 2014 are shown in Figure 4. As mentioned, CSOs, ASWs and SSOs all have time-variable flows, Q(t), as computed by the CSM. ILLDs are assumed to have a constant flow Q, estimated as 0.01393 ft3/s (9000 gal/day) based on data compiled by the NEORSD. Pollutant loads are computed as W = CQ, where C varies by system type but is assumed constant in time for each pollutant of concern (ammonia, E. Coli and phosphorus).

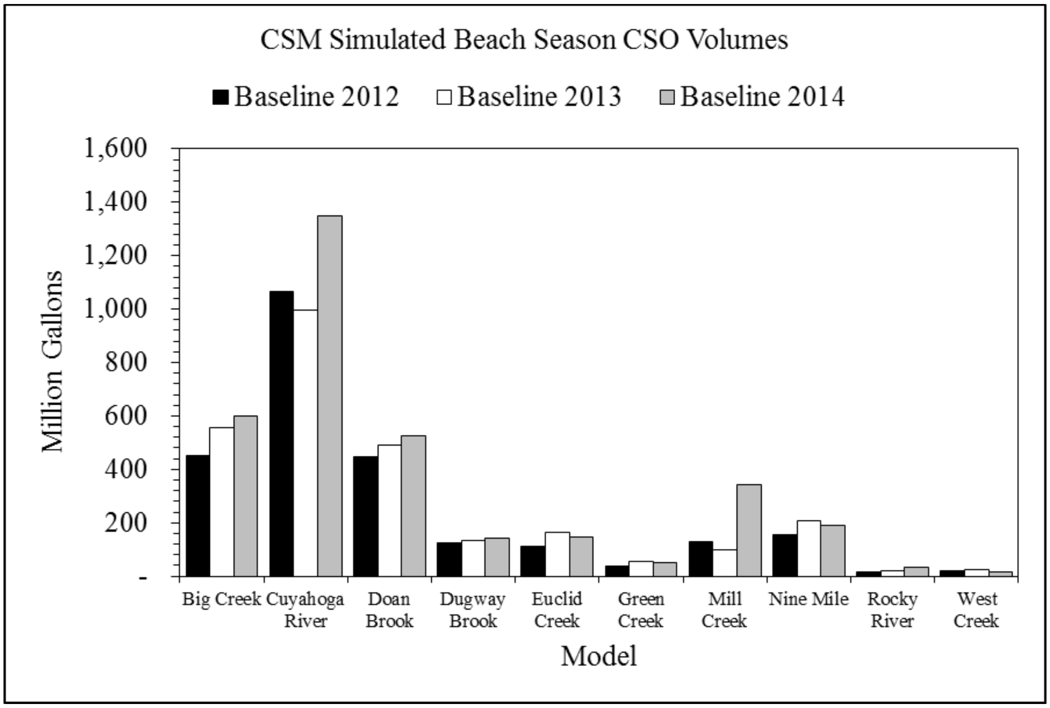

Figure 3. Collection System Model simulated CSO Volumes for the Beach Season 2012-2014

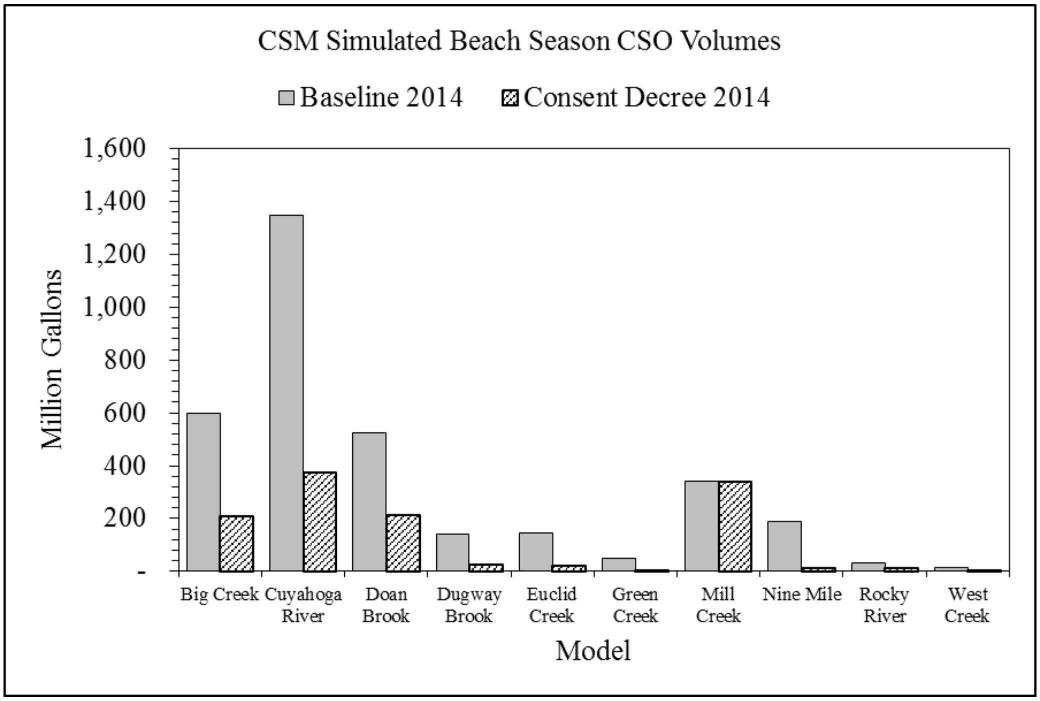

Figure 4. Collection System Model Simulated CSO Volumes for 2014 under Baseline and Consent Decree scenarios

In addition to the point-source discharges, different land uses and infrastructure system types are modeled as contributing to non-point source pollutant loadings. The system type contribution is modeled by applying an area-weighted concentration to the runoff time series from each subcatchment that is routed into the stream network. For each subcatchment, the area-weighted pollutant concentration is based on the proportion of each system type: combined, separate, and common-trench sewers, with common-trench further classified as dual manhole, dividing wall, and over-under (Fig. 5). Most of the combined sewer area is modeled by the CSM, with insignificant portions modeled in the SWMM5 subcatchments. The other areas are all represented in SWMM5. Separate sewer areas are where stormwater and wastewater are conveyed in different systems, and common trench areas are where they are separate but the pipes are in a common trench. Due to the various ways the different systems types are constructed and interact in wet weather flow events, they have varying impacts on water quality.

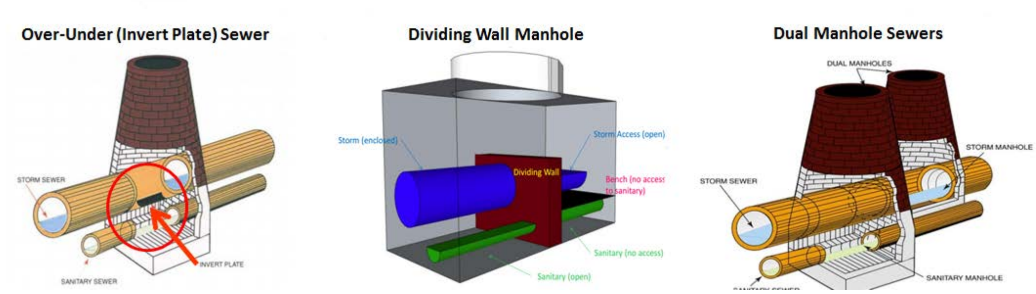

Figure 5. System Types that exist throughout the NEORSD. Image courtesy of the Northeast Ohio Regional Sewer District.

Bacteria (*E.Coli*) concentrations ranged from 19,325 CFU/100mL for separate trench systems to 100,000 CFU/100mL for divider wall systems, and phosphorus concentrations ranged from 0.10 mg/L 0.30 mg/L (Zngilec 2016). The final pollutant source included in the models was septic tanks. For subcatchments with septic tanks, a mass loading was input based on the number of septic tanks in the subcatchment. Similar to ILLDs, constant mass loading rates were assumed per septic tank, based on data provided by the NEORSD. Figure 6 shows the distribution of system types within each watershed.

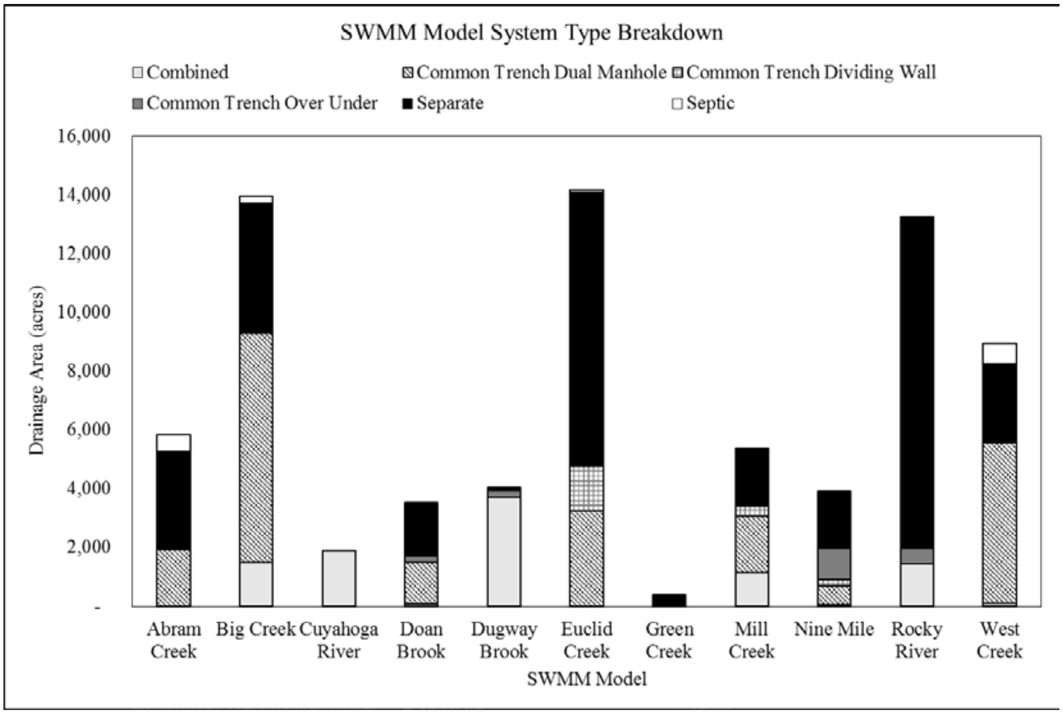

Figure 6. System types represented in SWMM5 models, by watershed

Rainfall Data

Fifteen-minute precipitation data was input to the SWMM5 models for continuous simulations of the summer seasons (May 15 – October 14) of 2012, 2013 and 2014. Prior to this update, the SWMM models were set up to simulate only daily design storm events. In contrast, using the 16 NEORSD rain gages, distributed across the service area, provided improved spatial and temporal resolution that otherwise would have been compromised by using design storm inputs or data from a single gage. Spatial variability in rainfall for the summer of 2014 is illustrated in Figure 7; as an example, the total rainfall measured at gage RMY was nearly double the amount measured at the gage RJA.

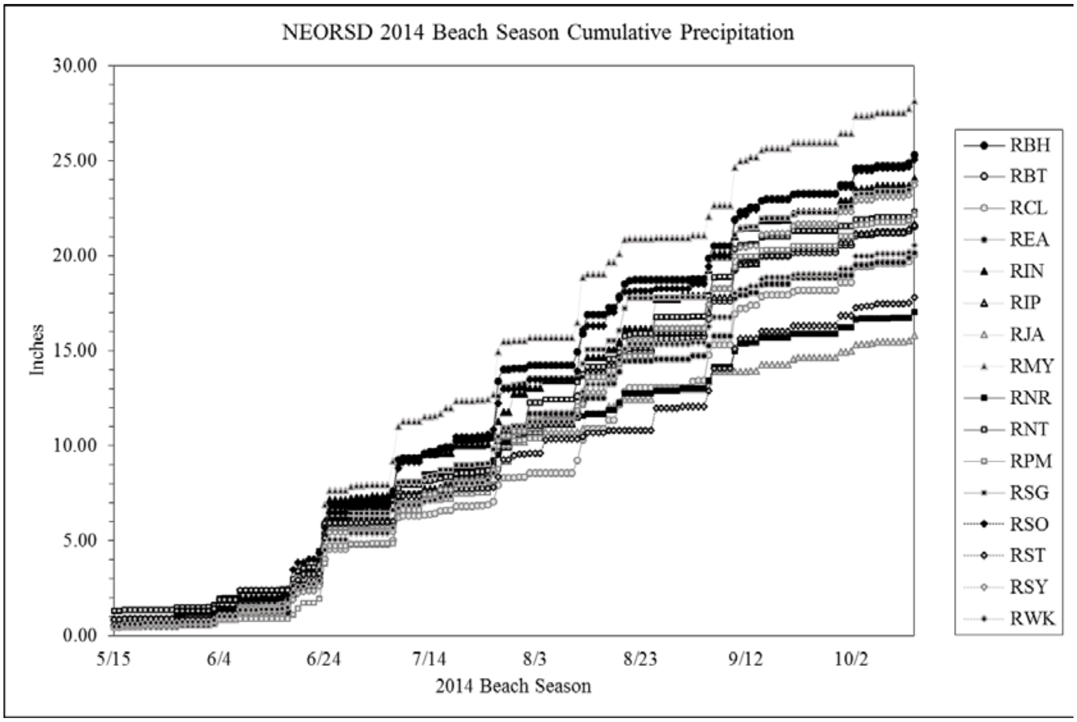

Figure 7. Cumulative daily precipitation during the 2014 beach season for the 16 NEORSD rain gages used as inputs into the SWMM models

Hydrology Calibration and Validation

For each watershed in the NEORSD service area with measured flow data, SWMM5 simulations were run for summer 2014, and specific events expected to contribute the majority of pollutant loads to the lake were selected for discharge volume comparisons in the calibration process. Based on rainfall data from a centrally located gage (RDA*), 15-20 rainfall events each having a total rainfall depth of 0.25 inches or more and an inter-event time of at least 12 hours were selected for each summer period (May 15 – October 14). The largest event (June 24, 2014) had a total rainfall depth of 1.29 inches. After calibration, results from SWMM5 simulations of 2012 and 2013 summer periods were used for validation.

Following a sensitivity analysis, calibration was done in PCSWMM using the Sensitivity-based Radio Tuning Calibration (SRTC) tool for adjustment of three parameters to which model results were found be most sensitive--subcatchment width, percent impervious, and depression storage for impervious sub-area (Barco et al., 2008). Two subcatchment parameters—depression storage for pervious sub-area and percent of impervious area with no depression storage—were not selected because model results were insensitive to changes in their values. The conduit parameter *n* for roughness in Manning's equation was not selected for calibration because it can be physically estimated. Once calibration parameters are selected, application of the SRTC tool starts with two sensitivity analysis runs for each parameter, one with the parameter value fixed at a specified lower bound and one at a specified upper bound, with the bounds selected by the user to represent parameter uncertainty. In this study, all three parameters were assigned upper and lower bounds of +/-25% of their initial values. The SRTC tool then allows for graphical sensitivity analysis assuming a linear model response within the ranges of the sensitivity analysis.

Three criteria were used for model calibration: 1) maximizing the correlation between observed and simulated event volumes, 2) minimizing the bias in simulated event volumes, and 3) improving the visual comparison of simulated and observed time series over the entire summer period (e.g., matching the timing and magnitudes of peak discharges). Using Euclid Creek as an example, a 20% reduction in subcatchment width, 12.5% increase in percent impervious, and 5% increase in depression storage resulted in an improved model fit over the 2014 summer period. The simulation bias in storm event discharge volumes improved from -11.1% to -4.4%, while a high R^2 value of 0.9619 was maintained (Figure 8). The match between simulated and observed time series of Euclid Creek discharges also improved slightly (Figure 9).

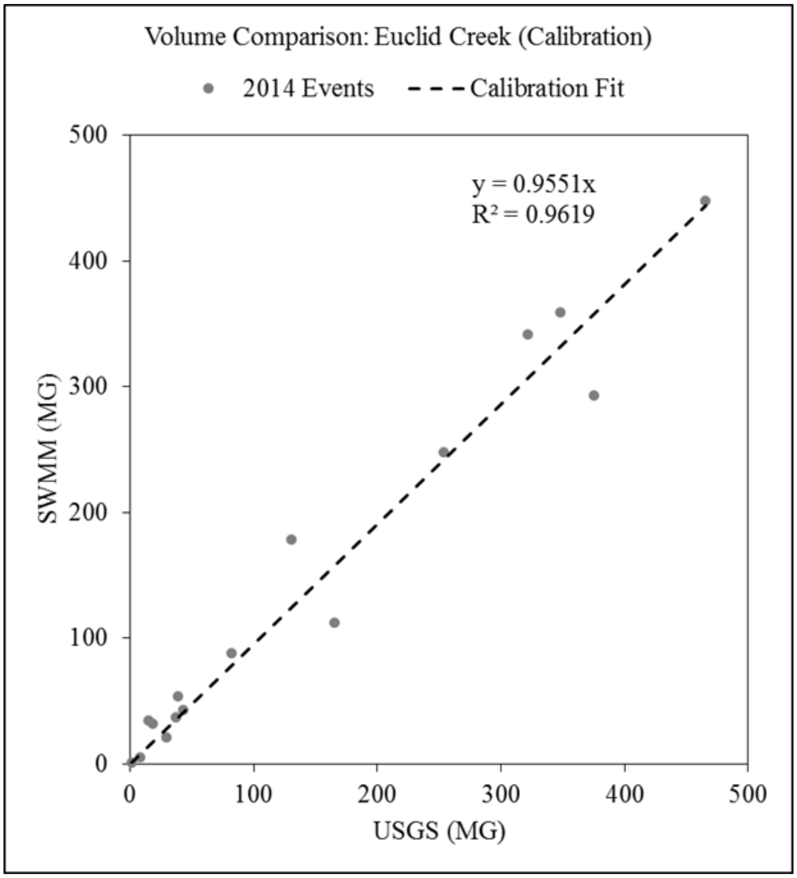

Figure 8. Euclid Creek SWMM5 calibration results for event discharge volumes in summer 2014

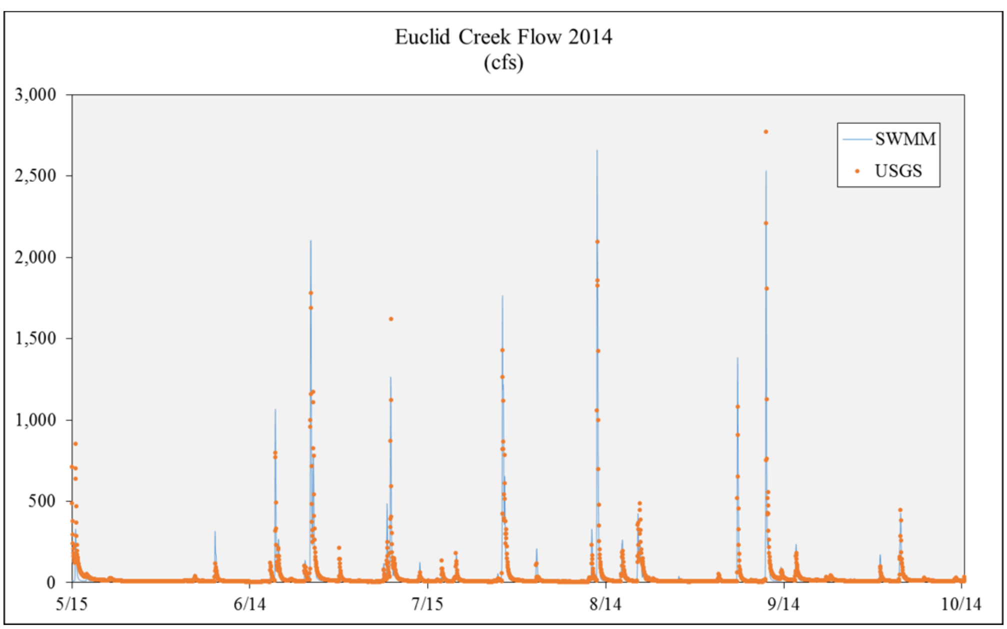

Figure 9. SWMM5 calibration results for Euclid Creek, summer 2014

With the parameter values resulting from calibration to 2014 observed flows, simulations for the 2012 and 2013 beach season were run for validation purposes. Comparison of event discharge volumes on Euclid Creek is shown in Figure 10, with an R^2 value of 0.7088 and an average bias of -6.3% for the 2012 and 2013 summer periods. Comparisons of simulated and observed hourly discharge time series are shown in Figures 11 and 12. Overall, the SWMM5 simulation results match the timing of observed peak discharges closely (typically within 1 hour), and the majority of peak discharges are matched within +/- 20%. Simulated flows also match observed low flows, which further validates the baseflow estimation process. Observed and simulated hourly time series for select storm events are shown in Figure 13.

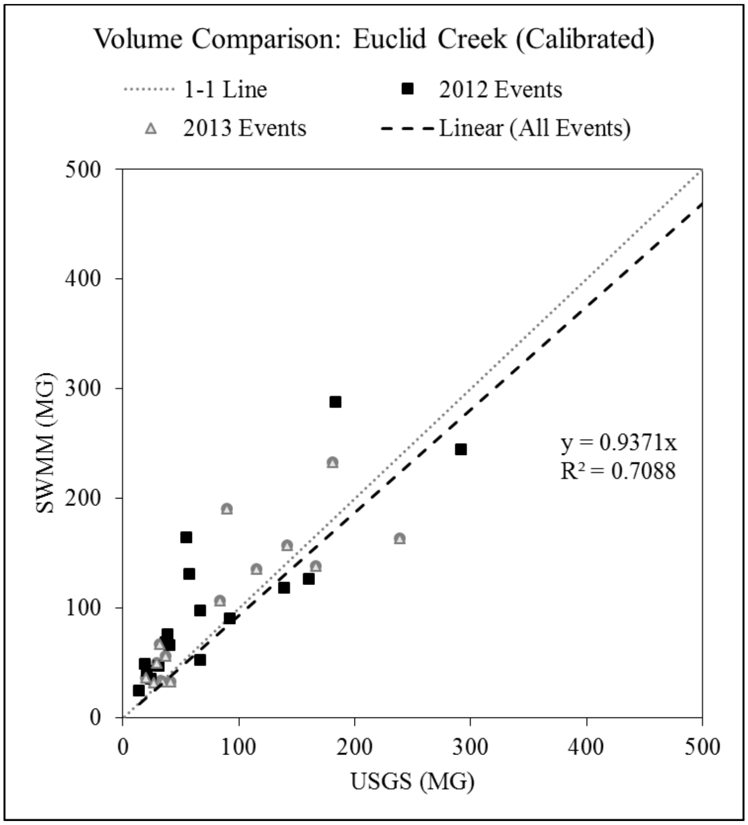

Figure 10. Volume Comparison for Euclid Creek calibration runs.

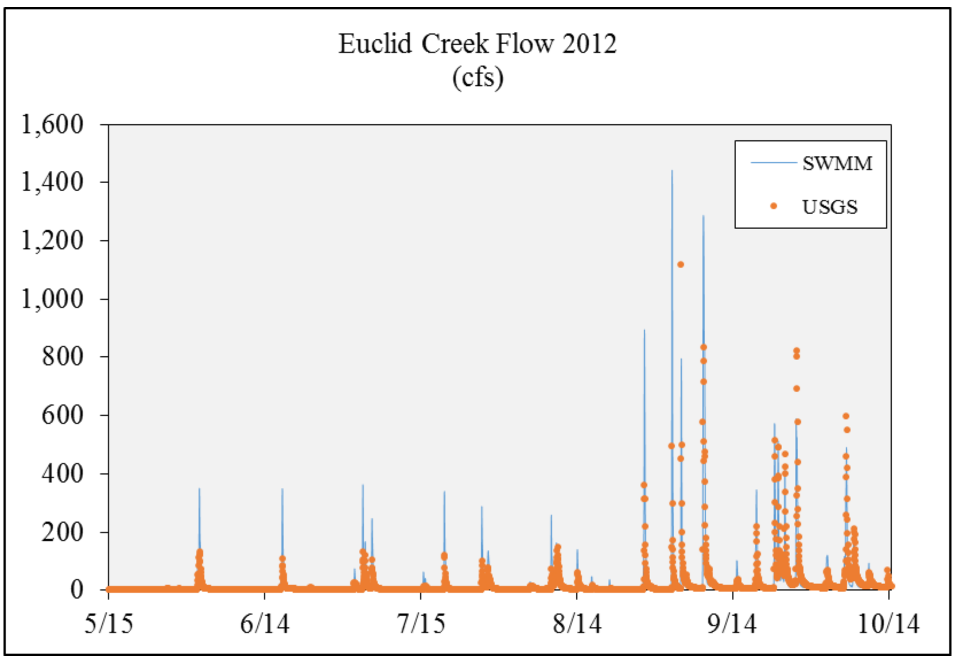

Figure 11. SWMM5 validation results for Euclid Creek 2012

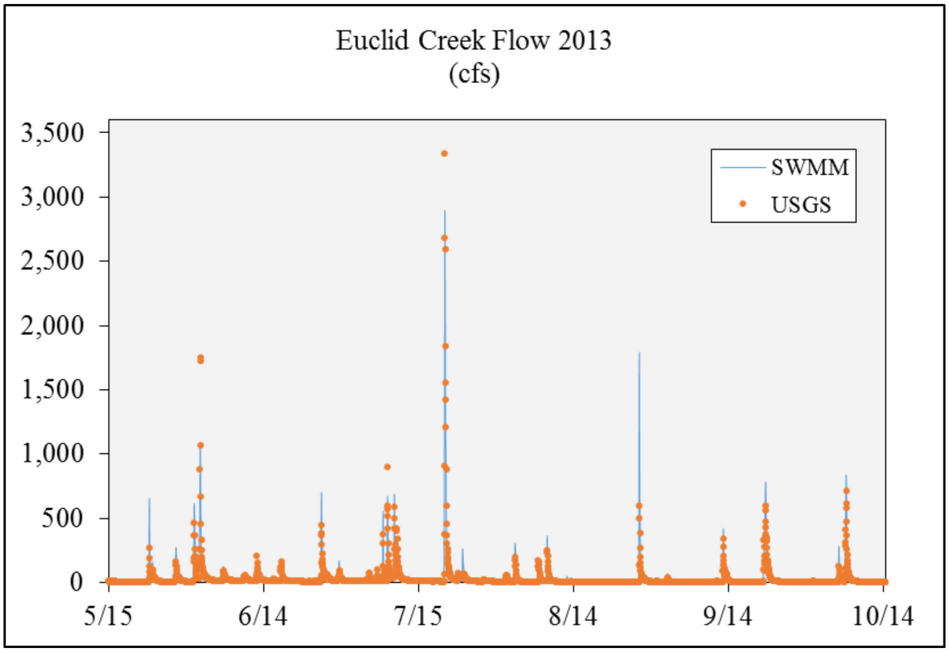

Figure 12. SWMM5 validation results for Euclid Creek 2013

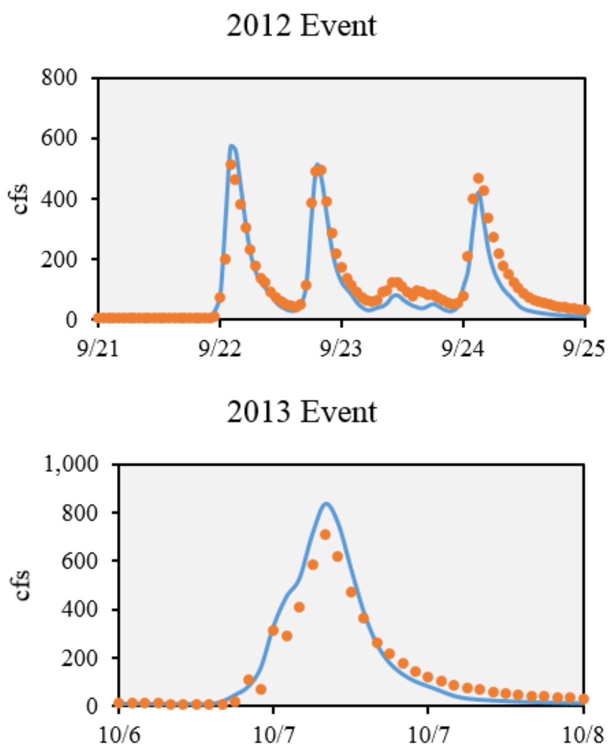

Figure 13. SWMM 5 calibrated and validated models, select events 2012-2013

Chapter 3: Comparison of Uniform and Distributed Rainfall Simulations

In previous studies, typically focusing on sub-watersheds or components of a particular WWTP's collection system, the NEORSD has used a "typical year" for rainfall inputs into the collection system model (NEORSD CSO Facilities Planning, Appendix C-4). The typical year was based on hourly rainfall data from the Hopkins International Airport from 1991 and 1993 to create a synthetic precipitation time series. As of 2012, however, the NEORSD has set up rain gages throughout the service area which gather data at fifteen-minute intervals at over 20 locations. Sixteen of these gages were used as inputs to the SWMM5 models used in this study, with the Thiessen polygon method applied to the SWMM5 subcatchments. Hydrology calibration and validation presented in Chapter 2 used the available 15-minute data.

This chapter summarizes the results of the simulations performed under various scenarios: 1) Baseline conditions with distributed rainfall, 2) Baseline conditions with uniform rainfall, 3) Consent Decree conditions with distributed rainfall, and 4) Consent Decree conditions with uniform rainfall. These comparisons are done to show how the system-wide loadings are sensitive to rainfall inputs, with the hypothesis that using uniform rainfall over the entire NEROSD service area can lead to inaccurate results, particularly for individual storms. Further, these comparisons will show how the Consent Decree will reduce the loadings over the beach season under both types of rainfall.

Comparison of results is illustrated using two SWMM5 models: Euclid Creek and West Creek. Additionally, the SWMM5 models were run for both the baseline conditions and consent decree conditions. Consent decree simulations have the same hydrology and hydraulics and settings as the baseline simulations, except that there are changes in CSM outputs such as CSO, ASW and WWTP time series. Table 3 shows a matrix of the eight simulations that are presented here.

Table 3. SWMM Simulation Scenarios

	Rainfall	
Model	**Distributed (Thiessen)**	**Uniform (Hopkins)**
Euclid Creek	*Baseline*	*Baseline*
	Consent Decree	*Consent Decree*
West Creek	*Baseline*	*Baseline*
	Consent Decree	*Consent Decree*

Figures 14 and 15 depict each case study watershed, respectively, showing where the CSOs and other point sources are integrated into the stream network, along with the spatial allocation of rain gages to the subcatchments (in color), based on the location of the subcatchment outlet.

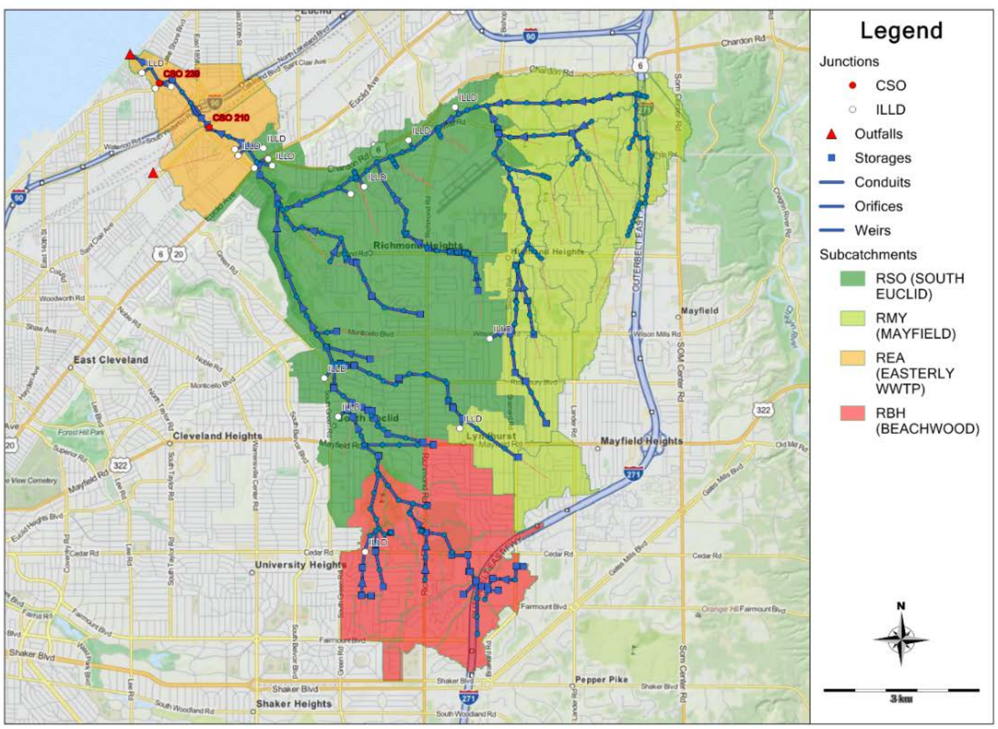

Figure 14. Map of the Euclid Creek watershed. Shown are CSOs and other point-source discharges. Colors show area apportionment to rain gages using the Thiessen polygon method.

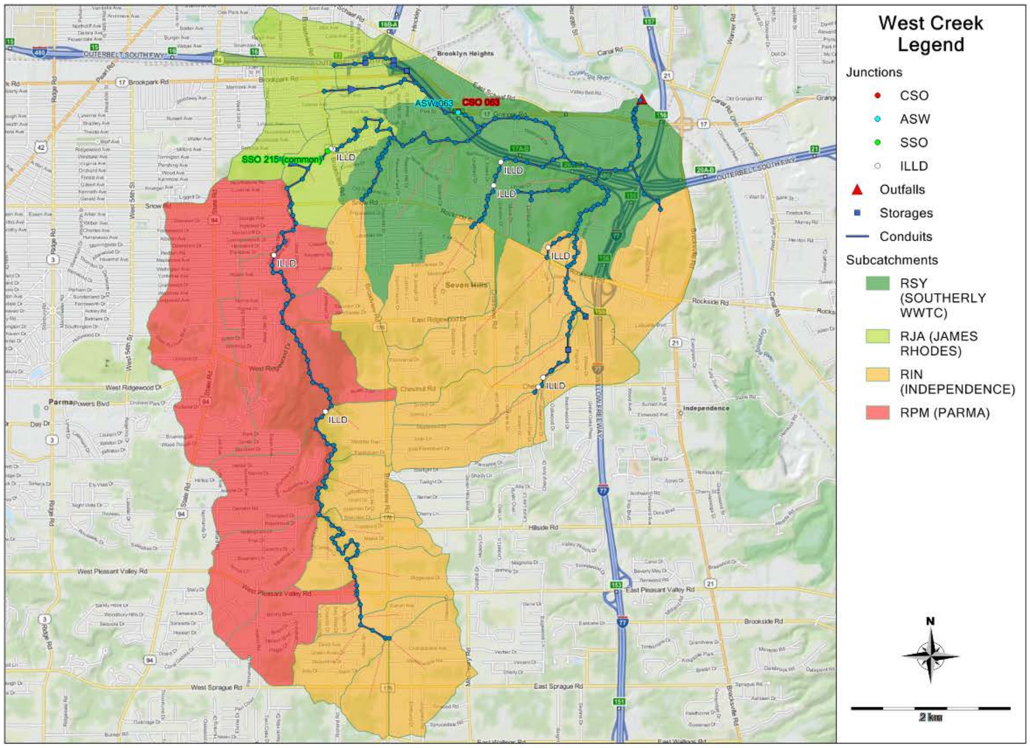

Figure 15. Map of the West Creek watershed. Shown are CSOs and other point-source discharges. Colors show area apportionment to rain gages using the Thiessen polygon method.

Rainfall Analysis

The NEORSD spans 350 square miles, so one rain gage will not accurately represent the spatial distribution of rainfall. Each model itself represents a large enough area to have significant spatial variability in rainfall over individual storm events and over an entire summer. For example, the 9/30/2014 storm had some areas of the watershed receive two or three times as much precipitation as other parts of the watershed, as shown in Figure 16. Spatial variability over the entire 2014 summer is depicted in Figure 17. Figure 18 shows the daily cumulative precipitation specifically for gages in Euclid Creek and West Creek watersheds compared with the Hopkins gage.

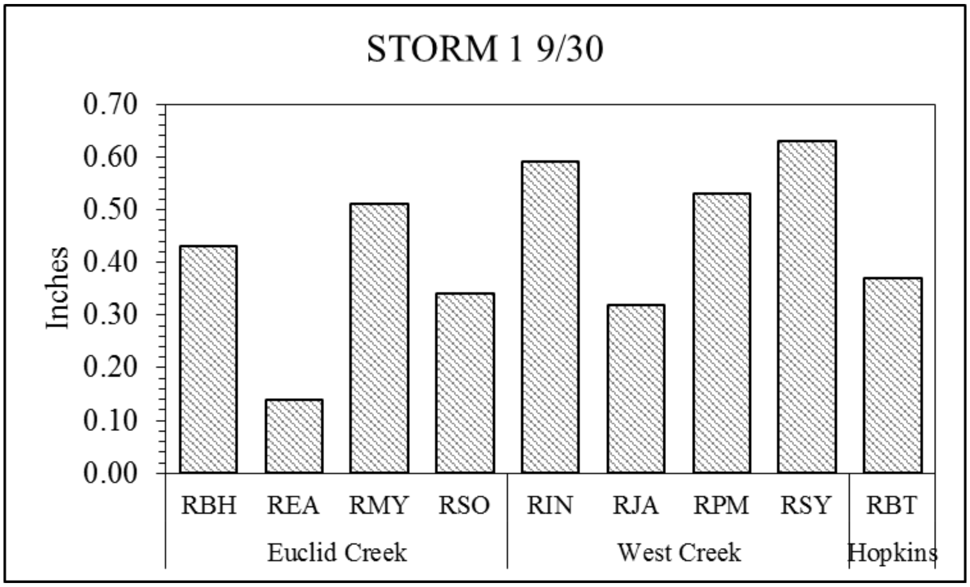

Figure 16. Rainfall volume (in) for the rain gages in Euclid Creek and West Creek for the 9/30/2014 storm.

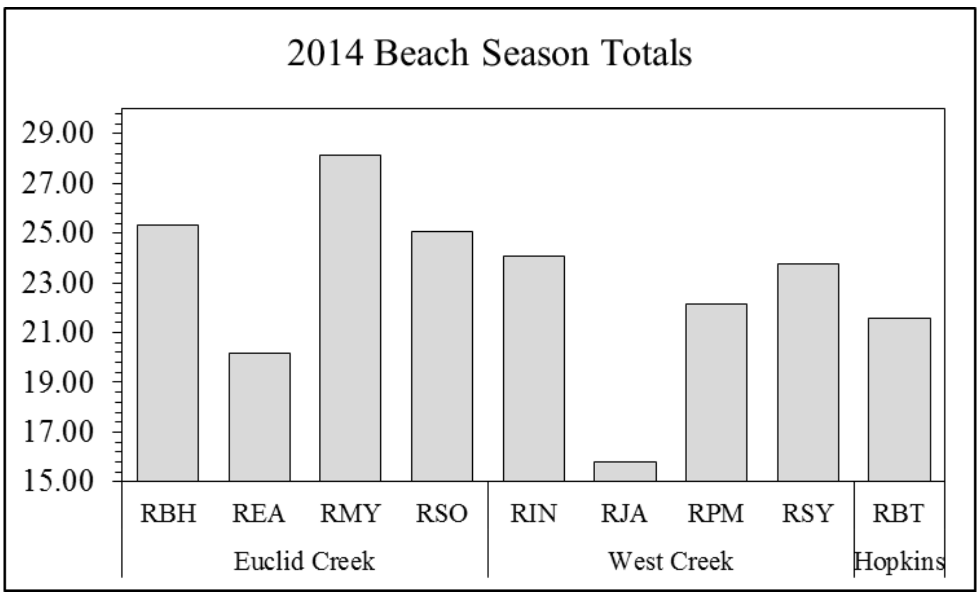

Figure 17. Rainfall volume (in) for the rain gages in Euclid Creek and West Creek for the 2014 beach season

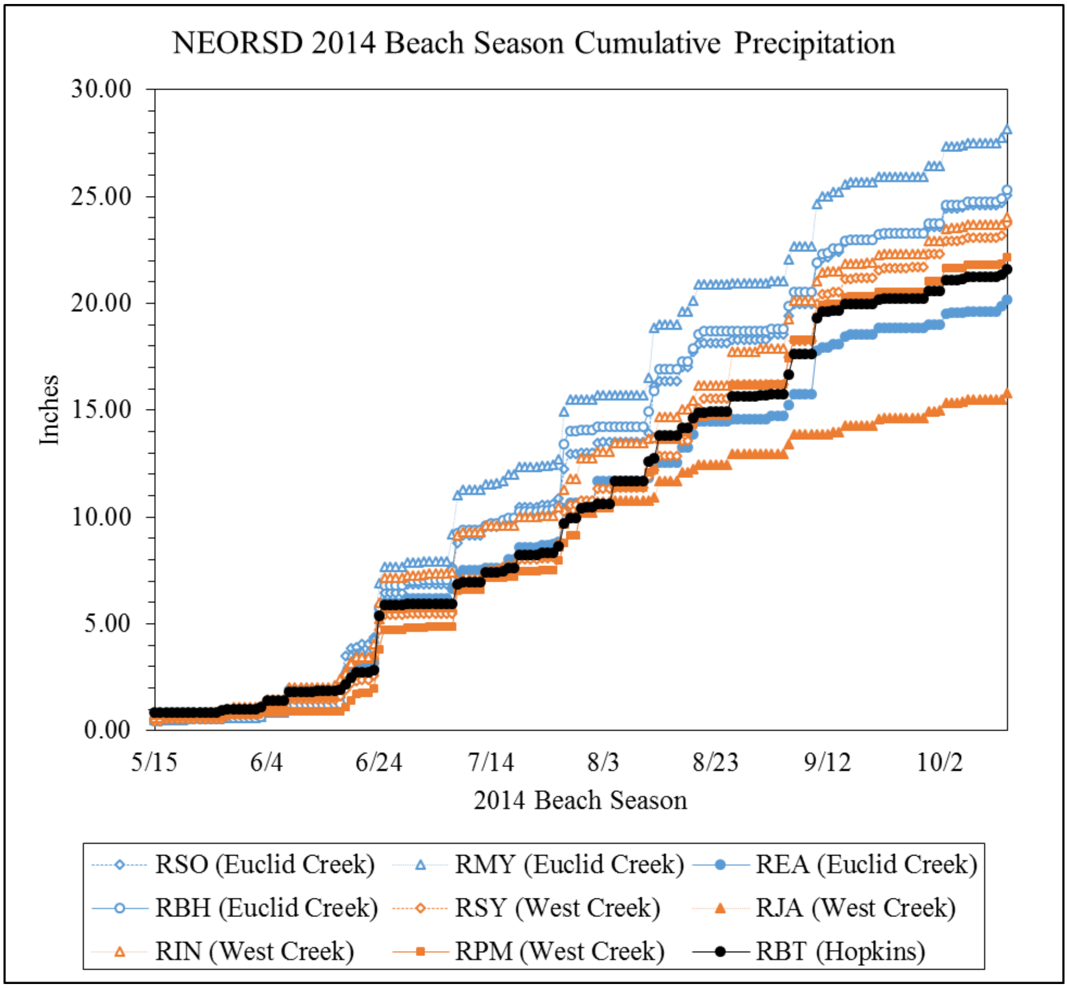

Figure 18. Daily cumulative total for the Euclid Creek and West Creek rain gages

CSM Baseline and Consent Decree Output

In addition to the rainfall volume, the second variable that is altered in this analysis is the CSM volumes in simulations of Baseline and Consent Decree conditions. Under the Consent Decree, various CSOs are either controlled to a certain extent or closed all together. It is possible for a CSO to be controlled and never overflow during the course of a simulation, but it would still be considered an active CSO and should be represented as such in the model. Table 4 shows the number of active CSOs in 2014 (excluding those that discharge directly into Lake Erie) and those that would be active under the Consent Decree.

Table 4. SWMM Model CSO count under baseline and consent decree

SWMM Model	Baseline CSO	Consent Decree CSO
Big Creek	18	15
Cuyahoga River	33	31
Doan Brook	16	16
Dugway Brook	2	2
Euclid Creek	3	3
Green Creek	2	2
Mill Creek	21	21
Nine Mile	2	2
Rocky River	6	6
West Creek	1	1
Grand Total	**104**	**99**

It should be noted that each CSO does not necessarily discharge the same amount or overflow at the same time. Figure 19 shows the changes in CSO volume that the CSM predicts under the consent decree compared to the baseline. Relative to other watersheds, Euclid Creek and West Creek have small CSO contributions to their total discharge; however, they each show a significant reduction of CSO discharge volume under the consent decree. Figure 20 zooms into these models further to show specifically which CSOs are being reduced. Figure 21 shows an example of CSO discharges from a single storm event under baseline and consent decree conditions.

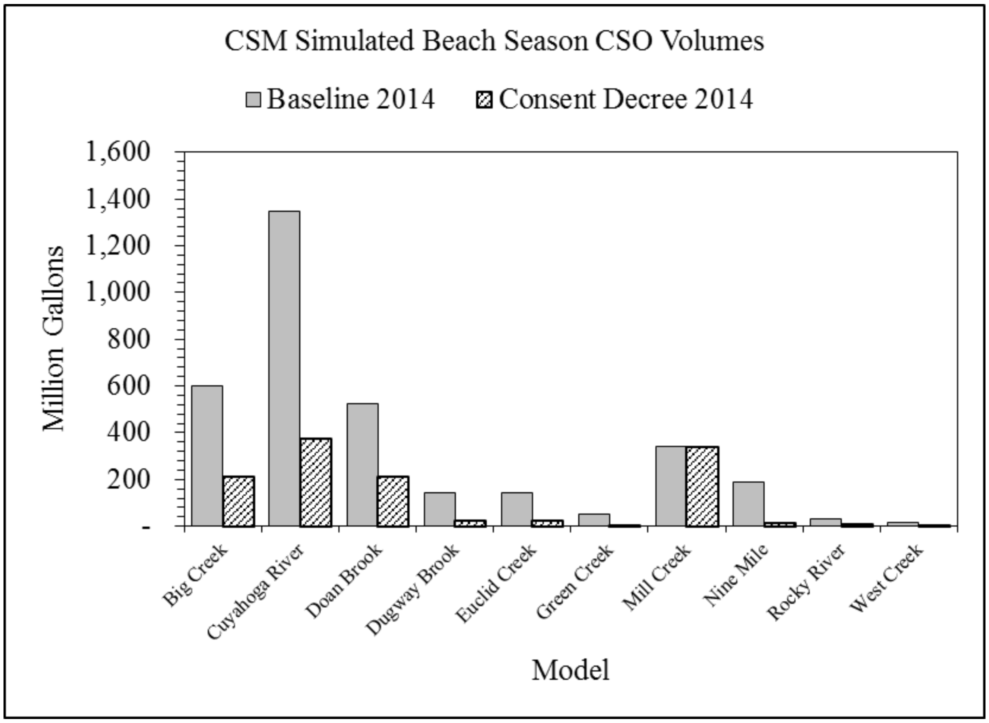

Figure 19. CSO volumes for baseline and consent decree simulations of the 2014 beach season

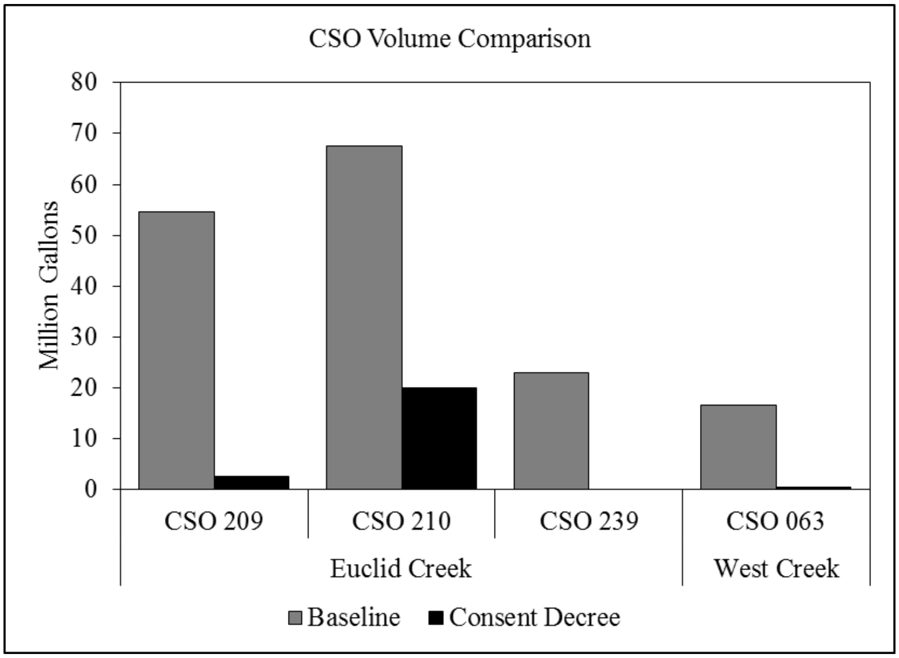

Figure 20. CSO volume comparisons for baseline and consent decree scenarios for CSOs on Euclid Creek and West Creek in 2014

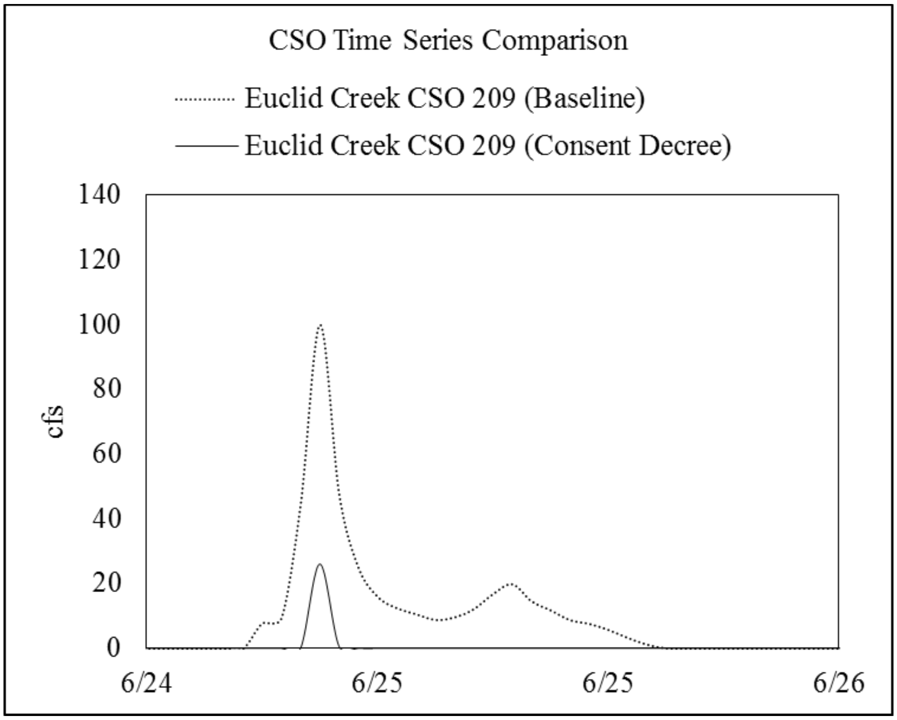

Figure 21. Time series comparison of CSO 209 under baseline and consent decree conditions, June 24-26, 2014.

SWMM Results

From these simulations it is evident that, under baseline conditions, the volume of discharges going into Lake Erie increases with the use of distributed rainfall. Consequently, the loads also increase. Figure 22 and 24 show that using the Hopkins rain gage produces less volume than when using distributed rainfall, when comparing 2014 beach season totals. Likewise, Figure 23 and Figure 25 show that the Hopkins rain gage consistently produces less loads for all POCs under both baseline and consent decree conditions. In Figure 26, comparisons are made by selecting the four largest storms from the RDA gage and comparing the storm volume totals. In these cases, the volume increase is more pronounced.

These results show that West Creek and Euclid Creek discharge volumes and loads are both reduced significantly under Consent Decree conditions, regardless of whether uniform or distributed rainfall is used. However, the uniform versus distributed rainfall comparisons showed that uniform rainfall tended to generate smaller loads than the distributed rainfall. These results were unanticipated, as it was expected that using distributed rainfall instead of rainfall from a single gage would lead, on average, to decreases in simulated discharges and loads. However, the Euclid and West creek watersheds are each less than 25 square miles, and the storms in the 2014 summer period are typically less than 24 hrs, which means the depth-area reduction factor is estimated to be approximately 0.96 (NOAA 1980). Considering the variability in rainfall patterns, this is not significantly different than 1.0 for a small sample of storms, and thus the results obtained are not improbable. In fact, for the storm events observed over the simulation period (2012-2014), the depth-area-reduction factor would be approximately 0.9 over the approximately 200 square miles where SWMM models extend over the NEORSD (NOAA 1980). Thus, over more summers and more storms, it is expected that using a single rain gage as input for all the SWMM models would overestimate the loads into Lake Erie.

In summary, the results presented herein can be explained by a limited sample size of one summer with a few large storms. More simulations—with more extreme events--need to be run to evaluate the true impacts of simulating loads over the entire NEORSD with uniform versus distributed rainfall. Regardless, simulations with distributed rainfall will certainly provide more accurate results for any given storm, which is critical for other applications such as predicting beach contamination events.

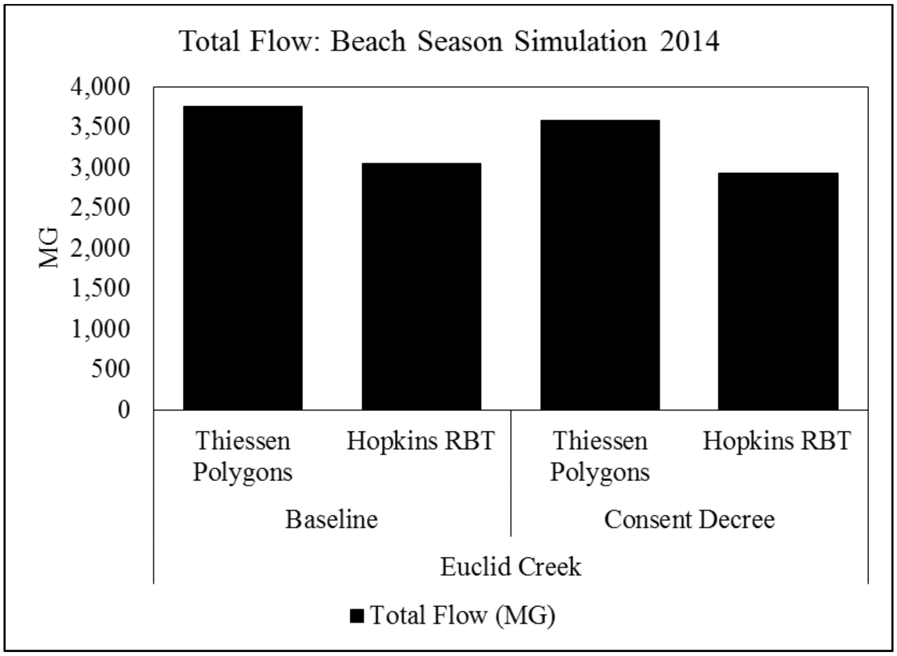

Figure 22. Volume comparison of Euclid Creek Baseline and Consent Decree simulations using distributed and uniform rainfall.

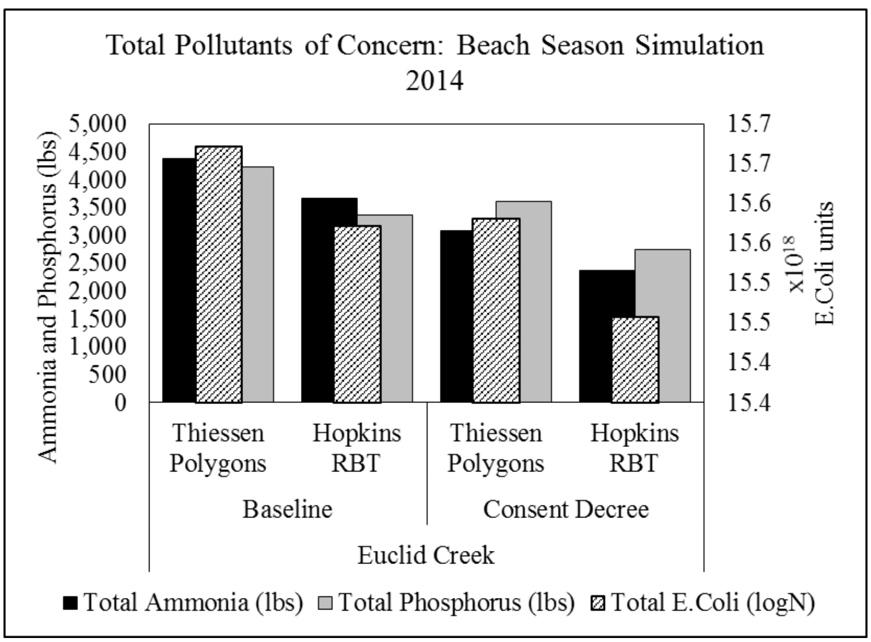

Figure 23. Load comparison of Euclid Creek Baseline and Consent Decree simulations using distributed and uniform rainfall

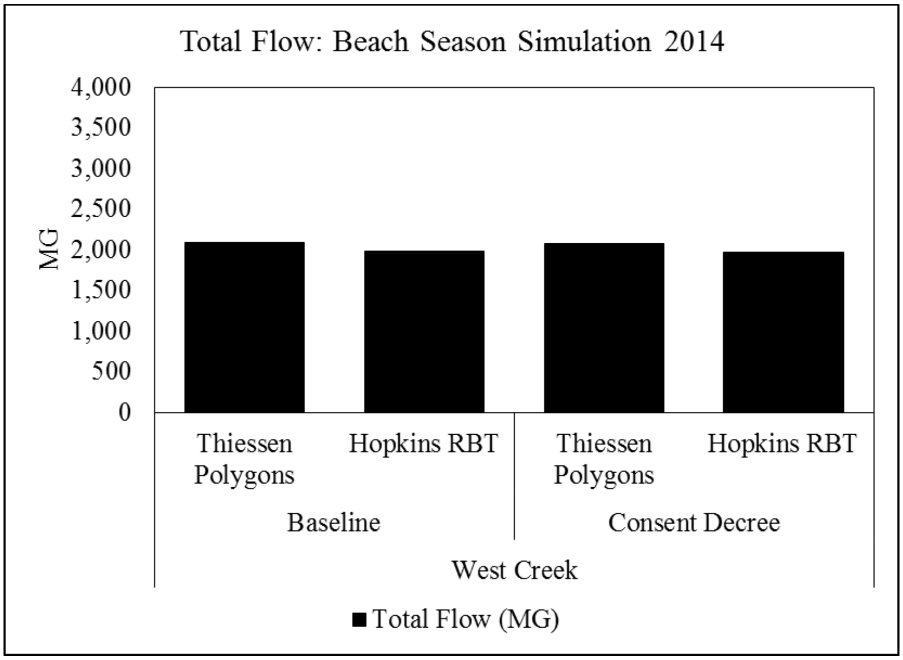

Figure 24. Volume comparison of West Creek Baseline and Consent Decree simulations using distributed and uniform rainfall.

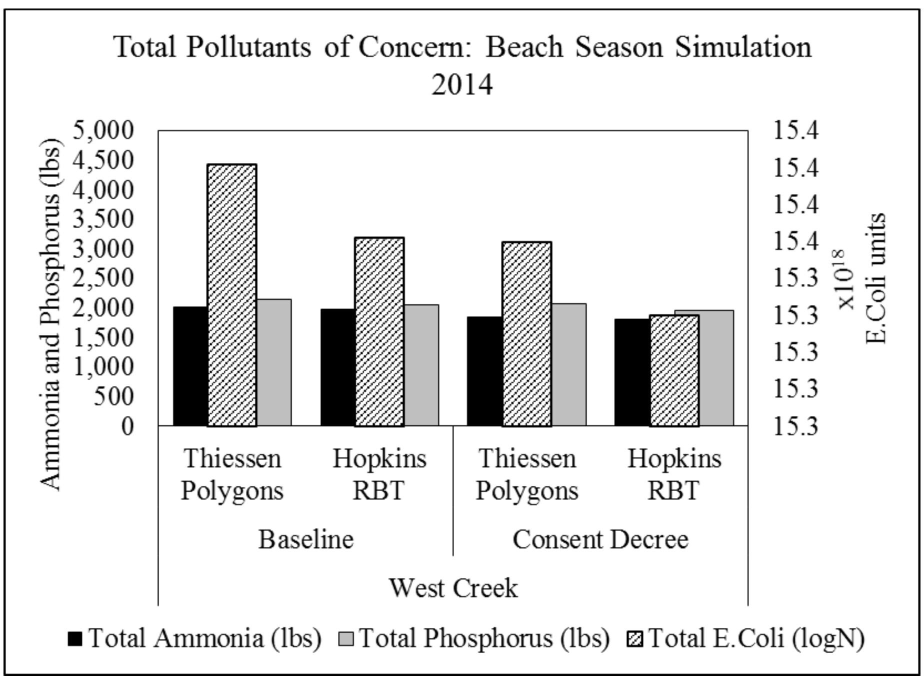

Figure 25. Load comparison of Euclid Creek Baseline and Consent Decree simulations using distributed and uniform rainfall

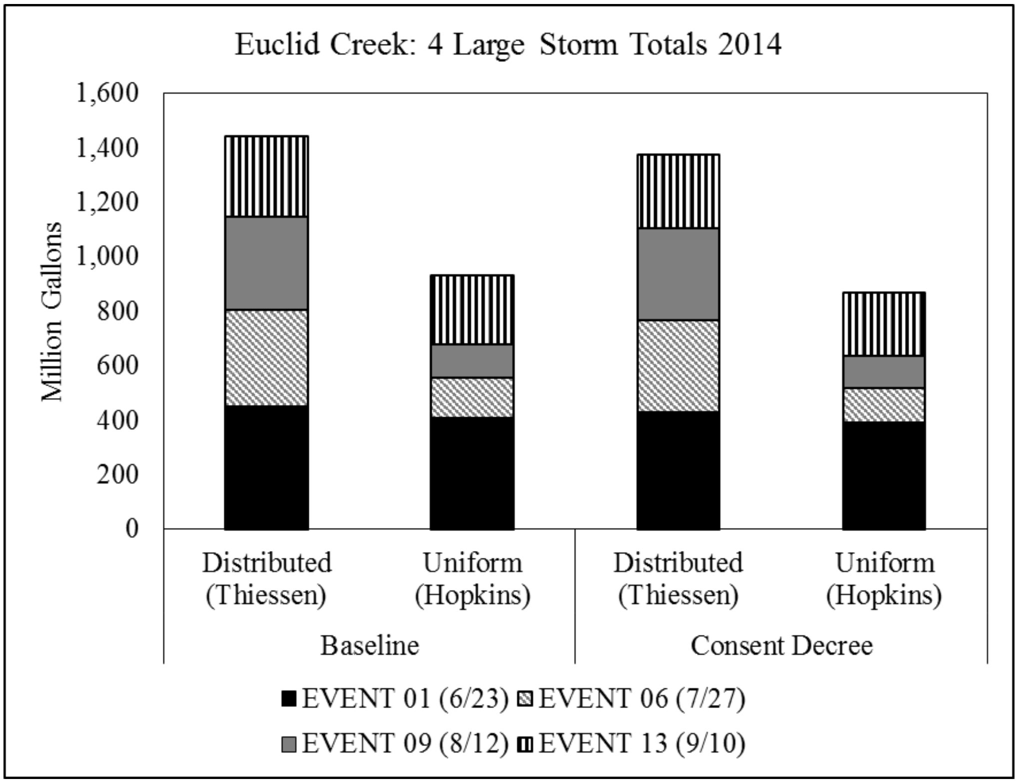

Figure 26. Volume comparison of 4 largest storms of Euclid Creek Baseline and Consent Decree simulations using distributed and uniform rainfall.

Chapter 4: Summary and Future Work

This research developed SWMM 5 models that were calibrated and validated for use in simulating stream flow and transport of pollutants of concern in ten Lake Erie tributary watersheds in Cleveland, Ohio. Model output provides load inputs to support a lake hydrodynamic model that, in turn, predicts ecological and human health impacts of a range of Integrated Planning alternatives under consideration by the NEORSD. Simulations were also done to compare the use of distributed and uniform rainfall under baseline and Consent Decree conditions, illustrating that significant differences can result.

While the models have demonstrated their ability to simulate representative streamflow and pollutant loads for continuous beach season periods, there is further research that could be done to improve the model accuracy and reliability. Additional time series data, improved boundary conditions, and more accurate and refined geospatial resolution of inputs can all improve model performance. Some recommendations for future studies are also given.

This research made use of the limited available streamflow data that was suitable for model calibration and validation. Presented herein was one of just four SWMM5 models that had USGS hourly streamflow data available to make comparisons over the study period of 2012-2014. The six other SWMM5 models either did not have USGS flow data or did not have data at a resolution higher than daily average flows. This research would be improved if the ungaged streams had hourly streamflow data so that those models could be calibrated and validated based on their hydrologic predictions.

The SWMM5 models represented CSOs, ASWs and SSOs from various collection system models that the NEORSD has previously run with uniform rainfall for the "typical year" hydrology mentioned in Chapter 3. In this study, the CSM model was run with distributed rainfall using the NEORSD rain gages. However, with the exception of a single wastewater treatment plant (WWTP) bypass and some WWTP effluent data, measured and reported data (e.g., CSO data) was unavailable for comparison to model results. In the future, the NEORSD CSO data should be compared with the CSM results to evaluate how the CSM models are performing. Awareness of any time lag in modeled and measured CSOs (even just one hour) would assist in water quality calibration and validation.

Further, this research assumed that all CSOs had the same POC concentrations across the NEORSD and over the entire summer, for modeling simplicity. To improve the level of detail in the SWMM5 models, additional monitoring data could allow variable CSO concentrations to be applied in the models, or at least the uncertainty in these POC concentrations could be better accounted for.

Boundary conditions for the SWMM5 models presented another source of uncertainty, particularly downstream boundary conditions representing water levels in Lake Erie, or at the mouths of the streams. For this research, SWMM5 outlet nodes were represented as a combination of fixed and free outfalls. Fixed outfalls assume a fixed water level that is used in the dynamic wave calculations and therefore affects the flow simulated in downstream conduits; free outfalls assume the downstream water level is below the invert of the most downstream conduit. A fixed or free outfall may be appropriate for a design storm, but throughout the beach season, the mean lake level and especially lake levels on the shoreline (due to winds and seiches) can change significantly. In some cases it is known that backflow even occurs in the streams. The current SWMM5 models cannot model backflow attributed to the lake levels changing. However, there is a feature in SWMM5 for time-variable boundary condition, and it is recommended for the next SWMM5/FVCOM modeling effort that boundary conditions be improved by exploring use of this feature. Likewise, some of the SWMM5 models are inputs into other SWMM5 models (i.e. Cuyahoga River and Rocky River), and perhaps a more realistic boundary condition could be implemented by using the same feature.

One growing concern that was not addressed in this research is climate change. This modeling scope used available summer data from 2012-2014. Further research could evaluate how these summers and particular events compared to other years, as well as and how climate model predictions vary for the Cleveland area with respect to rainfall volumes and storm intensities and frequencies. Further, the analysis could account for any potential increases or decreases in CSO volumes that are expected to result from climate change (EPA 2008). Similarly, effects of projected population growth and land use change could be evaluated through scenario analysis, to help predict the long-term performance and reliability of the various IP alternatives.

This research made use of the best available geospatial files for the SWMM5 models. However, some additional data and analysis is needed to better understand the overlap between the CSM and SWMM5 models. To do so would require "cleaned" GIS coverages of SWMM and CSM subcatchments such that the polygon areas are always consistent with model data. Further, a study could be done by the NEORSD to determine what percentage of the overlapping area drains to the collection system or to the streams. It is even possible that this percentage varies according to storm intensity, i.e., there may be a threshold storm for which additional area drains to the stream rather than the collection system, due to limited inlet capacity. The way in which the CSM models and SWMM5 models are set up now means that small storms and large storms both have the same fraction of water routed to the collection system model.

Lastly, the geospatially distributed rainfall analysis could be studied further by making use of radar-based rainfall measurements to represent the spatial distribution of rainfall at even higher resolution. Radar-based rainfall measurements are generally available at 2 km x 2 km grid resolution at 15-minute intervals. Additional work would likely be required, however, to evaluate and adjust for bias in these measurements compared to the rain gage inputs currently used in the SWMM5 models.

In conclusion, this research successfully updated SWMM4 models to SWMM5 and made upgrades to models so that they could be used for continuous simulations of existing and consent decree conditions. If another municipality with CSOs plans to use SWMM models in a similar fashion, a thorough review of the status of the models (e.g., previous model assumptions, parameter estimates, and data availability) should be done prior to the start of the study, and a vision of the final product should be made clear. This research has provided a procedure for applying SWMM5 to an Integrated Planning modeling project in which the spatial and temporal distribution of discharges and loads is important for quantifying the health and environmental impacts of planning alternatives.

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