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MODELING THE EFFECTS OF WASTEWATER INFRASTRUCTURE OPTIONS ON WATER QUALITY IN GREATER CLEVELAND, OHIO

By

Michael E. Foster

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

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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 Science.

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Acknowledgements

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Abstract

The city of Cleveland, OH, and the Northeast Ohio Regional Sewer District are in the process of an ambitious engineering project designed to reduce the amount of untreated wastewater that is discharged into Lake Erie and its tributaries. The project involves the construction of seven tunnels that will intercept combined sewer overflows for transport to wastewater treatment plants, along with upgrades to the treatment capacity of these plants. This report will examine the water quality impacts of this project, as well as the impact of six additional proposed management options, on the streams of Greater Cleveland and the Lake Erie nearshore. Impact will be quantified using metrics developed here for total ammonia nitrogen, total phosphorus and *E. coli* based on standards set by the United States and Ohio Environmental Protection Agencies. Two mathematical models (SWMM for tributaries and SWMM/FVCOM for the Lake Erie nearshore) will be used to simulate water quality conditions for baseline conditions and under potential management options. Ultimately, this model-based approach will be able to pinpoint which management options are most effective in terms of their water quality impact, as well as where the potential trouble spots are located for pollutant concentration guideline exceedances.

1 Introduction

The Northeast Ohio Regional Sewer District (NEORSD), which includes the city of Cleveland and its adjoining communities, is currently undergoing a 25-year, $3 billion dollar effort, Project Clean Lake, with the goal of reducing raw wastewater discharges into Lake Erie and its tributaries. This project grew out of a 2010 complaint by the United States Environmental Protection Agency (USEPA) against the Northeast Ohio Regional Sewer District (NEORSD). The USEPA considered NEORSD to be in violation of the Clean Water Act, and the two parties entered into a consent decree agreement to address the issue (United States of America and State of Ohio v. Northeast Ohio Regional Sewer District, 2011). While Project Clean Lake is intended to meet the demands brought forth by the consent decree, NEORSD also began working with various contractors and Michigan Technological University to produce a model (or models) that would be able to predict the water quality impacts of various management actions. These actions include both those present in the consent decree as well as potential additional management options to be taken at a more local scale, referred to as Municipal Community Infrastructure Programs (MCIPs).

The primary objective of Project Clean Lake is to reduce the amount of untreated wastewater that enters Lake Erie via combined sewer overflows (CSOs) and bypasses at NEORSD’s three wastewater treatment plants (WWTPs). A combined sewer is a design in which both stormwater runoff and sanitary waste utilize the same pipes. During heavy rains, flows that exceed the sewer’s carrying capacity are diverted into receiving waters via CSOs. The WWTP bypasses operate in a similar fashion, in that flows that exceed treatment capacity at the plant are diverted to bypasses and discharged directly into receiving waters. The consent decree attempts to reduce raw wastewater discharges via two means. The first attempts to remediate the region's CSOs by constructing a series of seven storage tunnels that will collect CSO discharges, storing them for subsequent return to WWTPs to be treated (Figure 1). The second addresses WWTP bypasses by increasing WWTP treatment capacity and adding disinfection processes to the bypasses.

Figure 1 - The Northeast Ohio Regional Sewage District service area, including the location of tunnel systems and wastewater treatment plants (W, Westerly, S, Southerly and E, Easterly).

The three pollutants of concern (POCs) associated with raw wastewater that are analyzed in this study are total ammonia, *E. coli*, and total phosphorus. Excessive ammonia concentrations can be harmful or even lethal to many aquatic organisms. *E. coli* is an indicator of risk to human health in recreational waters. Excessive phosphorus can lead to eutrophication and nuisance levels of algae and aquatic plants. The impacts and associated concentration criteria for these POCs varies depending on the type of water body. NEORSD is primarily interested in the impacts of *E. coli* on Cleveland area beaches, phosphorus in the Lake Erie nearshore, and all three mentioned POCs (ammonia, *E. coli*, and phosphorus) in its tributaries. By using models to predict the nature of these systems, it is possible to target areas where exceedances are likely to occur as well as determine which management options are likely to provide the best levels of water quality improvement.

2 Methods

The types of receiving waters NEORSD hopes to remediate, Lake Erie and its tributaries, behave very differently in terms of hydrologic and hydrodynamic properties, and thus are served most effectively by using different models for each type of system. This study uses PCSWMM, a tool developed by Computational Hydraulics International and based on the USEPA's SWMM 5 (Storm Water Management Model), to model the tributaries. FVCOM (Finite Volume Community Ocean Model) is used to simulate Lake Erie. The FVCOM Lake Erie model existed at Michigan Tech prior to this study and is published elsewhere (Xue et al., 2017, Huang et al., 2019), so its development will not be covered here in great detail. The SWMM models for the tributaries, however, were built from scratch immediately prior to the work covered within this report and will be detailed below.

SWMM models were developed for eleven Cleveland area creeks and rivers: Abrams Creek, Big Creek, Cuyahoga River, Doan Creek, Dugway Creek, Euclid Creek, Green Creek, Mill Creek, Ninemile Creek, Rocky River, and West Creek (Figure 2). Of these, all but the Cuyahoga and Rocky rivers originate in-district. Abrams Creek is a tributary of the Rocky River, while Big, Mill, and West creeks are all tributaries of the Cuyahoga River. Along with the two rivers, Doan, Dugway, Euclid, Green, and Ninemile creeks all empty directly into Lake Erie. A twelfth stream, Shaw Creek, was sampled but determined to be too insignificant hydrologically to require a dedicated SWMM model. It is instead represented by time series inputs to the FVCOM model. These time series were constructed using a Collection System Model (CSM) developed for NEORSD by WRCE (Water Resources & Coastal Engineering, Inc.).

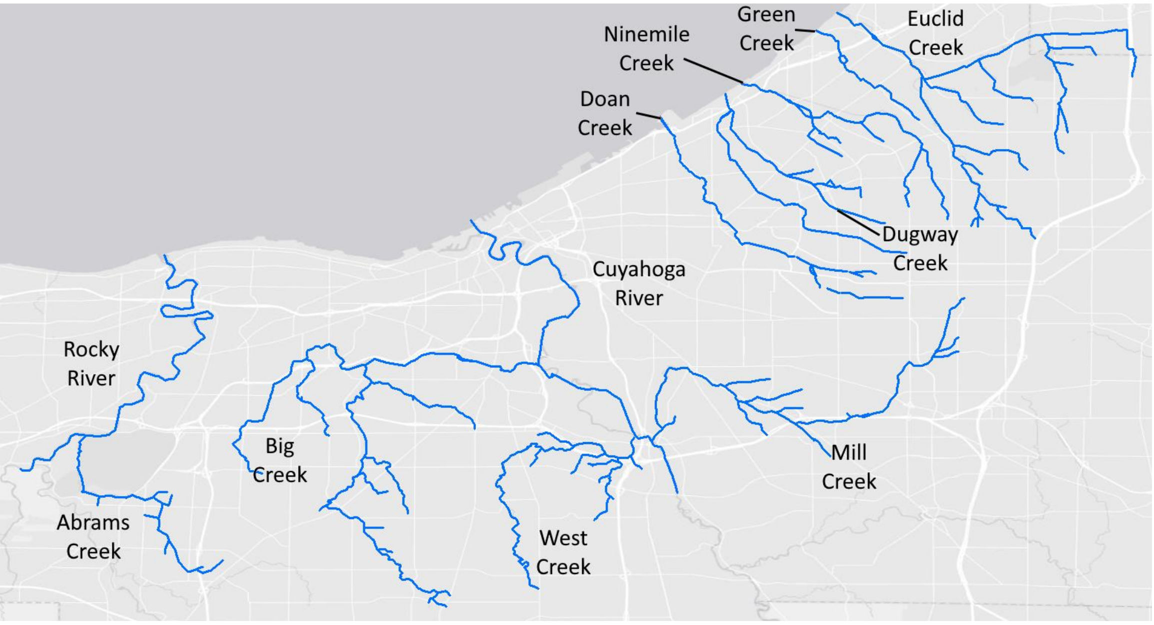

Figure 2 - Cleveland area rivers and streams.

Each tributary-specific SWMM model is comprised of nodes (which can be junctions or storages) connected by conduits (Figure 3). Using GIS, nodes were plotted out to create a geospatially accurate representation of each stream. Sewer type maps were imported into GIS and then broken down to form the subcatchments that comprise each stream’s watershed (Miller, 2016). The models were then calibrated hydrologically using 2014 stream gage data and confirmed using data from 2012 and 2013 (Zgnilec, 2016). A summary of persons responsible for the various tasks that comprised this modeling efforts is provided in Table 1.

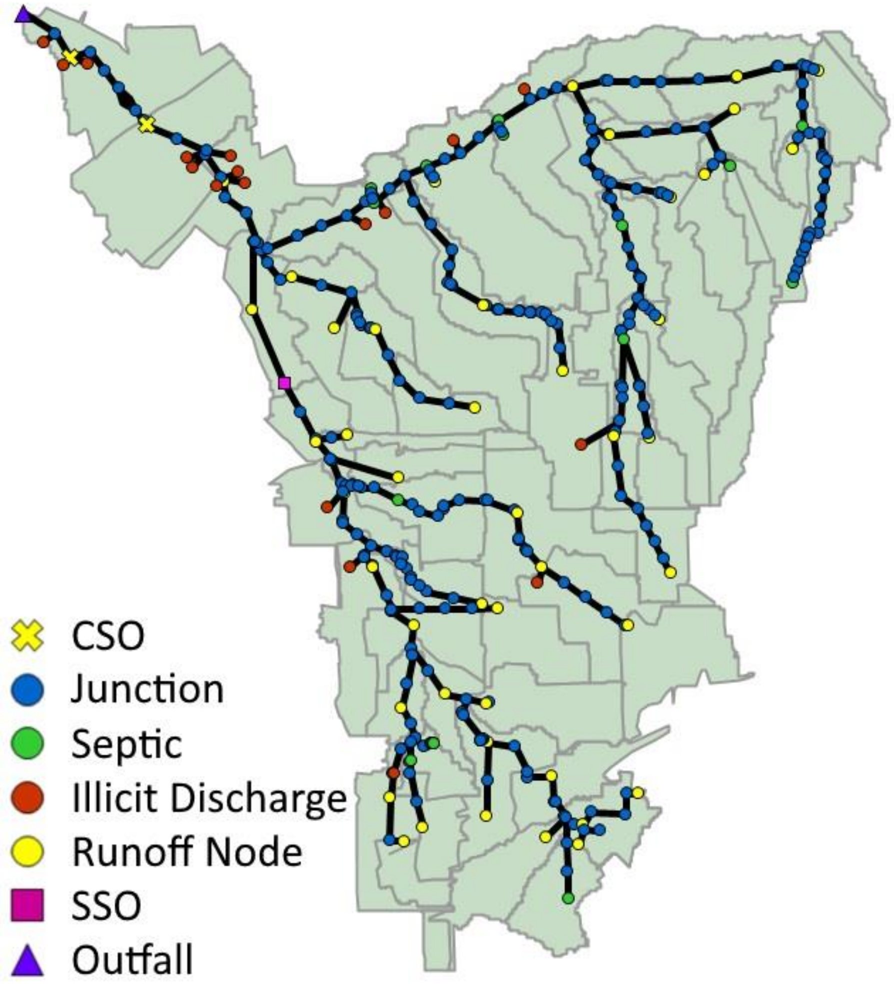

Figure 3 - Example SWMM model depicting Euclid Creek and its contributing watershed.

POC concentrations for point sources and sewer type-specific stormwater runoff were initially established based on NEORSD test studies, and then modified during model calibration to more accurately match the stream sampling data (Table 2), minor adjustments made subsequently to improve accuracy (Zgnilec, 2016).

Table 1 - Project task breakdown and responsible persons.

Task	**Person Responsible**
SWMM model creation	Zoe Miller
Sampling and data collection	Nathan Zgnilec
SWMM model calibration	Nathan Zgnilec
SWMM model refinement	Mike Foster
FVCOM model runs	Chenfu Huang
SWMM model runs	Mike Foster
Model output analysis	Mike Foster

Table 2 - POC concentrations for different system types used in SWMM models. Derived from Zgnilec, 2016.

System Type	***E. coli*** **(CFU/100mL)**	**Ammonia (mg/L)**	**Phosphorus (mg/L)**
Combined Sewer Overflows	280,000	1.75	0.60
Sanitary Sewer Overflows – Separate Trench	500,000	5.00	2.00
Sanitary Sewer Overflows – Common Trench	184,482	0.95	0.53
Common Trench – Dual Manhole Storm Sewer	60,000	0.15	0.20
Common Trench – Divider Wall Storm Sewer	100,000	0.20	0.30
Common Trench – Over/Under Storm Sewer	100,000	0.20	0.30
Separate Trench Storm Sewer	19,325	0.10	0.10
Illicit Discharges	20,000	0.50	0.60
Septic Systems	20,476,462	0.06	0.08

The sewer infrastructure modeled within the subcatchments consists of four sewer types, one of which has further subdivisions. These four are: combined sewer, common trench, separate trench, and septic systems. Combined sewers route sanitary and stormwater flows to the same pipe. As mentioned in the introduction section, these systems include CSOs to act as bypasses under heavy storm flows. A common trench has separate pipes for sanitary and stormwater flows, but contained within the same trench. This system type is then subdivided by its means of access. Dual-manhole common trench systems have less potential for cross-contamination between sanitary and stormwater pipes than the other access types, divider-wall and over-under. This is reflected in the dual-manhole subsystem's lower POC concentrations (above) compared to the other common trench types. Separate trench systems have separate pipes for sanitary and stormwater flows, contained in separate trenches, drastically reducing the opportunity for cross-contamination. This is reflected in POC concentrations well below those of the common trench systems. Lastly there are septic systems, which do not discharge sanitary waste directly to pipes but, when defective, can leak small amounts into the water table.

When the SWMM models are run, flows and POC loads enter the model through one of two means. One is runoff based – subcatchments within the model receive rainfall as determined by a time series assigned to each subcatchment. These time series were built from precipitation data for a number of rain gages located in Greater Cleveland. When precipitation occurs on a SWMM subcatchment, runoff volume is calculated based on the subcatchment's characteristics (such as permeability and soil depth), and then POC concentrations are applied to that volume based on the subcatchment's sewer type breakdown. The runoff from each subcatchment then enters the stream at its assigned node. The other way flows and loads enter the model is by being directly introduced at a node, either as a time series or a constant flow. Groundwater baseflow, septic inputs, and illicit discharges are modeled as constant flows. Flows introduced as time series at nodes include additional stormwater runoff (used in areas with combined sewer infrastructure, which means the subcatchment runoff is not routed to the stream), CSOs, sanitary sewer overflows (SSOs), WWTP effluents, and upstream boundary flows (in the case of the Cuyahoga and Rocky rivers). The time series for additional stormwater, CSOs, and SSOs are all derived from the Collection System Model developed by WRCE. The WWTP effluent time series are derived from measurements at the treatment plants. The tributary upstream boundary flows are derived from USGS stream gage data, while upstream boundary POC concentrations were determined by empirical relationships with flow rate (all Rocky River POCs) and turbidity (Cuyahoga River *E. coli*), or from field measurements (Cuyahoga River ammonia and phosphorus).

To simulate mass transport in Lake Erie and POC conditions at Cleveland's beaches, this study utilized the FVCOM model for Lake Erie. FVCOM is an unstructured-grid, finite-volume, three-dimensional primitive equation coastal ocean circulation model developed by the University of Massachusetts, Dartmouth, and the Woods Hole Oceanographic Institution (Chen et al. 2006). The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is represented using generalized terrain-following coordinates. See Figure 4 for an overhead view of the nearshore grid along the Cleveland waterfront. FVCOM uses environmental forcing conditions (e.g. air temperature and wind conditions) and calculates water temperature, density and momentum to simulate current speed and direction and the transport of POCs. For the purposes of this study, the model was run with 2014 climate forcing conditions. POC loads are input using time series derived from the CSM, WWTP data, and the tributary SWMM models.

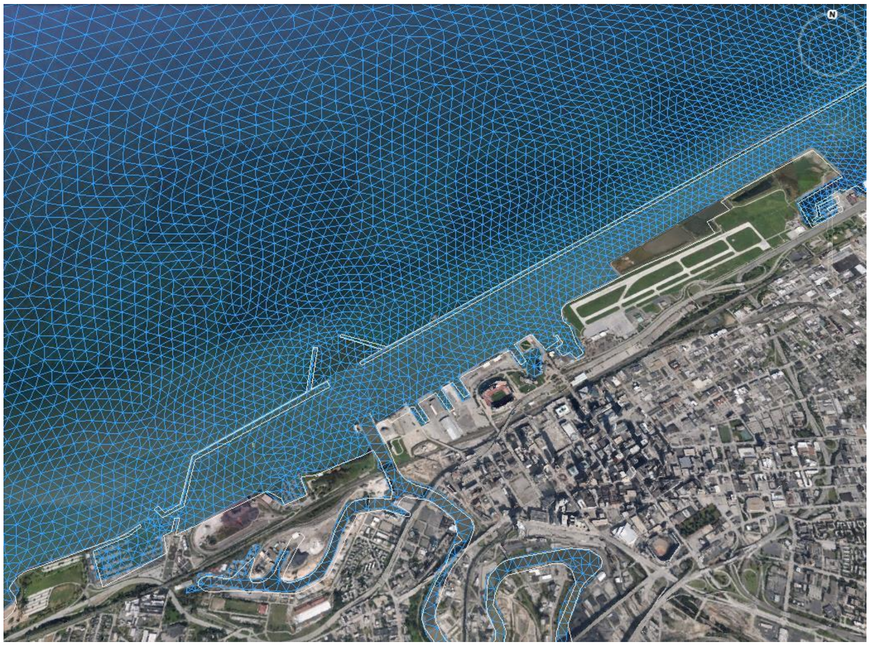

Figure 4 - FVCOM model grid along Cleveland shore.

This study examined eight management conditions: the 2014 baseline, the 2014 baseline with consent decree actions applied and the baseline condition with consent decree actions plus, serially, one of six MCIP programs. A decision was made to model the MCIP actions on top of the consent decree actions, as the consent decree is already legally binding and will be implemented no matter what. This results in eight SWMM models, each including eleven streams, along with eight potential FVCOM runs (although only a few of these were run, due to reasons to be discussed in the results section).

The details of MCIP modeling are discussed here, while their cost and feasibility are detailed in the Discussion section later. MCIP1 reduces stormwater runoff using green infrastructure to capture runoff and remove it via infiltration and evaporation rather than allowing it to reach receiving waters. The reduction amounts were determined for each sewer system type in NEORSD test studies that analyzed the effectiveness of green infrastructure. The MCIP1 SWMM model assumes green infrastructure is applied to 100% of common trench and separate trench sewer types in the district. MCIP2 models the conversion all septic infrastructure to separate trench sewers, eliminating septic tank inputs. MCIP3 models the elimination of all SSOs. MCIP4 upgrades separate trench infrastructure delineated by NEORSD as being “high infiltration & inflow” by modeling the disconnection of downspouts and catch-basins from sanitary sewers. This increases stormwater runoff while reducing WWTP effluent volumes. MCIP5 models the conversion of divider-wall and over-under common trench infrastructure to dual-manhole systems, which reduces POC loads due to a lowered risk of cross-contamination. In addition, similar to MCIP4, MCIP5 models the disconnection of downspouts and catch-basins from sanitary sewers, increasing stormwater runoff while reducing WWTP effluent volumes. MCIP6 models the elimination of all illicit discharges.

To analyze the water quality implications of these models, POC concentrations are compared with management guidelines developed from regulatory criteria as detailed in the Results section. Concentrations in excess of these guidelines are termed exceedances. These guidelines differ depending on the type of water body (stream or beach) and accommodate both spatial (distance over which exceedances occur) and temporal (duration of exceedance) dimensions. Thus, for streams, exceedances are expressed in terms of km*hours or km*days where the time period (hours/days) of predicted exceedance for a particular POC criterion is multiplied by the conduit length (km). This outcome may be summed for the stream over the time period simulated or represented visually by GIS maps showing the proportion of the modeled time period that each stream conduit was determined to experience an exceedance. For beaches, exceedances are summarized by the days/hours that each beach was predicted to experience an exceedance.

3 Results

As each POC exhibits different characteristics in terms of where they cause potential exceedances in the streams, as well as how they respond to different management options, they will each be discussed in subsections of this results section. An additional subsection will discuss modeled conditions at the beaches. The implications of these management options are detailed in the following Discussion section.

3.1 In-stream ammonia

Ammonia is toxic to aquatic animals at high concentrations (U.S. Environmental Protection Agency, 2013). The management guidelines used in this analysis are based on the standards set forth in the 2013 EPA document, "Aquatic Life Ambient Water Quality Criteria for Ammonia – Freshwater." This document contains formulas to express total ammonia nitrogen (TAN, mg N/L) limits as a function of stream pH and temperature. There are separate acute (CMC) and chronic (CCC) limits, each with their own formula. The analysis below calculated these guidelines using pH and temperature values one standard deviation above the mean of the summer sampling data, resulting in limits of 2.66 mg TAN/L (CMC) and 0.58 mg TAN/L (CCC). These values would be higher in May or October, given the lower temperatures, but conservative calculations allow the analysis to more effectively identify potential trouble spots in the streams during critical summer conditions. The CMC criterion considers any hourly average above the calculated CMC value to be an exceedance. The CCC criterion considers any rolling 30-day average above the CCC to be an exceedance, as well as any 4-day average that is 2.5 times the CCC.

Compared to the other two other POCs discussed below, the models did not show ammonia to be much of an issue in the Greater Cleveland tributaries. Referring back to Table 1, it becomes apparent that none of the stormwater runoff concentrations are high enough to exceed the CCC, let alone the CMC. Only CSOs and SSOs have a high enough concentration to exceed the CCC, and only SSOs have a high enough concentration to exceed the CMC. As both CSO and SSO flows are relatively short-term wet-weather events, a 30-day CCC exceedance becomes extremely unlikely. As would be expected then, no CCC exceedances were found to be present in any of the modeled streams, and CMC exceedances only showed up in two small creeks with minimal flow volumes that the SSOs were predicted to overwhelm. To better illustrate the areas where there are higher ammonia concentrations present on occasion, the management table and ammonia concentration map presented below reference “1-day” CCC exceedances. While the 30-day and 4-day CCC criteria were never exceeded, there were times when the CCC value was exceeded for shorter time periods.

Only four streams showed either a 1-day CCC exceedance or a 1-hour CMC exceedance (Figure 5). Rocky River 1-day CCC exceedances are caused by WWTP effluent, while the other areas with 1-day CCC exceedances are caused by either CSOs or SSOs. Both areas with CMC exceedances are caused by SSOs. The Consent Decree model scenario slightly improved water quality in terms of the 1-day CCC exceedances, while MCIP3 (SSO removal) completely eliminated the CMC exceedances (Table 3).

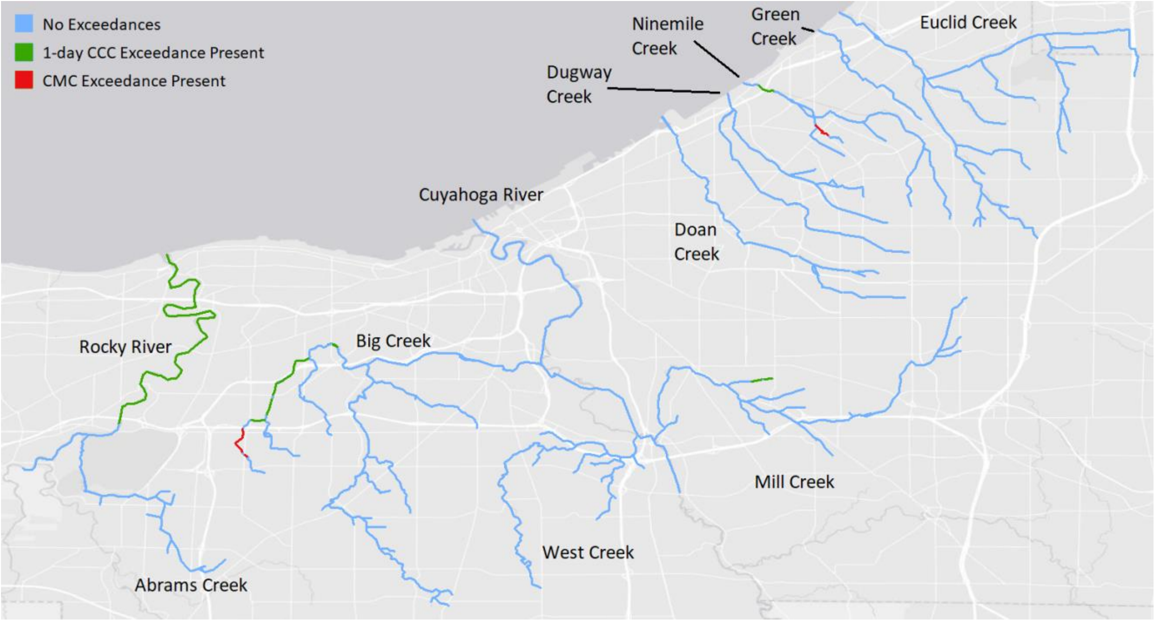

Figure 5 - Baseline model TAN/L exceedances. Green shading indicates 1-day CCC exceedances. Red shading indicates CMC exceedances.

Table 3 - TAN/L km*days management metric. SWMM model conduit lengths (km) are multiplied by the number of days or hours the conduit recorded an exceedance to calculate km*days or km*hrs. CMC represents an acute TAN criterion exceedance, while CCC is a chronic TAN criterion exceedance.

	Baseline		**Consent Decree**		**SSO MCIP**	
Tributary	CMC km*hrs	CCC km*days	CMC km*hrs	CCC km*days	CMC km*hrs	CCC km*days
Abram	0	0	0	0	0	0
Big	40.41	15.87	40.41	11.22	0	0
Cuyahoga	0	0	0	0	0	0
Doan	0	0	0	0	0	0
Dugway	0	0	0	0	0	0
Euclid	0	0	0	0	0	0
Green	0	0	0	0	0	0
Mill	0	0.72	0	0.72	0	0.72
Ninemile	42.34	5.74	42.34	6.98	0	3.58
Rocky	0	87.71	0	87.71	0	87.71
West	0	0	0	0	0	0

3.2 In-stream *E. coli*

E. coli concentrations in water have a positive correlation with illness rates in humans that use contaminated waters for recreation (U.S. Environmental Protection Agency, 2012). The management guidelines used in this analysis are based on the standards set forth in the 2012 EPA document, "Recreational Water Quality Criteria." This document sets an exceedance standard of 126 cfu/100mL for any 30-day rolling geometric mean. Of those 30 days, if any 3 or more have a daily average above 410 cfu/100mL, that is also considered an exceedance. For the purposes of this analysis, the *E. coli* concentration map and management table below examine daily average exceedances of the 126 cfu/100mL value, in order to better illustrate problem areas and management option improvements.

In contrast with ammonia criteria exceedances, *E. coli* concentrations are a serious issue throughout all Greater Cleveland streams examined here (Figure 6, Table 3). Many of the streams exceed a daily average of 126 cfu/100mL more than 75% of the duration of the model runs. Even the stream with the lowest proportion of exceedance days, Dugway Creek, still is in the 25-50% range. As can be seen in Table 4, the consent decree is of very limited effectiveness in terms of improvements to *E. coli* stream concentrations, and of the MCIPs, only MCIP6 has an appreciable impact. This is largely due to the nature of *E. coli* and urban stormwater runoff. Unlike with ammonia, where stormwater runoff concentrations are not high enough to cause many exceedances, stormwater runoff concentrations for *E. coli* are hundreds to thousands of times higher than the exceedance criteria. Thus, almost any wet-weather event is going to cause exceedances, regardless of infrastructure improvements, simply due to the nature of urban stormwater. MCIP6 is able to show good improvement in terms of km*days of exceedances because it is a dry-weather management option. While wet-weather events are extremely difficult to mitigate in terms of stream water quality impacts for *E. coli* (Marsalek & Rochfort, 2004), illicit discharges are by comparison much easier to eliminate, and this cleans up many of the days without precipitation. Even when applying MCIP1 and MCIP6 together on top of the Consent Decree, however, *E. coli* exceedances are still extremely common throughout the Cleveland area (Figure 7).

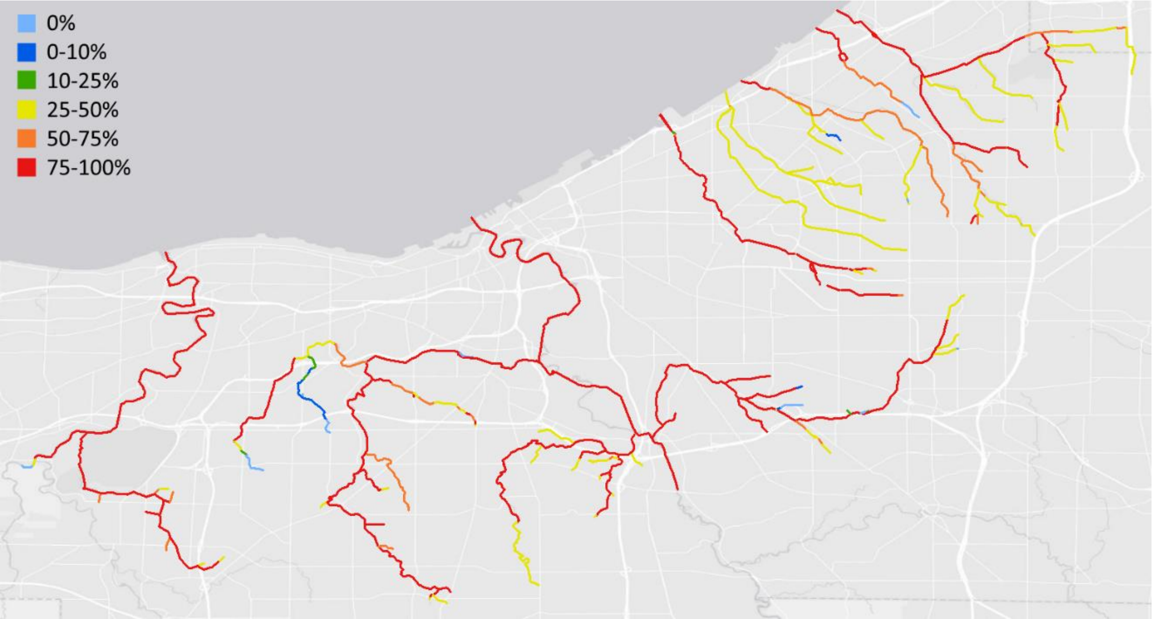

Figure 6 - *E. coli* Baseline map showing percent of model run days where daily average concentration exceeded 126 cfu/100mL.

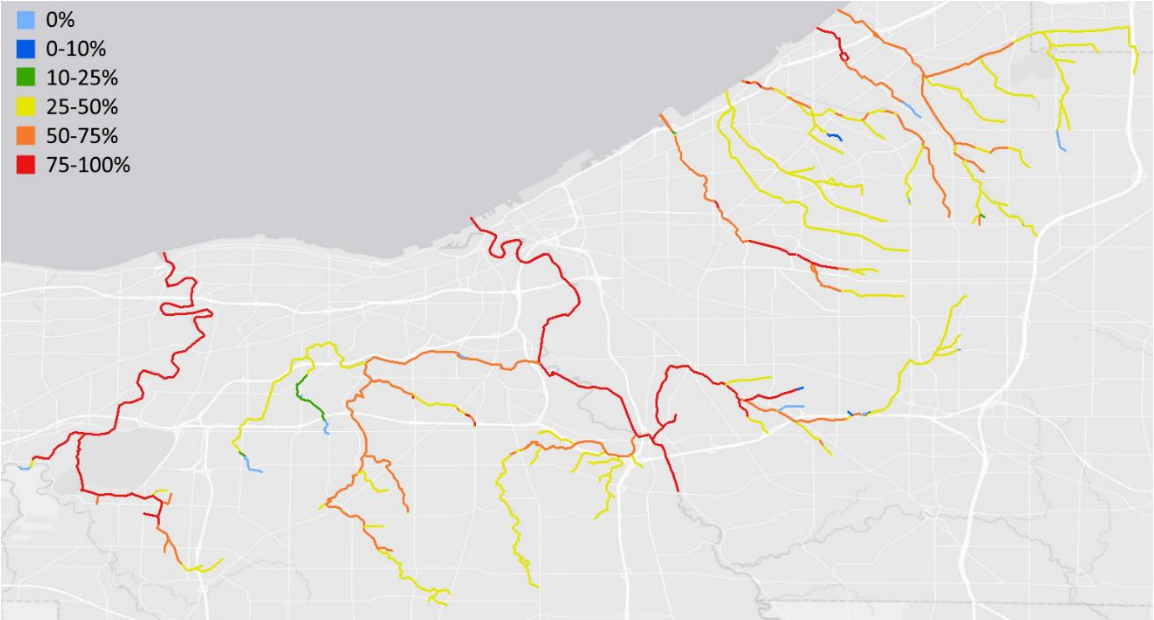

Figure 7 - *E. coli* Consent Decree + MCIP1 and MCIP6 map showing percent of model run days where daily average concentration exceeded 126 cfu/100mL.

Table 4 - E. coli cfu/100mL km*days management metric. SWMM model conduit lengths (km) are multiplied by the number of days the conduit recorded an exceedance to calculate km*days. An average concentration above 126 cfu/100mL is an exceedance.

Tributary	**BL**	**CD**	**MCIP 1**	**MCIP 6**	**MCIP 1+6**	**Max**
Abram	1938	1938	1930	1490	1458	2138
Big	6138	6110	6165	3915	3860	8108
Cuyahoga	3095	3095	3095	3095	3095	3192
Doan	2144	2136	1936	1863	1641	2452
Dugway	1361	1347	1316	1347	1316	3885
Euclid	5654	5654	5508	3966	3690	8027
Green	617	616	607	616	607	966
Mill	4218	4218	4200	3176	3104	5137
Ninemile	1648	1640	1579	1637	1575	3532
Rocky	2815	2815	2814	2815	2814	2916
West	2932	2932	2923	1681	1640	3870
Total	32559	32501	32071	25598	24799	44224

Table 5 - Management option effectiveness in reducing *E. coli* km*days. “CD” shows % Consent Decree improvement over the baseline model. MCIP columns show improvement over the Consent Decree model.

Tributary	**CD**	**MCIP 1**	**MCIP 2**	**MCIP 3**	**MCIP 4**	**MCIP 5**	**MCIP 6**	**MCIP 1+6**
Abram	0.0	0.4	0.0	0.0	0.0	0.0	23.1	24.8
Big	0.5	-0.9	0.0	1.0	0.0	0.0	35.9	36.8
Cuyahoga	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Doan	0.3	9.4	0.0	0.1	-0.1	3.1	12.8	23.2
Dugway	1.0	2.4	0.0	0.0	-0.4	-0.3	0.0	2.4
Euclid	0.0	2.6	0.0	0.0	-0.2	0.0	29.9	34.7
Green	0.1	1.5	0.0	0.0	0.0	0.0	0.0	1.5
Mill	0.0	0.4	0.0	0.0	0.0	0.2	24.7	26.4
Ninemile	0.5	3.7	0.0	2.2	0.0	1.5	0.2	4.0
Rocky	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West	0.0	0.3	0.0	0.0	0.0	0.0	42.7	44.1
Total	0.2	1.3	0.0	0.3	-0.1	0.3	21.2	23.7

3.3 In-stream phosphorus

Excessive phosphorus can lead to eutrophication and nuisance levels of algae and aquatic plants (Auer, et al., 2010). The management guidelines used in this analysis are based on the standards set forth in the 2000 EPA document “Ambient Water Quality Criteria Recommendations” for Rivers and Streams in Ecoregion VII. This document sets an exceedance standard of 0.033 mg/L total phosphorus for any daily average. The simplicity of this daily standard lends itself well to illustrate problem areas and management option improvements, as opposed to the more complex exceedance calculations required for the other two POCs discussed.

Problem areas and management options for phosphorus in some ways mirror that of the E. coli POC, but there are some significant differences. Phosphorus violates the management criteria throughout all Cleveland area streams, but not to the same severity that E. coli does (Figure 8, Table 5). It also responds to management slightly better than E. coli does (Table 6). Similar to E. coli, phosphorus criterion exceedances are driven largely by wet-weather events and illicit discharges, only showing significant improvement under MCIP1 (stormwater reduction) and MCIP6 (illicit discharge remediation). However, while E. coli concentrations modeled for stormwater runoff exceeded the E. coli management criterion by factors of one hundred or more, phosphorus concentrations modeled in stormwater only exceed the management criterion by factors of three to ten. Thus it is much better able to respond to stormwater management in MCIP1, showing a 9.0% overall improvement compared to a 1.3% improvement for E. coli. Combining the Consent Decree with MCIP1 and MCIP6 brings most streams under 25% criterion exceedance rates (Figure 9), with the notable exception of the Rocky and Cuyahoga rivers, which are largely driven by upstream flow.

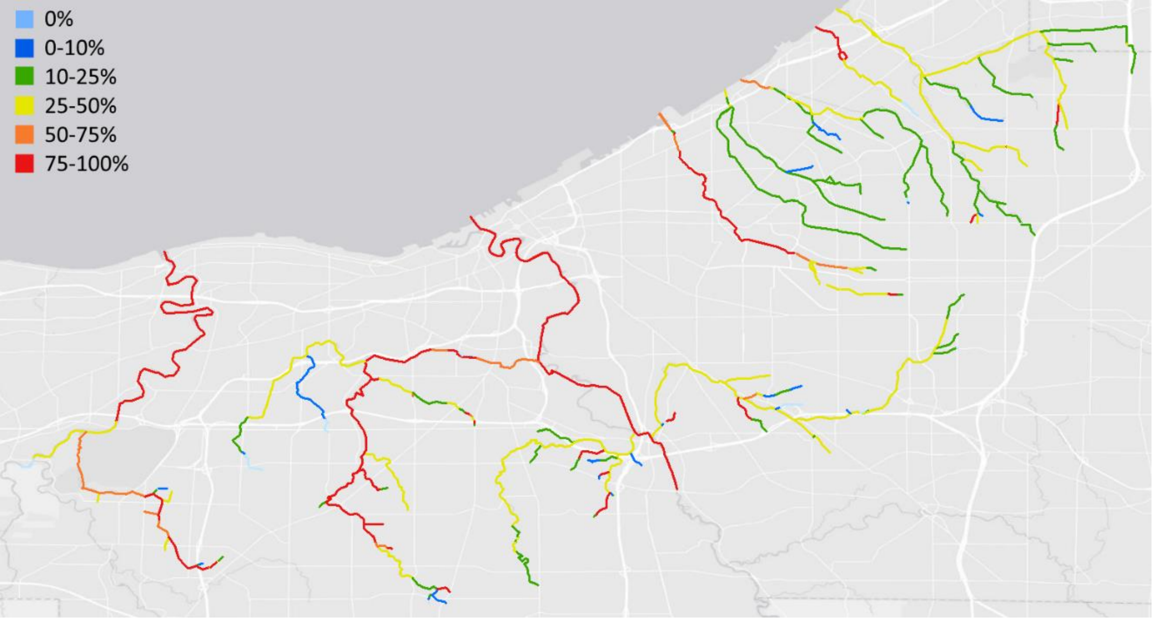

Figure 8 - Phosphorus Baseline map showing percent of model run days where daily average concentration exceeded 0.033 mg/L.

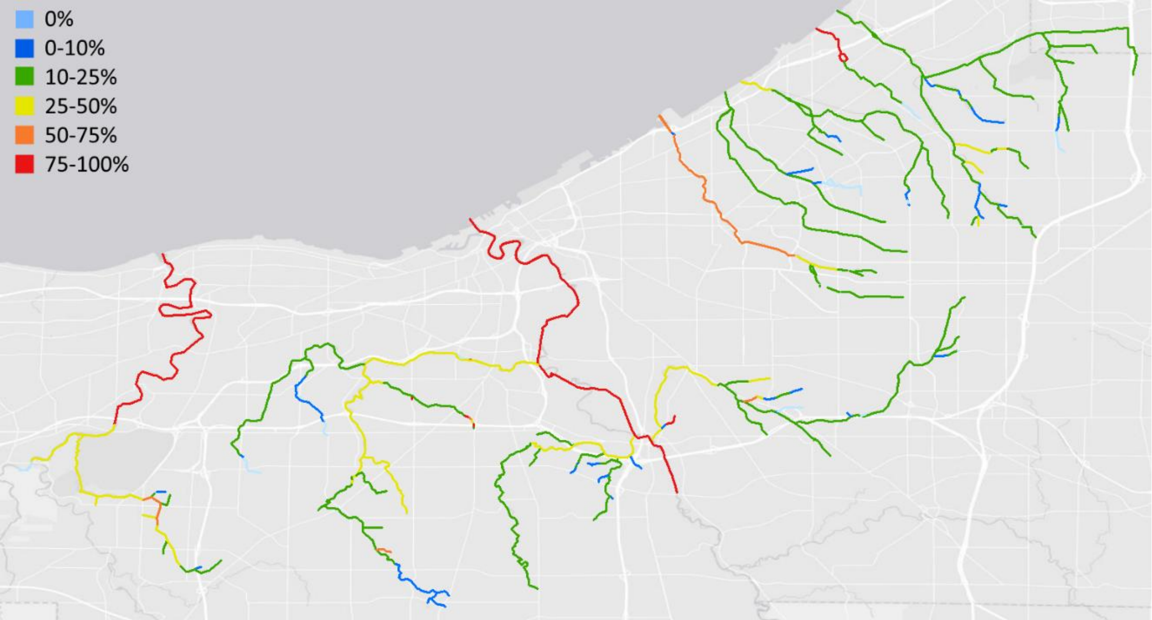

Figure 9 - Phosphorus Consent Decree + MCIP1 (stormwater runoff reduction) and MCIP6 (illicit discharge remediation) map showing percent of model run days where daily average concentration exceeded 0.033 mg/L

Table 6 - Phosphorus mg/L km*days management metric. SWMM model conduit lengths (km) are multiplied by the number of days the conduit recorded an exceedance to calculate km*days. An average concentration above 0.033 mg/L is an exceedance.

Tributary	**BL**	**CD**	**MCIP 1**	**MCIP 6**	**MCIP 1+6**	**Max**
Abram	1372	1372	1233	969	830	2152
Big	4325	4182	4052	2025	1786	8162
Cuyahoga	3214	3214	3214	3214	3214	3214
Doan	1690	1680	1384	1496	1181	2469
Dugway	756	746	567	746	567	3911
Euclid	2371	2366	1836	1976	1416	8080
Green	485	485	454	485	454	972
Mill	1833	1833	1599	1382	1151	5171
Ninemile	864	839	698	839	697	3555
Rocky	2110	2110	2098	2092	2092	2935
West	1365	1364	1243	866	728	3895
Total	20385	20191	18378	16090	14116	44517

Table 7 - Management option effectiveness in reducing phosphorus km*days. “CD” shows % Consent Decree improvement over the baseline model. MCIP columns show improvement over the Consent Decree model.

Tributary	**CD**	**MCIP 1**	**MCIP 2**	**MCIP 3**	**MCIP 4**	**MCIP 5**	**MCIP 6**	**MCIP 1+6**
Abram	0.0	10.1	6.5	0.1	0.0	-0.1	29.4	39.5
Big	3.3	3.1	1.4	1.5	0.0	-0.1	51.6	57.3
Cuyahoga	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Doan	0.6	17.6	0.0	0.6	-2.0	-3.9	11.0	29.7
Dugway	1.3	24.0	0.0	1.6	-0.1	12.7	0.0	24.0
Euclid	0.2	22.4	0.4	0.0	-0.3	2.3	16.5	40.2
Green	0.0	6.4	0.0	0.0	0.0	0.0	0.0	6.4
Mill	0.0	12.8	0.1	0.0	0.0	2.0	24.6	37.2
Ninemile	2.9	16.8	0.1	4.2	-0.2	7.3	0.0	16.9
Rocky	0.0	0.6	0.0	0.0	-0.1	-0.1	0.9	0.9
West	0.1	8.9	4.7	0.0	0.0	-0.1	36.5	46.6
Total	1.0	9.0	1.1	0.6	-0.2	0.8	20.3	30.1

3.4 Beach *E. coli*

Not only do all of the tributaries examined above empty into Lake Erie, but there are additional CSOs along the lakeshore as well. These CSOs are included in those being addressed by the Consent Decree, and NEORSD is interested in examining water quality conditions on two of Cleveland's public beaches: Edgewater Beach and Villa Angela Beach (adjacent to Euclid Creek). As with E. coli in the streams, the management guidelines used in this analysis are based on the standards set forth in the 2012 EPA document, "Recreational Water Quality Criteria." This document sets a standard of 235 cfu/100mL as a "Beach Action Value" not to be exceeded. Edgewater Beach, near the mouth of the Cuyahoga River, posted swimming advisories on 28 of 105 days between 5/19/2014 and 8/31/2014. Beach closures are based on the USGS Nowcast model, which predicts days with elevated E. coli counts based on weather conditions. E. coli was measured above 235 cfu/100mL on 17 of these days.

As was discussed, ammonia was found to be a non-issue for the most part, with no criterion exceedances outside of a few brief events in the upper reaches of two small creeks. Any concentrations in the streams are diluted further as they empty into Lake Erie. Phosphorus was modeled to have loads that could potentially be a concern, specifically in regards to nuisance Cladophora growth. Cladophora modeling in Lake Erie involves biokinetics outside the scope of this analysis and was examined separately. E. coli, however, can be quantified as a threat to human health by simply examining its concentration.

With the outputs from the SWMM models, fed into the Lake Erie FVCOM model, it is possible to model E. coli conditions on the beaches. For this analysis, the maximum concentration in the FVCOM cells along each beach is considered to be the beach concentration for any point in time. Exceedances are summarized in Table 8 in terms of hours as well as days, where days represent the maximum concentration for any day.

Table 8 - Modeled *E. coli* beach criterion exceedances. Any concentration above 235 cfu/100mL is an exceedance.

	Villa Angela Beach		**Edgewater Beach**	
Model	**Hrs**	**Days**	**Hrs**	**Days**
Baseline	710	53	413	35
CD	451	39	363	34
MCIP1	268	28	280	30
MCIP6	450	39	360	34
CD + BW	-	-	131	12

Villa Angela Beach demonstrated significant improvements in terms of exceedances going from the Baseline scenario to the Consent Decree scenario, and again when adding MCIP1 to the Consent Decree scenario. This sensitivity to management is due to the E. coli water quality issue on this beach originating from a variety of sources, all of which are in-district (Figure 10). Edgewater Beach, on the other hand, is not as sensitive to management impacts. This is due to that particular beach being dominated by the adjacent Cuyahoga river (Figure 11), which is itself heavily impacted by flows outside NEORSD’s boundary. These upstream flows are unimpacted by the management actions being modeled. MCIP6 (illicit discharge remediation) is included in the table above to demonstrate that certain actions may have a great impact on stream water quality and lack an impact in the nearshore. Both the upstream boundary as well as the difference in management impacts to streams and the nearshore are discussed further in the following section.

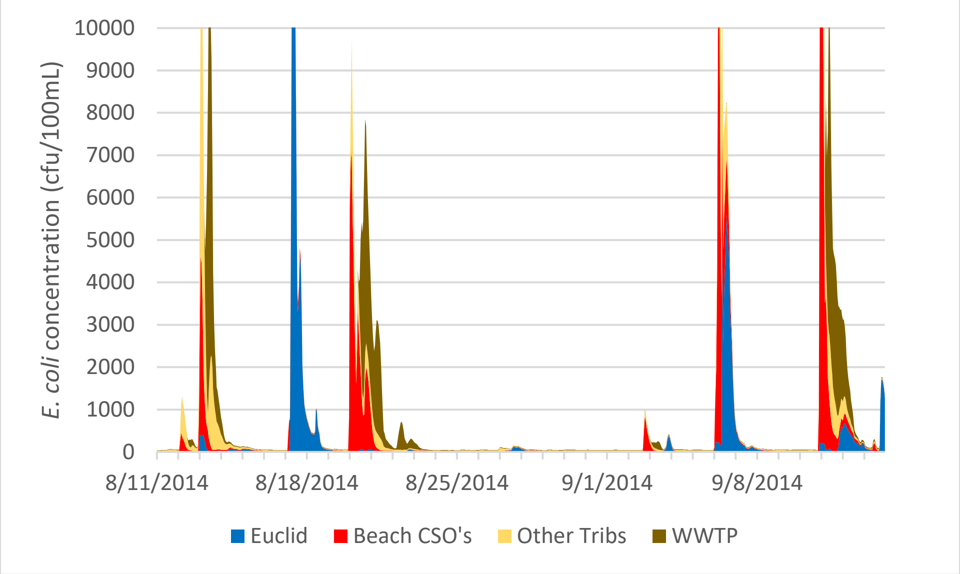

Figure 10 - Baseline model *E. coli* sources at Villa Angela Beach.

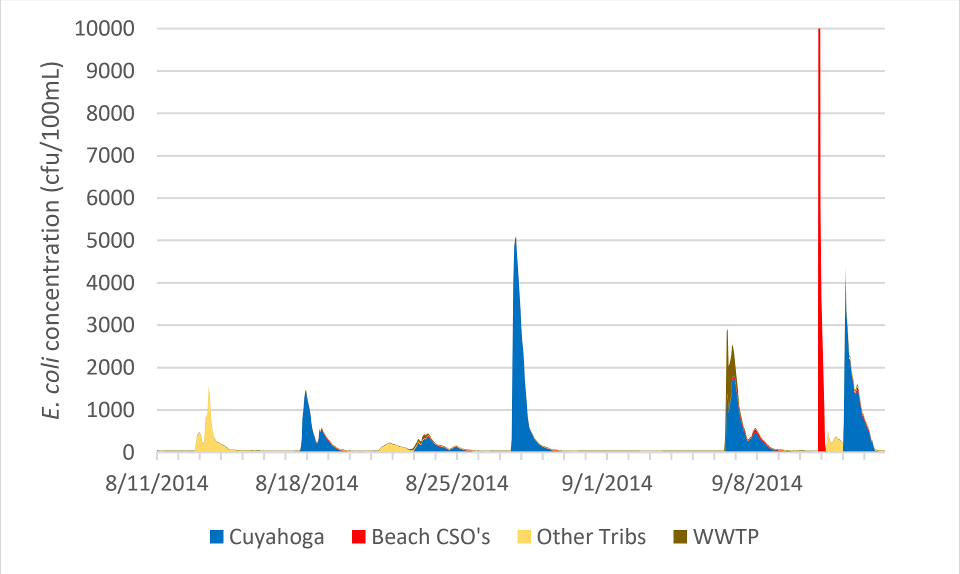

Figure 11 - Baseline model *E. coli* sources at Edgewater Beach.

The final scenario tested for Edgewater Beach (CD+Breakwall; Table 8) utilized a customization of the FVCOM model grid to simulate the closure of an opening in the breakwall separating the Cuyahoga River and Edgewater Beach (Figure 12). This relatively simple management option had a far greater impact in reducing the number of E. coli criterion exceedances than any of the infrastructure management options. In terms of both Edgewater and Villa Angela beaches, it is worth investigating such physical barriers further.

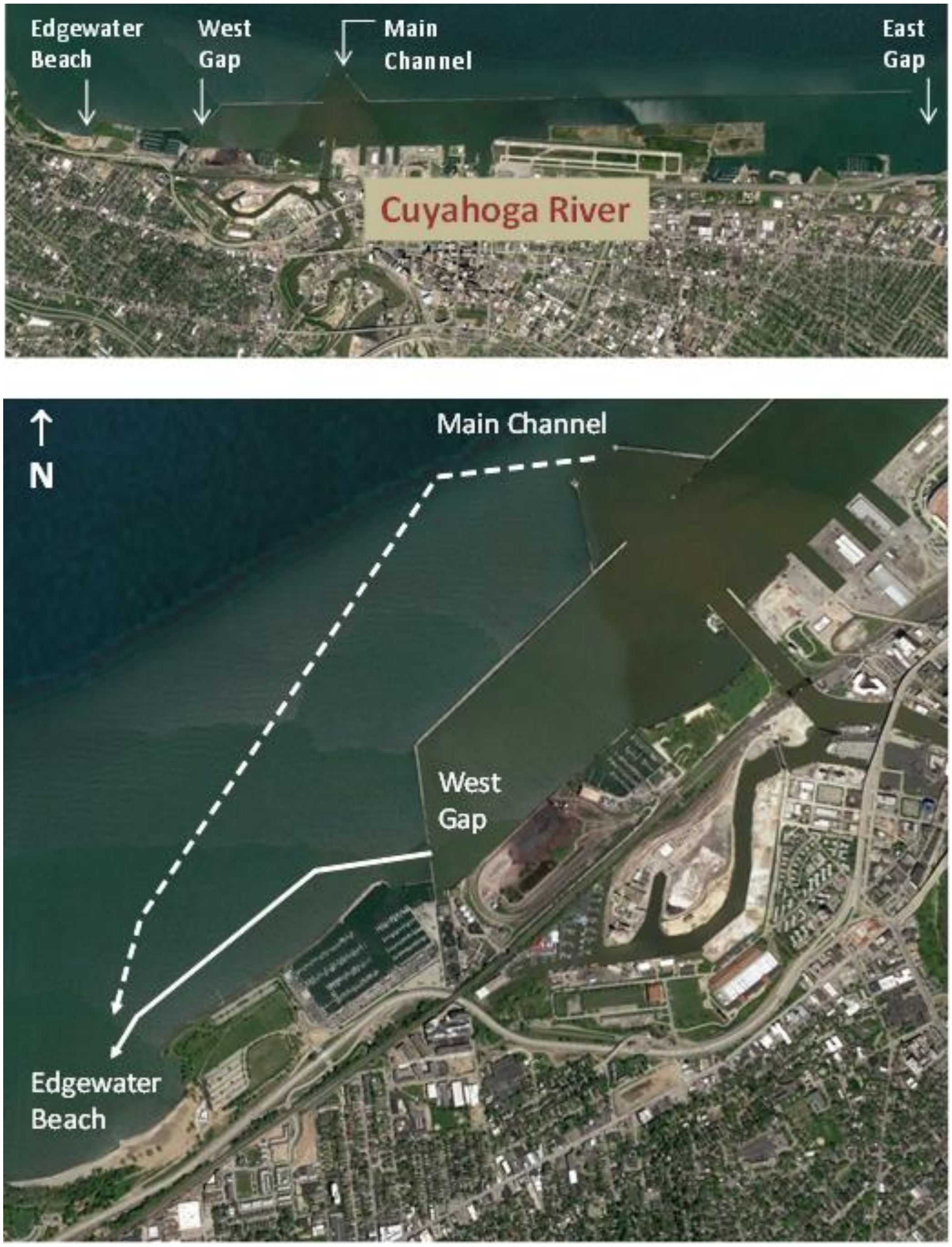

Figure 12 - Position of breakwall at the mouth of the Cuyahoga River and potential paths of plumes reaching Edgewater Beach.

4 Discussion

4.1 Comparing model output to field measurements

Calibration and confirmation of the SWMM models referenced here are covered in detail in previous studies at Michigan Tech (Miller, 2016; Zgnilec, 2016). The accuracy of the two linked models (SWMM and FVCOM) in matching with field measurements at the beaches has not been examined in the same detail. NEORSD took daily samples at Villa Angela and Edgewater beaches in 2014, at roughly 7 AM each day, from 5/19/2014 to 8/31/2014. They use these samples as part of their system to determine whether to post a beach advisory. By matching these values against the values at 7 AM in the model, it is possible to examine how well they correlate. If both the model and field measurements agreed that an exceedance would or would not occur, this was tallied as an 'agreement'. Otherwise the occurrence was tallied as a 'disagreement.' These tallies are summarized in Table 8 below. The "Agreement, Timing" row indicates an instance when only one of either the model or field measurements showed an exceedance, but the model is within 6 hours of agreeing with the field measurements. Allowance for this 6-hour window recognizes the resolution of the mass transport model at the hourly level. The "Resuspension" row indicates a time when the sample showed an exceedance while the model did not, but met a special condition. *E. coli* can become trapped within sediments and then resuspended during windy days, showing up in samples even during dry weather. FVCOM does not simulate this resuspension. Thus, if waves at the beach were measured at more than one standard deviation above the mean, while the sample showed an exceedance and the model did not, this is tallied in the "Resuspension" row.

Eliminating dates with a likelihood of a resuspension event occurring (Table 9) and adopting a timing window of +/-6 hours, model prediction of an exceedance agrees with measurements 93% of the time for Villa Angela Beach and 97% of the time for Edgewater Beach. If no special conditions are considered, this agreement rate drops to 79% at Villa Angela Beach and 85% for Edgewater beach. Figure 13 and Figure 14 below illustrate scatter plots for model/sample concentrations at both beaches.

Table 9 - Summary of sample/model agreement at beaches, based on *E. coli* concentration exceedance criterion (yes/no) of 235 cfu/100mL.

Outcome, with no special conditions considered		Villa Angela Beach	Edgewater Beach
Agreement	that an exceedance occurs	20	6
Agreement	that no exceedance occurs	63	82
Disagreement	that an exceedance does or does not occur	7	3
Disagreement (time window)	when no window of resolution is adopted	9	8
Disagreement (resuspension)	when no instances with the likelihood of a resuspension event are eliminated	6	5
Total		105	104
Percentage Agreement		79%	85%
Outcome, with special conditions considered			
Agreement	that an exceedance occurs	20	6
Agreement	that no exceedance occurs	63	82
Disagreement	that an exceedance does or does not occur	7	3
Agreement	that an exceedance does or does not occur if a 6-hour window of resolution is adopted	9	8
Elimination	when instances with the likelihood of a resuspension event occurring	-	-
Total		99	99
Percentage Agreement		93%	97%

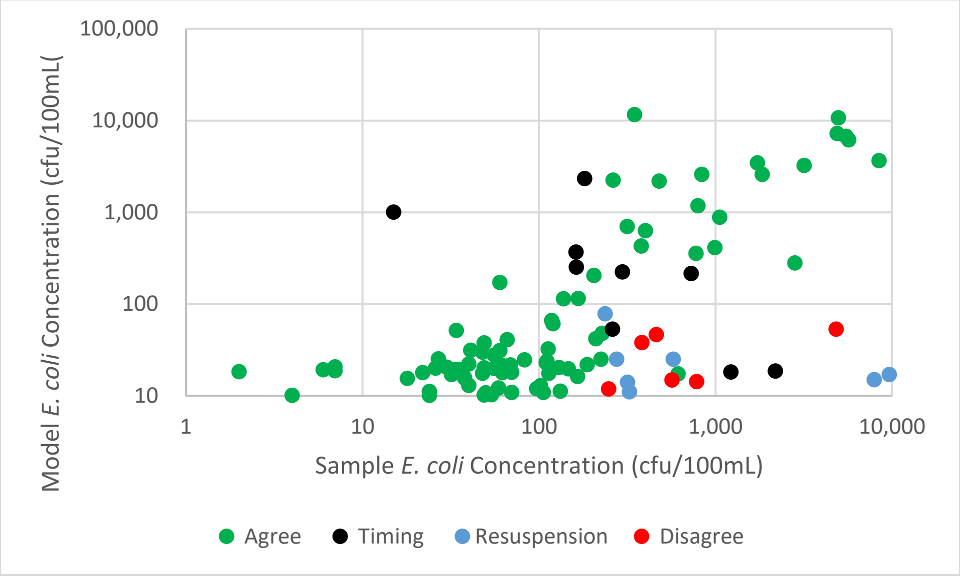

Figure 13 - Model/Field measurements agreement at Villa Angela Beach. Timing indicates the model and field measurement disagreed, but the disagreement may be due to timing uncertainty inherent in the model. Resuspension indicates the model and field measurement disagreed, but it may be due to sediment resuspension that the model did not account for.

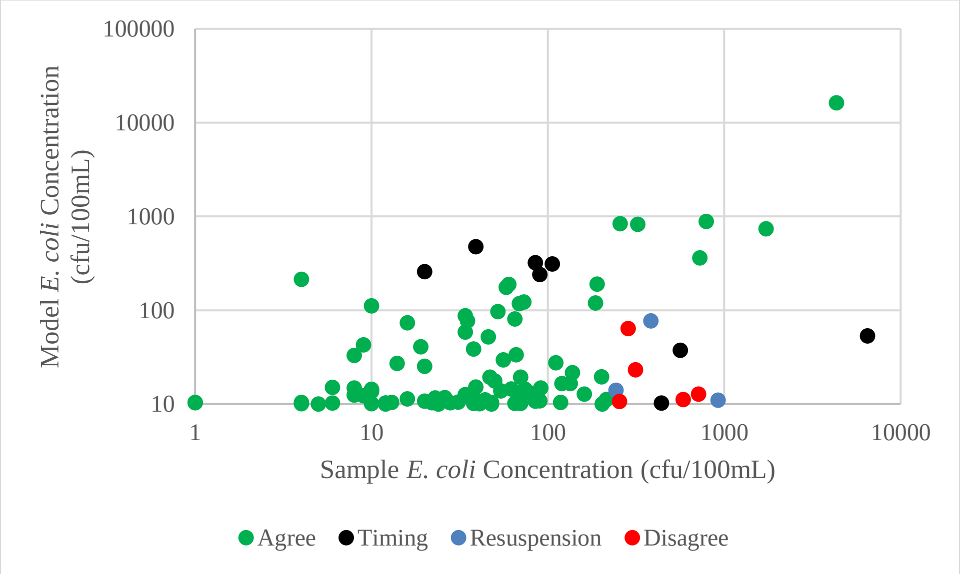

Figure 14 - Model/Field measurements agreement at Edgewater Beach. Timing indicates the model and field measurement disagreed, but the disagreement may be due to timing uncertainty inherent in the model. Resuspension indicates the model and field measurement disagreed, but it may be due to sediment resuspension that the model did not account for.

4.2 Concentrations versus loads

While concentrations dominate water quality in the streams (treated here as plug flow reactors without dispersion), loads are a better water quality indicator for the Lake Erie nearshore where mass transport processes (advection and dispersion) significantly impact the dimensions and nature of the waste field. Some management actions, such as those for MCIP6 (illicit discharge remediation), may show significant water quality improvement for the streams (local remediation without mixing) while showing little to no improvement in the nearshore (where concentration is driven by the load/mass transport relationship). This is outcome is evident for the MCIP6 management option (removal of illicit discharges), which significantly decrease exceedances during dry weather in the streams but are insignificant in terms of total load to Lake Erie (Figures 15 and 16).

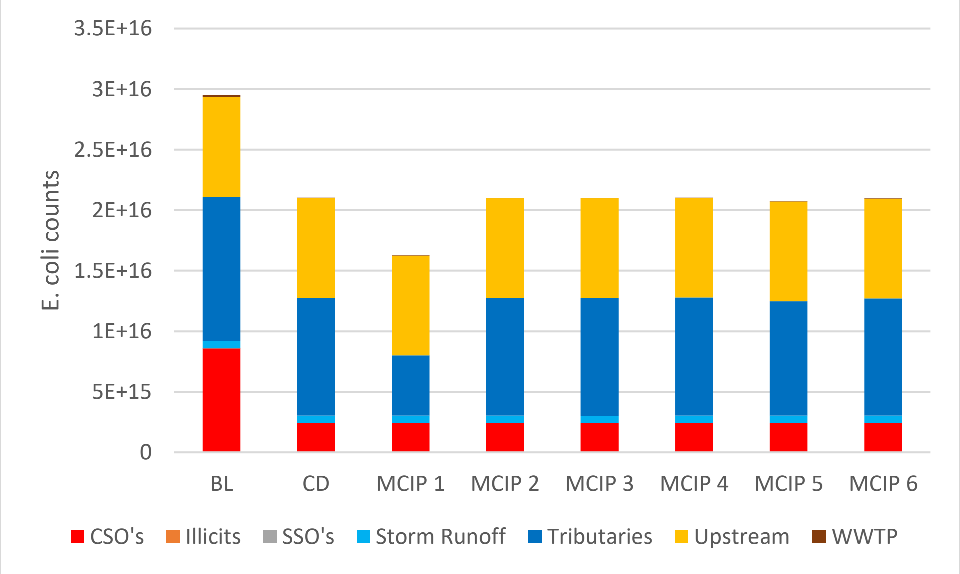

Figure 15 - Total *E. coli* load for the Cuyahoga River model, 5/19/2014-10/3/2014.

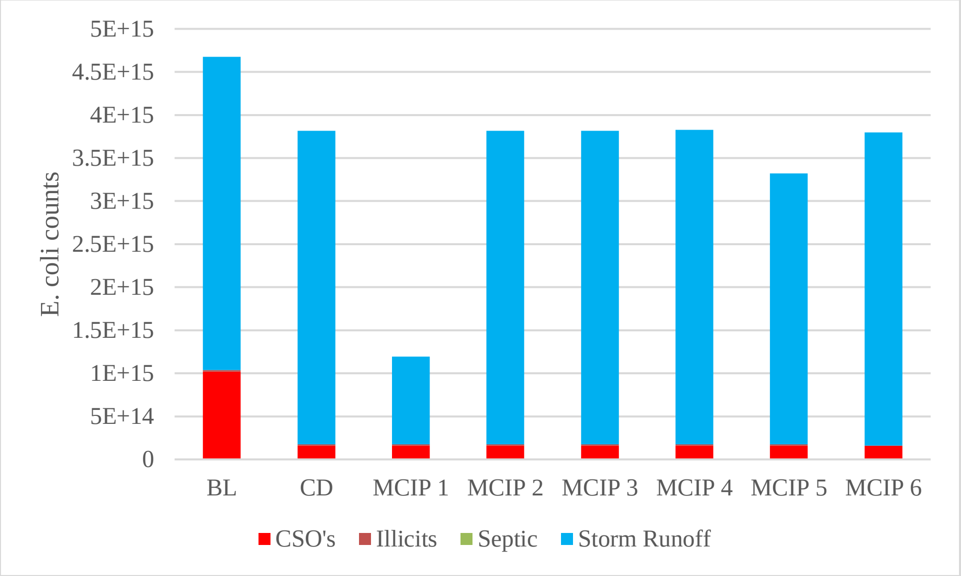

Figure 16 - Total *E. coli* load for the Euclid Creek model, 5/19/2014-10/3/2014.

4.3 Upstream dominance on the Cuyahoga and Rocky Rivers

When examining the tributary results for the phosphorus and *E. coli* POCs, it quickly becomes apparent that the Rocky and Cuyahoga rivers are insensitive to any of the proposed management options (Table 5 and Table 7). Exceedances for both rivers happen at a high frequency for the baseline model run and show little to no improvement under any of the management options. This lack of response is due to the primary sources of POCs in these two rivers, WWTPs and the upstream loading beyond the boundary of NEORSD’s jurisdiction. While some changes are being made to NEORSD WWTPs as a part of the Consent Decree, these are limited to expanding treatment capacity and adding disinfection to control bypass discharges. Despite the fact that contemporary WWTP effluent TP levels are sufficiently high to trigger an exceedance even in the absence of upstream loads (Figure 17), no upgrades in phosphorus removal efficiency have been proposed.

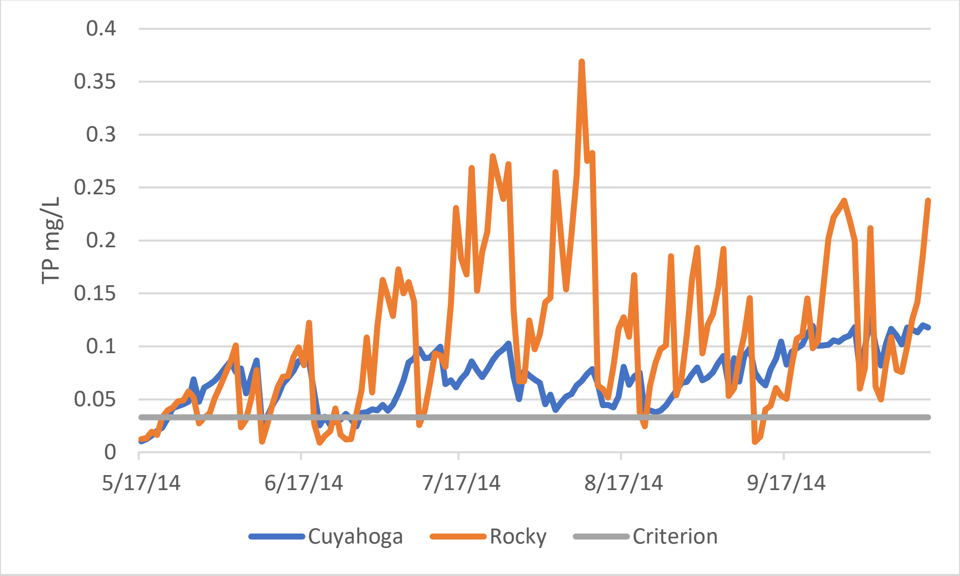

Figure 17 - Total Phosphorus concentration at river mouth with all POC sources other than WWTPs turned off.

The other major POC source for these two rivers, the upstream boundary input, is likewise enough to exceed POC concentration guideline on its own. The upstream boundary input is a problem for both E. coli and phosphorus (Figure 18, Figure 19). If NEORSD or the city of Cleveland wish to fully address water quality issues on the Cuyahoga and Rocky rivers, they will have to work with the responsible entities outside of their jurisdiction. However, their responsibility to address issues within their control should not be abdicated simply due to a lack of control over upstream inputs.

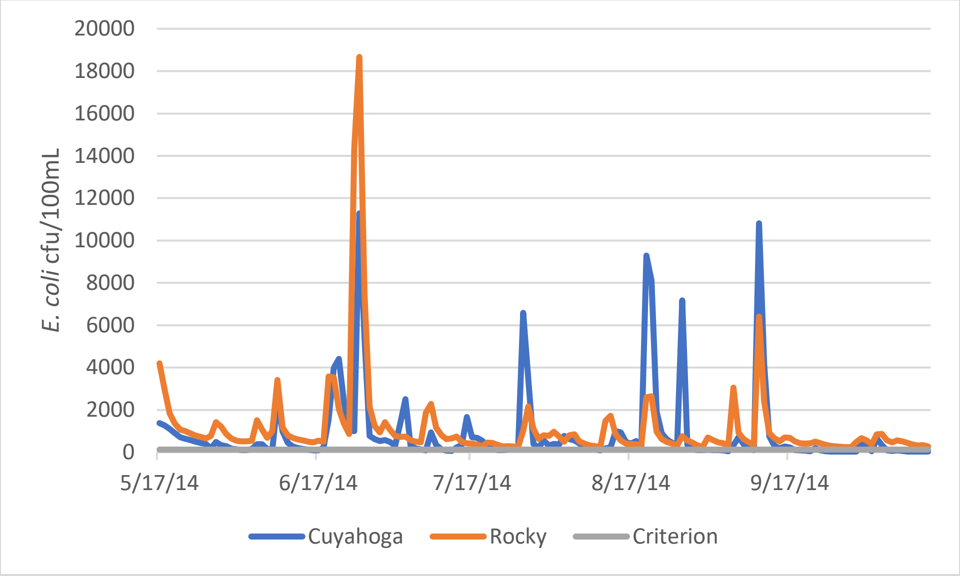

Figure 18 - *E. coli* concentration at river mouth with all POC sources other than the upstream boundary turned off.

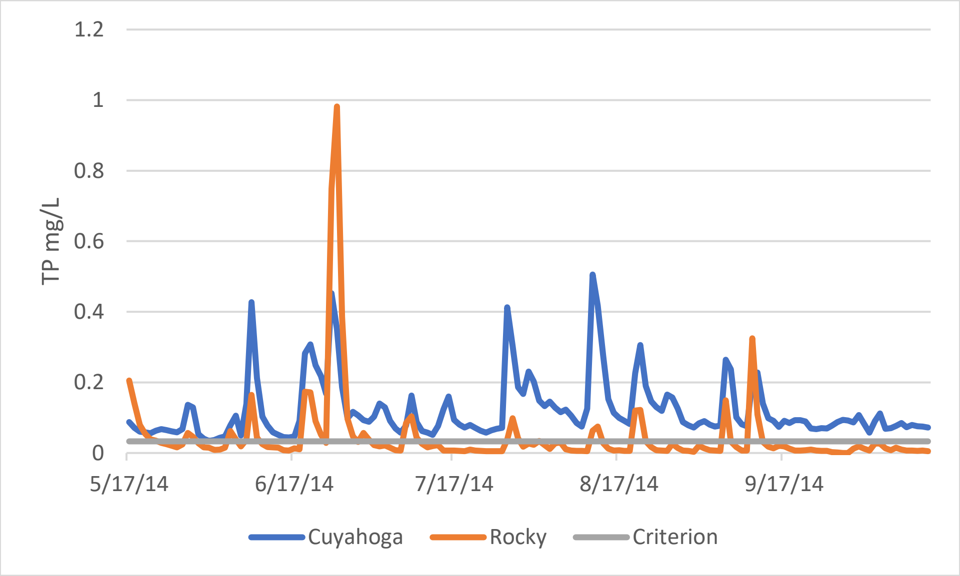

Figure 19 - Total Phosphorus concentration at river mouth with all POC sources other than the upstream boundary turned off.

4.4 Water quality sensitivity to Consent Decree improvements

It must be kept in mind that the primary goal of Project Clean Lake and the Consent Decree is to reduce the volume of untreated wastewater NEORSD discharges into Lake Erie and its tributaries, and by this metric it has been and will be successful. This is well illustrated in the graph below (Figure 20) showing in-district (upstream boundary excluded) tributary *E. coli* loads to Lake Erie. The Consent Decree significantly reduces *E. coli* loads through its reduction of CSO flows. However, when looking at concentration-based metrics rather than total loads, the Consent Decree scenario generates 0.2% and 1.0% km*day improvements for *E. coli* and phosphorus, respectively, using the exceedance metrics described in the Results section. These improvements largely took place on Big Creek (57% of the reduction in *E. coli* km*days and 72% of the reduction in phosphorus km*days). On the beaches, the Consent Decree scenario generated 26.4% fewer exceedance days at Villa Angela Beach, and only 2.9% fewer exceedance days at Edgewater beach. Given how much money is being spent on the Consent Decree, it may seem alarming that the water quality improvements it is projected to provide are so minimal. It is also important to note that the year used in models and analysis for this study, 2014, was a relatively wet year (National Oceanic and Atmospheric Administration, 2017). The Consent Decree and its collection tunnels are engineered around what is called a “representative year,” one that provides a median amount of rainfall. In a representative year, the Consent Decree is designed to remove 89% of the raw wastewater that currently reaches Lake Erie untreated. In this study, CSO volumes were reduced by only 69%. Since CSOs are wet-weather driven, precipitation in excess of the volume the system was designed for will result in a lower proportion of

CSO flows being captured in the storage tunnels. In addition, untreated stormwater is responsible for a significant portion of the *E. coli* loading and reducing stormwater volume entering streams is not part of Project Clean Lake, outside of the stormwater component of CSO flows.

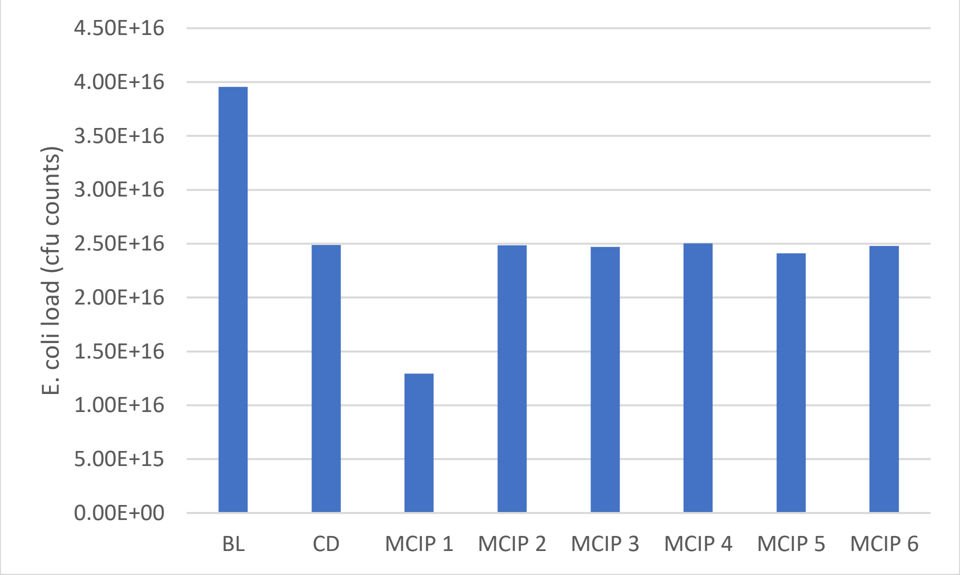

Figure 20 - Combined tributary *E. coli* load to Lake Erie, excluding Cuyahoga and Rocky river upstream boundary contributions. Insensitivity to infrastructure changes that do not heavily impact CSO or stormwater volumes is easily visible in MCIPs 2-6.

4.5 Wet-weather dominance and urban stormwater runoff

Analysis of the models used for this study demonstrates that water quality issues in Greater Cleveland are driven by wet-weather events. CSOs discharge during heavy precipitation and make up 53.5% of the in-district E. coli load. Stormwater runoff contributes 45.3% of the load, while all other E. coli sources combined (septic inputs, SSO flows, and illicit discharges) are only 1.2% of the total load (Figure 21). Even if CSO flows were completely eliminated, that would only solve half of the problem.

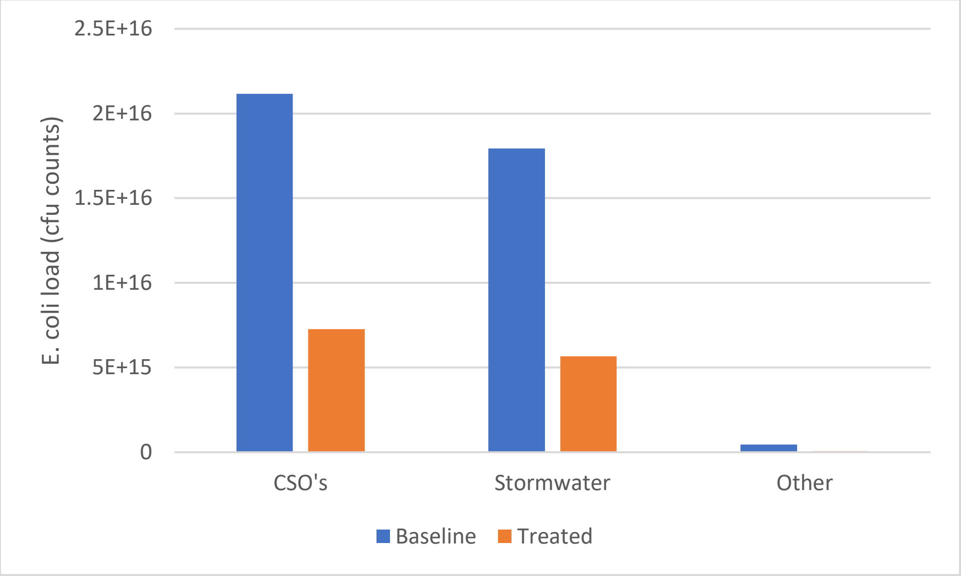

Figure 21 - In-district *E. coli* load sources (Treated column represents Consent Decree for CSOs and MCIP1 for Stormwater).

Single source models for the streams allow for a better illustration of where the exceedances discussed previously are coming from. These models entail separating the master models for each tributary into models containing only one source type (e.g., CSOs, SSOs, stormwater runoff, illicit discharges, WWTP effluent, and septic systems). While CSOs provide a large proportion of the POC load to Lake Erie, they only happen during large precipitation events. In contrast, stormwater runoff can raise POC concentrations in streams during even light rainfall. Combined with illicit discharges, these two sources are what drive most of the POC criteria exceedances in the streams (Table 10, Table 11).

Table 10 - Single source *E. coli* 126 cfu/100mL km*days management metric. SWMM model conduit lengths (km) are multiplied by the number of days the conduit recorded an exceedance to calculate km*days. An average concentration above 126 cfu/100mL is an exceedance. The results reported in this table were obtained from SWMM models with only a single type of POC source (either storm runoff, CSOs, SSOs, or illicit discharges). If neither "+ MCIP1" or "+ CD" is indicated, the scenario being reported is the baseline scenario.

Stream	**Storm Runoff**	**SR + MCIP1**	**CSOs + CD**	**SSOs Only**	**Illicits Only**
Abram	1490	1458	0	64	1575
Big	3769	3708	190	715	4893
Doan	1862	1159	187	808	740
Dugway	1347	1315	18	683	0
Euclid	3966	3690	15	0	3648
Green	616	607	40	0	0
Mill	3141	3069	623	0	3264
Ninemile	1602	1539	128	333	0
West	1679	1635	30	0	2360
Total	19471	18180	1230	2604	16480

Table 11 - Single source Phosphorus 0.033 mg/L km*days management metric. SWMM model conduit lengths (km) are multiplied by the number of days the conduit recorded an exceedance to calculate km*days. An average concentration above 0.033 mg/L is an exceedance. The results reported in this table were obtained from SWMM models with only a single type of POC source (either storm runoff, CSOs, SSOs, or illicit discharges). If neither "+ MCIP1" or "+ CD" is indicated, the scenario being reported is the baseline scenario.

Stream	**Storm Runoff**	**SR + MCIP1**	**CSOs + CD**	**SSOs Only**	**Illicits Only**
Abram	935	799	0	18	246
Big	1937	1645	124	227	2293
Doan	1473	508	113	403	51
Dugway	733	543	8	233	0
Euclid	1967	1407	11	0	246
Green	485	454	17	0	0
Mill	1290	1045	326	0	276
Ninemile	800	655	46	135	0
West	801	677	5	0	441
Total	10421	7733	650	1016	3553

Illicit discharges make up a small percentage of the total *E. coli* and phosphorus loads, but they act differently than CSOs, SSOs, and stormwater runoff. Unlike these other sources, illicit discharges contribute their loads during dry weather. Dry weather flows in the streams are lower than those during wet weather, allowing illicit discharges to have an impact even with relatively small loads. Dry weather also makes up a larger proportion of the model run than wet weather. This combination of factors leads to illicit discharges making a sizable contribution to exceedance days for *E. coli* and phosphorus.

Urban stormwater runoff is well known to carry high concentrations of a variety of pollutants including phosphorus and *E. coli* (Mallin, Johnson, & Ensign, 2009). While the engineering design to control NEORSD’s CSOs is already a monumental undertaking, the very nature of urban stormwater runoff makes completely clearing up water quality criteria exceedances an infeasible, if not impossible task. Though runoff can be reduced to a certain extent, such as with MCIP1 in this study, it comes with significant financial costs.

4.6 Other MCIP benefits and MCIP cost effectiveness

While this study focuses purely on water quality issues, the MCIPs it uses were designed with a more diverse set of benefits. In addition to water quality, NEORSD and Michigan Tech are interested in quantifying “Ecosystem Service Valuation,” which involves including recreational, health, and other intangible benefits along with economic and ecological benefits (Cangelosi, Weiher, Taverna, & Cicero, 2001). While MCIPs 1 (stormwater runoff reduction), 2 (septic system remediation), 3 (SSO remediation), and 6 (illicit discharge remediation) are primarily focused on water quality, MCIPs 4 (separate sewer upgrades) and 5 (common sewer upgrades) were envisioned to have additional benefits. Both these MCIPs drastically reduce the amount of stormwater runoff that makes it into sanitary sewers, and thus into receiving waters. For MCIP4 (Sanitary Sewer upgrades), this actually results in a detrimental effect on receiving water quality, since it routes stormwater from the sanitary system to the streams and does not offset that increase with any POC concentration reductions. However, both MCIPs 4 and 5 reduce the volume of water that WWTPs have to treat, and they reduce the chance of basements flooding with backed up sanitary sewer waste during heavy precipitation events since stormwater is no longer connected to sanitary lines.

Another financial item that must be noted is that while this study focuses purely on water quality, it does not take into account cost effectiveness. The Consent Decree storage tunnels, while effective in reducing the POC loads that reach Lake Erie, cost billions of dollars. Similarly, MCIP1, while showing great potential improvements for water quality and POC load reduction, is estimated by NEORSD to cost three to four times what the rest of the MCIPs would cost combined, if it were to be fully implemented as modeled. Green and LID infrastructure requires good coordination between government and private entities, and while cost effective in the long run, can be very expensive to fully implement initially (Montalto, et al., 2007). While water quality benefits are illustrated here, further study and design is required to access which management options provide the best benefits, both in terms of water quality and in ecosystem services, as well as which options are cost feasible and cost effective.

5 Future Work

The focus of the work detailed within this report is on water quality for the entire NEORSD district, without financial considerations. This leaves two obvious paths for future work to improve this study's results. Firstly, while NEORSD is a single entity, it covers many different cities and municipalities beyond Cleveland alone. Many of these municipalities have very different sewer infrastructure compositions, making any one-size-fits-all approach potentially infeasible for any number of individual municipalities. The MCIPs that are applied district-wide to the models in this study could be improved if they were to be individually tailored to the various municipalities. Secondly, while this report's results were purely water quality-driven, practical implementation of any modeled infrastructure changes will need to be accompanied by financial analysis as well. An option with a relatively small benefit may still be worth doing if its costs are sufficiently low, while at the same time an effective option may not be implementable if its costs are prohibitive.

Further analysis of MCIP 1, the stormwater runoff reduction management option, is another avenue of study worth pursuing. This option showed substantial reductions in POC loads as well as significant improvements in the various km*day and km*hour management options. However, this management option as modeled is an extremely aggressive approach, carrying with it the assumption that it is being applied to 100% of all areas with separate and common trench infrastructure. This results in a 60-70% decrease in stormwater runoff in these areas. In reality, it is infeasible if not impossible to convert such large areas completely over to green infrastructure and LID. Since this option showed such promise, further analysis should be carried out on the water quality impacts of applying this option to smaller proportions of targeted areas.

6 Conclusions

This study examined the potential effectiveness of Cleveland’s Consent Decree on wastewater discharges as well as six additional infrastructure management options (MCIPs). While the Consent Decree model did show significant reductions in pollutant loads to Lake Erie, its impact on water quality in Cleveland’s streams and on its beaches as modeled was not shown to be sufficient for significantly reducing exceedances of *E. coli* and phosphorus criteria. Four of the six proposed MCIPs showed very little impact on either POC loads or water quality management metrics. MCIP 1 showed promise for reducing stormwater runoff and thus the POCs associated with it. MCIP 6 showed that eliminating illicit discharges can drastically improve stream water quality by cleaning up POC concentrations during dry-weather periods.

Models showed that in addition to CSOs, the other main pollutant source is stormwater runoff. There are limits to how much runoff can be controlled, and urban runoff will carry significant levels of pollutants no matter what management options are implemented. Additionally, NEORSD will be constrained in their ability to improve the water quality of streams that originate outside of their jurisdiction. Cooperation with other entities will be necessary to limit upstream loads.

Further work should be done to investigate smaller scale management options rather than the district-wide approaches described here. Financial analysis of these options could narrow down which approaches are most feasible. Effective yet costly options such as MCIP 1 should be modeled at various scales to get the best value for water quality improvements. Other cost-effective approaches such as physical barriers or breakwalls near public beaches should also be investigated as alternatives or companions to watershed infrastructure improvements.

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