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Relationship of Escherichia Coli Levels to Rainfall, Runoff, and Water Quality Variables at Two Urban Sites in the Great Miami River Watershed

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Abstract

This report summarizes the results of an investigation to examine the relationship between occurrence and magnitude of *Escherichia Coli* (*E. coli*) with antecedent rainfall and runoff conditions and associated water quality parameters on the Great Miami and Mad rivers in Dayton, Ohio. The results of the investigation show statistical increases in *E. coli* concentrations from wet weather to dry weather conditions. In this study, dry weather *E. coli* concentrations mostly met Ohio Class A primary contact recreation standards but wet weather concentrations often did not meet those standards. Statistical correlations for various rainfall and runoff event-based variables using simple and multiple linear and log-linear regressions revealed antecedent rainfall conditions, changes in river flow, and the water quality parameters specific conductance and turbidity had the highest explanatory power for inter-event variations in *E. coli* concentration. These correlations allow for the development of mathematical models to predict whether or not *E. coli* levels are likely to exceed regulatory standards under current conditions. Future studies are needed to better define intra-event variations in *E. coli* in runoff, explore relationships that may exist with other explanatory variables, and determine major sources of *E. coli*.

Introduction

Background

The Miami Conservancy District (MCD) conducted this investigation to determine whether measurable antecedent rainfall and runoff conditions and associated water quality parameters influence the occurrence and magnitude of microbial pollutant concentrations in the Great Miami and Mad rivers in Dayton, Ohio.

According to the Ohio Environmental Protection Agency (OEPA), stormwater that originates in urban areas is a major source of pollution in the Great Miami River Watershed (OEPA, 2005, 2012, and 2013). Surface water is contaminated by a variety of pollutants from urban stormwater including: sediment, nutrients, heavy metals, and microorganisms. The microbial pollutants in urban stormwater often have a fecal origin possibly originating from sanitary sewer overflows, combined sewer overflows, cross connections between storm and sanitary sewers, and pet and wildlife waste.

Microbial pollutants that cause disease are referred to as pathogens. Pathogens in surface water pose potential health risk for people who engage in outdoor recreational activities in rivers, lakes, streams, and ponds. Studies show that increased health risks are associated with exposure to pathogens in water through bathing and other activities that result in full or partial immersion in water (Dorevitch et. Al., 2012; Fleisher et. al., 2010; Marion et al., 2010). Recent studies of the Great Miami River from Sidney to Dayton and from Dayton to the mouth of the Great Miami River by the Ohio Environmental Protection Agency (OEPA) conclude that microbial indicators of fecal contamination frequently exceed statewide contact recreation standards (OEPA, 2012; OEPA, 2013).

Elevated levels of microbial contaminants in surface water may also pose a public health threat to shallow water supply wells located in close proximity to the Great Miami River and its tributaries. Production wells installed in sand and gravel aquifers adjacent to the Great Miami River cause movement of water from the river through the riverbed and into the underlying aquifer through a process known as induced infiltration. High flow events in the Great Miami River result in riverbed scour which removes fine sediment from the riverbed increasing movement of water across the surface water/groundwater interface (Levy et. al., 2013). As a result, movement of microbial contaminants from surface water to groundwater may be enhanced, and under certain conditions, may reach production wells more quickly.

If significant relationships exist between rainfall and runoff conditions and the occurrence and magnitude of microbial pollutants, it may be possible to predict when microbial pollutant concentrations in surface water are likely to exceed contact recreation standards. Understanding microbial pollutant behavior in response to measurable rainfall, runoff, as well as other associated water quality variables can be useful for evaluating health risks from exposure to pathogens. This information could also be useful for assessing the risk that pathogens pose to shallow production wells that receive recharge from the Great Miami River.

Applicable Water Quality Standards

In Ohio, statewide numerical standards for *E. coli* are determined by OEPA and are based upon state-designated recreation uses. OEPA sets recreational use *E. coli* standards for streams designated for bathing and contact recreation (see Table 1). The Ohio Administrative Code defines Class A primary contact recreation waters as waters that are suitable for frequent full-body contact recreation activities such as, but not limited to, wading, swimming, boating, water skiing, canoeing, kayaking, and scuba diving. OEPA designated the Great Miami and Mad rivers in and near Dayton as Class A primary recreation use. For the purpose of this investigation, the Class A *E. coli* standards are used to evaluate *E. coli* data.

Table 1. Statewide numerical limits for the protection of recreation uses

Recreation use*	***E. coli* (colony counts per 100 mL)**	
	Seasonal geometric mean	**Single sample maximum**
Bathing water	126	235
Class A primary contact recreation	126	298
Class B primary contact recreation	161	523
Class C primary contact recreation	206	940
Secondary contact recreation	1030	1030

*The criteria above apply inside and outside the mixing zone for wastewater treatment plant discharges during the recreation season which runs from May 1 to October 31

Methods of Data Collection and Analysis

Data Collection

Measuring pathogens in natural waters directly is difficult because the variety, and often low concentration, of pathogenic bacteria and viruses make them difficult to detect and quantify individually. An alternative approach is to use indicator organisms as a surrogate for pathogenic microbes. Microbial indicators of fecal contamination are assumed to be present in water whenever pathogens from fecal contamination are present. Thus, microbial indicators of fecal contamination may be used to evaluate the risk for the occurrence of fecal pathogens. One of the most commonly used microbial indicator bacteria is *Escherichia coli* (*E. coli*). *E. coli* is a rod-shaped, gram negative bacterium, found in the gastrointestinal tract and feces of warm-blooded animals. It is one species within the fecal-coliform group of bacteria and can be distinguished from other fecal coliforms by biochemical tests. Most strains of *E. coli* are harmless, but some strains can cause illness. The presence of *E. coli* bacteria in water is indicative of the presence of fecal contamination which may contain pathogens.

From May 7 to October 4, 2018, MCD staff collected grab samples of surface water at two sampling stations. One station is located on the Great Miami River upstream of the Island Park low dam at the Dayton Rowing Club and one station is located on the Mad River just downstream of Huffman Dam (see Figure 1). Grab samples are single samples collected at a specific time. Water quality measurements for a particular grab sample represent the condition of the water at the time that sample was collected.

The sampling station on the Great Miami River is located on the left bank approximately 400 meters downstream from the confluence of the Stillwater and Great Miami rivers. Samples collected here likely reflect mixing of waters of the two rivers. The Mad River sampling station is located on the left bank of the Mad River approximately 250 meters downstream from MCD's Huffman Dam. Huffman Dam does not impound water during normal river flows or smaller runoff events on the Mad River, and so its presence does not have a significant impact on *E. coli* transport processes. Both sampling stations are surrounded by medium to high density developed land according to the National Land Cover dataset 2011. The watershed immediately upstream of both sampling stations is also heavily urbanized.

Precipitation and streamflow data was obtained from a network of United States Geological Survey (USGS) and MCD cooperative stream gage stations in the Dayton area. Stage and discharge were measured at 15-minute intervals at all cooperative stream gages. Water quality variables including temperature, pH, dissolved oxygen, specific conductance, turbidity, and dissolved organic matter were measured with YSI EXO2 multi-parameter sondes and by an In-Situ Aqua TROLL 600 multi-parameter sonde. The YSI sondes are deployed at, or in close proximity to, each of the sampling stations and log data continuously at one-hour intervals. MCD staff used the In-Situ sonde to compare water quality parameters at the exact grab sampling location with water quality parameters measured by the deployed YSI sondes. See Table 2 for a list of water monitoring stations used to support this investigation.

Figure1. Locations of *E.* coli sampling stations as well as stream and rain gages

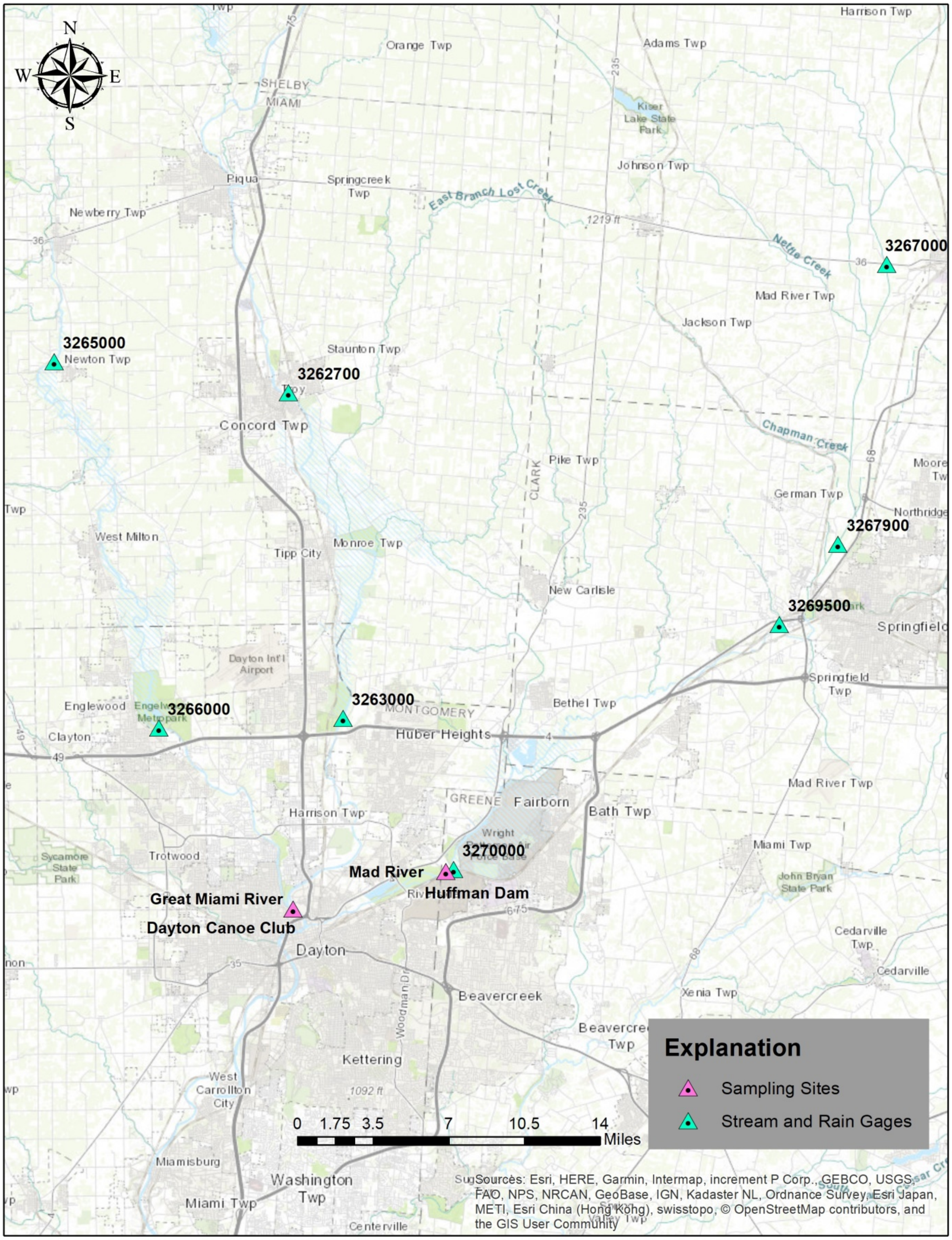

Table 2. Precipitation, streamflow, and water quality monitoring stations

Monitoring Station	Monitoring Network	Type of Data	Maintained by	Sampling Stations in Correlation Analysis
03270000	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Mad River
03269500	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Mad River
03267900	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Mad River
03267000	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Mad River
Huffman Dam	Storm Central/ WaterLOG	Water Quality	YSI	Mad River
03263000	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Great Miami River
03262700	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Great Miami River
03266000	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Great Miami River
03265000	USGS NWIS	Streamflow and Precipitation	USGS and MCD	Great Miami River
Dayton Canoe Club	Storm Central/ WaterLOG	Water Quality	YSI	Great Miami River

The sampling frequency was chosen so as to be representative of water quality in the river during both wet weather and dry weather conditions. MCD staff collected the water samples from the boat dock at the Great Miami River sampling station and by wading out near the middle of the river channel at the Mad River sampling station. Staff filled sterilized polypropylene sample containers preserved with sodium thiosulfate. The sample containers were immediately transferred to a cooler filled with ice, and transported to the laboratory within four hours of sample collection. The laboratory enumerated E. coli colonies using an IDEXX Quanti-Tray 2000™. All E. coli results are reported as a most probable number of colony forming units per 100 milliliters (mL) of water.

Statistics Used

Standard statistical methods using simple (one variable) and multiple (more than one variable) linear and log-linear regressions were used to determine significant correlations between response and explanatory variables. The coefficient of determination R^2 was used to determine whether or not a linear relationship existed for the simple regressions. The adjusted coefficient of determination ($\overline{R}^2$) was used to indicate if a linear relationship existed for the multiple regressions. The adjusted coefficient of determination was used to account for the tendency of R^2 to increase when additional explanatory variables are added to the regression model. Log-linear relationships were identified by using simple and multiple regressions on log transformed data and looking at the coefficient of determination (R_l^2) and the adjusted coefficient of determination ($\overline{R}_l^2$). All linear and log-linear regressions were performed at the 95% confidence level.

Explanatory and Response Variables

The eight explanatory variables used in the regression analyses were selected based on a review of previous data collected by MCD in the Great Miami River Watershed and a literature review (MCD, 2011; MCD 2013), (OEPA, 2012), & (Reutter et. al., 2006). See Table 3 for a brief description of each explanatory variable.

Table 3. Explanatory variables used in the simple and multiple regressions

Explanatory Variable	**Definition**
Q	discharge (cfs) of nearest upstream gage at time of sample collection
ABS ΔQ	absolute value of change in discharge (cfs) at nearest upstream gage over the hour prior to sample collection
P_{MAX72}	Maximum amount of rainfall (in) measured by upstream rain gages during the 72 hours prior to sample collection
P_{AVG72}	Average amount of rainfall (in) measured by upstream rain gages during the 72 hours prior to sample collection
P_{MAX96}	Maximum amount of rainfall (in) measured by upstream rain gages during the 96 hours prior to sample collection
P_{AVG96}	Average amount of rainfall (in) measured by upstream rain gages during the 96 hours prior to sample collection
SPCOND	Measured specific conductance (µS/cm) of the water column at the sampling station
TURB	Measured turbidity (fnu) of the water column at the sampling station
FDOM	Measured dissolved organic matter (qsu) in water column at the sampling station

The variables Q and ABSΔQ are flow variables that reflect stormwater runoff and potential transport of *E. coli*. The variables P_{AVG72}, P_{MAX72}, P_{AVG96}, and P_{MAX96} are antecedent rainfall variables that represent *E. coli* die-off and build-up. The variables SPCOND, TURB and FDOM are water quality variables that reflect changes to the quality of water in the stream or river during runoff events.

The response variable used in all regression analyses was the grab sample *E. coli* concentration. MCD staff hypothesized that grab sample *E. coli* concentrations at monitoring stations correlate significantly with one or more explanatory variables.

Results and Discussion

Summary Statistics

A statistical summary of all sampling results is shown in Table 4. Concentrations of *E. coli* had similar minimums, maximums, means, medians, and standard deviations between the stations.

Table 4. Summary statistics for *E. coli* concentrations at all sampling stations

Station	Number of samples	***E. coli* concentration as most probable number of colony forming units per 100 mL of water**				
		Minimum	**Maximum**	**Mean**	**Median**	**Standard Deviation**
Mad River	70	20	24,196	1,437	209	3,907
Great Miami River	70	10	24,200	1,036	220	3,417

Regulatory Compliance and Wet vs. Dry Weather Comparisons

Seasonal geometric mean concentrations of *E. coli* exceeded Class A primary contact recreation standards at each of the two sites (see Table 5). The single sample maximum standard was exceeded numerous times at both sampling stations.

Table 5. Summary of *E. coli* data in relation to regulatory standards

Station	**Number of samples**	**Geometric Mean**	**Number of samples with *E. coli* concentration > 298 colonies per 100 mL**
Mad River	70	329*	31
Great Miami River	70	248*	32

*Geometric mean concentrations exceeded regulatory standard of 126 colonies per 100mL

When sample *E. coli* concentrations are plotted with river discharge, it is apparent that high *E. coli* concentrations (*E. coli* concentrations > 298 colonies per 100 mL) are often associated with runoff events (see Figures 2 and 3). In order to examine the strength of this relationship, the *E.*

coli sample results were divided into two categories; wet weather and dry weather. A wet weather sample is defined as a sample collected when precipitation was greater than or equal to 0.3 inches was recorded at one or more of the upstream rain gages during the previous 72 hours. A dry weather sample is defined as a sample collected when precipitation was less than 0.3 inches at all of the upstream rain gages during the previous 72 hours.

Box and whisker plots of dry weather and wet weather sample concentrations show higher *E. coli* concentration distributions for wet weather samples when compared with dry weather samples (see Figure 4). Median concentrations for wet weather samples exceeded 298 colonies per 100mL at both sampling stations. Median and upper quartile *E. coli* concentrations for dry weather samples fell below 298 colonies per 100 mL at each of the two sampling stations.

A probability of exceedance analysis was conducted on all *E. coli* data collected at the two sampling stations during this investigation. Exceedance probabilities were determined for both wet and dry weather conditions. A comparison of sample exceedance probabilities for wet weather and dry weather *E. coli* concentration illustrates higher wet weather concentrations across all probability levels (see Figure 5). The wet weather exceedance probability for an E. coli concentration of 298 colonies per 100 mL is 0.61 whereas the dry weather exceedance probability is 0.19. These results show a clear relationship between precipitation events and elevated *E. coli* concentrations in the Great Miami and Mad rivers in the Dayton area.

Simple Regressions

Table 6 shows coefficient of determination values for simple linear and log-linear regressions between grab sample E. coli concentration and the various explanatory variables. None of the explanatory variables had high (> 0.50) linear correlations with E. coli at the Mad River station. The water quality variable SPCOND and the runoff variable ABSΔQ had the highest linear correlations, but neither variable could account for more than 35-percent of the variance. The variables P_{AVG72} and SPCOND had the highest log-linear correlations with E. coli at the Mad River station accounting for slightly more than 40-percent of the variance. Log-linear correlations were generally stronger than linear correlations for the Mad River station.

The antecedent rainfall variables P_{MAX72} and P_{AVG72} had the highest linear and log-linear correlations with *E. coli* at the Great Miami River station. Linear correlations for the two variables accounted for 40 and 38-percent of the variance respectively. In both cases the linear correlations were stronger than the log-linear correlations.

Although statistically significant simple regressions were obtained, none of the regressions had very high levels of explanatory power. Variables with the greatest explanatory power included $P_{MAX72,}$ $P_{AVG72,}$ and SPCOND. One possible explanation is that *E. coli* levels are dependent upon multiple explanatory variables. To explore this dependence multiple regressions are needed.

Figure 2. Sample *E. coli* concentrations for the Mad River sampling station plotted with river discharge

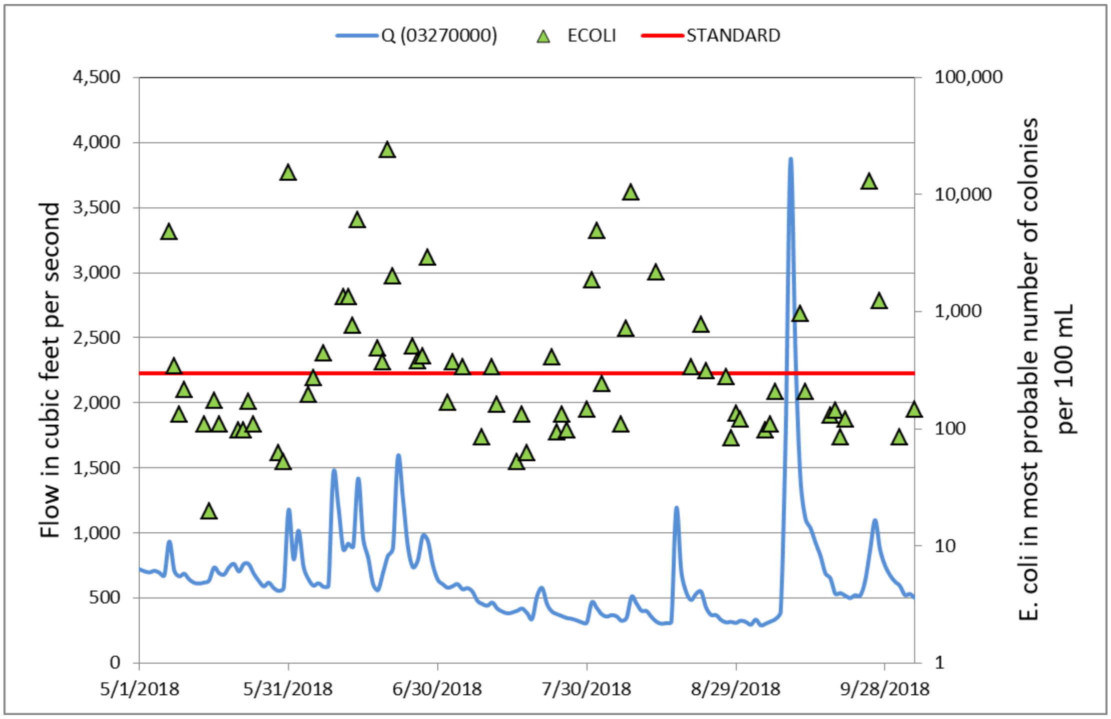

Figure 3. Sample *E. coli* concentrations for the Great Miami River sampling station plotted with river discharge

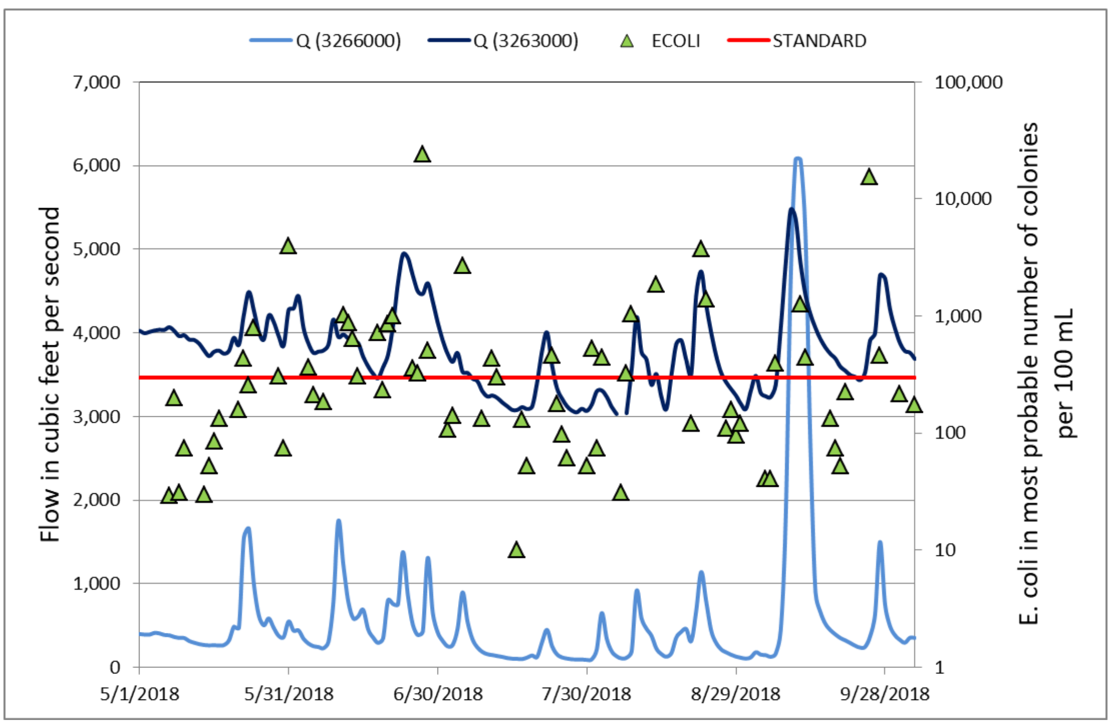

Figure 4. Box and whisker plots of wet and dry weather sample *E. coli* concentrations.

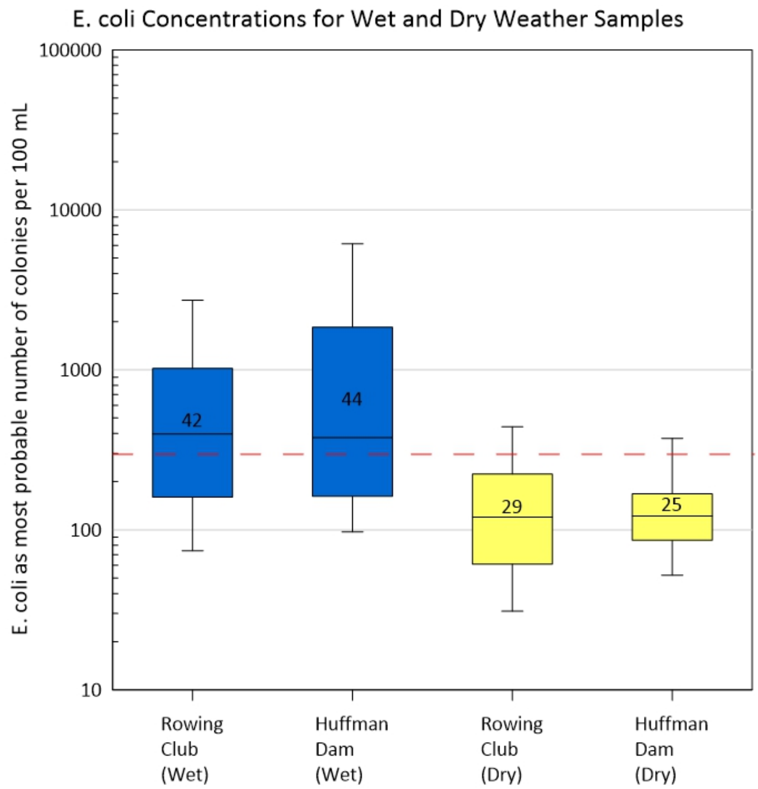

Figure 5. Exceedance probability curves for wet weather and dry weather sample concentrations

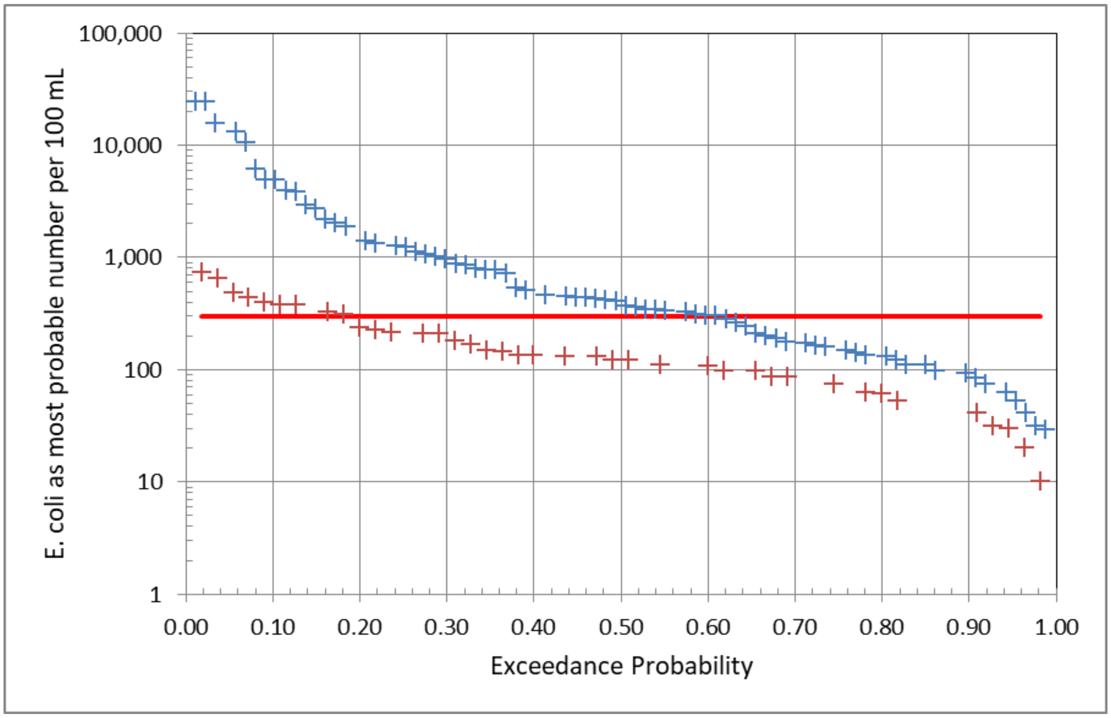

Table 6. Coefficient of determination values for simple linear and log-linear regressions

Explanatory Variable	Mad River		Great Miami River	
	R^2	R_l^2	R^2	R_l^2
Q	0.20	0.30	0.16	0.23
ABSΔQ	0.31	0.34	0.26	0.17
P_{MAX72}	0.13	0.35	**0.40***	0.34
P_{AVG72}	0.18	**0.44***	**0.38***	**0.35***
P_{MAX96}	0.07	0.24	0.31	0.29
P_{AVG96}	0.06	0.23	0.23	0.25
SPCOND	**0.35***	**0.43***	0.19	0.23
TURB	0.27	0.38	0.35	0.22
FDOM	0.10	0.26	NA	NA

* These values show the strongest correlations between the explanatory and response variables

NA – not analyzed due to absence of dissolved organic matter data

Multiple Regressions

A multiple regression analysis was conducted on the results from the two sampling stations in this investigation. MCD used the results of the simple regression analysis to select six explanatory variables for the analysis. One of the variables reflected antecedent rainfall conditions (P_{AVG72}), two of the variables reflected runoff (Q and ABSΔQ), and three of the variables reflected water quality (FDOM, SPCOND, and TURB).

Highest linear and log-linear correlations for the Mad River station were obtained when P_{AVG72} was paired with TURB and ABSΔQ (see Table 7). Multiple linear regression analysis of these variable pairings yielded adjusted coefficients of determination slightly greater than 0.30 meaning the variables together accounted for about 30-percent of the variance in *E. coli* concentrations. Multiple log-linear regression analysis increased the adjusted coefficients of determination above 0.50 such that the variables accounted for over 50-percent of the variance.

None of the multiple linear regression variable pairings for Great Miami River site proved to be statistically significant. Statistically significant multiple log-linear regressions were obtained when the variable P_{AVG72} was paired with the variables SPCOND and TURB. Adjusted coefficients of determination for these pairing exceeded 0.40 accounting for slightly more than 40-percent of the variance in *E. coli* concentrations. None of the other variable pairings had statistically significant relationships.

In general, multiple log-linear regressions significantly improved correlations between explanatory variables and E. coli concentrations for the Mad River sampling station over simple linear and log-linear regressions. However, multiple linear and multiple log-linear regressions only slightly improved correlations between explanatory variables and E. coli concentrations for the Great Miami River sampling station

The highest adjusted coefficients of determination among the sampling stations did not consistently have the same pair of explanatory variables, but there were some similarities between the two sampling stations. Antecedent rainfall variables were consistently present in the simple and multiple regressions with the highest adjusted coefficient of determination values. The following regression relationships best describe inter-event variations in *E. coli* levels at the two sampling stations:

Table 7. Coefficient and adjusted coefficient of determination values for linear and log-linear regressions

Variable 1	Variable 2	Mad River		Great Miami River	
		$\overline{R}^2$	$\overline{R}_l^2$	$\overline{R}^2$	$\overline{R}_l^2$
P_{AVG72}	SPCOND	NS	0.53	NS	**0.42***
P_{AVG72}	TURB	0.32	**0.60***	**0.45***	**0.42***
P_{AVG72}	ABSΔQ	0.33	**0.54***	NS	NS
P_{AVG72}	Q	0.22	0.48	NS	NS
P_{AVG72}	FDOM	NS	NS	NA	NA

NS – not statistically significant ($p > 0.05$)

NA – not analyzed due to absence of dissolved organic matter data

- Mad River: Log10(*E. coli*) = 2.01 + 0.72(P_{AVG72}) + 0.01(TURB)
- Mad River: Log10(*E. coli*) = 2.13 + 0.71(P_{AVG72}) + 0.008(ABSΔQ)
- Great Miami River: Log10(*E. coli*) = 3.33 + 0.57(P_{AVG72}) + 0.002(SPCOND)
- Great Miami River: *E. coli* = 62.76 + 67.59(P_{AVG72}) + 12.82(TURB)

These equations have an average adjusted coefficient of determination ($\overline{R}_l^2$) of 0.50 indicating the explanatory variables can explain on average 50% of the variation in inter-event *E. coli* levels at the two sampling stations.

Overall, the multiple regressions improved explanatory power over the simple regressions at both sampling stations. However, the explanatory power for most of the multiple regressions is not extremely high. It is possible that other explanatory variables are needed to adequately capture *E. coli* buildup, wash off, and die off processes. This would allow for better modeling of variations in *E. coli* levels between different events.

Future studies

Other explanatory variables mentioned in the literature showing high levels of correlation with *E. coli* include total evaporation, net radiation, sunshine hours, rainfall intensity, and concentrations of various nitrogen and phosphorus species (McCarthy et. al., 2007). Many of these parameters are difficult to monitor in real-time limiting their usefulness for forecasting purposes. There also may be other anthropogenic factors at play such as variations in upstream municipal wastewater and agricultural runoff *E. coli* loads. The findings of this investigation and future studies could be used to create better predictive models of microorganism concentrations in urban runoff. There is also a lack of knowledge as to the sources of *E. coli* loading to rivers and streams in the Dayton region. More knowledge of *E. coli* sources could help to better define explanatory variables that may have significant correlations with riverine *E. coli* concentrations.

Conclusions

The results of this investigation identify variables associated with antecedent rainfall, runoff, and water quality that correlate with levels of *E. coli* in the Great Miami and Mad rivers in the Dayton urban area. Data on variables related to antecedent rainfall, river flow, and river water quality are available from existing water monitoring networks, such as USGS stream gages and YSI Storm Central/WaterLOG that could be used to forecast *E. coli* levels. In this study, antecedent rainfall, changes in river flow, and the water quality parameters specific conductance and turbidity were found to be the most important variables that explain variations in E. coli concentrations in the Great Miami and Mad rivers *E. coli* in the Dayton area. Future studies are needed to better define intra-event variations in and sources of *E. coli* in urban runoff and to explore relationships that may exist with other explanatory variables.

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Miami Conservancy District

38 E. Monument Avenue

Dayton, Ohio 45402

Phone: (937) 223-1271

Fax: (937) 223-4730

www.mcdwater.org