

TRACKING AND MANAGING NON-POINT SOURCE POLLUTION AT LAKE HERRICK WATERSHED, ATHENS, GEORGIA

Ashwini Kannan¹, D.E. Radcliffe², T.A.P. Saintil², T. Rasmussen³, M. Molina⁴

AFFILIATIONS: ¹ College of Engineering; ² Crop and Soil Sciences Department, College of Agriculture and Environmental Sciences; ³ Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602; ⁴ US Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Athens, Georgia.

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Abstract. The Lake Herrick watershed is about 131 ha in area and covers portions of the University of Georgia's East campus, the Oconee Forest, and includes residential and commercial land use. The 6-ha reservoir was established in 1982 at the University of Georgia campus but closed in 2002 for recreation due to fecal contamination. Subsequent monitoring confirmed cyanobacteria blooms and elevated nutrient concentrations, especially phosphorus (P). In this study, two tributaries (Birdsong and Armadillo) and the outlet stream (Below Dam) were monitored for discharge, *E. coli*, nitrogen (N), and P under baseflow and stormflow conditions from February 2016 to October 2017. Our results showed that total P was significantly higher during stormflow compared to baseflow, but total N remained the same. *E. coli* results indicated that most of the bacteria entered the lake through the tributaries during stormflow. Microbial source tracking markers specific to dog, ruminant and human hosts were used to investigate bacterial sources. We found that dogs were a more likely source of this bacteria than humans or deer. The fact that human sources were at low concentrations in the Lake Herrick watershed indicated that there was reduced risk for human source contamination. Lake Herrick was reopened for limited recreation in October 2018.

INTRODUCTION

Urban catchments respond faster than other land uses to a storm due to higher impervious surface percentage (Aalst et al. 2010). The hydrographs are flashy, with the first flush usually washing more pollutants from the watershed. Watershed size is also important because it interacts with the land use and the effects of climate and weather. Rivers have lower residence time than lakes and they may flush the sediments as they enter the system. This process plays an important role in the suspension and resuspension of particulate P. Water bodies with long water residence time can aggregate sediments. The sediments can act as both a source and sink. Hence, careful monitoring is needed to estimate the pollutant loads and take relevant actions.

In 2002, Lake Herrick Beach, which was popular with students, was closed for recreation (swimming and fishing) due to high concentrations of fecal coliform (Christopher,

2015). Several research projects suggested that the impairment was mainly due to urban runoff and the tributaries that washed from the sub-catchments into the lake (UGA, 2017). Deer and Canada geese are common in the watershed. The Athens community uses the trails in the Oconee Forest Park to walk their dogs. Deer also leave droppings along streambeds increasing fecal coliform counts in the water. Most of the sewer lines in the watershed are within the Five Points neighborhood and could introduce human pathogens. In fact, one sewer line directly crosses one of the tributaries at the point of entry to the Lake. However, the Athens-Clarke County (ACC) public utilities department has not found any leaks from inspections. Storm drain pipes discharge untreated runoff into the lake and may account for some of the non-point sources of pollution.

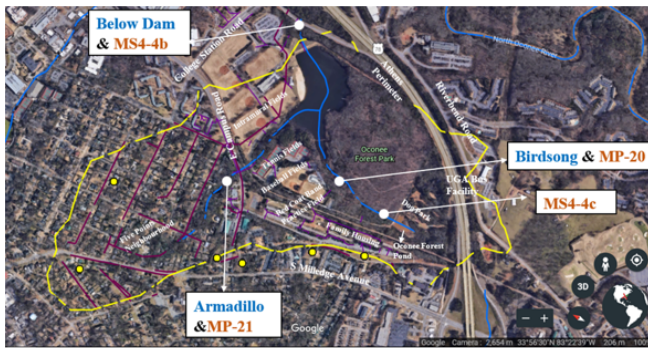
The objectives of our research were:

1. To compare baseflow and stormflow *E. coli* concentrations and the seasonal trends of *E. coli* concentration to aid in source identification. To identify bacteria sources using genetic and culturable *E. coli*, human-associated bacteroides markers HF183-MGB, ruminant-associated Rum-2-bac, and dog-associated Dogbac.
2. To determine the dynamics of nutrients at inlet tributaries and the outlet. To estimate the sources of various forms of P and N and determine the effect on algal blooms.

MATERIALS AND METHODS

Sampling Sites and Collection

Based on the recommendations from previous studies at Lake Herrick, three monitoring locations were chosen: one at each inlet tributary, Birdsong (BS) and Armadillo (AR), and the third one just below the dam (BD) (Figure 1). Samples were collected during storms using automated ISCO samplers installed at each location. Grab samples were also collected twice per month for less intensive sampling and four times per month for intensive sampling months under baseflow conditions. The automated ISCO samplers were triggered when stage increased for events greater than 0.25 cm. Each sampling station responded differently to storm events, hence the stage for each site was set individually.



Legend

- Septic Systems
- Storm Lines
- Sewer Lines
- ▭ Lake Herrick Watershed
- Streams

Figure 1. Lake Herrick Watershed Extent. Study Sites: Birdsong (BS), Armadillo (AR) and Below Dam (BD). Brown and Caldwell Sites: MS4-4c, MS4-4b, MP-20 and MP-21. Source: Google Earth

The inlet and outlet streams were monitored from February 2016 until November 2017 for stage, *E. coli*, turbidity, forms of N and P, temperature, pH, specific conductance and DO. The samples were analyzed using microbial source tracking from January 2017 until October 2017. A Quanta multimeter probe was used to measure in-situ parameters of specific conductance, pH, temperature, and dissolved oxygen (DO) during baseflow. The samples were divided into duplicates. One set of samples were analyzed for *E. coli*, turbidity, conductivity, and nutrients. The other set of samples were transported on ice to the EPA Office of Research and Development (ORD) laboratory facilities in Athens, GA.

Additional water level sensors were placed at all the sites close to the ISCO transducers to measure the water level in the stream. Samples were collected over a period of seven hours and they were removed from the refrigerated sampler within four hours.

Nutrients, *E. coli* and Source Tracking Analysis

A total of 103 samples were analyzed for seven analytes. The samples were analyzed for dissolved inorganic P (DIP), total dissolved P (TDP) and total P (TP). We calculated dissolved organic P (DOP), total particulate P (TPP), and total dissolved P (TDP) as follows:

$$\text{DOP} = \text{TDP} - \text{DIP}$$

$$\text{TPP} = \text{TP} - \text{DIP} - \text{DOP}$$

$$\text{TDP} = \text{DIP} + \text{DOP}$$

The samples were also analyzed for ammonium N ($\text{NH}_4^+\text{-N}$), nitrate N ($\text{NO}_3^-\text{-N}$), total dissolved N (TDN), and total N (TN). Dissolved organic N (DON) and total particulate N (TPN) were calculated as follows from the measured fractions:

$$\text{TPN} = \text{TN} - \text{TDN}$$

$$\text{DON} = \text{TDN} - \text{NH}_4^+\text{-N} - \text{NO}_3^-\text{-N}$$

We used the EPA and proposed Georgia standard for *E. coli* of a single sample, 235 MPN/100 mL, as a standard of water quality in our study. This value corresponds to 36 of out 1000 people getting sick who were exposed to the water. In this study, the *E. coli* concentrations were determined using IDEXX Colliert-18 kits at the UGA Soil Physics Laboratory within four hours after sample collection following the standard method (APHA, 1998). The concentration of *E. coli* is reported in MPN/100 mL.

For the source tracking analysis, we collected a total of 30 baseflow and 31 stormflow samples from January 2017 to October 2017. The baseflow samples were collected in a synoptic manner with weekly intensive sampling schemes. The storm samples were collected using the ISCO samplers at 30-min intervals as described above. The samples were taken to the EPA ORD Laboratory for further analysis. One hundred mL of water were filtered using 0.47- μm Iso-pore polycarbonate filters to concentrate *E. coli* cells for DNA extraction using MoBio Power-Soil DNA Isolation Kits (Mobio Laboratories, Carlsbad, CA).

Residence Time

Average hydraulic residence time (RT) is a measure of the time water spends in a lake from the time it enters the lake to the time it exits. Longer residence time can lead to significant effects on the water quality and more interaction with the bottom sediments. The average residence time for Lake Herrick was calculated for baseflow assuming uniform mixing and stratification using the equation shown below:

$$RT = V_L / F_b = 381 \text{ days}$$

where V_L = the average volume of lake ($60000 \text{ m}^2 * 5.5 \text{ m}$) and F_b = the average baseflow rate ($0.01 \text{ m}^3/\text{s}$). During high flows in storms with flow rates such as $1 \text{ m}^3/\text{s}$, the RT was about four days. Hence, the pollutants were flushed out of the lake faster during periods of high flow.

RESULTS AND DISCUSSIONS

Forms of Nitrogen and Phosphorus

A study by Guildford et al. (2000) plotted the ratios for 221 lakes in 14 countries and showed that a N deficiency was apparent at $\text{N:P} < 9$, P deficiency at $\text{N:P} > 22$ and both were co-limited in the intermediate range between 9 and 22. We calculated the N:P ratio at the three sites in our study using the TN and TP data. The N:P ratio is plotted as a function of TP in Figure 2. More than 50% of the combined samples were P-limited and less than 10% of the samples were N-limited at all sites. Baseflow samples were mostly P-limited with excess N and the system shifted to co-limited when P increased during stormflow.

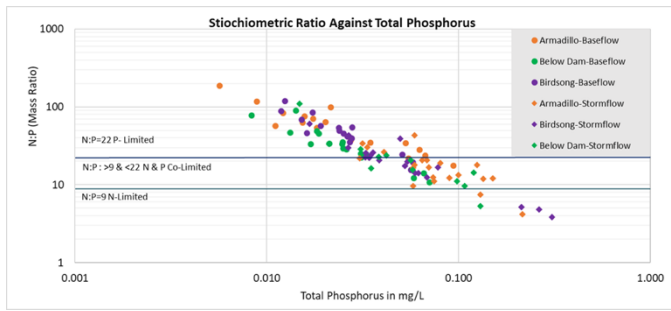


Figure 2. Stochiometric ratio as a function of TP.

TP concentrations for storm samples were significantly higher than the baseflow sample concentrations at all sites (Figures 3-5). TN concentrations were remarkably similar between baseflow and stormflow samples and there were no significant differences between samples at all sites (Figures 6-8). More than 95% of the samples exceeded the Eco-region criteria of 0.62 mg/L, Nutrient Ecoregion IX, level III Ecoregion 45 (USEPA, 2000) for TN and 54% to 72% of the samples exceeded the reference Eco-region criteria for 0.03 mg/L for TP.

TP and its forms did not differ statistically between sites (Figures 3-5), but TN concentrations were higher at Armadillo compared to Below Dam (Figure 7 and 8), indicating N transformations in the lake. Ammonium was higher at Below Dam compared to Armadillo and Birdsong (Figures 6-8), also indicating N transformations. TPN concentrations were higher at Armadillo compared to the forested Birdsong site (Figure 6 and 7), indicating fertilizer adsorbed to eroded or scoured sediment could have been the source.

The dominant form of P at all sites was TPP followed by DOP with less than 10% of the P being DIP (Figures 3-5). Also, DOP increased two-fold during stormflow at all the sites, signifying that organic P dominated the dissolved P pool. Three high values for total P recorded during May and June 2017 (263, 213 and 308 $\mu\text{g/L}$) probably indicated sediments washed from the Upper Pond renovation work. Renovation work at the Red Coats band practice field happened during the same period and runoff from the field discharges via a storm drain to Birdsong Creek close to the sampling location. A higher fraction of TPP in these three samples also implied the source of the higher concentration was runoff with sediments.

The dominant form of N was NO_3^- , followed by TPN or DON with NH_4^+ less than 15% of the N at all sites (Figure 6-8). Nitrate concentrations generally decreased during stormflow while particulate and organic forms increased. Below Dam differed from the other two sites with increased NH_4^+ and decreased NO_3^- , suggesting transformations in the lake.

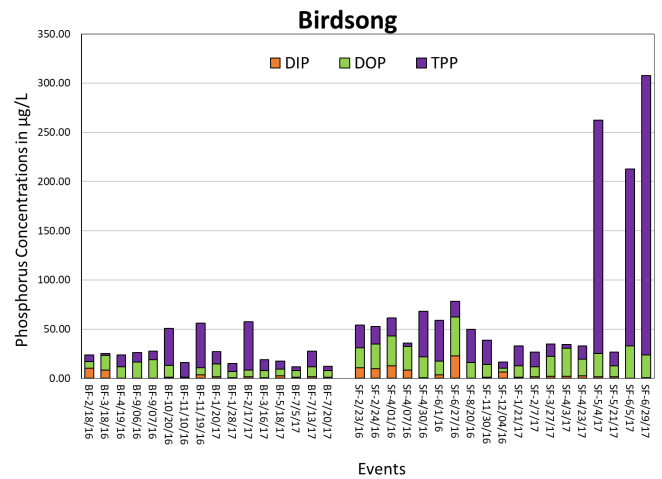


Figure 3. Phosphorus concentrations at the Birdsong Site. Baseflow samples are shown on the left and stormflow samples are shown on the right.

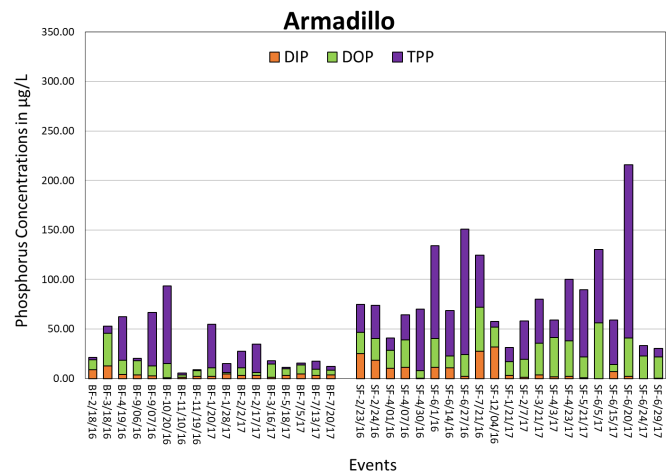


Figure 4. Phosphorus concentrations at the Armadillo Site. Baseflow samples are shown on the left and stormflow samples are shown on the right.

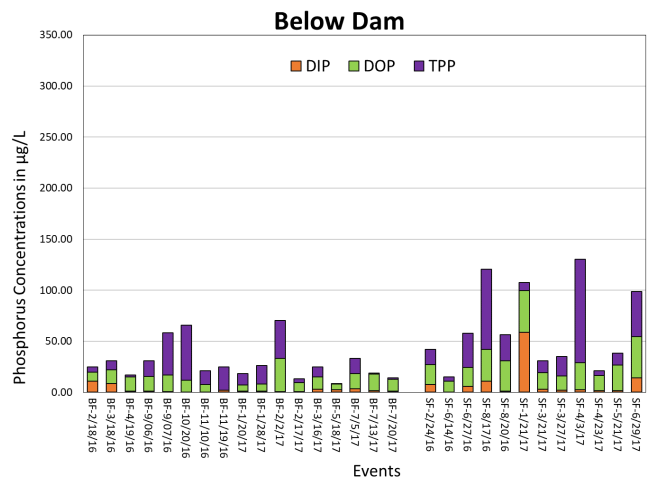


Figure 5. Phosphorus concentrations at the Below Dam Site. Baseflow samples are shown on the left and stormflow samples are shown on the right.

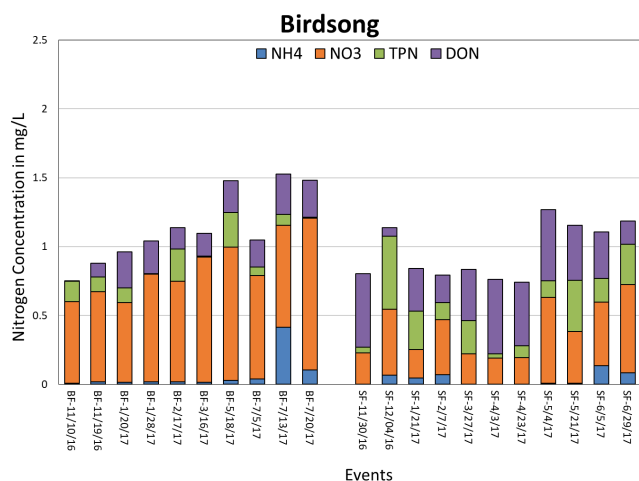


Figure 6. Nitrogen concentrations at the Birdsong Site. Baseflow samples are shown on the left and stormflow samples are shown on the right.

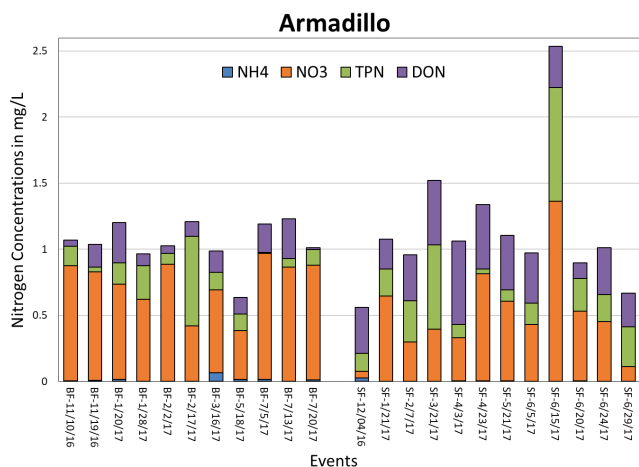


Figure 7. Nitrogen concentrations at the Armadillo Site. Baseflow samples are shown on the left and stormflow samples are shown on the right.

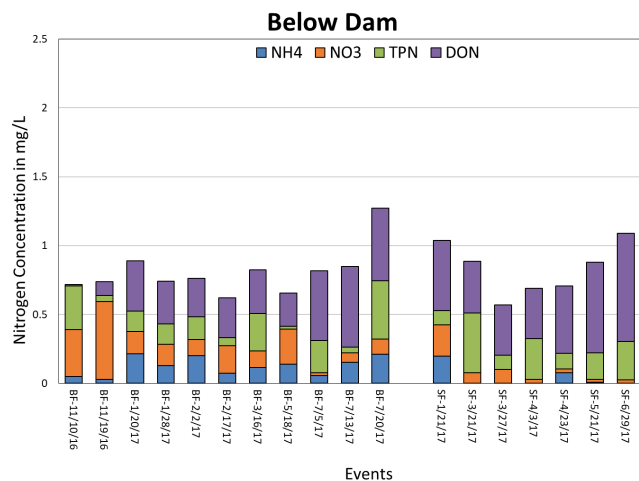


Figure 8. Nitrogen concentrations at the Below Dam Site. Baseflow samples are shown on the left and stormflow samples are shown on the right.

Table 1. *E. coli* concentrations at the three sites.

Season	No of Samples	Range	Mean Baseflow	Mean Stormflow	% Baseflow >235 MPN/100 mL	% Stormflow >235 MPN/100 mL
BIRDSONG						
Summer 2016	6	150-11960	518	7590	67%	100%
Winter 2016	11	100.5-10905	190	4499	20%	100%
Summer 2017	13	63-26340	147	10005	0%	100%
Winter 2017	11	141-7890	458	4643	60%	100%
ARMADILLO						
Summer 2016	6	100-142636	753	47664	67%	67%
Winter 2016	10	100-82390	977	20451	40%	100%
Summer 2017	14	181.5-164300	1247	45557	83%	100%
Winter 2017	10	57.5-92340	1202	32331	80%	100%
BELOW DAM						
Summer 2016	6	100-150	133	117	0%	0%
Winter 2016	6	3-123	43	36	0%	0%
Summer 2017	10	5-2740	202	878	17%	50%
Winter 2017	9	10-1275	37	365	0%	20%

E. coli Analysis

Table 1 shows the *E. Coli* concentrations at different sites during the monitoring period. The percentage of baseflow and stormflow samples exceeding the single time sample criteria of 235 MPN/ 100 mL are shown in last two columns. Samples exceeded the *E. coli* criteria more during the summer than the winter. Almost all the storm samples exceeded the criteria at the inlet sites during stormflow, implying that runoff or scouring of stream sediment containing bacteria was the source. In 2017, more samples exceeded the criteria compared to 2016 because of the frequent rainfall events during 2017.

Figure 9 presents boxplots of *E. coli* concentrations with the minimum, 25th percentile, median, 75th percentile and maximum values, plotted on a logarithmic scale. Stormflow *E. coli* concentrations at Armadillo and Birdsong were roughly 30-fold higher than the baseflow concentrations. Stormflow *E. coli* concentrations at Armadillo were approximately 6- and 80-fold higher than Birdsong and Below Dam. Stormflow concentrations below the dam were below the standard indicating bacteria die-off in the lake.

Source Tracking Analysis

Microbial source tracking (MST) results were based on 8 baseflow events and 8 (Below Dam) to 13 (Birdsong and Armadillo) stormflow events. MST detects genes in both culturable and non-culturable cells in units of gene copies per volume (GC/100 mL). We will refer to the MST concentrations as “genetic *E. coli*”. IDEXX only detects cells that can grow in units of MPN/100 mL and we will refer to the IDEXX concentrations as “culturable *E. coli*” (Lavender et al., 2009).

The two techniques are different and do not necessarily correlate. The genetic *E. coli* concentration is generally expected to be higher than the culturable *E. coli*, but results are not consistent as some experiments have shown culturable *E. coli* higher than genetic *E. coli* (Noble et al., 2010). On sunny, calm days when there is no outside contamination, genetic counts by MST are expected to be lower than culturable counts (Fujioka et al., 1981).

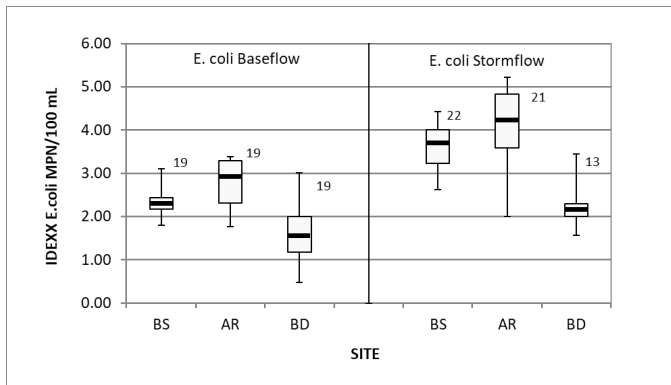


Figure 9. *E. coli* concentrations at all three sites under baseflow (left) and stormflow (right) conditions.

The percentage of samples that contained the different markers is shown in Figure 10. Genetic *E. coli* were present in 6 out of 8 baseflow events at Birdsong and Armadillo and in all 8 baseflow events at the Below Dam site. During stormflow, genetic *E. coli* were detected for all samples at all the three sites and stormflow concentrations were significantly higher than baseflow concentrations for genetic *E. coli* (as they were for culturable *E. coli*, Figure 9) at all the three sites.

Combining the baseflow and stormflow samples together at the three sites (Figure 11), the average genetic *E. coli* concentrations were 4 log₁₀ GC/100 mL at the Birdsong site, 5 log₁₀ GC/100 mL at the Armadillo site and 3 log₁₀ GC/100 mL at the Below Dam site. These concentrations were comparable to the average culturable *E. coli* concentrations with 3 log₁₀ MPN/100 mL at Birdsong, 4 log₁₀ MPN/100 mL at Armadillo and 2 log₁₀ MPN/100 mL at Below Dam.

A one-way ANOVA run for genetic *E. coli* showed that the average concentration at the Below Dam site was significantly lower than the other two sites. This was similar to the trend exhibited by culturable *E. coli*. Both results indicated that *E. coli* concentrations dropped in the lake. Since the 10-fold drop did not occur with TN and TP concentrations (Figure 3-8) the reduction in *E. coli* concentrations was probably due to die-off of bacteria and not dilution.

To determine the probable sources of *E. coli*, the correlation between culturable *E. coli* and each marker was tested. Pearson correlation coefficients were calculated for genetic and culturable *E. coli* using the marker data as the independent variable and the culturable *E. coli* as the response variable. Significant positive correlations existed between the genetic and culturable *E. coli* at the Birdsong, Armadillo, and Below Dam sites (Table 2), confirming that the markers and culturable *E. coli* were sampling the same populations.

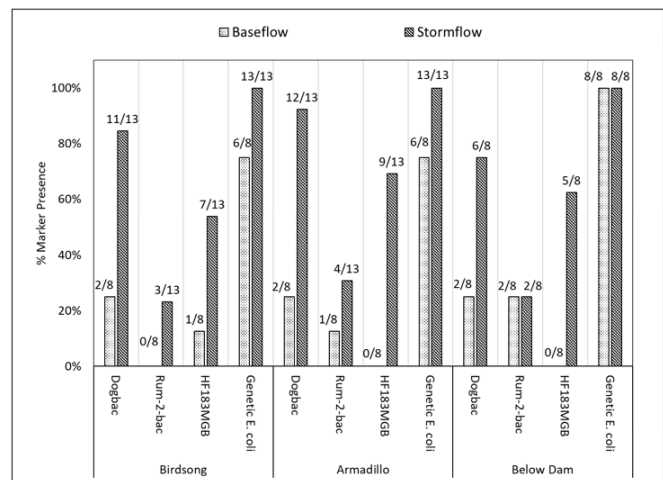


Figure 10. Percentage of markers detected at each site.

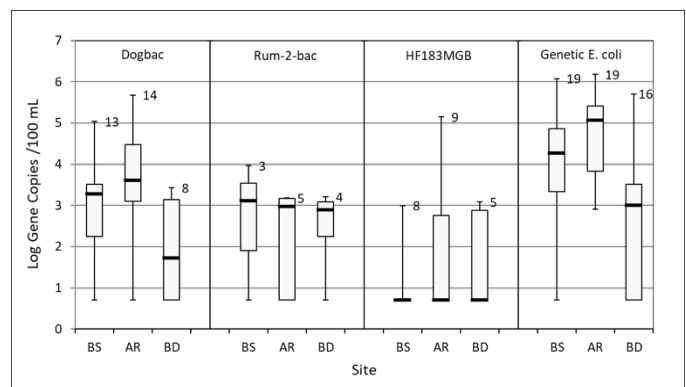


Figure 11. Concentration of markers in log₁₀ GC/100 mL at Birdsong (BS), Armadillo (AR), and Below Dam (BD).

Table 2. Pearson correlation co-efficients for culturable (IDEXX) *E. coli* and MST markers at each site. NS = not statistically significant.

Site	#	Dogbac	Rum-2-bac	HF183 MGB	Genetic <i>E. coli</i>
Birdsong	21	0.68	NS	NS	0.84
Armadillo	21	0.72	NS	NS	0.61
Below Dam	16	0.67	NS	0.62	0.78

The Dog marker was detected twice at each site under baseflow conditions (Figure 10). This suggested dog taking a dip in the water at the Below dam and Birdsong sites. Armadillo has residents that live close to the creek and a dog house was spotted at one of the residences during a stream walk by the monitoring team in 2016. Under stormflow conditions, Dog was the most commonly detected marker after *E. coli* and there was a good correlation with culturable *E. coli* at all the sites (Table 2) indicating dogs were a dominant source.

The highest concentration for the dog marker was almost 6 log₁₀ GC/100 mL at Armadillo (Figure 11). A source tracking study in Michigan found that *E. coli* in a storm sewer exceeded 10000 MPN/100 mL with no illicit

connection in the system. The sources were identified as pets (cats and dogs) and raccoons (Ram et al., 2007).

During baseflow, the human marker (HF183MGB) was detected only once at Birdsong and undetected at Armadillo and Below Dam (Figure 10). The absence of human markers during baseflow indicated that there were no illicit discharges within the watershed. During stormflow, the human marker was detected 7 out of 13 times at Birdsong, 9 out of 13 times at Armadillo and 5 out of 8 times at Below Dam (Figure 10). However, the gene copies were mostly below the detection limit for quantification of 0.70 log₁₀ TSC/100 mL (Figure 11).

The highest concentration of human marker occurred in a storm event at Armadillo with approximately 6 log₁₀ TSC/100 mL (Figure 11). This indicated that there may be occasional sewer leakage during storms in the Armadillo watershed. The sewer line runs parallel to the lake shore line at the point where Armadillo Creek drains into Lake Herrick. At the Below Dam site, there was a positive correlation between the human marker and culturable *E. coli* (Table 2). One study found that human markers were more persistent than other bacteria once released into the environment (Ishii et al., 2006).

Under baseflow conditions, the ruminant marker (Rum-2-bac) was found once at Armadillo and twice at Below Dam, but undetected in the predominantly forested Birdsong tributary (Figure 10). Since there are no cows or goats in the Lake Herrick watershed, deer are the likely source for this marker. Deer have been spotted by the monitoring team at night on Armadillo Creek. Deer may find refuge in forested areas but forage at the forest edge and in suburban areas at night along streams which provide a route into these areas (Guber et al., 2016; Parajuli et al., 2009). Under stormflow conditions, the ruminant marker was detected 3 out of 13 times at Birdsong, 4 out of 13 times at Armadillo and 2 out of 8 times at Below Dam. However, the correlation between the ruminant marker and culturable *E. coli* was not significant (Table 2), suggesting deer were not a dominant source of the *E. coli*.

CONCLUSIONS

Lake Herrick was reopened for limited recreation in October 2018. Our monitoring results showed that under baseflow conditions the water coming out of the lake met the *E. coli* standard most of the time (Table 1). However, *E. coli* concentrations in the two tributaries frequently exceeded the standard so sources still exist. Our source tracking results showed that dogs were a more likely source of this bacteria than humans or deer. Hobbies et al. (2017) found that pet waste was the source of most of the P input within a watershed where P fertilization was limited. Hence careful attention should be paid to picking up pet wastes and excluding dog pens from riparian areas, lawns, and landscape. Human markers detected at low levels during stormflow could have been due to the

exfiltration from sewer lines that run parallel to almost all tributaries. The fact that human sources were at low concentrations in the lake indicated reduced risk for human infection (J. Soller et al., 2015) and supports the decision to reopen Lake Herrick to limited recreational use.

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