Barbee lakes chain water quality assessment, pre- and post-public sewer installation

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Executive Summary

Wastewater has the capacity to harm surface water quality and safety, particularly through the addition of nutrients and bacteria. When not functioning properly, septic systems can introduce these materials to the groundwater, which then feed into local lakes. The purpose of this two-part study was to investigate lake water quality on the Barbee lakes chain before and after the installation of a public sewer system, or in other words, with and without private septic systems in the surrounding area. To observe the potential impacts of this installation, extensive lake and stream sampling was conducted in 2012-13 (pre-installation) and 2019-20 (post-installation). We selected the Chapman lakes chain as a study control, sampled in the same manner as the Barbee chain but maintaining the use of septic systems over the course of the study. Stream sampling for physical and chemical parameters occurred biweekly September-August on all inflowing and outflowing streams of both chains. Stream invertebrates, habitat quality, and *E. coli* were evaluated each summer. We conducted in-lake sampling for physical and chemical parameters monthly during June-August for the seven lakes of the Barbee lake chain and the two lakes of the Chapman chain. To establish a baseline understanding of nearshore *E. coli* counts, 59 sites were sampled around the shorelines of the lakes in the mid-summer. We also evaluated shoreline erosion by visual survey.

Several important results were identified over the course of the study. The Barbee chain receives much more water from inflowing streams that the Chapman chain does, likely do to its larger watershed. The dominant inflowing streams in the Barbee chain (Grassy Creek inflow and Putney Ditch) loaded high amounts of sediments and nutrients into their lakes relative to the dominant inflowing stream of the Chapman chain (Crooked Creek). The post-installation sampling year received more precipitation than the pre-study year, but the inflowing stream loads for many sediment/nutrients did not increase equivalently, if at all, depending on the stream. Lake *E. coli* samples were all well below the EPA human health threshold of 235 cfu/100 mL, while stream *E. coli* was above this threshold in 60% of all samples in the pre-installation study and 51% in the post-installation study. Minimal change occurred in stream habitat quality, macroinvertebrate surveys, and lake shoreline composition for the chains as a whole. Individual streams and lakes varied in their differences for these parameters over both study years, though no drastic changes were identified. Lake hypolimnion nutrient levels suggest that bottom sediments are a large source of lake nutrients for the Barbee chain in the summer.

Many water quality parameters measured in the Barbee chain were better (greater water clarity, lower nutrient concentration) in the summer of 2020 than 2013. Specific parameters and the magnitudes of the changes observed varied between the seven lakes of the Barbee chain. Changes in many of the same parameters were also observed in the Chapman chain as the control, making it difficult to attribute water quality improvements in the Barbee chain to the public sewer installation. Our data suggests two specific lakes in the Barbee chain, Sechrist and Kuhn, were the most likely to have been positively impacted by the sewer installation based on the present study. Total nitrogen decreases in other Barbee lakes also suggests lake water quality improvement beyond the impact of their inflowing streams and

which was not observed to a similar degree in the control chain. Further research on these lakes would differentiate their greatest influential factors, identify future methods of lake protection, and identify the impacts of sewer districts over greater lengths of time and at other scopes.

Introduction

Raw wastewater contains bacteria and nutrients, both of which can negatively impact the quality and safety of nearby bodies of water. Lake communities are inherently close to a body of water and can be densely populated, often leading to wastewater management challenges. Private septic systems are a common wastewater treatment system in rural areas and primarily treat wastewater by bacterial digestion and physical separation in a tank, followed by slow release of the effluent into the soil to percolate into the groundwater. This groundwater often feeds local lakes. The ability of septics to protect surrounding water quality from raw wastewater depends on many factors, including the type and quality of the soil, depth of the water table, size of drainage area, and mechanical quality of the septic tank and system itself. Due to these factors and potential state and federal regulations associated with them, some rural lake communities have stopped using private septic systems in favor of a public sewer district. Public sewer systems collect and process each property's wastewater at a centralized location and discharges treated water elsewhere. This was the case for the Barbee lakes chain in Kosciusko County, IN; in an effort to move away from potentially poorly functioning wastewater treatment systems already in place, construction of the Lakeland Regional Sewer District (LRSD) began July 2015, and residential connections were made starting in March 2017 (LRSD 2020a). As of this report, the LRSD serves an area of approximately 2500 ac. containing 1,649 properties (LRSD 2020b). A majority of the residential land use in the Barbee chain watershed is within hundreds of yards or less from the lakes (Richardson and Jones 2000).

This public sewer installation in the Barbee lakes chain provided an interesting research opportunity. By quantifying lake water quality before and after the public sewer system installation, we could observe if and how the Barbee lakes were influenced by the installation. To determine if observed water quality changes were the result of the sewer district specifically, other potential influences to lake water quality needed to be monitored too. The Chapman lakes chain served as an observational control to compare water quality changes. The chain had and kept septic systems over the course of the study and is geographically close to the Barbee chain such that it experienced similar weather and land management practices, which can also influence lake water quality. The study also necessitated stream monitoring, as inflowing water can be a significant influencer of lake water, and outflowing water is directly related to the water quality of the lake it flows from. Lastly, to quantify in-lake water quality and impacting variables, we sampled the lake water directly and surveyed the composition of the shorelines. All portions of this study needed to be performed twice – once before the public sewer was installed, and once after, with a waiting period between studies for residents to connect to the sewer and for the lake and groundwater to adjust to the new conditions.

To measure potential water quality changes, there are a few key insightful parameters to focus on. Phosphorus is an element found in organic materials and is a necessary nutrient, required for aquatic organism growth and survival. In lakes, phosphorus is often the main limiting nutrient; too much phosphorus will enable increased algae and other plant growth and accelerate the lake-aging process (eutrophication). As nutrient-rich septic effluent percolates through the ground, phosphorus readily binds to certain soils instead of joining the groundwater. However, phosphorus can more easily enter groundwater (and then a lake) if the soil becomes saturated due to a high water table, occasional flooding conditions, or the wrong types of soils dominate allowing less phosphorus binding (Mallin 2013). These situations can lead to phosphorus pollution in lakes. A diagnostic study of the Barbee lakes chain in 2000 hypothesized that the switch to public sewers around the chain would help reduce the lakes' upward-trending phosphorus levels (Richardson and Jones 2000).

Private septic system water is also rich with nitrogen, but nitrogen can have a less obvious influence than phosphorus depending on which nutrient is currently limiting plant growth in the lake (Mallin 2013). Nitrogen is much more mobile in soil: it makes its way into lakes via groundwater much faster. Nitrogen and phosphorus both occur in nature in multiple compounds with different properties, and both are regularly transformed between forms by organisms and chemical reactions in soil and water. To account for all relevant forms, the parameters total phosphorus (TP) and total nitrogen (TN) are emphasized here, though more forms were measured and reported.

Escherichia coli, or *E. coli*, is a species of bacteria associated with the fecal material of warm-blooded organisms, including humans, waterfowl, and pets. Like phosphorus, bacterial contamination can be mitigated by percolation through finer particulate soils, but sandy soils and high water or overflow events can lead to more leaching of *E. coli* and other bacteria into ground and surface. Other water quality parameters, such as Secchi disk water transparency and dissolved oxygen, were also monitored as key parameters.

Project Description

Study Area

The Barbee lakes chain is located in the glacial lakes area of northern Indiana in Kosciusko County. The lakes are part of the Tippecanoe watershed (HUC 05120106) which drains into the Wabash River near Lafayette, Indiana. For the purposes of the present study, the Barbee lake chain (HUC 051201060105) included Banning, Big Barbee, Irish, Kuhn, Little Barbee, Sawmill, and Sechrist lakes as well as the following streams: Grassy Creek inflow (inflow to Big Barbee), Heron Creek (inflow to Kuhn), McKenna Creek (inflow to Irish), Putney Ditch (inflow to Little Barbee), Rattlesnake Creek (inflow to Kuhn), Shoe Creek (inflow to Banning), and Grassy Creek outflow (outflow of the chain from Sawmill; **Figure 1**). The chain has a watershed area of approximately 33,150 acres and water surface area of 855 ac (Richardson and Jones 2000). Despite being connected, the lakes vary greatly, as evidenced in their residence times and littoral zones described in detail in previous diagnostic studies (**Tables 1**, **2**).

The Chapman chain (HUC 051201060205), located approximately 2 miles west, served as a control for the study. Private septic systems are still the wastewater management method around this chain. It includes Big Chapman and Little Chapman lakes along with the following streams: Arrowhead Drain (inflow to Little Chapman), Crooked Creek (inflow to Big Chapman), Gunter Creek (inflow to Big Chapman, may also be known as C27 Creek or Island Park Drain), Highland Drain (inflow to Little Chapman), Lozier's Creek (inflow to Little Chapman), and Heeter Ditch (outflow of the chain from Little Barbee; **Figure 2**). The Chapman chain has a watershed area of about 4,500 ac and water surface area of 638 ac. Residence times and littoral zones are also described for these lakes (**Tables 1, 2**).

Sampling Methods

Streams

We sampled streams for physical and chemical parameters biweekly September-August in 2012-13 and 2019-20 for each of the 13 stream sampling sites, referred to more generally as 2013 and 2020 through remainder of report (**Figures 1, 2**). At each site, a transect was stretched across the stream perpendicular to the flow. We calculated water flow by taking measurements of water velocity and depth

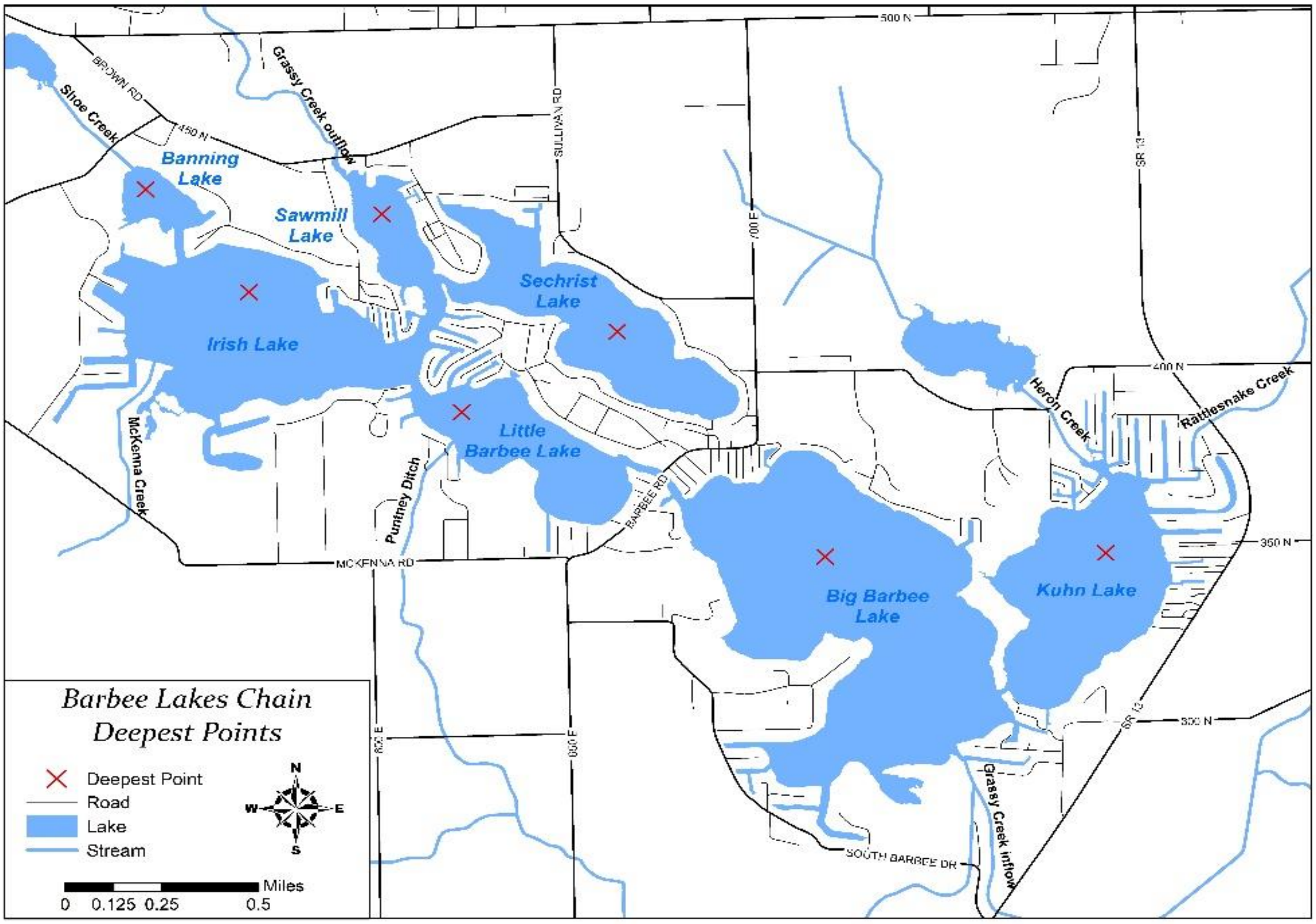

Figure 1: Map of the Barbee lakes chain and streams. Deep points for lake sampling are marked with a red "X".

measurements across the stream for a total of 12 measurements. If a stream was too narrow to measure 12 distinct points, the number of measurements was reduced to mark reasonably spaced points across the stream. An OTT MF Pro flow meter was used for velocity measurements, and a 1.5 m wading rod was used to measure water depth. Water temperature (°C), dissolved oxygen (DO; mg/L), percent saturation of dissolved oxygen (DO % sat.), pH, and conductivity (mS/cm) were measured at each stream site using a multiprobe sonde (Hydrolab Quanta in 2012-13; YSI ProDSS in 2019-20). A grab sample was retrieved from the thalweg just upstream of our transect. We stored this sample on ice and in the dark while in the field and in a refrigerator when at our facility, then transported the samples on ice in a cooler to the analytical lab. Lab analysis is described later in this section. Four instances of biweekly stream flow/nutrient/chemistry sampling were missed in 2020 from mid-March to mid-May due to COVID-19 shutdowns.

We also sampled stream *E. coli* weekly for 10 consecutive weeks, June-August 2013 and 2020. An *E. coli* sample was only collected if we observed measurable flow in the stream. Water was collected into a sterile 150 mL bottle containing sodium thiosulfate for dechlorination. Samples were handled without making contact to the insides of the bottle and lid, or sample water. All samples were transported on ice in the dark to the Kosciusko County Health Department for analysis the same day they were collected.

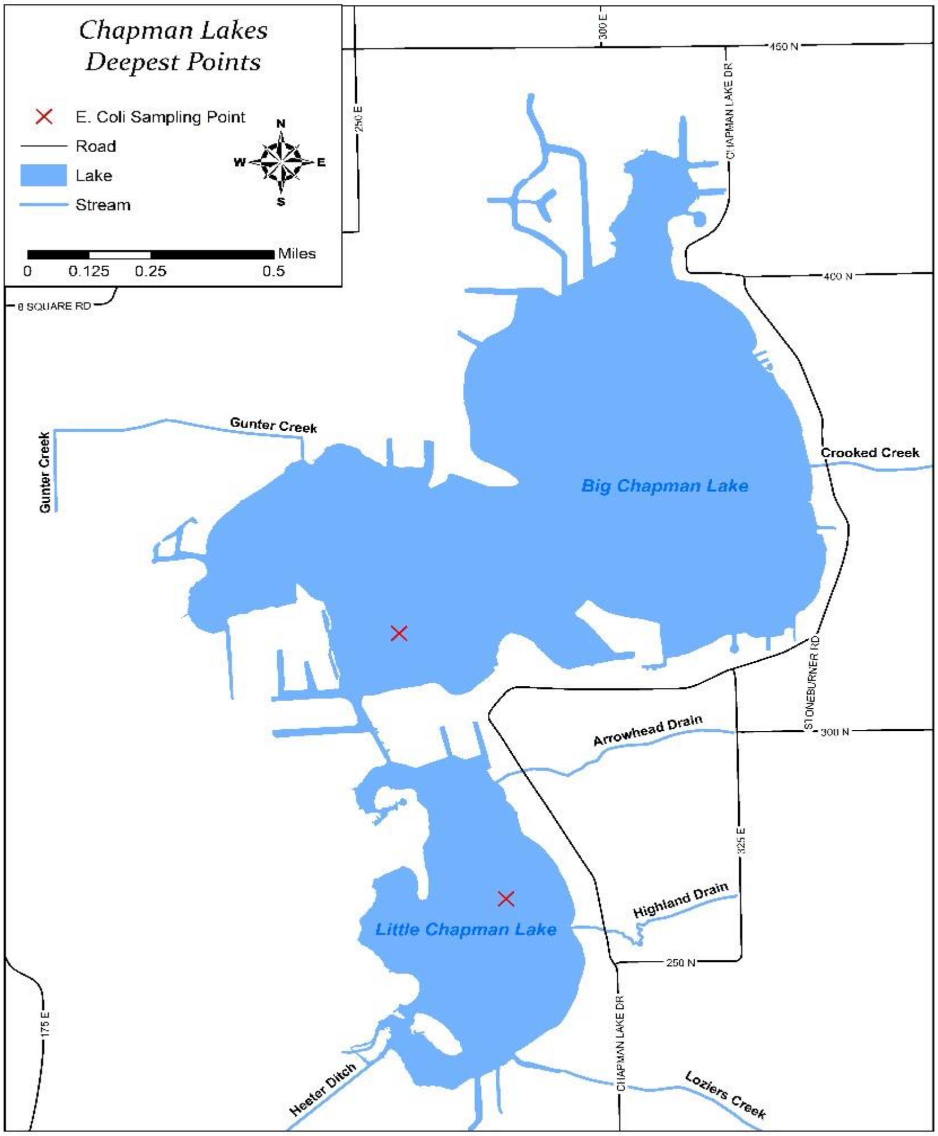

Figure 2: Map of Chapman lakes chain and streams. Deep points for lake sampling are marked with a red "X".

Table 1: Lake water residence time in days as reported in previous diagnostic studies (Richardson and Jones 2000; Giolitto and Jones 2001).

Lake	Residence time (days)
Banning	90
Big Barbee	52
Irish	19
Kuhn	135
Little Barbee	8
Sawmill	3
Sechrist	1571
Big Chapman	756
Little Chapman	128

Table 2: Lake littoral zone areas for lakes and chains and aquatic plant species diversity in the growing seasons from previous diagnostic studies (Ewolt 2010; Scribalo and Alix 2013).

	Littoral	Littoral	Number of species			
	Zone	Zone	Native		Invasive	
Lake	(acres)	(%)	Spring	Summer	Spring	Summer
Banning	13	76	6	7	2	1
Big Barbee	94	31	12	10	2	2
Irish	102	56	11	12	2	1
Kuhn	87	64	14	18	1	1
Little Barbee	28	38	4	4	2	1
Sawmill	19	53	7	5	2	2
Sechrist	43	41	10	15	2	2
Big Chapman	260	52	13	11	3	2
Little Chapman	42	30	6	8	2	1
Barbee Chain	386	45				
Chapman Chain	302	47				

We utilized Hoosier Riverwatch methodology for our stream habitat (CQHEI) and macroinvertebrate assessments (IDEM 2019). The bank erosion component of the CQHEI was also reported individually in this study. A stream bank classified as "raw" indicates banks without plant cover or collapsing banks, "stable" means hard or well-vegetated banks, and combination indicates a mix of both types in the survey section. A pollution tolerance index rating (PTIR) was calculated for each stream as outlined in the Riverwatch manual.

Lakes

We conducted in-lake sampling for physical and chemical parameters monthly during the height of the residential/recreational season, June-August 2013 and 2020, for the seven lakes of the Barbee lake chain and for the two lakes of the Chapman lake chain. We sampled at the deepest point of each lake (**Table 1; Figures 1, 2**). Water clarity was determined by Secchi disk depth (ft) from the shady side of the boat. We profiled water temperature (°C), dissolved oxygen (DO; mg/L), percent saturation of dissolved oxygen (DO % sat.), pH, and conductivity (mS/cm) every meter from the surface (0 m) to 1 m above the lake bottom using a multiprobe sonde (Hydrolab Quanta in 2013; YSI ProDSS in 2020).

We used a vertical Van Dorn water sampler to retrieve water from 1 m below the surface and 1 m above the lake bottom for nutrient analysis. These meter markings were used to represent the epilimnion (top water layer; sampled at 1 m) and hypolimnion (bottom water layer; 1 m above lake bottom) for all lake quality and nutrient/sediment sampling. We describe water sample handling and lab analysis later in this section.

To sample *E. coli* prevalence in the lakes, a total of 59 nearshore sites were sampled on July 2, 2013 and June 30, 2020 (**Figures 3, 4**). Sites were chosen to capture shoreline diversity, including shorelines on different sides of each lake, different vegetation conditions, different densities and types of homes, and more coverage on larger lakes. Sampling dates were chosen for proximity to the Independence Day holiday to capture a season of high lake home occupation, though occupancy rates were not measured in the present study. *E. coli* samples were collected from approximately 1 in under the surface of the water. A golf ball retriever was used to hold the sample bottles while retrieving the sample. Samples were transported to the Kosciusko County Health Department for analysis as described in the stream section.

Lake shoreline composition and stability was evaluated by visual survey from a boat. Each lake shoreline was divided into sections that could be visually inspected from a different vantage point on the lake and for which the length of each section was known. Each shoreline section was evaluated eroding (susceptible to wave action, exposed sand, soil, etc.) versus protected (stable seawall, plant coverage, stable glacial stone, etc.) by estimated percentage. Percentage composition was estimated the same way but into five categories: seawall, glacial stone, beach (sand), grass, and natural (other plants or wetlands). The composition and eroded/protected percentages were weighed based on the length of each section observed, then the percentages were summed for each shoreline type for each lake, resulting in a total percent composition and percent eroding/protected shoreline for each lake.

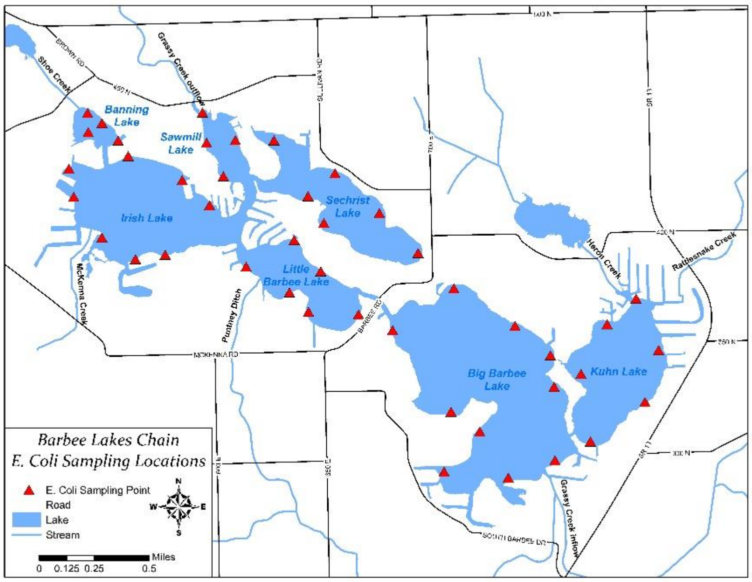

Figure 3: Nearshore *E. coli* sampling points around the Barbee chain.

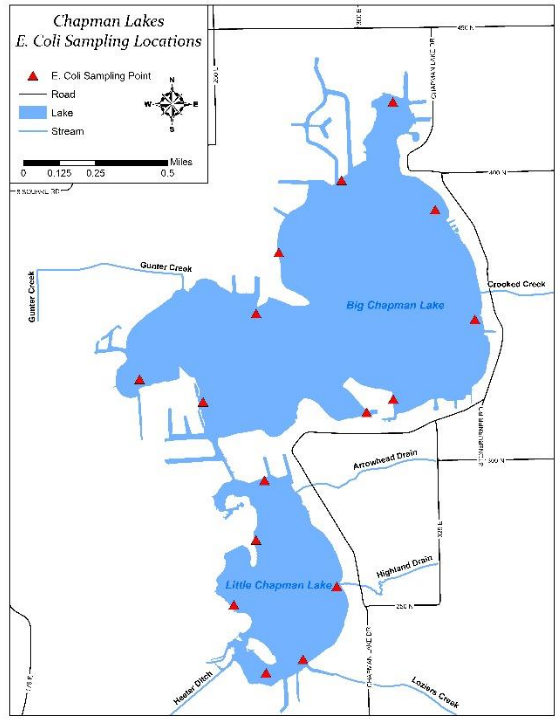

Figure 4: Nearshore *E. coli* sampling points around the Chapman chain.

Lab Analysis

Lake and stream water samples were collected and stored in 500 mL plastic bottles (first rinsed three times with sample water) and placed in a dark cooler on ice until transported back to the Lilly Center. The samples stayed refrigerated and in the dark while at our facility, and they were transported in coolers on ice to the lab the following week. In 2012-13, all nutrient/sediment analysis was performed by Heidelberg University's National Center for Water Quality Research. In 2019-20, stream samples from September 2019 through March 11, 2020 were analyzed by Heidelberg University, and stream and lake samples from June 2020 through the end of the project (August 2020) were analyzed by Ecosystems Connections Institute, LLC. All nutrient/sediment samples were analyzed for the following parameters: ammonia (NH_3), nitrite (NO_2), nitrate (NO_3), soluble reactive phosphorus (SRP), total phosphorus (TP), total Kjeldahl nitrogen (TKN), suspended sediments (SS), and total nitrogen (TN; calculated as the sum of NO_2, NO_3, and TKN results).

Data Analysis

Field data for streams and lakes were written on field log sheets and recorded electronically throughout the project to avoid any loss of data. Data was checked twice for accuracy during and after transcription from field sheets to Excel spreadsheets. All data storage and analysis was performed in Microsoft Excel.

To calculate stream loads, we first calculated daily mean flows for each of our streams. To fill in gaps between biweekly sampling events, streams flows were correlated to USGS gages at the Elkhart River (site # 4100500) for the Barbee chain and Judy Creek (site # 4101370) for the Chapman chain. These gages both offered the best R^2 value for that chain compared to other local USGS sites. It was also beneficial to the correlation strength to use two different gages between the chains as opposed to using the same site for both chains. (The goal for calculating daily mean flows is not identical treatment between each chain, but the best correlation for each stream possible.) Gage measurements were lined up for each of our sampling days to find a predictive trendline equation that fit the data most accurately. We took this equation and used it to calculate daily mean discharge for each date for each of our stream sampling sites.

We then aligned our nutrient results with the dates they were taken and used numeric integration to fill in the days where no water samples were taken one week before and after each sampling date. In the report published on the results of the pre-study, only that year of stream samples were available to make correlations to USGS gages. In this report, correlations were reestablished and loads reanalyzed for 2012-2013 with the addition of 2019-2020 flow measurements to the trendline for a more accurate correlation and equation.

E. coli results that were greater than the detection limit for the method, 2419.2 cfu/100mL, were treated as 2419.2 cfu/100mL for the purposes of calculating averages and geometric means, though the real *E. coli* population was likely higher.

Comparative Data

Secchi disk transparency and lake epilimnion TP concentration data from Richardson and Jones (2000) and Giolitto and Jones (2001) were used for comparison. These data points are average results from sampling events by Indiana University's Clean Lakes Program (CLP) in August of 1990, 1992, 1994, 1998, as well as the result calculated in the two diagnostic studies cited.

We also compared TP, TN, and Secchi disk transparency results with lake water quality recommendations published by the EPA in December 2000. This document focuses on lakes in Ecoregion VII, breaking them apart into "level III" sub-regions for greater local context. Northern Indiana is a part of level III ecoregion 56, which also includes the southern half of Michigan's lower peninsula. A subset of lakes in each sub-region were sampled and results reported to the EPA to develop upper and lower bounds on typical water quality for that area. The 25th percentile (P25), or the top fourth of results for water quality, can be used as a threshold or goal for high water quality for our area.

Results

Annual weather patterns likely influenced lake, stream, and groundwater conditions between the two portions of the study. The pre-sewer portion of the study included 2012 as a drought year with some lingering dry conditions extending into 2013 (Van Metre et al. 2016). In comparison, Kosciusko County experienced heavier rain and higher lake levels in early 2020 with less rain and lower lake levels in the second half of the summer. While these influences were outside the control of the present study, lake water quality is best understood with these atmospheric conditions considered as we do in the Discussion section below.

Streams

Inflowing streams in both lake chains experienced water quality parameters in expected ranges for both years (**Table 3**). Dissolved oxygen concentrations and pH measurements were slightly lower in 2013 in both chains while conductivity and water temperature were higher in 2013. Both lake chains experienced mostly parallel differences in these parameters between our study years.

Table 3: Stream water quality parameters. Average of all sampling events Sept. – Aug. for both studies.

Lake Chain	Stream	Temperature (°C) 2013	Temperature (°C) 2020	DO (mg/L) 2013	DO (mg/L) 2020	DO (% sat.) 2013	DO (% sat.) 2020	pH 2013	pH 2020	Conductivity (mS/cm) 2013	Conductivity (mS/cm) 2020
Barbee	Grassy (Inflow)	13.8	13.4	9.4	7.1	84	62	7.71	8.00	0.564	0.493
	Heron	16.8	14.0	6.3	7.8	59	67	7.70	7.93	0.529	0.498
	McKenna	17.8	10.9	8.7	11.0	93	96	8.28	8.25	0.644	0.554
	Putney	15.4	12.1	11.3	11.1	113	100	8.27	8.27	0.630	0.597
	Rattlesnake	17.5	12.2	6.8	10.2	68	60	7.78	7.86	0.622	0.569
	Shoe	16.7	11.3	3.3	4.4	27	22	6.92	7.03	0.311	0.236
	Grassy (Outflow)	14.6	15.3	11.3	10.4	111	99	8.17	8.30	0.478	0.432
Chapman	Arrowhead	13.4	8.9	9.2	10.5	88	89	7.90	7.99	0.685	0.605
	Crooked	13.1	12.9	11.0	10.1	101	90	7.98	7.99	0.674	0.583
	Gunter	12.5	12.7	10.9	10.5	100	95	8.08	8.21	0.684	0.590
	Highland	19.0	14.1	0.6	5.6	6	37	6.98	7.62	0.680	0.549
	Lozier's	18.3	15.3	6.6	10.4	70	95	7.78	8.13	0.674	0.595
	Heeter (Outflow)	18.7	15.0	8.1	9.8	84	96	7.80	7.92	0.537	0.566
Barbee	Inflow Average	16.3	12.7	7.6	8.8	74	72	7.78	7.95	0.550	0.491
Chapman	Inflow Average	15.3	13.1	7.7	9.5	73	84	7.74	7.98	0.679	0.584

The inflowing streams are particularly important for their nutrient and sediment contributions to the lakes. Stream water in Barbee contained a lower concentration of SS, SRP, and TP on average in 2020 (**Table 4**). Rattlesnake, Shoe, and Grassy saw the greatest reduction. The Chapman streams had slightly less SS on average, but approximately the same SRP and TP. Varying patterns arose in the nitrogen forms found in the inflowing streams (**Table 5**). The greatest change was found in NO_3 concentrations in both chains, which decreased by half or more on average, particularly in streams with the lowest flow. Less NO_3 paired with less TKN in streams on average results in a trend of about half the concentration of TN inflowing to both chains. For outflowing streams, nitrogenous compounds increased in concentration, while phosphorus compounds decreased or stayed the same in the Barbee outflow, and decreased slightly or increased in the Chapman outflow.

While concentrations are useful for considering how "thick" the water is with nutrients, it does not take into consideration how much water is flowing. Annual total flow increased in all streams in both chains, though the increase was not equivalent (**Table 6**). McKenna, Gunter, Lozier, and Heeter experienced the largest proportional flow increases. The load of sediments and nutrients did not behave similarly, however. Annual nutrient and sediment loads vary substantially by stream and nutrient. SS, SRP, and TP loads generally decreased in Barbee streams, with McKenna and Rattlesnake standing out with the largest proportional increases of loads more similar to their higher annual flow (**Table 7**). Lozier's in the Chapman chain behaved similarly, but Gunter's load was almost the same in spite a large flow increase. Crooked's phosphorus loads most notably compared to its similar annual flow. In general, many more kg of nitrogen flow into these chains than phosphorus, and Heron, McKenna, and Lozier's experienced some of the larger proportional increases in nitrogen loads in 2020 (**Tables 7, 8**).

Table 4: Sediment and phosphorus-compound concentrations (SS in mg/L; SRP and TP in mg P/L) for each stream. Results are averages of each sampling event Sept. – Aug. for both study years.

Lake Chain	Stream	SS 2013	SS 2020	SRP 2013	SRP 2020	TP 2013	TP 2020
Barbee	Grassy (Inflow)	16.7	4.6	0.013	0.027	0.091	0.092
	Heron	2.5	1.7	0.003	0.001	0.023	0.019
	McKenna	5.3	5.4	0.009	0.011	0.031	0.032
	Putney	12.9	13.7	0.050	0.031	0.184	0.099
	Rattlesnake	20.6	2.5	0.012	0.007	0.067	0.029
	Shoe	7.9	13.4	0.103	0.026	0.267	0.144
	Grassy (Outflow)	4.0	3.7	0.020	0.001	0.065	0.028
Chapman	Arrowhead	18.6	14.6	0.035	0.043	0.101	0.135
	Crooked	16.2	18.4	0.033	0.087	0.094	0.194
	Gunter	7.2	3.9	0.035	0.006	0.115	0.040
	Highland	6.6	12.5	0.036	0.070	0.063	0.138
	Lozier's	41.2	8.3	0.021	0.025	0.118	0.057
	Heeter (Outflow)	6.0	13.5	0.004	0.002	0.044	0.056
Barbee	Inflow Average	11.0	6.4	0.032	0.015	0.110	0.063
Chapman	Inflow Average	18.0	11.9	0.032	0.039	0.098	0.103

Table 5: Average nitrogenous-compound concentrations (mg N/L) for each stream. Results are averages of each sampling event Sept. – Aug. for both study years.

Lake Chain	Stream	NH_3 2013	NH_3 2020	NO_2 2013	NO_2 2020	NO_3 2013	NO_3 2020	TKN 2013	TKN 2020	TN 2013	TN 2020
Barbee	Grassy (Inflow)	0.094	0.234	0.044	0.048	1.851	1.062	1.163	1.126	3.058	2.236
	Heron	0.028	0.107	0.001	0.013	0.018	0.096	0.771	0.673	0.790	0.782
	McKenna	0.022	0.067	0.014	0.019	7.993	3.054	0.358	0.355	8.364	3.428
	Putney	0.037	0.077	0.024	0.020	4.642	2.499	0.754	0.599	5.421	3.117
	Rattlesnake	0.060	0.075	0.010	0.018	0.672	0.342	1.401	0.659	2.084	1.019
	Shoe	0.173	0.413	0.003	0.011	0.197	0.057	1.752	1.487	1.952	1.555
	Grassy (Outflow)	0.067	0.119	0.017	0.021	0.475	0.331	0.845	0.797	1.337	1.148
Chapman	Arrowhead	0.048	0.048	0.017	0.007	4.530	1.836	0.623	0.922	5.170	2.764
	Crooked	0.061	0.095	0.021	0.022	3.863	1.285	0.781	0.608	4.665	1.915
	Gunter	0.107	0.076	0.001	0.008	0.010	0.113	3.157	1.022	3.169	1.142
	Highland	0.035	0.060	0.003	0.015	2.588	0.665	0.332	0.462	2.923	1.142
	Lozier's	0.037	0.089	0.023	0.023	6.230	3.021	0.574	0.372	6.827	3.417
	Heeter (Outflow)	0.111	0.217	0.011	0.017	0.455	0.473	0.971	0.907	1.438	1.397
Barbee	Inflow Average	0.069	0.156	0.016	0.021	2.562	1.063	1.033	0.814	3.612	2.023
Chapman	Inflow Average	0.057	0.098	0.013	0.015	3.444	1.232	1.093	0.715	4.551	2.076

Table 6: Annual total flow (millions L/yr) and sediment/phosphorus loads (kg/yr) for both chains' streams.

Lake Chain	Stream	Flow 2013	Flow 2020	SS 2013	SS 2020	SRP 2013	SRP 2020	TP 2013	TP 2020
Barbee	Grassy (Inflow)	33,629	52,773	754,306	359,200	536	1,127	3,432	4,888
	Heron	486	942	1,622	1,957	2	1	12	17
	McKenna	32	150	129	527	0	1	1	4
	Putney	2,396	4,743	43,987	46,205	166	110	435	408
	Rattlesnake	297	586	3,021	6,077	3	19	17	50
	Shoe	50	106	398	1,901	6	2	13	12
	Grassy (Outflow)	24,750	39,241	132,105	134,866	470	23	1,827	1,107
Chapman	Arrowhead	54	70	520	926	16	2	5	8
	Crooked	827	1,551	17,674	18,945	35	137	96	321
	Gunter	1	12	12	13	0	0	0	0
	Highland	14	21	95	109	1	1	1	2
	Lozier's	122	746	3,003	5,087	1	10	11	39
	Heeter (Outflow)	3,546	10,188	30,302	114,721	26	25	241	551

Table 7: Annual total nitrogen-compound loads (kg/yr) for both chains' streams.

Lake Chain	Stream	NH_3 2013	NH_3 2020	NO_3 2013	NO_3 2020	TN 2013	TN 2020
Barbee	Grassy (Inflow)	3,268	10,254	98,547	74,314	144,784	139,781
	Heron	12	137	12	76	381	680
	McKenna	1	19	247	435	258	494
	Putney	78	655	11,548	13,598	13,569	16,414
	Rattlesnake	20	25	238	1,500	665	1,825
	Shoe	8	40	12	4	100	140
	Grassy (Outflow)	1,517	5,885	21,317	19,650	44,497	51,758
Chapman	Arrowhead	8	3	926	126	273	191
	Crooked	54	166	3,588	2,248	4,341	3,178
	Gunter	0	1	0	1	4	11
	Highland	0	2	37	17	42	24
	Lozier's	2	82	160	2,417	930	2,760
	Heeter (Outflow)	353	2,724	2,846	5,069	6,434	14,125

Table 8: Summary of annual total flow (millions L/yr) and sediment/nutrient loads (kg/yr) for both chains' streams, by inflowing and outflowing streams.

Lake Chain		Flow 2013	Flow 2020	SS 2013	SS 2020	SRP 2013	SRP 2020	TP 2013	TP 2020	NH_3 2013	NH_3 2020	NO_3 2013	NO_3 2020	TN 2013	TN 2020
Barbee	Inflows	36,890	59,299	803,463	415,867	712	1,259	3,909	5,379	3,386	11,130	110,603	89,928	159,757	159,333
	Outflow	24,750	39,241	132,105	134,866	470	23	1,827	1,107	1,517	5,885	21,317	19,650	44,497	51,758
Chapman	Inflows	1,018	2,400	21,305	25,080	52	149	113	371	65	254	4,712	4,809	5,591	6,165
	Outflow	3,546	10,188	30,302	114,721	26	25	241	551	353	2,724	2,846	5,069	6,434	14,125

Stream *E. coli* changes were mixed over 2013 and 2020 (**Table 9**). Grassy inflow, Rattlesnake, and Grassy outflow had lower *E. coli* counts in 2020 verses 2013. Many of Chapman's streams were not flowing during the summer during *E. coli* sampling, and so could not be compared here. Barbee's outflow, Grassy Creek, was lower in *E. coli* in 2020, while Heeter is higher in 2020 compared to 2013. Overall, stream *E. coli* levels in these streams are high; 60% of all pre-installation study samples were above the EPA human health threshold of 235 cfu/100 mL in a single sample (EPA 2012; IAC 2021), while 51% of samples fell above this threshold in the post-installation study. By chain, Barbee streams had *E. coli* levels >235 cfu/100 mL in 53% of samples in 2013 (n = 68) and 39% in 2020 (n = 49). Chapman streams went over the threshold in 70% of samples in 2013 (n = 56) and 74% in 2020 (n = 27). As described in the methods, the number of samples (n) varied due to days where some streams were not flowing, and therefore their *E. coli* levels were not assessed.

Our assessments of stream habitat shows little change between 2013 and 2020 except in the bottom substrate category (**Table 10**). Only minor contributing streams Gunter and Highland changed substantially in bank erosion classification (**Table 11**). Stream macroinvertebrate surveys reveal slight improvement in about half of the streams and overall by chain despite slightly lower habitat quality scores (**Table 12**). Two streams were not flowing at all in the last two months of the sampling season, so we could conduct no macroinvertebrate survey. In order to compare chain averages accurately, McKenna and Shoe's PTIR ratings were omitted from chain averages in 2013 as well. In 2013, our survey counted and identified 636 and 513 individual invertebrates in the Barbee chain and Chapman chain, respectively. In 2020, we found 729 and 349 individuals in the Barbee chain and Chapman chain, respectively.

Table 9: Geometric means of five equally spaced *E. coli* samples for each stream. Chain inflow averages are arithmetic means of the geometric means listed here. Asterisks denote geometric means calculated from fewer than five samples due to a lack of stream flow in one or more sampling events. A dash denotes no *E. coli* samples could be taken due to a lack of stream flow over the entire five-week period.

		E. coli (cfu/100mL)			
Lake		1st half of summer		2nd half of summer	
Chain	Stream	2013	2020	2013	2020
Barbee	Grassy (Inflow)	231	92	172	62
	Heron	227	223	155	*354
	McKenna	1051	1311	966	-
	Putney	408	529	249	*468
	Rattlesnake	251	81	*241	54
	Shoe	*1017	377	*806	-
	Grassy (Outflow)	11	4	30	6
Chapman	Arrowhead	*1437	-	*1578	*193
	Crooked	579	1053	551	*295
	Gunter	*231	-	*84	-
	Highland	1678	-	881	-
	Lozier's	841	567	719	*1676
	Heeter (Outflow)	86	217	74	284
Barbee	Inflow Average	531	436	432	234
Chapman	Inflow Average	953	810	899	721

Table 10: Stream habitat scores from Citizen Qualitative Habitat Evaluation Index (CQHEI) surveys. A higher score represents higher habitat quality.

Lake Chain	Stream	Total 2013	Total 2020	Bottom Substrate 2013	Bottom Substrate 2020	Fish Cover 2013	Fish Cover 2020	Stream Shape 2013	Stream Shape 2020	Riparian Area 2013	Riparian Area 2020	Depth & Velocity 2013	Depth & Velocity 2020	Riffles/ Runs 2013	Riffles/ Runs 2020
Barbee	Grassy (Inflow)	73	59	19	10	16	10	15	15	15	17	8	7	0	0
	Heron	70	48	16	0	10	8	20	15	19	20	1	1	4	4
	McKenna	80	58	18	10	12	10	17	17	19	20	4	1	11	0
	Putney	43	58	8	6	10	12	11	14	6	15	8	3	0	8
	Rattlesnake	56	49	11	0	10	12	14	17	16	15	5	1	0	4
	Shoe	48	42	11	0	8	8	12	15	16	18	1	1	0	0
	Grassy (Outflow)	63	52	16	16	14	10	12	6	12	11	9	9	0	0
Chapman	Arrowhead	88	33	20	10	16	2	17	6	17	9	5	6	13	0
	Crooked	82	58	19	10	12	10	17	14	13	15	9	1	12	8
	Gunter	32	45	0	0	2	10	12	15	14	20	4	0	0	0
	Highland	65	30	8	14	12	6	17	3	10	7	5	0	13	0
	Lozier's	78	55	21	0	12	12	17	20	15	18	5	1	8	4
	Heeter (Outflow)	47	47	6	0	12	12	15	15	6	13	8	7	0	0
Barbee	Average	62	52	14	6	11	10	14	14	15	16	5	3	2	2
Chapman	Average	65	44	12	6	11	9	16	12	12	13	6	3	8	2

Table 11: Stream bank classification from Citizen Qualitative Habitat Evaluation Index (CQHEI) surveys. Raw means exposed or erodion banks, stable indicates hard or vegetated banks, and combination means some of both type was present in our survey area.

Lake Chain	Stream Name	Lake Connection	Bank Erosion Classification 2013	Bank Erosion Classification 2020
Barbee	Grassy (Inflow)	Inflow to Big Barbee	Raw	Combination
	Heron	Inflow to Kuhn	Stable	Stable
	McKenna	Inflow to Irish	Stable/Combination	Stable
	Putney	Inflow to Little Barbee	Combination	Stable
	Rattlesnake	Inflow to Kuhn	Combination	Combination
	Shoe	Inflow to Banning	Combination	Combination
	Grassy (Outflow)	Outflow from Sawmill	Combination	Combination
Chapman	Arrowhead	Inflow to Little Chapman	Combination	Combination
	Crooked	Inflow to Big Chapman	Combination	Combination
	Gunter	Inflow to Big Chapman	Raw	Stable
	Highland	Inflow to Little Chapman	Raw	Stable
	Lozier's	Inflow to Little Chapman	Raw	Combination
	Heeter (Outflow)	Outflow from Little Chapman	Raw	Raw

Table 12: Pollution tolerance index ratings (PTIR) for each stream and chain. Numbers under the tolerance categories represent number of taxa observed, as used by the Hoosier Riverwatch survey to calculate PTIR scores. McKenna and Shoe lack 2020 ratings due to a lack of streamflow at the end of our sampling season. To accurately compare averages, McKenna and Shoe were omitted from 2013 Barbee average. Although no classification difference, there was slight numerical improvement in both chains on average.

Lake Chain	Stream	PTIR Score		PTIR Category		Intolerant		Moderately intolerant		Fairly tolerant		Very tolerant	
		2013	2020	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
Barbee	Grassy (Inflow)	19	32	Good	Excellent	2	4	3	4	1	1	0	2
	Heron	19	12	Good	Fair	1	0	4	3	1	1	1	1
	*McKenna	8		Bad		1		1		0		1	
	Putney	16	29	Fair	Excellent	2	4	2	3	0	1	2	2
	Rattlesnake	14	17	Fair	Good	1	3	2	1	1	0	2	2
	*Shoe	13		Fair		0		3		1		2	
	Grassy (Outflow)	27	19	Excellent	Good	3	2	3	2	2	2	2	1
Chapman	Arrowhead	17	15	Good	Fair	1	1	3	2	1	1	2	3
	Crooked	9	17	Bad	Good	0	2	1	2	2	1	2	1
	Gunter	12	18	Fair	Good	1	2	2	2	0	1	2	2
	Highland	16	9	Fair	Bad	0	1	4	0	1	1	2	3
	Lozier's	7	2	Bad	Bad	0	0	1	0	1	1	2	0
	Heeter (Outflow)	11	34	Fair	Excellent	1	4	1	4	1	1	2	4
Barbee	Averages	*19	22	Good	Good	2	3	3	3	1	1	1	2
Chapman	Averages	12	16	Fair	Fair	1	2	2	2	1	1	2	2

Lakes

Lake shorelines for both chains were slightly more protected from erosion in 2020 compared to 2013 (**Table 13**) with the most notable increases occurring on Sechrist and Little Barbee in the Barbee chain. Banning and Kuhn shoreline stabilities decreased from 2013 to 2020. More homeowners have adopted seawall and glacial stone for their shorelines since 2013 (**Table 14**), in particular favor over grass shorelines, which stayed the same or decreased on all lakes.

Table 13: Lake shoreline stability assessment by percentage of shoreline length.

Lake	Shoreline Length (m)	Shoreline Erosion (%) Eroding		Protected	
		2013	2020	2013	2020
Banning	1,621	5	12	95	88
Big Barbee	10,587	4	4	96	96
Irish	12,087	7	3	93	97
Kuhn	8,165	4	10	96	90
Little Barbee	5,971	34	18	66	82
Sechrist	4,770	19	6	81	94
Sawmill	2,354	30	30	70	70
Big Chapman	51,510	7	6	93	94
Little Chapman	23,791	3	0	97	100
Barbee Chain	45,555	12	8	88	92
Chapman Chain	75,301	6	4	94	96

Table 14: Shoreline composition classifications by percentage of shoreline length.

		Shoreline Classification (%)									
	Shoreline	Seawall		Stone		Beach		Grass		Natural	
Lake	Length (m)	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
Banning	1,621	10	0	2	0	0	4	16	8	72	88
Big Barbee	10,587	50	60	7	10	1	1	6	1	37	28
Irish	12,087	50	66	0	1	3	0	9	0	38	33
Kuhn	8,165	58	60	5	7	2	4	6	0	29	29
Little Barbee	5,971	42	54	7	9	1	1	41	17	9	19
Sechrist	4,770	45	45	17	35	3	0	32	4	4	16
Sawmill	2,354	40	40	5	5	5	5	45	45	5	5
Big Chapman	51,510	57	62	7	16	0	0	15	3	21	19
Little Chapman	23,791	40	35	10	5	0	0	10	0	40	60
Barbee Chain	45,555	48	56	5	9	2	1	17	5	28	28
Chapman Chain	75,301	52	53	8	13	0	0	13	2	27	32

Water clarity was higher in 2020 for all lakes on both chains (**Figure 5**). The largest difference occurred on Sechrist, followed by Kuhn, Banning, and Irish. Other lake characteristics in the epilimnion layer include water temperature, which was just slightly lower on both chains, as was dissolved oxygen (**Table 15**), though the percent saturation of dissolved oxygen was closer to 100% on the Barbee chain in 2020. The pH levels of all lakes stayed relatively consistent, and conductivity decreased slightly on all lakes. Hypolimnion results indicate no major differences between 2013 and 2020 (**Table 16**). Most notably, the average percent oxygen decrease in the Barbee chain is driven by large decreases in oxygen in Banning and Little Barbee's bottom waters. All other Barbee lakes increased in percent saturation between the two years. Only Kuhn Lake has a healthy amount of oxygen in the bottom water in the summertime in 2020; all other lakes suffered from hypoxia (oxygen less than 2.0 mg/L) both years.

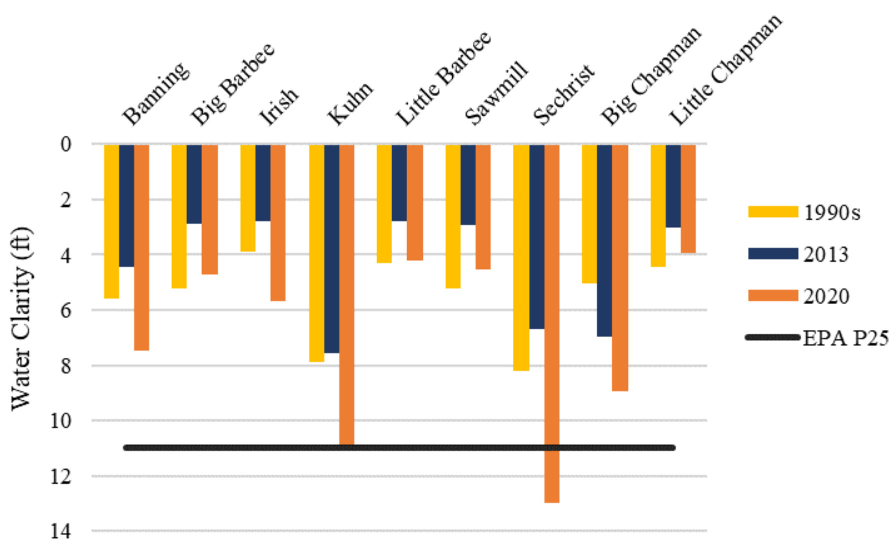

Figure 5: Secchi disk depth for each study year as compared to the EPA P25 for Northern IN ecoregion (11 ft) and August 1990s data reported in previous diagnostic studies (EPA 2000; Richardson and Jones 2000; Giolitto and Jones 2001). The EPA P25 represents the top 25% of lakes in northern IN and southern MI for water quality. The 1990's data is the average of 3-4 samples, each taken in August, between 1990 and 1999. 2013 generally had poorer water clarity than the 1990's and 2020 for these lakes, and only Sechrist and Kuhn lakes in 2020 hit or exceed the EPA P25 guidelines for water clarity.

Table 15: Lake epilimnion water quality parameters by year. Results are the average of three monthly samplings in the summer. Epilimnion samples are taken 1 m below the surface of the water at the lake's deepest point.

	Water Clarity (ft)		Temperature (°C)		Dissolved Oxygen (mg/L)		Dissolved Oxygen (% sat.)		pH		Conductivity (mS/cm)	
Lake	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
Banning	4.4	7.5	24.7	25.8	6.1	6.59	76	80	7.9	7.9	0.433	0.382
Big Barbee	2.9	4.7	24.2	25.4	9.6	7.81	117	95	8.5	8.7	0.463	0.437
Irish	2.8	5.7	25.0	25.8	10.7	8.12	134	100	8.7	8.4	0.418	0.408
Kuhn	7.6	10.9	24.7	25.8	8.2	8.36	102	103	8.4	8.4	0.451	0.412
Little Barbee	2.8	4.2	24.4	25.7	10.3	8.30	127	102	8.5	8.5	0.460	0.433
Sawmill	2.9	4.5	24.7	25.6	9.9	7.92	123	97	8.5	8.3	0.441	0.416
Sechrist	6.7	13.0	25.4	26.0	8.4	8.57	105	106	8.6	8.9	0.415	0.382
Big Chapman	7.0	8.9	26.4	26.3	8.2	8.70	105	108	8.4	8.6	0.437	0.403
Little Chapman	3.0	3.9	26.6	26.1	10.2	9.52	131	118	8.8	8.9	0.390	0.391
Barbee Chain	4.3	7.2	24.7	25.7	9.0	7.95	112	98	8.4	8.4	0.440	0.410
Chapman Chain	5.0	6.4	26.5	26.2	9.2	9.11	118	113	8.6	8.8	0.414	0.397

Table 16: Lake hypolimnion water quality parameters by year. Results are the average of three monthly readings in the summer. Sampled 1 m above the lake bottom at each lake's deepest point.

	Temperature (°C)		Dissolved Oxygen (mg/L)		Dissolved Oxygen (% sat.)		pH		Conductivity (mS/cm)	
Lake	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
Banning	20.2	18.6	1.33	0.61	15	6	7.52	7.04	0.425	0.424
Big Barbee	9.9	11.1	0.12	0.36	1	3	7.59	7.79	0.553	0.519
Irish	10.6	11.9	0.22	0.88	2	10	7.60	7.40	0.509	0.479
Kuhn	14.3	14.6	0.92	3.47	9	11	7.64	7.62	0.499	0.452
Little Barbee	16.1	13.0	1.16	0.35	12	3	7.62	7.42	0.501	0.547
Sawmill	12.3	11.0	0.21	0.49	2	4	7.47	7.29	0.549	0.519
Sechrist	7.9	8.2	0.22	0.39	2	3	7.58	7.39	0.466	0.425
Big Chapman	10.6	12.3	0.14	0.28	1	3	7.43	7.54	0.527	0.464
Little Chapman	13.0	11.5	0.26	0.36	3	4	7.36	7.38	0.491	0.510
Barbee Chain	13.1	12.6	0.60	0.94	6	6	7.57	7.42	0.500	0.481
Chapman Chain	11.8	11.9	0.20	0.32	2	3	7.40	7.46	0.509	0.487

Epilimnion layers of the Barbee lakes were lower in most sediment and nutrient water quality measures in 2020 compared to 2013 (**Tables 17 and 18**). The Chapman lakes chain showed a similar but less consistent general trend with improved water quality in lake epilimnion layers from 2013 to 2020 as well. Hypolimnion nutrient levels were consistently higher compared to epilimnion nutrient levels in both lake chains across both years (**Tables 19 and 20**).

Much variation was observed between lakes and years for TP and TN in the epilimnion (**Figures 7**, **8**). Nutrient levels were typically higher in the 1990s and 2013 for most lakes compared to 2020. Exceptions include TN increases from 2013 to 2020 for Banning and Sawmill, as well as TP increases in Banning and Little Barbee. The largest decreases were seen in Big Barbee, Irish and Little Barbee for TN and Big Barbee and Sawmill for TP.

Table 17: Lake epilimnion sediment/phosphorus concentrations in mg/L. Results are the average of three monthly samples in the summer.

	SS		SRP		TP	
Lake	2013	2020	2013	2020	2013	2020
Banning	7.79	0.17	0.005	0.000	0.045	0.122
Big Barbee	7.61	3.67	0.003	0.000	0.047	0.018
Irish	5.75	2.50	0.003	0.002	0.048	0.026
Kuhn	5.26	2.67	0.004	0.002	0.039	0.009
Little Barbee	9.50	2.67	0.003	0.000	0.058	0.094
Sawmill	5.18	3.33	0.048	0.000	0.102	0.031
Sechrist	1.87	0.83	0.004	0.000	0.028	0.008
Big Chapman	1.18	2.50	0.004	0.000	0.030	0.021
Little Chapman	8.68	5.67	0.003	0.007	0.048	0.021
Barbee Chain	6.14	2.26	0.010	0.001	0.052	0.044
Chapman Chain	4.93	4.08	0.003	0.004	0.039	0.021

Table 18: Lake epilimnion nitrogen concentrations in mg N/L. Results are the average of three monthly samples in the summer.

	NH_3		NO_2		NO_3		TKN		TN	
Lake	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
Banning	0.042	0.103	0.004	0.003	0.017	0.000	0.986	1.044	1.006	1.047
Big Barbee	0.066	0.108	0.067	0.021	1.363	0.178	1.257	0.806	2.687	1.005
Irish	0.060	0.114	0.037	0.012	0.467	0.072	1.189	0.627	1.693	0.711
Kuhn	0.080	0.108	0.007	0.003	0.097	0.000	0.777	0.508	0.881	0.511
Little Barbee	0.076	0.115	0.057	0.019	1.403	0.201	1.345	1.522	2.805	1.742
Sawmill	0.523	0.127	0.021	0.015	0.251	0.100	1.603	0.866	0.203	0.982
Sechrist	0.022	0.088	0.007	0.006	0.110	0.000	0.743	0.754	0.860	0.760
Big Chapman	0.049	0.205	0.001	0.002	0.024	0.037	0.663	0.483	0.687	0.522
Little Chapman	0.004	0.142	0.001	0.004	0.001	0.007	0.961	0.707	0.963	0.718
Barbee Chain	0.124	0.109	0.028	0.011	0.530	0.079	1.129	0.875	1.448	0.965
Chapman Chain	0.027	0.173	0.001	0.003	0.012	0.022	0.812	0.595	0.825	0.6199

Table 19: Lake hypolimnion sediment/phosphorus concentrations. Results are the average of three monthly samples in the summer.

	SS		SRP		TP	
Lake	2013	2020	2013	2020	2013	2020
Banning	10.77	3.17	0.004	0.000	0.074	0.016
Big Barbee	4.50	4.67	0.256	0.285	0.368	0.351
Irish	3.65	0.83	0.062	0.103	0.139	0.165
Kuhn	3.99	2.00	0.002	0.015	0.025	0.208
Little Barbee	5.06	8.00	0.112	0.183	0.239	0.431
Sawmill	5.01	3.17	0.093	0.070	0.183	0.117
Sechrist	8.41	1.67	0.101	0.081	0.178	0.047
Big Chapman	5.06	4.33	0.004	0.000	0.060	0.038
Little Chapman	14.99	8.50	0.156	0.088	0.322	0.409
Barbee Chain	5.91	3.36	0.090	0.105	0.172	0.191
Chapman Chain	10.03	6.42	0.080	0.044	0.191	0.223

Table 20: Lake hypolimnion nitrogen concentrations in mg N/L. Results are the average of three monthly samples in the summer.

	NH_3		NO_2		NO_3		TKN		TN	
Lake	2013	2020	2013	2020	2013	2020	2013	2020	2013	2020
Banning	0.138	0.201	0.004	0.003	0.027	0.000	1.376	1.080	1.407	1.083
Big Barbee	1.108	0.532	0.060	0.041	0.747	0.107	2.503	1.687	3.309	1.836
Irish	1.047	0.170	0.017	0.006	0.207	0.092	1.971	1.560	2.195	1.658
Kuhn	0.270	0.122	0.007	0.004	0.047	0.000	0.845	1.562	0.898	1.566
Little Barbee	0.983	0.333	0.033	0.029	0.367	0.040	1.924	3.042	2.324	3.111
Sawmill	1.488	0.457	0.007	0.023	0.033	0.034	2.839	2.009	2.880	2.066
Sechrist	0.998	0.532	0.001	0.014	0.001	0.020	2.131	1.313	2.133	1.346
Big Chapman	1.005	0.457	0.001	0.003	0.007	0.000	2.305	1.089	2.313	1.092
Little Chapman	1.971	0.208	0.001	0.004	0.007	0.004	4.407	2.827	4.415	2.835
Barbee Chain	0.862	0.335	0.018	0.017	0.204	0.042	1.941	1.750	2.164	1.809
Chapman Chain	1.488	0.332	0.001	0.004	0.007	0.002	3.356	1.958	3.364	1.964

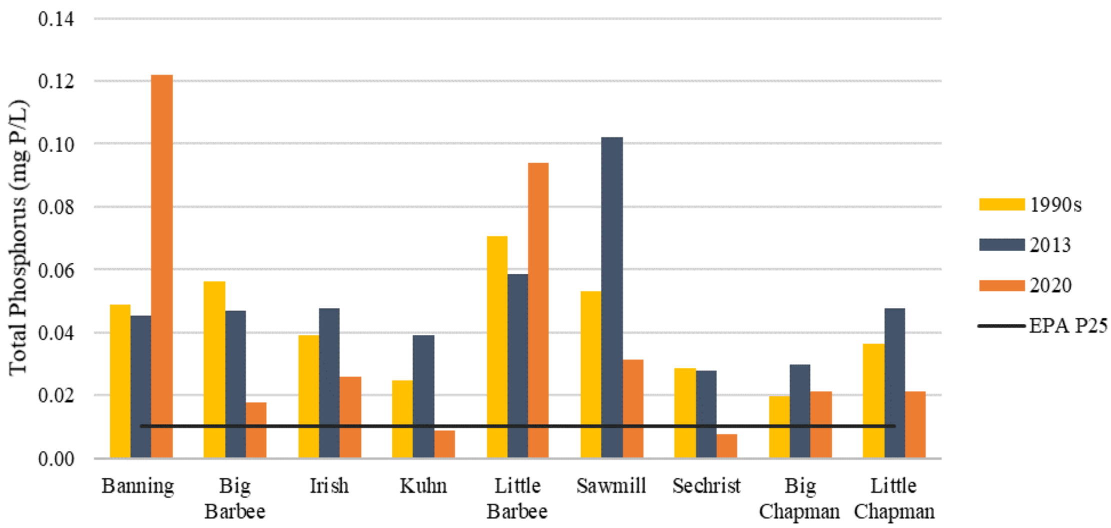

Figure 7: Lake epilimnion total phosphorus concentrations by year compared to the EPA P25 for Northern IN ecoregion (0.01 mg P/L) and August 1990s data reported in previous diagnostic studies (EPA 2000; Richardson and Jones 2000; Giolitto and Jones 2001). 2013 and 2020 results are the average of three monthly readings in the summer. The EPA P25 represents the top 25% of lakes in northern IN and southern MI for water quality. The 1990's data is the average of 3-4 samples, each taken in August, between 1990 and 1999. Only Kuhn and Sechrist lakes in 2020 fall below the EPA P25 guideline for total phosphorus content.

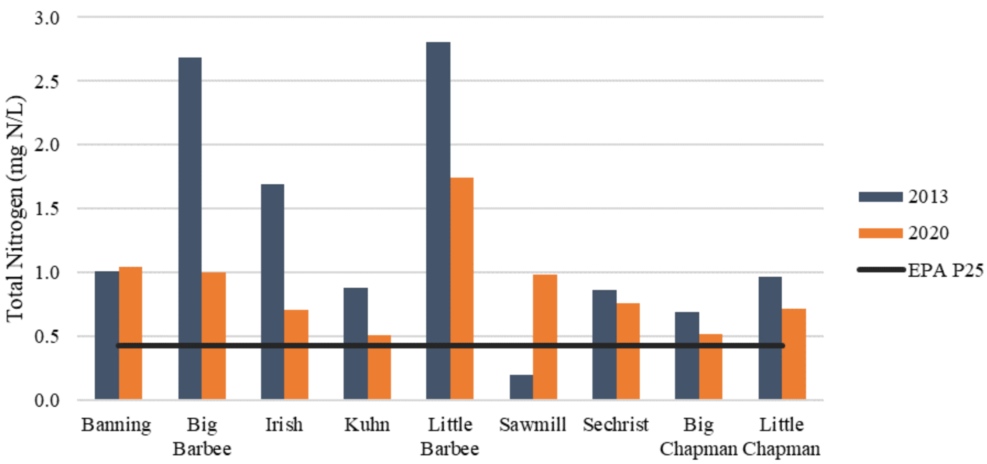

Figure 8: Lake epilimnion total nitrogen concentrations by year compared to the EPA P25 for Northern IN ecoregion (0.43 mg N/L; EPA 2000). Results are the average of three monthly readings in the summer. The EPA P25 represents the top 25% of lakes in northern IN and southern MI for water quality. All lakes except Sawmill and Banning had lower epilimnion TN in 2020.

In our lake *E. coli* survey, near shore *E. coli* levels were consistently below human health threshold of 235 cfu/100mL for all lakes in both 2013 and 2020 (**Table 21; Figure 9**). Banning, Little Barbee, and Little Chapman were the only lakes that showed a clear decrease from 2013 to 2020.

	E. coli (cfu/100 ml)		
Lake	2013	2020	*n*
Banning	13.7	3.4	4
Big Barbee	14.5	1.6	10
Irish	10.0	16.6	8
Kuhn	18.2	10.7	6
Little Barbee	15.3	1.3	6
Sechrist	7.9	4.7	6
Sawmill	14.4	8.2	4
Big Chapman	41.1	10.4	10
Little Chapman	13.6	1.5	*6
Barbee Chain	13.4	6.6	
Chapman Chain	27.3	5.9	

Table 21: Nearshore lake *E. coli* results and sample size per lake. Asterisk denotes attempted sample size; only five of the six samples could be fully enumerated due to a lab spill.

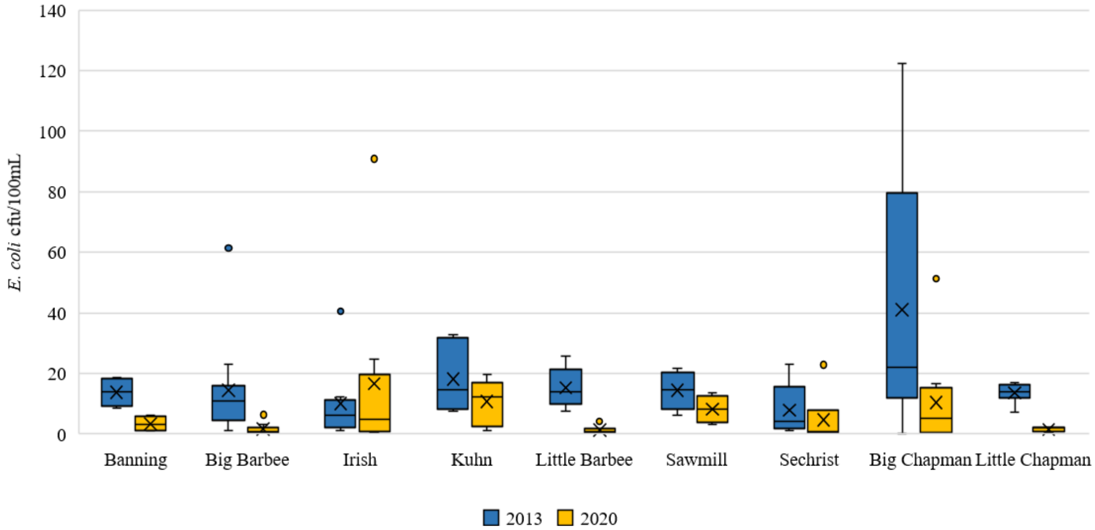

Figure 9: Nearshore *E. coli* results as a box-and-whisker plot. X's denote the average, horizontal line the 50th percentile or interquartile range, and upper and lower whiskers mark the maximum and minimum, respectively. Dots denote outliers, calculated as 1.5 times the interquartile range value.

Discussion

Streams

While stream quality is interesting for its own sake, the value of collecting stream data in this study is to determine whether changes in the Barbee chain's water quality are due to the sewer installation, or some other variable(s). More water moved into and out of the Barbee chain than Chapman during these study years, likely due to Barbee's larger watershed area. Chapman's large outflow volume suggests greater groundwater influences in this chain, while more water is entering the Barbee chain than is leaving, suggesting a large amount of water evaporating while flowing through the chain. Inflowing streams greatly influence lake quality, especially in chains with large watersheds, such as Barbee, while outflowing streams give a sense for the lake water quality as it leaves the system. While individual streams underwent slightly different changes, both chains inflowing streams changed in similar ways on average. The pattern observed is one of slight improvement in the streams, but not drastic for any particular parameter. It is reasonable to believe Barbee and Chapman's inflowing streams had a greater influence on all the lakes in 2020 due to increased flow overall. However, most of that flow occurred at the middle of the post-installation study, with flooding conditions on the lake in the spring of 2020 and dry streams and low lake water levels in late summer that year.

Despite differences in precipitation, lower nutrient concentrations in 2020 compared to 2013 resulted in more comparable loads than might have been expected for both years for most parameters. The same goes for our other stream variables; habitat quality, stream bank health, pollution tolerance, and *E. coli* indicate fluctuations in the quality of individual streams, but these fluctuations result in similar stream behavior for each chain. The lakes in the Barbee chain also vary in their susceptibility to inflowing stream influence. For example, the locations of inflowing streams relative to our lake sampling points and the hydrology of the chain may have an impact on lake water quality. Putney Ditch contributes the second highest percentage of water and nutrients to the Barbee chain (second to Grassy Creek inflow) and enters the chain close to the deepest point of Little Barbee. Conversely, Lozier's Ditch is the second greatest contributor to the Chapman chain, but it enters Little Chapman close to the outflowing stream on the south end of the lake. This may influence the movement and use of stream-contributed nutrients around the lake. Sechrist is the most insulated of the Barbee lakes, with no stream inputs and a small watershed, contributing to its high water residence time. Differences in precipitation from one year to another may not obscure lake water quality changes for Sechrist as much as the other lakes.

Outflowing streams, as indicators of lake water quality over the entire sampling year, help us understand potential changes in these lakes as well. These outflowing streams did not have the parallel changes we saw in the inflowing streams. Nutrient concentrations in outflowing water from the Barbee chain were lower in 2020 for SRP, TP, NO_3, and TKN. Only SRP and TKN were lower in 2020 from the Chapman chain. Stream nutrient loads show higher amounts of nutrients entered both lake chains from inflowing streams in 2020 compared to 2013, but only TP outflow loads from the Barbee chain actually decreased in 2020. This might suggest that the Barbee lakes chain was able to use more phosphorus compared to the Chapman lakes chain in 2020, due to another phosphorus source decreasing around the Barbee lakes since 2013 (such as removal of private septic systems). Indications of water quality by PTIR's run contrary to those proposed by nutrient/sediment results; Chapman's outflow (Heeter) improved substantially from 2013 to 2020 while Barbee's outflow (Grassy) declined substantially. CQHEI results suggest these macroinvertebrate results are related to stream characteristics not related to outflowing lake water quality itself, such as sedimentation in the Chapman chain and stream shape in the Barbee chain. Other influential factors likely exist.

Lakes

Overall, water quality as measured in the lakes themselves of both the Barbee and Chapman chains improved from 2013 to 2020 despite nutrient loads being higher in inflowing streams in 2020. Nutrient levels in the epilimnion of lakes in both chains decreased from 2013 to 2020. This likely led to less algae growth in the surface water which was confirmed by higher water clarity measurements in 2020 as well as lower dissolved oxygen measurements in 2020. Lower algae populations in the surface waters of a lake often lead to lower oxygen levels near the surface since there is less algae to produce oxygen in the water through photosynthesis. Hypolimnion levels were higher than the epilimnion in both years, suggesting these lakes experience internal loading: nutrients diffusing from the bottom sediment into the water column and feeding plant and algae communities.

Specific lakes differ by parameter. Paying particular attention to the lakes with the highest residence time due to less inflowing streams, Sechrist and Kuhn show drops in sediments and nutrients in the epilimnion similar to other lakes, despite these two lakes being more isolated from stream inflows. These two lakes also had the highest average water clarity of the Barbee chain in 2013 and had the highest increase in water clarity in 2020. In the Chapman chain, Big Chapman had the highest water clarity in 2013 and also increased in 2020 though not as much as Sechrist and Kuhn in the Barbee chain. This could be because Big Chapman has more inflowing streams and could have been more influenced by increasing stream loads in 2020. Sechrist and Kuhn are the only two lakes that approached or exceeded the EPA P25 water clarity standard of 11 ft on average in 2020. These two lakes also were the only two lakes that were below the EPA P25 TP standard of 0.010 mg/L in 2020. Given the more isolated nature of these two lakes in the Barbee chain, they might be the best indicators of potential impacts of the public sewer installation. The fact that water clarity and epilimnion TP improved most in these lakes might then indicate a water quality improvement attributed to the installation. Some other water quality measures like sediments and TN did not improve most in these two lakes relative to other lakes. Big Barbee, Irish, and Little Barbee lakes, which are more influenced by their inflowing streams, saw much larger TN decreases in their epilimnion, but those inflowing streams (Grassy inflow, Putney, and McKenna) loaded the same or slightly more TN into their lakes in 2020. This suggests TN reductions in those lakes is due to another source. Nitrogen's high mobility in soils strongly associates it with septic effluent in groundwater, which gives reason to attribute that beneficial reduction in TN to the sewer installation. The TN content for Big and Little Chapman's epilimnion and inflowing streams supports this observation, as the lakes reduced TN much less dramatically while their streams behaved similarly to Barbee's.

It is unclear whether the sewer installation was the deciding factor in reduced nearshore lake *E. coli* levels. Big Chapman and Little Chapman were also lower in 2020, and all of the levels were relatively low in both lake chains in 2013 and 2020. One confounding variable for *E. coli* is the presence of waterfowl and other animal droppings. Waterfowl excrement is transient but potent, full of nutrients and bacteria. The presence of a flock before a sample was taken could explain a few of the outliers we observe in the near-shore survey, though we were careful not to sample where there were waterfowl present.

While 2013 is our comparison year for this study, we have historical data that can provide context for water quality before major settlement around these lakes. In a report by Indiana University researcher Will Scott, Big Barbee was hypoxic at 4 m and deeper in the summer of 1914 compared to the lake's maximum depth of 15 m (Scott 1916). Sechrist (the other lake profiled in the Barbee chain in this historical survey) and Big Chapman were hypoxic starting below 10 m and below 8 m, respectively. Even before these lakes were densely populated, Big Barbee was a particularly productive lake. (Chapman and Sechrist also ran out of oxygen, but at greater depths.) With this in mind, we should be careful not to assume each of these lakes will look the same when lake management strategies are enacted, such as public sewer installation or reducing inflowing stream nutrient loads. It may take longer for Sechrist's water quality to change because of its high residence time and large maximum depth compared to the other lakes in this study, though its capacity for clear water, low nutrient levels, and lower plant and algae activity may be greater for the same reason. Big Barbee, in turn, may continue to be very productive, though perhaps less so, with restorative efforts in the lake or its watershed.

Historical data collected and reported more recently in diagnostic studies show potential improvement in some lakes compared to the 90's, but Banning and Little Barbee have epilimnetic TP values higher than their 90's and 2013 results. Only results from Kuhn and Sechrist in 2020 meet or fall beneath the EPA P25 value of 0.010 mg P/L, and they do so after previous years of even higher values.

Areas of Further Research

More potential confounding influences exist that were not part of the present study. These lakes are sprayed for weeds regularly, the extent and rates of which we did not compare between 2013 and 2020. Aquatic plants can benefit the lake by stabilizing bottom sediment and absorbing more nutrients. The prevalence and diversity of aquatic plants in these chains has been described thoroughly elsewhere (Aquatic Weed Control 2020; Ewoldt 2009). Further research would be required to determine whether or not and to what extent weed removal, by spraying or pulling, impacts water quality.

Another confounding influence is ongoing efforts on both chains to improve water quality. Other partner groups of the Lilly Center such as the Barbee Lake Property Owners Association, Chapman Lakes Conservation Association, Chapman Lakes Foundation, Kosciusko County Soil and Water Conservation District, Natural Resource Conservation Service, and The Watershed Foundation are also working in these areas to improve land and water management for the benefit of the lakes. Such efforts are not specifically quantified or explicitly considered here, but many of these potential impacts would likely be included in the various measurements in the present study.

Some of those management efforts likely impact inflowing streams more directly. While not the primary focus of this study, inflowing streams are an area of potential management of these lakes. These streams are a large source of sediments and nutrients, as shown here by their annual loads and high sediment/nutrient concentrations. If their contributions were reduced, the impact of in-lake management could be more clearly understood, and the lakes themselves would benefit and. Grassy Creek (inflow) and Putney Ditch are good candidates for continued work; they contributed 97% of the inflowing water both study years, and 98% or more of the TN and TP load. Similarly, on the Chapman chain, Crooked and Lozier's contribute the highest percentage of flow and nutrients by far, though their overall water volume and load contributions are smaller than that of Grassy and Crooked.

This study also does not account for potential differences in groundwater influence. It may be that the lakes of the Barbee or Chapman chains are more or less groundwater fed such that some lakes could be more indicative of public sewer installation impacts beyond what we have discussed here. Much more work could be performed in the analysis of groundwater before and after such sewer installations. Since the undertaking of this study, there has been discussion and approval of a sewer district for the Chapman and Tippecanoe lakes chains. Similar research opportunities abound, both with the goal to assess sewer system effectiveness and to understand these lakes more thoroughly.

The Barbee lakes chain could be assessed similarly in the future to assess for trends in water quality with the continued operation of the sewer system, as predicted in Richardson and Jones (2000). Additional years of data collection would help to reduce impacts of weather conditions outside of the control of this study as well. Also, further consideration of internal loading of nutrients from the sediments in the lakes themselves would allow additional insights in this analysis.

Conclusion

Wastewater has strong capacity to negatively influence surface water safety and quality. The Barbee lakes chain transitioned from private septic systems to a public sewer district mostly completed in spring of 2017 in an effort to move away from potentially poorly functioning wastewater treatment systems already in place as suggested by previous work on these lakes. Our study assessed inflowing and outflowing streams and the lakes of the Barbee chain, utilizing the Chapman chain as a control for comparison. Many water quality parameters measured in the Barbee chain were better (greater water clarity, lower nutrient concentration) in the summer of 2020 than 2013. Specific parameters and the magnitudes of the changes observed varied between the seven lakes of the Barbee chain. Changes in many of the same parameters were also observed in the Chapman chain as the control, making it difficult to attribute water quality improvements in the Barbee chain to the public sewer installation. Our data suggests two specific lakes in the Barbee chain, Sechrist and Kuhn, were the most likely to have been positively impacted by the sewer installation based on the present study. Total nitrogen decreases in other Barbee lakes also suggest lake water quality improvement beyond the impact of their inflowing streams which was not observed to a similar degree in the control chain. Further research on these lakes would differentiate their greatest influential factors, identify future methods of lake protection, and identify the impacts of sewer districts over greater lengths of time and at other scopes.

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