University of Lynchburg
Digital Showcase @ University of Lynchburg

Undergraduate Theses and Capstone Projects Student Publications

Spring 5-2020

Water Quality Degradation from Dam Removal: Impact on an Urban River System in Central Virginia

Wrenn Cleary
cleary_w@alum.lynchburg.edu

Follow this and additional works at: https://digitalshowcase.lynchburg.edu/utcp

Part of the Water Resource Management Commons

Recommended Citation

Cleary, Wrenn, "Water Quality Degradation from Dam Removal: Impact on an Urban River System in Central Virginia" (2020). *Undergraduate Theses and Capstone Projects*. 161.
https://digitalshowcase.lynchburg.edu/utcp/161

This Thesis is brought to you for free and open access by the Student Publications at Digital Showcase @ University of Lynchburg. It has been accepted for inclusion in Undergraduate Theses and Capstone Projects by an authorized administrator of Digital Showcase @ University of Lynchburg. For more information, please contact digitalshowcase@lynchburg.edu.

Water Quality Degradation from Dam Removal: Impact on an Urban River System in Central Virginia, USA.

Wrenn Cleary

Senior Honors Project

Submitted in partial fulfillment of the graduation requirements
of the Westover Honors College

Westover Honors College

May, 2020

Thomas Shahady, Ph.D.

David Perault, Ph.D.

Nancy Cowden, Ph.D.

Abstract

Dam removal in the United States is an increasingly common practice as dams built decades ago begin to experience structural issues or environmental changes necessitating this action. In Lynchburg, Virginia, College Lake, an 18 Ha reservoir, was briefly overtopped during strong storms during August 2018 causing minor damage to the dam. In response, the City of Lynchburg deemed it necessary to drain the lake to protect property owners downstream fearing complete dam failure. During assessment to determine the best practice for dam removal, College Lake remained drained for 12 weeks as debate to conclusively determine a best course of action occurred. This system has been extensively studied for 10 years prior to the overtopping prompting the current study of dam removal to aid the scientific community on the resulting environmental effects of dam removal. During the draining period of time (August –October 2018), I sampled the biological and physical components of river water quality downstream of the lake. Simultaneously, I assessed river water quality above the lake to compare to the changes downstream. I also sampled Ivy Creek, a tributary to Blackwater Creek unimpacted by the draining of the lake as a control. Through comparisons, the resulting trends suggested a high increase in downstream sediment likely due to the exposed lakebed of College Lake when compared to historical trends and control. Coupled concurrently with a decline in other measured water quality standards, I suggest the lake is a critical water quality improvement feature in this watershed. This indicates a strong need to understand the water quality function of reservoirs before future removal.

Keywords

Water Quality, Dam Removal, Sedimentation, River systems, Reservoir

Introduction

Watershed and river landscapes' function

Watersheds are areas that drain runoff into another body of water such as a river, lake, stream, or ocean (Cushing and Allen 2001). A watershed typically is defined by the surrounding topography or elevation causing the runoff to filter down slopes in certain ways. Watershed boundaries separate these runoff areas from one another. Watersheds also function to capture precipitation in the soils through infiltration temporarily storing water in the soils. When this water is released, it flows either as groundwater or as lateral discharge into streams creating surface flow. As runoff varies with topography, water flows collect into tributaries feeding into larger streams and rivers. Therefore, a river in a watershed is characterized by the surrounding landscape. Humans have a great capacity to impact a river in a watershed through increases in developments leading to increases in impervious surfaces. Water that once would have seeped into the ground instead finds its way directly into a waterway. Impervious surfaces indirectly decrease the amount of wetlands and riparian zones, causing strain on river channels as they redirect the majority of precipitation to surface flow. Direct river inflow from impervious surfaces also results in an influx of sediment, phosphorus, nitrogen, and other pollutants.

Constructing dams in watersheds

Storage of water is important for drinking, flood control, hydroelectric power and recreation thus we built dams in the eastern United States (McCully 1996). Once the dam is in place, the resulting reservoir provides a relatively stable water supply and storage not only for aforementioned purposes but also irrigation and agriculture. The resulting reservoir becomes part of the watershed and over time integral to ecological function particularly in urban areas where impervious surface growth is substantial.

Downstream of the dam, water flow usually remains constant as discharge is often controlled or regulated (Poff et al. 1997). Within the reservoir the river system is altered as debris that would flow downstream now become trapped along with sediment behind the dam. As sediment is captured, preventing flow downstream, the erosion of riverbanks may occur due to lack of replenishing sediment building up these banks. Yet sedimentation rates depend upon season and rainfall. And if the dam was constructed for the purpose of hydroelectric power generation, flow rates are further altered to meet power generation at times of peak demand. Additionally, aquatic organisms are impacted both upstream and downstream while fish spawning can be interrupted or isolated. However, below dams water quality of streams can be greatly improved (Mantel et al. 2017). Dams can also prevent invasive species from dominating in the downstream environment (Gangloff 2013), and the sediment accumulation behind the dam prevents the pollutants attached to the sediments from continued suspension in the water column.

Urban Lakes and Stormwater Ponds

Urban lakes are a unique sub-set of man-made reservoirs built in highly urbanized areas. They typically have a relatively small direct catchment, a surface area limited to a few hectares, and an average depth of 3-5 meters or less (Naselli-Flores 2008). Due to anthropogenic influences, urban lakes experience alterations in water quality such as eutrophication. Urban lakes generally have a higher phosphorus load, causing phytoplankton blooms and increased growth of aquatic weeds and algae. Accumulation of phytoplankton can cause sanitary risks during production of toxic compounds as phytoplankton shift toward cyanobacteria dominance (Naselli-Flores 2008). A high presence of impervious surfaces due to surrounding construction increases surface runoff with a higher percentage of pollutants making their way into the lake instead of being absorbed in the soils. Heavy metals, including arsenic, cadmium, chromium, lead, mercury, nickel, and zinc, and toxic organic pollutants are commonplace in sediment cores from urban lakes (Mahler, Van Metre & Callende 2006).

While urban lakes may receive an uptick in pollutants from serving as catchment areas, this prevents these pollutants from continuing downstream. Wildi et al. (2004) found that, in urban lakes, there was an increase in heavy metals and pollutants in bottom sediment. These pollutants were stored in the sediment and potentially pose an environmental risk if remobilized, particularly through dam removal. As urban lakes are positioned to receive runoff from the surrounding watershed, their water quality directly reflects problems and concerns from human activities and land cover.

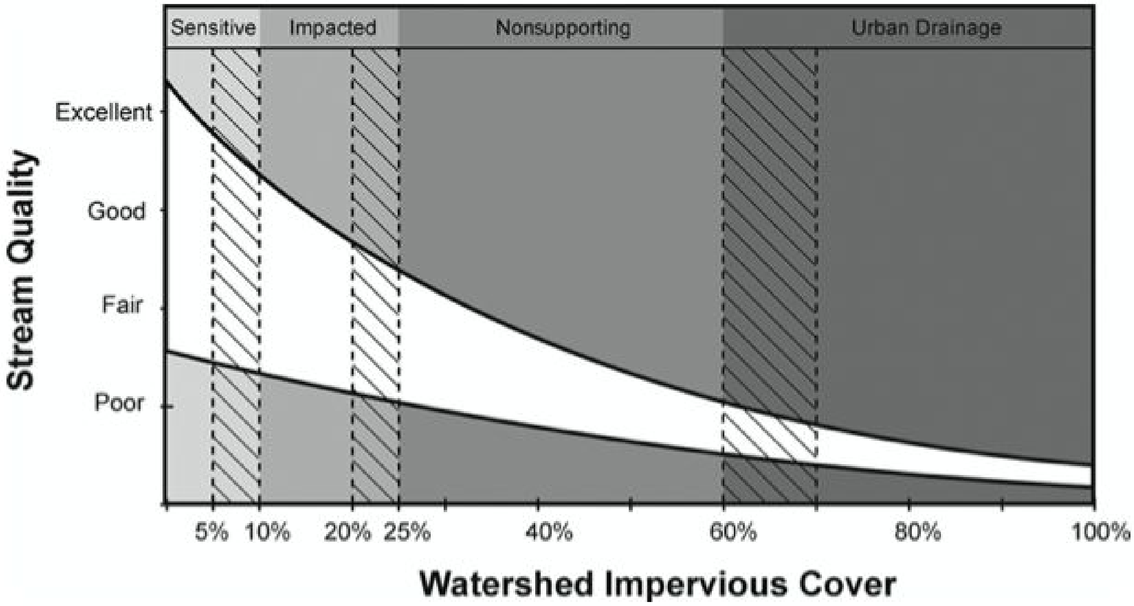


Figure 1 – Changes in water quality resulting from increases in impervious cover (Schueler, Franley-McNeal & Cappiella 2009).

Within urban catchments impervious surfaces are a critical factor describing water quality in a watershed. Schueler, Franley-McNeal & Cappiella (2009) reaffirmed the well-researched standard for impervious cover and its relation to water quality. Waterways can be impacted when impervious cover in the surrounding watershed is as low as 10%. Once a watershed reaches 25% impervious cover, the waterway is nonsupporting as necessary biological, physical, and ecological function become insufficient. The modified Impervious Cover Model (ICM), first developed by the Center for Watershed Protection in 1998, is used by watershed scientists to quantify the impact these surfaces have on water quality (Fig. 1). The ICM describes transition zones as a watershed develops greater proportions of impervious cover. The highest line forms a "cone" with the lower line to visually convey an overall variance in water quality. This is because percent impervious cover does not take into consideration land use type, e.g. agricultural land or, more importantly, a reservoir that may function as an in-line water quality retention pond. Because of these mitigating factors, impervious surface should not be the sole factor in determining water quality. However, impervious cover is beneficial as a measure for urbanization and particularly when used in tandem with other measures.

Environmental Costs and Benefits of Dam Removal

Aging dams are often costly to maintain and are implicated in negative ecological effects such as fish passage (Bowen, Bovee & Waddle 2003). Dams were commonly constructed rapidly as a means for economic value, and considerations for longevity and maintenance were lacking. With dams increasingly deteriorating structurally and accumulating sediment behind them, there has been a corresponding resurgence in dam removal across the United States; 548 dams were removed in 2010 alone compared to 147 dams removed in 1990 (Oliver & Grant 2017). The primary reluctance for removal of a dam is managing the sediment accumulation present and the consequences of this sediment flow downstream. When dams are removed quickly, a knickpoint, or a waterfall created in a lakebed by steep gradient changes can form and cut through exposed sediment, continuously cutting further upstream and washing more sediment loads downstream (Oliver & Grant 2017). In order to limit an influx of sediment, dams are best removed in stages or sections. The time length for removal depends on a variety of factors including the size of the dam, the amount and type (potentially contaminated or not) of sediment accumulated, and age of the dam (Oliver & Grant 2017).

The collection of sediment behind the dam alters a reservoir, creating a basin of sediment rather than water storage and various environmental risks (Stanley & Doyle 2003). These concerns continue to be the main impetus for dam removal. Sediment buildup raises concern for toxic chemicals that may be released to the detriment of human and ecosystem health (Poff & Hart 2002). Rapid draining has resulted in massive landslides and mudflows containing numerous contaminants (Oliver & Grant 2017). Upon removal of a dam, the dry lakebed itself can be expected to be severely affected. At first, a deep channel cutting through exposed sediment commonly forms, leaving banks unstable and subject to collapse and a widening of the channel (Evans et al. 2000). As these channels are so unstable, their unpredictability and meandering form new channels leading to collapse of sediment and further sedimentation downstream for many years post dam removal. New changes in stream hydrology further undercut stream banks continuing sedimentation and alter stream morphology for decades.

This study specifically analyzes the downstream water quality effects of dam removal from College Lake. A dam removal like scenario occurred following a large storm in fall of 2018. After this storm and heavy precipitation amounts, College Lake was drained, and the dam no longer functioned as its purpose of creating an urban reservoir. This study includes analysis of water quality from three sites to determine the effects College Lake had on water quality while the dam was operable and compared to effects dam removal had on downstream water quality.

Methods

Study Sites

<u>*College Lake*</u>

College Lake is a reservoir located in the City of Lynchburg, Virginia. The reservoir was constructed in 1934 along Blackwater Creek, a tributary to the James River and part of the Chesapeake Bay Watershed. The lake was created through a partnership between the city and Lynchburg College by constructing Route 221 Lakeside Drive, over Blackwater Creek along with the current dam. Upon completion, College Lake originally encompassed 18 ha of surface area with a maximum depth of 9 m (Carico et al. 1973). In its formative years College Lake was a site for recreation and relaxation with a shed for boat rentals (Lynchburg College 1973). Later urbanization led to a rise of development throughout the watershed feeding into College Lake and, as a result, greatly accelerated sedimentation into the lake. In 1971 the maximum recorded depth was 8 m while in 2002 the maximum depth was < 6 m (Newman, Perault & Shahady 2006). Most recent measures in 2014 indicated 7.69 ha remaining of surface area, which is only 42.72% of the original (Talian 2014).

Decreasing lake depth reduces the storage capacity, rendering the lake more susceptible to extreme precipitation events. This lessens the lake's ability to handle surges in inflow during significant precipitation events. Storage capacity of the lake in 1971 was 265,000 m^3 with a watershed to reservoir ratio of 42:1 (Newman, Perault & Shahady 2006). By 2002, the storage capacity fell by 169,000 m^3 to become roughly 96,000m^3, and the watershed to reservoir ratio more than doubled to be 68:1 from an original 29:1 in 1934.

On August 2, 2018, approximately 17 cm of rain fell within the City of Lynchburg, causing severe flooding throughout the area. College Lake's storage capacity was exceeded, and flooding overtopped the dam, releasing water onto Lakeside Drive. The city feared a dam failure and executed an emergency evacuation order to 150 residents downstream of the dam. On August 4th, crews from the city opened the sluice gate draining College Lake. The rapid draining created severe channel cutting through the lakebed.

The continued draining of the lake through the sluice gate created ongoing problems with debris clogging the sluice gate opening from subsequent flood events. To mitigate this, the city employed a dive team to continuously remove debris from the sluice gate opening to prevent lake levels from rising. Fatigued by the cost and labor associated with this task, the city closed the sluice gate on October 19th, allowing the lake to refill. The lake refilled on October 21st, 2018.

Three sampling sites were selected to gage the impact of lake draining on water quality. These included Tomahawk Creek (above the inflow to College Lake), Peaksview Park (part of Ivy Creek that is adjacent and independent from College Lake draining), and Hollins Mill (at the confluence of both Blackwater Creek and Ivy Creek). Sampling these sites allowed the comparison of Ivy Creek watershed, which was unimpacted by College Lake draining, and the Blackwater Creek watershed that contained College Lake. Then, through comparison over a similar sample period, it was possible to infer the exact impact of College Lake on water quality.

The Tomahawk sampling site provided a direct comparison for how the quality of water before it enters College Lake (Fig. 2). Tomahawk Creek is the largest of three tributaries creating Blackwater Creek before entrance into College Lake. Tomahawk Creek is of river order 3. This site was selected to determine the quality of the water entering into College Lake when compared to the outflows from the lake.

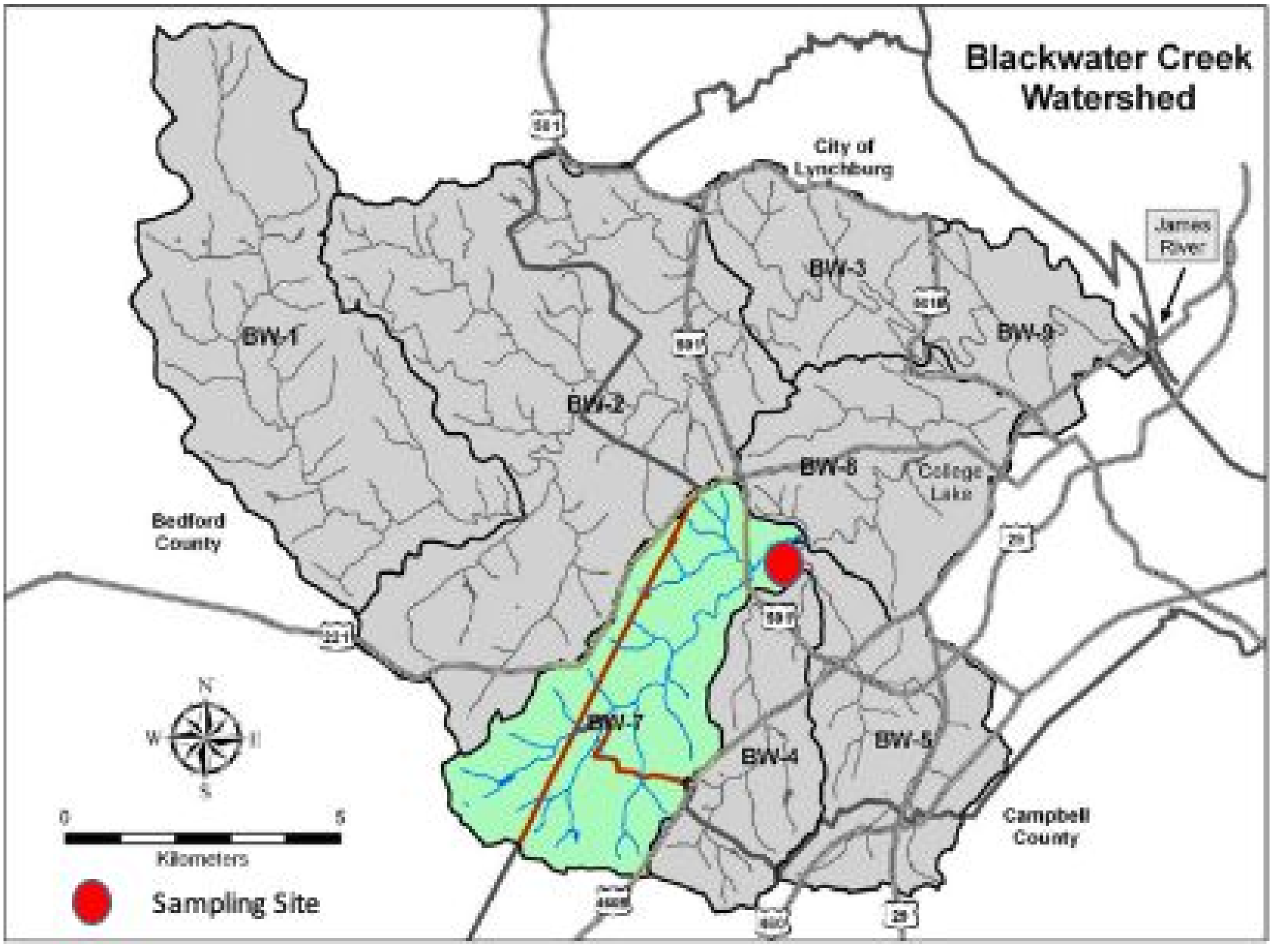


Figure 2 – The Blackwater Creek Watershed with individual sub-watersheds labeled throughout. Sub-watershed BW-7 highlighted in green with the Tomahawk sampling site marked as a red dot (Blackwater Creek Watershed Planning Committee 2008).

Ivy Creek, a tributary to Blackwater Creek, was sampled at Peaksview Park in Lynchburg (Fig. 3). Peaksview is a river order 4. This site was sampled as a control for comparison to Blackwater Creek. Additionally, Ivy Creek joins Blackwater Creek just before the sampling site of Hollins Mill. Ivy Creek drains approximately half of the watershed flowing to the Hollins Mill sampling site. Not only does the Peaksview Park sampling site provide a comparison for Blackwater Creek, but it also influences water quality at Hollins Mill through dilution. Therefore, I inferred exactly how College Lake filters pollutants by analyzing Hollins Mill in comparison to the degree to which Ivy Creek affects water quality at Hollins Mill.

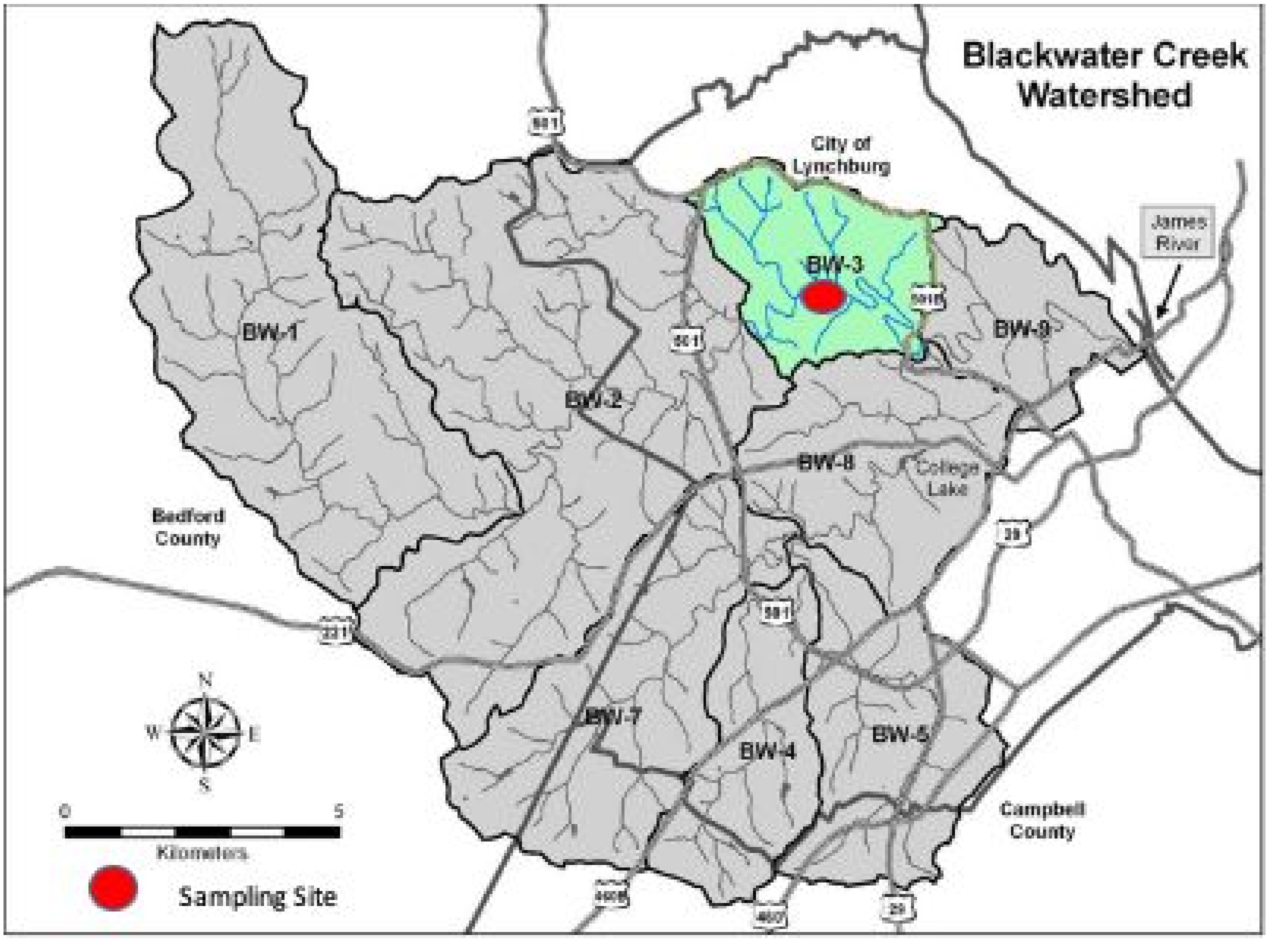


Figure 3. The Blackwater Creek Watershed similar to Figure 2. The Lower Ivy Creek sub-watershed is labeled as BW-3 highlighted in green. The Peaksview Park sampling site is marked with a red dot (Blackwater Creek Watershed Planning Committee 2008).

Hollins Mill Park is located along Blackwater Creek downstream of College Lake and the confluence with Ivy Creek (Fig. 4). This site is of river order 5. This site was selected to gather data on the water quality effects from draining College Lake. Using the historical trend (2008-2016) at Hollins Mill from the impact of College Lake filtering out pollutants from the Blackwater Creek watershed and the Ivy Creek watershed suggested this as a low-impacted stream. By comparison, it was expected that water quality at Hollins Mill when College Lake was drained would be a markedly lower without the benefit of College Lake filtration. Additionally, draining College Lake not only resulted in the loss of its filtering capacity, but also the release of stored pollutants from the time of the lake’s inception.

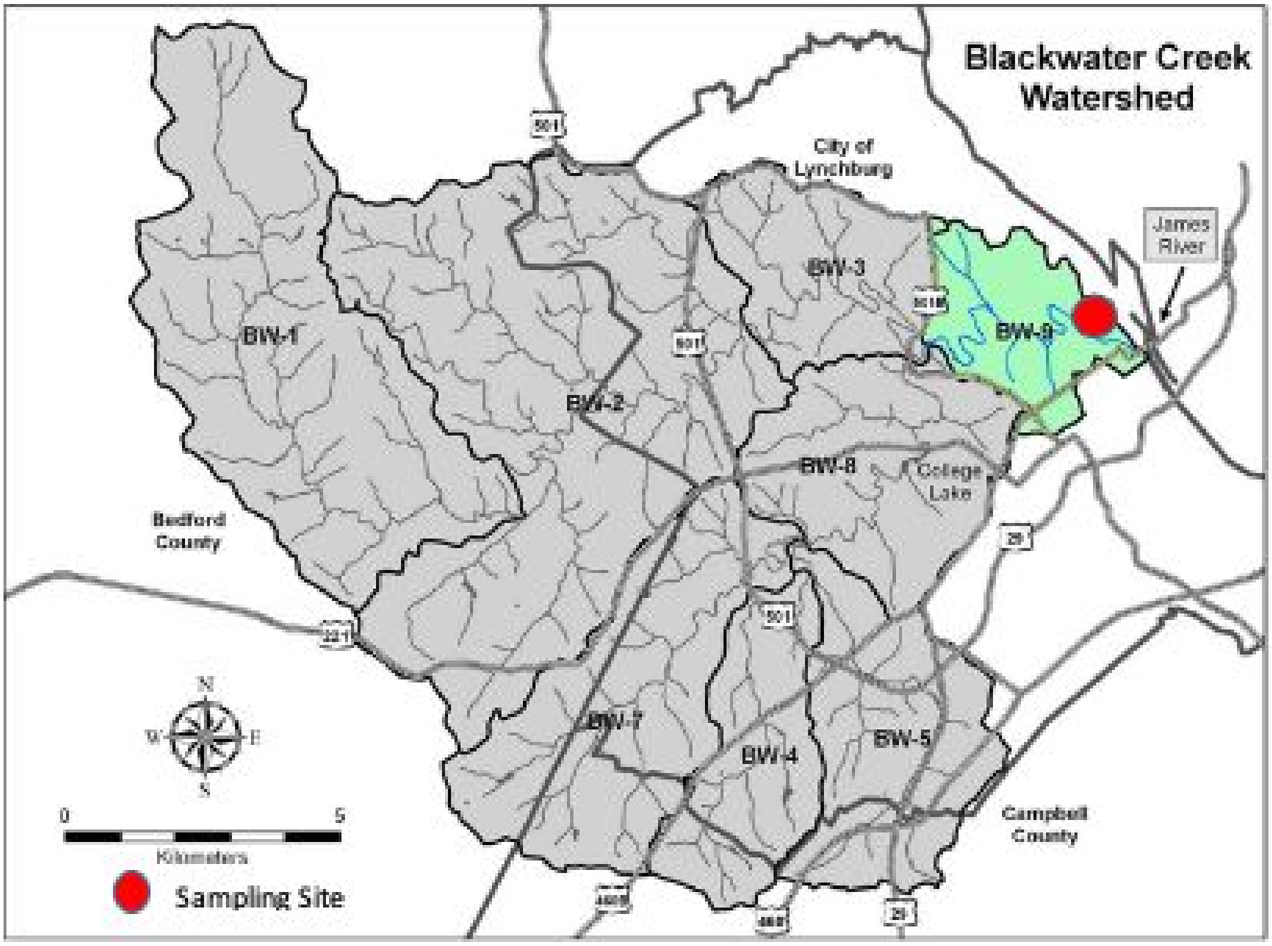


Figure 4. The Blackwater Creek Watershed similar to Figure 2. The Lower Blackwater Creek sub-watershed is labeled as BW-9 highlighted in green. The Hollins Mill sampling site is marked with a red dot (Blackwater Creek Watershed Planning Committee 2008).

Historical Data

Data collected annually each April from 2008 – 2018 until the draining of College Lake was incorporated into this study for the three stations studied. This historical data were compiled for purposes including monitoring trends in parameters, impervious surface coverage, and growth of urban development. The data provide an understanding of how stream quality was affected by the presence of College Lake and the changes in land use over a decade.

Land cover percentage (Table 1) was calculated using the United States Geological Survey’s StreamStats website (Ries et al. 2008). The StreamStats website calculates details on watersheds at any given point along a stream and is available for online public access. I selected each sampling point from my study on the website and then collected data on watershed details based on these calculations. Changes in land use percentages, size of delineated watershed above the sampling point and urban growth along with correlations to impervious surfaces were used to correspond with changes in water quality degradation.

Stream Collections

I collected samples from the three study sites from September through November of 2018 to correspond to the draining of College Lake. I used a YSI 556 multiprobe meter (Xylem, Yellow Springs, Ohio) to measure chemical water quality parameters following pre and post calibration QA/QC procedures in accordance with EPA protocols (EPA 2017). I collected pH, dissolved oxygen, conductivity, temperature and ORP using the YSI meter. The 2018 sampling dates of September 24th, October 5th, and October 9th reflect data gathered during College Lake draining and lakebed exposure; these dates are significant because they reflect water quality changes immediately after the draining event and can be inferred to reflect water quality from dam removal. Information from these three dates most directly reflect conditions of dam removal and release of 50 years of sediment and pollutant accumulation from the lakebed impacting water quality downstream. After refill of College Lake on October 21st, 2018, I continued sampling weekly until November 28th. These dates, while within a short time frame of lake drainage, can suggest the utility of the lake to act as a filter to improve water quality by returning to filter pollutants instead of release downstream. Sampling after the lake refilled also provides information on the efficacy of downstream stream recuperation from water quality degradation and loss of aquatic life.

Macroinvertebrates were used because they are bioindicators of water quality and are indicative of changing conditions in aquatic environments. They are highly responsive to changes in water quality, and the presence of certain families suggest higher or lower water quality conditions. To collect macroinvertebrates I used EPA Rapid Bioassessment Methodology (Barbour et al. 1999) modified using a square net. Macroinvertebrates were preserved in alcohol and later identified to family using Voshell (2002).

To measure bacterial contamination I used the Colilert-18 (IDEXX, Westbrook, Maine) test to quantify *Escherichia coli* concentration levels. The Colilert-18 is an approved test meeting all EPA standards for testing (Warden et al. 2011). This methodology uses Most Probable Number (MPN) to quantify E. *coli*, and I report my findings as MPN/100 ml of sample in accordance with federal and state standards.

Total phosphorus (TP) levels were quantified for all sites over the sampling periods to infer how high amounts of phosphorus entering waterways from diffuse sources may impact aquatic life through eutrophication and an inhospitable environment for invertebrates, fish, and other aquatic life forms. I measured total phosphorus levels using the ascorbic acid phosphorus method. I collected water samples in acid washed Nalgene bottles carefully collecting each sample in the water column of the stream avoiding contamination with bottom sediments or other debris. I used an EasyChem autoanlyzer (Systea, Italy) following all procedures and QA/QC for Total Phosphorus analysis. The EasyChem analysis is compatible with Ascorbic Acid Total Phosphorus Analysis detailed in Standard Methods for Analysis of Water and Wastewater (Baird and Bridgewater 2017).

Data Analysis

Calculated indices for macroinvertebrates included Ephemeroptera, Plecoptera, and Trichoptera (EPT, Plafkin et al. 1989), Index of Biological Integrity (IBI, Karr and Chu 1999), Percent Model Affinity (PMA, Novak and Bode 1992), and Family Biotic Index (FBI, Hilsenhoff, 1977). EPT is an index measuring macroinvertebrate orders of Ephemeroptera, Plecoptera, and Trichoptera suggesting these orders respond to different levels of water quality. An EPT greater than 10 would indicate excellent water quality, 6-10 would indicate slightly impacted, 2-5 would be moderately impacted and 0-1 would be severely impacted (Lillie, Szczytklo & Miller, 2003).

Index of Biological Integrity (IBI) is an index using ecological response variables to quantify changes in macroinvertebrate communities. Each ecological parameter is assigned a value from 1-5 depending on adherence to high or low quality based on a similar reference condition (Karr and Chu 1999). In this index I used degree of dominance (percentage in sample of the most dominate macroinvertebrate family), total number of macroinvertebrates captured, total number of families captured, percent tolerant, percent intolerant, total Ephemeroptera, total Plecoptera and total Tricoptera.

Percent Model Affinity (PMA) is an index measuring abundance of macroinvertebrates. The expected percentages of the seven major macroinvertebrates groups from a control stream are 40% Ephemeroptera, 20% Chrionomidae, 10% Plecoptera, 10% Trichoptera, 10% Coleoptera, 5% Plecoptera, 5% Oligochaeta, and 10% other based on similar reference condition (Novak & Bode 1992). These expected values are compared to the sampled rates, and if the resulting PMA is greater than 64.0, the stream's water quality has not been negatively impacted; if the PMA is less than 35.0, the stream would be heavily impacted and result in very low water quality (Lillie, Szczytklo & Miller 2003).

The Family Biotic Index (FBI) assigns each family of macroinvertebrates a number from 0-10 based on published sensitivities (Hilsenhoff 1987) and adjusted regionally (Lenat 1993). The index ranges from 0 being the most sensitive to 10 being the least sensitive based on tolerance to organic pollution (Lillie, Szczytklo & Miller 2003).

I used Principal Components Analysis (PCA) using XLSTAT (Addinsoft, 2019) to examine historical and post-draining to find all relevant correlations of all measured parameters for water quality. Once the most indicative parameters were determined from PCA analysis, an Analysis of Variation (ANOVA) was used on these most significant parameters to compare average means between historical and lake draining data. The significance of difference in mean values for the parameters were determined in order to assess exactly to what degree water quality was affected downstream of the lake drainage.

Results

The three studied watersheds differ in levels of land use, size and other studied parameters (Table 1). Hollins Mill watershed encompasses the largest acreage followed by Peaksview Park and then Tomahawk. Tomahawk is the most urbanized, correlating with the greatest amount of impervious surfaces. Data from 2001-2011 suggest Tomahawk is urbanizing at the greatest rate: over 4% in this 10-year period. A Q10 event, or a storm calculated to only occur once every 10 years, would result in Hollins Mill having the greatest flow rate (Table 1).

Table 1 - Watershed parameters retrieved from Streamstats data. Refer to Figs. 1-3 for sample points. Data only available up to year 2011.

	Blackwater Creek	Ivy Creek	Tomahawk	Peaksview Park	Hollins Mill
Size (hectares)	6371.0	9687.0	1,711.9	8,546.9	16,834.9
%Urban 2011	67.8	24.9	63.9	21.1	43.0
%impervious 2001	19.2	4.9	13.1	3.9	11.2
%impervious 2006	20.8	5.2	15.7	4.3	12.0
%impervious 2011	23	5.9	17.3	5	13.2
Q10 (cms) 2011	107.60	99.70	49.55	90.90	167.92

Principal components analysis

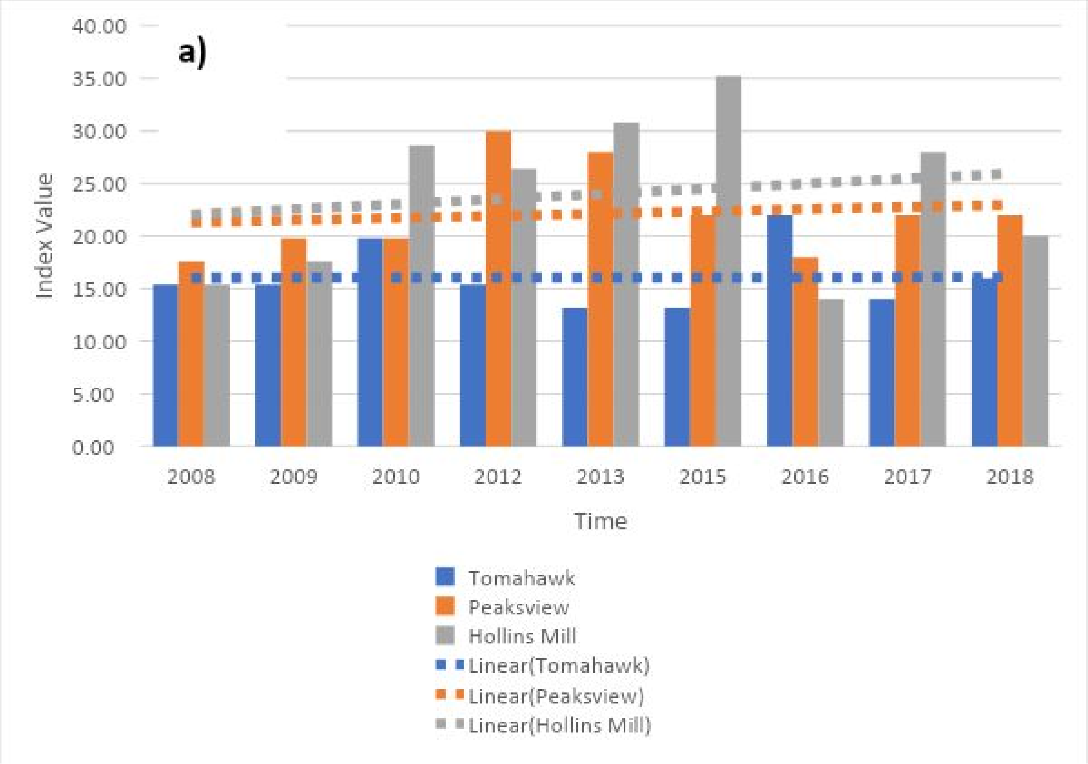
The variables most reflective of water quality were every macroinvertebrate index and the abiotic parameters: conductivity, temperature, nitrates, and dissolved oxygen (Table 2). This analysis was used to narrow down the scope of the study to focus upon the most pertinent parameters.

Table 2. Squared cosine values from Principle components analysis for the top two factors (indicate % variation accounted for here) for data before draining (historical) and post draining (draining) of College Lake. Bold indicates significance at $p<0.05$.

	Factor 1 Historical	Factor 1 Draining	Factor 2 Historical	Factor 2 Draining
Temperature	0.082	0.280	0.003	**0.564**
pH	0.161	0.082	**0.310**	0.063
Conductivity	0.102	**0.612**	**0.447**	0.135
Dissolved Oxygen	0.001	0.071	**0.373**	0.207
Nitrates (NO3)	0.009	0.178	**0.508**	**0.471**
Total Phosphorus	0.134	0.347	0.211	0.000
FBI	**0.728**	**0.432**	0.017	0.125
EPT	**0.715**	**0.427**	0.059	0.005
PMA	**0.576**	**0.497**	0.005	0.002
IBI	**0.826**	**0.606**	0.054	0.001

Principle components analysis suggests IBI macroinvertebrates displayed a strong positive correlation of 0.606 and a high EPT value of 0.497 for data gathered in the draining period. Every macroinvertebrate index had significant values, suggesting they are the strongest indicators of water quality changes in this study, prompting further analysis using these variables. Analyzing each measured chemical parameter, I found only $-NO^{3-}$ and conductivity to be significant in both the historical and draining analysis for both factors 1 and 2 (Table 2). This prompted further analysis of both of these parameters. While other measured parameters displayed significance in only one of my analyzed scenarios (either historical or draining but not both), I discarded them from further analysis.

In comparing IBI macroinvertebrates values between the two sampling periods (Fig. 5), several patterns emerged. Data gathered throughout the historical collection period illustrate a clear distinction between water quality at Hollins Mill, Tomahawk Creek and Peaksview Park. Trendlines suggest that historically, Hollins Mill is reflective of Peaksview Park water quality rather than Tomahawk Creek (Fig. 5a). Both Hollins Mill and Peaksview Park trend between 20-25 on this scale, with a slight increase through time. Tomahawk Creek consistently trends at 16 on this scale. During the sampling period after draining of the Lake (Fig. 5b), all sites trend between 14-16 on this scale, mirroring water quality levels in Tomahawk Creek. Additionally, the draining data suggest improving trends at the end of the sampling period, when the lake was refilled.


a)
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Index Value
2008
2009
2010
2012
2013
2015
2016
2017
2018
Time
Tomahawk
Peaksview
Hollins Mill
Linear(Tomahawk)
Linear(Peaksview)
Linear(Hollins Mill)

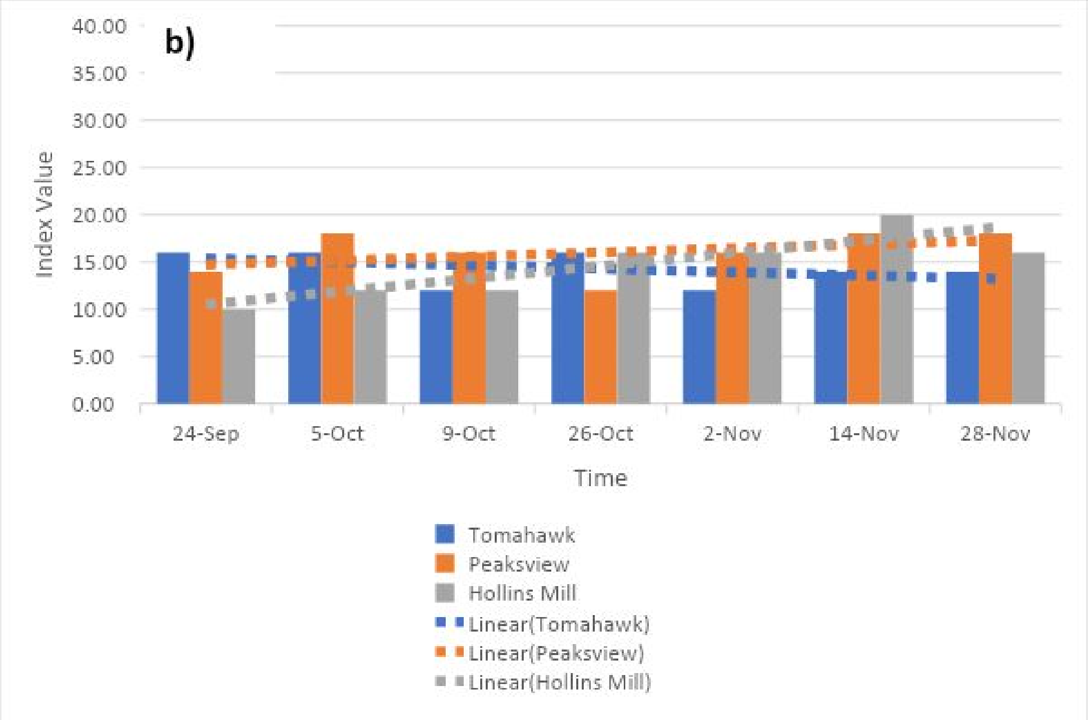

b)
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Index Value
24-Sep
5-Oct
9-Oct
26-Oct
2-Nov
14-Nov
28-Nov
Time
Tomahawk
Peaksview
Hollins Mill
Linear(Tomahawk)
Linear(Peaksview)
Linear(Hollins Mill)

Figure 5 – Calculated IBI macroinvertebrate indices for the three sampled stations historically (a) and during draining of College Lake (b).

Comparing EPT macroinvertebrates values between the two sampling periods (Fig. 6), a similar pattern emerges. Data gathered throughout the historical collection period illustrate that both Hollins Mill and Peaksview Park water quality is distinctive from Tomahawk Creek. Hollins Mill and Peaksview EPT increase in water quality from 2008 until 2015, as compared to the moderately low values found in Tomahawk during the same period in time (Fig 6a). Tomahawk consistently has lower EPT values compared to either Hollins Mill or Peaksview with the lowest value of 1.0 in 2013. Hollins Mill EPT water quality was the highest recorded in this study at 13.0 during 2015 but more recently was declining. Yet during the draining of the lake, this site experienced an unprecedented rapid decline to a value of 1.0 at the first sampling date after draining of the lake. Both Hollins Mill and Peaksview Park trend between 6 – 10 while Tomahawk Creek consistently trends between 2-4 on this scale. Similar to the IBI index, Hollins Mill water quality began to show improvement from the draining event once the lake began to refill toward the end of my data collection (Fig 6b).

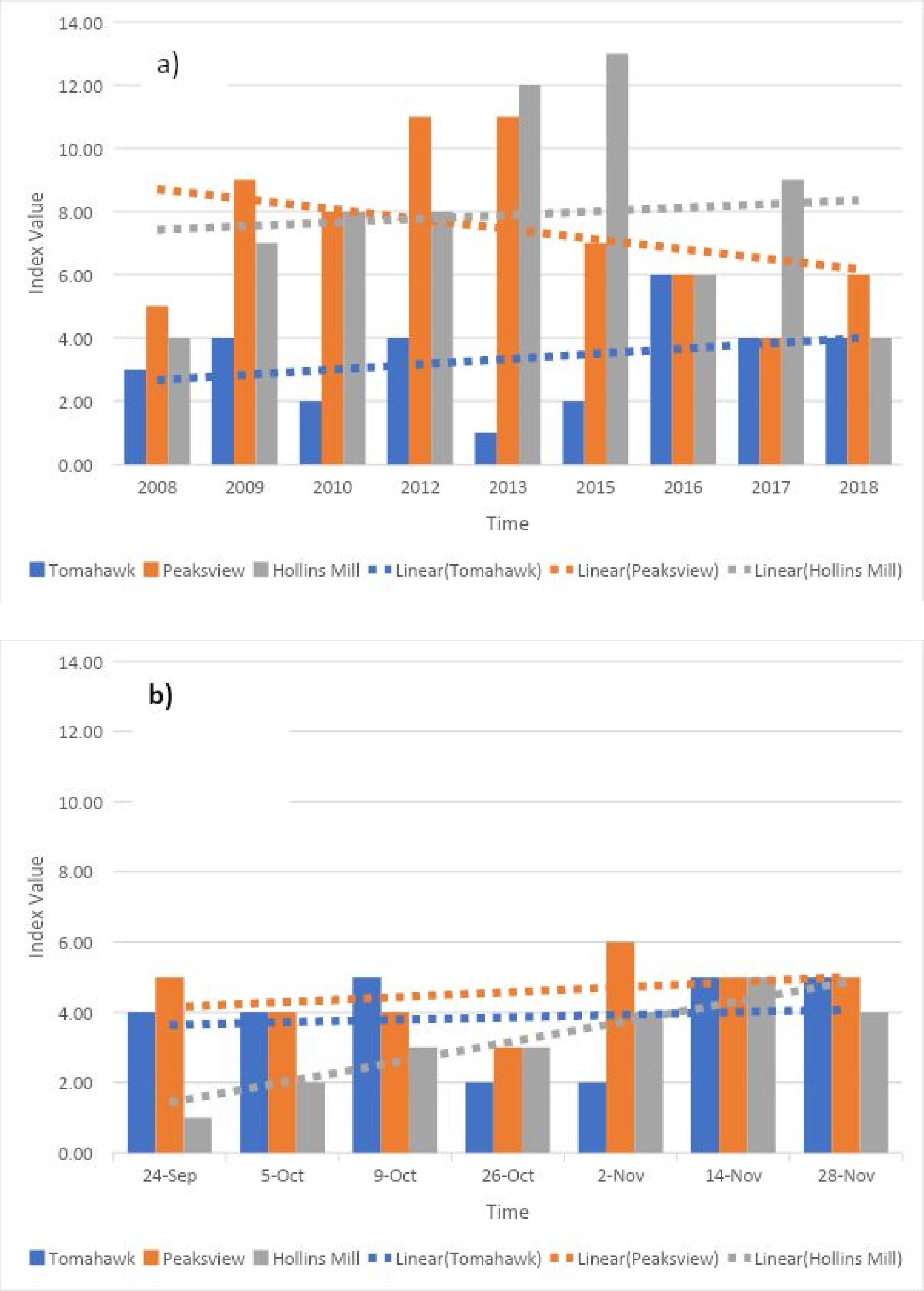


Figure 6 –Calculated EPT macroinvertebrate indices for the three sampled stations historically (a) and during draining of College Lake (b).

Historically, Tomahawk consistently has the lowest Percent Model Affinity (PMA) values (Fig. 7). PMA values for Tomahawk reached the lowest point in 2013, and yet in the same year, Peaksview and Hollins Mill had maintained higher and much better water quality, suggesting Hollins Mill is buffered from changes in water quality in the Blackwater Creek portion of the watershed. Again, while trend lines may differ in trajectory, Hollins Mill follows Peaksview's trends more so than Tomahawk in the historical portion of this study (Fig. 7a).

After College Lake was drained (beginning Sept 24, 2018) these trends changed (Fig 7b). Hollins Mill water quality fell well beyond any historical measure of water quality in this study while the other two stations did not. Hollins Mill had the steepest decline, by 91.40% from 72.20 measured in April of 2018 to just 6.25 on September of 2018. Data gathered at Hollins Mill did suggest an increase in water quality standards after that first measure in draining data, but remained relatively poor (PMA measures between 35-45) rather than the historically good to excellent water quality (PMA measures between 60-70) at this location. Some natural variation is evident here as Peaksview Park trended lower during the draining period for this index when compared to historical (Figs. 7a and b), but this may be isolated to this portion of the watershed as Tomahawk Creek measures were within historical observations.

Figure 7 –Calculated PMA macroinvertebrate indices for the three sampled stations historically (panel a) and during draining of College Lake (panel b).

Family Biotic Index values present a somewhat different view of water quality in this watershed (Fig. 8). Tomahawk Creek water was consistent with the lowest overall water quality in this study and the lowest historical value recorded at 7.0 in 2013 (Fig. 8a). Yet in contrast with other macroinvertebrate indices, Peaksview and Hollins Mill remained historically low and not better in water quality than Tomahawk Creek. During draining and recovery period (Fig. 8b) Hollins Mill had the overall worst value of 7.3 on October 9th, 2018, consistent with other macroinvertebrate indices. Yet this index suggests an influx of more intolerant macroinvertebrate species throughout the entire watershed, with declining water quality over time. This index may also be the most responsive to change (Fig. 8b), showing a rapid improvement at Hollins Mill and abruptly changing from the active draining (Sept. 24-Oct 9) to refilling of the lake (Oct 26 – Nov 28).

Figure 8 –Calculated FBI macroinvertebrate indices for the three sampled stations historically (a) and during draining of College Lake (b).

Comparing the measured sites chemically through conductivity (Fig. 9) I see a reverse in the patterns. Historically, Hollins Mill showed a trend more reflective of Tomahawk Creek than Peaksview Park (Fig. 9a). Peaksview measured the lowest conductivity in the study, at 66.0 µS. This result directly correlates with the lowest impervious surface coverage, just 5%, in the watershed above the sample point throughout my study (Table 3). Tomahawk had the highest levels of conductivity throughout, with Hollins Mill conductivity very closely resembling those values. This suggested that while the Blackwater portion of the watershed is 39.7% of the total watershed area, it contributes a greater proportion of total water flow through the Hollins Mill area (Table 3). In fact and supported by the conductivity data similarities between Hollins Mill and Tomahawk Creek, urban flow now dominates the water quality at this sapling site. Due to the increasing levels of impervious surfaces, conductivity of Tomahawk Creek continued to trend upward while the downward trend at Peaksview Park appeared reflective in the steady trending of Hollins Mill (Fig. 9a). Similar trending during the lake draining and subsequent refilling were seen in the conductivity data (Fig. 9b). Conductivity values at Hollins Mill tracked strongly with Tomahawk during the draining period and then began to decline after the lake was refilled. The importance of College Lake impacting water quality is strongly visible in these trends.

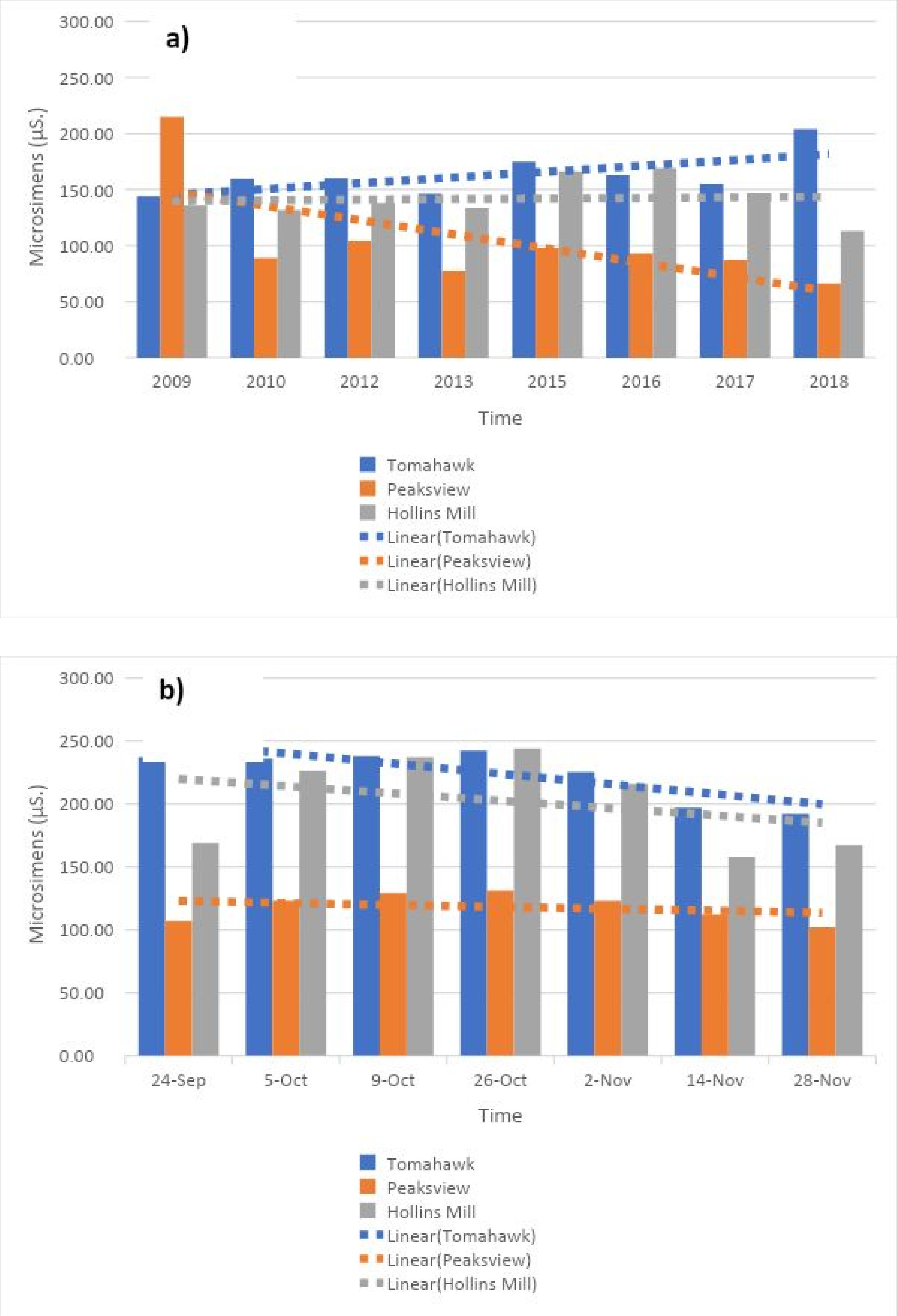


Figure 9 – Measured conductivity for the three sampled stations historically (a) and during draining of College Lake (b).

Nitrate concentrations were variable throughout the historical sampling period (Fig. 10a). Tomahawk consistently had the highest nitrate levels, trending upward through the sampling period. Hollins Mill and Peaksview Park tracked very closely together. During the draining period (Fig. 10b), Hollins Mill nitrate levels were much more in line with Tomahawk Creek than Peaksview Park. When the lake refilled these levels began to trend back toward measures at Peaksview Park, in line with historical levels.

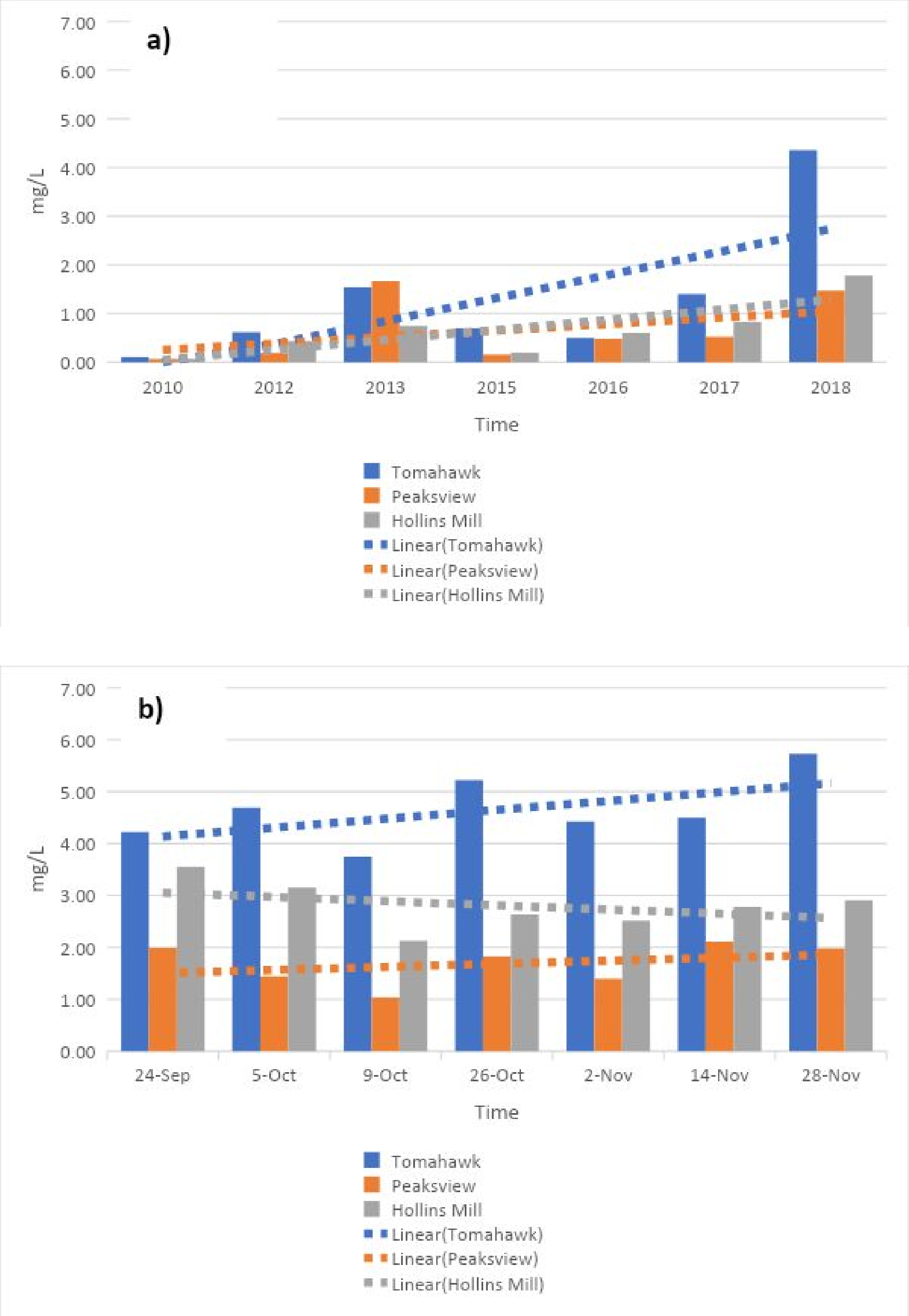


Figure 10 – Measured concentrations of nitrates for the three sampled stations historically (a) and during draining of College Lake (b).

Comparisons of the historical and draining measures yielded multiple patterns concerning the lake draining event and the natural variability of macroinvertebrates in this watershed (Table 3). EPT is a good measure of water quality but also quite variable compared to historical data. In the historical data, Hollins Mill (EPT = 7.89) and Peaksview Park (EPT = 7.44) are very similar while Tomahawk Creek (EPT = 3.33) water quality is much lower in this index. Changes during the draining event at Hollins Mill were highly significant, with worsening water resembling Tomahawk Creek rather than historical similarities with Peaksview Park. Yet over this same sampling period, Peaksview Park EPT water quality significantly changed as well. Thus, while EPT is a good measure of water quality, it is variable among the sampling episodes to suggest its measure is more reflective of macroinvertebrate life cycle changes than response to pollution events.

The remaining indices suggest otherwise (Table 3). Reductions in IBI and PMA at Hollins Mill were significantly different than historical trends only at this site. The other sampling sites were not significantly different. This reflected a change between historical data and post draining data at Hollins Mill that can be attributed to the draining event because Tomahawk and Peaksview are not downstream of the draining of College Lake. The FBI index, while suggesting a worsening at all of the sites, was not significantly different. As suggested earlier (Fig. 8), the FBI index did not indicate differences between sites in this data set and is not a good representative demonstrating change here.

Table 3 – Comparison of means of historical (2008-2018) vs draining data (Sept – Nov 2018) macroinvertebrate data. I used an ANOVA with Tukey's HSD to derive each pairwise comparison. Values in bold represent significance difference at 0.05 level. Values reported as mean ± standard error.

	Historical (N=9)	*Draining (N=7)*	*Significance*
Hollins Mill EPT	7.89 ± 1.05	3.14 ± 0.51	**0.001**
Hollins Mill IBI	24.00 ± 2.49	14.57 ± 1.49	**0.014**
Hollins Mill PMA	66.49 ± 2.9	40.43 ± 6.51	**0.004**
Hollins Mill FBI	4.44 ± 0.36	4.84± 0.63	0.671
Tomahawk Crteek EPT	3.33 ± 0.5	3.86 ± 0.51	0.499
Tomahawk Creek IBI	16.04 ± 0.99	14.29 ± 0.68	0.229
Tomahawk Creek PMA	41.41 ± 5.8	44.76 ± 5.85	0.819
Tomahawk Creek FBI	4.83 ± 0.38	5.35± 0.29	0.367
Peaksview Park EPT	7.44 ± 0.84	4.57 ± 0.37	**0.026**
Peaksview Park IBI	22.13 ± 1.42	16.00 ± 0.87	0.051
Peaksview Park PMA	64.79 ± 3.31	52.13 ± 3.43	0.101
Peaksview Park FBI	4.29 ± 0.33	4.88 ±0.23	0.852

Discussion

Environmental Parameters Measuring Water Quality Change

Monitoring of macroinvertebrates is well recognized as a good measure of water quality (Lenat and Crawford 1994, Wallace and Webster 1996, Barbour et al. 1999) in response to changing land use (Allan 2004), urbanization (Morse et al. 2003) and increasing impervious surface (Booth and Jackson 1997). The principle components analysis supported the use of macroinvertebrates to indicate critical differences between measured historical and draining data sets. The addition of nitrates and conductivity can be warranted as indicators of varied land use (Line 2013) and stormwater impact (Mallin et al. 2009). These parameters provided reliable indicators suggesting changes in water quality due to lake draining. Total phosphorus, a limiting nutrient in freshwater systems and the third major pollutant in rivers (Parry 1998), was excluded from my analysis. Phosphorus is typically a reliable standard to judge water quality, however in this study, TP levels were not a significant predictor. Temperature was an important factor in this study during draining, and Prathumratana, Sthiannopkao and Kim (2008) found temperature correlated well with water quality changes, causing algal blooms and rising pollutant levels. However, because data gathered during historical and draining were in different seasons, I could not justify addressing this parameter. Also, pH, while an important factor from historical data, did not change during the draining and thus did not provide adequate predictions of change in this analysis.

Water Quality Impact of Dam Draining

The removal of small headwater dams often changes water chemistries minimally while adversely impacting macroinvertebrates (Mbaka & Mwanik 2015, Sullivan & Manning 2017).

I found this to be true in my study. Conductivity is known to directly correlate to volume of water flowing through waterways (Rusydi 2018), and thus the observation of Hollins Mill closely tracking with Tomahawk Creek conductivity before and after draining is expected. This infers a strong water chemistry relationship to the highly urbanized Blackwater portion of the watershed and the importance of College Lake Dam in filtration of pollutants. Nitrate data are more difficult to interpret. Urbanization throughout the watershed was driving up the concentrations of this nutrient independent of filtration from College Lake Dam (Fig. 10). After dam removal, Bohrerova et al. (2017) found increases in both nitrate and *E. coli* concentrations in streams. My data supports this conclusion with nitrates, and although I did not have historical data for *E. coli* comparisons, measures at the Hollins Mill averaged 1009.8 cfu/100ml while Tomahawk Creek and Peaksview Park were 221.6 and 416.4 cfu/100ml respectively. These trends deserve strong consideration as the city moves toward dam removal.

Observed changes in macroinvertebrate indices suggest the greatest concern and support for the decline of water quality that will result from dam removal. In my study all of the macroinvertebrate indices immediately responded negatively to the draining event. It is known that dams fundamentally change lotic ecosystems and the macroinvertebrate communities living in and around these dams (Tinneman et al. 2005, Martinez et al. 2013). My results suggest that the dam in this study maintained a positive effect on water quality while its removal may produce very adverse impacts. The lotic environment that the College Lake dam has created throughout Blackwater Creek over its 85-year existence has evolved around profound changes in the watershed urbanization and impervious surface. My data demonstrate (Table 1) that the Blackwater Creek portion of the watershed is very urbanized, and the Ivy Creek portion is urbanizing. Thus, it is important to understand the dynamics occurring in this watershed to completely understand how dam removal will impact water quality.

As water from Blackwater Creek flows through College Lake, it enters into a confluence with Ivy Creek and, eventually, to the sampling site of Hollins Mill. With the city of Lynchburg and the community of Forest continuing to urbanize and initiate developments, the percentage of impervious surfaces continues to increase while forested areas decline. As a result the rise in impervious surfaces detracts from available recharge zones. During precipitation events the water that once fell onto the soils of Lynchburg and filtered down into groundwater sources instead falls upon impervious surfaces. Modern, urban drainage systems funnel this water directly into waterways, creating an influx not naturally present. In addition to a sharp uptick in water quantity, an increase of urban developments and human presence correlates to additional pollutants collected in rain events. These additional pollutants then directly funnel into the waterways of Lynchburg. Tomahawk Creek displays this trend in increasing urbanization and corresponding worsening water quality. Our polluted waterways pose health risks to people living along the streams or participating in aquatic recreational activities as well as creating an unappealing environmental aesthetic. The urban development rates do not affect just the citizens of Lynchburg, but as the waters flow into the James River, all communities downstream are subject to this water quality decline in addition to their own concerns.

The waters of Blackwater Creek flow through highly urbanized areas and reflect this in the lower water quality standards. Hollins Mill should reflect equally the water quality of both Blackwater Creek and Ivy Creek as the watersheds are approximately equal in size, yet this is not the case. Blackwater Creek joins with Ivy Creek above Hollins Mill. Water quality of Hollins Mill remains slightly impaired due to Blackwater Creek’s input but is far less impacted due to

College Lake filtering, as suggested by the historical data. An expected equal mix between upstream water quality of Blackwater Creek and Ivy Creek does not appear in the data gathered at Hollins Mill. Historically, Hollins Mill did not reflect the impaired waters of Blackwater Creek, as sampled at Tomahawk and to predicted levels.

Tomahawk represents roughly one third of the total Blackwater Creek watershed. The additional watersheds of Blackwater Creek not included in this study include Dreaming Creek (22 % impervious) and Rock Castle Creek (22.8% impervious) which are highly urbanized similarly to Tomahawk Creek. It is obvious that College Lake plays a critical role in filtering pollutants present upstream in Blackwater Creek. As College Lake filters water from all of these urbanized streams, these captured pollutants and sediments do not impact Hollins Mill at the level expected based on equal volume contributions of Ivy and Blackwater creeks. As water in Blackwater Creek reaches College Lake, pollutants that were present in the Tomahawk sampling site are filtered out. Once the water quality is improved after filtering through College Lake, Blackwater Creek joins with Ivy Creek. Therefore, when sampling is done at Hollins Mill, this water reflects water quality contribution more from Ivy Creek than Blackwater Creek. College Lake acts as a filter, for the lower quality of water above the lake at Tomahawk is shown not to have as strong a contribution via the outflow of Blackwater Creek as Ivy Creek.

The system in place since 1934 of College Lake filtering pollutants upstream in Blackwater Creek will be altered with removal of the dam. Removing the dam at College Lake suggests Blackwater Creek has the potential to return to its natural state of a complete stream system without a reservoir. However, College Lake had been filtering pollutants from Blackwater Creek for over 80 years. Removal of the dam system will expose collected toxins from almost a century, washing them downstream as stream channelization cuts through past decades of sediment accumulation. I have demonstrated that every single macroinvertebrate index achieved their lowest value ever recorded during the draining of College Lake. Because macroinvertebrates were the most indicative parameter for water quality standards, as suggested in PCA analysis, their steep decline in value indicates the removal of the College Lake dam will flush pollutants downstream, impacting overall water quality in the city and the Chesapeake Bay Watershed.

The current plans in place by the city of Lynchburg for removal of College Lake Dam need careful consideration. If these plans come into fruition, it is highly advisable to ensure strict mitigation to maintain water quality standards. This study indicates the detrimental effects on water quality that removing the functionality of the dam caused in late 2018. Exposed sediment washed downstream, and Blackwater Creek cut a channel into the lake bed, which steadily widened and allowed more sediment to enter the waterway. Eliminating the existence of College Lake necessitates a number of operations to ensure water quality does not degrade rapidly.

Solutions

The City of Lynchburg has been in conversation with AECOM Technical Services, Inc., an engineering firm, to develop a plan for the removal of the College Lake Dam. This includes investigations into wetland construction and restoration, preservation, and enhancement. In addressing concerns of channel creation and in order to prevent the channel collapse occurring in 2018 during the period of lake drainage, AECOM sought to develop a riverine system morphologically in accordance with surrounding geomorphology, hydrology, and ecology. The University of Lynchburg and the City of Lynchburg cooperated to plan for establishment of a wetland learning laboratory, where students would have the opportunity to engage in analyzing ecological functions of this newly constructed wetland.

A possible solution for removal of the dam is to establish wetlands where the lakebed of College Lake had previously existed, as AECOM proposes. Wetland-obligate species are already present as sedimentation creates areas of shallower depths within College Lake. Additionally, wetlands are one of the most viable ecosystems for improving water quality. They can act as sediment traps, where sediment in the water column settles as the wetland decreases flow velocity. Wetland plants generate a high amount of dissolved oxygen, providing an ideal environment for bacteria to break down pollutants (Kennedy & Mayer 2002). In the case of urban constructed wetlands, nutrient removal is an average of 60% (Shutes 2001. However, in man-made wetlands, there is a great need for consideration of the surrounding environment in the construction process. In a survey of 120 constructed wetlands, a majority encountered problems with distribution of inflow, debris collection in the outflow, weed infestations, tree growths, and above-ground flow (Cooper, Griffin & Cooper 2005). Establishing a wetland at the site of College Lake would not solve the concern of sediment accumulation. As stated, wetlands slow the velocity of the inflow, allowing sediment to settle. The surrounding watershed of College Lake suggests this sediment problem would continue. With a riverine system it's possible sediment accumulation would have a greater impact due to the lower ratio of water volume compared to the water volume of College Lake. Constructed wetlands require a great deal of oversight and planning to be effective in their ecological role.

Sediment starvation, or the loss of sediment present downstream of dams, can be cited as a supporting factor when considering dam removal. The absence of sediment in a lotic system can lead to erosion of river banks and beds (Kondolf 1997). However, as toxins and heavy metals are tied to sediment in urbanized watersheds (Poff & Hart 2002), there is an ecological advantage of allowing the sediment to settle in College Lake instead of filtering downstream. Sediment starvation is typically a main concern in systems with large dams or dams in immediate proximity to coastal ecosystems (Kondolf, Rubin & Minear 2014).

In addition to removing College Lake and constructing wetlands, a possible solution to mitigate flood risk would be to keep the dam and dredge College Lake. Lake dredging, like constructed wetlands, is a relatively new solution to the detrimental effects of anthropogenic activities. In the water column after dredging of a lake, phosphorus organic matter, total suspended solids, Chlorophyll *a* and turbidity levels decreased (Zhang et al. 2010). This same study found water depth, electrical conductivity, total dissolved solids, and nitrate levels increased after dredging. Dredging College Lake would result in a greater water depth, mitigating the issue of dam failure in the event of heavy storms. The water storage capacity could as well be reminiscent of what it once was in the Lake's formative years.

When the eventual action occurs for implementing a solution to mitigate the risk of College Lake dam failure, it is of societal and ecological benefit to limit the corresponding consequences. Viable longevity of the mitigation will additionally limit the possibility of once again considering solutions to this problem. As this study has suggested, downstream water quality is cause for concern in this instance of dam removal. If the lake basin is to become a wetland, preliminary dredging of sediment would decrease the possibility of releasing stored pollutants and keep limits within state and federal regulations. For example, *E. coli* levels were found to be in violation of Virginia Law 9VAC25-260-170 by exceeding accepted levels of a mean of 126 counts/100mL due to sediment release during draining. Wetland construction does offer a way to minimize pollutant and bacteria release in the event of dam removal. College Lake has already seen an increase in wetland areas along the perimeter due to sediment accumulation, and these areas should be expanded to not allow for any exposed lakebed. Detailed and thorough plans for the lakebed are necessary to prevent any event like the 2018 draining.

References

Addinsoft, 2019. XLSTAT statistical and data analysis solution. Long Island, NY, USA. https://www.xlstat.com.

Allan JD., 2004. Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. *Annual Revew of Ecology, Evolution and Systematics*. 35: 257–284.

Baird, R. and L. Bridgewater, 2017. *Standard methods for the examination of water and wastewater*. 23rd edition. Washington, D.C.: American Public Health Association.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Blackwater Creek Watershed Planning Committee. 2008. *Blackwater Creek Watershed Management Plan.* Retrieved from https://www.lynchburg.edu/wp-content/uploads/watershed-management/Blackwater-Creek-Watershed-Management-Plan.pdf

Bohrerova, Z., E. Park, K. Halloran, and J. Lee. 2017. Water quality changes shortly after low-head dam removal examined with cultural and microbial source tracking methods. *River Research and Applications*. 33: 113-122.

Booth D. and D. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resoures Association,* 33: 1077–1090.

Bowen, Z.H., K.B. Bovee, and T.J. Waddle. 2003. Effects of flow regulation on shallow-water habitat dynamics and floodplain connectivity. *Transactions of the American Fisheries Society*, 132: 809-823.

Carico, J.E., S.J. Gamble, C. Gibbon, P.J. Osborne, G.W. Ramsey, W.G. Rivers, W.A. Sherwood, O.O. Stenroos, and S. Whitt. 1973. An Outdoor Instructional Laboratory: Lynchburg College Lake. Lynchburg College. Lynchburg, Virginia.

Cooper, D., P. Griffin, and P. Cooper. 2005. Factors affecting the longevity of sub-surface horizontal flow systems operating as tertiary treatment for sewage effluent. *Water Science and Technology*, 51(9): 127–135.

Cushing, C. and J. Allen. 2001. *Streams: Their Ecology and Life*. Gulf Professional Publishing, Houston TX.

EPA. 2017. Standard operating procedure calibration of field instruments. Quality Assurance Unit U.S. Environmental Protection Agency - Region 1, North Chelmsford, MA.

Evans, J.E., S.D. Mackey, J.F. Gottgens, and W.M. Gill. 2000. Lessons from a dam failure. *Ohio Journal of Science,* 100: 121– 31.

Gangloff, M. M. 2013. Taxonomic and ecological tradeoffs associated with small dam removals. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 23: 475–480.

Hilsenhoff, W. L. 1977. Use of arthropods to evaluate water quality of streams. Technical Bulletin Number 100, Department of Natural Resources, Madison, Wisconsin, USA.

Karr, J.R. and E.W. Chu. 1999. *Restoring Life in Running Waters: Better Biological Monitoring*. Island Press, Washington DC.

Kennedy, G., and T. Mayer. 2002. Natural and constructed wetlands in Canada: an overview. *Water Quality Research Journal,* 37 (2): 295–325.

Kondolf, G. M. 1997. Hungry water: Effects of dams and gravel mining on river channels, *Environmental Management*, 21(4): 533– 551.

Kondolf, G. M., Z.K. Rubin, and J.T. Minear. 2014. Dams on the Mekong: Cumulative sediment starvation, *Water Resources Research,* 50: 5158– 5169.

Lenat, D. 1993. A biotic index for the southeastern United States: derivation and list of tolerance values, with criteria for assigning water-quality ratings. *Journal of the North American Benthological Society*. 12: 279-290.

Lenat, D.R. and J.K. Crawford. 1994. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. *Hydrobiologia,* 294: 185–199.

Lillie, R.A., S.W. Szczytklo, and M.A. Miller. 2003. *Macroinvertebrate Data Interpretation Guidance Manual*. Wisconsin Department of Natural Resources.

Line, D. 2013. Effect of development on water quality for seven streams in North Carolina. Environmental Monitoring and Assessment.185: 6277-6289.

Lynchburg College. 1973. A brief history of College Lake. *Improving instruction in environmental studies through development of College Lake as an instructional laboratory* 4-7.

Mahler B.J., P.C. Van Metre, and E. Callender. 2001. Trends in metals in urban and reference lake sediments across the United States, 1970 to 2001. *Environmental Toxicology and Chemistry*, 25(7): 1698-1709.

Mallin, M., V. Johnson, and S. Ensign. 2009. Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. *Environ Monit Assess* 159: 475–491.

Mantel, S., N. Rivers-Moore, and P. Ramulifho. 2017. Small dams need consideration in riverscape conservation assessments, *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27:748–754.

Martínez, A., A. Larrañaga, A. Basaguren, J. Perez, C. Mendoza-Lera, and J. Pozo. 2013. Stream regulation by small dams affects benthic macroinvertebrate communities: from structural changes to functional implications. *Hydrobiologia,* 711: 31–42.

Mbaka, J.G. and M.W. Mwaniki. 2015. A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates. *Environmental Reviews,* 23: 257–262.

McCully, P. 1996. *Silenced Rivers: The ecology and politics of large dams*. Zed Books. London England.

Morse C., A. Huryn, and C. Cronan. 2003. Impervious surface area as a predictor of the effects of urbanization on stream insect communities in Maine, U.S.A. *Environ Monit Assess* 89: 95–127.

Naselli-Flores, L. 2008. Urban Lakes: Ecosystems at risk, worthy of the best care, *Proceeding of Taal 2007: The 12th World lake conference*, Sengupta, M. and Dalwani, R., Ed., 1333-1337.

Newman, J., D.R. Perault, and T.D. Shahady. 2006. Watershed development and sediment accumulation in a small urban lake. *Lake and Reservoir Management,* 22(4): 303-307.

Novak, M. and R. Bode. 1992. Percent model affinity: A new measure of macroinvertebrate community composition. *Journal of the North American Benthological Society*, 50C. 11: 80-85.

Oliver, M. and G. Grant. 2017. Liberated rivers: lessons from 40 years of dam removal. Science Findings 193. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p.

Parry, R. 1998. Agricultural phosphorus and water quality: A U.S. Environmental Protection Agency perspective. *Journal of Environmental Quality,* 272: 258-261.

Plafkin, J. L., M. T. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. United States Environmental Protection Agency EPA/ 444/4-89-001.

Poff, N.L. and D.D. Hart. 2002. How dams vary and why it matters for the emerging science of dam removal. *BioScience* 52: 659– 68.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The Natural Flow Regime: A paradigm for river conservation and restoration. *BioScience,* 47: 769-784.

Prathumratana, L., S. Sthiannopkao, and K.W. Kim. 2008. The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. *Environment International*, 34: 860-866.

Ries, K.G., J.D. Guthrie, A.H. Rea, P.A. Steeves, and D.W. Stewart. 2008. StreamStats: A water resources web application: U.S. Geological Survey Fact Sheet 2008-3067, 6 p.

Rusydi, A.F. 2018. Correlation between conductivity and total dissolved solid in various type of water: A review. *IOP Conf. Series: Earth and Environmental Science,* 118: 012019.

Schueler, T.F., L. Franley-McNeal, and K. Cappiella. 2009. Is impervious cover still important? Review of Recent Research. *Journal of Hydrological Engineering,* 14: 309-315.

Shutes, R.B.E. 2001. Artificial wetlands and water quality improvement. *Environment International* 26.5-6: 441–447.

Stanley, E. H. and M.W. Doyle. 2003. Trading off: the ecological effects of dam removal. *Frontiers in Ecology and the Environment*, 1: 15-22.

Sullivan, S.M. and D.W. Manning. 2017. Seasonally distinct taxonomic and functional shifts in macroinvertebrate communities following dam removal. *PeerJ.* 5: e3189.

Talian, J. 2014. *The College Lake dam study: Fact sheet*. City of Lynchburg.

Tiemann, J.S., D.P. Gillette, M.L. Wildhaber, and D.R. Edds. 2005. Effects of lowhead dams on the ephemeropterans, plecopterans, and trichopterans group in a North American river. *Journal of Freshwater Ecology,* 20: 519–525.

Wallace, J. and J. Webster. 1996. The role of macroinvertebrates in stream ecosystem function. *Annual Review of Entomology*, 41: 115–139.

Warden, P., M. DeSarno, S. Volk, and B. Eldred. 2011. Evaluation of Colilert-18 for detection and enumeration of fecal coliform bacteria in wastewater using the U.S. Environmental Protection Agency alternative test procedure protocol. *Journal of AOAC International*. 94:1573-1580.

Wildi, W., J. Dominik, J.L. Loizeau, R.L Thomas, P.Y. Favarger, L. Haller, A. Perroud, and C. Peytremann. 2004. River, reservoir and lake sediment contamination by heavy metals downstream from urban areas of Switzerland. *Lakes & Reservoirs: Research & Management,* 9: 75-87.

Voshell, JR. 2002. *A guide to common freshwater invertebrates of North America.* McDonald and Woodward Publishing.

Zhang, S., Q. Zhou, D. Xu, J. Lin, S. Cheng, and Z. Wu. 2010. Effects of sediment dredging on water quality and zooplankton community structure in a shallow of eutrophic lake. *Science Direct,* 22: 218-224.

Acknowledgements

I would like to thank each member of my committee for their help with my research and thesis. For Dr. Perault, in his willingness to help if I needed it and encouragement of my research interests. For Dr. Cowden, in her detailed comments and dedication to creating a polished final research product. For Dr. Shahady, in walking me through all steps of conducting research and being exceedingly patient with me during this process and throughout the years we have worked together.

I would also like to thank my friends, who listened to my gripes with writing but always reminded me of the importance of this project and the great benefit this has for me and the Lynchburg community.