Restoring Water Quality in the Lake Memphremagog Basin: 2016 Water Quality Report

Prepared for the

NorthWoods Stewardship Center and

Vermont Department of Environmental Conservation

by

Fritz Gerhardt, Ph.D.

10 March 2017

Memphremagog Watershed Association

The Memphremagog Watershed Association (MWA), founded in 2007, is a nonprofit organization dedicated to the preservation of the environment and natural beauty of the Lake Memphremagog Basin. The Memphremagog Watershed Association achieves this mission by 1) promoting the ecological awareness of people who live in, work in, and visit the Lake Memphremagog Basin; 2) promoting efforts to preserve the environment and natural beauty of the basin; 3) working with area lake associations; local, state, and federal governments; and businesses to develop guidelines and policies that protect and improve the quality of life in and around the basin; and 4) participating in efforts to monitor water quality in the lake and its tributaries, clean-up and re-naturalize shorelines, and protect local plants and wildlife.

Beck Pond LLC

Beck Pond LLC, a limited liability company founded in 2009, partners with public and private organizations to conduct scientific research that not only increases our understanding of the natural environment but also informs and guides on-the-ground conservation and management. Among other projects, Beck Pond LLC has conducted scientific studies and participated in conservation projects that assess the impacts of historical land uses on forest plant communities; assess the impacts of invasive plants on grasslands and forests; identify, assess, and propose solutions to water quality problems in the Lake Memphremagog Basin and other watersheds in Vermont; protect and restore floodplain forests and wetlands in the Lake Memphremagog Basin and along the Connecticut River; and identify and protect critical wildlife habitats across northern New England and eastern Canada.

Cover. *Wetlands fill this old channel of the Barton River in Irasburg, Vermont on 21 August 2015. These wetlands formed when the Barton River was diverted and channelized to allow construction of the Connecticut & Passumpsic Rivers Railroad along the floodplain of the Barton River in 1863. These wetlands are currently managed by the Vermont Fish & Wildlife Department as part of the Willoughby Falls Wildlife Management Area and provide important habitat for fish and wildlife and improve water quality by filtering nutrients and sediment and absorbing floodwaters.*

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Executive Summary

1. Over the past decade, there has been increasing concern about water quality conditions in Lake Memphremagog, especially the high phosphorus levels and more frequent and widespread algal and cyanobacterial blooms. Because most of the lake's watershed lies in Vermont, considerable effort has been expended to identify, assess, and remediate nutrient and sediment sources along the Vermont tributaries of Lake Memphremagog. In 2016, we undertook a three-part project to continue these efforts by further pinpointing and assessing possible sources of water quality problems and identifying and developing projects to correct those problems.

2. In the first part of this project, we undertook targeted water quality sampling to further pinpoint and assess possible nutrient and sediment sources and to gauge the effectiveness of phosphorus-reduction projects and practices that have been implemented along the Vermont tributaries of Lake Memphremagog and the Tomifobia River. To accomplish these goals, we collected and analyzed water samples for total phosphorus, total nitrogen, and turbidity at 31 sites on eight dates during April-October 2016. With these data, we were able to further pinpoint and assess the sources of the high phosphorus and nitrogen levels measured previously in three tributaries (Airport and St. Onge tributaries and the north branch of Sucker Brook). In addition, we assessed nutrient and sediment levels in four tributaries that had not been sampled previously (Town Line Brook and three tributaries of Stearns Brook).

3. Finally, we evaluated the success of water quality improvement projects and practices along five tributaries. In general, water quality conditions remained greatly improved along Crystal Brook and the Strawberry Acres Tributary, where phosphorus-reduction projects were implemented previously. In addition, some improvement in water quality was evident at several sites along Brighton Brook and its northern tributary and the tributary of Stearns Brook, where farmstead improvement projects and field practices were implemented during 2015-2016. On the other hand, phosphorus and sediment levels remained high at several sites along the Junkyard Tributary, where field practices have been improved in several steep, highly-erodible corn fields.

4. In the second part of this project, we updated the mapping and identification of the subwatersheds that exhibited the highest total phosphorus concentrations along the Vermont tributaries of Lake Memphremagog during 2005-2016. Like previous analyses, the highest mean total phosphorus concentrations were concentrated in several areas, including upstream sections of the Black River and three of its tributaries (Brighton Brook and the Airport and St. Onge tributaries), downstream sections of the Barton River and two of its tributaries (Hamel and Junkyard Tributaries), downstream sections of the Johns River and its tributary Crystal Brook, two small tributaries that flow directly into Lake Memphremagog (Holbrook Bay and Wishing Well Tributaries), and several tributaries of Stearns Brook. We will focus efforts to identify and correct specific sources of water quality problems in these priority subwatersheds, especially those actions undertaken through the Memphremagog Regional Conservation Partnership Program (RCPP).

5. In the third part of this project, we continued developing and testing a methodology for calculating phosphorus load reductions that might be achieved by implementing Best Management Practices (BMP) as part of the Total Maximum Daily Load (TMDL) and Basin Plan being developed for Lake Memphremagog. To do this, we modified the BMP Scenario Tool developed for Lake Champlain to represent the land uses, projects and practices, and loading reductions that were most appropriate for the Lake Memphremagog Basin. We then tested this tool for six tributary watersheds of Lake Memphremagog. For these six watersheds, we estimated that implementing various projects and practices has the potential to reduce phosphorus loads by 25-60% across a broad range of land uses, including farmsteads, cultivated lands, hay, pasture, dirt roads, and developed impervious surfaces. In addition, the modeled reductions in phosphorus loads often corresponded well with other estimates of the load reductions achieved to date by projects and practices that had already been implemented in these same six watersheds.

6. Finally, we continued to share the results of these analyses with key project partners in order to identify and assess possible nutrient and sediment sources, to develop and implement projects and practices that improve water quality, and to engage land owners and land managers in efforts to develop and implement projects and practices that most effectively protect and improve water quality.

7. Collectively, these data and analyses greatly increased our understanding of water quality conditions and possible sources of water quality problems in the Lake Memphremagog and Tomifobia River Basins. With these data, we were able to identify and assess possible nutrient and sediment sources and to identify and develop projects and practices to protect and improve water quality. In 2017, we will continue to refine our knowledge about nutrient and sediment sources along the Vermont tributaries of Lake Memphremagog and the Tomifobia River and to identify and implement on-the-ground protection and restoration projects that most effectively reduce nutrient and sediment inputs into the surface waters of the Lake Memphremagog and Tomifobia River Basins.

Introduction

Lake Memphremagog straddles the United States/Canada border between the Northeast Kingdom of Vermont and the Eastern Townships (Cantons de l'Est) of Quebec. Lake Memphremagog and its tributaries are highly-valued resources that provide important ecological, economic, and aesthetic benefits. Over the past decade, there has been increasing interest in protecting and improving water quality in Lake Memphremagog and its tributaries. This interest has been spurred by concerns that water quality in Lake Memphremagog was declining and is now threatened by high nutrient and sediment levels, more frequent and widespread algal blooms, and accelerated eutrophication (Figure 1). This concern has been further exacerbated by more frequent and widespread occurrences of cyanobacterial (blue-green algal) blooms, especially during the past several years (Figure 2).

Figure 1. *Turbid water and algae near the mouth of the Johns River in Derby, Vermont in 2006. Excessive nutrients and sediment increase plant and algal growth and decrease water quality.*

Figure 2. *Cyanobacterial bloom along the north shore of Derby Bay in Derby, Vermont on 23 September 2008 (photo courtesy of Karen Lippens). Cyanobacterial blooms are exacerbated by high nutrient and sediment levels and indicate that water quality is declining in Lake Memphremagog.*

Lake Memphremagog and its tributaries support a wide array of recreational activities, economic benefits, and ecological functions. Water bodies in the basin are used extensively for boating, swimming, fishing, hunting, nature-viewing, and other recreational activities. Lake Memphremagog and the Clyde River (one of four principal tributaries of Lake Memphremagog in Vermont) are important links in the Northern Forest Canoe Trail, which extends 1,191 km (740 mi) from Old Forge, New York through Vermont, Quebec, and New Hampshire to Fort Kent, Maine. Lake Memphremagog and other water bodies in the basin serve as public water supplies, provide hydroelectric power and disposal of treated wastewater, and support agricultural and industrial production. The floodplains and the many wetlands around the lake and its tributaries serve important flood control and water filtration functions and provide important fish and wildlife habitat. In addition, the surface waters and associated habitats support a number of rare plants and animals and significant natural communities, which contribute greatly to regional biodiversity.

Lake Memphremagog and its tributaries currently face a number of threats, including elevated sediment and nutrient levels, elevated mercury levels, excessive algal growth, eutrophication, and exotic species invasions (State of Vermont 2012, 2014b, 2014c, Quebec/Vermont Steering Committee 2008). The Southern Basin, which lies primarily in Vermont and is the shallowest segment of Lake Memphremagog, is listed by the State of

Vermont as impaired and in need of a Total Maximum Daily Load (TMDL) due to elevated phosphorus levels, nutrient enrichment, and excessive algal growth (Part A, State of Vermont 2014b). Lake Salem, which is situated along the Clyde River, is already subject to an approved TMDL addressing elevated mercury levels in walleye (*Stizostedion vitrium*)(Part D, State of Vermont 2014b). Several lakes and ponds in the basin have been altered by locally abundant Eurasian watermilfoil (*Myriophyllum spicatum*): Lakes Derby and Elligo and Brownington and Great Hosmer Ponds (Part E, State of Vermont 2014b). Two water bodies have been altered by flow regulation: an unnamed tributary of the Clyde River, due to possible lack of minimum flows below a water supply intake, and Shadow Lake, where seasonal water level fluctuations may be altering aquatic habitats and aesthetics (Part F, State of Vermont 2014b). Finally, a number of water bodies have been listed as stressed: 1) Johns River due to elevated nitrogen and turbidity levels; 2) Lake Memphremagog, South Bay, and Clyde Pond due to elevated mercury levels in walleye; 3) Lake Salem due to elevated *Escherichia coli* levels in the inlet streams and lake; and 4) the Barton River in Orleans due to the presence of toxins (State of Vermont 2014c).

Efforts to identify and assess the various threats and to protect and improve water quality in the Lake Memphremagog Basin are coordinated by the Quebec/Vermont Steering Committee on Lake Memphremagog, an international partnership of governmental and non-governmental stakeholders from Quebec and Vermont. Since 2004, the Steering Committee has coordinated water quality monitoring efforts in both Quebec and Vermont. The overall goal of these efforts has been to identify, prioritize, and implement projects that protect and improve water quality throughout the Lake Memphremagog Basin. To that end, monitoring efforts have focused on documenting water quality conditions throughout the basin, assessing compliance with applicable water quality standards, calculating phosphorus loading in order to develop a comprehensive pollution control plan for the Vermont waters, identifying possible sources of water quality problems, identifying and prioritizing watersheds where protection and restoration projects will most effectively reduce nutrient and sediment loads, and developing and implementing on-the-ground projects and practices to protect and improve water quality in the basin. Since 71% of the basin lies in Vermont, monitoring efforts have focused on assessing water quality conditions and identifying nutrient and sediment sources along the Vermont tributaries of Lake Memphremagog.

Study Goals

In 2016, the NorthWoods Stewardship Center, Memphremagog Watershed Association (MWA), Vermont Department of Environmental Conservation (DEC), and Beck Pond LLC again partnered to undertake a multi-part program to protect and improve water quality in the Lake Memphremagog Basin as well as along Stearns Brook, a tributary of the Tomifobia River. First, we undertook targeted water quality sampling focused on three categories of sites: 1) four tributaries where nutrient and sediment data were lacking because they had not been sampled previously, 2) three tributaries where high phosphorus levels had been measured previously but remained poorly understood, and 3) five tributaries where phosphorus-reduction projects and practices had been implemented previously. Second, we used the water quality data collected during 2005-2016 to identify and prioritize those subwatersheds that exhibited the highest total phosphorus concentrations and where protection and restoration projects would likely be most effective at reducing phosphorus inputs into the surface waters of the Lake Memphremagog Basin. Third, we continued to develop and test models for estimating the phosphorus load reductions that would be achieved by implementing phosphorus-reduction projects and practices to accomplish the goals of the Total Maximum Daily Load (TMDL). As in previous years, we continued to share these data and analyses with key agency and organizational partners, who were able to further evaluate the need for and develop and implement projects and practices to reduce nutrient and sediment exports into the Lake Memphremagog Basin. Collectively, these efforts greatly increased our understanding of water quality problems and allowed us to continue developing and implementing protection and restoration projects and practices where they will most effectively reduce nutrient and sediment exports into Lake Memphremagog.

Study Area

The Lake Memphremagog Basin is located in the Northeast Kingdom of Vermont and the Eastern Townships (Cantons de l'Est) of Quebec and is a tributary watershed of the Saint-François River, which ultimately flows into the St. Lawrence River. This study focused on the Vermont portion of the Lake Memphremagog Basin, which includes approximately 1,266 km^2 (489 mi^2) in Orleans, Essex, Caledonia, and Lamoille Counties in northeastern Vermont (Figure 3). The Southern Basin of Lake Memphremagog is fed by three major tributaries that lie entirely within the state of Vermont (Barton, Black, and Clyde Rivers) and one medium-sized tributary that straddles the Quebec/Vermont border (Johns River). In addition, numerous small tributaries flow from the eastern and western shores directly into Lake Memphremagog.

The Black River (Waterbody ID VT17-09/10) drains an area of 349 km^2 (135 mi^2) extending from its headwaters in the towns of Craftsbury and Greensboro downstream to the western shore of South Bay in Newport City. The watershed includes one medium-sized tributary (Lords Creek) and several small lakes and ponds. Lake Elligo and Great Hosmer Pond have been altered by aquatic invasive species due to locally abundant Eurasian watermilfoil (Part E, State of Vermont 2014b).

The Barton River (Waterbody ID VT17-07/08) drains an area of 445 km^2 (172 mi^2) extending from its headwaters in the towns of Barton, Glover, and Westmore downstream to the south end of South Bay in Coventry. This watershed includes one large tributary (Willoughby River) and several large lakes, including Lake Willoughby [657 ha (1,623 acres)] and Crystal Lake [274 ha (677 acres)]. The Barton River in Orleans is listed as stressed due to the presence of toxins (State of Vermont 2014c). Brownington Pond has been altered by invasive aquatic species due to locally abundant Eurasian watermilfoil (Part E, State of Vermont 2014b).

Finally, Shadow Lake has been altered by seasonal water level fluctuations that may be harming aquatic habitats and aesthetics (Part F, State of Vermont 2014b).

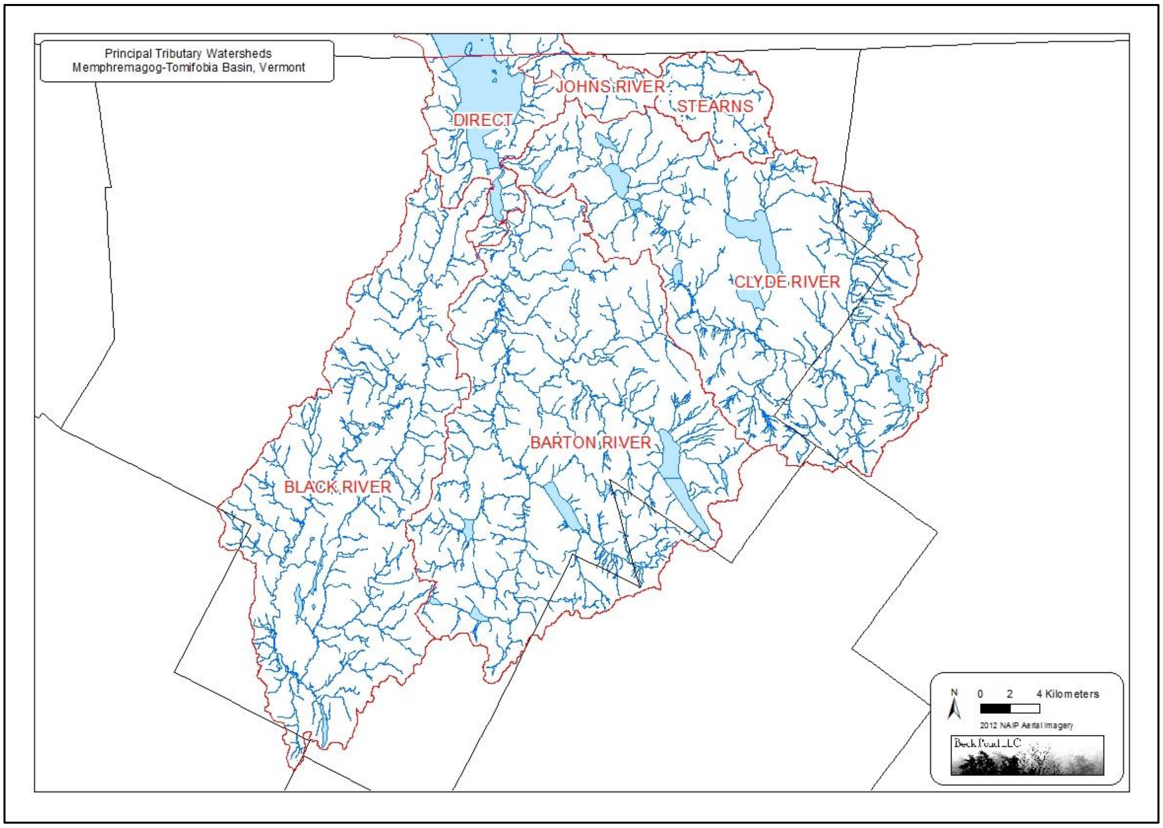

Figure 3. *Vermont portion of the Lake Memphremagog Basin, including the watersheds of the four principal tributaries (Barton, Black, Clyde, and Johns Rivers), and the watershed of Stearns Brook, a tributary of the Tomifobia River.*

The Clyde River (Waterbody ID VT17-04) drains an area of 373 km^2 (144 mi^2) extending from its headwaters in the towns of Brighton and Morgan downstream to its mouth in Newport City. The watershed includes two medium-sized tributaries (Pherrins River and the outlet of Seymour and Echo Lakes) and numerous large lakes, including Seymour Lake [667 ha (1,648 acres)], Lake Salem [232 ha (573 acres)], and Island Pond [221 ha (546 acres)]. Lake Salem is already part of an approved TMDL addressing elevated mercury levels in walleye (Part D, State of Vermont 2014b). Lake Derby has been altered by aquatic invasive species due to locally abundant Eurasian watermilfoil (Part E, State of Vermont 2014b). Two ponds in the watershed have been listed as stressed: Clyde Pond due to elevated mercury levels in walleye and Lake Salem due to elevated *Escherichia coli* levels in the inlet streams and lake (State of Vermont

2014c). Finally, an unnamed tributary in Brighton has been altered by flow regulation due to the possible lack of minimum flows below a water supply intake (Part F, State of Vermont 2014b).

The Johns River (Waterbody ID VT17-01) drains an area of approximately 29 km^2 (11 mi^2) in the towns of Derby, Vermont and Stanstead, Quebec. The Johns River is fed by Crystal Brook and several smaller tributaries and flows into Lake Memphremagog at Derby Bay, just south of the Quebec/Vermont border. The Johns River has been listed as stressed due to elevated nitrogen and turbidity levels (State of Vermont 2014c). However, Crystal Brook in Derby was recently removed from the list of impaired surface waters in need of a TMDL thanks to projects that reduced sediment and nutrient inputs from agricultural runoff.

In addition, the Southern Basin of Lake Memphremagog is fed by numerous small tributary streams that flow directly into the eastern and western shores of the lake. Although small, any nutrients or sediments carried by these tributaries are delivered directly into and impact the health of the lake. None of these tributaries are listed as impaired or stressed (State of Vermont 2014b, 2014c), although high nutrient and sediment levels have been measured in several of these tributaries (Gerhardt 2009, 2010).

Finally, in 2014, we expanded this project to assess water quality conditions, to pinpoint and assess possible nutrient and sediment sources, and to work with landowners to implement phosphorus-reduction projects and practices in several small tributaries of Stearns Brook, which is a tributary of the Tomifobia River and ultimately of Lac Massawippi in Quebec. Stearns Brook (Waterbody ID VT17-02) drains an area of approximately 33 km^2 (13 mi^2) in the towns of Derby and Holland, Vermont and Stanstead-Est, Quebec. One of its tributaries is listed as impaired and in need of a TMDL due to elevated nutrients from agricultural runoff (Part A, State of Vermont 2014b). Stearns Brook itself is listed as stressed due to sediment eroding from streambanks, poor logging practices, and poor road maintenance (State of Vermont 2014c).

Water Quality Sampling

Methods

In 2016, we sampled and analyzed water quality at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook (Figure 4; see Appendix A for descriptions of all 31 sites). These 31 sites included nine sites along four tributaries of the Black River, three sites along one tributary of the Barton River, two sites along one tributary of the Clyde River, two sites along the Johns River and Crystal Brook, two sites along a small tributary that flows directly into Lake Memphremagog, and 13 sites along four tributaries of Stearns Brook. Seven of these sites were resampled to further pinpoint and assess the source(s) of the high phosphorus and sediment levels measured previously in two tributaries of the Black River (Airport and St. Onge tributaries) and one tributary of the Clyde River (Sucker Brook). Four new sites were established to sample small tributaries that had not been sampled previously along the Black River (Town Line Brook) and Stearns Brook and two of its tributaries. Finally, 20 sites were sampled to assess the success of phosphorus-reduction projects and practices that had been or were being implemented along tributaries of the Black River (Brighton Brook), Barton River (Junkyard Tributary), Johns River (Crystal Brook), a small tributary that flows directly into Lake Memphremagog (Strawberry Acres Tributary), and a tributary of Stearns Brook. In a separate study, the Vermont DEC continued to sample water quality at three sites near the mouths of the three largest Vermont tributaries of Lake Memphremagog (Barton, Black, and Clyde Rivers), which have been sampled every year since 2005.

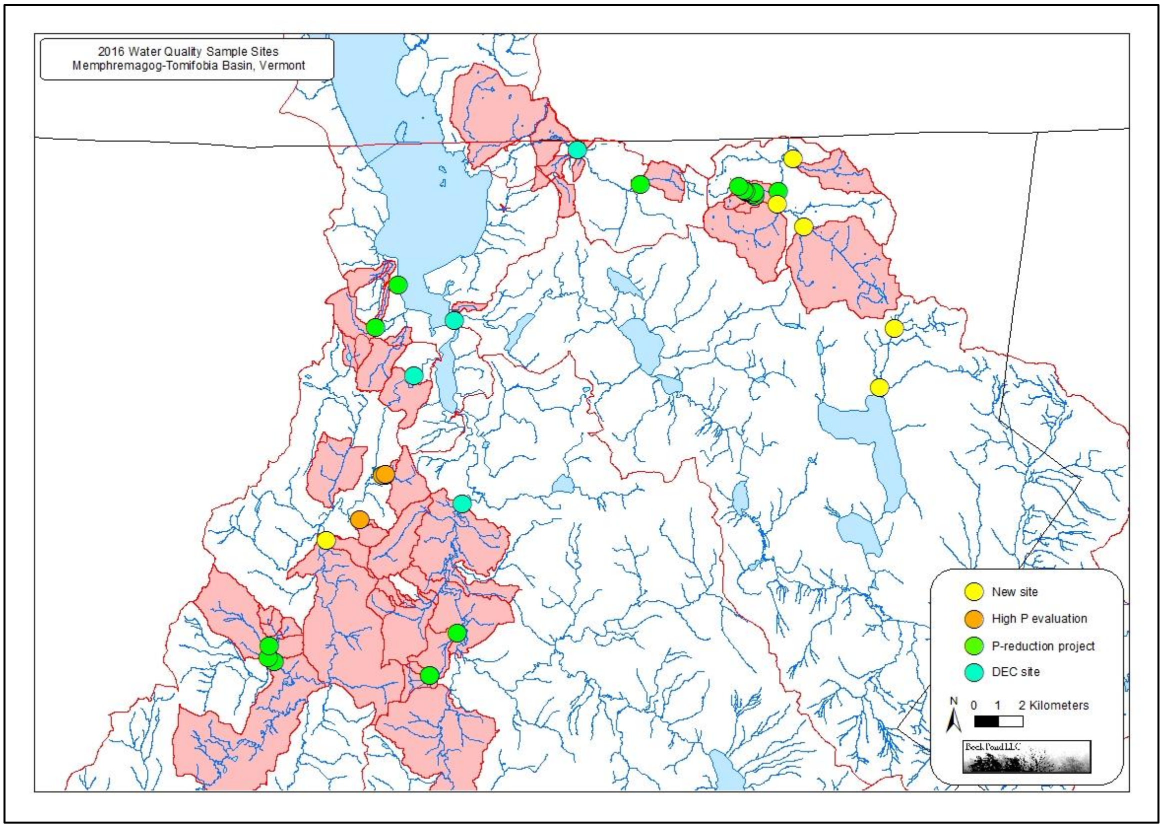

Figure 4. *Locations of 31 sample sites (plus three Vermont DEC sites) where water quality was sampled along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. The red shading highlights the 63 subwatersheds that exhibited the highest total phosphorus concentrations during 2005-2016.*

To accomplish the goals of this study, we sampled water quality at the 31 sites on eight dates during 12 April-28 October 2016 (the three DEC-maintained sites were sampled separately and on a different schedule, and those data are not reported here). On each sample date, we collected water samples from each site to be analyzed for total phosphorus, total nitrogen, and turbidity. Due to low or nonexistent flows, seven sites were not sampled on 1-6 dates each, and, due to logistical constraints, turbidity samples were not collected on 28 October 2016. Samples were collected in pre-labeled, sterilized bottles according to protocols established in conjunction with the Vermont DEC and the Vermont Agriculture and Environmental Laboratory (State of Vermont 2006, 2009). At all sites, we collected grab samples with a dip sampler. Before collecting samples, we rinsed the total nitrogen and turbidity bottles and the dip sampler with sample water three times. All samples were collected on a single day, stored in coolers, and delivered to the Vermont Agriculture and Environmental Laboratory the next day or the following morning. This schedule ensured that the laboratory was able to process the samples in a timely manner.

Prior to sampling, we prepared a Quality Assurance Project Plan (QAPP) in conjunction with the Vermont DEC and U.S. Environmental Protection Agency. Based on the Quality Assurance Project Plan, we collected three sets of field blanks and three sets of field duplicates on each sample date. Blank sample containers were rinsed and filled with de-ionized water and, if done properly, should result in values below the detection limits for each parameter (5 µg/l for total phosphorus, 0.1 mg/l for total nitrogen, and 0.2 NTU for turbidity). Field duplicates required collecting a second set of samples at the same time and place as the original set of samples. When done properly, the mean relative percent difference among all pairs of duplicate samples should be less than 30% for total phosphorus, 20% for total nitrogen, and 15% for turbidity. For total phosphorus, we also collected matrix spikes at three sites on each sample date, so that the Vermont Agriculture and Environmental Laboratory could perform in-house quality assurance analyses.

To relate the water quality data to stream flows, we relied on a single source of stream flow data. The U.S. Geologic Survey maintains gage stations that measure water depths and stream flows on the Barton, Black, and Clyde Rivers. During 2010-2015, the Vermont DEC also maintained a seasonal gage station that measured water depths on the Johns River. For the latter, daily stream flows were estimated using a rating curve developed from the water depths recorded by a YSI 600 LS vented sonde (YSI, Yellow Springs, Ohio) and stream flows measured by a SonTek Acoustic Doppler Flowtracker (SonTek, San Diego, California). Since this gage station was not maintained in 2015-2016, we used a linear regression to estimate stream flows for the Johns River based on those measured at the Black River (linear regression based on data collected during 2010-2014; $y = 0.089x^{0.7952}$, where x = flow at the Black River gage and y = flow at the Johns River site; $R^2 = 0.7639$). For this study, we used the daily stream flows measured or estimated for the Johns River site as a proxy for stream flows at all sites, because all of the sites were located on streams that were more similar in size and gradient to the Johns River than to the Black River.

Both field and laboratory data were entered into Microsoft Excel spreadsheets. All data sheets and analyses were archived by the author, and the electronic data were uploaded to the Vermont DEC for inclusion in their online databases.

Results and Discussion

The data for all parameters, sites, and sample dates are presented in Appendix B.

Quality Assurance

This project was conducted in accordance with a Quality Assurance Project Plan developed in conjunction with the Vermont DEC. In general, our 2016 sampling met the quality assurance standards for two of the three parameters (quality assurance data are presented in Appendix C). The field blanks, which indicate possible contamination during sampling, exceeded the detection limits for six of 69 samples. Two of the 24 field blanks for both total nitrogen and total phosphorus greatly exceeded the detection limits (0.1 mg/l and 5 μg/l, respectively), but all were collected on the same date (6 September) and from the same two sites (total nitrogen = 0.99 and 1.13 mg/l, total phosphorus = 21.7 and 42.4 μg/l). Two of the 21 field blanks for turbidity also exceeded the detection limit (0.2 NTU), although the deviations were relatively minor (0.21 and 0.59 NTU). The higher of these two values was measured on the same date and at one of the same sites as the elevated total nitrogen and total phosphorus blanks. The elevated values at the two sites on 6 September raised concerns; however, review of the data, data sheets, and sampling protocols suggested that these elevated levels might have occurred due to contaminated de-ionized water, a problem that has occurred once previously (Gerhardt 2014), rather than due to other possible causes (e.g. wrong labels, contaminated pole sampler, improper sampling technique, etc.).

The mean relative percent differences between duplicate samples were well below the prescribed differences for two of the three parameters [total phosphorus = 6% (prescribed difference <30%) and total nitrogen = 3% (prescribed difference <20%)]. In addition, none of the 24 pairs of total nitrogen samples and only one of the 24 pairs of total phosphorus samples exceeded the prescribed differences. In contrast, the mean relative percent difference between the duplicate turbidity samples did exceed the prescribed difference [turbidity = 22% (prescribed difference <15%)], and ten of the 21 pairs of turbidity samples differed by >15% (range = 17-98%). The good results for total nitrogen and total phosphorus and the relatively poor results for turbidity parallel our findings in almost every year during 2005-2016 and also parallel those obtained by other water quality monitoring programs (e.g. White, Mad, and Missisquoi Rivers and Lake Carmi).

Thus, although the quality assurance samples, including both field blanks and field duplicates, indicated that the water samples were generally being collected in a repeatable manner and were generally not being contaminated during collection or processing, the field blanks and field duplicates indicated that there were possible quality control issues with samples collected on one date and that we continue to encounter difficulties in collecting repeatable and uncontaminated turbidity samples for some unknown reason.

Stream Flow

Stream flow measures the volume of water passing a specific location per unit of time (usually measured as cubic feet or cubic meters per second) and is calculated by multiplying the cross-sectional area of the stream by water velocity. Stream flow affects both water quality and the quality and characteristics of aquatic and riparian habitats. For example, fast-moving streams are more turbulent and better aerated than slow-moving streams. High flows also dilute dissolved and suspended pollutants but, at the same time, typically carry more surface runoff and stormwater and the associated sediment and nutrients. Stream flow is extremely dynamic and changes frequently in response to changes in temperature, precipitation, and season.

To approximate stream flows at our sample sites, we relied on stream flow measurements from a gage maintained seasonally by the Vermont DEC on the Johns River (as estimated from the USGS gage on the Black River in 2015-2016 but measured directly in 2010-2014). The 2016 sampling season was characterized by moderately high peak spring flows during April (Figure 5). Otherwise, flows were generally low to moderate throughout the summer and remained relatively low into the autumn, although slightly higher flows were measured sporadically during most months.

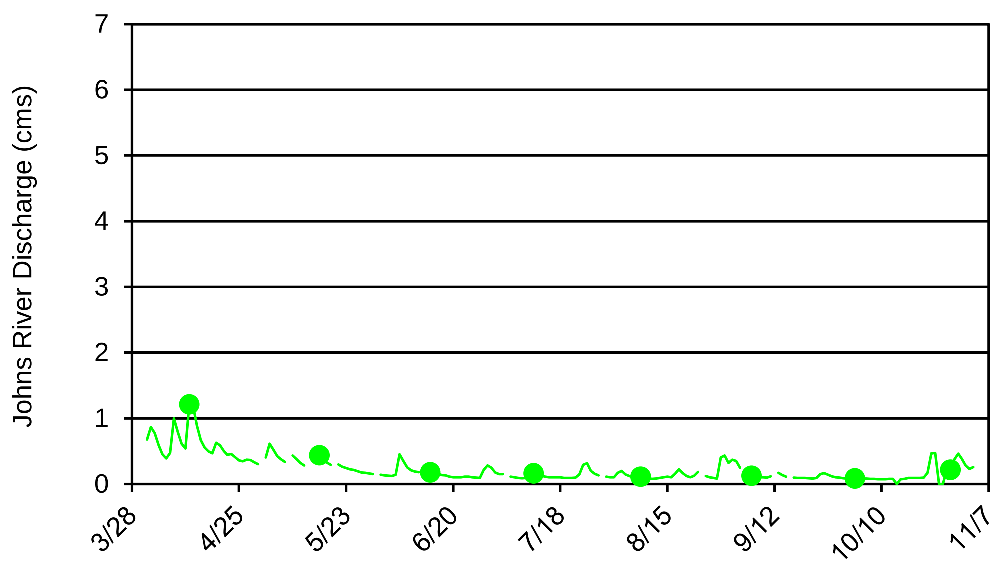

Figure 5. *Stream flows along the Johns River during April-October 2016. The eight dates on which water samples were collected are indicated by circles. Stream flows for the Johns River were estimated based on the measurements from the USGS gage on the Black River.*

Our sample dates largely reflected the variation in stream flows that occurred in 2016 (Figure 5). These sample dates included one high-flow event (12 April), four moderate-flow events (16 May, 14 June, 11 July, and 28 October), and three low-flow events (8 August, 6 September, and 3 October). The first sample date (12 April) followed heavy rains and snowmelt, and a second sample date (28 October) was ideally timed during a rain event to allow us to better pinpoint and assess nutrient and sediment sources. Collecting water samples across this range of stream flows enhanced our ability to identify and assess water quality problems, especially those affected by stream flows. Low flows were most informative for identifying and assessing nutrient and sediment inputs originating from point and groundwater sources. In contrast, moderate and high flows were more informative for identifying and assessing nutrient and sediment inputs originating from surface runoff and other nonpoint sources, which typically generate the majority of the sediment and nutrient loads exported from these watersheds.

Total Phosphorus

Total phosphorus measures the concentration of all forms of phosphorus in the water column, including dissolved phosphorus, phosphorus attached to suspended sediments, and phosphorus incorporated into organic matter. Phosphorus is typically the limiting nutrient and regulates the amount of aquatic life in northern freshwater ecosystems. Consequently, elevated phosphorus concentrations can lead to eutrophication, in which excessive algal and plant growth lead to oxygen depletion and increased mortality of aquatic life. In Vermont, most phosphorus originates from soil erosion, wastewater, manure, and synthetic fertilizers applied to lawns and agricultural fields.

In 2016, total phosphorus concentrations at the 31 sites ranged between 6.35-6,500 µg/l. As in previous years, total phosphorus concentrations showed no marked seasonal pattern (Figure 6). Median total phosphorus concentrations were highest on the sample dates with the highest flows and during rain events (12 April and 28 October), when surface runoff likely carried large amounts of sediment and nutrients into rivers and streams.

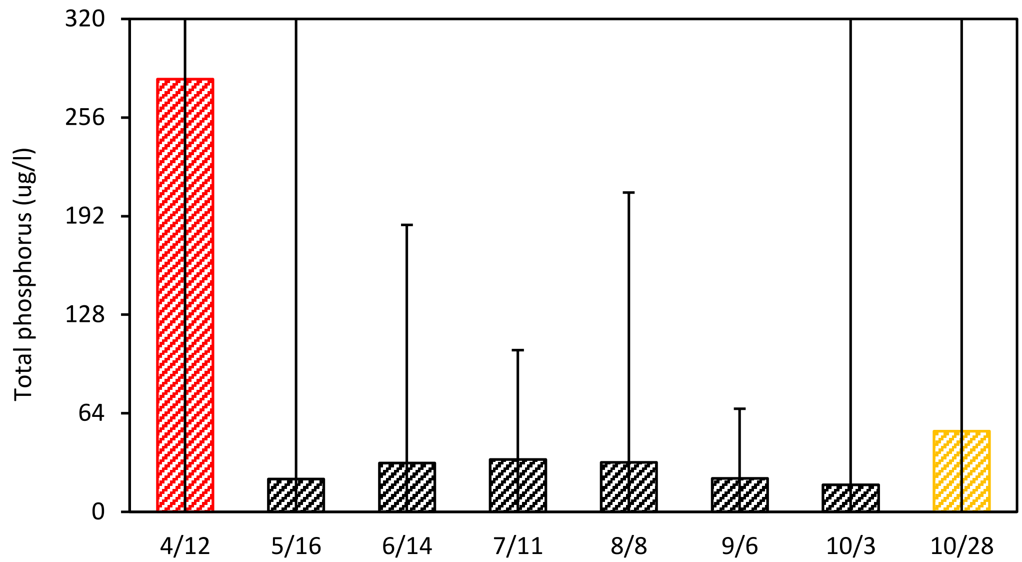

Figure 6. *Median total phosphorus concentrations (±1 SD) measured on each sample date at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Red hatching indicates the high-flow event; orange hatching indicates the rain event.*

Since our sampling was focused on assessing streams with high phosphorus levels, total phosphorus concentrations were moderate to extremely high at all but seven of the 31 sites (Figure 7-8). More specifically, total phosphorus concentrations were high (median values >35 µg/l) along several tributaries of the Black River (Brighton and Town Line Brooks and the Airport and St. Onge tributaries), Barton River (Junkyard Tributary), and three tributaries of Stearns Brook. All of these tributaries drained areas of diverse land uses but included large areas of agricultural fields and agricultural production areas (e.g. barns, barnyards, and manure and silage storage). In contrast, total phosphorus concentrations were low (median value <20 µg/l) at seven sites along Sucker and Crystal Brooks, the Strawberry Acres Tributary, and the upper reaches of the tributary of Stearns Brook. These tributaries generally drained more limited areas of agricultural land uses, several of which had been subject to implementation of phosphorus-reduction projects and practices, and more extensive areas of forest and residential land uses. Finally, total phosphorus concentrations were intermediate (median values = 20-35 µg/l) at selected sites along Brighton Brook; the Airport, St. Onge, Junkyard, and Strawberry Acres Tributaries; and the tributary of Stearns Brook. (Individual watersheds and sites are discussed in greater detail later in this report.)

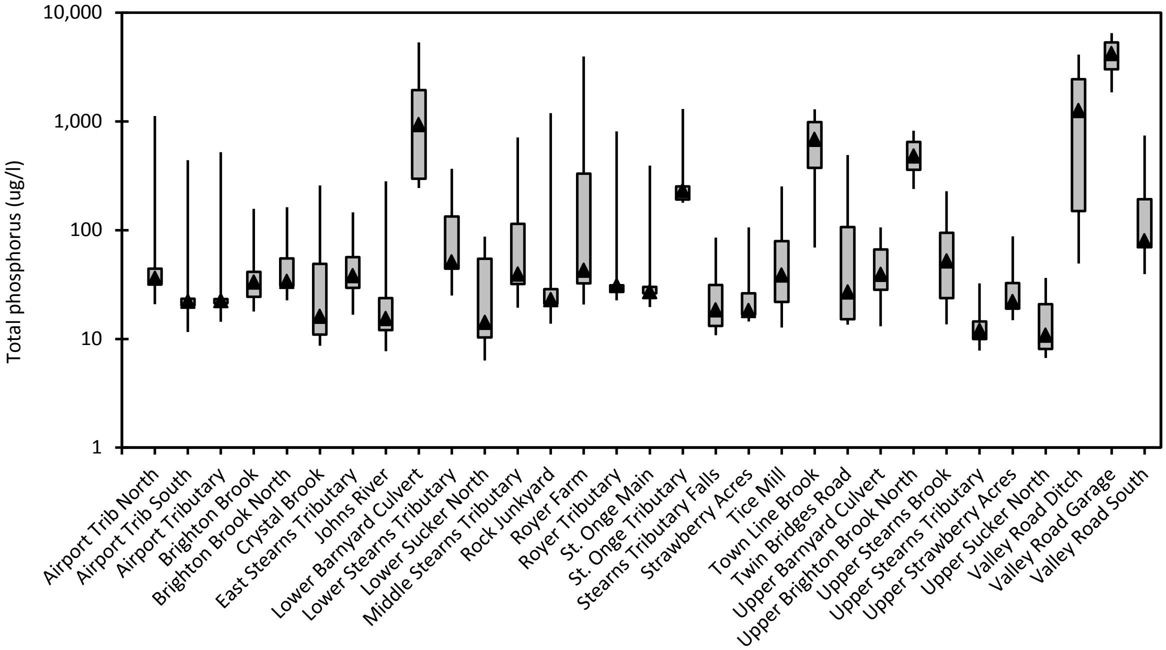

Figure 7. *Total phosphorus concentrations at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Values are the median (triangle), 1st and 3rd quartiles (rectangle), and minimum and maximum (line). Note the logarithmic scale on the y-axis.*

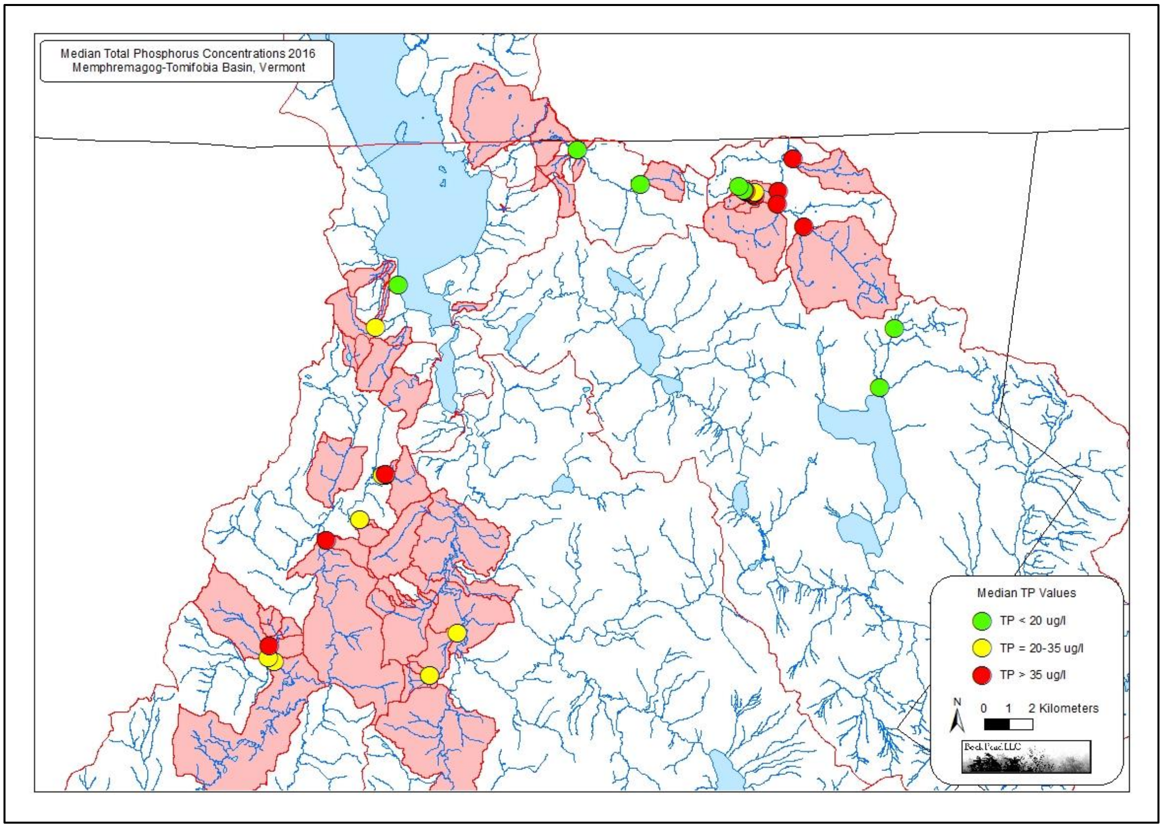

Figure 8. *Median total phosphorus concentrations at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. The red shading highlights the 63 subwatersheds that exhibited the highest total phosphorus concentrations during 2005-2016.*

Total Nitrogen

Total nitrogen measures the concentration of all forms of nitrogen in the water column, including nitrogen gas (N_2), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), ammonium (NH_4), and particulate nitrogen (N). Although typically not the limiting nutrient in northern freshwater ecosystems, nitrogen is an essential plant nutrient, and high levels of nitrogen can impact both in-lake and in-stream water quality and can exacerbate algal blooms and eutrophication and lead to more frequent and more toxic cyanobacterial blooms. In Vermont, most nitrogen in surface waters originates from wastewater, stormwater, agricultural runoff, and atmospheric deposition.

In 2016, total nitrogen concentrations at the 31 sites ranged between 0.12-37.77 mg/l. As in previous years, total nitrogen concentrations showed no marked seasonal trend (Figure 9). Like total phosphorus, total nitrogen concentrations were highest on the sample dates with the highest flows and during rain events (12 April and 28 October), when surface runoff likely carried large amounts of sediment and nutrients into rivers and streams.

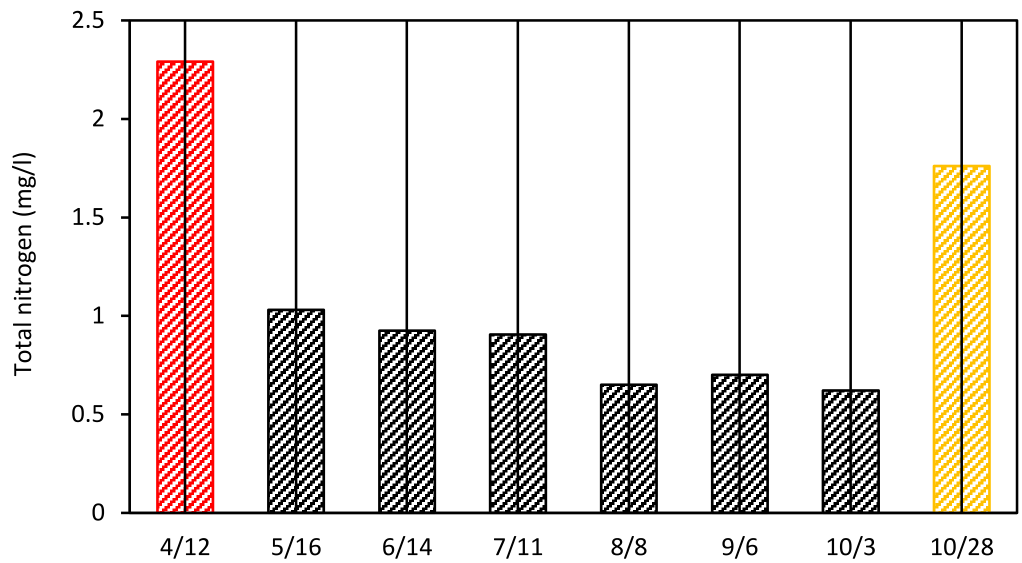

Figure 9. *Median total nitrogen concentrations (±1 SD) measured on each sample date at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Red hatching indicates the high-flow event; orange hatching indicates the rain event.*

Since our sampling was focused on assessing streams with high phosphorus levels, total nitrogen concentrations were also generally moderate to high at many of the same sites (Figure 10-11). Total nitrogen concentrations were high (median values >2 mg/l) at 13 sites along two tributaries of the Black River (Brighton and Town Line Brooks), the Johns River, and the tributary of Stearns Brook. All of these tributaries drained areas of diverse land uses but included large areas of agricultural fields and agricultural production areas (e.g. barns, barnyards, and manure and silage storage). Total nitrogen concentrations were generally intermediate (median values = 1-2 mg/l) along one tributary of the Barton River (Junkyard Tributary), Crystal Brook, and two other tributaries of Stearns Brook. These tributaries also drained watersheds with large areas of agricultural and other land uses, but several of these areas (e.g. Junkyard Tributary and Crystal Brook) have already been addressed by water quality improvement projects and practices. Finally, total nitrogen concentrations were generally low (median values <1 mg/l) along two tributaries of the Black River (Airport and St. Onge tributaries), Sucker Brook, and another tributary of Stearns Brook. These tributaries generally drained watersheds with fewer and/or smaller agricultural production areas, little or no corn, and more extensive areas of forest. (Individual watersheds and sites are discussed in greater detail later in this report.)

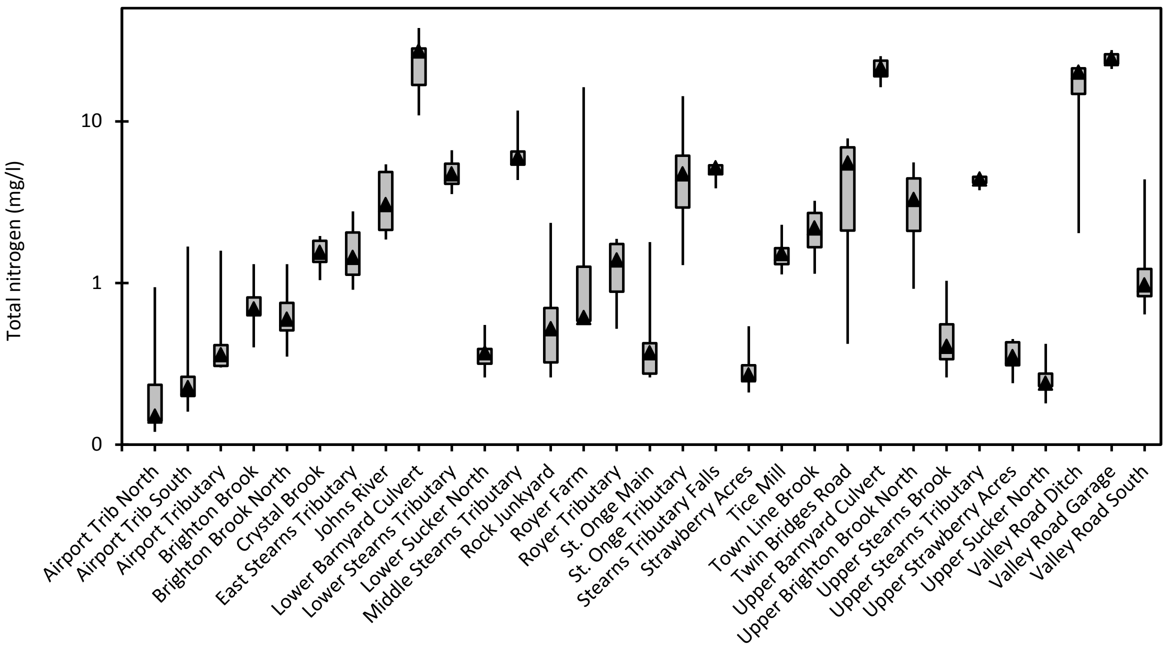

Figure 10. *Total nitrogen concentrations at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Values are the median (triangle), 1st and 3rd quartiles (rectangle), and minimum and maximum (line). Note the logarithmic scale on the y-axis.*

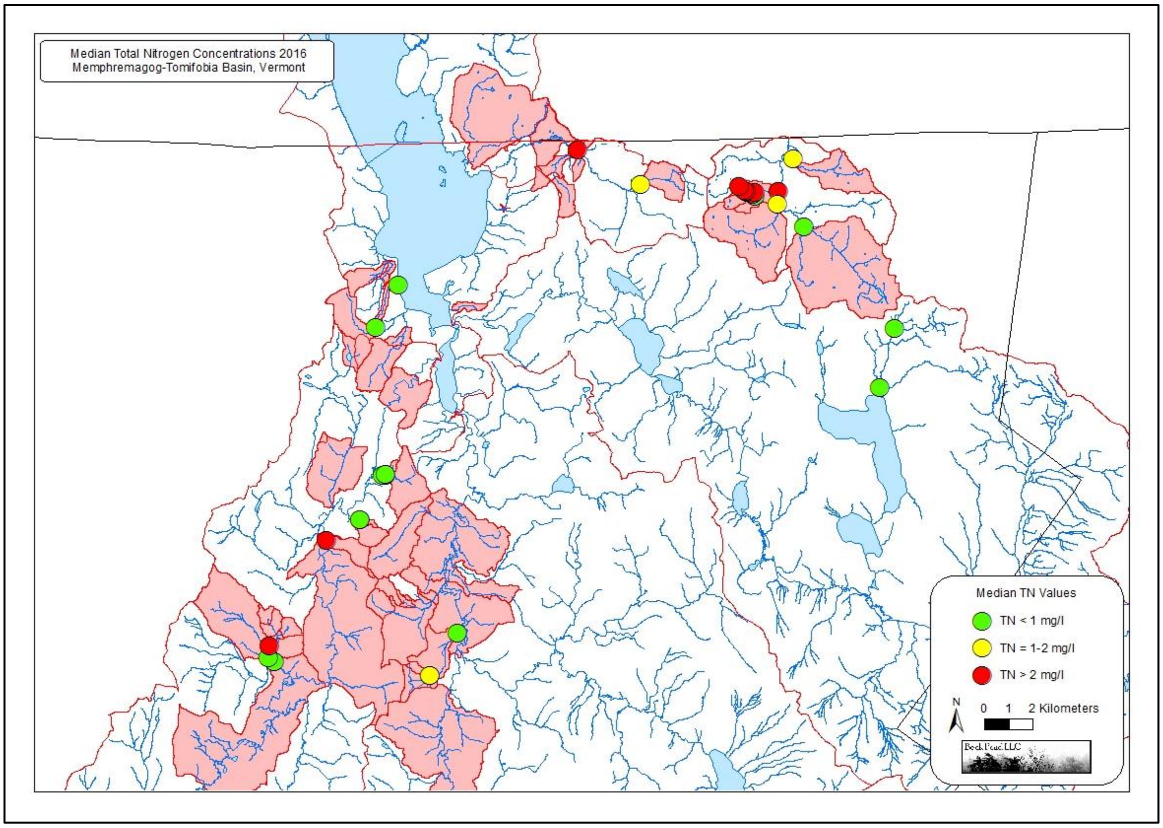

Figure 11. *Median total nitrogen concentrations at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. The red shading highlights the 63 subwatersheds that exhibited the highest total phosphorus concentrations during 2005-2016.*

Turbidity

Turbidity, which is measured in Nephelometric Turbidity Units (NTU), measures the light-scattering properties of all dissolved and suspended materials in the water column. Turbidity greatly affects the health of aquatic ecosystems, as more turbid waters allow less light to penetrate into the water column and transport more pollutants, nutrients, and sediments. In addition, sediment and other suspended materials can settle out of the water column and smother aquatic biota and their habitats. Much of the dissolved and suspended material in the water column originates from stormwater and surface runoff associated with agriculture, forestry, urban and suburban development, and stream channel adjustment processes. However, turbidity is also affected by natural biological and chemical processes and chemical pollutants.

In 2016, turbidity levels at the 31 sites ranged between 0.24-7,710 NTU. Like total phosphorus and total nitrogen, turbidity levels showed no marked seasonal pattern (Figure 12).

Turbidity levels were highest on the sample date with the highest flows (12 April), when surface runoff likely carried large amounts of sediment and nutrients into rivers and streams (turbidity was not measured during the rain event on 28 October).

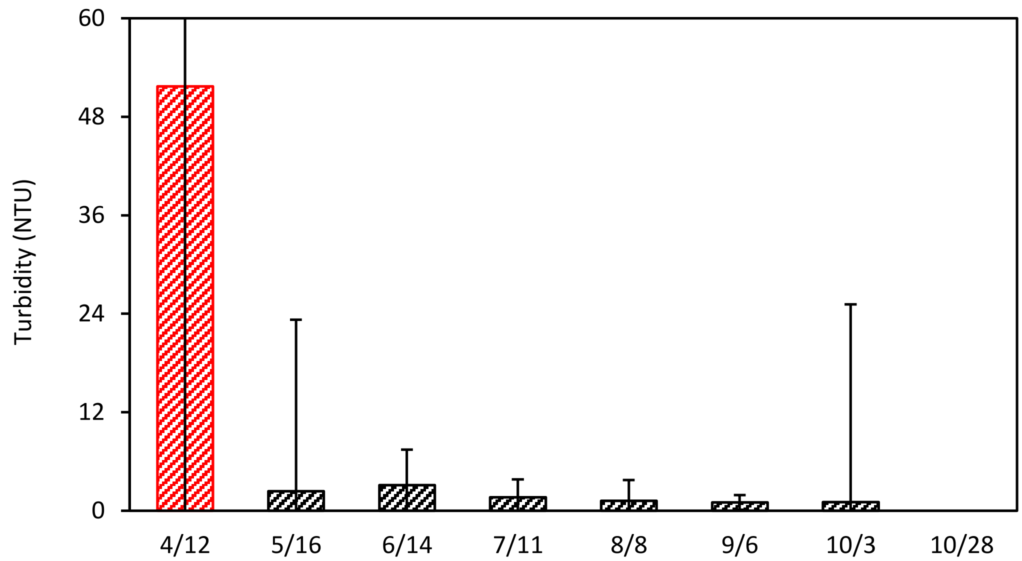

Figure 12. *Median turbidity levels (±1 SD) measured on each sample date at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Red hatching indicates the high-flow event (note that turbidity was not measured during the rain event on 28 October).*

Unlike total phosphorus and total nitrogen, turbidity levels were generally low at most sites along most tributaries (Figure 13-14). Turbidity levels were intermediate or high (median levels >5 NTU) at only six of the 31 sites, all of which were located along three tributaries of the Black River (Brighton and Town Line Brooks and the St. Onge tributary) and the tributary of Stearns Brook. All of these sites were located immediately downstream of large agricultural production areas (e.g. barns, barnyards, and manure and silage storage) and/or large agricultural fields, especially corn. In contrast, turbidity levels were generally low (median values <5 NTU) at the remainder of the sites and indicated that, at least on most sample dates, there were not large amounts of dissolved and suspended materials being transported by these rivers and streams. (Individual watersheds and sites are discussed in greater detail later in this report.)

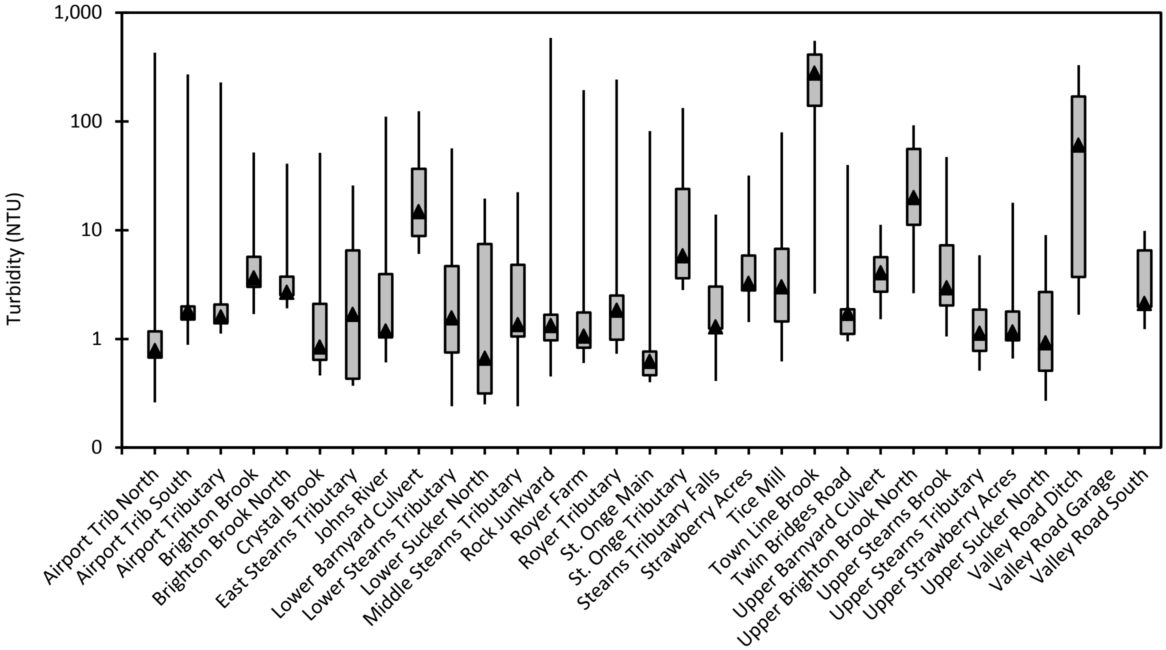

Figure 13. *Turbidity levels at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Values are the median (triangle), 1st and 3rd quartiles (rectangle), and minimum and maximum (line). Note the logarithmic scale on the y-axis.*

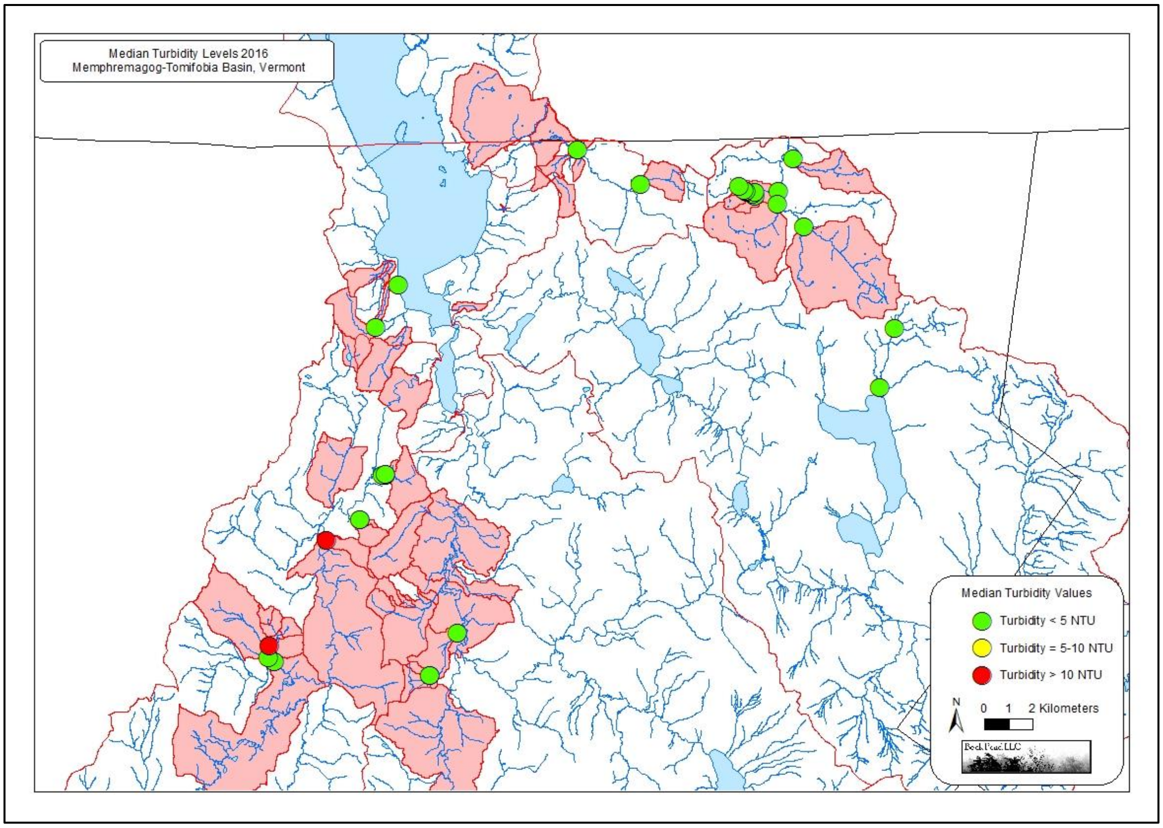

Figure 14. *Median turbidity levels at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. The red shading highlights the 63 subwatersheds that exhibited the highest total phosphorus concentrations during 2005-2016.*

Individual Sites and Subwatersheds

The 31 sites sampled in 2016 represented a more limited number of watersheds in the Lake Memphremagog and Tomifobia River Basins. In the sections that follow, we describe in greater detail the water quality data, possible sources of water quality problems, potential water quality protection and improvement projects, and the current status of any efforts to protect and improve water quality for selected watersheds and sites.

Black River

Airport Tributary

The Airport Tributary, a small tributary of the Black River, drains approximately 296 ha (730 acres) in the town of Coventry. This small tributary includes two major branches: the northern branch, which drains much of the Newport State Airport, and the eastern branch, which drains part of the airport as well as wetlands, forests, and agricultural fields, some of which were cleared of forest in 2011. Water quality in this tributary was first sampled at one downstream site in 2013, when elevated levels of phosphorus and turbidity were first identified as issues of concern. In 2015, two sites were added along the northern and eastern branches of this tributary.

During 2015-2016, we sampled water quality at three sites to further pinpoint and assess possible nutrient and sediment sources along this tributary. In both 2015 and 2016, total phosphorus concentrations were markedly higher along the northern branch of this tributary (Airport Trib North, median = 36.1 µg/l, range = 20.9-2,920 µg/l) than along the southern branch (Airport Trib South, median = 22.9 µg/l, range = 11.6-452 µg/l) and at the downstream site (Airport Tributary, median = 23.5 µg/l, range = 14.4-570 µg/l). At all three sites, total phosphorus concentrations generally increased with increasing flows (Figure 15). Total nitrogen concentrations were generally low or moderate at all three sites (range across all three sites = 0.11-2.50 mg/l), and turbidity levels were generally low on 12 of the 15 sample dates. During three rain events, turbidity levels were extremely high at the Airport Trib North site (27 April 2015 = 80.6 NTU, 9 June 2015 = 1,854 NTU, 12 April 2016 = 429.5 NTU)(Figure 16). Thus, in both 2015 and 2016, it was clear that large proportions of the sediment and nutrients originated along the northern branch of this tributary.

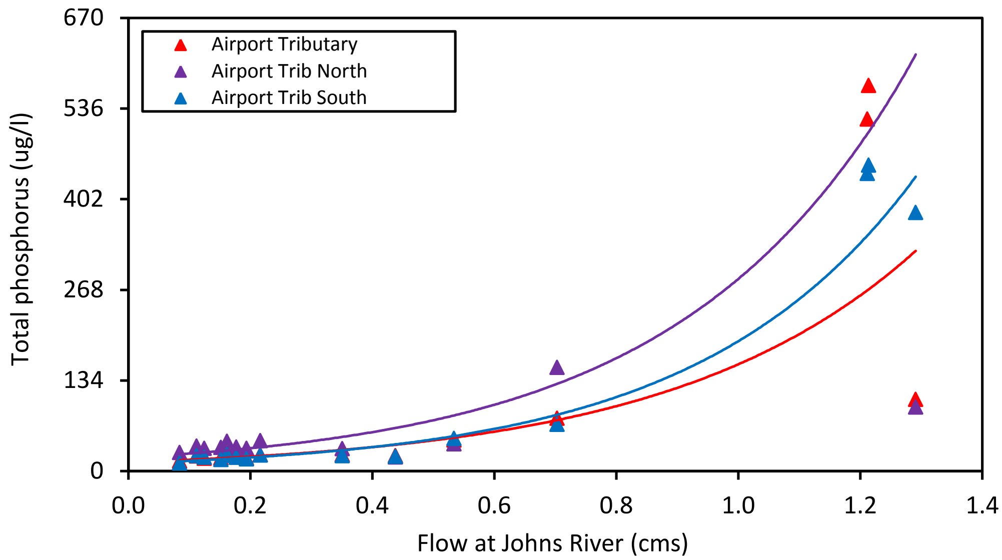

Figure 15. *Total phosphorus concentrations in relation to stream flow at three sites along the Airport Tributary during April-October 2015-2016. Stream flows were estimated from the USGS gage on the Black River. The regression lines indicate the exponential relationships between the two parameters. Note that two moderate-flow values for the Airport Trib North site exceed the scale on the y-axis.*

Figure 16. *Extremely turbid, sediment-laden water flows in the northern branch of the Airport tributary in Coventry, Vermont following heavy rains on 9 June 2015.*

Due to the extremely turbid waters flowing from the northern branch following heavy rains on 9 June 2015, we scouted the entire length of this branch and observed numerous areas of extreme stream bank erosion, stream channel incision, and head-cutting in a series of gullies extending along much of the length of this branch (Figure 17). Based on our observations, we identified excessive amounts of stormwater runoff from the Newport State Airport as the likely cause of the extreme erosion of this stream channel, since much of the stormwater runoff from the hardened surfaces of the airport (e.g. runways, taxiways, etc.) and intervening grasslands now appears to flow into this tributary. As part of a larger project to develop designs for stormwater retrofits, the Memphremagog Watershed Association contracted with Watershed Consulting to develop a stormwater master plan (30% design) to create a step-pool system to reduce erosion and increase infiltration at the head of the northern branch.

Figure 17. *Extreme stream bank erosion and stream channel incision was noted along the northern branch of the Airport tributary on 9 June 2015, possibly due to excessive amounts of stormwater flowing from the Newport State Airport.*

St. Onge Tributary

The St. Onge tributary, a small tributary of the Black River, drains 101 ha (248 acres) along Coventry Station Road in the town of Coventry. After concerns were raised regarding water quality conditions, staff from the Vermont DEC sampled water quality in this tributary on 12 November 2014. These samples revealed extremely high concentrations of both total phosphorus (3,820 µg/l) and total nitrogen (27 mg/l) along a branch of this tributary that drained an agricultural production area. In addition, extensive growths of "sewage fungus"

(*Sphaerotilus natans*, a filamentous bacterium closely associated with polluted water) were observed completely covering the streambed along at least 100 m (328 ft) of this tributary (Figure 18). In the autumn of 2015, the Biomonitoring and Aquatic Studies Section (BASS) of Vermont DEC found that the macroinvertebrate community further downstream only ranked as "Fair". Based on these data and observations, staff from the Vermont DEC and Vermont Agency of Agriculture, Foods and Markets (VAAFM) visited and identified problems at a small farm operation further upstream. First, leachate from a silage storage bunker was draining into the stream, and so the owner installed a temporary barrier around the bunker and is reportedly working on a permanent solution to this problem. Second, an overflow pipe in the manure pit was supposed to have been removed but had been plugged with clay instead.

Figure 18. *Extensive growths of Sphaerotilus natans, a bacterium associated with polluted water, covered the streambed of the St. Onge tributary on 12 November 2014 (photograph courtesy of Ben Copans).*

In 2015, we sampled a single site to assess the extremely high nutrient and sediment levels measured in a small branch of this tributary. Water samples collected at this site (St. Onge Tributary) exhibited extremely high total phosphorus concentrations (median = 332 µg/l, range = 142-5,180 µg/l), very high total nitrogen concentrations (median = 5.5 mg/l, range = 3.0-29.8 mg/l), and high turbidity levels (median = 10.1 NTU, range = 1.3-333 NTU). In 2016, we added a second site (St. Onge Main) to further assess the extremely high nutrient and sediment levels measured in this tributary. The water samples collected from the small branch of this tributary (St. Onge Tributary) continued to exhibit extremely high total phosphorus concentrations (median = 230 µg/l, range = 179-1,300 µg/l), very high total nitrogen concentrations (median =

4.7 mg/l, range = 1.3-14.3 mg/l), and moderately high turbidity levels (median = 5.8 NTU, range = 2.8-133 NTU). In contrast, the samples collected from the main branch of this tributary (St. Onge Main) exhibited much lower total phosphorus concentrations (median = 27.2 µg/l, range = 19.7-393.2 µg/l), total nitrogen concentrations (median = 0.40 mg/l, range = 0.26-1.8 mg/l), and turbidity levels (median = 0.62 NTU, range = 0.40-81.4 NTU). During 2015-2016, both total nitrogen and total phosphorus increased slightly with increasing stream flows at the St. Onge Tributary site and were markedly higher at all flows than at the St. Onge Main site (Figure 19-20). Thus, the majority of the sediment and nutrients in this stream were likely originating from the watershed of the small tributary, and we recommend that agency staff continue to work with the owner of the small farm to ensure that farm operations do not harm water quality in this tributary. Although the flows from this stream are small, the high nutrient and sediment levels indicated that the total loading from this stream may still be substantial.

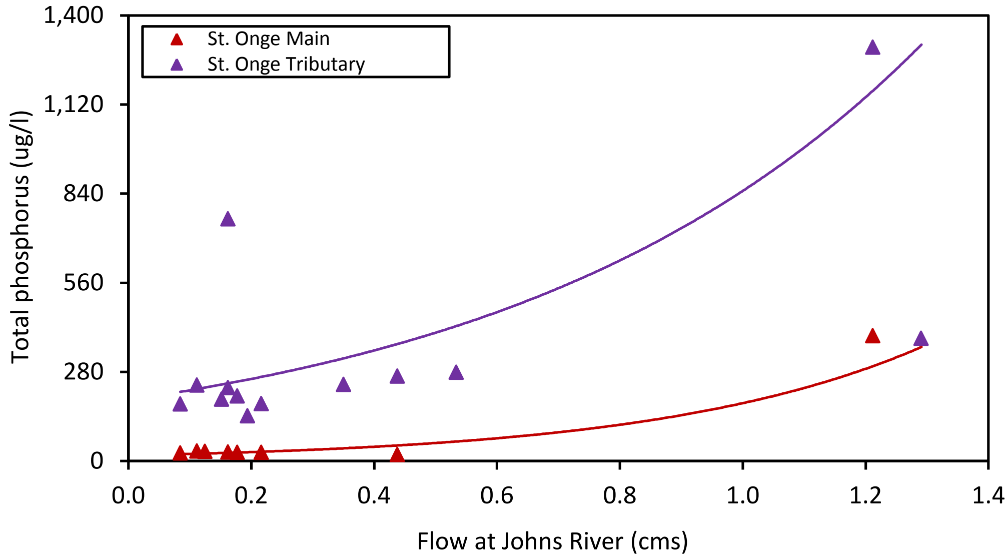

Figure 19. *Total phosphorus concentrations in relation to stream flow at two sites along the St. Onge tributary during April-October 2015-2016. Stream flows were estimated from the USGS gage on the Black River. The regression lines indicate the exponential relationships between the two parameters. Note that one low-flow value for the St. Onge Tributary site exceeds the scale on the y-axis.*

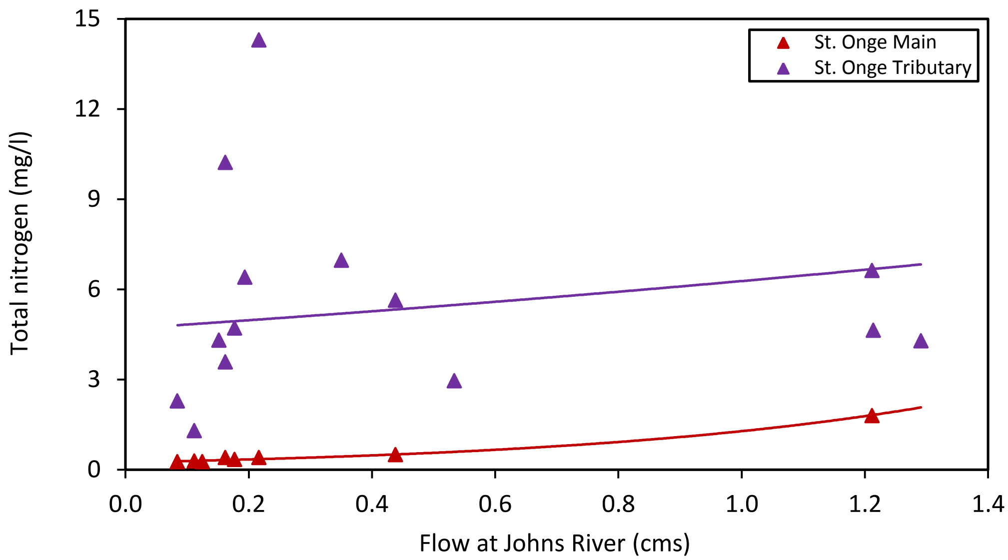

Figure 20. *Total nitrogen concentrations in relation to stream flow at two sites along the St. Onge tributary during April-October 2015-2016. Stream flows were estimated from the USGS gage on the Black River. The regression lines indicate the exponential relationships between the two parameters. Note that two low-flow values for the St. Onge Tributary site exceed the scale on the y-axis.*

Brighton Brook

Brighton Brook, a tributary of the Black River, drains approximately 1,403 ha (3,466 acres) in the towns of Irasburg and Newport Town. Water quality in Brighton Brook was first sampled in 2010 and exhibited high levels of phosphorus, nitrogen, and turbidity. In subsequent years, we sampled water quality at additional sites along this stream and its tributaries to better pinpoint and assess possible nutrient and sediment sources. During 2011-2016, total phosphorus and total nitrogen concentrations have been consistently high along the northern branch of Brighton Brook and extremely high in a small tributary of the northern branch. This small tributary drains an area encompassing a large agricultural production area, including barns, manure pits, silage storage bunkers, and a mortality compost pile, as well as large fields of corn and hay. Identifying the source(s) of the high nutrient levels in this tributary was complicated by 1) the presence of a series of small ponds and wetlands that likely store nutrients during high flows and release them during low flows in late summer, 2) the draining and filling of a large wetland formerly located in the upper watershed, and 3) installing drain pipes in many of the corn fields and wetlands in the upper watershed. Nevertheless, following heavy rains in 2014, we were able to identify leachate from the large mortality compost pile as the likely source of the nutrients flowing into the northern branch of Brighton Brook (Figure 21). Despite repeated requests to relocate and/or collect the leachate from this mortality compost pile, no actions were undertaken, and so the State of Vermont pursued an enforcement action that resulted in an agreement to correct this problem in July 2015.

Figure 21. *Mortality compost pile (to front and left of barns) and agricultural production area on a large farm operation along the northern branch of Brighton Brook in Irasburg, Vermont on 8 October 2013. Note the darkened ground where leachate from the compost pile flowed along and puddled at the bottom of the farm road.*

In 2016, we resampled three sites along the main stem and northern branch of Brighton Brook in order to evaluate whether water quality conditions had improved as a result of the corrective actions. Based on conversations with agency staff and field observations, it appeared that the mortality compost pile was removed slowly during the summer of 2016. As in previous years, total phosphorus concentrations were moderately high at the downstream-most site (Brighton Brook, median = 33.1 µg/l, range = 17.9-157 µg/l), slightly higher at the downstream site on the northern branch (Brighton Brook North, median = 33.7 µg/l, range = 22.7-163 µg/l), and much higher at the upstream site (Upper Brighton Brook North, median = 479.5 µg/l, range = 240-821 µg/l). Total phosphorus concentrations exhibited a strongly negative relationship with stream flow at the Upper Brighton Brook North site but a positive relationship with stream flow at the Brighton Brook and Brighton Brook North sites (Figure 22). During the past seven years (2010-2016), mean total phosphorus concentrations have generally decreased at all three sites (Figure 23). Thus, there is reason to be optimistic that water quality conditions are improving in this tributary of the Black River, and, given the very high phosphorus concentrations measured there previously, these improvements may substantially reduce phosphorus loading into the Black River.

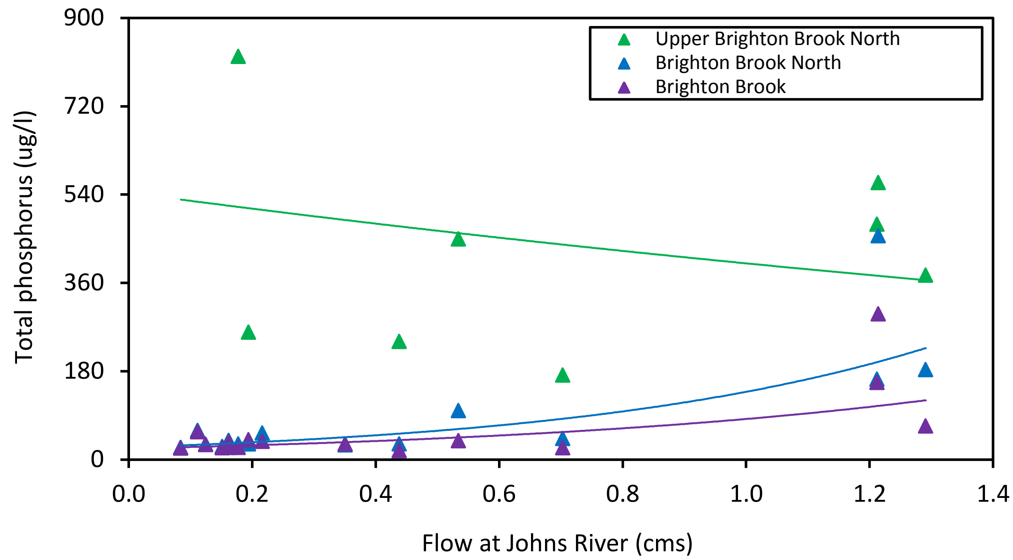

Figure 22. *Total phosphorus concentrations in relation to stream flow at three sites along the main stem and northern branch of Brighton Brook during April-October 2015-2016. Stream flows were estimated from the USGS gage on the Black River. The regression lines indicate the exponential relationships between the two parameters. Note that one low-flow value for the Upper Brighton Brook North site exceeds the scale on the y-axis.*

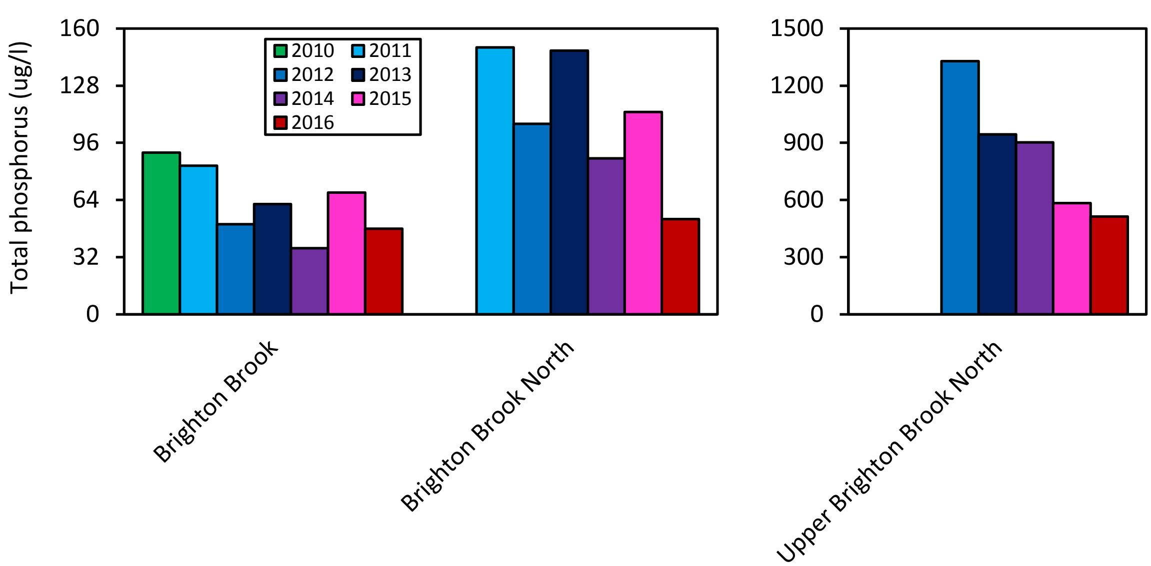

Figure 23. *Annual mean total phosphorus concentrations at three sites along the main stem and northern branch of Brighton Brook during 2010-2016.*

Barton River

Junkyard Tributary

The Junkyard Tributary, a small tributary of the Barton River, drains approximately 348 ha (860 acres) in the towns of Irasburg and Barton. This small tributary drains large areas of agricultural land uses, almost 2 km (1.2 mi) of Interstate 91, small blocks of forest, and a residential area in the village of Orleans. Water quality in this tributary was first sampled in 2012 and identified elevated phosphorus levels as an issue of concern. In 2013, we added a second site further upstream, and, in 2014, we added two additional sites where this tributary forks in order to better pinpoint and assess possible nutrient and sediment sources. Based on our data and observations, staff from VAAFM and Vermont DEC visited a medium farm operation in this watershed on 14 November 2014 to discuss water quality concerns. Subsequently, the owner submitted an Environmental Quality Incentives Program (EQIP) application to develop a nutrient management plan, undertook no-till and cover-cropping, created a filter strip to capture runoff and sediment at the downhill edge of the steepest corn field, converted another corn field to hay, widened a riparian buffer in one area, and relocated the mortality pile. In the future, the owner hopes to build additional storage capacity and infrastructure to capture any overflow from the manure pit and leachate from the silage storage bunker.

In 2016, we continued our efforts to pinpoint and assess nutrient and sediment sources and to evaluate possible improvements in water quality along the main stem and two branches of this tributary. During 2014-2016, total phosphorus concentrations were moderately low at the downstream site (Rock Junkyard, median = 26.1 µg/l, range = 13.8-1,190 µg/l), intermediate at the Royer Tributary site (median = 31.2 µg/l, range = 22.0-980 µg/l), and high at the Royer Farm site (median = 44.4 µg/l, range = 20.7-9,150 µg/l). For the most part, total nitrogen concentrations were relatively low at two of the three sites [Rock Junkyard (median = 0.60 mg/l, range = 0.26-4.3 mg/l) and Royer Farm (median = 0.74 mg/l, range = 0.48-49.8 mg/l)] but moderately high at the Royer Tributary site (median = 1.5 mg/l, range = 0.52-5.6 mg/l). Total phosphorus concentrations showed only slight, positive relationships with stream flow at both the Rock Junkyard and Royer Farm sites but a more strongly positive relationship at the Royer Tributary site (Figure 24). In contrast, total nitrogen concentrations showed strong, positive relationships with stream flow at all three sites (Figure 25). In addition, following heavy rains on 28 October 2016, extremely high nutrient and sediment levels were measured at two sites further upstream of the Royer Farm site, and these measurements (total phosphorus = 6,550 and 7,500 µg/l, total nitrogen = 43.96 and 46.76 mg/l) confirmed that much of the nutrients and sediment were originating in surface runoff from the steep corn field. Thus, despite improved field practices, neither total phosphorus nor total nitrogen showed significant decreases during the years sampled in this study (Figure 26).

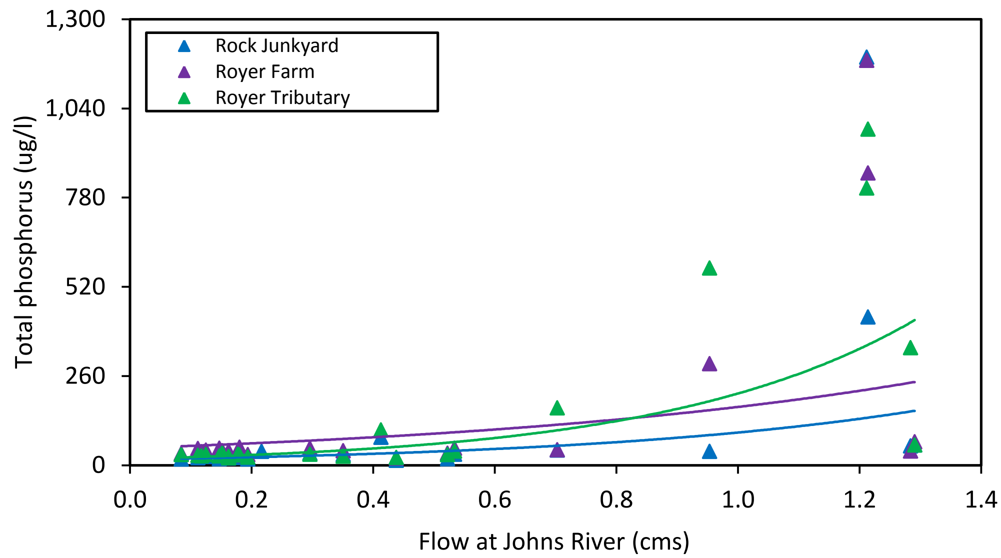

Figure 24. *Total phosphorus concentrations in relation to stream flow at three sites along the main stem and two branches of the Junkyard Tributary during April-October 2015-2016. Stream flows were estimated from the USGS gage on the Black River. The regression lines indicate the exponential relationships between the two parameters. Note that two moderate-flow values for the Royer Farm site exceed the scale on the y-axis.*

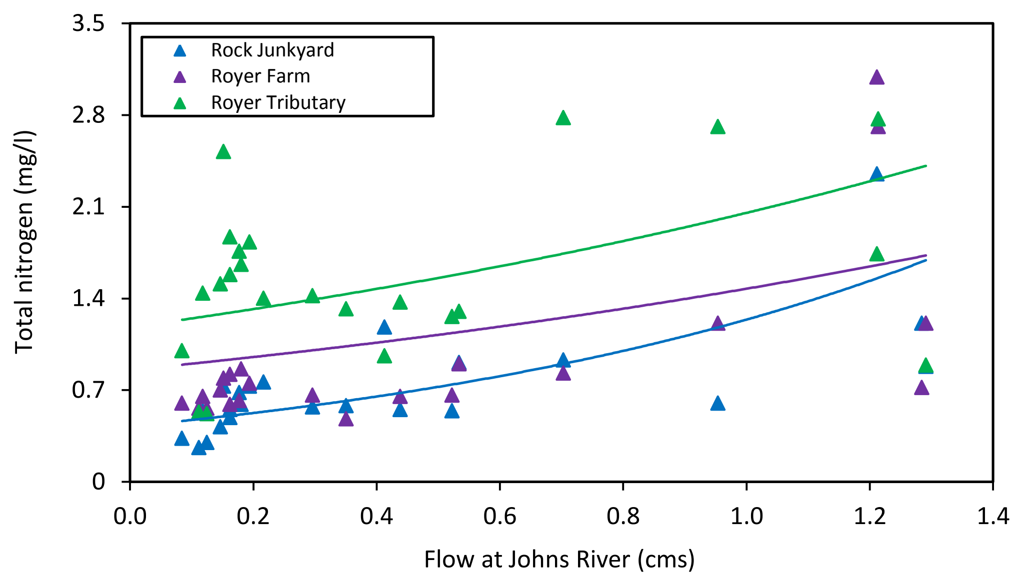

Figure 25. *Total nitrogen concentrations in relation to stream flow at three sites along the main stem and two branches of the Junkyard Tributary during April-October 2015-2016. Stream flows were estimated from the USGS gage on the Black River. The regression lines indicate the exponential relationships between the two parameters. Note that one moderate-flow value for the Royer Farm site exceeds the scale on the y-axis.*

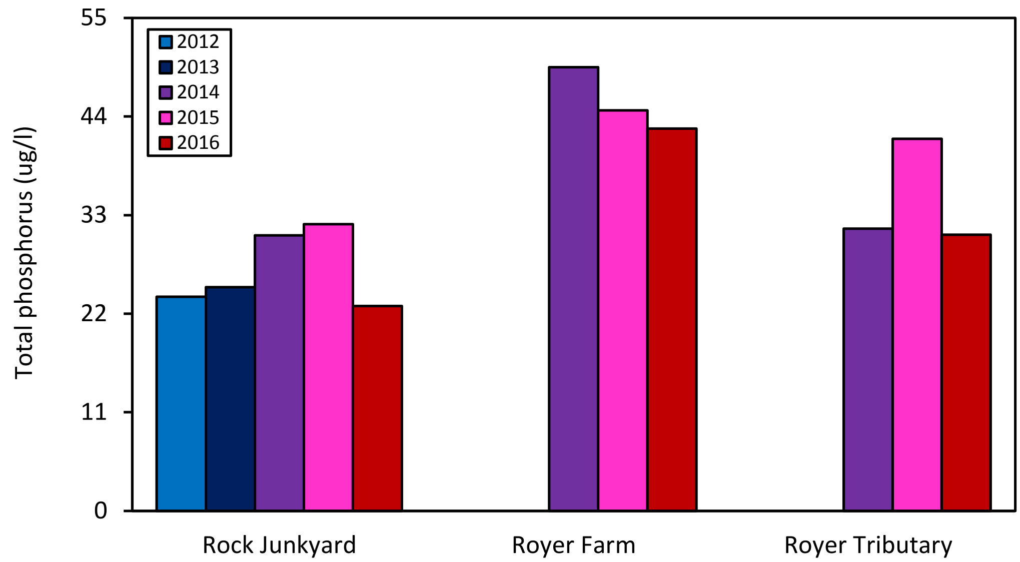

Figure 26. *Annual median total phosphorus concentrations at three sites along the main stem and two branches of the Junkyard Tributary during 2012-2016.*

Clyde River

Sucker Brook

The north branch of Sucker Brook, which is a tributary of Seymour Lake and the Clyde River, drains an area of 157 ha (387 acres) in the towns of Morgan and Holland. Due to concerns about possible water quality issues, we sampled water quality at two sites along this tributary in 2016. In particular, we had observed livestock-induced streambank erosion in several pastures and had heard reports about a possible overflowing manure pit along this tributary. A small farm along this tributary had been inspected in 2015, but the inspectors observed that the manure pit was not overflowing at that time. Unlike in 2015, when the manure pit was often filled to near capacity, the manure pit was less full throughout the summer of 2016. Nevertheless, the farmer is reportedly interested in implementing Best Management Practices to address resource concerns along this tributary.

In 2016, we sampled two sites along this tributary, and both total phosphorus and, to a lesser extent, total nitrogen concentrations increased modestly from the upstream to downstream sites (Figure 27). Total phosphorus concentrations were low at the upstream site (Upper Sucker North, median = 10.8 µg/l, range = 6.7-36.4 µg/l) and only slightly higher at the downstream site (Lower Sucker North, median = 14.2 µg/l, range = 6.4-87.3 µg/l). Likewise, total nitrogen concentrations were low at the upstream site (Upper Sucker North, median = 0.24 mg/l, range = 0.18-0.42 mg/l) and only slightly higher at the downstream site (Lower Sucker North, median = 0.37 mg/l, range = 0.26-0.55 mg/l). However, on two dates following rain events, total phosphorus concentrations did increase sharply from the upstream to the downstream site (Figure 27). Thus, implementation of various Best Management Practices on the small farm along this tributary would likely benefit water quality in this stream and further downstream in Seymour Lake.

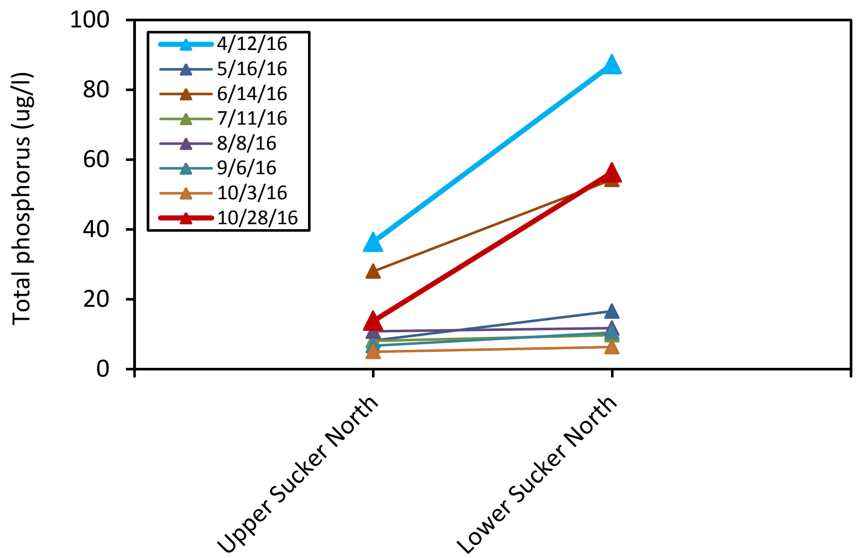

Figure 27. *Total phosphorus "profile" along the north branch of Sucker Brook from Upper Sucker North downstream to Lower Sucker North during April-October 2016. The two rain events are highlighted by larger symbols and thicker lines.*

Johns River

Crystal Brook

Crystal Brook, which is the largest tributary of the Johns River, drains approximately 356 ha (878 acres) in the town of Derby. Crystal Brook drains large areas of agricultural land uses but also forests on the western slope of the ridge separating the Lake Memphremagog and Tomifobia River Basins. Water quality in this stream was first sampled in 2006 after high phosphorus and nitrogen levels were measured further downstream in the Johns River. In 2006, we measured extremely high concentrations of total phosphorus (median = 128 µg/l, range = 29.1-655 µg/l) and moderately high concentrations of total nitrogen (median = 1.6 mg/l, range = 1.3-3.2 mg/l). In addition, the Biomonitoring and Aquatic Studies Section of the Vermont DEC had designated this stream as impaired and in need of a TMDL due to nutrients and sediment from agricultural runoff (Part A, State of Vermont 2004). Based on these data and other assessments, it was determined that much of these nutrients were originating from a leaking manure pit located immediately alongside Crystal Brook, and so, with financial support from the USDA Natural Resources Conservation Service (NRCS) and VAAFM, the owner replaced the leaking manure pit with a larger, sealed manure lagoon in 2007 and a new drainage system to capture leachate from the silage storage bunkers in 2009.

Subsequently, we have continued to monitor nutrient and sediment levels to ensure that these projects were successful in improving water quality in Crystal Brook. Total phosphorus concentrations decreased dramatically between 2006 and 2008 and remained relatively low on all dates, except during one rain event in 2014 (Figure 28). Thus, these data indicated that phosphorus levels in Crystal Brook generally remained improved over those measured prior to the replacement of the manure lagoon in 2007. However, extremely high phosphorus and nitrogen concentrations (total phosphorus = 2,940 µg/l and total nitrogen = 14.2 mg/l) were measured during one rain event on 28 July 2014 (Figure 29). These high concentrations caused a dramatic increase in mean total phosphorus concentrations in 2014 (Figure 28) and suggested that there were still serious problems with runoff from a large barn complex along Crystal Brook. In addition, biomonitoring data collected by the Vermont DEC in September 2014 indicated that both the macroinvertebrate and especially the fish communities had declined in health since the previous sampling in 2010 (Steve Fiske and Rich Langdon, personal communication). Collectively, these data suggested that one or more acute toxicity events, perhaps caused by ammonia-rich runoff, may have occurred in this stream during 2013 and/or 2014. Subsequently, the State of Vermont successfully undertook an enforcement action to correct water quality problems arising from barnyard runoff at this large barn complex.

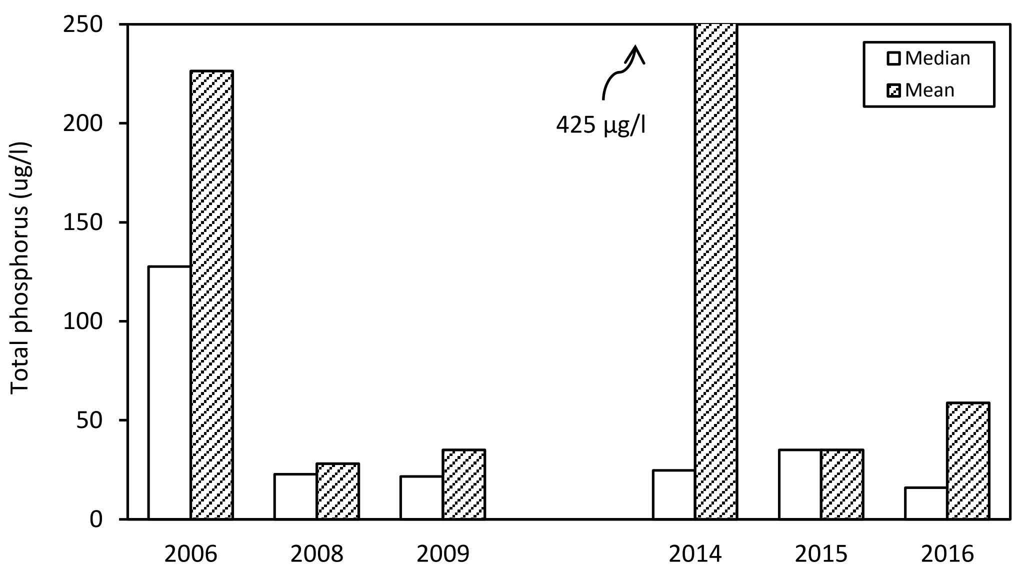

Figure 28. *Annual median and mean total phosphorus concentrations at the Crystal Brook site during 2006-2016.*

Figure 29. *Extremely turbid water was observed in Crystal Brook in Derby, Vermont during the rain event on 28 July 2014 (photograph courtesy of Ben Copans).*

In 2015 and 2016, we resampled the Crystal Brook site to further evaluate the success of these latest efforts to improve agricultural practices and water quality conditions in Crystal Brook. In 2016, total phosphorus concentrations were again relatively low at the Crystal Brook site (median = 16.1 µg/l, range = 8.7-258 µg/l). Compared to 2006, total phosphorus concentrations at the Crystal Brook site remained generally low across most stream flows. Although median total phosphorus concentrations have remained consistently low during all years since 2007 (representing 13-27% of their 2006 value), mean total phosphorus concentrations clearly reflected the impacts of the extremely high total phosphorus concentrations measured during the rain event in 2014. Fortunately, such extreme values were not measured in 2015 and 2016, and, thus, these data indicated that the earlier and more recent agricultural improvement projects and enforcement actions have greatly improved water quality conditions in Crystal Brook.

Direct Tributaries

Strawberry Acres Tributary

The Strawberry Acres Tributary, which is a small tributary that flows directly into the southwest corner of Lake Memphremagog, drains approximately 331 ha (818 acres) in the towns of Newport Town and Coventry. This stream drains agricultural and residential areas as well as extensive forests and wetlands, especially in its headwaters. Water quality in this tributary was first sampled at a downstream site in 2008, and a second site was added further upstream in 2010. During 2008-2010, phosphorus levels were moderately high at both of these sites (median total phosphorus concentrations = 36.8-45.7 µg/l at the downstream site and 32.4 µg/l at the upstream site). Based on conversations with NRCS staff, we identified a small dairy farm along the upper reaches of this tributary as a possible source of the elevated phosphorus levels. In 2014, NRCS assisted the farmer with a number of farmstead improvement projects, including installing a new manure pit, concrete barnyard pad, laneways, and livestock exclusion fencing (Figure 30).

Figure 30. *Improved barnyard (foreground) and manure lagoon (background) at a small dairy farm along the upper reaches of the Strawberry Acres Tributary in Coventry, Vermont on 4 November 2014.*

In 2015 and 2016, we resampled water quality at the two sites to gauge whether or not these projects had improved water quality in this tributary. Total phosphorus concentrations at both sites were markedly lower in 2015 and 2016 than in 2010: Median total phosphorus concentrations decreased 47-76% and mean total phosphorus concentrations decreased 23-47%

at distances of 1.2 km (0.75 mi) and 3.6 km (2.2 mi) downstream from this farmstead (Figure 31-32). Thus, these data indicated that the farmstead and pasture improvement projects greatly improved water quality in this tributary of Lake Memphremagog.

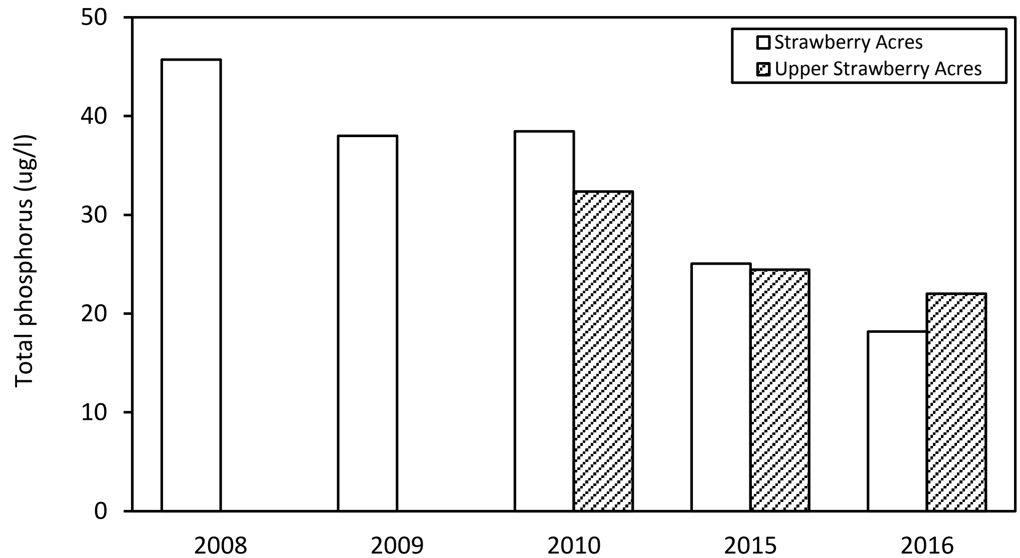

Figure 31. *Median total phosphorus concentrations at two sites along the Strawberry Acres Tributary during 2008-2016.*

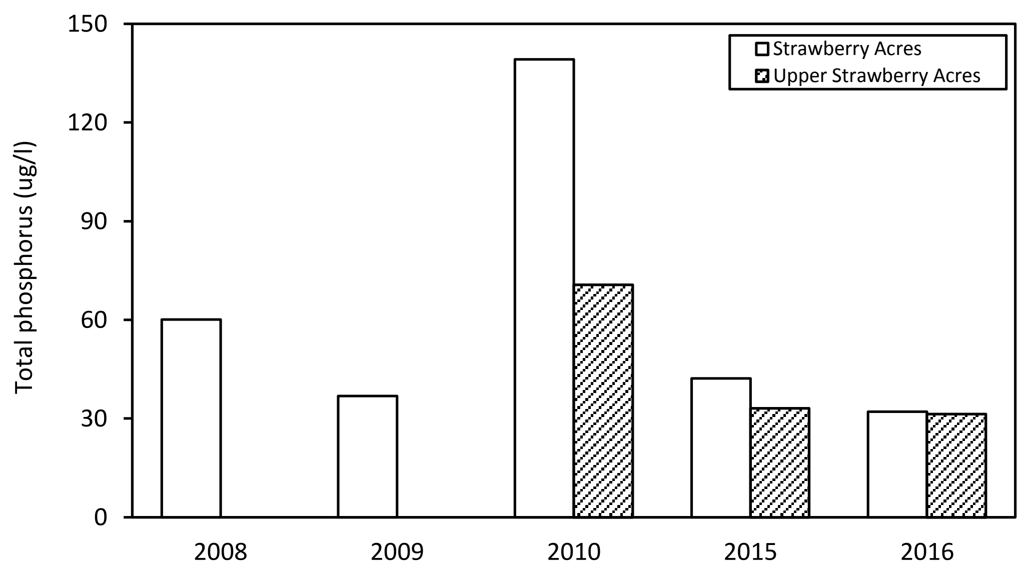

Figure 32. *Mean total phosphorus concentrations at two sites along the Strawberry Acres Tributary during 2008-2016.*

Stearns Brook

East Stearns Tributary

This eastern tributary of Stearns Brook drains 316 ha (782 acres) along the U.S./Canada border in the town of Holland. Based on observations of serious overgrazing and hillside and streambank erosion, we initiated water quality sampling at one site along this tributary in 2016 (Figure 33). Both total phosphorus (median = 38.0 µg/l, range = 16.7-146 µg/l) and total nitrogen concentrations (median = 1.4 mg/l, range = 0.91-2.77 mg/l) were moderately high, but turbidity levels were generally low (median = 1.7 NTU, range = 0.37-25.7 NTU). Based on discussions with staff from the Orleans County Natural Resources Conservation District (NRCD), at least one farm along this tributary is interested in developing nutrient management and grazing plans and installing livestock exclusion fencing. Thus, we recommend that additional sampling be undertaken at multiple sites along this tributary in 2017 to further pinpoint and assess possible nutrient and sediment sources.

Figure 33. *Severe trampling and hillside erosion in a pasture along a small tributary draining into Stearns Brook in Holland, Vermont on 4 November 2015.*

Tributary of Stearns Brook

This western tributary of Stearns Brook drains approximately 275 ha (679 acres) in the towns of Holland and Derby. Based on their assessment of aquatic life, the Biomonitoring and Aquatic Studies Section of the Vermont DEC had designated this tributary as impaired and in need of a TMDL due to nutrients and sediment from agricultural runoff (Part A, State of

Vermont 2014b). Beginning in 2014, we analyzed water quality conditions at six sites along the main stem (four sites) and two smaller tributaries (two sites) in order to pinpoint and assess possible nutrient and sediment sources. In addition, whenever there were sufficient flows, we sampled the outflows from two culverts and two ditches that drained the farmstead of a large farm operation. Based on the sampling in 2014 and 2015, we determined that phosphorus levels increased dramatically downstream of the two upstream sites (Upper Stearns Tributary and Stearns Tributary Falls) and upstream of the next site downstream (Middle Stearns Tributary). In addition, total phosphorus concentrations were consistently high in one of the two small tributaries (Valley Road South) and extremely high during rainfall events in the other small tributary (Twin Bridges Road). Total phosphorus concentrations showed positive relationships with stream flow at all six sites, especially Middle Stearns Tributary and Twin Bridges Road. Like total phosphorus, total nitrogen concentrations increased steadily from the upstream sites down to the Middle Stearns Tributary site, but they were also extremely high in one of the two small tributaries (Twin Bridges Road). We also measured extremely high phosphorus and nitrogen levels in the water flowing from the two culverts and two ditches that drained much of the farmstead. Collectively, these data suggested that much of the nutrients and sediment in this stream was originating from the farmstead and adjacent agricultural fields located upstream of the Middle Stearns Tributary site. In partnership with VAAFM and Vermont DEC, the owners of this farm developed and implemented a number of projects and practices in 2015-2016 to divert runoff from driveways into hay fields, to divert clean water away from the barnyards and laneways, to collect contaminated runoff from the barnyards and laneways in the manure pits, and to add filter strips and cover-cropping to many of the corn fields (Figure 34).

Figure 34. *The Gray Farm undertook numerous clean water diversion and runoff control projects in 2015 and 2016 to improve water quality conditions in a tributary of Stearns Brook. The top photo shows a barnyard area prior to construction on 3 July 2015, and the bottom photo shows the same area during construction of a barrier to separate clean and contaminated water on 28 September 2015 (bottom photograph courtesy of Ben Copans).*

In 2016, we again sampled water quality at these same ten sites along the main stem, two small tributaries, two culverts, and two ditches in order to evaluate the success of the farmstead and field practice improvements undertaken by the large farm operation and to identify any additional needs. Based on this sampling, we were able to confirm that phosphorus levels had decreased dramatically at several sites that drained areas where farmstead and field improvements had been undertaken, especially the Middle Stearns Tributary, Twin Bridges Road, and Upper Barnyard Culvert sites (Figure 35-36). Although they also decreased markedly, phosphorus levels remained high at two other sites (Lower Barnyard Culvert and Valley Road Garage), and they remained high and unchanged at the Valley Road Ditch site. Although considerably lower, phosphorus levels also remained largely unchanged at the Lower Stearns Tributary and Valley Road South sites. Total nitrogen concentrations, on the other hand, did not change dramatically at any site, except Valley Road Garage, where levels decreased dramatically between 2015 and 2016 (Figure 37-38). Thus, the water samples collected in 2016 indicated that there were significant improvements in water quality at many of the sites along this tributary. Based on these results, we recommend continuing to sample all of these sites in 2017 to further evaluate the success of the ongoing agricultural improvement projects and practices as well as further pinpointing and assessing any remaining source(s) of water quality problems.

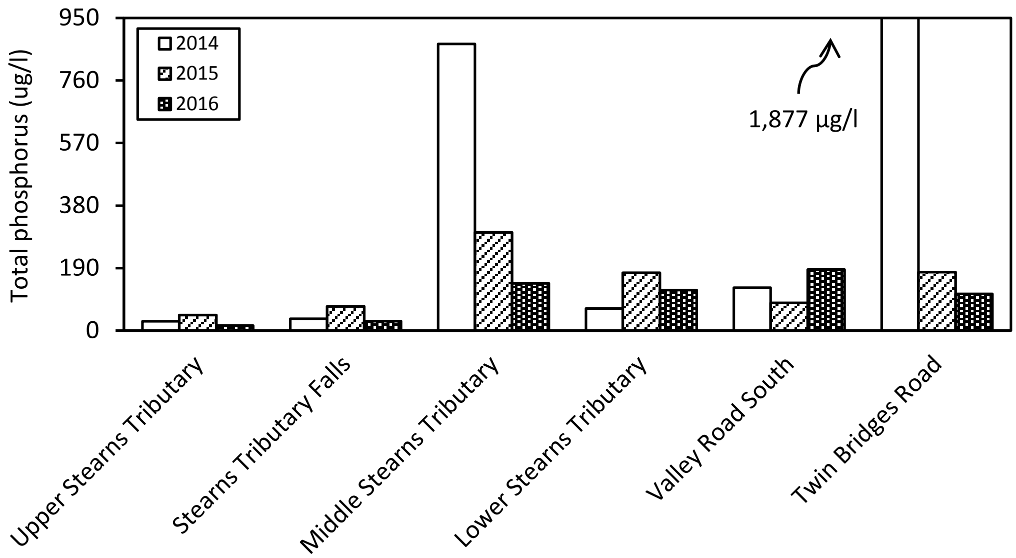

Figure 35. *Mean total phosphorus concentrations at six sites along the tributary of Stearns Brook from Upper Stearns Tributary downstream to Lower Stearns Tributary during 2014-2016.*

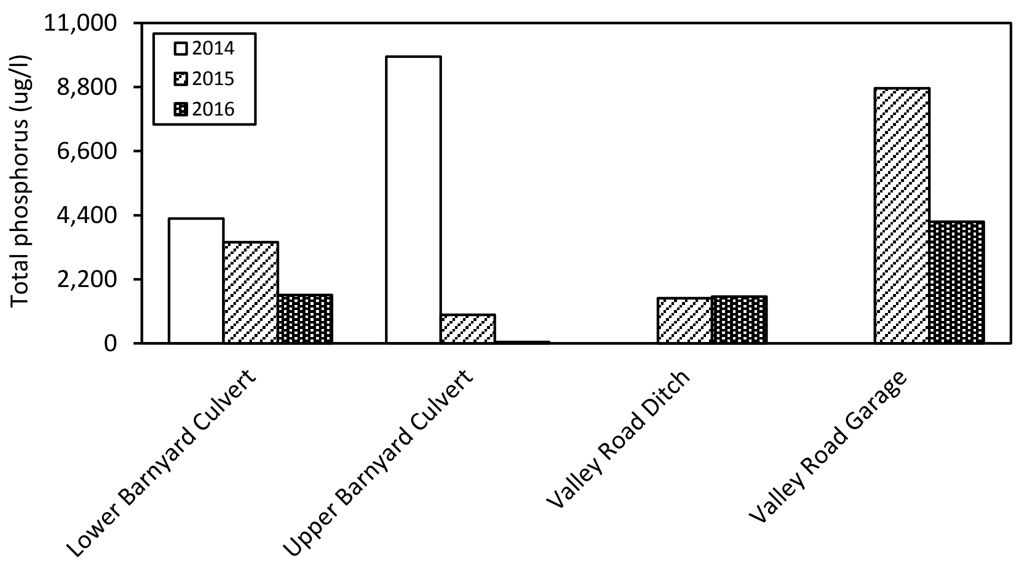

Figure 36. *Mean total phosphorus concentrations at four sites along ditches and culverts draining into the tributary of Stearns Brook during 2014-2016.*

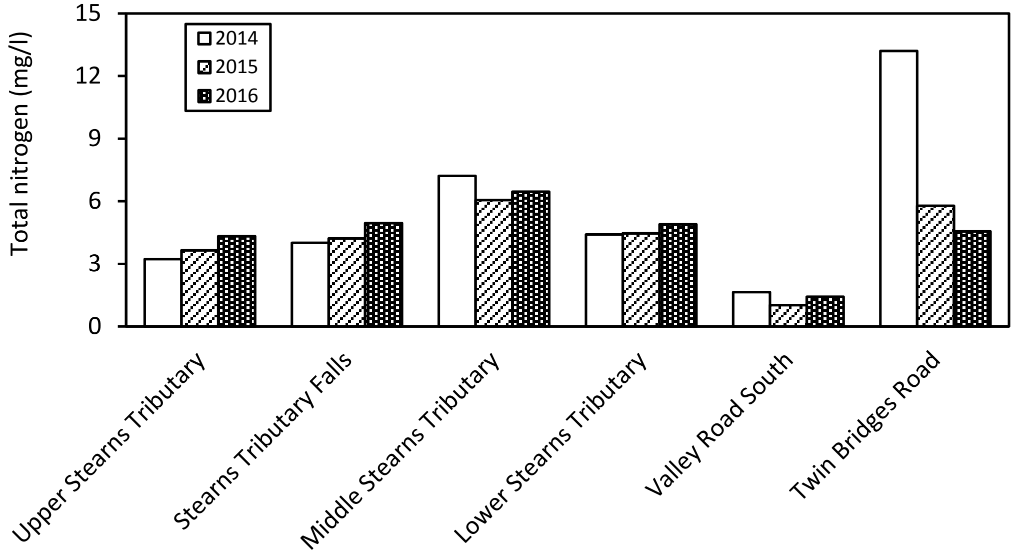

Figure 37. *Mean total nitrogen concentrations at six sites along the tributary of Stearns Brook from Upper Stearns Tributary downstream to Lower Stearns Tributary during 2014-2016.*

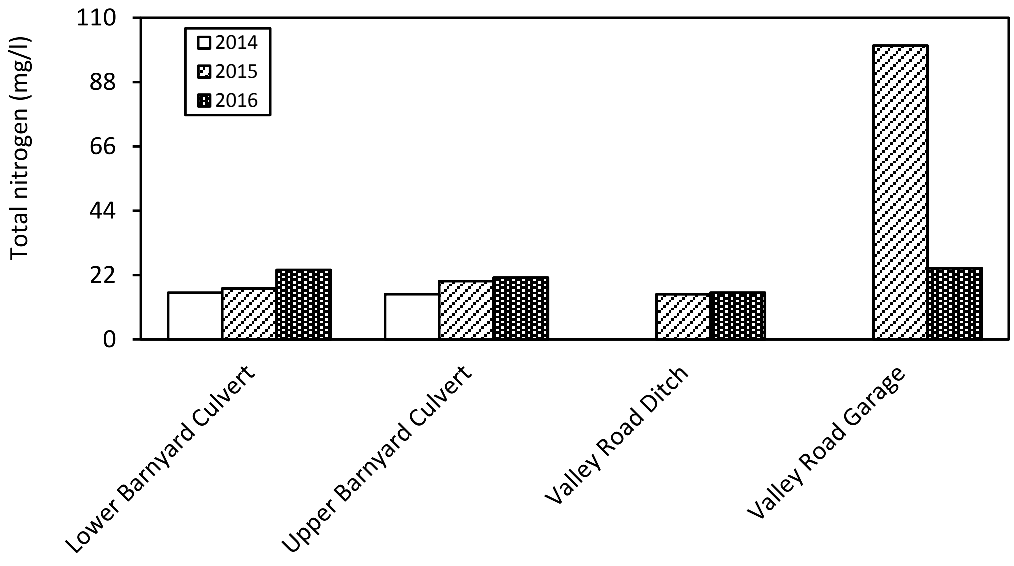

Figure 38. *Mean total nitrogen concentrations at four sites along ditches and culverts draining into the tributary of Stearns Brook during 2014-2016.*

Priority Subwatersheds

In 2016, we continued our efforts to identify, develop, and implement phosphorus-reduction projects and practices in areas where they will most effectively reduce nutrient and sediment exports along the Vermont tributaries of Lake Memphremagog. As part of these efforts, we updated our earlier analyses that had mapped and identified the subwatersheds exhibiting the highest total phosphorus concentrations along the Vermont tributaries of Lake Memphremagog (Gerhardt 2013, 2015). Since the GIS layers and supporting data had not been updated since 2014, we added the new subwatersheds that were first sampled in 2015 and 2016, and we added the water quality data collected during 2015-2016 to those collected during 2005-2014. With these updated data and GIS layers, we flagged those subwatersheds exhibiting the highest total phosphorus concentrations as priority subwatersheds, where we will focus efforts to identify and assess possible sources of water quality problems and develop and implement phosphorus-reduction projects and practices. Throughout this project, we shared information about possible sources of water quality problems and potential phosphorus-reduction projects and practices with the appropriate agency and/or organizational staff, who will work with landowners and land managers to develop and implement the appropriate phosphorus-reduction projects and practices.

Methods

To accomplish this project, we used the water quality data collected along the Vermont tributaries of Lake Memphremagog during 2005-2016 to identify those subwatersheds that exhibited the highest total phosphorus concentrations. First, we used the U.S. Geological Survey's Streamstats program (http://streamstats.usgs.gov/) to delineate the boundaries of each subwatershed drained by each sample site and then imported and merged these boundaries in a Geographic Information System (ArcGIS 10, ESRI, Redlands, California). Second, we calculated the arithmetic mean total phosphorus concentration for each sample site, as mean values tend to give greater weight to those higher concentrations that typically occur only at high flows. We then identified a subset of priority subwatersheds in which to focus our efforts to identify and assess possible sources of water quality problems and to develop and implement phosphorus-reduction projects and practices (however, we will continue to pursue opportunities in other areas, where water quality issues and/or potential phosphorus-reduction projects and practices were identified). In this study, the priority subwatersheds were identified as those subwatersheds in which mean total phosphorus concentrations exceeded 44 µg/l.

Results and Discussion

This project required multiple steps. First, we added twelve new subwatersheds that were first sampled in 2015 or 2016. These subwatersheds included six that were located along two tributaries of the Black River (Town Line Brook and St. Onge tributary) and three tributaries of Stearns Brook (Upper Stearns Brook, East Stearns Tributary, and Tice Mill) that had not been sampled previously. In addition, we further subdivided four subwatersheds into ten subwatersheds, where we had added additional sample sites to better pinpoint and assess nutrient and sediment sources (Stony and Sucker Brooks and the Airport and Hamel tributaries). Ultimately, we analyzed total phosphorus concentrations in 158 subwatersheds in the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook (Table 1, Figure 39).

Table 1. Numbers of subwatersheds sampled, mapped, and assessed as part of efforts to identify possible phosphorus sources and to develop and implement phosphorus-reduction projects and practices in the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook during 2005-2016. The numbers for the updated analysis includes all subwatersheds examined in the previous analyses.

	Previous Analysis (2005-2014 Data)	Updated Analysis (2005-2016 Data)
Barton River	31	32
Black River	43	49
Clyde River	29	31
Johns River	24	24
Direct tributaries	14	14
Stearns Brook	5	8
Total number of subwatersheds	146	158

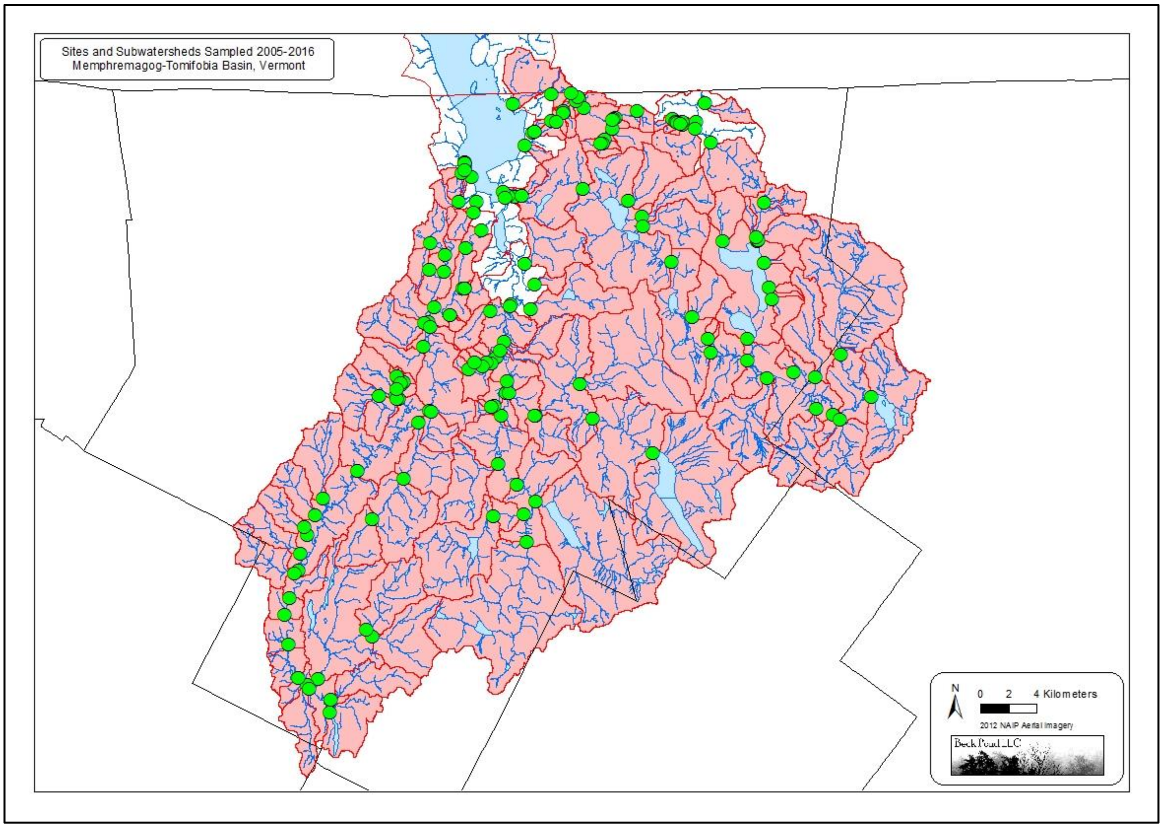

Figure 39. *The 158 sample sites and their associated subwatersheds in the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook during 2005-2016. The shaded polygons indicate the subwatersheds drained by each of the sample sites.*

Second, we added the two most recent years of water quality data (2015-2016) to our earlier analyses of water quality data collected during 2005-2014. We used all of these data (2005-2016) to calculate the mean total phosphorus concentrations for all 158 subwatersheds. In general, mean total phosphorus concentrations were highest in several areas of the Black River watershed, in the downstream sections of the Barton River watershed, in several areas of the Johns River watershed, along several small tributaries that flow directly into Lake Memphremagog, and along several tributaries of Stearns Brook (Figure 40). More specifically, the subwatersheds with the highest mean total phosphorus concentrations occurred along two reaches of the main stem of the Black River and four of its tributaries (Stony and Brighton Brooks and the Airport and St. Onge tributaries), three reaches of the main stem of the Barton River and two of its tributaries (Junkyard and Hamel tributaries), several areas in the Johns River watershed, five small tributaries that flow directly into Lake Memphremagog (Holbrook Bay, Wishing Well, Strawberry Acres, East Side, and Sunset Acres tributaries), and several tributaries of Stearns Brook. In contrast, the subwatersheds with the lowest mean total phosphorus concentrations occurred throughout the Clyde River watershed, upstream sections of the Barton River watershed, and along many tributaries of the Black and Johns Rivers.

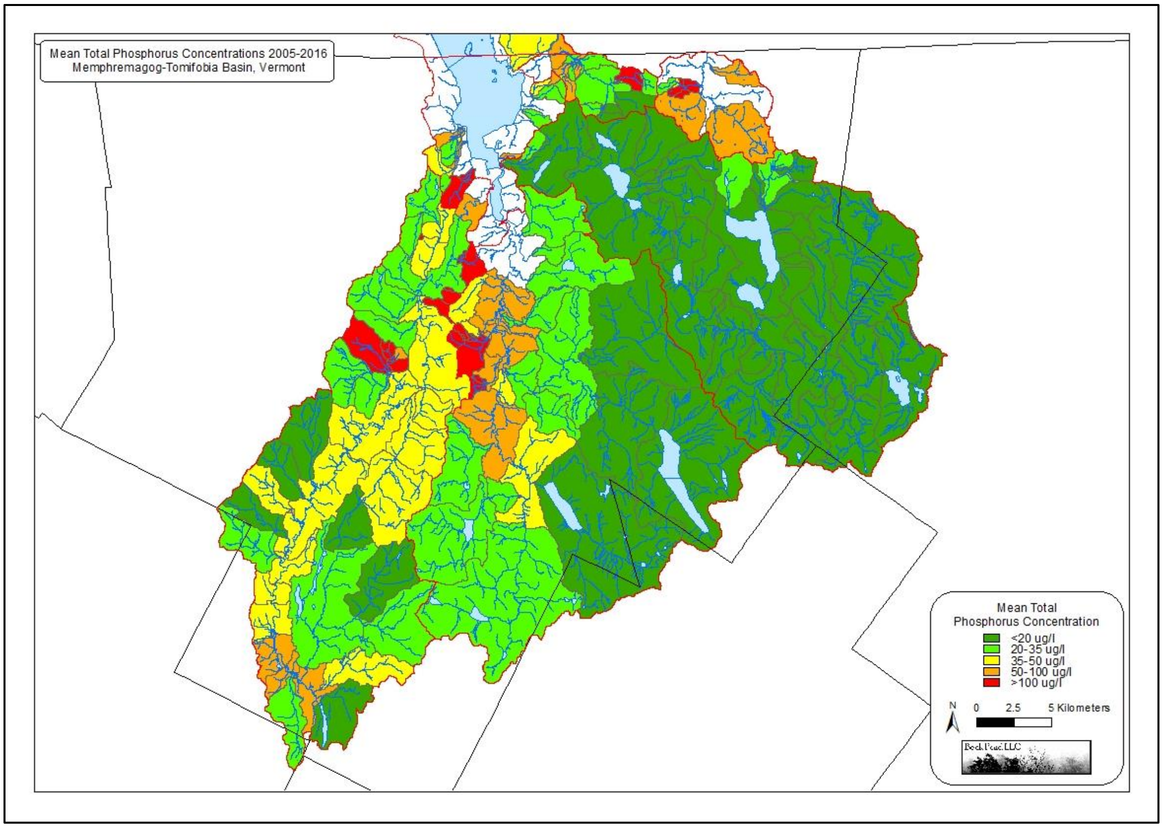

Figure 40. *Mean total phosphorus concentrations in 158 subwatersheds in the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook during 2005-2016.*

From these 158 subwatersheds, we prioritized 63 subwatersheds in which mean total phosphorus concentrations exceeded 44 μg/l during 2005-2016 (Table 2, Figure 41). These 63 priority subwatersheds covered 182 km^2 (70 mi^2) or 14.8% of the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook and were distributed throughout the watersheds of the Black and Johns Rivers, downstream sections of the Barton River, several small tributaries that flow directly into Lake Memphremagog, and several tributaries of Stearns Brook (Figure 41). In contrast, none of the priority subwatersheds were located in the watershed of the Clyde River.

Table 2. Priority subwatersheds, defined as those subwatersheds in which mean total phosphorus concentrations exceeded 44 µg/l, in the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook during 2005-2016.

Black River (24 Subwatersheds)

Airport Trib North	Airport Trib South	Airport Tributary
Black River	Brighton Brook	Brighton Brook North
Cemetery Road	Coventry Bridge	Irasburg
Lower Nelson Farm	Mud Pond	Nelson Northeast
Nelson Northwest	North Craftsbury Road	Post Road
Shalney Branch	St. Onge Tributary	Sunrise Farm
St. Onge Main	Stony Brook	Tanner Road
Town Line Brook	Upper Brighton Brook North	Upper Nelson Northwest

Barton River (13 Subwatersheds)

Barton Alder Brook	Barton River	Ethan Allen
Hamel Marsh	Middle Hamel Tributary	Rock Junkyard
Royer Farm	Royer Tributary	Upper Hamel Marsh
Upper Hamel Tributary	Upper Junkyard	Upper Middle Hamel Tributary
Webster Road		

Clyde River (0 Subwatersheds)

Johns River (7 Subwatersheds)

Beebe Plain	Crystal Brook	Darling Hill
DHM	Johns River	Middle Darling Hill
North Derby Road		

Direct Tributaries (12 Subwatersheds)

Eagle Point	East Side	Holbrook Bay
Holbrook Bay North	Holbrook Bay South	Holbrook South Pond
Strawberry Acres	Sunset Acres	Upper Strawberry Acres
Upper Sunset Acres North	Upper Wishing Well	Wishing Well

Stearns Brook (7 Subwatersheds)

East Stearns Tributary	Lower Stearns Tributary	Middle Stearns Tributary
Stearns Tributary Falls	Tice Mill	Upper Stearns Brook
Valley Road South		

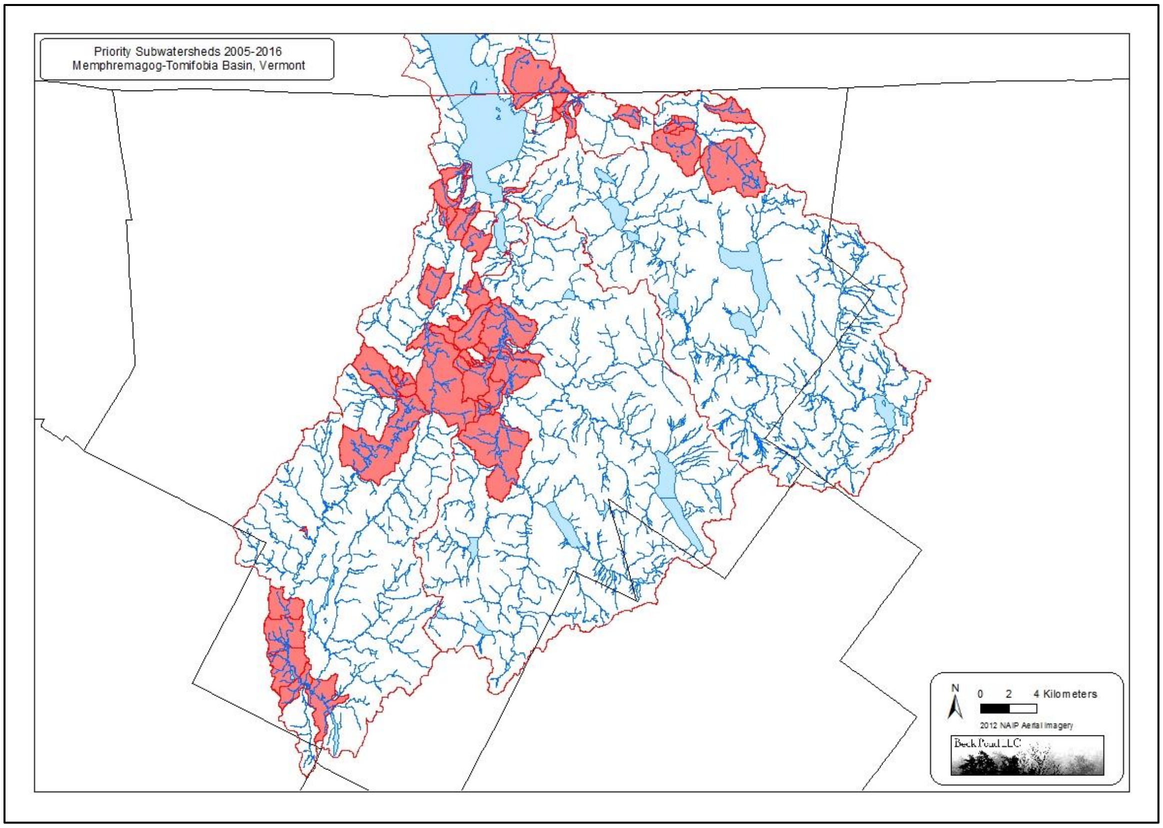

Figure 41. *Priority subwatersheds in the Vermont portion of the Lake Memphremagog Basin and the watershed of Stearns Brook during 2005-2016. The priority subwatersheds were defined as those subwatersheds in which mean total phosphorus concentrations exceeded 44 µg/l during 2005-2016.*

Phosphorus Load Reductions

Finally, we developed and tested a methodology for calculating the phosphorus load reductions that might be achieved by implementing various phosphorus-reduction projects and practices as part of the Total Maximum Daily Load (TMDL) and Basin Plan (State of Vermont 2012) being developed for the Lake Memphremagog Basin.

Methods

To accomplish this task, we modified the Best Management Practices (BMP) Scenario Tool developed for the Lake Champlain Basin. For each watershed examined, we used the area of each land use as mapped in the Cropland Data Layer from the National Agricultural Statistics

Service (NASS), the phosphorus load attributable to each land use based on a modified phosphorus export model (SMi 2009), a list of possible phosphorus-reduction projects and practices that could be implemented for each land use, and the efficiency with which those projects and practices reduce phosphorus loading from each land use. Collectively, these inputs allowed us to calculate the absolute and proportional reductions in phosphorus load that might be attained by implementing projects or practices on some or all of the area encompassed by each land use in each watershed.

In this project, we evaluated six watersheds in order to develop and test this methodology (Brighton Brook North, Shalney Branch, Crystal Brook, and the Junkyard, Strawberry Acres, and Wishing Well Tributaries). We chose these six watersheds, because they had diverse land uses but included both agricultural production areas and large areas of agricultural fields, including corn, hay, and pasture. In addition, these six watersheds had already received considerable attention, including multiple years of water quality sampling and implementation of various phosphorus-reduction projects and practices over the past few years. To assess the feasibility of using the modified BMP Scenario Tool to identify and prioritize projects and practices that most effectively reduce phosphorus exports into Lake Memphremagog, we evaluated two scenarios: 1) implementation of all suitable projects and/or practices in all of the appropriate areas of each land use and 2) implementation of only those projects and/or practices that have already been completed. For several of the land uses, there were either no applicable best management practices (water, wetland, and herb/shrub) or only a single suitable practice (forest, all four classes of dirt road, and farmstead)(Table 3). For two of the land uses, we considered implementation of only a single surface infiltration practice applied to either 2% (developed pervious) or 10% (paved roads) of the area classified as that land use. Finally, for developed pervious lands, barren lands, and three of the agricultural land uses (cultivated land, hay, and pasture), multiple practices were possible, and so we used aerial photographs and field observations to identify which areas were suitable for each of the possible projects and practices. For example, riparian and ditch buffers were only suitable for agricultural fields that were bisected by or bordered a stream or ditch. We then used this information to calculate the percentage of the area encompassed by that land use on which each project or practice could be applied.

Table 3. Best Management Practices applicable to each land use in the Lake Memphremagog Basin. Efficiency is the proportion of the phosphorus load that would be eliminated by implementing each project or practice on that land use. Efficiencies of individual projects and practices may be reduced if more than one project or practice is applied to a land use (although total efficiency will be increased). Max values indicate the maximum proportion of that land use to which that practice could be applied.

Land Use	Project or Practice	Required Condition(s)	Efficiency (%)
Developed (pervious)	No phosphorus fertilizer	Fertilized lawn (max=12%)	50
	Ditch buffer	Ditch in or beside site	51
	Riparian buffer	Stream in or beside site	67
Developed (impervious)	Impervious area removal	Various	89
	Biofiltration with underdrains	Various (max=40%)	38-89
	Surface infiltration practices	Various (max=40%)	54-99
	Sand filter	Various (max=40%)	42-65
	Infiltration trench	Various (max=40%)	51-93
	Extended dry detention pond	Various (max=40%)	19
	Open channel/dry swale	Various (max=40%)	34
	Gravel wetland	Various (max=40%)	30-66
	Wet pond/created wetlands	Various (max=40%)	42-65
	Ditch buffer	Ditch in or beside site	51
	Riparian buffer	Stream in or beside site	67
Septic	Strengthened regulations	N/A	20
Paved road	Leaf litter collection	N/A	5
	Mechanical broom sweeper	N/A	1-3
	Regenerative air-vacuum	N/A	8
	Catch basin cleaning	Catch basin	2
	Biofiltration with underdrains	Various	38-89
	Surface infiltration practices	Various	54-99
	Infiltration trench	Various	51-99
	Extended dry detention pond	Various	19
	Gravel wetland	Various	30-66
	Wet pond/created wetlands	Various	42-65
Dirt road	Roadside erosion control	N/A	50
Farmstead	Barnyard management	N/A	80

Table 3. Continued.

Land Use	Project or Practice	Required Condition(s)	Efficiency (%)
Cultivated soil	Manure injection	N/A	9
	Reduced P manure	N/A	5-14
	Change in crop rotation	N/A	25
	Crop to hay	N/A	77-80
	Conservation tillage	N/A	15-50
	Cover crop	N/A	28
	Grassed waterway	Cropped wet swale	25-40
	Ditch buffer	Ditch in or beside field	51
	Riparian buffer	Stream in or beside field	67
Hay	Grassed waterway	Gully erosion	52
	Ditch buffer	Ditch in or beside field	51
	Riparian buffer	Stream in or beside field	67
	Manure injection	N/A	2
	Reduced phosphorus manure	N/A	2
	Conversion to forest land	N/A	90
Pasture	Fencing (riparian buffer)	Stream in or beside field	74
	Fencing (no riparian buffer)	Stream in or beside field	55
	Managed intensive grazing	N/A	24
Forest	Stream crossing/sediment	N/A	5
Barren land	Conversion to developed land	N/A	75
	Conversion to forest	N/A	97
Streambank	Restoration of equilibrium	N/A	55
Shrub/herb	None	N/A	0
Wetland	None	N/A	0
Water	None	N/A	0

Results and Discussion

In the six watersheds evaluated, the dominant land uses were forest and hay: Forests covered 22-71% and hay covered 16-40% of each of the six watersheds (Table 4). Pasture was a widespread land use in two of the watersheds (Junkyard = 11% and Wishing Well = 12%), and developed pervious lands were also widespread in the watershed of the Junkyard Tributary (10%).

Table 4. Area (ha) covered by each land use in six tributary watersheds of Lake Memphremagog. Bold font indicates those land uses covering >10% of each watershed.

Land Use	Brighton Br. North	Strawberry Acres	Shalney Branch	Wishing Well	Crystal Brook	Junkyard
Water	0.0	0.9	0.1	0.0	0.0	0.0
Developed pervious	10.8	11.4	10.1	14.4	7.8	**36.4**
Developed impervious	10.8	2.7	3.5	8.0	7.8	16.7
Paved road	3.3	2.2	1.7	5.5	2.5	10.1
Dirt road	4.3	0.5	1.8	1.3	1.8	1.4
Dirt road low erosion	5.2	1.2	3.7	1.6	2.7	0.8
Dirt road mod. erosion	1.5	0.4	1.6	0.1	0.5	0.0
Dirt road high erosion	0.2	0.0	0.2	0.0	0.0	0.0
Farmstead	17.9	2.3	2.2	3.3	5.8	3.8
Hay	**216.2**	**44.4**	**114.5**	**126.1**	**114.7**	**123.9**
Pasture	66.0	13.6	34.9	**38.5**	35.0	**37.8**
Cultivated A soils	8.5	0.0	0.0	0.0	0.0	0.0
Cultivated B soils	58.7	0.0	0.0	0.7	0.2	0.0
Cultivated C soils	33.1	0.7	0.2	1.3	12.7	11.0
Cultivated D soils	19.5	0.1	0.0	0.1	0.1	23.1
Cultivated unknown soils	0.2	0.0	0.0	0.0	0.0	0.0
Barren land	0.3	0.3	0.0	0.3	0.0	0.0
Wetland	3.0	3.8	14.3	1.4	1.9	0.4
Shrub/herb	18.0	3.9	10.1	3.8	8.1	6.2
Forest	**448.4**	**188.8**	**497.0**	**110.2**	**200.5**	**76.5**
Total area	926.0	277.0	696.0	316.5	402.1	347.9

In contrast, different sets of land uses were the primary sources of phosphorus exports in these same six watersheds (Table 5). Reflecting the importance of agriculture (18-57% of land cover in these six watersheds), the majority of the phosphorus exports in these watersheds originated from farmsteads, hay fields, pasture, and cultivated lands. Despite covering larger areas of these six watersheds (22-71%), forests exported a notable proportion of the phosphorus exports in only two subwatersheds (Shalney Branch and Strawberry Acres), both of which had the largest proportions of forest in their subwatersheds (68 and 71%, respectively). In contrast, pervious and impervious developed lands and paved and dirt roads represented relatively minor sources of phosphorus exports in these six watersheds, probably due to the limited extent of these land uses in five of the six watersheds.

Table 5. Estimated annual phosphorus exports (kg/year) for each land use in six tributary watersheds of Lake Memphremagog. Bold font indicates those land uses representing >10% of the phosphorus exports from each watershed.

Land Use	Brighton Br. North	Strawberry Acres	Shalney Branch	Wishing Well	Crystal Brook	Junkyard
Water	0.0	0.1	0.0	0.0	0.0	0.0
Developed pervious	7.2	7.2	6.7	9.1	4.2	22.2
Developed impervious	25.1	6.0	8.0	17.6	14.8	35.5
Paved road	4.2	2.7	2.1	6.6	2.6	12.1
Dirt road	16.3	1.8	6.9	4.9	5.7	4.9
Dirt road low erosion	36.3	8.3	26.3	10.4	15.5	5.6
Dirt road mod. erosion	15.6	4.2	16.9	1.3	4.3	0.0
Dirt road high erosion	2.8	0.0	2.8	0.0	0.0	0.0
Farmstead	**216.0**	**26.1**	26.8	**38.4**	**56.6**	**43.4**
Hay	**181.5**	**35.5**	**96.1**	**100.9**	**78.6**	**99.1**
Pasture	55.4	10.8	29.3	**30.8**	24.0	30.2
Cultivated A soils	7.7	0.0	0.0	0.0	0.0	0.0
Cultivated B soils	**270.9**	0.0	0.0	2.8	0.9	0.0
Cultivated C soils	**117.3**	2.2	0.6	4.5	**36.7**	37.2
Cultivated D soils	103.6	0.5	0.0	0.5	0.4	**116.8**
Cultivated unknown soils	0.9	0.0	0.0	0.0	0.0	0.0
Barren land	0.7	0.6	0.0	0.7	0.0	0.0
Wetland	1.4	1.7	6.9	0.6	0.7	0.2
Shrub/herb	3.4	0.7	1.9	0.7	1.2	1.1
Forest	36.2	**14.5**	**40.2**	8.5	13.2	5.9
Total export	1057.7	133.5	300.1	249.1	309.0	418.3

North Branch of Brighton Brook

The north branch of Brighton Brook, a tributary of the Black River, drains approximately 926 ha (2,288 acres) in the towns of Irasburg and Newport Town. This watershed is dominated by forest [448 ha (1,108 acres)] and agriculture, primarily hay [216 ha (534 acres)] and cultivated soils [111 ha (275 acres)]. The total estimated phosphorus export from this watershed is 1,058 kg/year (2,332 lb/year) with the majority originating from cultivated soils, farmsteads, and hay fields (Table 5).

For the north branch of Brighton Brook, we examined two scenarios for BMP implementation (Table 6). First, we evaluated the phosphorus load reductions that would be achieved if all of the suitable projects and practices were applied to the appropriate areas of each land use. In this scenario, the greatest reductions in phosphorus loads would occur if barnyard improvement projects were applied to 100% of the farmsteads; riparian buffers were applied to 63% of the hay fields; and cover crops, conservation tillage, grassed waterways, and ditch and riparian buffers were applied to most of the cultivated soils. Collectively, these and the other feasible projects and practices could be applied to 745 ha (1,841 acres) and would reduce phosphorus loads by 635 kg/year (1,400 lb/year), a 60% reduction. Although forest is the dominant land use covering almost 48% of this watershed, applying stream crossing erosion and sedimentation control practices on 100% of the forest would reduce phosphorus loads by only 0.2%.

Second, we evaluated the phosphorus load reductions that should have resulted from the projects and practices that have already been implemented in this watershed (Table 6). These projects and practices included barnyard improvements (relocating a mortality compost pile to drain into an existing manure pit) that were applied to roughly 6% of the farmstead and installing grass waterways in some of the corn fields (20% of Class B soils and 100% of the Class C soils) that had previously been drained by ditches and wetlands. In addition, we assumed that there had been a 12% reduction in the area of developed, pervious lands that were receiving phosphorus fertilizer. Collectively, these projects and practices, which were applied to 47 ha (117 acres), should have reduced phosphorus loads by 68 kg/year (150 lb/year), a 6% reduction. This modeled reduction is considerably less than the 61-69% reduction in total phosphorus concentrations measured at the upstream site on the north branch of Brighton Brook in 2016.

Table 6. Phosphorus load reductions potentially achieved by implementing various phosphorus-reduction projects and practices under two different scenarios in the watershed of the north branch of Brighton Brook. Reductions were calculated by the BMP Scenario Tool modified for the Lake Memphremagog Basin. Bold font indicates load reductions of greater than 5% of the total.

Land Use	Project(s) and/or Practice(s)	Area (ha)	Load Reduction (kg)	% Reduction
Feasible Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.3	0.4	0.0
Developed	Ditch buffer (pervious)	1.1	0.4	0.0
Developed	Surface infiltration practices 0.9" (impervious)	0.2	0.5	0.0
Paved road	Surface infiltration practices .9"	0.2	0.2	0.0
Dirt road	Roadside erosion control	1.1	2.0	0.2
Dirt road low	Roadside erosion control	2.6	9.1	0.9
Dirt road mod	Roadside erosion control	1.3	7.0	0.7
Dirt road high	Roadside erosion control	0.2	1.4	0.1
Farmstead	**Barnyard management**	**17.9**	**172.8**	**16.3**
Hay	**Riparian buffer**	**136.2**	**76.6**	**7.2**
Pasture	Fencing/livestock exclusion w/buffers	14.5	9.0	0.8
Cultivated A	Cover crop, conservation tillage, etc.	8.5	4.9	0.5
Cultivated B	Cover crop, conservation tillage w/buffers	5.3	23.0	2.2
Cultivated B	**Cover crop, conservation tillage, etc.**	**53.4**	**161.7**	**15.3**
Cultivated C	Cover crop, conservation tillage w/buffers	10.9	36.4	3.4
Cultivated C	Cover crop, conservation tillage, etc.	22.1	49.0	4.6
Cultivated D	Cover crop, conservation tillage w/buffers	1.8	8.9	0.8
Cultivated D	**Cover crop, conservation tillage, etc.**	**17.8**	**68.9**	**6.5**
Cultivated	Cover crop, conservation tillage, etc.	0.2	0.5	0.1
Forest	Stream crossing control	448.4	1.8	0.2
Total		744.8	634.5	60.0
Completed Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.3	0.4	0.0
Farmstead	Barnyard management	1.1	10.4	1.0
Cultivated B	Grassed waterways	11.7	21.7	2.0
Cultivated C	Grassed waterways	33.1	35.2	3.3
Total		47.2	67.7	6.4

Shalney Branch

Shalney Branch, a tributary of the Black River, drains approximately 696 ha (1,720 acres) in the towns of Albany and Lowell. This watershed is dominated by forest [497 ha (1,228 acres)] and agriculture, primarily hay [114 ha (283 acres)]. The total estimated phosphorus export from this watershed is 300 kg/year (662 lb/year) with the majority originating from hay fields, forest, and pasture (Table 5).

For Shalney Branch, we examined two scenarios for BMP implementation (Table 7). First, we evaluated the phosphorus load reductions that would be achieved if all of the suitable projects and practices were applied to the appropriate areas of each land use. In this scenario, the greatest reductions in phosphorus loads would occur if barnyard improvement projects were applied to 100% of the farmsteads, livestock exclusion fencing was installed in 100% of the pasture, and riparian buffers were installed in 53% of the hay fields. Collectively, these and the other feasible projects and practices would be applied to 603 ha (1,491 acres) and would reduce phosphorus loads by 92 kg/year (203 lb/year), a 31% reduction. Although forest is the dominant land use covering almost 71% of this watershed, applying stream crossing erosion and sedimentation control practices on 100% of the forest reduced phosphorus loads by only 0.7%.

Second, we evaluated the phosphorus load reductions that should have resulted from the projects and practices that have already been implemented in this watershed (Table 7). These projects and practices included barnyard improvements (hardened laneway with water bars) that were applied to roughly 11% of the farmsteads. In addition, we assumed that there had been a 12% reduction in the area of developed, pervious lands that were receiving phosphorus fertilizer. Collectively, these projects and practices, which were applied to 1.5 ha (3.7 acres), should have reduced phosphorus loads by 2.8 kg/year (6.2 lb/year), a 0.9% reduction. This modeled reduction is considerably less than the 50% reduction in total phosphorus concentrations measured at the downstream site on Shalney Branch in 2012-2013 (Gerhardt 2014).

Table 7. Phosphorus load reductions potentially achieved by implementing various phosphorus-reduction projects and practices under two different scenarios in the watershed of Shalney Branch. Reductions were calculated by the BMP Scenario Tool modified for the Lake Memphremagog Basin. Bold font indicates load reductions of greater than 5% of the total.

Land Use	Project(s) and/or Practice(s)	Area (ha)	Load Reduction (kg)	% Reduction
Feasible Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.2	0.4	0.1
Developed	Ditch buffer (pervious)	3.0	1.0	0.3
Developed	Surface infiltration practices .9" (impervious)	0.1	0.1	0.0
Paved road	Surface infiltration practices .9"	0.2	0.2	0.1
Dirt road	Roadside erosion control	0.5	0.9	0.3
Dirt road low	Roadside erosion control	1.9	6.6	2.2
Dirt road mod	Roadside erosion control	1.4	7.6	2.5
Dirt road high	Roadside erosion control	0.2	1.4	0.5
Farmstead	**Barnyard management**	**2.2**	**21.4**	**7.1**
Hay	**Riparian buffer**	**60.7**	**34.1**	**11.4**
Pasture	**Fencing/livestock exclusion (no buffers)**	**34.9**	**16.1**	**5.4**
Forest	Stream crossing control	497.0	2.0	0.7
Total		603.3	91.9	30.6
Completed Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.2	0.4	0.1
Farmstead	Barnyard management	0.2	2.4	0.8
Total		1.5	2.8	0.9

Junkyard Tributary

The Junkyard Tributary, a tributary of the Barton River, drains approximately 348 ha (860 acres) in the towns of Irasburg and Barton. This watershed is dominated by agriculture, primarily hay [124 ha (306 acres)] and pasture [38 ha (93 acres)], forest [76 ha (189 acres)], and pervious and impervious developed lands [53 ha (131 acres)]. The total estimated phosphorus export from this watershed is 418 kg/year (922 lb/year) with the majority originating from cultivated soils, hay fields, and farmsteads (Table 5).

For the Junkyard Tributary, we examined two scenarios for BMP implementation (Table 8). First, we evaluated the phosphorus load reductions that would be achieved if all of the suitable projects and practices were applied to the appropriate areas of each land use. In this scenario, the greatest reductions in phosphorus loads would occur if barnyard improvement projects were applied to 100% of the farmsteads and cover crops, conservation tillage, grassed waterways, and ditch or riparian buffers were applied to a majority of the cultivated soils. Collectively, these and the other feasible projects and practices could be applied to 153 ha (378 acres) and would reduce phosphorus loads by 184 kg/year (406 lb/year), a 44% reduction. Although forest is the second most important land use covering almost 22% of this watershed, applying stream crossing erosion and sedimentation control practices on all 100% of the forest would reduce phosphorus loads by only 0.1%.

Table 8. Phosphorus load reductions potentially achieved by implementing various phosphorus-reduction projects and practices under two different scenarios in the watershed of the Junkyard Tributary. Reductions were calculated by the BMP Scenario Tool modified for the Lake Memphremagog Basin. Bold font indicates load reductions of greater than 5% of the total.

Land Use	Project(s) and/or Practice(s)	Area (ha)	Load Reduction (kg)	% Reduction
Feasible Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	4.4	1.3	0.3
Developed	Ditch buffer (pervious)	7.3	2.3	0.5
Developed	Surface infiltration practices .9" (impervious)	0.3	0.7	0.2
Paved road	Surface infiltration practices .9"	1.0	1.1	0.3
Dirt road	Roadside erosion control	0.3	0.6	0.1
Dirt road low	Roadside erosion control	0.4	1.4	0.3
Farmstead	**Barnyard management**	**3.8**	**34.7**	**8.3**
Hay	Riparian buffer	19.8	10.6	2.5
Pasture	Fencing/livestock exclusion (no buffers)	4.9	2.2	0.5
Cultivated C	Cover crop, conservation tillage w/buffers	4.2	13.3	3.2
Cultivated C	Cover crop, conservation tillage, etc.	6.8	14.4	3.4
Cultivated D	**Cover crop, conservation tillage w/buffers**	**13.4**	**64.8**	**15.5**
Cultivated D	**Cover crop, conservation tillage, etc.**	**9.7**	**35.9**	**8.6**
Forest	Stream crossing control	76.5	0.3	0.1
Total		152.8	183.5	43.9
Completed Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	4.4	1.3	0.3
Cultivated	**Cover crop, conservation tillage, etc.**	**17.6**	**77.1**	**18.4**
Cultivated	Crop to hay conversion	3.7	14.3	3.4
Total		25.7	92.8	22.2

Second, we evaluated the phosphorus load reductions that should have resulted from the projects and practices that have already been implemented in this watershed (Table 8). These projects and practices included cover crops, conservation tillage, grassed waterways, and ditch buffers that were applied on 76% of cultivated soils and conversion from to crop to hay on 16% of cultivated soils. In addition, we assumed that there had been a 12% reduction in the area of developed, pervious lands that were receiving phosphorus fertilizer. Collectively, these projects and practices, which were applied to 26 ha (63 acres), should have reduced phosphorus loads by 93 kg/year (205 lb/year), a 22% reduction. This modeled reduction is roughly similar to the 26% reduction in median total phosphorus concentrations measured at the downstream-most site on the Junkyard Tributary in 2016.

Crystal Brook

Crystal Brook, a tributary of the Johns River, drains approximately 402 ha (994 acres) in the town of Derby. This watershed is dominated by forest [200 ha (495 acres)] and agriculture, primarily hay [115 ha (284 acres)]. The total estimated phosphorus export from this watershed is 309 kg/year (681 lb/year) with the majority originating from hay fields, farmsteads, and cultivated soils (Table 5).

For Crystal Brook, we examined two scenarios for BMP implementation (Table 9). First, we evaluated the phosphorus load reductions that would be achieved if all of the suitable projects and practices were applied to the appropriate areas of each land use. In this scenario, the greatest reductions in phosphorus loads would occur if barnyard improvement projects were applied to 100% of the farmsteads; riparian buffers were installed in 37% of the hay fields; and cover crops, conservation tillage, and grassed waterways were applied to 100% of the cultivated soils. Collectively, these and the other feasible projects and practices would be applied to 271 ha (668 acres) and would reduce phosphorus loads by 97 kg/year (214 lb/year), a 32% reduction. Although forest is the dominant land use covering almost 50% of this watershed, applying stream crossing erosion and sedimentation control practices on 100% of the forest would reduce phosphorus loads by only 0.2%.

Second, we evaluated the phosphorus load reductions that should have resulted from the projects and practices that have already been implemented in this watershed (Table 9). These projects and practices included barnyard improvements (new manure pit, diversion of silage leachate into manure pit, and better management of barnyard runoff) that were applied to 76% of the farmsteads. In addition, we assumed that there had been a 12% reduction in the area of developed, pervious lands that were receiving phosphorus fertilizer. Collectively, these projects and practices, which were applied to 5.3 ha (13 acres), should have reduced phosphorus loads by 35 kg/year (77 lb/year), a 11% reduction. This modeled reduction is substantially lower than the 73-85% reductions in median and mean total phosphorus concentrations measured in Crystal Brook in 2016.

Table 9. Phosphorus load reductions potentially achieved by implementing various phosphorus-reduction projects and practices under two different scenarios in the watershed of Crystal Brook. Reductions were calculated by the BMP Scenario Tool modified for the Lake Memphremagog Basin. Bold font indicates load reductions of greater than 5% of the total.

Land Use	Project(s) and/or Practice(s)	Area (ha)	Load Reduction (kg)	% Reduction
Feasible Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	0.9	0.3	0.1
Developed	Ditch buffer (pervious)	1.6	0.5	0.1
Developed	Surface infiltration practices .9" (impervious)	0.2	0.3	0.1
Paved road	Surface infiltration practices .9"	0.3	0.2	0.1
Dirt road	Roadside erosion control	0.5	0.7	0.2
Dirt road low	Roadside erosion control	1.4	3.9	1.3
Dirt road mod	Roadside erosion control	0.5	2.0	0.6
Farmstead	**Barnyard management**	**5.7**	**45.3**	**14.6**
Hay	**Riparian buffer**	**39.0**	**17.9**	**5.8**
Pasture	Fencing/livestock exclusion (no buffers)	7.4	2.8	0.9
Cultivated C	**Cover crop, conservation tillage, etc.**	**12.7**	**22.9**	**7.4**
Forest	Stream crossing control	200.4	0.7	0.2
Total		270.5	97.3	31.5
Completed Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	0.9	0.3	0.1
Farmstead	**Barnyard management**	**4.4**	**34.4**	**11.1**
Total		5.3	34.6	11.2

Strawberry Acres Tributary

The Strawberry Acres Tributary, which flows directly into the southwest corner of Lake Memphremagog, drains approximately 277 ha (685 acres) in Newport City and the towns of Newport Town and Coventry. This watershed is dominated by forest [189 ha (467 acres)] and agriculture, primarily hay [44 ha (110 acres)]. The total estimated phosphorus export from this watershed is 133 kg/year (294 lb/year) with the majority originating from hay fields and farmsteads but also forests (Table 5).

For the Strawberry Acres Tributary, we examined two scenarios for BMP implementation (Table 10). First, we evaluated the phosphorus load reductions that would be achieved if all of the suitable projects and practices were applied to the appropriate areas of each land use. In this scenario, the greatest reductions in phosphorus loads would occur if barnyard improvement projects were applied to 100% of the farmsteads. Collectively, these and the other feasible projects and practices would be applied to 208 ha (515 acres) and would reduce phosphorus loads by 34 kg/year (75 lb/year), a 25% reduction. Although forests are the dominant land use covering almost 68% of this watershed, applying stream crossing erosion and sedimentation control practices on 100% of the forest would reduce phosphorus loads by only 0.5%.

Table 10. Phosphorus load reductions potentially achieved by implementing various phosphorus-reduction projects and practices under two different scenarios in the watershed of the Strawberry Acres Tributary. Reductions were calculated by the BMP Scenario Tool modified for the Lake Memphremagog Basin. Bold font indicates load reductions of greater than 5% of the total.

Land Use	Project(s) and/or Practice(s)	Area (ha)	Load Reduction (kg)	% Reduction
Feasible Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.4	0.4	0.3
Developed	Ditch buffer (pervious)	1.3	0.4	0.3
Developed	Surface infiltration practices .9" (impervious)	0.1	0.1	0.1
Paved road	Surface infiltration practices .9"	0.2	0.2	0.2
Dirt road	Roadside erosion control	0.1	0.2	0.2
Dirt road low	Roadside erosion control	0.6	2.1	1.5
Dirt road mod	Roadside erosion control	0.4	1.9	1.4
Farmstead	**Barnyard management**	**2.3**	**20.8**	**15.6**
Hay	Riparian buffer	10.2	5.5	4.1
Pasture	Fencing/livestock exclusion (no buffers)	3.1	1.4	1.0
Forest	Stream crossing control	188.8	0.7	0.5
Total		208.4	33.8	25.3
Completed Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.4	0.4	0.3
Farmstead	**Barnyard management**	**2.3**	**20.8**	**15.6**
Pasture	Livestock fencing (no buffers)	3.1	1.4	1.0
Total		6.7	22.6	17.0

Second, we evaluated the phosphorus load reductions that should have resulted from the projects and practices that have already been implemented in this watershed (Table 10). These projects and practices included barnyard improvement projects (hardened barnyard, new manure pit, new laneways) that were applied to 100% of the farmsteads and livestock exclusion fencing with no riparian buffers that were applied to 23% of the pasture. In addition, we assumed that there had been a 12% reduction in the area of developed, pervious lands that were receiving phosphorus fertilizer. Collectively, these projects and practices, which were applied to 6.8 ha (17 acres), should have reduced phosphorus loads by 23 kg/year (51 lb/year), a 17% reduction. This modeled reduction is somewhat less than the 32-53% reductions in median total phosphorus concentrations measured at the two sites on the Strawberry Acres Tributary in 2016.

Wishing Well Tributary

The Wishing Well Tributary, which flows directly into the southwest corner of Lake Memphremagog, drains approximately 316 ha (782 acres) in Newport City and the town of Coventry. This watershed is dominated by forest [110 ha (272 acres)] and agriculture, primarily hay [126 ha (312 acres)] and pasture [38 ha (95 acres)]. The total estimated phosphorus export from this watershed is 249 kg/year (549 lb/year) with the majority originating from hay fields, farmsteads, and pasture (Table 5).

For the Wishing Well Tributary, we examined two scenarios for BMP implementation (Table 11). First, we evaluated the phosphorus load reductions that would be achieved if all of the suitable projects and practices were applied to the appropriate areas of each land use. In this scenario, the greatest reductions in phosphorus loads would occur if barnyard improvement projects were applied to 100% of the farmsteads and managed intensive grazing and livestock exclusion fences were applied to 100% of the pasture. Collectively, these and the other feasible projects and practices would be applied to 183 ha (453 acres) and would reduce phosphorus loads by 68 kg/year (150 lb/year), a 27% reduction. Although forest is the second most important land use covering almost 35% of this watershed, applying stream crossing erosion and sedimentation control practices on 100% of the forest would reduce phosphorus loads by only 0.2%.

Second, we evaluated the phosphorus load reductions that should have resulted from the projects and practices that have already been implemented in this watershed. These projects and practices included barnyard improvement projects (hardened barnyard and clean water diversions) that were applied to approximately 15% of the farmsteads, ditch buffers that were applied to 20% of the hay fields, and managed intensive grazing and livestock exclusion fencing without riparian buffers that were applied to 100% of the pasture. In addition, we assumed that there had been a 12% reduction in the area of developed, pervious lands that were receiving phosphorus fertilizer. Collectively, these projects and practices, which were applied to 66 ha (163 acres), should have reduced phosphorus loads by 36 kg/year (79 lb/year), a 14% reduction. Unfortunately, these modeled load reductions exceeded the largely unchanged total phosphorus concentrations measured in this tributary following the implementation of these projects and practices (Gerhardt 2014).

Table 11. Phosphorus load reductions potentially achieved by implementing various phosphorus-reduction projects and practices under two different scenarios in the watershed of the Wishing Well Tributary. Reductions were calculated by the BMP Scenario Tool modified for the Lake Memphremagog Basin. Bold font indicates load reductions of greater than 5% of the total.

Land Use	Project(s) and/or Practice(s)	Area (ha)	Load Reduction (kg)	% Reduction
Feasible Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.7	0.5	0.2
Developed	Ditch buffer (pervious)	1.0	0.3	0.1
Developed	Surface infiltration practices .9" (impervious)	0.2	0.3	0.1
Paved road	Surface infiltration practices .9"	0.6	0.6	0.2
Dirt road	Roadside erosion control	0.3	0.6	0.2
Dirt road low	Roadside erosion control	0.8	2.6	1.0
Dirt road mod	Roadside erosion control	0.1	0.6	0.2
Farmstead	**Barnyard management**	**3.3**	**30.7**	**12.3**
Hay	Ditch buffer	26.5	10.8	4.3
Pasture	**Managed intensive grazing (no buffers)**	**38.5**	**20.3**	**8.1**
Forest	Stream crossing control	110.2	0.4	0.2
Total		183.1	67.8	27.2
Completed Projects and Practices				
Developed	Ban on phosphorus fertilizer (pervious)	1.7	0.5	0.2
Farmstead	Barnyard management	0.5	4.6	1.8
Hay	Ditch buffer	25.2	10.3	4.1
Pasture	**Managed intensive grazing (no buffers)**	**38.5**	**20.3**	**8.1**
Total		65.9	35.7	14.3

Conclusions

In general, the BMP Scenario Tool was useful for identifying and prioritizing actions to protect and improve water quality, especially by reducing phosphorus loads. Using this approach, we were able to identify general types of projects and practices that would likely lead to the greatest reductions in phosphorus exports from the six watersheds that we examined. Ultimately, however, this approach is only useful if it translates into development and implementation of on-the-ground projects and practices that protect and improve water quality in the Lake Memphremagog Basin.

As with any model, this approach has a number of limitations. First, this approach was highly dependent on accurate mapping and classification of land uses. The Cropland Data Layer from the National Agriculture Statistics Service (NASS) provided a fairly accurate mapping and classification of land uses across the broader landscape but was less accurate at the scale of individual sites and land uses. Thus, we found it necessary to cross-reference the NASS data with other land-use maps developed from aerial photographs and field observations. This discrepancy was especially important when identifying the appropriate projects and practices that could be implemented on specific sites. Second, this approach did not incorporate any measures of distance to surface waters, possible pathways that would allow nutrients and sediment to move from their sources into surface waters, and other topographic elements (e.g. slope) that likely have significant impacts on the phosphorus loads being exported from these watersheds. Third, this approach assumed an "average" loading and loading reduction efficiency across all sites of a particular land use, but, as alluded to in the previous point, individual sites likely differ in both their loading due to those and other factors and also the efficiency with which that loading can be reduced by various projects and/or practices. Fourth, only a subset of projects and/or practices may be applicable across large areas of any one land use due to lack of opportunities (e.g. riparian buffers are not applicable in corn, hay, or pasture where no river or stream bisects or borders the site). Fifth, identifying the appropriate projects and/or practices that are suitable for several of the land uses required considerable effort, including reviewing aerial photographs and land-use maps and on-the-ground field assessments. For larger watersheds, this step will be time-consuming, especially if the land uses in the watersheds have not been mapped accurately or precisely. Finally, implementation of many of these projects and practices will require willing landowners and land managers and may require considerable financial and other resources. However, implementation of many of these projects and practices will ultimately be necessary in order to meet the goals of the Total Maximum Daily Load and Basin Plan (State of Vermont 2012).

Reviewing our results, it is clear that implementing agricultural improvement projects and practices, many of which are now mandated by the Required Agricultural Practices recently adopted by VAAFM, offered some of the best opportunities for achieving large reductions in phosphorus exports from many of these watersheds. In watersheds where farmsteads were responsible for significant phosphorus loading, improving barnyard management by diverting clean water and collecting contaminated water, including barnyard and laneway runoff and leachate from silage bunkers and mortality compost piles, in manure pits offered very effective approaches for reducing phosphorus loads. In many watersheds, cultivated lands across the range of soil hydric classes also offered important opportunities to greatly reduce phosphorus loading through cover crops, conservation tillage, grassed waterways, and riparian and ditch buffers. Substantial reductions in phosphorus loading are also possible in hay fields, especially where riparian and/or ditch buffers can be installed, and pasture, through livestock exclusion fencing and managed intensive grazing. However, it is important to note that the six watersheds that we examined generally contained more agricultural land uses than many other subwatersheds and were ones where we had previously identified agricultural land uses as potential sources of phosphorus loading. Thus, the selection of watersheds was biased towards those in which agriculture, rather than other land uses, was likely to be the even dominant source of phosphorus loading.

The six watersheds that we analyzed also contained large areas of forest (range = 22-71% of the area in each watershed). Despite the large extent of forests in these watersheds, implementing best management practices in forests offered more limited opportunities for phosphorus load reductions, primarily because phosphorus exports are already quite low from forests. Nevertheless, there are opportunities to improve forest management and to reduce phosphorus exports even further by reducing erosion and sedimentation associated with woods roads and stream crossings. Given the large amount of forest in the Lake Memphremagog Basin [855 km^2 (330 mi^2), representing almost 68% of the Vermont portion of the basin], implementing these actions will likely be important for meeting the phosphorus-reduction targets required to improve water quality in Lake Memphremagog.

Our initial effort used a modified version of the Best Management Practices (BMP) Scenario Tool to highlight those projects and practices that would most effectively reduce phosphorus loading into Lake Memphremagog. In 2015 and 2016, we developed and tested this tool to assess six tributary watersheds of Lake Memphremagog. In the future, these efforts could be expanded to other watersheds in the Lake Memphremagog Basin, although completing these analyses for all but the smallest watersheds - or for the entire Vermont portion of the Lake Memphremagog Basin - is not a trivial task. However, the information gained by developing and testing this approach will be helpful in creating a more realistic basin-wide BMP Scenario Tool that can be used to identify and implement the actions that best reduce phosphorus loading into Lake Memphremagog as required by the Total Maximum Daily Load (TMDL) and Basin Plan (State of Vermont 2012).

Recommendations

Our efforts in 2016 succeeded in pinpointing and assessing possible nutrient and sediment sources and evaluating the success of phosphorus-reduction projects and practices. Nevertheless, many opportunities remain for additional efforts in order to protect and improve water quality along the Vermont tributaries of Lake Memphremagog and the Tomifobia River. Future monitoring and assessment efforts should continue to focus on pinpointing and assessing nutrient and sediment sources, refining the identification of priority subwatersheds in which to focus efforts to develop and implement phosphorus-reduction projects and practices, and evaluating the success of previously-implemented phosphorus-reduction projects and practices. More specifically, we recommend continuing to sample water quality along the following tributaries in 2017 for the following reasons:

Brighton Brook - During 2010-2015, our sampling indicated that nutrient and sediment levels were extremely high in this tributary of the Black River. Furthermore, the sampling in 2014 confirmed that leachate flowing from a mortality compost pile at a large farm operation was one of the major sources of these high phosphorus, nitrogen, and turbidity levels. In 2016, we continued to sample water quality at three sites along this tributary to assess whether the corrective actions had been successful in improving water quality in this tributary. Although these actions did not occur until late in the growing season, mean total phosphorus concentrations did appear to be decreasing at all three sites. Thus, we recommend resampling these three sites again in 2017 to further gauge the success of these corrective actions.

Junkyard Tributary - Our sampling in 2014-2016 allowed us to further pinpoint and assess the sources of the high nutrient and sediment levels in the two upstream branches of this tributary of the Barton River. Despite numerous improvements in field practices, the 2016 data did not show any clear and consistent improvements in water quality at any of the three sites along this tributary. In order to further assess the effectiveness of these improvements in field practices and other projects and practices, we recommend sampling all three sites again in 2017 and, if possible, adding additional sites further upstream of and along the ditch that drains the steep corn field on the south side of Vermont Route 58.

North Branch of Sucker Brook - Our sampling in 2016 indicated that there were modest but consistent increases in phosphorus and nitrogen concentrations along this tributary of Seymour Lake. However, our two sample sites were located relatively far upstream and downstream of a small farm that is an important land use along this tributary. In order to further pinpoint and assess possible nutrient and sediment sources along this tributary and to aid the farmer in developing and implementing projects and practices to improve both farm operations and water quality in this tributary, we recommend adding additional sample sites closer to the farmstead and farm fields.

Crystal Brook - Our sampling in 2015-2016 confirmed that water quality remained much improved in Crystal Brook since the manure lagoon was replaced in 2007 and barnyard improvement projects were undertaken in 2007 and 2015. Resampling this stream in 2017 would further confirm that these improvements in water quality remain intact.

Tributary of Stearns Brook - Our sampling in 2014-2016 indicated that nutrient and sediment levels were very high in the tributary of Stearns Brook, especially along the main stem and two small tributaries draining a large farm operation. In 2015 and 2016, the owners of the large farm operation undertook numerous farmstead improvement and clean water diversion projects. Thus, we recommend resampling these sites in 2017 in order to further evaluate the success of these projects and the need for additional phosphorus-reduction projects and practices along this tributary.

In 2016, we identified several other tributaries where additional water quality sampling would be helpful in identifying and assessing possible water quality problems. In two other tributaries of Stearns Brook (Stearns Tributary East and Tice Mill), we measured consistently high total phosphorus and/or total nitrogen concentrations, and we recommend sampling these two sites as well as additional sites along these two tributaries in 2017 to further pinpoint and assess possible nutrient and sediment sources and to identify and develop phosphorus-reduction projects and/or practices where they are most needed. In addition, through the Memphremagog Regional Conservation Partnership Program (RCPP), we have identified three other tributaries (Cass and Greens Brooks and an unnamed tributary of Whitney Brook) where farmers are interested in implementing projects and/or practices to improve their farm operations as well as to protect and improve water quality, and we recommend sampling water quality in these tributaries to assist farmers in implementing and evaluating the success of these projects and practices.

Although water quality conditions remain poorly understood in some areas (e.g. Town Line Brook, St. Onge tributary, and two branches of the Hamel tributary, which were not sampled in 2016), it is not clear that additional sampling will be beneficial in further identifying and assessing possible source(s) of water quality problems in these tributaries. Thus, these streams might not be sampled in 2017, although they could be resampled in future years if that was deemed useful. In the meantime, we encourage the appropriate agencies and organizations to work with landowners and land managers to identify and implement projects and practices to protect and improve water quality in these watersheds. In addition, we do not recommend resampling the three sites along the Airport Tributary, because our sampling in 2014-2016 allowed us to identify the probable source of the high nutrient and sediment levels in the northern branch of this tributary, where excess stormwater from the Newport State Airport was causing severe streambank erosion and streambed incision. A consultant working with the Memphremagog Watershed Association has developed a "30% design" for mitigating the impacts of this excess stormwater, and we recommend delaying additional sampling until these mitigation projects commence. Finally, we no longer recommend sampling the two sites along the Strawberry Acres Tributary, because our sampling there in 2015-2016 confirmed that water quality conditions had greatly improved following the completion of numerous improvements to the farmstead and fields in the headwaters of this tributary.

In 2017, we will continue to use the water quality data and other analyses to identify, prioritize, and develop phosphorus-reduction projects and practices that will best improve water quality conditions along the Vermont tributaries of Lake Memphremagog and the Tomifobia River. As part of these efforts, we will coordinate our efforts with those of other key partners to pinpoint and assess both agricultural and non-agricultural sources of water quality problems and to develop and implement projects or practices to correct those problems.

Education and Outreach

As an integral part of this project, we continued to educate local communities and stakeholders about water quality issues and efforts to protect and improve water quality in the Lake Memphremagog Basin. First, several individuals from the local community volunteered to collect and process water samples, and their efforts and their interactions with the salaried employees, paid consultants, and other volunteers furthered the education and outreach objectives of this project. Second, the results of this and previous studies were presented to both the Steering and Technical Committees of the Quebec/Vermont Steering Committee on Lake Memphremagog, which coordinates efforts to protect and improve water quality in the Lake Memphremagog Basin. Third, the results of this study were presented to the Memphremagog Agricultural Work Group, a partnership of the Vermont DEC, VAAFM, VACD, Orleans

County NRCD, and NRCS that shares information about and coordinates efforts to develop and implement agricultural projects and practices that protect and improve water quality. Fourth, we presented the results of this and previous studies at the annual conference of the New England Association of Environmental Biologists in Rockland, Maine and the Weekly Seminar Series of the Department of Natural Sciences at Lyndon State College in Lyndon, Vermont. Finally, we continued to develop partnerships with other agencies and organizations working to protect and improve water quality in the Lake Memphremagog Basin, including the Quebec ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques; Municipalités régionales de comté de Memphrémagog; Memphrémagog Conservation Inc. (MCI); and the cities of Newport, Sherbrooke, and Magog.

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Appendix A. Descriptions of 31 sites (plus three Vermont DEC sites) sampled along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016 (locations are mapped in Figure 4).

Black River (9 Sites):

Site Name	Site Description
Airport Tributary	Unnamed tributary along High Acres Road in Coventry (also sampled in 2013-2015)
Airport Trib North	Northern branch of unnamed tributary along woods road off High Acres Road in Coventry (also sampled in 2015)
Airport Trib South	Southern branch of unnamed tributary along woods road off High Acres Road in Coventry (also sampled in 2015)
St. Onge Main	Southern branch of unnamed tributary behind residence on Coventry Station Road in Coventry
St. Onge Tributary	Northern branch of unnamed tributary behind residence on Coventry Station Road in Coventry (also sampled in 2015)
Town Line Brook	Unnamed tributary upstream of U.S. Route 5 in Irasburg
Brighton Brook	Brighton Brook downstream of Gage Road in Irasburg (also sampled in 2010-2015)
Brighton Brook North	Northern branch of Brighton Brook upstream of Vermont Route 58 in Irasburg (also sampled in 2011-2015)
Upper Brighton Brook North	Northern branch of unnamed tributary to Brighton Brook downstream of Back Coventry Road in Irasburg (also sampled in 2012-2015)

Barton River (3 Sites):

Site Name	Site Description
Rock Junkyard	Unnamed tributary upstream of River Road in Irasburg (also sampled in 2012-2015)
Royer Farm	Main stem of unnamed tributary along Vermont Route 58 in Irasburg (also sampled in 2014-2015)
Royer Tributary	Northern branch of unnamed tributary downstream of Vermont Route 58 in Irasburg (also sampled in 2014-2015)

Clyde River (2 Sites):

Site Name	Site Description
Lower Sucker North	West branch of Sucker Brook upstream of Valley Road in Morgan
Upper Sucker North	West branch of Sucker Brook downstream of Valley Road in Holland

Johns River (2 Sites):

Site Name	Site Description
Johns River	Main stem beside old well house off Beebe Road in Derby (also sampled in 2005-2006, 2008-2009, and 2014-2015)
Crystal Brook	Crystal Brook downstream of U.S. Route 5 and upstream of snowmobile bridge in Derby (also sampled in 2006, 2008-2009, and 2014-2015)

Direct Tributaries (2 Sites):

Site Name	Site Description
Strawberry Acres	Unnamed tributary downstream of Fishing Access Road in Newport Town (also sampled in 2008-2010 and 2015)
Upper Strawberry Acres	Unnamed tributary upstream of City Road in Newport Town (also sampled in 2010 and 2015)

Stearns Brook (13 Sites):

Site Name	Site Description
Upper Stearns Brook	Stearns Brook downstream of Valley Road in Holland
East Stearns Tributary	Unnamed tributary upstream of Stearns Brook Road in Holland
Lower Stearns Tributary	Lower site on unnamed tributary along Twin Bridges Road in Holland (also sampled in 2014-2015)
Middle Stearns Tributary	Lower middle site on unnamed tributary downstream of Twin Bridges Road in Holland (also sampled in 2014-2015)
Stearns Tributary Falls	Upper middle site on unnamed tributary along Valley Road in Holland (also sampled in 2014-2015)
Upper Stearns Tributary	Upper site on unnamed tributary along Valley Road in Derby (also sampled in 2014-2015)
Twin Bridges Road	Unnamed tributary downstream of Twin Bridges Road in Holland (also sampled in 2014-2015)
Valley Road South	Unnamed tributary downstream of Valley Road in Holland (also sampled in 2014-2015)
Valley Road Ditch	Ditch along north side of Valley Road west of intersection with Twin Bridges Road in Holland (also sampled in 2015)
Valley Road Garage	Ditch along south side of Valley Road across from intersection with Twin Bridges Road in Holland (also sampled in 2015)
Lower Barnyard Culvert	Outflow of culvert at lower driveway of the Gray Farm along Valley Road in Holland (also sampled in 2015)
Upper Barnyard Culvert	Outflow of culvert at upper driveway of the Gray Farm along Valley Road in Holland (also sampled in 2015)
Tice Mill	Unnamed tributary upstream of Tice Mill Road in Holland

Vermont DEC Sites (3 Sites):

Site Name	Site Description
Barton River	Main stem upstream of Coventry Station Road in Coventry (also sampled in 2005-2015)
Black River	Main stem upstream of Airport Road in Coventry (also sampled in 2005-2015)
Clyde River	Main stem upstream of Gardner Park Road in Newport City (also sampled in 2005-2015)

Appendix B. Water quality data collected at 31 sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Bold or italicized fonts highlight levels greater than Vermont water quality standards (State of Vermont 2014a) or what might be considered elevated levels if no water quality standards apply: total phosphorus >20 µg/l (italics) or >35 µg/l (bold), total nitrogen >1 mg/l (italics) or >2 mg/l (bold), and turbidity >5 NTU (italics) or >10 NTU (bold).

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
Airport Trib North	4/12/2016	0.94	**1,120**	**429.5**
Airport Trib North	5/16/2016	0.30	*20.9*	0.78
Airport Trib North	6/14/2016	0.14	**35.2**	0.71
Airport Trib North	7/11/2016	0.15	**43.9**	1.56
Airport Trib North	8/8/2016	0.17	**36.9**	0.26
Airport Trib North	9/6/2016	0.14	*33.6*	0.64
Airport Trib North	10/3/2016	<0.10	*27.3*	0.78
Airport Trib North	10/28/2016	0.12	**45.0**	-
Airport Trib South	4/12/2016	*1.68*	**440**	**271.5**
Airport Trib South	5/16/2016	0.36	*21.5*	1.78
Airport Trib South	6/14/2016	0.22	*20.4*	0.88
Airport Trib South	7/11/2016	0.20	*23.8*	1.80
Airport Trib South	8/8/2016	0.20	*22.6*	2.13
Airport Trib South	9/6/2016	0.23	*20.2*	1.84
Airport Trib South	10/3/2016	0.16	11.6	1.23
Airport Trib South	10/28/2016	0.23	*23.3*	-
Airport Tributary	4/12/2016	*1.58*	**520**	**228.5**
Airport Tributary	5/16/2016	0.38	*22.4*	2.25
Airport Tributary	6/14/2016	0.34	*22.4*	1.42
Airport Tributary	7/11/2016	0.31	*23.1*	1.12
Airport Tributary	8/8/2016	0.41	*22.2*	1.59
Airport Tributary	9/6/2016	0.42	18.7	1.90
Airport Tributary	10/3/2016	0.30	14.4	1.40
Airport Tributary	10/28/2016	0.30	*24.0*	-

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
Brighton Brook	4/12/2016	*1.31*	**157**	**51.7**
Brighton Brook	5/16/2016	0.40	17.9	1.69
Brighton Brook	6/14/2016	0.66	*24.4*	2.73
Brighton Brook	7/11/2016	0.77	**35.2**	4.16
Brighton Brook	8/8/2016	0.65	**56.1**	*7.23*
Brighton Brook	9/6/2016	0.72	*31.0*	3.28
Brighton Brook	10/3/2016	0.59	*24.5*	3.63
Brighton Brook	10/28/2016	0.94	**36.5**	-
Brighton Brook North	4/12/2016	*1.31*	**163**	**40.9**
Brighton Brook North	5/16/2016	0.35	*31.1*	1.91
Brighton Brook North	6/14/2016	0.45	*31.6*	2.67
Brighton Brook North	7/11/2016	0.61	**35.7**	3.41
Brighton Brook North	8/8/2016	0.58	**59.1**	4.06
Brighton Brook North	9/6/2016	0.68	*29.9*	2.64
Brighton Brook North	10/3/2016	0.53	*22.7*	2.40
Brighton Brook North	10/28/2016	0.98	**53.6**	-
Crystal Brook	4/12/2016	*1.37*	**127**	**51.3**
Crystal Brook	5/16/2016	*1.40*	8.68	1.01
Crystal Brook	6/14/2016	*1.04*	*23.2*	3.18
Crystal Brook	7/11/2016	*1.29*	16.2	0.84
Crystal Brook	8/8/2016	*1.95*	15.9	0.50
Crystal Brook	9/6/2016	*1.69*	11.1	0.78
Crystal Brook	10/3/2016	*1.80*	10.7	0.46
Crystal Brook	10/28/2016	*1.91*	**258**	-
East Stearns Tributary	4/12/2016	*1.61*	**146**	**25.7**
East Stearns Tributary	5/16/2016	*1.26*	*30.4*	4.18
East Stearns Tributary	6/14/2016	0.91	**73.6**	*8.81*
East Stearns Tributary	7/11/2016	*1.16*	**43.8**	1.68
East Stearns Tributary	8/8/2016	**2.77**	*32.1*	0.39
East Stearns Tributary	9/6/2016	**2.10**	*27.0*	0.47
East Stearns Tributary	10/3/2016	**2.04**	16.7	0.37
East Stearns Tributary	10/28/2016	*1.01*	**50.9**	-

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
Johns River	4/12/2016	*1.90*	**280.8**	**111**
Johns River	5/16/2016	**2.20**	12.1	2.50
Johns River	6/14/2016	*1.86*	*32.2*	*5.42*
Johns River	7/11/2016	**3.34**	17.7	0.96
Johns River	8/8/2016	**5.42**	13.0	1.15
Johns River	9/6/2016	**4.75**	12.0	1.18
Johns River	10/3/2016	**5.14**	7.7	0.61
Johns River	10/28/2016	**2.74**	*20.9*	-
Lower Barnyard Culvert	4/12/2016	**28.28**	**4,025**	**42.5**
Lower Barnyard Culvert	5/16/2016	**28.2**	**976**	**19.7**
Lower Barnyard Culvert	6/14/2016	**10.9**	**295.8**	*6.03*
Lower Barnyard Culvert	7/11/2016	**18.06**	**298.2**	*8.50*
Lower Barnyard Culvert	8/8/2016	**27.7**	**890**	*9.74*
Lower Barnyard Culvert	9/6/2016	**37.77**	**244**	-
Lower Barnyard Culvert	10/3/2016	**26.65**	**5,340**	**124.4**
Lower Barnyard Culvert	10/28/2016	**12.81**	**1,245**	-
Lower Stearns Tributary	4/12/2016	**4.18**	**367.2**	**56.6**
Lower Stearns Tributary	5/16/2016	**4.88**	**50.4**	2.58
Lower Stearns Tributary	6/14/2016	**3.54**	**64.9**	*6.78*
Lower Stearns Tributary	7/11/2016	**4.54**	**47.9**	1.55
Lower Stearns Tributary	8/8/2016	**5.22**	**51.6**	0.86
Lower Stearns Tributary	9/6/2016	**6.63**	*33.0*	0.24
Lower Stearns Tributary	10/3/2016	**6.22**	*25.0*	0.64
Lower Stearns Tributary	10/28/2016	**3.90**	**339**	-
Lower Sucker North	4/12/2016	0.55	**87.3**	**19.5**
Lower Sucker North	5/16/2016	0.32	16.6	2.81
Lower Sucker North	6/14/2016	0.38	**54.3**	**12.1**
Lower Sucker North	7/11/2016	0.31	9.77	0.66
Lower Sucker North	8/8/2016	0.42	11.7	0.25
Lower Sucker North	9/6/2016	0.36	10.5	0.25
Lower Sucker North	10/3/2016	0.26	6.35	0.38
Lower Sucker North	10/28/2016	0.38	**56.3**	-

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
Middle Stearns Tributary	4/12/2016	**4.34**	**189**	**22.3**
Middle Stearns Tributary	5/16/2016	**5.44**	**89.2**	*5.01*
Middle Stearns Tributary	6/14/2016	**5.27**	**37.4**	4.59
Middle Stearns Tributary	7/11/2016	**11.64**	*25.7*	1.32
Middle Stearns Tributary	8/8/2016	**6.30**	*34.2*	0.79
Middle Stearns Tributary	9/6/2016	**6.47**	19.4	0.24
Middle Stearns Tributary	10/3/2016	**6.54**	**41.2**	1.35
Middle Stearns Tributary	10/28/2016	**5.60**	**712**	-
Rock Junkyard	4/12/2016	**2.35**	**1,190**	**585**
Rock Junkyard	5/16/2016	0.55	13.8	1.32
Rock Junkyard	6/14/2016	0.68	*22.7*	1.52
Rock Junkyard	7/11/2016	0.49	*23.0*	1.82
Rock Junkyard	8/8/2016	0.26	*21.9*	0.90
Rock Junkyard	9/6/2016	0.30	*25.1*	0.45
Rock Junkyard	10/3/2016	0.33	18.2	1.04
Rock Junkyard	10/28/2016	0.76	**39.9**	-
Royer Farm	4/12/2016	**3.09**	**1,180**	**194**
Royer Farm	5/16/2016	0.65	*20.7*	2.23
Royer Farm	6/14/2016	0.62	*29.2*	0.60
Royer Farm	7/11/2016	0.59	**41.3**	1.06
Royer Farm	8/8/2016	0.56	**49.0**	1.27
Royer Farm	9/6/2016	0.56	**44.0**	1.04
Royer Farm	10/3/2016	0.60	*33.5*	0.62
Royer Farm	10/28/2016	**16.23**	**3,960**	-
Royer Trib 2	10/28/2016	**46.76**	**6,550**	-
Royer Trib 2 Road	10/28/2016	**43.96**	**7,500**	-
Royer Tributary	4/12/2016	*1.74*	**808**	**242.5**
Royer Tributary	5/16/2016	*1.37*	*22.6*	1.15
Royer Tributary	6/14/2016	*1.76*	*31.4*	2.50
Royer Tributary	7/11/2016	*1.87*	*25.5*	0.93
Royer Tributary	8/8/2016	0.53	*28.8*	<0.2
Royer Tributary	9/6/2016	0.52	*30.8*	0.73
Royer Tributary	10/3/2016	*1.00*	*30.8*	2.52
Royer Tributary	10/28/2016	*1.40*	-	-

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
St. Onge Main	4/12/2016	*1.79*	**393.2**	**81.4**
St. Onge Main	5/16/2016	0.50	19.7	0.82
St. Onge Main	6/14/2016	0.34	*26.9*	0.40
St. Onge Main	7/11/2016	0.40	*27.4*	0.47
St. Onge Main	8/8/2016	0.28	*30.6*	0.46
St. Onge Main	9/6/2016	0.26	*30.0*	0.71
St. Onge Main	10/3/2016	0.26	*24.8*	0.62
St. Onge Main	10/28/2016	0.40	*26.8*	-
St. Onge Tributary	4/12/2016	**6.62**	**1,300**	**132.5**
St. Onge Tributary	5/16/2016	**5.64**	**266.1**	4.52
St. Onge Tributary	6/14/2016	**4.71**	**204**	3.32
St. Onge Tributary	7/11/2016	**3.58**	**230**	2.82
St. Onge Tributary	8/8/2016	*1.29*	**238**	*7.02*
St. Onge Tributary	10/3/2016	**2.28**	**179**	**29.5**
St. Onge Tributary	10/28/2016	**14.29**	**180**	-
Stearns Tributary Falls	4/12/2016	**3.85**	**85.4**	**13.9**
Stearns Tributary Falls	5/16/2016	**4.76**	10.8	1.26
Stearns Tributary Falls	6/14/2016	**5.00**	*28.2*	4.23
Stearns Tributary Falls	7/11/2016	**5.34**	15.8	1.29
Stearns Tributary Falls	8/8/2016	**5.34**	*21.1*	1.23
Stearns Tributary Falls	9/6/2016	**5.39**	11.3	0.41
Stearns Tributary Falls	10/3/2016	**5.30**	13.8	1.84
Stearns Tributary Falls	10/28/2016	**4.56**	**40.7**	-
Strawberry Acres	4/12/2016	0.54	**106**	**31.8**
Strawberry Acres	5/16/2016	0.27	19.7	3.17
Strawberry Acres	6/14/2016	0.3	18.2	1.43
Strawberry Acres	7/11/2016	0.32	*33.0*	2.67
Strawberry Acres	9/6/2016	0.27	14.5	3.29
Strawberry Acres	10/3/2016	0.21	15.6	*6.70*
Strawberry Acres	10/28/2016	0.23	17.8	-
Tice Mill	4/12/2016	**2.29**	**252.6**	**79.3**
Tice Mill	5/16/2016	*1.54*	18.0	3.64
Tice Mill	6/14/2016	*1.24*	**63.1**	*9.86*
Tice Mill	7/11/2016	*1.13*	*33.2*	1.06
Tice Mill	8/8/2016	*1.33*	**43.7**	2.99
Tice Mill	9/6/2016	*1.49*	*23.2*	1.84
Tice Mill	10/3/2016	*1.59*	12.7	0.62
Tice Mill	10/28/2016	*1.79*	**129**	-

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
Town Line Brook	4/12/2016	**3.23**	**1,290**	**550**
Town Line Brook	5/16/2016	*1.14*	**69.3**	2.61
Twin Bridges Road	4/12/2016	**7.01**	**165**	**39.7**
Twin Bridges Road	5/16/2016	**7.82**	13.5	1.55
Twin Bridges Road	6/14/2016	**5.51**	*27.0*	0.97
Twin Bridges Road	7/11/2016	0.74	**48.2**	1.87
Twin Bridges Road	9/6/2016	**6.79**	15.6	0.95
Twin Bridges Road	10/3/2016	0.42	14.8	1.86
Twin Bridges Road	10/28/2016	**3.48**	**491.5**	-
Upper Barnyard Culvert	4/12/2016	**18.12**	**84.1**	4.03
Upper Barnyard Culvert	5/16/2016	**24.2**	**106**	*5.89*
Upper Barnyard Culvert	6/14/2016	**23.62**	**43.4**	3.11
Upper Barnyard Culvert	7/11/2016	**25.28**	*34.6*	2.33
Upper Barnyard Culvert	8/8/2016	**19.3**	**60.9**	*5.44*
Upper Barnyard Culvert	9/6/2016	**23.16**	19.7	1.52
Upper Barnyard Culvert	10/3/2016	**16.22**	*31.3*	**11.2**
Upper Barnyard Culvert	10/28/2016	**19.39**	13.05	-
Upper Brighton Brook North	4/12/2016	**5.58**	**479.5**	**91.9**
Upper Brighton Brook North	5/16/2016	0.92	**240**	2.63
Upper Brighton Brook North	6/14/2016	**3.28**	**821**	**19.8**
Upper Royer Farm	10/28/2016	*1.04*	**228**	-
Upper Royer Trib 2	10/28/2016	0.86	**58.5**	-
Upper Stearns Brook	4/12/2016	*1.03*	**162**	**47.0**
Upper Stearns Brook	5/16/2016	0.43	18.5	2.94
Upper Stearns Brook	6/14/2016	0.51	**72.2**	**10.9**
Upper Stearns Brook	7/11/2016	0.35	**52.5**	3.67
Upper Stearns Brook	8/8/2016	0.38	**51.3**	2.23
Upper Stearns Brook	9/6/2016	0.26	*25.4*	1.83
Upper Stearns Brook	10/3/2016	0.3	13.6	1.05
Upper Stearns Brook	10/28/2016	0.69	**228**	-
Upper Stearns Tributary	4/12/2016	**3.75**	*32.4*	*5.88*
Upper Stearns Tributary	5/16/2016	**4.16**	9.08	1.12
Upper Stearns Tributary	6/14/2016	**4.21**	17.5	2.33
Upper Stearns Tributary	7/11/2016	**4.66**	10.8	0.92
Upper Stearns Tributary	8/8/2016	**4.54**	13.0	0.51
Upper Stearns Tributary	9/6/2016	**4.55**	10.3	1.39
Upper Stearns Tributary	10/3/2016	**4.54**	7.8	0.63
Upper Stearns Tributary	10/28/2016	**4.16**	13.5	-

Site	**Date**	**Total Nitrogen (mg/l)**	**Total Phosphorus (µg/l)**	**Turbidity (NTU)**
Upper Strawberry Acres	4/12/2016	0.43	**87.7**	**17.9**
Upper Strawberry Acres	5/16/2016	0.28	*21.3*	1.68
Upper Strawberry Acres	6/14/2016	0.32	*20.0*	1.15
Upper Strawberry Acres	7/11/2016	0.43	**38.6**	1.89
Upper Strawberry Acres	8/8/2016	0.45	*22.7*	0.95
Upper Strawberry Acres	9/6/2016	0.37	15.7	0.99
Upper Strawberry Acres	10/3/2016	0.24	14.9	0.66
Upper Strawberry Acres	10/28/2016	0.33	*30.7*	-
Upper Sucker North	4/12/2016	0.42	**36.4**	*9.01*
Upper Sucker North	5/16/2016	0.23	8.15	1.02
Upper Sucker North	6/14/2016	0.38	*28.0*	3.27
Upper Sucker North	7/11/2016	0.23	8.06	0.41
Upper Sucker North	8/8/2016	0.24	10.8	0.81
Upper Sucker North	9/6/2016	0.24	6.67	<0.20
Upper Sucker North	10/3/2016	0.18	<5.00	0.27
Upper Sucker North	10/28/2016	0.24	13.8	-
Valley Road Ditch	4/12/2016	**21.08**	**4,125**	**330.5**
Valley Road Ditch	5/16/2016	**19.00**	**2,440**	**116**
Valley Road Ditch	6/14/2016	-	**150**	4.38
Valley Road Ditch	7/11/2016	**2.03**	**49.4**	1.67
Valley Road Ditch	10/28/2016	**21.98**	**1,255**	-
Valley Road Garage	4/12/2016	**21.07**	**6,500**	**7710**
Valley Road Garage	10/28/2016	**27.58**	**1,855**	-
Valley Road Pipe	7/11/2016	**6.38**	**278.4**	**11.2**
Valley Road Pipe	10/3/2016	**18.43**	**1,660**	-
Valley Road Pipe	10/28/2016	**78.76**	**8,550**	-
Valley Road South	4/12/2016	**4.38**	**744**	*9.60*
Valley Road South	5/16/2016	0.73	**71.6**	3.43
Valley Road South	6/14/2016	0.94	**63.8**	2.11
Valley Road South	7/11/2016	*1.04*	**220**	*9.86*
Valley Road South	8/8/2016	0.86	**87.5**	2
Valley Road South	9/6/2016	*1*	**71.9**	1.95
Valley Road South	10/3/2016	0.64	**39.6**	1.23
Valley Road South	10/28/2016	*1.76*	**184**	-

Appendix C. Quality assurance data, including field blanks and field duplicates, collected at 31 sample sites along the Vermont tributaries of Lake Memphremagog and Stearns Brook during April-October 2016. Bold values indicate field blanks that exceeded detection limits (5 µg/l for total phosphorus, 0.1 mg/l for total nitrogen, and 0.2 NTU for turbidity) or field duplicates that differed by >30% for total phosphorus, >20% for total nitrogen, and >15% for turbidity.

Field Blanks:

Site	Date	Total Nitrogen (mg/l)	Total Phosphorus (µg/l)	Turbidity (NTU)
Airport Trib North	4/12/2016	<0.1	<5	<0.2
Lower Sucker North	4/12/2016	<0.1	<5	<0.2
Upper Stearns Tributary	4/12/2016	<0.1	<5	<0.2
Airport Trib South	5/16/2016	<0.1	<5	<0.2
Crystal Brook	5/16/2016	<0.1	<5	<0.2
Upper Sucker North	5/16/2016	<0.1	<5	<0.2
East Stearns Tributary	6/14/2016	<0.1	<5	<0.2
St. Onge Main	6/14/2016	<0.1	<5	<0.2
Strawberry Acres	6/14/2016	<0.1	<5	<0.2
Brighton Brook North	7/11/2016	<0.1	<5	<0.2
Tice Mill	7/11/2016	<0.1	<5	**0.21**
Upper Strawberry Acres	7/11/2016	<0.1	<5	<0.2
Airport Trib South	8/8/2016	<0.1	<5	<0.2
Crystal Brook	8/8/2016	<0.1	<5	<0.2
Upper Sucker North	8/8/2016	<0.1	<5	<0.2
Airport Tributary	9/6/2016	**0.99**	**42.4**	**0.59**
Brighton Brook North	9/6/2016	<0.1	<5	<0.2
Lower Stearns Tributary	9/6/2016	**1.13**	**21.7**	<0.2
Airport Trib South	10/3/2016	<0.1	<5	<0.2
Brighton Brook	10/3/2016	<0.1	<5	<0.2
Middle Stearns Tributary	10/3/2016	<0.1	<5	<0.2
Airport Trib North	10/28/2016	<0.1	<5	-
Brighton Brook North	10/28/2016	<0.1	<5	-
Twin Bridges Road	10/28/2016	<0.1	<5	-

Field Duplicates:

Total Nitrogen

Site	Date	1st Total Nitrogen (mg/l)	2nd Total Nitrogen (mg/l)	Relative % Difference
Airport Trib North	4/12/2016	0.94	0.97	3
Lower Sucker North	4/12/2016	0.55	0.56	2
Upper Stearns Tributary	4/12/2016	3.75	3.69	2
Airport Trib South	5/16/2016	0.36	0.37	3
Crystal Brook	5/16/2016	1.40	1.41	1
Upper Sucker North	5/16/2016	0.23	0.22	4
East Stearns Tributary	6/14/2016	0.91	0.91	0
St. Onge Main	6/14/2016	0.34	0.33	3
Strawberry Acres	6/14/2016	0.30	0.29	3
Brighton Brook North	7/11/2016	0.61	0.61	0
Tice Mill	7/11/2016	1.13	1.12	1
Upper Strawberry Acres	7/11/2016	0.43	0.43	0
Airport Trib South	8/8/2016	0.20	0.20	0
Crystal Brook	8/8/2016	1.95	1.93	1
Upper Sucker North	8/8/2016	0.24	0.24	0
Airport Tributary	9/6/2016	0.42	0.43	2
Brighton Brook North	9/6/2016	0.68	0.65	5
Lower Stearns Tributary	9/6/2016	6.63	6.67	1
Airport Trib South	10/3/2016	0.16	0.17	6
Brighton Brook	10/3/2016	0.59	0.59	0
Middle Stearns Tributary	10/3/2016	6.54	6.62	1
Airport Trib North	10/28/2016	0.12	0.14	15
Brighton Brook North	10/28/2016	0.98	0.89	10
Twin Bridges Road	10/28/2016	3.48	3.66	5
Mean				**3**

Total Phosphorus

Site	Date	1st Total Phosphorus (µg/l)	2nd Total Phosphorus (µg/l)	Relative % Difference
Airport Trib North	4/12/2016	1,120	1,130	1
Lower Sucker North	4/12/2016	87.3	85.3	2
Upper Stearns Tributary	4/12/2016	32.4	31.0	4
Airport Trib South	5/16/2016	21.5	21.8	1
Crystal Brook	5/16/2016	8.68	9.06	4
Upper Sucker North	5/16/2016	8.15	8.42	3
East Stearns Tributary	6/14/2016	73.6	75.9	3
St. Onge Main	6/14/2016	26.9	26.4	2
Strawberry Acres	6/14/2016	18.2	18.1	1
Brighton Brook North	7/11/2016	35.7	33.3	7
Tice Mill	7/11/2016	33.2	33.3	0
Upper Strawberry Acres	7/11/2016	38.6	38.1	1
Airport Trib South	8/8/2016	22.6	21.1	7
Crystal Brook	8/8/2016	15.9	15.4	3
Upper Sucker North	8/8/2016	10.8	11.0	2
Airport Tributary	9/6/2016	18.7	21.3	13
Brighton Brook North	9/6/2016	29.9	31.0	4
Lower Stearns Tributary	9/6/2016	33.0	29.8	10
Airport Trib South	10/3/2016	11.6	12.7	9
Brighton Brook	10/3/2016	24.5	29.3	18
Middle Stearns Tributary	10/3/2016	41.2	69.0	**50**
Airport Trib North	10/28/2016	45.0	44.9	0
Brighton Brook North	10/28/2016	53.6	53.4	0
Twin Bridges Road	10/28/2016	491.5	496	1
Mean				**6**

Turbidity

Site	**Date**	**1st Turbidity (NTU)**	**2nd Turbidity (NTU)**	**Relative % Difference**
Airport Trib North	4/12/2016	429.5	525	**20**
Lower Sucker North	4/12/2016	19.5	16.5	**17**
Upper Stearns Tributary	4/12/2016	5.88	6.49	10
Airport Trib South	5/16/2016	1.78	1.98	11
Crystal Brook	5/16/2016	1.01	0.78	**26**
Upper Sucker North	5/16/2016	1.02	1.01	1
East Stearns Tributary	6/14/2016	8.81	7.72	13
St. Onge Main	6/14/2016	0.40	0.39	3
Strawberry Acres	6/14/2016	1.43	1.38	4
Brighton Brook North	7/11/2016	3.41	3.33	2
Tice Mill	7/11/2016	1.06	1.23	15
Upper Strawberry Acres	7/11/2016	1.89	1.23	**42**
Airport Trib South	8/8/2016	2.13	1.69	**23**
Crystal Brook	8/8/2016	0.50	0.42	**17**
Upper Sucker North	8/8/2016	0.81	0.63	**25**
Airport Tributary	9/6/2016	1.90	1.84	3
Brighton Brook North	9/6/2016	2.64	1.90	**33**
Lower Stearns Tributary	9/6/2016	0.24	0.57	**81**
Airport Trib South	10/3/2016	1.23	1.23	0
Brighton Brook	10/3/2016	3.63	3.95	8
Middle Stearns Tributary	10/3/2016	1.35	3.96	**98**
Mean				**22**

Appendix D. Glossary [based largely on Picotte and Boudette (2005) and Dyer and Gerhardt (2007)].

Algae – Aquatic organisms that generally are capable of photosynthesis but lack the structural complexity of plants. Algae range from single-celled to multicellular organisms and can grow on the substrate or suspended in the water column (the latter are also known as phytoplankton).

Algal bloom – A population explosion of algae usually in response to high nutrient levels (particularly phosphorus and nitrogen), warm water temperatures, and long periods of sunlight. When these algae die, their decomposition can deplete oxygen to levels that are too low to support most aquatic life.

Basin – A geographic area bounded peripherally by a divide and draining into a particular water body. The relative size of a basin and the human alterations to that basin greatly affect water quality in the water body into which it drains.

Concentration – The quantity of a dissolved substance per unit of volume.

Detection limit – The lowest value of a physical or chemical parameter that can be measured reliably and reported as a value greater than zero by a given method or piece of equipment.

Erosion – The loosening and transport of soil and other particles. Erosion is a natural process but can be accelerated by human activities, such as forest clearance and stream channel alteration.

Eutrophication – The natural aging process whereby nutrients and sediments increase in a water body over time, increase its productivity and eventually turn it into a wetland. Human activities often accelerate this process.

Flow – The volume of water moving past a given location per unit of time (usually measured as cubic meters or feet per second).

Groundwater – Water that lies beneath the earth's surface in porous layers of clay, sand, gravel, and bedrock.

Limiting nutrient – A nutrient that is scarce relative to demand and that limits plant and animal growth in an ecosystem.

Load – The total amount of a physical or chemical substance, such as sediment or a nutrient, being transported in the water column per unit of time.

Mean - A number describing the central tendency of a set of numerical values and calculated by summing all of the values in the set and dividing by the number of values.

Median – A number describing the central tendency of a set of numerical values and defined as the value in an ordered set of numbers below and above which there are equal numbers of values.

Nonpoint source pollution – Pollution that originates from many, diffuse sources spread across the landscape (e.g. surface runoff from lawns or agricultural fields).

Nutrient – A chemical required for growth, development, or maintenance of a plant or animal. Nutrients are essential for sustaining life, but too much of any one nutrient can upset the balance of an ecosystem.

Photosynthesis – The biological process by which plants, algae, and some other organisms convert sunlight, carbon dioxide, and water into sugar and oxygen.

Point source pollution – Pollution that originates from a single location or source (e.g. a discharge pipe from a wastewater treatment plant or industrial facility).

Quality assurance (QA) – An integrated system of measures designed to ensure that data meet predefined standards of quality with a stated level of confidence.

Quartile – The value at the boundary of the 25th, 50th, or 75th percentiles of an ordered set of numbers divided into four equal parts, each containing one quarter of the numbers.

Riparian buffer – A strip of unmanaged vegetation growing along the shoreline of a river or stream. Riparian buffers reduce erosion, filter sediments and pollutants, and provide important aquatic and riverine habitats.

Standard deviation (SD) – A statistic that measures the variability of a set of numbers.

Surface waters – Water bodies that lie on top of the earth's surface, including lakes, ponds, rivers, streams, and wetlands.

Tributary – A water body, such as a river or stream, that flows into another body of water.

Total Maximum Daily Load (TMDL) – The maximum amount of a pollutant that a water body can receive in order to meet water quality standards.

Watershed – See basin.

Wetland – Land on which water saturation is the dominant factor determining the nature of soil development and the types of plant and animal communities that live there.

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