Muskrat Lake Watershed

2014-2017 Water Quality

January 2019

Rebecca L. Dalton, Ph.D

ALGONQUIN COLLEGE Office of Applied Research and Innovation

Ontario

Muskrat Watershed Council

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Foreword

The Muskrat Watershed Council is very pleased to present this report, which outlines the water quality of the Muskrat Lake watershed from 2014-2017. This report would not have come to fruition without the help of many individuals and teams from various community organizations, local businesses, municipal, provincial, and feder-al government agencies, as well as academic institutions.

The Muskrat Watershed Council would like to first thank Jp2g Consultants, Inc. for fully funding the latest version of the Water Quality in the Muskrat Lake Watershed (2014-2017) report. We would also like to thank the Ministry of Environment and Climate Change for continuing to support the analysis of water samples collected from the Water Quality Monitoring Network in the Muskrat Lake Watershed.

Our thanks also extend to our partners at Algonquin College in Pembroke, who have collaborated with us on many projects and have conducted regular sampling of the Water Quality Monitoring Network in the Muskrat Lake watershed for over 4 years.

Lastly, we would like to thank Dr. Rebecca L. Dalton for interpreting the data collected over the years and writing our past 2014 report and this latest 2014-2017 report. We are very fortunate as an organization to have her level of expertise and knowledge to generate a credible and highly informative scientific report. Her hard work has enhanced our knowledge of the watershed, allowing us to form a better understanding of the issues faced by the watershed and where to focus our efforts. With this information, we will continue to implement best management practices in the region. We also hope this report will help garner more financial support and partnerships with government, academic institutions and organizations, with the goal of saving our watershed.

Of course, there are many other people and organizations to thank for their direct and indirect support over the years. We would like everyone to know that their support and generosity means a lot to our organization. We have learned that water quality issues are not small issues. Many people, places, and beings are affected. No single individual or organization can tackle these problems alone. Real change happens when partnerships founded on trust, respect and the sharing of knowledge are forged. We need many hearts and hands to combat the issues and to advocate for everyone’s right to clean water and a thriving community.

Sincerely,

Karen Coulas

Karen Coulas
Chair of the Muskrat Watershed Council

Summary

In aquatic ecosystems, excessive inputs of the nutrients nitrogen and phosphorus from agricultural, urban and industrial activities may lead to eutrophication. Eutrophication is characterized by excessive growth of algae and aquatic plants and can led to negative effects such as toxic algal blooms, oxygen depletion and fish kills. Concern regarding eutrophication in Muskrat Lake has led to efforts to assess water quality issues in the surrounding watershed in relation to land use activities. This report examines water quality in the Muskrat Lake watershed from 2014-2017 and builds on an earlier report that summarized data from 2014. This report focuses on water samples collected from 22 field sites in the Muskrat Lake watershed from May to September 2014-2017. Water samples were analyzed for a number of water quality parameters including nitrate, total nitrogen, reactive phosphorus, total phosphorus and total suspended sediments. Overall, the Muskrat Lake watershed had high concentrations of nitrogen and phosphorus and moderate concentrations of total suspended sediments. High concentrations persisted throughout the sampling period for each year and concentrations frequently exceeded thresholds for impairment of streams. Several tributaries were identified as being highly enriched in nitrogen, phosphorus or both nutrients including: the Cobden Wetland, Upper Harris Drain, North Tributary, O'Gorman Agnew Drain, Stoqua Creek and Unnamed Creek (SC-02). Portions of Mink Creek and Snake River were also nutrient enriched, whereas Muskrat River generally did not exceed threshold values for impairment. These trends were consistent from 2014-2017. At the watershed scale, nutrients and total suspended sediments typically increased with increasing annual crop land and decreased with increasing natural habitat. Efforts to improve water quality in the Muskrat Lake watershed should focus on reducing inputs of nutrients and total suspended sediments from annual crop land. A pilot project to install two controlled tile drainage structures has already been implemented. The effectiveness of these structures in reducing exports of nutrients to streams should be examined and potential locations for other beneficial management practices and local initiatives assessed. Another key step would be to examine sites that are potential point sources of phosphorus, such as the Cobden Wetland, and begin assessing options to mitigate nutrient loading. A reduction in nutrient loading to Muskrat Lake is essential to improving its water quality.

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1.0 Introduction

1.1 Effects of excess nutrients and suspended sediments on water quality

Nutrients such as nitrogen and phosphorus are essential to life in general and to the natural growth of plants and algae in particular. Nitrogen gas comprises approximately 78% of the atmosphere but is unavailable for uptake by most organisms. Processes such as lightning and nitrogen fixation by bacteria and algae are essential to transform nitrogen gas to usable forms of nitrogen such as nitrate and ammonium. Human activities, such as the production of synthetic fertilizers and the intensification of agriculture, have dramatically altered the nitrogen cycle and have increased the amount of bioavailable nitrogen in terrestrial and aquatic ecosystems. Unlike nitrogen, phosphorus is scarce in the atmosphere but relatively abundant in the lithosphere (Earth's crust and upper mantle). Weathering of rocks represents the major natural source of phosphorus. Phosphorus typically occurs naturally in low concentrations in surface waters and bioavailable forms such as reactive phosphorus are quickly incorporated into organic tissues. Anthropogenic sources of phosphorus may enter waterbodies from agricultural sources (e.g. synthetic fertilizers and manure) and urban sources (e.g. wastewater effluent, septic tank leakages, runoff from lawns, golf courses and urban development) (Dubrovsky et al., 2010).

Excessive inputs of phosphorus and nitrogen from agricultural, urban and industrial activities are a major threat to water quality in many parts of the world. Nutrient enrichment may lead to eutrophication which is characterized by undesirable increases in the growth of algae and aquatic plants. Subsequent negative effects of eutrophication can include the formation of toxic algal blooms, oxygen depletion, fish kills and a loss of biodiversity (Carpenter et al., 1998). The consequences of eutrophication can be severe, resulting in a decline in the health and functioning of aquatic ecosystems and the impairment of water for drinking as well as industrial, agricultural and recreational activities. Point (direct) sources of nutrient pollution (e.g. municipal sewage treatment effluent) are relatively easy to identify. Non-point (diffuse) sources of nutrient pollution (e.g. runoff from agricultural fields) are much more difficult to identify and control because elevated concentrations often occur in pulses and originate from many diffuse sources across large areas of land.

Total suspended sediments may also impair water bodies and are often linked to nutrient pollution. Total suspended sediments in water refer to any material retained on a filter (2 µm) and include silt and clay particles, algae and decomposing matter. Total suspended sediments may contain phosphorus adsorbed to fine soil particles. Sources of total suspended sediments include soil erosion and runoff from agricultural fields, roads, industrial activities and sewage effluent. In excess, total suspended sediments may absorb heat from sunlight, increase water temperatures, increase decomposition of organic material and reduce oxygen concentrations. Particles that eventually settle out of the water column can clog fish gills and have adverse effects on sediment-dwelling organisms.

1.2 Muskrat Lake and its surrounding watershed

Muskrat Lake (1201 ha) is located within the Township of Whitewater Region of eastern Ontario (coordinates 45.654, -76.891). It is the drinking water source for the nearby town of Cobden. Water and sewage treatment facilities for Cobden are located adjacent to the lake. Muskrat Lake is also used recreationally for swimming, boating and fishing by both permanent and seasonal residents as well as visitors. The lake has a maximum depth of 64 m and average depth of 18 m (OMNRF, 2018). Muskrat Lake supports a number of fish species including: blue gill, brown bullhead, lake trout, largemouth bass, muskellunge, northern pike, pumpkinseed, rainbow smelt, rock bass, smallmouth bass, walleye, white sucker and yellow perch (OMNRF, 2018). It is stocked annually with ~ 7000 yearling lake trout (OMNRF, 2018). Muskrat Lake is highly nutrient enriched and concerns have arisen over its water quality, particularly the formation of blooms of blue-green algae (cyanobacteria).

Muskrat Lake is part of the larger Muskrat River watershed (114,458 ha) which commences near Renfrew, Ontario and flows into a chain of lakes, including Muskrat Lake, and eventually discharges into the Ottawa River near Pembroke, Ontario. The total area of land draining into Muskrat Lake is 51,072 ha and is referred to here as the Muskrat Lake watershed. This watershed includes: tributaries to the north of Muskrat Lake (5072 ha), the south eastern portion of the Muskrat River watershed (6647 ha) and the Snake River watershed (39,353 ha) (Fig. 1). The Snake River watershed represents 77% of the land draining into Muskrat Lake.

The headwaters of the Snake River begin in the mainly forested Boreal Shield Ecozone where Black Creek flows into Lake Dore (1516 ha), with the main branch of the Snake River commencing at the lake’s outlet. Snake River flows through wetland and agriculture areas in the Mixedwood Plains Ecozone before discharging into Muskrat Lake. Overall land use of the three areas draining into Muskrat Lake and forming the Muskrat Lake watershed is classified as forest and pasture (Fig. 1). Agricultural activities surrounding Muskrat Lake are having a negative impact on the water quality of Muskrat Lake (Dalton, 2015).

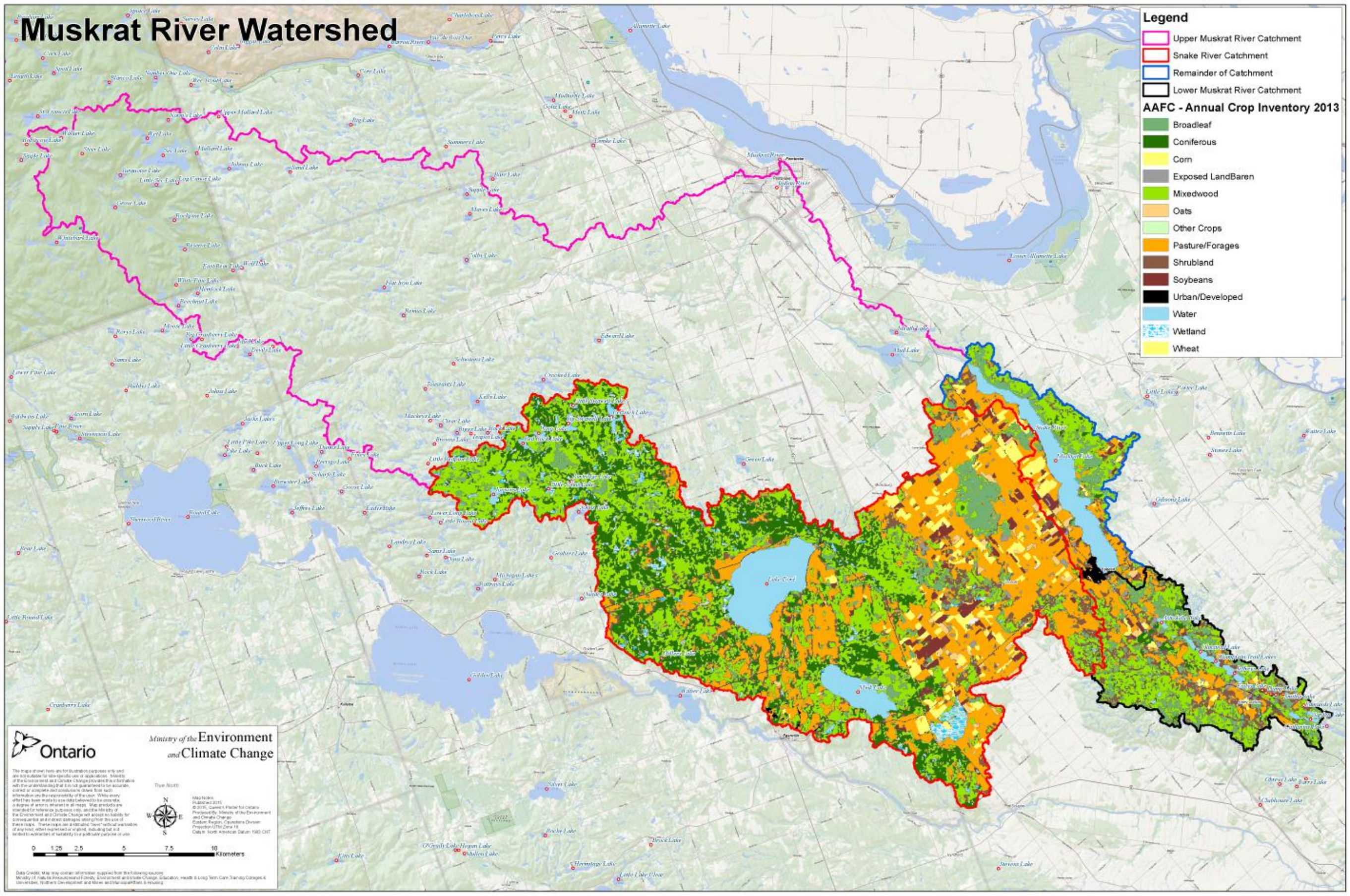

Fig. 1. Map of the Muskrat Lake watershed, within the Muskrat River watershed (Ontario Ministry of the Environment and Climate Change, 2015).

1.3 Report scope and objectives

Unlike most parts of southern Ontario, the Muskrat Lake watershed lacks a Conservation Authority to provide a coordinated approach to nutrient management and water quality initiatives vis-à-vis farming practices, although local organizations are working in these areas. In 2014, a comprehensive effort was made to assess water quality issues in the Muskrat Lake watershed in relation to land use activities. The project was led by Algonquin College (Pembroke) and the Muskrat Watershed Council. As part of this project, water quality parameters were analyzed at sites located throughout the Muskrat Lake watershed by the Ontario Ministry of the Environment and Climate Change (MOECC). Nutrient and suspended sediment data for 2014 were summarized in Dalton (2015). Water quality monitoring has continued in the Muskrat Lake watershed, with data now available up to October 2017.

The scope of this report was the analysis of water quality monitoring data from 22 field sites in the Muskrat Lake watershed (Fig. 2). This report focused on samples collected monthly from May to September 2014-2017. Data for key nutrients involved in eutrophication, as well as total suspended sediments, were analyzed. The main objectives were 1) to prepare a report that reviews, summarizes, analyzes and interprets water quality monitoring data from the Muskrat Lake watershed, 2) to examine trends over time where possible and 3) to provide recommendations for future analysis and sampling.

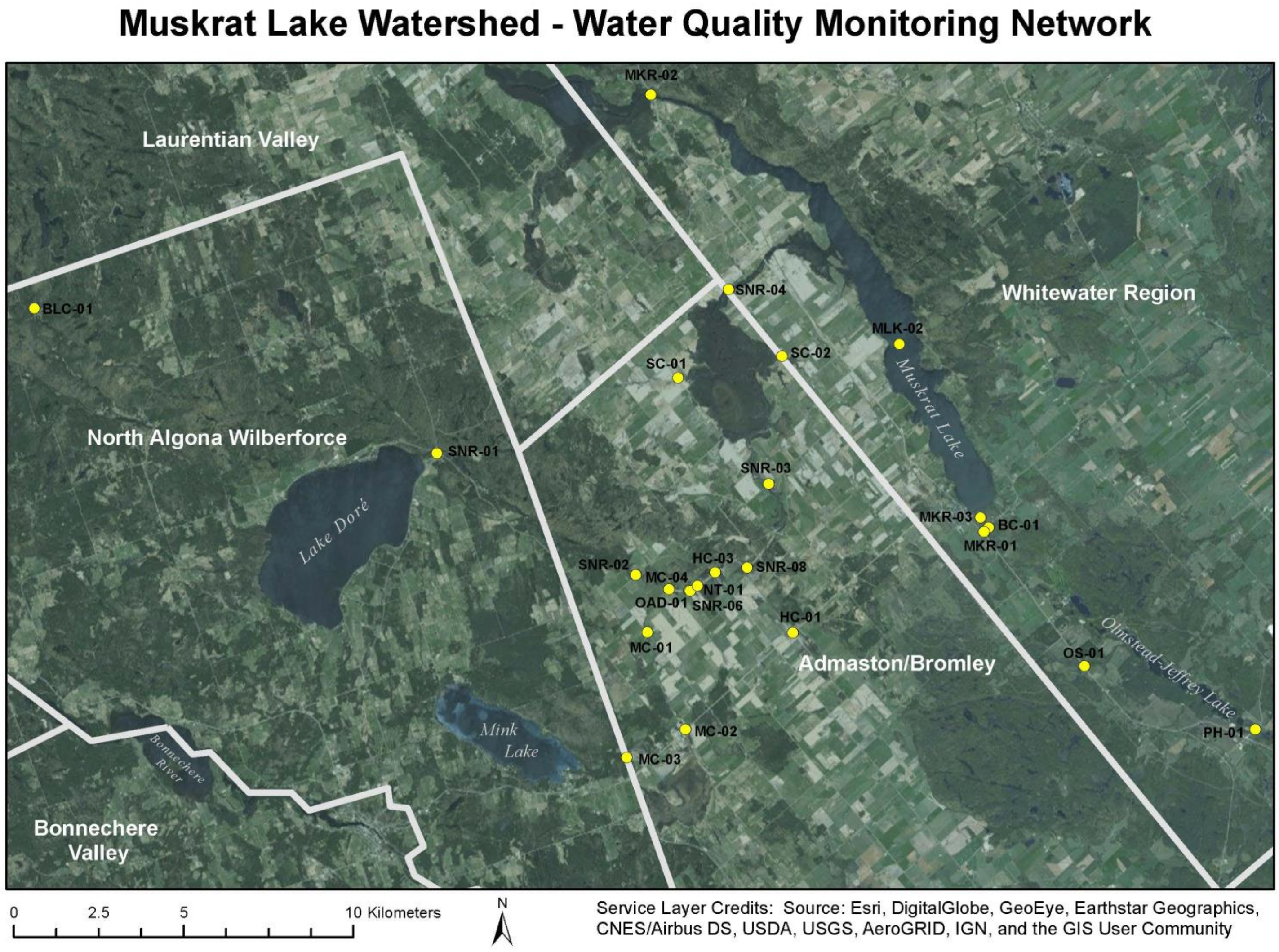

Fig. 2. Map of 22 field stream/river field sites and a lake field site in the Muskrat Lake watershed, Canada.

2.0 Methods

2.1. Field sites

This report focused on 22 field sites located throughout the Muskrat Lake watershed (Fig. 2; Appendix A, Table A1). The monitoring network included field sites located in both the Muskrat River (6 sites) and Snake River sub-watersheds (16 sites). Field sites included several locations along the Muskrat and Snake Rivers as well as their main tributaries. A reference site, Black Creek (BLC-01), was included to estimate nutrient background concentrations. Dalton (2015) reported 2014 water quality monitoring results for 27 sites. Several sites were dropped in 2015 to optimize resources.

2.2 Water quality sampling

Water quality sampling was coordinated by Algonquin College from 2014 to 2017. The sampling campaign typically began in April or May and concluded in September or October of each year. Grab samples were collected monthly from each site. This report focused on samples collected from May (2014-2017) to late September (2014, 2015, 2017) or early October (2016) of each year. Although the dataset included samples collected in early October 2016, for convenience the sampling period is referred to as “May to September” throughout this report. The selection of this subset of data allowed monthly trends to be compared across years because data were typically available during this timeframe for most field sites, whereas April and late October data were not available for all years (Table A2).

Chemical analyses of water samples were conducted by the MOECC Laboratory Services Branch following established analytical methods. In total, 43 parameters were measured including measures of general water chemistry (8 parameters), major fractions of nitrogen and phosphorus (7 parameters) and metals (28 parameters) (Table A3). This report focused on the major fractions of nitrogen, phosphorus and sediments/ solids (Table A4). Specifically, the report focused on nitrate, total nitrogen, reactive phosphorus, total phosphorus and total suspended sediments.

2.3 Data Analysis

Nutrient and total suspended sediment data were summarized and average (± standard deviation) concentrations and their ranges were calculated. Nitrate and reactive phosphorus concentrations were compared to estimated background concentrations calculated from a comprehensive survey of streams in the United States (Dubrovsky et al., 2010). Total nitrogen and total phosphorus were compared to thresholds for stream impairment that were developed for the Mixedwood Plains Ecozone of Ontario (Chambers et al., 2012). Total suspended sediments were compared to an ideal performance standard developed for the Mixedwood Plains of Ontario as part of Canada's National Agri-Environmental Standards Initiative (Culp et al., 2009). Note that 2014 concentrations reported here are somewhat different than concentrations reported in Dalton (2015). Dalton (2015) summarized data for 27 field sites and the current report included data for 22 field sites.

Statistical differences between nutrient and total suspended sediment concentrations across field sites and over time were assessed with a series of two-way analyses of variance (ANOVA). The dependent variables were nitrate, total nitrogen, reactive phosphorus, total phosphorus and total suspended sediments. Average concentrations of nutrients and total suspended sediments were calculated from May to September samples for each year and site separately. The independent variables were field site and year. No interaction term was included because the samples were not replicated. The model assumption of normality of residuals was evaluated with a Shapiro-Wilk's test and data transformed (base 10 logarithm) to improve normality. Sidak post-hoc tests were conducted to assess which years differed when the variable year was significant.

Nutrient and suspended sediment concentrations can be affected by environmental factors such as precipitation and discharge (water flow) but these data were lacking at the individual field site level. Black Creek (BLC-01) was selected as a reference site because it is relatively pristine and represented background concentrations of nutrients and total suspended sediments in the absence of agricultural or urban inputs. A second series of two-way ANOVAs was conducted to assess whether nutrient and total suspended sediment concentrations differed between years, after adjusting the data for time-specific environmental factors using data from

Black Creek. For each sampling period, nutrient and total suspended sediment concentrations for Black Creek were subtracted from concentrations of all other field sites. This resulted in adjusted concentrations that were normalized for the specific environmental conditions at the time of sampling. Total nitrogen data for July 2014 were removed from the analysis because total nitrogen for Black Creek at this time point was an order of magnitude higher than at any other time point. Two-way ANOVAs were conducted as described above.

The effects of land use on nutrients and total suspended sediments were assessed by examining land use immediately upstream of each site as described in Dalton (2015). Briefly, upstream land use was calculated in a 1000 m long and 200 m wide area (100 m on either stream/river bank) using 30 m resolution satellite imagery data from Agriculture and Agri-food Canada's 2014 Crop Inventory. The percentages of annual crop land, pasture/ forage land, natural habitat and developed land were calculated. Annual crop land was composed primarily of corn and soybean crops. Pasture and forage crop land included pasture land and land that is periodically cultivated with grasses and perennial crops such as alfalfa and clover for hay, pasture or seed. Natural habitat included broadleaf, coniferous and mixedwood forests, shrubland, wetlands, water and non-vegetated/ non-developed land (e.g. rocks, sediments). Developed land included roads, buildings, paved surfaces, urban/suburban areas and associated vegetation. Simple linear regressions were used to assess the effects of land use (independent variables) on the average concentrations of nutrients and total suspended sediments (dependent variables) at the 22 field sites. For each dependent variable, a single average concentration was calculated for each field site using data from May to September 2014-2017. Model assumptions of normality of residuals were evaluated with Shapiro-Wilk's tests and data transformed (square root, base 10 logarithm or inverse transformations) to improve normality. All statistical analyses were conducted with SPSS V24 (IBM Corp., Armonk, USA).

3.0 Results from May to September 2014-2017

3.1 Nitrogen

Overall concentrations of both nitrate and total nitrogen were high in the Muskrat Lake watershed (Table 1). Average concentrations of nitrate exceeded the estimated background concentration of nitrate due to natural processes (240 µg/L) in each month and year sampled (Table 1). Elevated concentrations of nitrate, such as the ones observed, represent contamination due to agricultural and urban activities (Dubrovsky et al., 2010). Maximum concentrations of total nitrogen for each month and year were above the threshold for stream impairment (1100 µg/L) developed for the Mixedwood Plains Ecozone of Ontario (Chambers et al., 2012) (Table 1). However, average total nitrogen concentrations were typically below the threshold, with the exception of 2014 where most of the average concentrations were above the threshold (Table 1).

As in Dalton (2015), nitrogen concentrations ranged between sub-watersheds, tributaries and within tributaries (Tables 2, 3). Sites differed significantly in both nitrate ($F=41.0$; $p<0.001$; $R^2=0.934$) and total nitrogen ($F=45.5$; $p<0.001$; $R^2=0.941$) average concentrations. Concentrations ranged from 20 to 9020 µg/L nitrate and 180 to 9460 µg/L total nitrogen. Sites within the Muskrat River sub-watershed were less nitrogen enriched compared to sites within the Snake River sub-watershed. Sites within the Muskrat River sub-watershed never exceeded total nitrogen thresholds for impairment and rarely exceeded background concentrations for nitrate (Tables 2, 3). In contrast, a number of sites within the Snake River sub-watershed frequently exceeded both background concentrations for nitrate and the threshold for impairment for total nitrogen (Tables 2, 3). Of particular concern were a number of small tributaries that were highly nitrogen enriched, including the Upper Harris Drain (HC-01, HC-03), North Tributary (NT-01), O'Gorman Agnew Drain (OAD-01) and site MC-01 on Mink Creek (Tables 2, 3). Along a given tributary, nitrogen tended to be higher at downstream sites compared to sites located upstream due to the movement of nutrients and sediments downstream and the larger area of land drained. For example, nitrogen increased from upstream to downstream along the Snake River. However, nitrogen was lower at the most downstream site (SNR-04) after passing through the Snake River Marsh (a portion of which is a provincial conservation reserve) where nitrogen was likely taken up by plants and converted to nitrogen gas by denitrifying bacteria.

Table 1. Seasonal trends in nitrate (NO_3) and total nitrogen (TN) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviation are shown with the range in brackets.

	2014		**2015**		**2016**		**2017**		**Monthly Average**	
	NO_3 (µg/L)	**TN (µg/L)**	**NO_3 (µg/L)**	**TN (µg/L)**	**NO_3 (µg/L)**	**TN (µg/L)**	**NO_3 (µg/L)**	**TN (µg/L)**	**NO_3 (µg/L)**	**TN (µg/L)**
Annual Average	**750 ± 1338** (20 – **7860**)	**1366 ± 1474** (230 – **8220**)	**548 ± 1380** (20 – **9020**)	1031 ± **1375** (180 – **9460**)	**638 ± 1045** (20 – **4630**)	**1136 ± 1198** (220 – **6150**)	**463 ± 738** (20 – **4010**)	824 ± **772** (180 – **4360**)	**602 ± 1150** (20 – **9020**)	1092 ± **1243** (180 – **9460**)
May	**856 ± 1531** (38 – **6790**)	**1432 ± 1718** (400 – **7770**)	**534 ± 1163** (20 – **5370**)	975 ± **1098** (240 – **5220**)	**456 ± 762** (20 – **3440**)	834 ± **840** (220 – **3930**)	**630 ± 921** (42 – **4010**)	918 ± **936** (220 – **4040**)	**619 ± 1127** (20 – **6790**)	1042 ± **1205** (220 – **7770**)
June	**979 ± 1805** (20 – **7860**)	**1388 ± 1832** (230 – **8190**)	**414 ± 709** (20 – **3020**)	830 ± 702 (180 – **3060**)	**368 ± 451** (20 – **1390**)	750 ± **503** (250 – **1790**)	**616 ± 904** (28 – **3600**)	1019 ± **1050** (250 – **4360**)	**594 ± 1101** (20 – **7860**)	997 ± **1148** (180 – **8190**)
July	**742 ± 1466** (21 – **6930**)	**1762 ± 1705** (380 – **8220**)	**438 ± 1015** (27 – **3890**)	913 ± **1116** (290 – **4680**)	**1322 ± 1512** (20 – **4630**)	**2024 ± 1829** (330 – **6150**)	**453 ± 790** (20 – **3120**)	827 ± **741** (260 – **3120**)	**761 ± 1279** (20 – **6930**)	**1416 ± 1507** (260 – **8220**)
August	**377 ± 470** **(20 –** 1510)	956 ± **478** (440 – **1980**)	**725 ± 2047** (20 – **9020**)	**1292 ± 2033** (300 – **9460**)	**424 ± 929** (41 – **4210**)	985 ± **968** (330 – **4460**)	**272 ± 318** (21 – **1140**)	570 ± 354 (180 – **1300**)	**444 ± 1130** (20 – **9020**)	947 ± **1159** (180 – **9460**)
September	**744 ± 929** (30 – **3060**)	**1230 ± 1080** (250 – **3390**)	**647 ± 1764** (20 – **7280**)	**1185 ± 1733** (270 – **7600**)	**608 ± 1036** (20 – **4220**)	1081 ± **1037** (290 – **4660**)	**341 ± 568** (20 – **1610**)	766 ± **527** (250 – **1960**)	**585 ± 1111** (20 – **7280**)	1063 ± **1136** (250 – **7600**)

Blue bold values exceed stream background concentrations for nitrate (240 µg/L) (Dubrovsky et al., 2010)

Red bold values exceed thresholds for impairment for total nitrogen (1100 µg/L) for streams in the Mixedwood Plains of Ontario (Chambers et al., 2012)

Table 2. Trends in nitrate (µg/L NO_3) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviations are shown with the range in brackets.

Sub-Watershed	Tributary	Site code[a]	2014	2015	2016	2017	Average
Muskrat	Buttermilk Creek	BC-01	84 ± 35 (35 – 129)	23 ± 7 (20 – 35)	95 ± 74 (20 – 217)	94 ± 61 (20 – 167)	73 ± 56 (20 – 217)
	Muskrat River	PH-01	80 ± 33 (44 – 130)	26 ± 13 (20 – 50)	38 ± 24 (20 – 75)	45 ± 35 (20 – 96)	47 ± 33 (20 – 130)
	Muskrat River	OS-01	34 ± 17 (20 – 61)	23 ± 6 (20 – 33)	30 ± 13 (20 – 44)	31 ± 15 (20 – 55)	29 ± 13 (20 – 61)
	Muskrat River	MKR-01	62 ± 53 (33 – 156)	24 ± 8 (20 – 39)	33 ± 12 (20 – 52)	35 ± 15 (20 – 55)	38 ± 30 (20 – 156)
	Cobden Wetland	MKR-03	50 ± 19 (31 – 70)	24 ± 9 (20 – 41)	116 ± 142 (24 – **360**)	25 ± 9 (20 – 35)	57 ± 82 (20 – **360**)
	Muskrat River	MKR-02	111 ± 30 (83 – 152)	21 ± 3 (20 – 27)	153 ± **129** (39 – **297**)	136 ± **168** (20 – **406**)	105 ± 114 (20 – **406**)
Snake	Black Creek	BLC-01	56 ± 33 (20 – 102)	49 ± 55 (20 – 147)	67 ± 37 (23 – 113)	35 ± 10 (20 – 44)	52 ± 36 (20 – 147)
	Upper Harris Drain	HC-01	**1956 ± 883** (**1040 – 3230**)	**1098 ± 377** **(814 – 1740)**	**1018 ± 1217** (20 – **3120**)	**1294 ± 260** **(1030 – 1700)**	**1342 ± 814** (20 – **3230**)
	Upper Harris Drain	HC-03	**1722 ± 1085** (102 – **2920**)	**650 ± 130** **(506 – 757)**	**1402 ± 1691** (41 – **4270**)	**1065 ± 837** (20 – **1860**)	**1272 ± 1124** (20 – **4270**)
	Mink Creek	MC-03	59 ± 20 (34 – 79)	23 ± 7 (20 – 36)	41 ± 19 (20 – 58)	51 ± 26 (20 – 83)	43 ± 22 (20 – 83)
	Mink Creek	MC-02	**241 ± 122** (84 – **359**)	**325 ± 501** **(63 – 1220)**	**540 ± 829** (20 – **2010**)	172 ± **129** (20 – **369**)	**323 ± 485** (20 – **2010**)
	Mink Creek	MC-01	**1122 ± 488** **(680 – 1760)**	**4315 ± 3790** **(458 – 9020)**	**2611 ± 1635** **(596 – 4220)**	**829 ± 473** **(451 – 1610)**	**2219 ± 2389** **(451 – 9020)**
	Mink Creek	MC-04	**1186 ± 406** **(862 – 1870)**	**874 ± 192** **(738 – 1010)**	**494 ± 511** (52 – **1310**)	**855 ± 379** **(525 – 1470)**	**848 ± 469** (52 – **1870**)
	North Tributary	NT-01	**1597 ± 906** (163 – **2280**)	**1121 ± 814** (223 – **1810**)	**1384 ± 566** **(528 – 1900)**	**885 ± 948** (107 – **2440**)	**1260 ± 800** (107 – **2440**)
	O'Gorman Agnew Drain	OAD-01	**5100 ± 2998** **(861 – 7860)**	**2957 ± 2445** **(481 – 5370)**	**2395 ± 2021** (128 – **4630**)	**2222 ± 1884** (48 – **4010**)	**3239 ± 2499** (48 – **7860**)
	Stoqua Creek	SC-01	**702 ± 398** (20 – **1060**)	230 ± **237** (20 – **491**)	**722 ± 914** (20 – **2320**)	**471 ± 377** (20 – **851**)	**547 ± 549** (20 – **2320**)
	Snake River	SNR-01	51 ± 24 (20 – 76)	23 ± 8 (20 – 37)	30 ± 14 (20 – 46)	35 ± 15 (20 – 56)	35 ± 18 (20 – 76)
	Snake River	SNR-02	166 ± **91** (74 – **306**)	46 ± 39 (20 – 106)	123 ± 82 (37 –**254**)	77 ± 57 (20 – 154)	104 ± 80 (20 – **306**)
	Snake River	SNR-06	**622 ± 213** **(360 – 796)**	**598 ± 584** (156 – **1260**)	**786 ± 433** **(244 – 1310)**	**475 ± 353** (143 – **1030**)	**623 ± 372** (143 – **1310**)
	Snake River	SNR-03	**737 ± 161** **(539 – 892)**	656 ± 368 (218 – 1080)	**1345 ± 1108** **(268 – 2940)**	**636 ± 335** **(313 – 1070)**	**844 ± 637** (218 – **2940**)
	Snake River	SNR-04	199 ± **59** (110 – **266**)	111 ± 104 (20 – **272**)	**517 ± 797** (61 – **1930**)	162 ± **238** (20 – **581**)	**248 ± 419** (20 – **1930**)
	Unnamed Creek	SC-02	54 ± 14 (40 – 71)	20 ± 0 (20 – 20)	**439 ± 923** (20 – **2090**)	157 ± **290** (20 –**675**)	191 ± **514** (20 – **2090**)

Blue bold values exceed stream background concentrations for nitrate (240 µg/L) (Dubrovsky et al., 2010)

[a] Multiple sites located along the same tributary are ordered from upstream to downstream.

Table 3. Trends in total nitrogen (µg/L TN) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviations are shown with the range in brackets.

Sub-Watershed	**Tributary**	**Site code[a]**	**2014**	**2015**	**2016**	**2017**	**Average**
Muskrat	Buttermilk Creek	BC-01	514 ± 170 (370 – 810)	352 ± 51 (290 – 420)	426 ± 189 (270 – 730)	343 ± 114 (230 – 450)	412 ± 149 (230 – 810)
	Muskrat River	PH-01	640 ± 132 (440 – 790)	536 ± 247 (300 – 930)	392 ± 56 (350 – 490)	284 ± 39 (220 – 320)	463 ± 192 (220 – 930)
	Muskrat River	OS-01	390 ± 48 (340 – 440)	322 ± 33 (300 – 380)	318 ± 33 (290 –370)	254 ± 30 (220 – 290)	321 ± 60 (220 – 440)
	Muskrat River	MKR-01	464 ± 88 (310 – 520)	480 ± 20 (450 – 500)	422 ± 131 (290 – 610)	316 ± 43 (250 – 360)	421 ± 100 (250 – 610)
	Cobden Wetland	MKR-03	515 ±187 (280 – 710)	440± 92 (350 – 580)	556 ± 147 (360 – 740)	367 ± 15 (350 – 380)	479 ± 138 (280 – 740)
	Muskrat River	MKR-02	600 ± 140 (490 – 800)	448 ± 92 (330 – 560)	558 ± 60 (490 – 630)	494 ± 120 (320 – 650)	521 ± 112 (320 – 800)
Snake	Black Creek	BLC-01	994 ± **1071** (420 – **2900**)	558 ± 170 (340 – 760)	516 ± 105 (360 – 620)	400 ± 109 (260 – 520)	617 ± **553** (260 – **2900**)
	Upper Harris Drain	HC-01	**2488 ± 819** **(1520 – 3540)**	**1472 ± 363** **(1230 – 2110)**	**1564 ± 1127** (920 – **3560**)	**1552 ± 224** **(1300 – 1850)**	**1769 ± 794** (920 – **3560**)
	Upper Harris Drain	HC-03	**2628 ± 1165** (950 – **3750**)	**1500 ± 212** **(1340 – 1740)**	**2222 ± 1882** (860 – **5490**)	**1640 ± 719** (850 – **2390**)	**2053 ± 1221** (850 – **5490**)
	Mink Creek	MC-03	544 ± 184 (420 – 860)	346 ± 50 (270 – 410)	388 ± 61 (350 – 490)	323 ± 17 (300 – 340)	404 ± 130 (270 – 860)
	Mink Creek	MC-02	723 ± 91 (600 – 810)	952 ± **660** (520 – **2060**)	1094 ± **1031** (430 – **2920**)	554 ± 156 (400 – 760)	**836 ± 622** (400 – **2920**)
	Mink Creek	MC-01	**1776 ± 623** **(1230 – 2750)**	**4790 ± 3774** (880 – **9460**)	**3100 ± 1627** (1070 – **4660**)	**1212 ± 459** (740 – **1960**)	**2720 ± 2383** (740 – **9460**)
	Mink Creek	MC-04	**1770 ± 549** **(1380 – 2710)**	**1295 ± 262** **(1110 – 1480)**	824 ± **521** (420 – **1620**)	**1244 ± 352** (900 – **1800**)	**1281 ± 565** (420 – **2710**)
	North Tributary	NT-01	**2624 ± 971** (960– **3320**)	**2037 ± 754** **(1240 – 2740)**	**2042 ± 610** **(1150 – 2780)**	**1598 ± 1115** (770 – **3370**)	**2079 ± 908** (770 – **3370**)
	O'Gorman Agnew Drain	OAD-01	**5800 ± 3176** **(1430 – 8220)**	**3097 ± 2105** (1010 – **5220**)	**3115 ± 2464** (510 – **6150**)	**2512 ± 1875** (460 – **4360**)	**3724 ± 2658** (460 – **8220**)
	Stoqua Creek	SC-01	**1352 ± 401** (740 – **1760**)	1100 ± 218 (830 – **1310**)	**1620 ± 1114** (670 – **3080**)	952 ± **384** (480 – **1320**)	**1264 ± 650** (480 – **3080**)
	Snake River	SNR-01	418 ± 193 (230 – 690)	290 ± 81 (180 – 370)	304 ± 65 (220 – 370)	288 ± 108 (180 – 470)	325 ± 125 (180 – 690)
	Snake River	SNR-02	526 ± 256 (300 – 930)	434 ± 159 (280 – 610)	408 ± 98 (300 – 530)	295 ± 30 (270 – 330)	422 ± 171 (270 – 930)
	Snake River	SNR-06	1050 ± **310** (660 – **1350**)	1003 ± **580** (560 – **1660**)	**1138 ± 461** (580 – **1680**)	792 ± **364** (410 – **1350**)	995 ± **403** (410 – **1680**)
	Snake River	SNR-03	**1716 ± 1088** (800 – **3600**)	**1182 ± 393** (630 – **1560**)	**1810 ± 1359** (600 – **3920**)	870 ± **350** (510 – **1260**)	**1395 ± 924** (510 – **3920**)
	Snake River	SNR-04	796 ± 210 (570 – 1100)	692 ± 157 (600 – 970)	**1132 ± 1165** (520 – **3210**)	673 ± 173 (480 – 890)	831 ± **598** (480 – **3210**)
	Unnamed Creek	SC-02	**1248 ± 935** (780 – **2650**)	877 ± 177 (760 – 1080)	**1442 ± 1150** (550 – **3420**)	648 ± 206 (510 – 1010)	1063 ± **789** (510 – **3420**)

Red bold values exceed thresholds for impairment for total nitrogen (1100 µg/L) for streams in the Mixedwood Plains of Ontario (Chambers et al., 2012)

[a] Multiple sites located along the same tributary are ordered from upstream to downstream.

3.2 Phosphorus

Overall concentrations of both reactive and total phosphorus were high throughout the Muskrat Lake watershed (Table 4). Average concentrations of reactive phosphorus exceeded the estimated background concentration of reactive phosphorus due to natural processes (10 μg/L) in each month and year sampled (Table 4). Elevated concentrations of reactive phosphorus, such as the ones observed, represent contamination due to agricultural and urban activities (Dubrovsky et al., 2010). With few exceptions, average total phosphorus concentrations exceeded the threshold for stream impairment (30 μg/L) developed for the Mixedwood Plains Ecozone of Ontario (Chambers et al., 2012) during most time points sampled (Table 4).

As with nitrogen, phosphorus concentrations ranged between sub-watersheds, tributaries and within tributaries (Table 5, 6). Sites differed significantly in both reactive phosphorus ($F=29.1$; $p<0.001$; $R^2=0.907$) and total phosphorus ($F=45.9$; $p<0.001$; $R^2=0.941$) average concentrations. Concentrations ranged from 1 to 448 μg/L reactive phosphorus and 5 to 1580 μg/L total phosphorus. Similar to results from Dalton (2015), a number of small tributaries were highly phosphorus enriched, including the Unnamed Creek (SC-02), Stoqua Creek (SC-01), O’Gorman Agnew Drain (OAD-01) and Upper Harris Drain (HC-03) (Table 5, 6). In addition, the Cobden Wetland (MKR-03) is a considerable source of phosphorus (Table 5, 6).

Table 4. Seasonal trends in reactive phosphorus (RP) and total phosphorus (TP) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviation are shown with the range in brackets.

	2014		**2015**		**2016**		**2017**		**Monthly Average**	
	RP (µg/L)	**TP (µg/L)**	**RP (µg/L)**	**TP (µg/L)**	**RP (µg/L)**	**TP (µg/L)**	**RP (µg/L)**	**TP (µg/L)**	**RP (µg/L)**	**TP (µg/L)**
Annual Average	**31 ± 50** (1 – **282**)	**55 ± 159** (5 – **1580**)	**33 ± 59** (2 – **299**)	**62 ± 98** (8 – **785**)	**30 ± 56** (4 – **448**)	**48 ± 80** (5 – **590**)	**24 ± 39** (2 – **221**)	**41 ± 49** (5 – **264**)	**29 ± 51** (1 – **448**)	**51 ± 104** (5 – **1580**)
May	**14 ± 30** (1 – **121**)	24 ± **35** (5 – **151**)	**32 ± 68** (2 – **292**)	**57 ± 81** (8 – **350**)	**13 ± 17** (5 – **75**)	20 ± **27** (5 – **107**)	**11 ± 12** (2 – **43**)	21 ± **16** (5 – **56**)	**18 ± 39** (1 – **292**)	**31 ± 49** (5 – **350**)
June	**25 ± 47** (1 – **209**)	**40 ± 72** (5 – **340**)	**34 ± 53** (2 – **223**)	**55 ± 59** (8 – **242**)	**18 ± 27** (4 – **129**)	**33 ± 37** (6 – **164**)	**20 ± 30** (3 – **123**)	**37 ± 35** (8 – **152**)	**24 ± 41** (1 – **223**)	**41 ± 53** (5 – **340**)
July	**35 ± 62** (1 –**282**)	**113 ± 331** (5 – **1580**)	**35 ± 72** (3 – **299**)	**84 ± 189** (14 – **785**)	**27 ± 36** (7 – **179**)	**44 ± 54** (8 – **268**)	**34 ± 52** (5 – **221**)	**47 ± 59** (6 – **264**)	**33 ± 55** (1 – **299**)	**71 ± 194** (5 – **1580**)
August	**45 ± 48** (4 – **160**)	**45 ± 50** (11 – **176**)	**38 ± 62** (2 – **242**)	**61 ± 69** (11 – **264**)	**51 ± 98** (6 – **448**)	**83 ± 141** (8 – **590**)	**23 ± 32** (4 – **132**)	**43 ± 48** (5 – **148**)	**39 ± 65** (2 – **448**)	**58 ± 87** (5 – **590**)
September	**38 ± 54** (1 – **203**)	**49 ± 56** (8– **216**)	**28 ± 37** (5 – **147**)	**60 ± 71** (10 – **280**)	**40 ± 61** (5 – **220**)	**64 ± 80** (6 – **260**)	**32 ± 51** (2 – **200**)	**58 ± 67** (7 – **228**)	**35 ± 52** (1 – **220**)	**58 ± 68** (6 – **280**)

Blue bold values exceed stream background concentrations for reactive phosphorus (10 µg/L) (Dubrovsky et al., 2010)

Red bold values exceed thresholds for impairment for total phosphorus for streams in the Mixedwood Plains of Ontario (30 µg/L) (Chambers et al., 2012)

Table 5. Trends in reactive phosphorus (µg/L RP) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviation are shown with the range in brackets.

Sub-Watershed	**Tributary**	**Site code**[a]	**2014**	**2015**	**2016**	**2017**	**Average**
Muskrat	Buttermilk Creek	BC-01	**26 ± 10** **(16 – 42)**	**24 ± 5** **(18 – 32)**	**18 ± 7** (10 – **25**)	**18 ± 6** **(11 – 25)**	**22 ± 8** (10 – **42**)
	Muskrat River	PH-01	3 ± 2 (1 – 7)	6 ± 3 (2 – **11**)	6 ± 1 (5 – 8)	4 ± 2 (2 – 7)	5 ± 3 (1 – **11**)
	Muskrat River	OS-01	3 ± 1 (1 – 4)	6 ± 2 (4 – 9)	6 ± 1 (5 – 7)	4 ± 3 (2 – 7)	5 ± 2 (1 – 9)
	Muskrat River	MKR-01	**15 ± 7** (5 – **25**)	**24 ± 9** **(15 – 37)**	**16 ± 6** (9 – **22**)	**12 ± 6** (2 – **19**)	**17 ± 8** (2 – **37**)
	Cobden Wetland	MKR-03	**84 ± 38** **(28 – 109)**	**134 ± 116** **(43 – 292)**	**84 ± 87** **(15 – 220)**	**29 ± 7** **(23 – 36)**	**89 ± 83** **(15 – 292)**
	Muskrat River	MKR-02	3 ± 0.5 (2 – 3)	5 ± 2 (2 – 7)	8 ± 1 (6 – 10)	6 ± 2 (4 – 9)	6 ± 2 (2 – 10)
Snake	Black Creek	BLC-01	3 ± 2 (1 – 5)	4 ± 2 (3 – 7)	7 ± 2 (5 – 9)	5 ± 2 (3 – 9)	5 ± 2 (1 – 9)
	Upper Harris Drain	HC-01	**46 ± 50** (3 – **130**)	**27 ± 13** (8 – **41**)	**15 ± 6** (8 – **25**)	**19 ± 6** **(13 – 26)**	**27 ± 27** (3 – **130**)
	Upper Harris Drain	HC-03	**39 ± 36** (4 – **89**)	**77 ± 84** **(12 – 172)**	**54 ± 46** (6 – **119**)	**15 ± 9** (7 – **26**)	**43 ± 46** (4 – **172**)
	Mink Creek	MC-03	6 ± **9** (1 – **22**)	3 ± 1 (2 – 5)	6 ± 1 (4 – 7)	4 ± 1 (3 – 6)	5 ± 5 (1 – **22**)
	Mink Creek	MC-02	**14 ± 22** (1 – **47**)	**15 ± 10** (4 – **25**)	**13 ± 7** (6 – **24**)	10 ± **6** (4 – **19**)	**13 ± 11** (1 – **47**)
	Mink Creek	MC-01	**18 ± 21** (1 – **50**)	**11 ± 6** (5 – **20**)	**11 ± 5** (6 – **17**)	10 ± **6** (6 – **20**)	**12 ± 11** (1 – **50**)
	Mink Creek	MC-04	**16 ± 16** (4 – **36**)	7 ± 1 (7 – 8)	8 ± **3** (5 – **11**)	**11 ± 6** (7 – **22**)	**11 ± 9** (4 – **36**)
	North Tributary	NT-01	**10 ± 6** (4 – **17**)	**21 ± 12** (8 – **30**)	**33 ± 22** (9 – **67**)	**16 ± 7** (7 – **24**)	**20 ± 15** (4 – **67**)
	O'Gorman Agnew Drain	OAD-01	**82 ± 61** **(21 – 160)**	**122 ± 115** **(13 – 242)**	**29 ± 17** **(19 – 54)**	**98 ± 67** **(43 – 200)**	**81 ± 69** **(13 – 242)**
	Stoqua Creek	SC-01	**92 ± 79** (7 – **203**)	**131 ± 114** **(46 – 299)**	**148 ± 176** **(18 – 448)**	**74 ± 31** **(36 – 119)**	**110 ± 108** (7 – **448**)
	Snake River	SNR-01	3 ± 2 (1 – 6)	4 ± 2 (2 – 6)	6 ± 1 (5 – 7)	4 ± 1 (3 – 5)	4 ± 2 (1 – 7)
	Snake River	SNR-02	**12 ± 11** (3 – **31**)	9 ± 4 (5 – **13**)	8 ± 2 (5 – 10)	5 ± 2 (2 – 7)	9 ± **6** (2 – **31**)
	Snake River	SNR-06	**11 ± 5** (4 – **18**)	**16 ± 13** (8 – **31**)	9 ± **3** (5 – **13**)	8 ± **3** (5 – **13**)	**11 ± 6** (4 – **31**)
	Snake River	SNR-03	**15 ± 9** (6 – **26**)	**16 ± 6** **(12 – 25)**	**15 ± 7** (9 – **25**)	**12 ± 4** (8 – **16**)	**15 ± 6** (6 – **26**)
	Snake River	SNR-04	**29 ± 24** (6 – **69**)	**21 ± 12** (9 – **38**)	**22 ± 12** (8 – **36**)	**68 ± 86** **(15 – 221)**	**35 ± 46** (6 – **221**)
	Unnamed Creek	SC-02	**187 ± 74** **(121 – 282)**	**138 ± 38** **(97 – 171)**	**131 ± 37** **(75 – 179)**	**93 ± 52** **(21 – 149)**	**134 ± 59** **(21 – 282)**

Blue bold values exceed stream background concentrations for reactive phosphorus (10 µg/L) (Dubrovsky et al., 2010)

[a] Multiple sites located along the same tributary are ordered from upstream to downstream.

Table 6. Trends in total phosphorus (µg/L TP) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviation are shown with the range in brackets.

Sub-Watershed	**Tributary**	**Site code**[a]	**2014**	**2015**	**2016**	**2017**	**Average**
Muskrat	Buttermilk Creek	BC-01	**36 ± 8** (24 – **45**)	**53 ± 13** **(35 – 70)**	**32 ± 13** (18 – **46**)	**31 ± 5** (27 – **37**)	**38 ± 13** (18 – **70**)
	Muskrat River	PH-01	13 ± 4 (9 – 18)	15 ± 6 (11 – 26)	9 ± 3 (5 – 14)	9 ± 2 (6 – 11)	12 ± 5 (5 – 26)
	Muskrat River	OS-01	11 ± 5 (6 – 19)	17 ± 5 (12 – 24)	10 ± 4 (5 – 14)	10 ± 2 (6 – 12)	12 ± 5 (5 – 24)
	Muskrat River	MKR-01	27 ± **12** (15 – **46**)	**45 ± 11** **(35 – 62)**	28 ± **11** (10 – **39**)	21 ± 8 (9 – 28)	30 ± **13** (9 – **62**)
	Cobden Wetland	MKR-03	**95 ± 44** **(33 – 135)**	**160 ± 131** **(52 – 350)**	**106 ± 96** (25 – **260**)	**55 ± 14** **(42 – 69)**	**110 ± 92** (25 – **350**)
	Muskrat River	MKR-02	12 ± 3 (10 – 15)	21 ± 9 (15 – **37**)	14 ± 3 (11 – 18)	23 ± **10** (15 – **37**)	18 ± 8 (10 – **37**)
Snake	Black Creek	BLC-01	13 ± 6 (7 – 20)	14 ± 5 (8 – 18)	16 ± 7 (8 – 23)	10 ± 2 (8 – 14)	13 ± 5 (7 – 23)
	Upper Harris Drain	HC-01	**36 ± 23** (10 – **62**)	**63 ± 24** **(34 – 87)**	30 ± **25** (6 – **72**)	**38 ± 10** (28 – **55**)	**42 ± 23** (6 – **87**)
	Upper Harris Drain	HC-03	**83 ± 66** (14 – **180**)	**112 ± 105** **(36 – 232)**	**84 ± 53** (17 – **144**)	**51 ± 29** (19 – **94**)	**79 ± 60** (14 – **232**)
	Mink Creek	MC-03	7 ± 3 (5 – 11)	10 ± 2 (8 – 14)	7 ± 1 (5 – 8)	6 ± 1 (5 – 8)	8 ± 3 (5 – 14)
	Mink Creek	MC-02	12 ± 6 (8 – 20)	**33 ± 22** (13 – **62**)	20 ± **14** (5 – **38**)	20 ± 9 (12 – 29)	22 ± **15** (5 – **62**)
	Mink Creek	MC-01	20 ± **19** (7 – **52**)	**34 ± 17** (17 – **58**)	21 ± **12** (6 – **31**)	21 ± 6 (15 – 30)	24 ± **14** (6 – **58**)
	Mink Creek	MC-04	23 ± **18** (11 – **54**)	24 ± 1 (23 – 24)	16 ± 8 (6 – 25)	21 ± 8 (14 – **33**)	20 ± **11** (6 – **54**)
	North Tributary	NT-01	**48 ± 51** (18 – **140**)	**62 ± 33** **(41 – 100)**	**61 ± 27** (23 – **88**)	**52 ± 43** (21 – **126**)	**55 ± 37** (18 – **140**)
	O'Gorman Agnew Drain	OAD-01	**89 ± 63** (27 – **176**)	**155 ± 99** **(71 – 264)**	**64 ± 23** **(38 – 93)**	**119 ± 69** **(56 – 228)**	**104 ± 67** (27 – **264**)
	Stoqua Creek	SC-01	**100 ± 87** (17 – **216**)	**314 ± 326** **(73 – 785)**	**206 ± 230** **(37 – 590)**	**106 ± 54** **(54 – 196)**	**174 ± 198** (17 – **785**)
	Snake River	SNR-01	14 ± 8 (6 – 25)	13 ± 3 (8 – 15)	11 ± 4 (5 – 16)	13 ± 5 (7 – 20)	13 ± 5 (5 – 25)
	Snake River	SNR-02	13 ± 4 (9 – 19)	**31 ± 14** (19 – **50**)	14 ± 3 (10 – 18)	16 ± 4 (11 – 19)	18 ± 10 (9 – **50**)
	Snake River	SNR-06	21 ± 6 (15 – 28)	**35 ± 13** (25 – **49**)	21 ± **11** (6 – **32**)	17 ± 5 (13 – 25)	22 ± **10** (6 – **49**)
	Snake River	SNR-03	24 ± **12** (5 – **35**)	**45 ± 7** **(35 – 51)**	**33 ± 14** (12 – **48**)	**32 ± 13** (21 – **54**)	**34 ± 13** (5 – **54**)
	Snake River	SNR-04	**37 ± 18** (17 – **65**)	**48 ± 13** **(37 – 70)**	**37 ± 18** (17 – **58**)	**92 ± 97** **(41 – 264)**	**54 ± 52** (17 – **264**)
	Unnamed Creek	SC-02	**560 ± 686** **(151 – 1580)**	**191 ± 48** **(144 – 240)**	**226 ± 99** **(107 – 364)**	**139 ± 58** **(39 – 188)**	**273 ± 346** **(39 – 1580)**

Red bold values exceed thresholds for impairment for total phosphorus for streams in the Mixedwood Plains of Ontario (30 µg/L) (Chambers et al., 2012)

[a] Multiple sites located along the same tributary are ordered from upstream to downstream.

3.3 Total suspended sediments

Total suspended sediments were moderately high across the Muskrat Lake watershed (Table 7). Average total suspended sediments exceeded the ideal performance standard (4.1 mg/L) developed for the Mixedwood Plains of Ontario (Culp et al., 2009) in almost all sampling months from 2014-2017 (Table 7). Concentrations of total suspended sediments differed between field sites (F=10.1; $p<0.001$; $R^2=0.788$) and ranged from 0.5 to 120 mg/L. Total suspended sediments were high in two tributaries that were also nutrient enriched, the Upper Harris Drain (HC-01, HC-03) and North Tributary (NT-01) (Table 8). Along the Snake River, total suspended sediments increased from upstream to downstream sites. Total suspended sediments peaked in concentration at SNR-03 before declining at SNR-04. The Snake River Marsh, located between SNR-03 and SNR-04 appeared to be a considerable sink for total suspended sediments. Average total suspended sediments were ~ 4 × lower in SNR-04 compared to SNR-03 after passing through the wetland (Table 8).

Table 7. Seasonal trends in total suspended sediments (µg/L) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviation are shown with the range in brackets.

	2014	**2015**	**2016**	**2017**	**Monthly Average**
Annual Average	**6.0 ± 7.8** (0.5 – **62.6**)	**8.9 ± 9.5** (0.5 – **42.9**)	**7.8 ± 14.2** (0.5 – **120.0**)	**5.5 ± 8.0** (0.5 – **52.5**)	**7.0 ± 10.3** (0.5 – **120.0**)
May	3.6 ± **3.0** (1.0 – **14.5**)	**10.2 ± 9.7** (2.4 – **36.5**)	**4.4 ± 3.0** (1.2 – **12.8**)	3.9 ± **2.9** (0.5 – **11.3**)	**5.6 ± 6.1** (0.5 – **36.5**)
June	**6.4 ± 7.4** (0.5 – **27.8**)	**6.5 ± 6.6** (0.9 – **30.7**)	**5.5 ± 6.8** (0.7 – **28.4**)	**7.4 ± 10.1** (0.5 – **48.4**)	**6.4 ± 7.7** (0.5 – **48.4**)
July	**7.1 ± 12.9** (0.5 – **62.6**)	**10.0 ± 11.3** (1.3– **33.8**)	**7.7 ± 9.5** (1.0 – **35.4**)	**4.3 ± 3.8** (0.7 – **14.8**)	**7.1 ± 9.9** (0.5 – **62.6**)
August	**5.8 ± 4.7** (0.9 – **19.2**)	**11.6 ± 11.7** (0.8 – **42.9**)	**7.8 ± 12.4** (0.5 – **44.2**)	**6.5 ± 12.4** (0.6 – **52.5**)	**7.9 ± 10.9** (0.5 – **52.5**)
September	**7.2 ± 7.0** (0.5 – **26.0**)	**6.4 ± 7.2** (0.5 – **24.4**)	**13.4 ± 26.2** (0.5 – **120.0**)	**5.6 ± 6.5** (0.5 – **24.5**)	**8.3 ± 15.1** (0.5 – **120.0**)

Purple bold values exceed the ideal performance standard for streams in the Mixedwood Plains of Ontario (4.1 mg/L) (Culp et al., 2009)

Table 8. Trends in total suspended sediments (mg/L TSS) at 22 stream/river sites in the Muskrat Lake watershed, Canada from May to September 2014-2017. Average concentrations ± standard deviation are shown with the range in brackets.

Sub-Watershed	**Tributary**	**Site code**[a]	**2014**	**2015**	**2016**	**2017**	**Average**
Muskrat	Buttermilk Creek	BC-01	**4.2 ± 2.5** (1.4 – **6.8**)	**7.3 ± 4.2** (0.6 – **11.7**)	**4.2 ± 2.0** (1.0 – **6.4**)	**4.2 ± 3.8** (0.9 – **8.3**)	**5.0 ± 3.2** (0.6 – **11.7**)
	Muskrat River	PH-01	2.6 ± 1.4 (1.5 – **4.4**)	2.3 ± 1.3 (0.8 – **4.2**)	1.7 ± 1.0 (0.5 – 2.7)	1.5 ± 0.4 (1.1 – 2.0)	2.0 ± 1.1 (0.5 – **4.4**)
	Muskrat River	OS-01	1.0 ± 0.5 (0.5 – 1.9)	**8.9 ± 15.5** (1.2 – **36.5**)	1.9 ± 1.4 (0.6 – **4.2**)	0.9 ± 0.5 (0.5 – 1.5)	3.2 ± **7.9** (0.5 – **36.5**)
	Muskrat River	MKR-01	2.8 ± 0.5 (2.0 – 3.3)	**5.3 ± 2.3** (2.7 – **7.8**)	2.6 ± 0.5 (1.9 – 3.2)	2.3 ± 0.8 (1.2 – 3.0)	3.3 ± **1.7** (1.2 – **7.8**)
	Cobden Wetland	MKR-03	0.9 ± 0.5 (0.5 – 1.3)	**9.4 ± 13.8** (0.8 – **33.8**)	1.8 ± 0.5 (1.3 – 2.4)	2.0 ± 1.1 (0.7 – 2.9)	3.8 ± **7.9** (0.5 – **33.8**)
	Muskrat River	MKR-02	**4.3 ± 5.5** (1.2 – **12.5**)	2.1 ± 1.0 (0.9 – 3.3)	1.2 ± 0.8 (0.5 – 2.5)	**3.4 ± 2.3** (1.2 – **7.2**)	2.7 ± **2.8** (0.5 – **12.5**)
Snake	Black Creek	BLC-01	3.6 ± **2.6** (1.4 – **7.8**)	2.8 ± **1.5** (1.7 – **5.3**)	**2.9 ± 1.5** (1.6 – **5.4**)	1.0 ± 0.6 (0.5 – 2.1)	2.6 ± **1.8** (0.5 – **7.8**)
	Upper Harris Drain	HC-01	**11.0 ± 11.1** (1.5 – **26.0**)	**13.3 ± 8.9** **(5.0 – 24.8)**	**18.0 ± 15.0** (3.2 – **35.1**)	**5.6 ± 3.1** (2.7 – **10.4**)	**12.0 ± 10.6** (1.5 – **35.1**)
	Upper Harris Drain	HC-03	**9.5 ± 8.1** (3.2 – **23.3**)	**19.0 ± 20.7** **(6.6 – 42.9)**	**28.4 ± 16.2** **(4.8 – 44.2)**	**12.8 ± 11.7** (2.0 – **31.1**)	**17.3 ± 14.9** (2.0 – **44.2**)
	Mink Creek	MC-03	2.1 ± 0.3 (1.8 – 2.5)	2.7 ± **1.8** (0.5 – **5.3**)	1.0 ± 0.5 (0.5 – 1.6)	2.2 ± 1.4 (1.2 – **4.3**)	2.0 ± 1.2 (0.5 – **5.3**)
	Mink Creek	MC-02	3.9 ± **1.1** (3.1 – **5.5**)	**6.1 ± 2.6** (2.7 – **10.0**)	3.9 ± **1.7** (1.7 – **6.1**)	**3.8 ± 4.0** (0.9 – **10.8**)	**4.5 ± 2.6** (0.9 – **10.8**)
	Mink Creek	MC-01	**4.5 ± 1.0** (3.4 – **6.0**)	**11.6 ± 7.9** (3.8 – **24.4**)	**3.8 ± 1.7** (1.7 – **6.2**)	**3.3 ± 3.0** (0.5 – **8.2**)	**5.8 ± 5.3** (0.5 – **24.4**)
	Mink Creek	MC-04	**6.8 ± 1.0** **(5.5 – 7.8)**	**8.1 ± 0.6** **(7.6 – 8.5)**	**6.3 ± 4.5** (2.5 – **14.1**)	**5.0 ± 2.6** (3.0 – **9.3**)	**6.3 ± 2.8** (2.5 – **14.1**)
	North Tributary	NT-01	**19.9 ± 24.3** **(4.2 – 62.6)**	**23.9 ± 9.5** **(13.0 – 30.7)**	**17.3 ± 10.0** **(8.5 – 28.4)**	**27.7 ± 22.2** (3.4 – **52.5**)	**22.0 ± 17.5** (3.4 – **62.6**)
	O'Gorman Agnew Drain	OAD-01	**6.0 ± 2.5** (3.1 – **9.8**)	**9.3 ± 9.2** (3.5 – **19.9**)	**36.2 ± 56.1** (2.3 – **120.0**)	**7.7 ± 6.6** (2.0 – **15.1**)	**14.2 ± 27.8** (2.0 – **120.0**)
	Stoqua Creek	SC-01	**7.6 ± 10.4** (1.0 – **25.5**)	**13.6 ± 11.5** **(5.2 – 30.4)**	**5.8 ± 2.3** (2.6 – **8.6**)	**5.9 ± 3.4** (1.7 – **10.2**)	**7.9 ± 7.7** (1.0 – **30.4**)
	Snake River	SNR-01	2.0 ± 0.9 (0.9 – 3.3)	2.1 ± 0.8 (0.9 – 2.9)	2.1 ± 0.6 (1.5 – 2.9)	2.4 ± 0.4 (2.1 – 3.1)	2.2 ± 0.6 (0.9 – 3.3)
	Snake River	SNR-02	**4.2 ± 1.8** (2.8 – **7.0**)	**9.9 ± 7.1** (2.4 – **18.0**)	3.3 ± **1.2** (2.3 – **4.9**)	**3.5 ± 1.1** (1.9 – **4.3**)	**5.3 ± 4.5** (1.9 – **18.0**)
	Snake River	SNR-06	**9.4 ± 2.8** **(6.5 – 13.4)**	**16.6 ± 8.4** **(11.5 – 26.3)**	**8.2 ± 3.6** (3.9 – **12.6**)	**6.3 ± 2.6** (3.1 – **9.2**)	**9.4 ± 5.2** (3.1 – **26.3**)
	Snake River	SNR-03	**16.1 ± 6.7** **(10.5 – 27.8)**	**22.9 ± 6.6** **(15.8 – 29.7)**	**11.0 ± 3.6** **(5.6 – 14.4)**	**11.2 ± 3.4** **(7.2 – 16.5)**	**15.3 ± 7.0** **(5.6 – 29.7)**
	Snake River	SNR-04	2.7 ± **2.5** (0.8 – **7.1**)	**8.5 ± 7.9** (2.5 – **21.3**)	3.1 ± **1.9** (1.4 – **6.1**)	3.0 ± **2.5** (0.8 – **7.3**)	**4.3 ± 4.8** (0.8 – **21.3**)
	Unnamed Creek	SC-02	**5.0 ± 3.5** (1.4 – **8.4**)	2.0 ± 0.3 (1.8 – 2.4)	**11.9 ± 18.1** (1.5 – **43.9**)	3.6 ± 2.8 (1.1 – 6.7)	**6.1 ± 10.1** (1.1 – **43.9**)

Purple bold values exceed the ideal performance standard for streams in the Mixedwood Plains of Ontario (4.1 mg/L) (Culp et al., 2009)

[a] Multiple sites located along the same tributary are ordered from upstream to downstream.

3.4 Trends over time

Two-way ANOVAs were used to determine the main effects of field site and year on average nutrient and total suspended sediment concentrations. As described above, nutrient and total suspended sediments concentrations different significantly between field sites. Average concentrations also differed significantly between years for nitrate (F=9.0; p<0.001; R^2=0.934), total nitrogen (F=19.1; p<0.001; R^2=0.941), total phosphorus (F=12.0; p<0.001; R^2=0.941) and total suspended sediments (F=7.0; p<0.001; R^2=0.788). Reactive phosphorus concentrations did not differ between years (F=2.0; p=0.117; R^2=0.907). Of the water quality parameters that differed between years, only total nitrogen showed a trend with total nitrogen decreasing over time (Table 3). Nitrate, total phosphorus and total suspended sediments concentrations differed only between specific years. For example, nitrate was lower in 2015 than in 2014 and 2016 and both total phosphorus and total suspended sediments were higher in 2015 than in other years. No overall upward or downward trend in concentrations were observed for nitrate, reactive phosphorus, total phosphorus or total suspended sediments.

A second series of 2-way ANOVAs was used to determine the effects of field site and year on nutrient and total suspended sediments concentrations, after subtracting time-specific background concentrations using data from the reference site Black Creek (BLC-01). The goal of this analysis was to assess whether there were trends in water quality parameters over time, after controlling for time-specific differences due to environmental factors such as precipitation and discharge. Average adjusted concentrations differed between years for nitrate (F=2.8; p=0.048; R^2=0.880), total nitrogen (F=3.6; p=0.018; R^2=0.852), reactive phosphorus (F=9.4; p<0.001; R^2=0.924), total phosphorus (F=14.2; p<0.001; R^2=0.926) and total suspended sediments (F=7.1; p<0.001; R^2=0.766). However, only reactive phosphorus showed a trend, with adjusted concentrations decreasing over time. The other parameters differed between specific years but no upward or downward trend was observed.

Overall, there was little evidence to suggest that nutrients and total suspended sediments were either increasing or decreasing at a watershed scale from 2014-2017. This was an expected result because trends may only become apparent on a longer time scale than is presently available. Also, it was unlikely that there were changes in nutrient inputs large enough to affect concentrations at a watershed scale over a four year period. Total nitrogen appeared to decrease over time but this trend was not observed when data were adjusted for time-specific reference concentrations and was not observed for nitrate concentrations. The observed decrease in total nitrogen could be the result of differences between precipitation, discharge and atmospheric deposition of nitrogen rather than land use changes. While no difference between years was observed for unadjusted reactive phosphorus concentrations, a downward trend was observed for reactive phosphorus concentrations adjusted for time-specific reference conditions. Since a similar trend was not observed for total phosphorus, which includes contributions from planktonic algae, this trend could reflect increased growth and uptake of reactive phosphorus by aquatic plants or periphyton (attached algae). However, these interpretations are somewhat speculative and require further study and data over a longer time period.

3.5 Effects of land use

Average 2014 land use upstream of the 22 field sites in the Muskrat Lake watershed was predominately natural habitat (average 59.6 ± standard deviation 37.4%), followed by areas of annual crop land (24.8 ± 31.0%) and pasture/forage land (12.4 ± 15.9%). Developed land represented a small portion of total land use (3.2 ± 2.5%, ranging from 0 to 9.3%). Across the watershed, land use varied from 0 to 98.3% natural habitat, 0 to 92.8% annual crop land and 0 to 68.2% pasture/forage land.

In-stream concentrations of both nitrate and total nitrogen increased as the percentage of upstream land in annual crops increased (Fig. 3). Annual crops, particularly the cultivation of corn crops, are associated with the application of nitrogen-based synthetic fertilizers as well as manure. The inverse relationship was observed for natural habitat with nitrate and total nitrogen concentrations decreasing as the percentage of natural habitat increased (Fig. 3). No statistical relationship was observed between nitrate and nitrogen and the percentage of pasture and forage land (Fig. 3).

Reactive phosphorus increased as the percentage of annual crop land increased and decreased as the percentage of natural habitat increased (Fig. 4). No relationship was observed between reactive phosphorus and the percentage of pasture and forage land (Fig. 4). This land use type is expected to be variable in terms of its effect on water quality. For example, some forage crops have low fertilizer requirements, whereas grazing cattle with unrestricted access to nearby waterbodies may be a significant point source of phosphorus. No statistical relationship was observed between total phosphorus and different land use types (Fig. 4). Phosphorus enrichment likely occurred as a result of non-point source pollution (e.g. surface runoff from agricultural fields and tile drains) but also from point sources that are not necessarily associated with agriculture (e.g. wastewater treatment plant).

Total suspended sediments increased with increasing annual crop land, as well as with increasing pasture and forage land, and decreased with increasing natural habitat (Fig. 5). Suspended sediments can enter waterbodies through runoff from agricultural fields, whereas natural vegetation prevents suspended sediments from entering waterbodies. Specific land use activities also have an impact. For example, restricting cattle access to streams and having vegetated buffers zones around crops can reduce erosion and the export of suspended sediments to waterbodies.

The relationships between 2014-2017 nutrients and various 2014 land uses tended to be weaker than those reported in Dalton (2015). One explanation is that the current report analyzed data for 22 field sites and Dalton (2015) analyzed data for 27 field sites. The reduction in the number of field sites reduces the statistical power to detect trends and outliers have a greater influence on the dataset. Another explanation is that the effects of 2014 land use on 2014 nutrient and total suspended sediment concentrations were assessed in Dalton (2015) and the present report assessed the effects of 2014 land use on nutrient and total suspended sediment concentrations averaged from 2014-2017. Recent changes in land use (e.g. from annual to forage crops) were not reflected in the latter analysis. However, overall trends remained the same over time. Nutrients and suspended sediments tended to increase with increasing annual crop land and decrease with increasing natural habitat.

Several sites (e.g. SC-01, SC-02 and MKR-03) consistently had higher phosphorus concentrations than would be expected based on the surrounding land use (Table 9), warranting further investigation of potential sources of phosphorus. The specific sampling locations at both Stoqua Creek (SC-01) and Unnamed Creek (SC-02) are located in close proximity to annual crop land (Muskrat Watershed Council, personal communication), suggesting that the influence of agriculture may be higher than indicated by the moderate percentages of calculated upstream annual crop land (Table 9). Both tributaries also have areas with unrestricted cattle access (Muskrat Watershed Council, personal communication) which could be a significant point source of phosphorus that contributed to the elevated concentrations of reactive and total phosphorus at Stoqua Creek (SC-01) and Unnamed Creek (SC-02) (Table 9). Low summer discharge and the presence of numerous geese during the spring and fall are two additional potential explanations for high phosphorus concentrations at Unnamed Creek (SC-02) (Muskrat Watershed Council, personal communication). Given the high percentage of surrounding pasture/ forage land and high phosphorus concentrations, Stoqua Creek would be a good tributary for exploring the feasibility of the installation of cattle exclusion fencing.

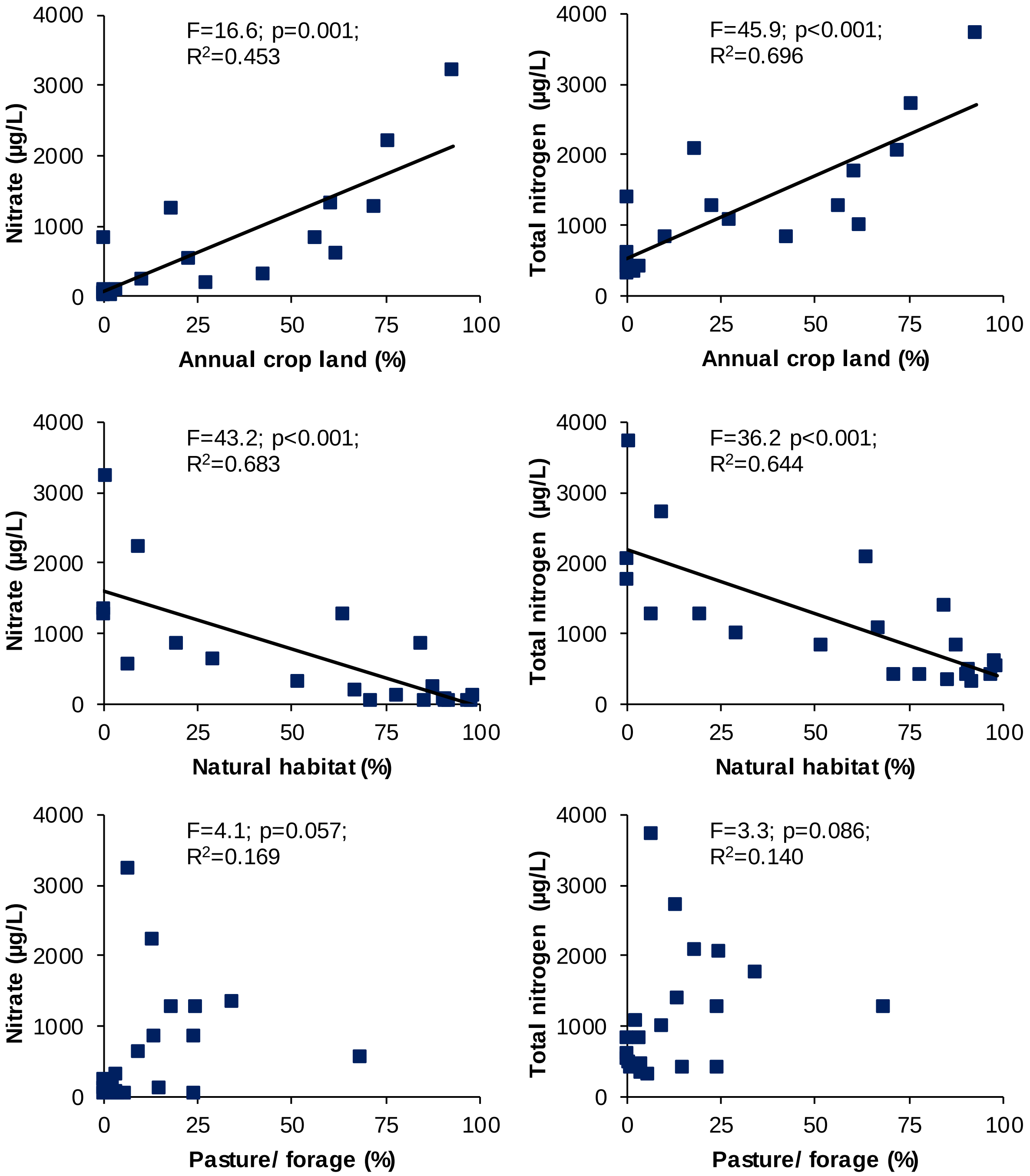

Fig. 3. Relationship between average nitrate and total nitrogen and the dominant land uses 1 km upstream of 22 sites located in the Muskrat Lake watershed, Canada. Significant ($p \leq 0.05$; solid lines) linear regressions are shown.

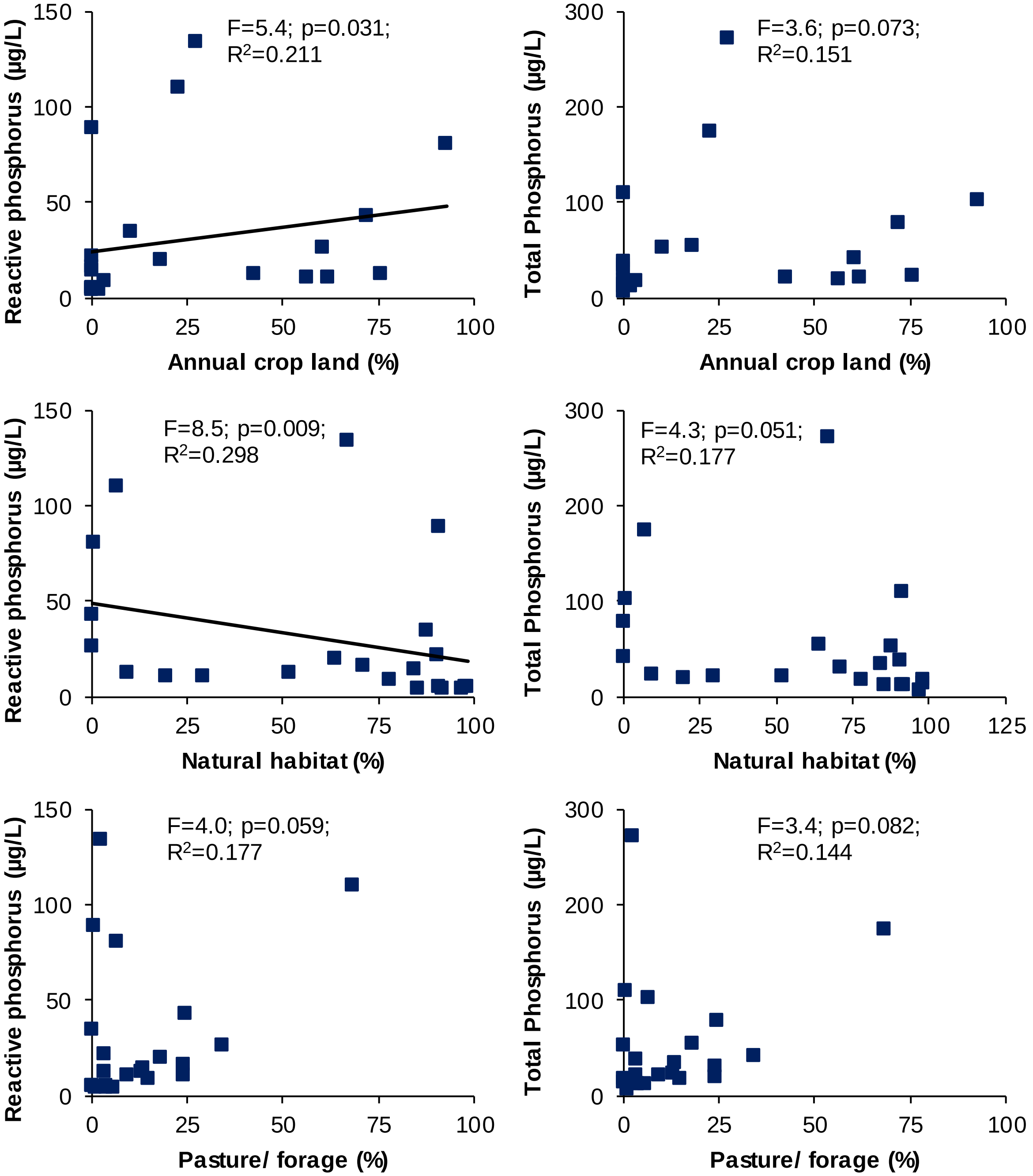

Fig. 4. Relationship between average reactive phosphorus and total phosphorus and the dominant land uses 1 km upstream of 22 sites located in the Muskrat Lake watershed, Canada. Significant ($p \leq 0.05$; solid lines) linear regressions are shown.

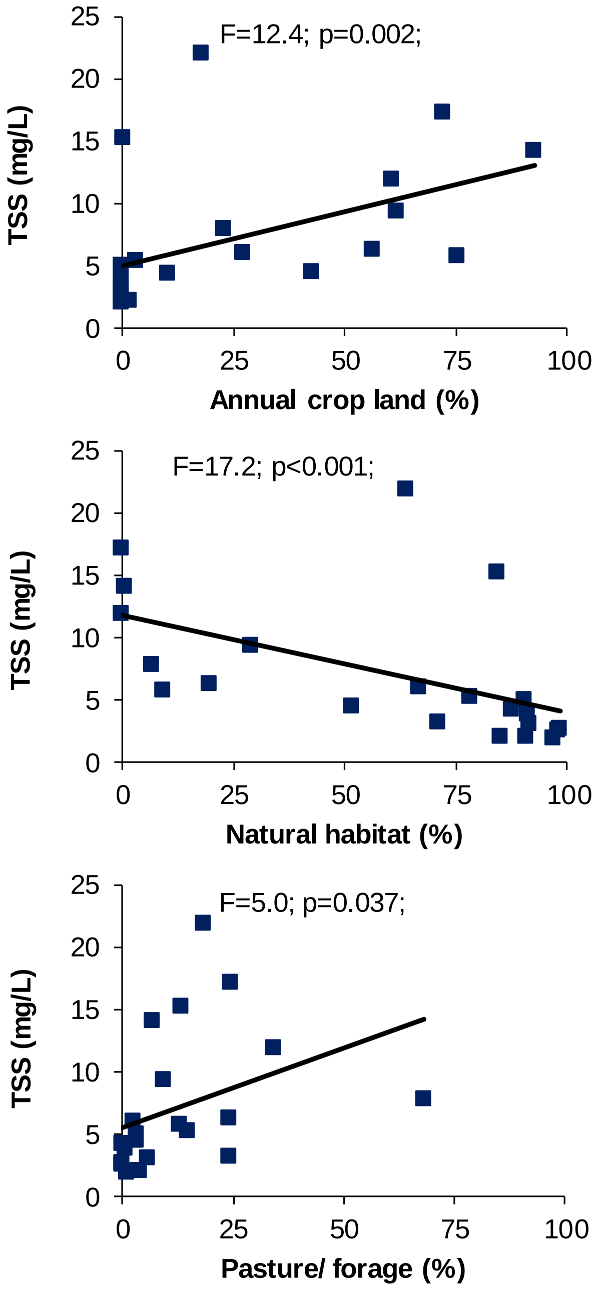

Fig. 5. Relationship between average total suspended sediments (TSS) and the dominant land uses 1 km upstream of 22 sites located in the Muskrat Lake watershed, Canada. Significant ($p \leq 0.05$; solid lines) linear regressions are shown.

Table 9. Relationship between landuse (2014) and water quality parameters (May to September 2014-2017) at 22 stream/river sites in the Muskrat Lake watershed, Canada. Average concentrations ± standard deviation are shown.

Sub-Watershed	**Tributary**	**Site code**[a]	**Annual crop land (%)**	**Natural habitat (%)**	**Pasture/ forage land (%)**	**Developed land (%)**	**Nitrate (µg/L)**	**Total nitrogen (µg/L)**	**Reactive phosphorus (µg/L)**	**Total phosphorus (µg/L)**	**Suspended sediments (mg/L)**
Muskrat	Buttermilk Creek	BC-01	0.0	90.4	3.2	6.4	73 ± 56	412 ± 149	**22 ± 8**	**38 ± 13**	**5.0 ± 3.2**
	Muskrat River	PH-01	0.0	90.9	3.5	5.6	47 ± 33	463 ± 192	5 ± 3	12 ± 5	2.0 ± 1.1
	Muskrat River	OS-01	0.0	91.7	5.7	2.5	29 ± 13	321 ± 60	5 ± 2	12 ± 5	3.2 ± **7.9**
	Muskrat River	MKR-01	0.0	71.2	24.0	4.8	38 ± 30	421 ± 100	**17 ± 8**	30 ± **13**	3.3 ± **1.7**
	Cobden Wetland	MKR-03	0.0	91.1	0.7	8.3	57 ± 82	479 ± 138	**89 ± 83**	**110 ± 92**	3.8 ± **7.9**
	Muskrat River	MKR-02	0.0	98.3	0.0	1.7	105 ± 114	521 ± 112	6 ± 2	18 ± 8	2.7 ± **2.8**
Snake	Black Creek	BLC-01	0.0	98.0	0.0	2.0	52 ± 36	617 ± **553**	5 ± 2	13 ± 5	2.6 ± **1.8**
	Upper Harris Drain	HC-01	60.7	0.0	34.4	5.0	**1342 ± 814**	**1769 ± 794**	**27 ± 27**	**42 ± 23**	**12.0 ± 10.6**
	Upper Harris Drain	HC-03	72.2	0.0	24.4	3.4	**1272 ± 1124**	**2053 ± 1221**	**43 ± 46**	**79 ± 60**	**17.3 ± 14.9**
	Mink Creek	MC-03	0.0	97.0	0.9	2.2	43 ± 22	404 ± 130	5 ± 5	8 ± 3	2.0 ± 1.2
	Mink Creek	MC-02	42.6	51.8	3.1	2.5	**323 ± 485**	836 ± **622**	**13 ± 11**	22 ± **15**	**4.5 ± 2.6**
	Mink Creek	MC-01	75.5	9.4	13.0	2.1	**2219 ± 2389**	**2720 ± 2383**	**12 ± 11**	24 ± **14**	**5.8 ± 5.3**
	Mink Creek	MC-04	56.3	19.6	24.1	0.0	**848 ± 469**	**1281 ± 565**	**11 ± 9**	20 ± **11**	**6.3 ± 2.8**
	North Tributary	NT-01	17.9	63.9	18.2	0.0	**1260 ± 800**	**2079 ± 908**	**20 ± 15**	**55 ± 37**	**22.0 ± 17.5**
	O'Gorman Agnew Drain	OAD-01	92.8	0.6	6.6	0.0	**3239 ± 2499**	**3724 ± 2658**	**81 ± 69**	**104 ± 67**	**14.2 ± 27.8**
	Stoqua Creek	SC-01	22.8	6.7	68.1	2.3	**547 ± 549**	**1264 ± 650**	**110 ± 108**	**174 ± 198**	**7.9 ± 7.7**
	Snake River	SNR-01	1.7	85.2	3.8	9.3	35 ± 18	325 ± 125	4 ± 2	13 ± 5	2.2 ± 0.6
	Snake River	SNR-02	3.3	78.1	14.8	3.8	104 ± 80	422 ± 171	9 ± **6**	18 ± 10	**5.3 ± 4.5**
	Snake River	SNR-06	61.7	29.2	9.1	0.0	**623 ± 372**	995 ± **403**	**11 ± 6**	22 ± **10**	**9.4 ± 5.2**
	Snake River	SNR-03	0.1	84.4	13.4	2.1	**844 ± 637**	**1395 ± 924**	**15 ± 6**	**34 ± 13**	**15.3 ± 7.0**
	Snake River	SNR-04	10.3	87.7	0.0	2.1	**248 ± 419**	831 ± **598**	**35 ± 46**	**54 ± 52**	**4.3 ± 4.8**
	Unnamed Creek	SC-02	27.4	66.8	2.4	3.4	191 ± **514**	1063 ± **789**	**134 ± 59**	**273 ± 346**	**6.1 ± 10.1**

Blue bold values exceed stream background concentrations for nitrate (240 µg/L) or reactive phosphorus (10 µg/L) (Dubrovsky et al., 2010); **Red bold** values exceed thresholds for impairment for total nitrogen (1100 µg/L) or total phosphorus (30 µg/L) (Chambers et al., 2012); **Purple bold** values exceed the ideal performance standard for streams in the Mixedwood Plains of Ontario (4.1 mg/L) (Culp et al., 2009).

3.5.1 Phosphorus in the Cobden Wetland (MKR-03)

Reactive and total phosphorus concentrations were consistently high in the Cobden Wetland (MKR-03) (Table 5; Table 6), despite a high percentage of surrounding natural habitat (Table 9). This site is located on the Muskrat River, within a wetland complex, and is the site located closest to the inflow of Muskrat Lake (Fig. 6). Cobden Wetland (MKR-03) is located downstream of Buttermilk Creek (BC-01) and Muskrat River (MKR-01) and is also in close proximity to the effluent outlet for the Cobden Water Pollution Control Plant (Fig. 6). At Buttermilk Creek (BC-01), average concentrations of reactive phosphorus and total phosphorus exceeded background concentrations (10 µg/L) and the threshold for impairment (30 µg/L) respectively from 2014-2017 (Table 5, 6). At Muskrat River (MKR-01), average concentrations of reactive phosphorus also exceeded background concentrations of reactive phosphorus from 2014-2017 (Table 5) but total phosphorus concentrations exceeded the threshold for impairment only occasionally (Table 6). The moderately high phosphorus concentrations at BC-01 and MKR-01 do not fully explain the highly elevated phosphorus concentrations at MKR-03, suggesting that internal phosphorus loading and/or a significant point source of phosphorus are affecting the water quality of this site.

The Cobden Water Pollution Control Plant treats sewage from the Town of Cobden. Effluent is discharged from an outfall sewer to an earth-bermed enclosure which permits dispersion of effluent to the Cobden Wetland at four locations (Ontario Clean Water Agency, 2018). The effluent is then discharged to the Muskrat River, including MKR-03, before being discharged to Muskrat Lake. Data from the Ontario Clean Water Agency (2015, 2016, 2017, 2018) were extracted and are summarized below. From 2014-2017, the Cobden Water Pollution Control Plant operated close to its design capacity of 696 m^3/day with an average day flow (± standard deviation) of 715 ± 107 m^3/day (range 605 to 857 m^3/day), corresponding to 103 ± 15 % overcapacity (87 to 123 %). During these four years, the monthly average effluent objective of 1000 µg/L total phosphorus was nearly always met, with the objective exceeded only in October 2017 (10,343 µg/L) and December 2017 (1900 µg/L). The overall monthly average effluent concentration from 2014-2017 was 489 ± 1492 µg/L total phosphorus (77 to 10,343 µg/L). The Cobden Water Pollution Control Plant is significantly overcapacity in terms of maximum day flows. From 2014-2017, the average maximum day flow was 2740 ± 792 m^3/day (1570 to 3281 m^3/day), corresponding to 394 ± 114 % (226 to 471 %) overcapacity. Three or four bypass events were reported each year and were typically a result of high flows due to spring snowmelt or rainfall events. From 2014-2017, sewage bypass events led to the release of an estimated 12,628,185 L of raw or partially treated effluent, as well as an additional 2,074,000 L of final effluent that was not disinfected due to issues with the chlorine pump.

Fig. 6. Map of the Cobden Wetland (MKR-03) and its proximity to Buttermilk Creek (BC-01), Muskrat River (MKR-01) and the Cobden Water Pollution Control Plant (Cobden WWT Wetland Effluent Outlet).

4.0 Conclusions and Recommendations

4.1 Conclusions from water quality monitoring from 2014-2017

The Muskrat Lake watershed was characterized by high concentrations of nitrogen and phosphorus and by moderate concentrations of total suspended sediments. High nutrient concentrations were not transient but were persistent from May to September over four years. Nutrient enrichment and excessive total suspended sediments were directly and positively related to annual crop land. Nutrients and total suspended sediments were lowest in areas with high percentages of natural habitat, highlighting the importance of conserving natural habitat. The strong positive relationship between nitrate and annual crop land provided evidence that annual crop land was a significant contributor of non-point source nitrogen pollution from runoff and tile drainage. Annual crop land was also a contributor of non-point source phosphorus pollution. However, the relationship was less clear and there was also evidence of point sources of phosphorus pollution, characterized by sites surrounded by low percentages of annual crop land and high phosphorus concentrations. Several tributaries were identified as being highly impacted by nutrients:

- Cobden Wetland- high phosphorus
- Upper Harris Drain- high nitrogen and phosphorus
- North Tributary- high nitrogen and phosphorus
- O'Gorman Agnew Drain- high nitrogen and high phosphorus
- Stoqua Creek- moderately high nitrogen and high phosphorus
- Unnamed Creek (SC-02)- high phosphorus

Portions of Mink Creek and Snake River were also nutrient enriched, whereas the Muskrat River generally did not exceed threshold values for impairment. Nutrient enrichment in tributaries of the Muskrat Lake watershed is contributing to eutrophication in Muskrat Lake. Reducing nutrient loading from tributaries draining into Muskrat Lake is an essential step to improving its water quality.

4.2 Recommendations for the monitoring network

This report examined data from 22 field sites located throughout the Muskrat Lake watershed (Fig. 2). This monitoring network was optimized in 2015 and consists of the major tributaries in the Muskrat and Snake River sub-watersheds. Four years of data (2014-2017) have now been collected from these field sites. In addition, samples were collected from Muskrat Lake (MLK-01) monthly from May to September beginning in 2015.

Recommendations:

1. The existing monitoring network of 22 field sites should be maintained in future years so that trends in water quality can be assessed.
2. Data from SNR-08 (Snake River) were not included in this report as data were missing for most sampling months in 2015 and 2016. This site could be discarded as there are sites located both upstream and downstream. Alternatively, the site could be added back into the monitoring network if it will be feasible to sample this site in future years.
3. An additional site, SC-03 (Stoqua Creek), was added in 2017. This site is located upstream of a controlled tile drainage structure that was installed in 2016. This site could be added to the monitoring network to support an assessment of the impacts of controlled tile drainage structures on water quality.
4. Although Muskrat Lake (MLK-01) data were not specifically addressed in this report, monthly samples should continue to be taken from this site to establish a consistent record of water quality within the lake.
5. Overall data needs should be assessed. For example, metals data from 2014-2017 have not been examined in detail. The elimination of the metals suite could reduce the overall cost of chemical analysis of water samples. Given that current water quality issues in the Muskrat Lake watershed are primarily related to major nutrients, this would be preferable to reducing the number of field sites in the monitoring network.
6. Additional site-specific recommendations and their rationales are given in Table 10.

Table 10. Recommendations for the Muskrat Lake watershed monitoring network[a].

Sub-Watershed	Tributary	Site code	Status	Level of impact	Importance to sampling	Recommendation	Rationale
Muskrat	Buttermilk Creek	BC-01	New in 2014	Moderate	Moderate	Keep	Only site on this tributary.
	(Harlow Trail Creek)	(HT-01)	(Discarded in 2015)	(Moderate)	(Moderate)	(Discard)	(This site had low discharge and was only moderately impacted by nutrients. No new data since 2014.)
	Muskrat River	PH-01	New in 2014	Low	High	Keep	Most upstream site.
	Muskrat River	OS-01	New in 2014	Low	Moderate	Keep	This site reflects important land use changes from PH-01 (e.g. increased development and agriculture).
	Muskrat River	MKR-01	Existing prior to 2014	Low to Moderate	Moderate	Keep	Existing site.
	Cobden Wetland	MKR-03	New in 2014	High Phosphorus	High	Keep	High phosphorus. This wetland warrants further study to assess the impact of the sewage treatment plant on export of phosphorus to Muskrat Lake.
	Muskrat River	MKR-02	New in 2014	Low	High	Keep	Most downstream site.
Snake	Black Creek	BLC-01	New in 2014	Low	High	Keep	Reference site.
	Upper Harris Drain	HC-01	New in 2014	High	High	Keep	Highly impacted, most upstream site.
	(Upper Harris Drain)	(HC-02)	(Discarded in 2015)	(High)	(Low)	(Discard)	(There were sites located both upstream and downstream of this site. No new data since 2014.)
	Upper Harris Drain	HC-03	New in 2014	High	High	Keep	Highly impacted, most downstream site.
	Mink Creek	MC-03	Existing prior to 2014	Low	High	Keep	Most upstream site.
	Mink Creek	MC-02	Existing prior to 2014	Moderate to High	Moderate	Keep	Existing site.
	Mink Creek	MC-01	Existing prior to 2014	High	High	Keep	Located upstream of controlled tile drainage structure installed summer 2016.
	Mink Creek	MC-04	New in 2014	High	High	Keep	Most downstream site.
	North Tributary	NT-01	New in 2014	High	High	Keep	Highly impacted, only site on this tributary.
	O'Gorman Agnew Drain	OAD-01	New in 2014	High	High	Keep	Highly impacted, only site on this tributary.
	(Stoqua Creek)	(SC-03)	(New in 2017)	(High)	(Moderate)	(Add)	(New site. Located upstream of controlled tile drainage structure installed summer 2016.)
	Stoqua Creek	SC-01	Existing prior to 2014	High	High	Keep	Existing, highly impacted site.
	Snake River	SNR-01	Existing prior to 2014	Low	High	Keep	Existing, most upstream site.
	Snake River	SNR-02	Existing prior to 2014	Low to Moderate	Moderate	Keep	Existing site.

Sub-Watershed	**Tributary**	**Site code**	**Status**	**Level of impact**	**Importance to sampling**	**Recommendation**	**Rationale**
Snake	(Snake River)	(SNR-05)	(Discarded in 2015)	(Moderate)	(Low)	(Discard)	(There were sites located both upstream and downstream of this site. Only moderately impacted. Access was difficult. No new data since 2014.)
	Snake River	SNR-06	New in 2014	Moderate to High	Moderate	Keep	This site reflects upstream to downstream changes along the Snake River.
	(Snake River)	(SNR-07)	(Discarded in 2015)	(High)	(Low)	(Discard)	(There were sites upstream and downstream of this site. No new data since 2014.)
	(Snake River)	(SNR-08)	(New in 2014)	(High)	(Low to Moderate)	(Discard)	(This site reflects upstream to downstream changes along the Snake River (e.g. downstream of Upper Harris Drain. However, data are missing for most sampling months in 2015 and 2016.)
	Snake River	SNR-03	Existing prior to 2014	High	High	Keep	Existing, highly impacted site. Located upstream of the Snake River Marsh.
	Snake River	SNR-04	Existing prior to 2014	High	High	Keep	Existing, highly impacted, most downstream site.
	Unnamed Creek	SC-02	Existing prior to 2014	High	High	Keep	Existing, highly impacted site. Only site on this tributary.
(Lake)	(Muskrat Lake)	(MLK-01)	(Existing prior to 2014)	(High)	(High)	(Keep)	(Critical site for establishing long-term trends in nutrients within Muskrat Lake.)

[a] Sites not included directly in the current report are listed in brackets.

4.3 Recommendations for sampling frequency

From 2014-2017, the sampling campaign typically began in April or May and concluded in September or October of each year with grab samples collected monthly from each site. This report focused on samples collected from May to September because data were typically available during this time period for most field sites, whereas April and late October data were not available for all years. Careful consideration should be given before altering the sample campaign in future years as this would affect the comparability with data from previous years. Grab samples are point-in-time estimates that provide a snapshot of concentrations of nutrients and total suspended sediments. Peaks in concentrations are expected to occur in pulses following rain events and therefore concentrations may be variable even within a short time scale. Despite the potential for variation, data from 2014-2017 clearly demonstrated that a number of sites are highly nutrient enriched.

Recommendations:

1. Monthly grab samples should continue to be collected between May and September in future years.
2. To facilitate comparison between field sites and years, samples should be taken over a short time period and at a consistent time each month (as is typically done).
3. Data from April and October were not available consistently from 2014-2017. Sampling can be more challenging during these months due to high stream flows and colder temperatures. It is reasonable to drop these months from future sampling campaigns.
4. The collection of samples from additional sites, during additional months or at a higher frequency may be warranted for future site-specific projects (e.g. to evaluate the performance of controlled tile drainage structures).

4.4 Recommendations for data quality control and management

A considerable amount of water quality monitoring data were generated from 2014-2017. Careful consideration is needed to manage, analyze, synthesize and store the data. This is particularly important due to the lag in time from sample collection, to chemical analysis and reporting by MOECC, to statistical analysis and synthesis in a report. Details that seem obvious at the time of sample collection (e.g. a sample wasn't collected due to low stream flow) get lost over time. Some recommendations for ensuring data quality and making future work more efficient are below.

Recommendations:

1. Include metadata for each sampling period. For example, indicate the number of sites sampled. If any field sites were not sampled, specify why. Record conditions that might affect water quality parameters (e.g. recent rainfall, low water flow, algal blooms). A checklist could be included with field notebooks.
2. Check that the information submitted to MOECC with water samples is correct. One challenge in sorting through the data was that field site codes and field site descriptions were sometimes conflicting. Be consistent with site codes. For example, OAD-01, 0AD-01, OAD-O1 and OAD01 are "read" as four different sites in Excel.
3. Import text files from MOECC reports into Excel when they are received. Verify that the data are complete and note any values that appear to be outliers.
4. Store raw data and compiled data in a central location such as GoogleDrive. Lock master versions of the data so that they cannot be accidentally altered.
5. Consider collecting duplicate samples for 10% of all samples to demonstrate that the data are reproducible. If a reference condition approach to data analyses will be used in future years, consider taking duplicate samples from Black Creek (BLC-01) regularly. This would reduce the impact of outliers on the statistical analyses.

4.5 Considerations for improving water quality in the Muskrat Lake watershed

Nutrient concentrations were high in the Muskrat Lake watershed and this trend was consistent from 2014-2017. Action should be taken to reduce nutrient loading. Efforts to improve water quality in the Muskrat Lake watershed should be targeted and based on scientific evidence. Data from 2014-2017 clearly identified several tributaries that are highly nutrient enriched and these are good candidates for further assessment of options to reduce nutrient loading to Muskrat Lake. Nutrient enriched sites fell into two groups: 1) sites where nutrient enrichment appeared to be related to agricultural non-point sources of nutrients and 2) sites where there appeared to be a point source of nutrients and/or nutrients originating from sources other than annual crop land.

For sites where nutrient enrichment was related to agricultural activities, different types of Beneficial Management Practices (BMPs) can be explored. The Watershed Evaluation of Beneficial Management Practices program (2004-2013) was a comprehensive initiative by the Government of Canada to determine the economic and water quality impacts of several BMPs in nine watershed sites across Canada. A key finding from work in the South Nation River watershed, Ontario was that controlled tile drainage (CTD) structures dramatically reduced the loss of nutrients from fields to surface waters and reduced the export of nitrate by 65% and phosphorus by 63% (Agriculture and Agri-Food Canada, 2010). Other BMPs such as conservation tillage, vegetated buffer strips and cattle exclusion fencing have potential to improve water quality and reduce the export of nutrients to Muskrat Lake. However, their benefits were less clear than those of CTDs and in some cases there is the potential for increased export of phosphorus (Agriculture and Agri-Food Canada, 2011). Work to assess the potential effectiveness of BMPs has already begun with the installation of CTD structures along Mink Creek and Stoqua Creek. However, the effectiveness of these structures needs to be assessed.

Land use data are key in linking nutrients to their sources and to eventually implementing beneficial management practices. The AAFC Annual Crop Inventory provides useful data, especially at the watershed scale. It would be worthwhile to assess whether land use has changed since 2014. At the site level, aerial images would be useful to identify specific land use in more detail. Landowner surveys and reconnaissance may also be needed to assess patterns in crop rotation, tilling practices and the presence of tile drains.

For all sites throughout the watershed, the measurement of nutrient concentrations is an effective way to determine whether nutrients are in excess of expected background concentrations and whether they exceed thresholds for impairment. As efforts to improve water quality continue, estimates of nutrient loading may be useful. For example, several sites have little or no flowing water during late summer on occasion. This may result in data gaps or somewhat misleading data. Nutrients and total suspended sediments may become highly concentrated during periods of low flow but during these periods, movement of these compounds to Muskrat Lake is also low. Discharge measurements would allow estimates of nutrient loading to be calculated and this could help prioritization of future efforts to improve water quality.

Further information is needed for sites where there may be a point source of nutrients and/or nutrients originating from sources other than annual crop land. For example, the Cobden Wetland (MKR-03) is highly enriched in phosphorus. The nearby Cobden Water Pollution Control Plant is likely affecting water quality at this site and has the potential to be a significant source of phosphorus loading to Muskrat Lake. Planned upgrades to the plant will increase its capacity and add tertiary sewage treatment. This will reduce the number and severity of bypass events and will produce higher quality effluent with lower phosphorus concentrations. Effluent is currently discharged to an earth-bermed enclosure. However, this enclosure is a historical structure that is failing in areas and is not part of the current or future design and function of the Cobden Water Pollution Control Plant. An assessment of the Cobden Wetland could include an evaluation as to whether the berm could be optimized to retain nutrients and minimize their discharge into Muskrat Lake. Stormwater contains phosphorus from urban run-off (e.g. from lawns and roads) originating from sources such fertilizers, pet waste, soil, plant material and road salt/ alternative de-icers. The contribution of stormwater to phosphorus loading in the Cobden Wetland and Muskrat Lake is currently unknown. Finally, wetlands can be considerable nutrient sinks but can also be sources in some instances. Further research is needed to understand nutrient dynamics in the Cobden Wetland.

Recommendations:

1. Evaluate existing data from the Mink Creek and Stoqua Creek CTD structures to assess whether this BMP has been effective in reducing loads of nitrogen, phosphorus and total suspended sediments. If the CTD structures have been effective, what can be done to encourage their installation at additional sites? More comprehensive sampling may be required. Pay particular attention as to whether reactive phosphorus has decreased.
2. An overall assessment of various BMPs is needed, including their feasibility and their likelihood of improving water quality in the Muskrat Lake watershed. This should include details of current farming practices and other specific land uses at the watershed, tributary and site level. Existing data could be used to target sites and optimize efforts for new and existing local initiatives.
3. Consider measuring discharge so that estimates of nutrient loading can be calculated. These data would be useful at all 22 field sites. However, if this is not feasible consider estimating discharge at a sub-set of field sites to help prioritize locations for BMPs.
4. Further information is needed to assess sites that may have point sources of nutrients and/or nutrients originating from sources other than annual crop land. In particular, an assessment is needed for the Cobden Wetland (MKR-03).
5. Reducing nutrient loading to Muskrat Lake is essential to improving its long-term water quality. Efforts to control internal loading of phosphorus in Muskrat Lake will be costly and ineffective in the long-term without a reduction in nutrient loading from the surrounding watershed.
6. Continue efforts to educate and engage the public with simple and clear messaging. For example, the Minnesota Pollution Control Agency put together a list of ways that residents, farmers and cities can reduce nutrients in lakes and streams: https://www.pca.state.mn.us/water/15-ways-reduce-nutrients-lakes-and-streams.

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Appendix A

Table A1. Coordinates for 22 stream/river sites in Muskrat Lake watershed, Canada

Watershed	Tributary	Site code	Easting	Northing
Muskrat	Buttermilk Creek	BC-01	354318	5053859
	Muskrat River	PH-01	362174	5047911
	Muskrat River	OS-01	357146	5049780
	Muskrat River	MKR-01	354178	5053726
	Cobden Wetland	MKR-03	354082	5054143
	Muskrat River	MKR-02	344384	5066594
Snake	Black Creek	BLC-01	326225	5060307
	Upper Harris Drain	HC-01	348562	5050762
	Upper Harris Drain	HC-03	346272	5052530
	Mink Creek	MC-03	343662	5047089
	Mink Creek	MC-02	345399	5047908
	Mink Creek	MC-01	344283	5050769
	Mink Creek	MC-04	344915	5052044
	North Tributary	NT-01	345750	5052142
	O'Gorman Agnew Drain	OAD-01	345540	5051983
	Stoqua Creek	SC-01	345174	5058263
	Snake River	SNR-01	338075	5056042
	Snake River	SNR-02	343937	5052457
	Snake River	SNR-06	345506	5052002
	Snake River	SNR-03	347843	5055143
	Snake River	SNR-04	346660	5060866
	Unnamed Creek	SC-02	348236	5058893

Table A2. Summary of data available from the Muskrat Lake watershed monitoring network from 2014-2017. Green boxes refer to data used in this report, blue boxes refer to data not used and yellow boxes represent missing data.

Sub-Watershed	Tributary	Site code	2014							2015							2016							2017								
			4	5	6	7	8	9	10	4	5	6	7	8	9	10	4	5	6	7	8	9	10	2	3	4	5	6	7	8	9	10
Muskrat	Buttermilk Creek	BC-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟦
	Harlow Trail Creek	HT-01	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Muskrat River	PH-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Muskrat River	OS-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Muskrat River	MKR-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Cobden Wetland	MKR-03	🟦	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟩	🟦
	Muskrat River	MKR-02	🟦	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
Snake	Black Creek	BLC-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦
	Upper Harris Drain	HC-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦
	Upper Harris Drain	HC-02	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Upper Harris Drain	HC-03	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦
	Mink Creek	MC-03	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟦
	Mink Creek	MC-02	🟦	🟩	🟩	🟩	🟩	🟨	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Mink Creek	MC-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦
	Mink Creek	MC-04	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦
	North Tributary	NT-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨
	O'Gorman Agnew Drain	OAD-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Stoqua Creek	SC-03	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Stoqua Creek	SC-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟨	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟦	🟨	🟦	🟩	🟩	🟩	🟩	🟩	🟦
	Snake River	SNR-01	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Snake River	SNR-02	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟦
	Snake River	SNR-05	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Snake River	SNR-06	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨
	Snake River	SNR-07	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Snake River	SNR-08	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟨	🟨
	Snake River	SNR-03	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Snake River	SNR-04	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟩	🟩	🟩	🟩	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
	Unnamed Creek	SC-02	🟦	🟩	🟩	🟩	🟨	🟩	🟦	🟦	🟩	🟩	🟨	🟨	🟩	🟦	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟦
Lake	Muskrat Lake	MLK	🟨	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟦	🟦	🟦	🟦	🟨	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟦	🟨

Table A3. List of parameters measured in water samples

Category	Parameter	MOECC method	Method detection limit (MDL)
Category	Alkalinity	PHALCO3218	2.5 mg/L CaCO3
	Carbon; dissolved inorganic	DCSI3370	1 mg/L
	Carbon; dissolved organic	DCSI3370	0.5 mg/L
	Conductivity	PHALCO3218	5 µS/cm
	pH	PHALCO3218	none listed
	Solids; dissolved	TSD3188	50 mg/L
	Solids; suspended (sediments)	TSD3188	2.5 mg/L
	Solids; total	TSD3188	50 mg/L
Major Nutrient Fractions	Nitrogen; ammonia + ammonium	DISNUT3364	0.01 mg/L
	Nitrogen; nitrate + nitrite	DISNUT3364	0.025 mg/L
	Nitrogen; nitrite	DISNUT3364	0.005 mg/L
	Nitrogen; total	TOTNUT3516	0.05 mg/L
	Nitrogen; total Kjeldahl	TOTNUT3516	0.05 mg/L
	Phosphorus; phosphorus	DISNUT3364	0.0025 mg/L
	Phosphorus; total	TOTNUT3516	0.005 mg/L
Metals	Aluminum	MET3497	2 µg/L
	Barium	MET3497	0.1 µg/L
	Beryllium	MET3497	0.1 µg/L
	Bismuth	MET3497	5 µg/L
	Cadmium	MET3497	0.8 µg/L
	Calcium	MET3497	0.05 mg/L
	Chromium	MET3497	1 µg/L
	Cobalt	MET3497	1 µg/L
	Copper	MET3497	0.5 µg/L
	Hardness	MET3497	1 mg/L
	Iron	MET3497	3 µg/L
	Lead	MET3497	7 µg/L
	Lithium	MET3497	5 µg/L
	Magnesium	MET3497	0.01 mg/L
	Manganese	MET3497	0.5 µg/L
	Molybdenum	MET3497	2 µg/L
	Nickel	MET3497	2 µg/L
	Potassium	MET3497	0.02 mg/L
	Silicon; reactive silicate	DCSI3370	0.1 mg/L
	Silver	MET3497	9 µg/L
	Sodium	MET3497	0.02 mg/L
	Strontium	MET3497	0.3 µg/L
	Tin	MET3497	9 µg/L
	Titanium	MET3497	0.5 µg/L
	Uranium	MET3497	3 µg/L
	Vanadium	MET3497	0.5 µg/L
	Zinc	MET3497	2 µg/L
	Zirconium	MET3497	1 µg/L

Table A4. Major fractions of nutrients and solids/sediments

	Fraction	Abbreviation	Description
Phosphorus (P)	Reactive phosphorus	RP	Includes orthophosphate and other types of reactive phosphorus. These are the most available types of P for algae and plants.
	Total phosphorus	TP	All forms of P including organic, inorganic, particulate and dissolved.
Nitrogen (N)	Ammonia + Ammonium	NH_3 + NH_4^+	Sources include nitrogen fixation, decomposition and fertilizers/manure. Converted to nitrate.
	Nitrite	NO_2^-	Intermediate form in the conversion of ammonium to nitrate. Generally found at low concentrations. Unstable and converted to NO_3^-.
	Nitrate + Nitrite	NO_3^-	Main form of inorganic N in surface waters. Elevated concentrations indicate nutrient pollution.
	Total Kjeldahl Nitrogen	TKN	Laboratory measurement of organic N, NH_3 + NH_4^+.
	Total Nitrogen	TN	Sum of nitrogen forms (TKN + NO_2^- + NO_3).
Solids	Dissolved Solids	DS	Includes calcium, chlorides, nitrate, phosphorus, iron, sulfur and other ion particles smaller than 2 μm.
	Total Suspended Solids/Sediments	TSS	Includes silt and clay particles, algae, fine organic debris and other particulate matter.
	Total Solids	TS	Sum of dissolved and suspended solids.

About the Author

Dr. Rebecca Dalton is an ecotoxicologist and freshwater biologist with expertise in assessing the effects of human activities on aquatic ecosystems. Rebecca's research has focused on assessing the effects of chemicals and other stressors on aquatic ecosystems such as streams, rivers, lakes and wetlands through laboratory, mesocosm (e.g., artificial pond) and watershed scale studies. Rebecca has Ph.D. and M.Sc. degrees in Biology with a specialization in Chemical and Environmental Toxicology from the University of Ottawa and Carleton University respectively. She also has a H.B.Sc. degree in Biology with Environmental Science from the University of Western Ontario. Rebecca completed a Postdoctoral Fellowship in Ecotoxicology at Carleton University in 2017 and now works as a Senior Evaluator in the Ecological Assessment Division of Environment and Climate Change Canada. Rebecca is passionate about science and volunteers many hours towards professional service. In addition to publishing her own research in international peer-reviewed journals, Rebecca serves as a peer reviewer for multiple scientific journals. Rebecca is actively involved with several scientific organizations, most notably with the Society of Environmental Toxicology and Chemistry, where she has taken on a number of leadership roles at the provincial level. In her spare time, Rebecca enjoys spending time at her family cottage on the Ottawa River.