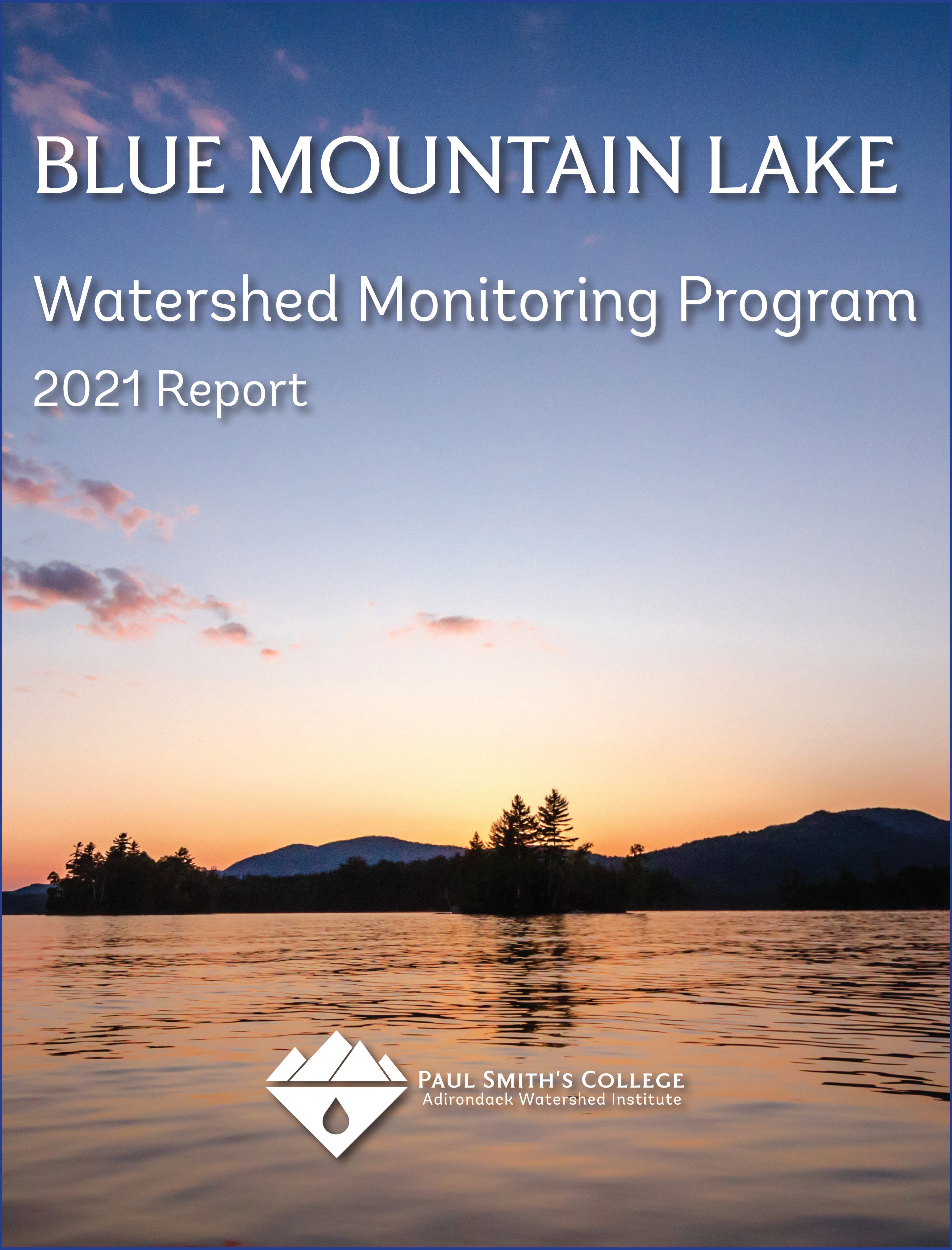
BLUE MOUNTAIN LAKE

Watershed Monitoring Program

2021 Report



PAUL SMITH'S COLLEGE
Adirondack Watershed Institute

Financial support for the Blue Mountain Lake watershed monitoring program is provided by Blue Mountain Lake Water Watch, an organization dedicated to the preservation of the quality of water in Blue Mountain Lake. Funding for the in-stream data recorders was provided by the Blue Mountain Lake Fund. The narrative and results presented in this report were produced by Brendan Wiltse, Corey Laxson, Elizabeth Yerger, Lija Treibergs, and Daniel Kelting. Field and laboratory assistance was provided by Hunter Favreau, Danielle Ulrich, Isaac Stoufer, Joline Hall, and Connor Vara. Paul Smith's college provided office and laboratory space.

Brendan Wiltse*
Elizabeth C. Yerger
Lija Treibergs
Joline Hall
Connor Vara
Corey Laxson
Daniel L. Kelting

Paul Smith's College Adirondack Watershed Institute
PO Box 265
Paul Smith's, NY 12970
www.adkwatershed.org

*Corresponding Author: Brendan Wiltse, bwiltse@paulsmiths.edu (518) 327-6460

Please cite this report as: Wiltse, B., Yerger, E.C., Treibergs, L.A., Hall, J., Vara, C., Laxson, C.L., and Kelting, D.L. 2021. Blue Mountain Lake Watershed Monitoring Program, 2021 Report. Paul Smith's College Adirondack Watershed Institute.

Table of Contents

Report Summary

The Blue Mountain Lake watershed has been monitored by the Adirondack Watershed Institute in one form or another for the past 25 years. In 2015, the program was changed from one that performed nutrient analysis on specific segments of two tributaries (Museum and Potter Brooks); to one that takes a more comprehensive look at the five major streams flowing into the lake. The goal of this enhanced program is to gain a better understanding of nutrient loading to the lake and the impact of road deicers. To support the upgraded program, each stream was instrumented with stage recorders and in-stream conductivity meters. This report covers the past six years of monitoring.

1. Correlation between the stream height recorded by the Levelogger and discharge for the study streams was excellent, with coefficient of determination values (R^2) ranging from 0.89 to 0.99. With these relationships we were able to successfully quantify the volume of water entering Blue Mountain Lake at 30 minute intervals from May 2015 through September 2021.

2. The stream water entering Blue Mountain Lake tended to be acidic in the early spring, and circumneutral the remainder of the field season. This is a common pattern in many Adirondack watersheds and is primarily related to acidic snow melt. The streams typically had moderate acid neutralizing ability.

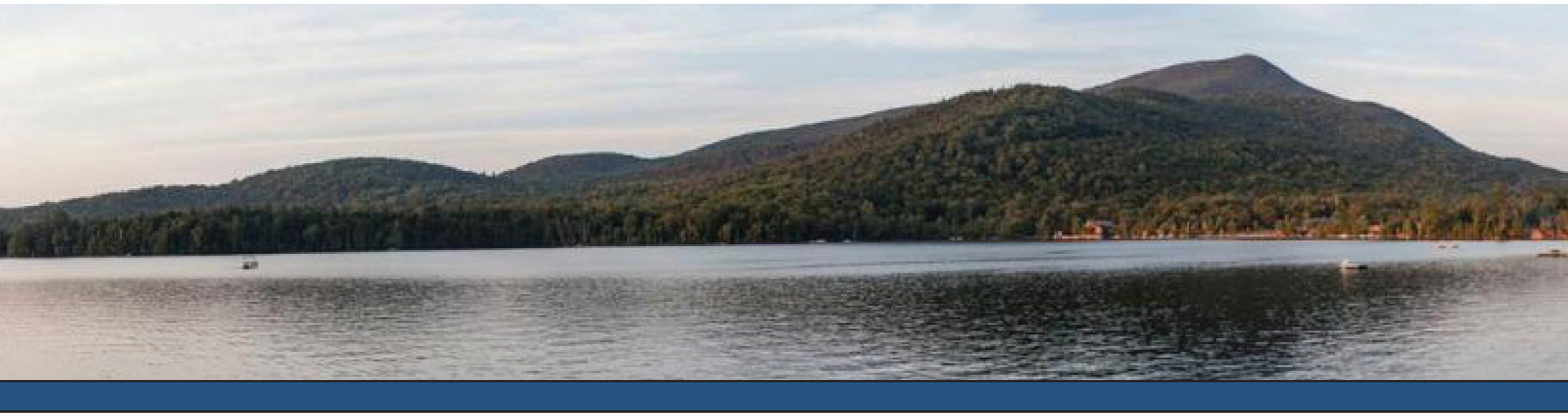
3. The greatest export of phosphorus and nitrate came from Museum Brook. The elevated concentrations are almost certainly related to the permitted discharge from the Adirondack Museum. Overall, nutrient export to the lake is quite low from all of the tributaries (including Museum Brook) and is within the range of nutrient export observed for least impacted streams in the AWI database.

4. The eastern side of the Blue Mountain Lake watershed is significantly influenced by road salt. In general, export of sodium and chloride to the lake increases with road density in the sub watersheds.

5. Correlation between the in-stream conductivity measurements recorded by the Hobo conductivity meters and chloride concentration for the salt impacted watersheds was excellent, with coefficient of determination values (R^2) ranging from 0.82 to 0.96. The successful development of the conductivity – chloride model allowed us to quantify salt export from the Blue Mountain Lake sub-watersheds at 30 minute intervals.

6. Beaver Brook and Minnow Brook West are the two sub-watersheds that have no salted roads, and thus serves as a good benchmark for the non-impacted condition. The median export coefficient of chloride from these watersheds ranged from 4 to 5 g/ha/day, which is similar to other non-impacted watersheds in the AWI database (2-10 g/ha/day; AWI unpublished data). Conversely, sub-watersheds of Blue Mountain Lake with salted roads experienced median chloride exports that were 25 to 100 times greater than the least-impacted condition.

7. We observed a clear signal that a significant proportion of the salt applied to roadways is migrating to the groundwater. The concentration of chloride increased substantially during the low flow period of summer and early autumn in all three of the salted watersheds. Because streams are supplied primarily by ground water during this time, increased concentration during base flow periods are indicative of groundwater contamination.



Introduction

Water Watch and the Paul Smith's College Adirondack Watershed Institute have been monitoring the Blue Mountain Lake watershed since 1993 in a semi-ongoing study referred to colloquially as the Brooks Study (Martin 1994). Historically, monitoring has focused primarily on analysis of nutrient concentration in specific segments of Museum and Potter Brooks in an attempt to isolate the influence of current and proposed development in those watersheds. In 2015, the approach changed from segment analysis on these two streams to a more comprehensive study that included all of the major tributaries to the lake. The goal of this retooled monitoring program was to develop a more complete understanding of nutrient inputs into the lake and the impacts of road salting to the lake and its major tributaries. Road salt, although previously not monitored, has become a pollutant of concern across the northern hemisphere, with increasing focus and concern within the Adirondack Region (Kelting et al. 2012; Regalado and Kelting 2015; Sutherland et al. 2018; Wiltse et al. 2019). Blue Mountain Lake is one of many salt impacted lakes in the Adirondacks; recent analysis has demonstrated that chloride concentration in the lake is 87 times greater than background levels (Laxson et. al 2019).

To bolster the new monitoring effort, stage recorders and in-stream conductivity meters were installed at the pour point of the five major sub watersheds and supported by regular water quality analysis. The specific objectives of this study were to: (1) document the water quality characteristics of the five major tributaries of the lake, (2) compare nutrient export from least impacted and developed sub-watersheds, (3) quantify the export of saline runoff from salted roads to the lake, and (4) assess how nutrient and salt export have changed over time.

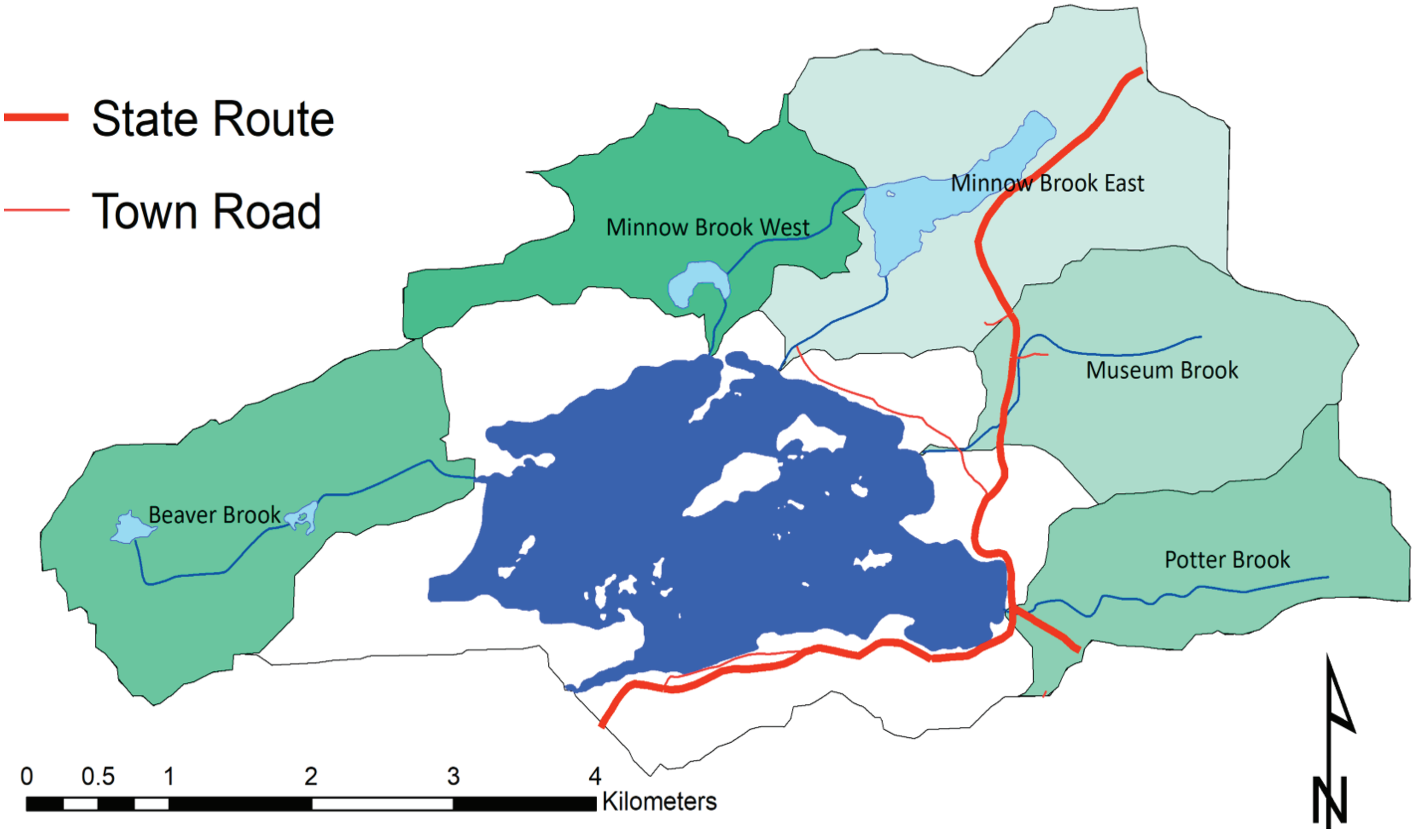


Figure 1. The Blue Mountain Lake Watershed including the major roadways and sub-watersheds monitored in this study.

Understanding Watershed Data

Watersheds

A watershed is an area of land that drains all the streams and precipitation to a common outlet such as the outflow of a lake, the mouth of a bay, or any defined point along a stream. The word watershed is derived from the German word wasser scheidend, which translates to "water parting", and is often used synonymously with terms like catchment basin or drainage basin. Because a watershed includes surface and groundwater, soils, bedrock, vegetation, and humans, it is considered a fundamental unit for studying water movement and human impacts on water resources.

One of the main functions of a watershed is to temporarily store and transport water from the terrestrial landscape to a receiving water body. The composition of the watershed can have numerous effects on the quantity and quality of the water during the storage and transport process. For example, water that discharges from a developed watershed with a high density of impervious surfaces will be substantially different in its content and flow characteristics than the water that is exported from a neighboring forested watershed.

Stream Discharge

Stream discharge is the total volume of water moving through a specific location per unit of time, typically in units of cubic meters per second (m^3/s). Stream discharge at any given point in time is dependent on a number of factors, including precipitation, watershed size, groundwater exchange, evaporation, evapotranspiration, and stream modifications such as dams and irrigation. Discharge is an essential measurement for understanding watersheds. Since streams are essentially conveyors of water, raw materials, and energy, knowledge of the rate of movement is vital for calculating inputs to the lake as well as losses from the watershed.

Stream discharge at a given location is the product of its velocity (length of travel per unit time) and cross-sectional area, and is described using the formula:

$$Q = V \times D \times W$$

where:

Q = stream discharge (m^3/s)

V = velocity (m/s)

D = stream depth (m)

W = stream width (m)

Stream discharge can be monitored continuously by using a rating curve. In hydrology, a rating curve is a graph of stream discharge versus stream height (known as stage height). The first step in developing a rating curve is to measure stage height and corresponding stream discharge numerous times over a variety of stream conditions. The second step is to develop a mathematical relationship between stage height and stream discharge. The final step is to measure only stage height, and use the rating curve to calculate the discharge (Kennedy 1984).

Export / Loading

Export is the amount of a substance (chemical, nutrient, sediment, etc.) that is lost from the watershed and imported to a receiving waterbody. Export is expresses in units of weight per time, typically kg/year or g/day. The terms loading and export are synonymous, but are intended to describe the position of the observer. Loading is used when the question relates to the amount of material entering the lake per time. For example, lake managers are often concerned about nutrient loading from developed or agricultural watersheds. Alternatively, the term export is used if the question deals with the amount of substance leaving the watershed. For example, land managers may be interested in the amount soil leaving an agricultural watershed each season.

The total amount of material exported from a watershed is a function of its size. In order to compare export between watersheds the difference in size must be factored out. Areal export coefficients (g/ha/day) are calculated by dividing the daily export by the surface area of the sub-watersheds. Areal export coefficients provide a better comparison of chemical flux between watersheds because the factor of watershed size is normalized.

Table 1. Assessment of surface water acidity based on pH.

Lake acidity	Status
pH less than 5	Acidic: Critically Impaired
pH 5.0 – 6.0	Acidic: Threatened
pH 6 – 6.5	Acidic: Acceptable
pH 6.5 – 7.5	Circumneutral: non-impacted
pH >7.5	Alkaline: non-impacted

Table 2. Assessment of acid buffering ability based on alkalinity.

Alkalinity (mg/L)	Buffering Ability	Acidification status
< 0	none	acidified
0 - 2	low	extremely sensitive
2 - 10	moderate	moderately sensitive
10 - 25	adequate	low sensitivity
> 25	high	not sensitive

Acidity: pH and Alkalinity

In chemistry, pH is used to communicate the acidity of a substance. Technically pH is a surrogate measure of the concentration of hydrogen ions in water. Hydrogen ions are very active, and their interaction with other molecules determines the solubility and biological activity of gases, nutrients, and heavy metals; thus pH is considered a master variable for its influence on chemical processes and aquatic life. pH exists on a logarithmic scale from 0-14, with 7 being neutral. pH values less than 7 indicate increasing acidity, whereas pH values greater than 7 indicate increasingly alkaline conditions. Because pH exists on a logarithmic scale a decrease in 1 pH unit represents a 10 fold increase in hydrogen ion activity. Surface water can become acidified when they are influenced by organic acids from wetlands and bogs or when acidic precipitation falls on a poorly buffered watershed (Driscoll et al. 2003). In the Adirondacks acidification status can be assessed from pH values based on the guidelines outlined in Table 1. pH is measured in the field and the laboratory with a pH meter, a specialized electrode that generates voltage proportional to the amount of hydrogen ions in solution.

Alkalinity (or acid neutralizing ability) is the capacity of a water body to neutralize acids and thereby resist changes in pH. Alkalinity plays a major role in whether or not surface water is impacted by acid deposition. Alkalinity is a function of the amount of calcium carbonate in the water which is derived mainly from the watershed. Most Adirondack watersheds exist on slowly weathering granitic bedrock that has a slow rate of calcium carbonate generation, and therefore lower acid neutralizing ability. The opposite is true for watersheds that exist on bedrock derived from ancient ocean deposits, such as limestone or dolomite. Soil depth also plays a role in acid neutralizing capacity, with deeper soils offering more buffering ability than shallower soils.

Alkalinity is quantified by analyzing the amount of dilute acid required to lower the pH of a lake sample to 4.3 pH units, the point at which all of the carbonate and bicarbonate alkalinity is consumed and the buffering ability of the sample has been fully depleted. The acid neutralizing ability of a lake can be generally assessed following the parameters presented in Table 2. The results of this analysis are reported in mg/L of $CaCO_3$.

Phosphorus

Phosphorus is of major importance to the structure and metabolism of all organisms. However, in freshwater systems it exists in relatively small amounts compared to other essential nutrients such as carbon, hydrogen, oxygen, and sulfur. Therefore, phosphorus is typically the limiting nutrient in aquatic systems and the addition of extra phosphorus allows production to increase greatly because all other essential elements are typically available in excess (Schindler 1974, Wetzel 2001). Natural weathering releases phosphorus from rocks and soils, and it also enters our watersheds in fertilizers, human waste, and atmospheric deposition. Phosphorus exists in a number of forms in aquatic systems, including readily available dissolved phosphate, and organically and inorganically bound phosphorus. Total phosphorus is all of the forms of phosphorus combined and serves as an important indicator of overall trophic status of a lake. Generally speaking, lakes of low productivity (oligotrophic) have total phosphorus concentrations less than 10 µg/L, while highly productive lakes (eutrophic) have total phosphorus concentrations greater than 20 (NYS DEC assessment criteria).

Nitrogen

Nitrogen is an essential element that can be the limiting nutrient for algal productivity in lakes, but it is generally the second most limiting nutrient after phosphorus. Nitrogen does not typically receive the attention that phosphorus does because it is more abundant and has a variety of sources in the watershed. Nitrogen exists in many forms in surface water, including inorganic and organic molecules. The inorganic forms include nitrogen gas (N_2), nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+). Nitrogen gas is the most abundant form of nitrogen; it makes up 78% of the earth's atmosphere and readily dissolves into water. This gaseous form of nitrogen is unusable by the vast majority of organisms, only some species of cyanobacteria can "fix" this form of nitrogen into a form they can utilize, giving cyanobacteria a competitive edge in environments with limited usable nitrogen. Plants and algae can assimilate the other forms of inorganic nitrogen. Nitrate, nitrite, and ammonium enter water though precipitation, atmospheric deposition and surface runoff. These inorganic forms of nitrogen are continually cycled through bacterial decomposition of organic matter. Concentrations may become elevated due to anthropogenic sources such as waste water discharge, agricultural runoff, and urban development. Organic nitrogen represents the stores of nitrogen that are locked up in organic molecules, such as proteins, amino acids, urea, and living and decomposing organisms. Organic nitrogen is not readily available for algal productivity until bacteria decompose the organic material and excrete usable forms of inorganic nitrogen. Total nitrogen is a measure of all of the non-gaseous inorganic and organic forms of nitrogen in the water.

Conductivity

Conductivity is a measurement of the ability of a water sample to conduct electricity. Pure H_2O is a poor conductor of electricity. The ability of water to conduct electricity increases as the concentration of dissolved ions in the water increases. Thus, conductivity is considered a strong indicator of the amount of dissolved ions in water. Typically the stream conductivity in an undeveloped Adirondack watershed is in the range of 10-30 µS/cm (AWI unpublished data). Elevated conductance may be indicative of road salt pollution, faulty septic systems, or the influence of bogs and wetlands in the watershed. Conductivity is a useful surrogate when the relationships between ion concentrations and conductivity are known. For example, conductivity can be used to estimate sodium and chloride concentrations in streams as carried out by Daley et al. (2009), and this report.

Sodium and Chloride

Surface water in the Adirondack region has naturally low concentrations of sodium and chloride, with median background concentrations of 0.5 mg/L and 0.2 mg/L respectively (Kelting et al. 2012). However, wide spread use of road deicers (primarily sodium chloride) have significantly increased the concentration of these chemicals in the environment. Each year approximately 98,000 metric tons of road deicers are spread across state roads in the Adirondacks (Kelting and Laxson 2014). Recent research by Kelting et al. (2012) highlighted that concentrations of sodium and chloride in Adirondack Lakes are directly proportional to the density of state roads within the watershed.

Road salt can have direct and indirect effects on aquatic ecosystems. It is clear that the direct impact of road salt on organisms is not well understood, and is highly variable across taxa. Based on laboratory studies the lethal concentration for most aquatic organisms is much higher than concentrations encountered in a lake environment. However, at times lethal concentrations can be encountered in near-road environments that receive direct run-off such as road side streams or vernal pools (reviewed by Findlay and Kelly 2011; Kelting and Laxson 2010).

High load of salt applied to NYS Route 3 in Bloomingdale, NY.

Indirect effects to aquatic systems have also been documented. For example, sodium actively displaces base cations (Ca, K, and Mg) as well as heavy metals from the soil, potentially elevating their concentration in surface waters (Kelting & Laxson, 2021). In some extreme cases, excessive road salt pollution can interfere with lake stratification due to salts effect on water density (Bubeck et al. 1971; Kjensmo 1997). Sodium and chloride impart an undesirable taste to drinking water and corrode plumbing at high concentrations, damaging appliances and releasing heavy metals into your drinking water. The NY DOH has standards of 250 mg/L for chloride and 20 mg/L for sodium for public drinking water supplies, with these values only serving as non-enforceable guidelines for private drinking water.

Methods

Lake and Watershed Characteristics

Blue Mountain Lake is located within the Town of Indian Lake in the central Adirondacks (Figure 1). The lake is 697 ha in surface area and has 44 km of shoreline. The maximum depth is 30.5 m, and the lake flushes approximately every 3.8 years. The watershed of the lake is 2,972 ha, 22% of this area is surface water. The watershed is dominated by forest cover, with 62% deciduous, 7% evergreen, and 7% mixed forest. There are 13 km of roads that pass through the watershed, 4km are local roads (county, town, local) and 9 km are state highway (Laxson et al. 2019).

The Blue Mountain watershed is drained by five major tributaries that account for 58% of the total catchment area (Table 3, Figure 1). The drainage area for Minnow Brook East represents the largest sub-watershed at 477 ha and contains a NYS road density of 0.60 km/km^2, and limited development. Analysis of the USGS topographical map (Deerland, NY) suggests that Minnow Pond, located within the Minnow Brook East sub-watershed, has two outlets at East and West Minnow Brooks. It appears to us that the pond only drains through Minnow Brook East, and would drain to the western branch of Minnow Brook only during periods of extremely high water. Therefore, we consider the 260 ha Minnow Brook West sub-watershed to represent a least-impacted condition because it does not drain salted roads and has no development. The second largest sub-watershed is Beaver Brook, another least impacted catchment on the western end of the lake. Museum and Potter Brooks are impacted by road runoff and contain a road density of 0.56 and 0.55 km/km^2 respectively. Twenty percent of the Blue Mountain Lake watershed is not drained by a specific tributary, denoted as the shoreline and adjacent uplands that are uncolored in Figure 1.

Field Sampling and Laboratory Analysis

Permanent monitoring stations were installed at the pour point (near the lake) of each of the five major tributaries on December 10th, 2014. Each station was equipped with a submersible conductivity logger (Onset, HOBO U-24), and differential pressure transducer to measure stream height (Solinist, Levelogger Edge). Both the Levelogger and the conductivity meter collect data at 30 minute intervals. Due to equipment backorder, the Levelogger did not begin collecting stream height data until May 6th, 2015. Conductivity loggers were replaced on October 17th, 2018 and again on June 24th, 2021 due to dead batteries. There were several periods of data loss over the study period due to dead batteries or other problems with the data loggers. Study streams were visited five separate times per year, roughly one month apart between May and October, with the exception of 2016 when an additional April visit was made. During each visit a stream discharge measurement was made and a water sample was collected for chemical analysis.

Table 3. Size and NYS road density of each of the Blue Mountain Lake sub-watersheds

Sub-watershed	Area (ha)	Percent of BML Watershed	Road Density (lane km/km^2)
Minnow Brook West	260	9	0
Minnow Brook East	477	16	0.60
Museum Brook	321	11	0.56
Potter Brook	256	9	0.55
Beaver Brook	374	13	0

Collecting data from the Blue Mountain Lake watershed. Clockwise from left: AWI Research Associate Elizabeth Yerger quantifying stream discharge with the Flow Tracker ADV. Underwater view of the acoustic Doppler sensor of the flow tracker. Underwater view of the PVC housing that contains the Hobo conductivity meter.

Stream discharge was measured using standard procedures developed by the US Geological Survey (Turnipseed and Sauer 2010). Cross sectional area and stream velocity were measured at ten segments across the width of each stream using an acoustic Doppler velocity meter (SonTek, Flow Tracker ADV), these measurements were then integrated into total stream discharge (m^3/second). Rating curves for each of the study streams were developed by plotting the stream discharge against the corresponding stream height recorded by the Levelogger. The rating curves were then used to calculate stream discharge at 30 minute intervals across the three year study period. Water samples were collected, preserved, and analyzed using standard methodologies. Samples were analyzed at the Adirondack Watershed Institute's Environmental Research Lab for total phosphorus (APHA 4500-P,H), nitrate+nitrite (APHA 4500 I), ammonium (Lachat: 10-107-06), total nitrogen (APHA 4500 N), chloride (EPA 300.0), sodium (EPA 200.7), alkalinity (EPA 301.2), conductivity (APHA 2510-B) and pH (EPA 9040C). All laboratory analyses included quality control (QC) measures such as check standards, blanks, matrix spikes, and duplicates that were assessed on an on-going basis.

Export Calculation

Export is the amount of a substance (chemical, nutrient, sediment, etc.) that is lost from the watershed and imported to the lake expressed as weight/time (typically weight/day). Phosphorus and nitrogen loading for each of the study streams was calculated by converting the instantaneous discharge (m^3/sec) recorded during each site visit to daily discharge (m^3/day), multiplied by that day's nutrient concentration (mg/L). For analytes that were below the limits of laboratory detection, a value equal to 50% of the detection limit concentration was entered into the calculation. Areal export coefficients (g/ha/day) were calculated by dividing the daily export by the surface area of the sub-watersheds. Areal export coefficients provide a better comparison of chemical flux between watersheds because the factor of watershed size is normalized. Differences in nutrient export between watersheds were assessed by comparing descriptive statistics, specifically the median and interquartile range.

High resolution estimates of chloride export were calculated to assess the magnitude of road salt influence in the Blue Mountain Lake watershed. We regressed the chloride concentration observed during each site visit against the electrical conductance recorded for that date and time on the in stream conductivity data loggers. The resulting calibration curve was then used to calculate chloride concentration at 30 minute intervals over the study period. Total chloride export for each 30 minute interval was then calculated as the product of stream discharge and chloride concentration and summed for each day of the study period. The magnitude of salt impact was examined by comparing areal loading coefficients between the least impacted sub-watersheds (Beaver and Minnow West) to the impacted watersheds (Museum, Potter, and Minnow East).

Results

Stream Discharge

Correlation between the stream height recorded by the Levelogger and discharge for the study streams was excellent, with coefficient of determination values (R^2) ranging from 0.89 to 0.99 (Figure 2). This indicates that the stream height explained 89 to 99% of the variability in discharge measurements. As expected, the greatest discharges were observed during winter and spring thaws, and the lowest discharges were observed during the base flow conditions of August through October (Figure 3).

Acidity

The tributaries of Blue Mountain Lake ranged from acidic to circumneutral. Generally, the lowest pH values were encountered in the spring during the acidic pulse associated with snow melt (Figure 4).

Median alkalinity values ranged from a low of 5.6 mg/L at Minnow Brook East, to a high of 14.2 mg/L at Potter Brook. Overall, we found significant differences in pH between the sites (Figure 4. Kruskal Wallace: H= 12.90, p = 0.01, df = 4). Post-hoc comparisons between sites using a Wilcoxon rank sum test identified that Minnow Brook West had significantly higher pH than Minnow Brook East and Potter Brook, there were no significant differences across all other comparisons.

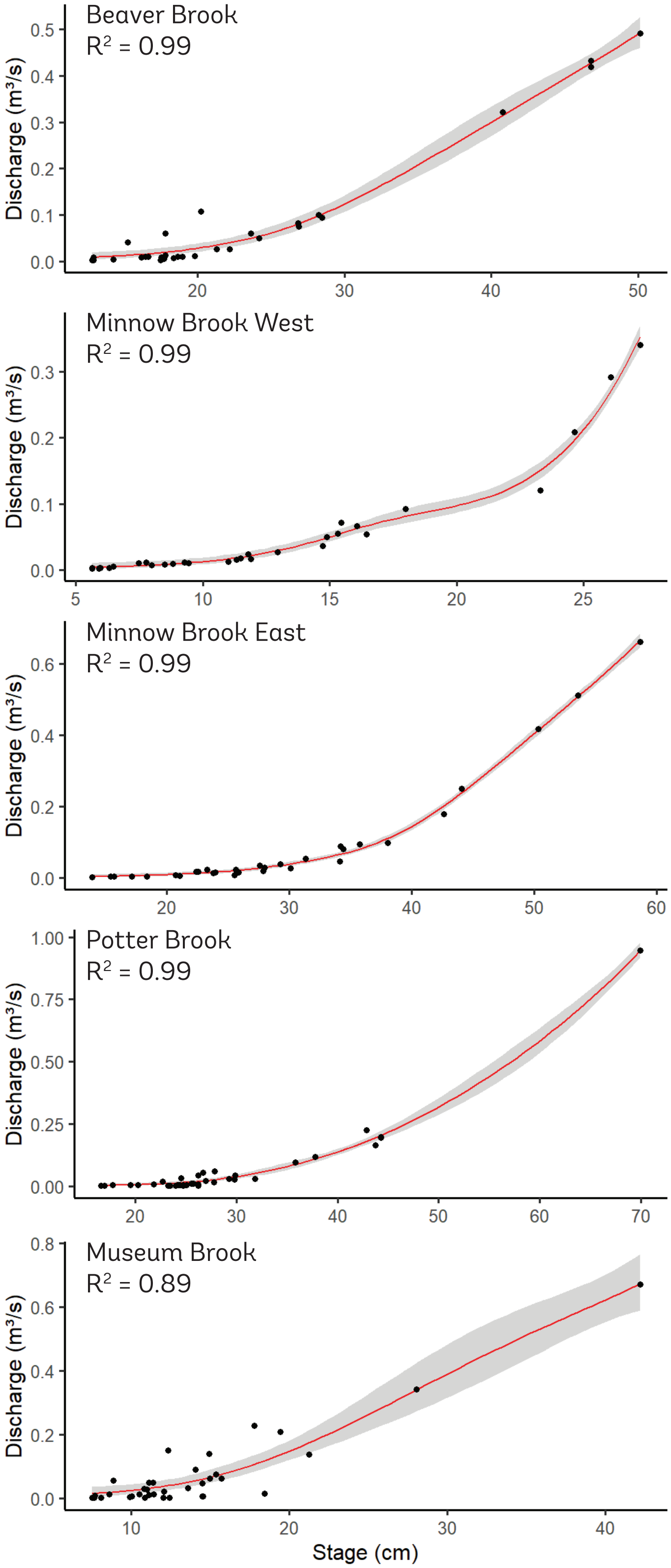


Figure 2. Stage discharge curves for each sub-watershed. Curves were developed using generalized additive models (GAMs). The red lines depict the model prediction, grey shaded areas represent the 95% confidence interval of the prediction.

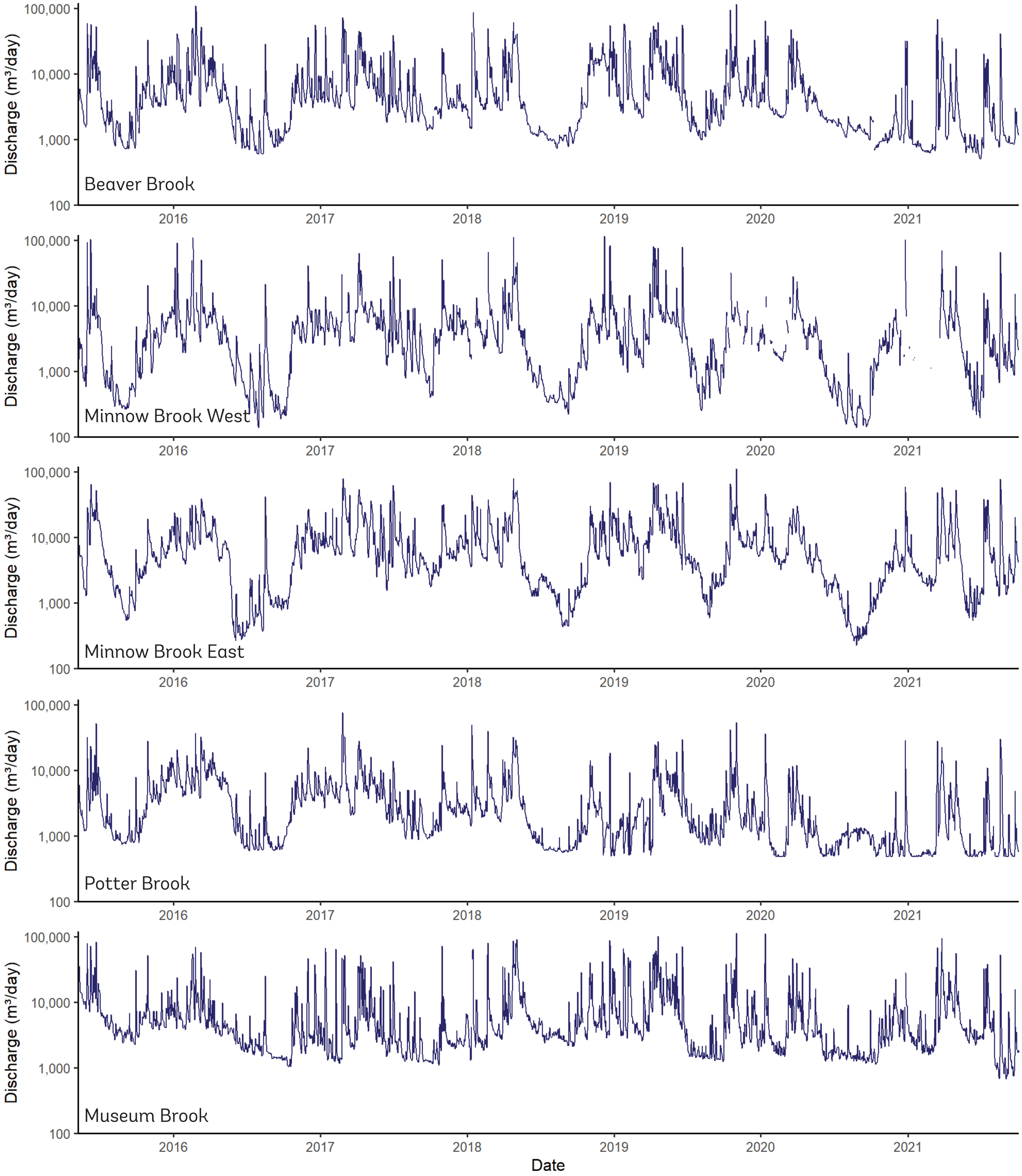


Figure 3. Daily discharge from the five study watersheds, May 2015 to September 2021. Year is positioned at January 1. Note that the y-axis scale is logarithmic.

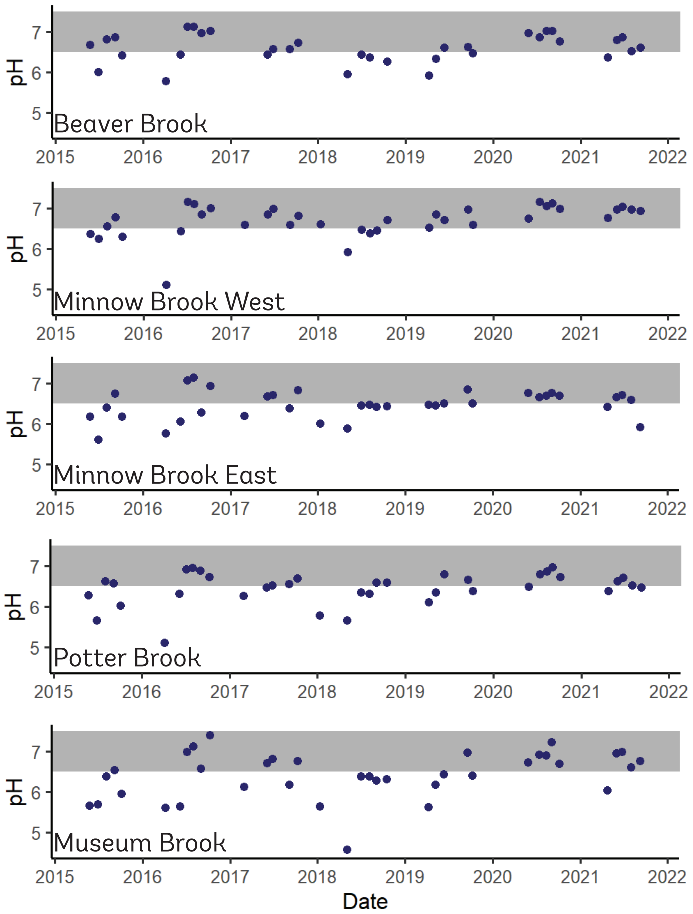


Figure 4. Stream pH during each of the site visits, 2015-2021. Shaded areas denote circumneutral condition, unshaded areas denote acidic conditions.

Nutrients

Phosphorus

Total phosphorus concentration during the study period was similar across all sites, with median values ranging from 6 µg/L in both Minnow Brook East and Potter Brook, to 9 µg/L in both Beaver Brook and Minnow Brook West. Museum Brook had the highest observed concentration at 207 µg/L. Both the median and range of concentration observed across all sites tended to be lower during the current study period (July 2018 to September 2021) as compared to the prior study period (May 2015 to June 2018) (Figure 5).

The phosphorus export coefficients were similar across sites and generally lower in the current study period. Museum Brook had the highest observed export coefficient at 1,343 mg/ha/day (Figure 5).

Nitrogen

Nitrate concentration was similar across all sites (median 51-81 µg/L) with the exception of Beaver Brook which had a median concentration of less than 1 µg/L. Median values and interquartile ranges were lower in the recent study period for Potter Brook and Museum Brook.

The nitrate export coefficients were highest in Museum Brook (median 337 mg/ha/day) and lowest in Beaver Brook (median 26 mg/ha/day). As with nitrate concentration, the export coefficients in the current study period were lower across all sites.

Road Salt Contaminants

Sodium

Sodium concentration during the current study period in the least impacted watersheds were nearly indistinguishable, with median concentrations of 0.9 mg/L for Museum Brook West and 1.0 mg/L for Beaver Brook. Sodium concentration was substantially higher in watersheds with salted roads. Museum Brook and Minnow Brook East both had similar concentrations, 23.9 and 23.0 mg/L, respectively. Potter Brook had an intermediate concentration at 18.3 mg/L. Of the impacted watersheds, Minnow Brook East had the least variation in sodium, with 50% of the observations ranging from 21.3 to 24.7 mg/L (Figure 7).

The total mass of sodium exported to the lake was similar between the two least impacted watersheds, with median exports of 1.4 kg/day at Beaver Brook and 1.3 kg/day at Minnow Brook West during the current study period. Sodium export was markedly higher in salted watersheds and was greatest in Minnow Brook East and Museum Brooks, where median export was approximately 54 kg/day. The maximum daily export was observed in Minnow Brook East at 695 kg/day (Figure 7).

When corrected for watershed area, the export of sodium from the least impacted watersheds was similar, and ranged from 4 to 5 g/ha/day. The greatest export coefficient was found in the Minnow Brook East watershed at 1,456 g/ha/day. Median export coefficients across the impacted watersheds ranged from 61 g/ha/day in Potter Brook to 167 g/ha/day in Museum Brook (Figure 7).

Chloride

Correlation between the in-stream conductivity measurements recorded by the Hobo conductivity meters and chloride concentration for the salt im-

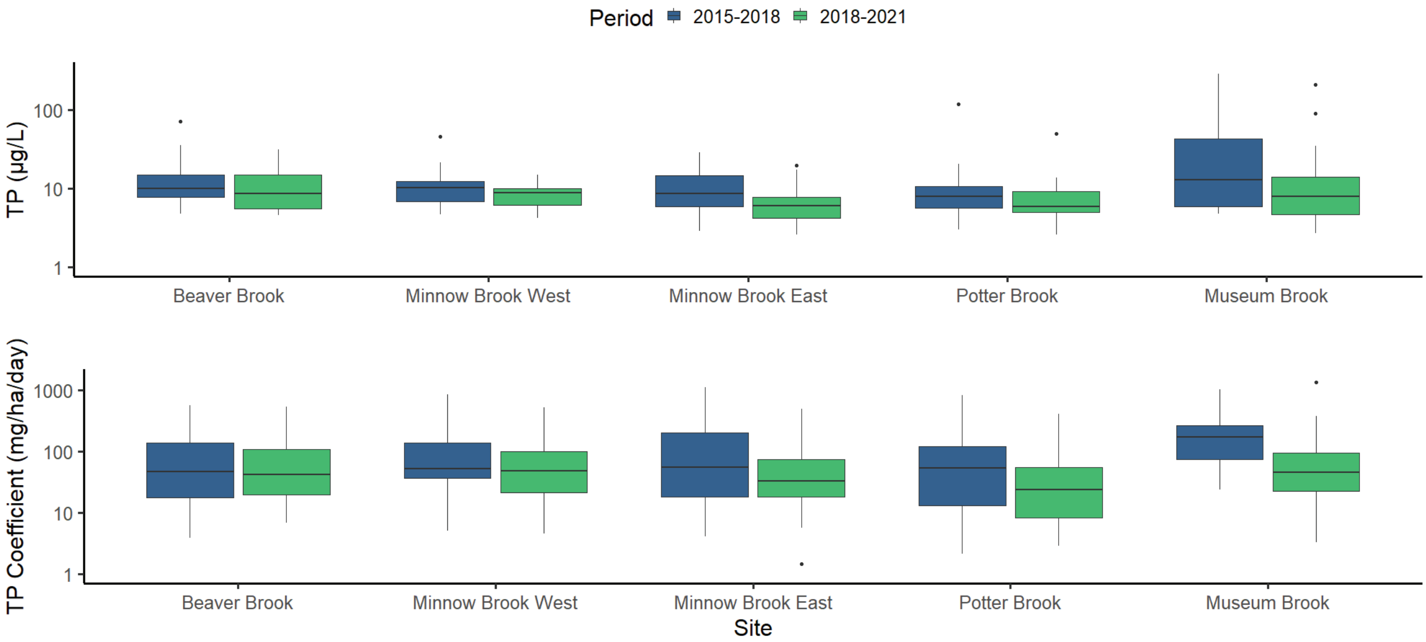


Figure 5. Boxplots of stream concentration and watershed export coefficients of total phosphorus from the five sub-watersheds of Blue Mountain Lake. Data is grouped based on study period. Note that the y-axis scale is logarithmic.

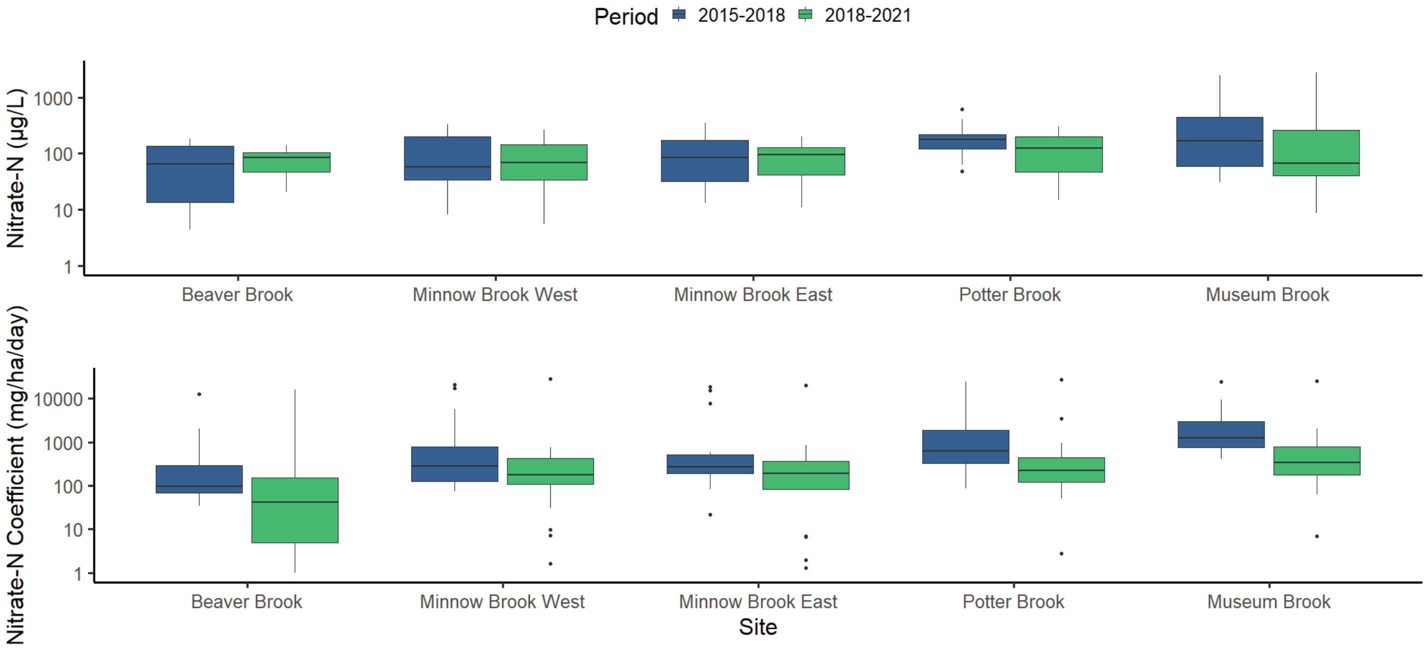


Figure 6. Boxplots of stream concentration and watershed export coefficients of nitrate-N from the five sub-watersheds of Blue Mountain Lake. Data is grouped based on study period. Note that the y-axis scale is logarithmic.

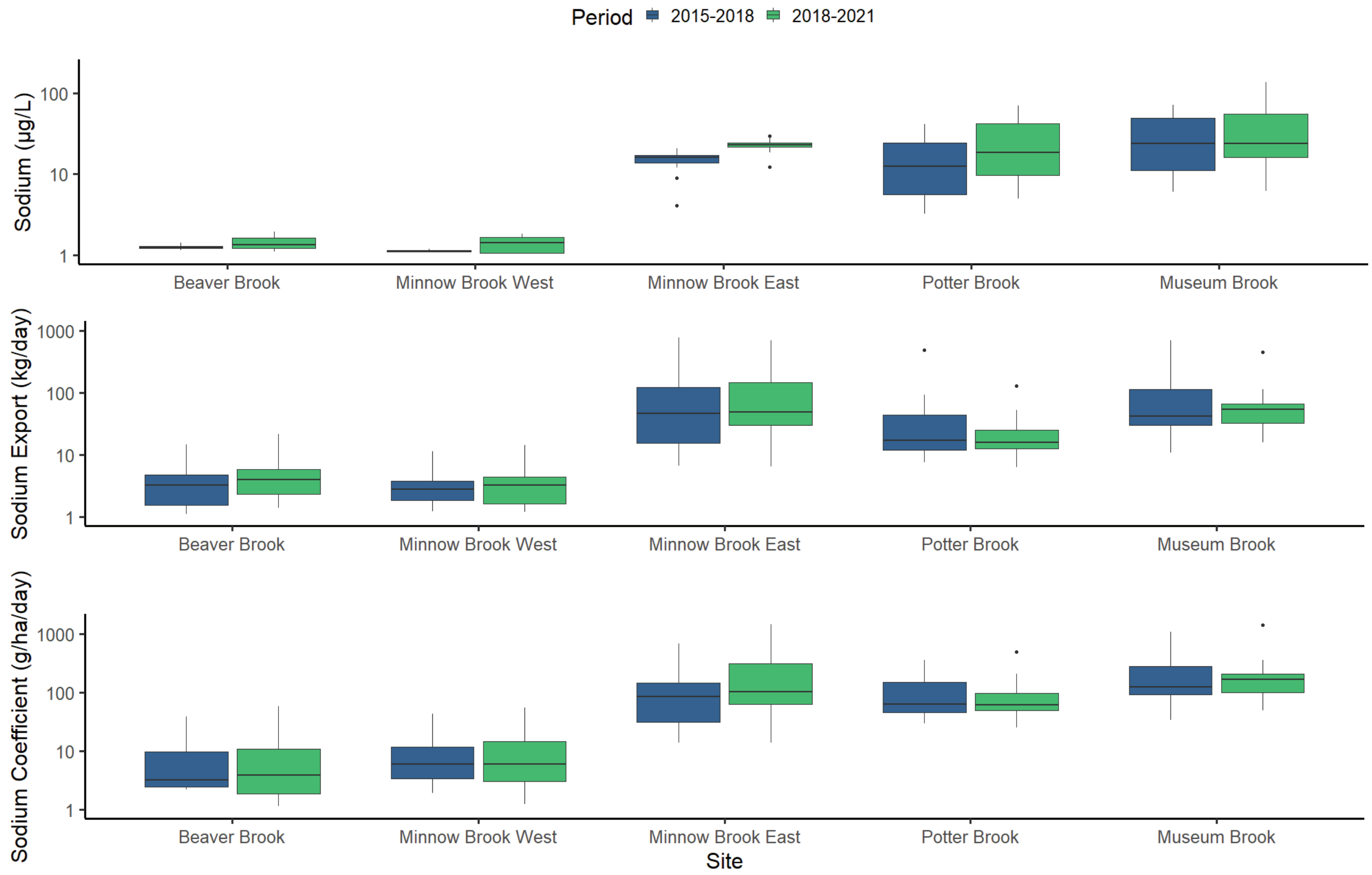


Figure 7. Stream concentration and watershed export of sodium from the five sub-watersheds of Blue Mountain Lake. Shaded boxes denote sub-watersheds that are impacted by road runoff. Data is pooled from the entire three year study, 2015 – 2018, n= 18. Min, Q1,Median, Q3, and Max follow the description in Table 4.

pacted watersheds was excellent, with coefficient of determination values (R^2) ranging from 0.82 to 0.96, indicating that 82 to 96% of the variability in chloride concentration is explained by in-stream conductivity. In contrast, the models for the least impacted watershed explained 11% of the variation in chloride (R^2 = 0.11). While the models for the least impacted sites have greater relative uncertainty they were both significant at an alpha of 0.10. Additionally, the models perform better at low concentrations than when pooling data across all sites, as was done in the initial study (Laxson et al. 2018). The much larger dataset, encompassing both study periods, also contributes greater statistical power (Figure 8).

Conversion of in-stream conductivity to chloride concentration allowed us to observe the movement of road salt contaminants into the lake at 30 minute intervals over the six-year study period (Figure 9). Chloride concentration in the least impacted streams exhibited little variation around the median concentration of 0.5 mg/L in Beaver Brook and 0.4 mg/L in Minnow Brook West. Median chloride concentrations in the streams of the salted watershed were 56 to 100 times greater, ranging from 28 mg/L in Potter Brook to 50 mg/L in Museum Brook. Typically, the highest persistent chloride concentrations in the impacted watersheds occurred in the summer and early autumn. Short duration spikes in chloride concentration were also observed during the winter and spring in association with runoff events (Figure 9).

Concentrations in the non-impacted sites never exceeded thresholds set by New York State Department of Environmental Protection (NYS DEC), the Canadian government, or US Environmental Protection Agency (US EPA) for the protection of aquatic life. Minnow Brook East mostly stayed below the thresholds but did exceed the threshold set by NYS DEC during the summer of 2020 during a period of particularly low discharge. Museum Brook and Potter Brook were frequently above the NYS DEC threshold. Potter Brook regularly exceeded the Canadian threshold for aquatic life but never for the full 7-day exposure period. Potter Brook exceeded the USA EPA threshold once but not for the 4-day exposure period. Museum Brook exceeded the Canadian threshold for >7 days in March 2018, March 2019, & February, July, August, and September 2020. Museum Brook exceeded the EPA threshold on a total of 8-days but never for >4 days continuously (Figure 9).

The total mass of chloride exported to Blue Mountain Lake from the two least impacted streams during the current study period was similar, with median exports ranging from 0.9 kg/day in Minnow Brook West to 1.2 kg/day in Beaver Brook. Chloride export from the salt impacted watersheds was considerably higher, and ranged from 32 k g/day at Potter Brook to 187 kg/day at Museum Brook. The maximum daily export was observed at Museum Brook at 8,044 kg/day (Figure 10).

When corrected for watershed area, chloride export was typically 4 to 5 g/ha/day from the least impacted watersheds while median export coefficients ranged from 125 to 584 g/ha/day in the salted watersheds. The largest export coefficients were observed in the Museum Brook watershed where the maximum coefficient observed was 25,059 g/ha/day (Figure 10).

Discussion

The key to comprehending the water quality of lakes is to develop an understanding of the chemical inputs from the watershed. Recent evaluation of the water quality of Blue Mountain Lake by Laxson et al. (2019) reinforced the assessment that Blue Mountain Lake is: (1) circumneutral in terms of its acidity, with moderate acid neutralizing ability, (2) oligotrophic, with high transparency and low concentration of phosphorus and other nutrients, and (3) impacted by road runoff, with elevated concentrations of sodium and chloride.

We found that the tributary streams entering Blue Mountain tended to be acidic during spring runoff and circumneutral during the remainder of the year. This is a common occurrence in the Northeast. Snowpack is acidic, with an average pH of 5.0 at Huntington Forest in the central Adirondacks (National Trends Network 2018). When the snow melts in the spring a flush of acidic meltwater fills the streams. Later in the year the streams are supplied by groundwater, which in most cases has percolated through the soil and acquired acid neutralizing components such

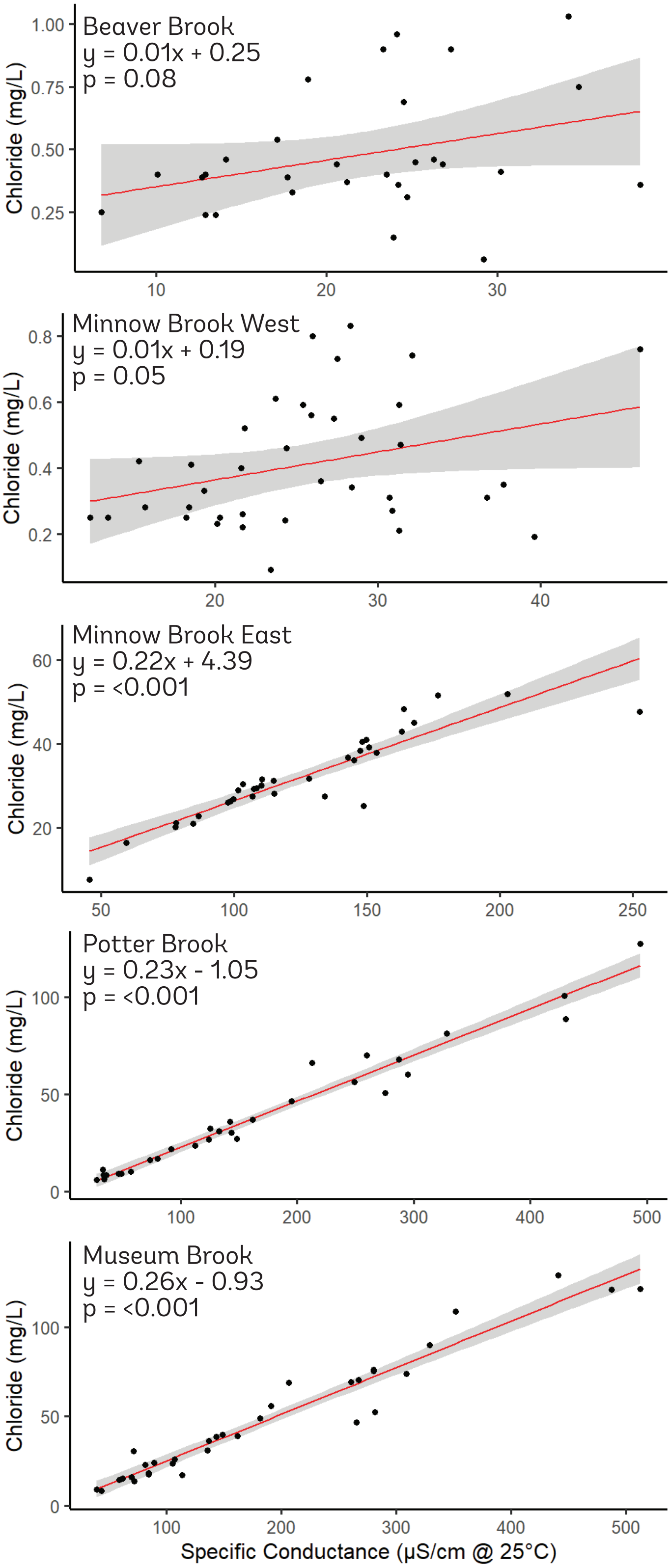


Figure 8. Relationship between in-stream conductivity and chloride concentration for all five study sites.

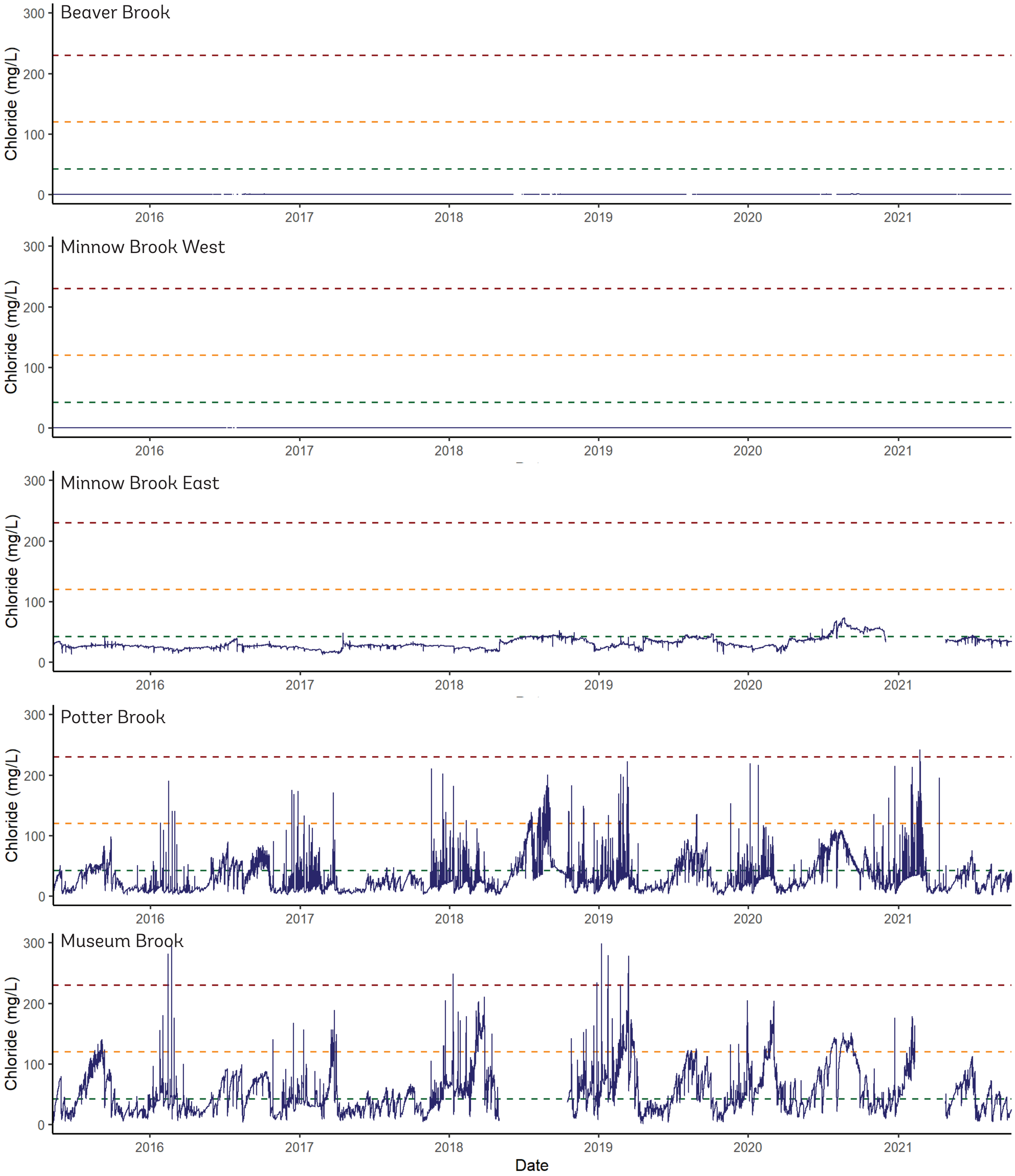


Figure 9. Chloride export coefficient at 30-minute intervals from May, 2015 to May of 2016 for the five sub-watersheds of Blue Mountain Lake. Solid blue = chloride concentration, dashed green = NYS DEC threshold for stress due to chloride, dashed yellow = Canadian guideline for protection of aquatic life, dashed red = USA EPA guideline for protection of aquatic life. Year is positioned at January 1.

as carbonates and dissolved organic matter. Prior to entering the lake, all of the Blue Mountain study watersheds drain lowland areas or wetlands, these areas provide deeper soils which increases the buffering ability of the water. Overall, the Adirondack Region has experienced a decrease in acid deposition (Strock et. al 2014). Data from Huntington Forest reveals that the primary indices of acid deposition, H^+ and the acid anions sulfate and nitrate, are all exhibiting significant reductions over the past 26 years (National Trends Network 2018).

This study has demonstrated that nutrient export from the surrounding watersheds to Blue Mountain Lake is generally low. Median phosphorus export ranged from 24 to 47 mg/ha/day. Similarly, nitrate export coefficients were similar ranging from a median of 54 to 65 mg/ha/day, with the exception of Beaver Brook with a median of 0 mg/ha/day. During the previous study period Museum Brook had high exports for both total phosphorus and nitrate, This may be explained by changes in Adirondack Experience, The Museum on Blue Mountain Lake shifts in operation during the COVID-19 pandemic. The museum typically welcomes over 50,000 visitors annually and has a full time staff of 23 individuals as well as numerous volunteers and seasonal employees. Although treated, waste water effluent typically has elevated concentrations of phosphorus and nitrogen as well as other anions and cations (SPDES # NY0240273). Analysis of the detailed facility report did not yield any violations of the Clean Water Act through the end of 2020; however, permit limits, monitoring requirements, and pollutant export data from the facility do not exist on the EPA Enforcement and Compliance website as we would expected them to (www.echo.epa.gov). Therefore, it is not possible to definitively link the reduction in nutrient export from Museum Brook to changes in the operation of this specific facility.

Even though the nutrient export from Museum Brook is elevated compared to neighboring watersheds, it is important to recognize that nutrient export is quite low from all the tributaries of Blue Mountain Lake, even Museum Brook. For comparison purposes, phosphorus export from undeveloped

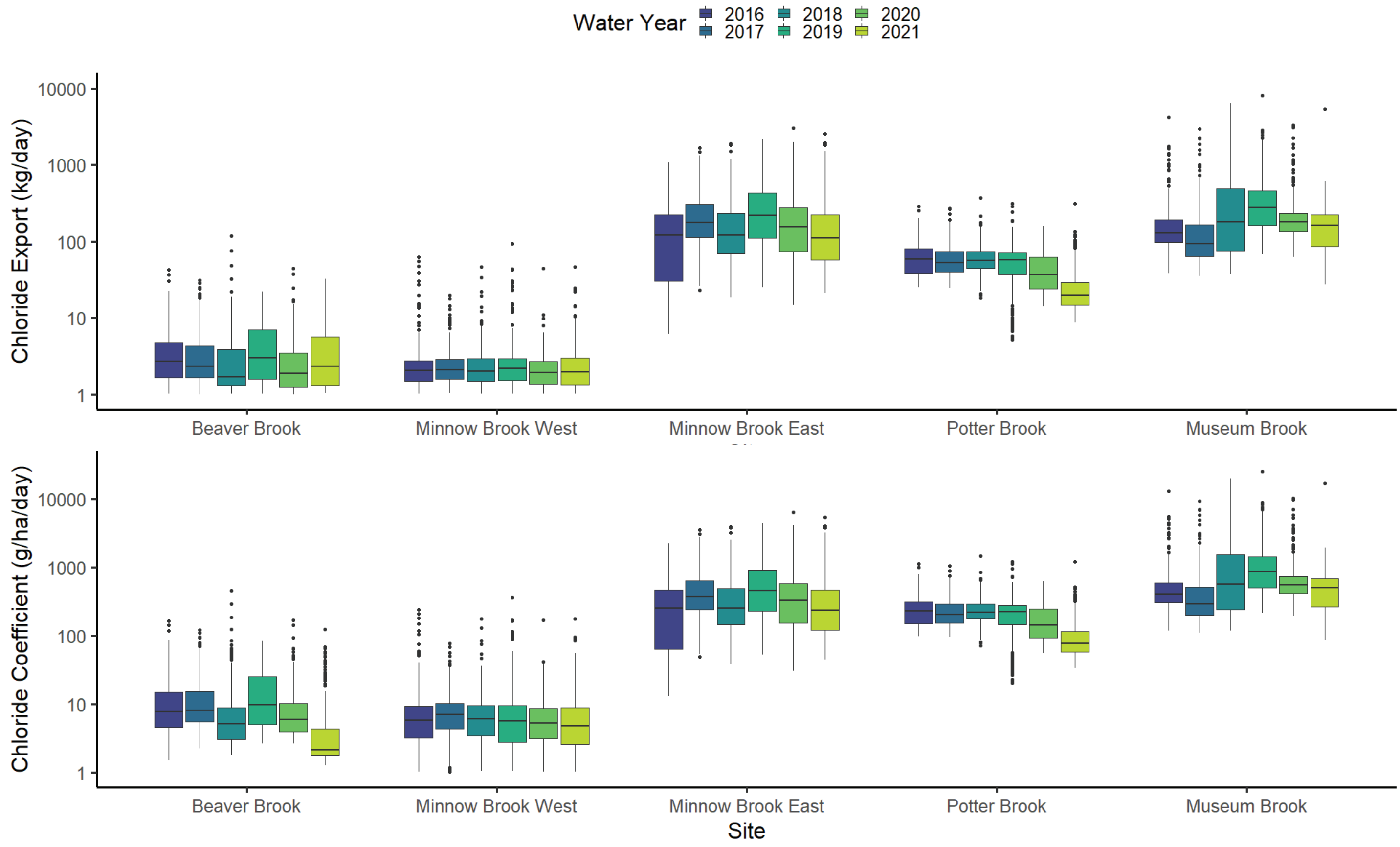


Figure 10. Boxplots of chloride export and export coefficients for each site by water year. Note that the scale is logarithmic.

streams of similar size in the St. Regis and Ausable River watersheds during the same time period ranged from 10 to 190 mg/ha/day for phosphorus and 10 to 610 mg/ha/day for nitrate (AWI unpublished data 2018). Nutrient exports from the Blue Mountain Lake sub-watersheds are all within the range of least impacted watersheds for phosphorus and nitrate with the exception of Museum Brook, where nitrate export was elevated above similar least impacted watersheds during the previous study period. In contrast, streams impacted by nutrient rich agricultural runoff in the Finger Lakes region of New York may export as much as 2,360 mg/ha/day of phosphorus and 131,000 mg/ha/day of nitrate (Makarewicz et.al 2009).

The chemistry of the Blue Mountain Lake watershed is significantly influenced by road salt. The concentrations of sodium and chloride in the surface water of the lake are greater than 86% of the waterbodies that participated in the Adirondack Lake Assessment Program in 2018 (n=68), and the chloride concentration in the lake is approximately 87 times greater than background levels (Laxson et. al. 2019). The elevated salt in the lake is undoubtedly due to saline run off from NYS routes 28 and 30, which drains through the Minnow Brook East, Museum Brook, and Potter Brook sub-watersheds, as well as 587 hectares of land along the lake that is not drained by any specific tributary (Figure 1). The New York State Department of Transportation applies an average of 23 tons of salt per lane kilometer of state annually (personal communication, NYS Department of Records, 2012). Given that there are 18 lane-km of state roads in the Blue Mountain Lake watershed, we can coarsely estimate annual road salt load of over 400 tons of NaCl per year.

The application of in-stream data loggers in this study allowed us to develop a fine scale understanding of salt export from impacted sub-watersheds around the lake. Surface water in the Adirondacks has naturally low concentrations of chloride. The only natural source of chloride is the slow weathering of granitic bedrock and a small contribution from atmospheric deposition. Beaver Brook and Minnow Brook West are the two sub-watersheds that have no salted roads, and thus serve as a good benchmark for the non-impacted condition. The median export coefficient of chloride from these watersheds ranged from 4 to 5 g/ha/day, which is similar to other non-impacted watersheds in the AWI database (2-10 g/ha/day; AWI unpublished data). Conversely, sub-watersheds of Blue Mountain Lake with salted roads experienced median chloride exports that were 25 to 100 times greater than the non-impacted condition. The greatest export was at Museum Brook (Figure 10).

Using the high resolution data obtained in this project, we can conservatively estimate that the instrumented watersheds in this study exported a total of 155,726 to 285,839 kg of chloride to the lake each year. We are confident in the accuracy of these estimates because they mathematically relate to the concentration of chloride in Blue Mountain Lake. For example, in water year 2020 we quantified a total export of 189,728 kg of chloride from all five instrumented watersheds. When this export is divided by the lake volume (37.5 x 10^9 m^3) and multiplied by the retention time of the lake (3.8 years) we arrive at a lake concentration of 19.2 mg/L, which is within 10% of the actual concentration of 20.6 mg/L reported in the 2020 ALAP report (Yerger et al. 2021).

Both sodium and chloride concentrations were highly variable in the impacted streams as compared to the least impacted streams. Minnow Brook East is a notable exception in that it had much lower variation in concentrations in comparison to Potter Brook and Museum Brook. The presence of Minnow Pond within the Minnow Brook East watershed acts to buffer concentrations of road salt in the downstream reaches of Minnow Brook East. The fate and transport of road runoff and salt in this watershed is fundamentally different than the other impacted watersheds.

While a major focus of this study is understanding watershed processes that influence Blue Mountain Lake, it is also worth noting the potential for impacts of road runoff on each of the study streams. We plotted continuous chloride concentrations for the study period along with thresholds set by the NYS DEC for stress due to chloride (42.7 mg/L), the Canadian guideline for protection of aquatic life (120 mg/L, 7-day exposure), and the US EPA guideline for protection of aquatic life (230 mg/L, 4-day exposure). Of the three thresholds presented here the lowest, set by NYS DEC, is likely the most ecologically relevant to the protection of aquatic life in Adirondack streams. Based on recent scientific literature there are likely to be notable changes in the ecological communities at the concentrations set by the Canadian and US governments (Brown and Yan, 2015; Arnott et al. 2020). All three of the impacted streams exceeded the NYS DEC threshold. Museum Brook and Potter Brook occasionally exceeded the others, with Museum Brook having several instances of exceeding the Canadian threshold for longer than the 7-day chronic exposure period (Figure 9). A model developed to predict in-stream median chloride concentration along a 10-meter grid for the entire Adirondack Park suggests that a reach of Museum Brook upstream of the current monitoring station may have higher chloride concentrations and thus greater frequency of exceeding the aforementioned thresholds (personal communication, Jesse Rock). Impacts to the ecological communities of these streams from road salt is likely and should be investigated further.

We observed a clear signal that a significant proportion of the salt applied to roadways is migrating to the groundwater. The concentration of chloride increased substantially during the low flow period of summer and early autumn in all three of the salted watersheds (Figure 9). Because streams are supplied primarily by ground water during this time, increased concentration during base flow periods are indicative of groundwater contamination (Kelly et al. 2019). Additionally, our course estimate of 400 tons of salt applied to state roads, along with our estimate of annual chloride export, suggest that anywhere from 27-35% of the salt applied to state roads is retained in the watershed.

A Adirondack Park wide study of private drinking water wells found that 64% of wells downslope of state roads exceeded drinking water guidance values for sodium, compared to 20% of wells downslope of local roads, and 0% of wells not influenced by roads. These findings reflect the significantly higher road salt application rates used on state roads and highlight the potential for regional groundwater pollution from road salting. Any current or new municipal and private wells within the impacted watersheds should be evaluated for contamination from road salt.

In conclusion, the Blue Mountain Lake Stream Monitoring Program was established primarily to understand the lake itself. The sub-watersheds draining into the lake are slightly acidic to circumneutral depending on the time of year and have moderate acid neutralizing capacity. Museum Brook loaded the greatest amount of phosphorus and nitrate to the lake. The source of the elevated nutrients is likely the permitted discharge from the Museum's waste water treatment plant. All of the nutrient loads to the lake are within the range of least impacted streams, which suggest no cause for concern. Road salt runoff has substantially altered the chemistry of three of the five sub watersheds and has infiltrated the groundwater. We estimate the salt loading to the lake from these impacted streams to be 25 to 100 times greater than baseline conditions.

AWI technician Hunter Favreau collecting direct road runoff from NYS Rt. 28/30 prior to entering Museum Brook in March of 2017. This sampled contained over 700 mg/L of chloride, which is approximately 1,400 times the concentration of unimpacted surface runoff.

Recommendations

1. Increase site visits during the winter time to download data loggers and capture runoff events. This will reduce the likelihood of data loss from loggers that have died due to low voltage or ice damage.
2. Phase in data loggers that have telemetry to remotely report data. Prioritize installation at the impacted sites. This will further protect against data loss while also giving AWI scientists the ability to plan site visits during specific event types.
3. Target sample collection during specific stage and conductivity ranges in order to improve mathematical relationships with discharge and chloride. Note: this is only possible when data loggers have telemetry.
4. Add a conductivity logger upstream of the current site on Museum Brook at the location identified by the runoff model as having the highest median chloride concentration.
5. Enroll Minnow Pond in the Adirondack Lake Assessment Program in order to better understand the impact of road salt on this specific water body.
6. Conduct a full biological assessment of all five streams to better understand the ecological impacts of road salt on these systems.
7. Engage with the NYS DOT on road salt reduction strategies within the watershed.

Literature Cited

Arnott, S.E., Celis-Salgado, M.P., Vallaeu, R.E., et. al. 2020. Road salt impacts freshwater zooplankton at concentrations below current water quality guidelines. Environmental Science & Technology, 54:9398-9407.

Bubeck, R.C., Diment, W.H., Deck, B.L., Baldwin, A.L. and Lipton, S.D., 1971. Runoff of deicing salt: effect on Irondequoit Bay, Rochester, New York. Science, 172(3988), pp.1128-1132.

Brown, A.H. and Yan, N.D. 2015. Food quantity affects the sensitivity of Daphnia to road salt. Environmental Science & Technology, 49:4673-4680.

Daley, M.L., Potter, J.D., and McDowell, W.H. 2009. Salinization of urbanizing New Hampshire streams and groundwater: effects of road salt and hydrologic variability. Journal of the North American Benthological Society, 28(4):929–940.

Driscoll, C.T., Driscoll, K.M., Mitchell, M.J., and Raynal, D.J. 2003. Effects of acidic deposition on forest and aquatic ecosystems in New York State. Environmental Pollution, 123:327–336.

Findlay, S.E. and Kelly, V.R., 2011. Emerging indirect and long-term road salt effects on ecosystems. Annals of the New York Academy of Sciences, 1223(1), pp.58-68.

AWI Reseach Associate Lija Treigbergs downloading a data logger on Potter Brook.

Kelly, V.R., Findlay, S.E., Hamilton, S.K., Lovett, G.M., and Weathers, K.C. 2019. Seasonal and long-term dynamics in stream water sodium chloride concentrations and the effectiveness of road salt best management practices. Water, Air, and Soil Pollution, 230(13):1-9.

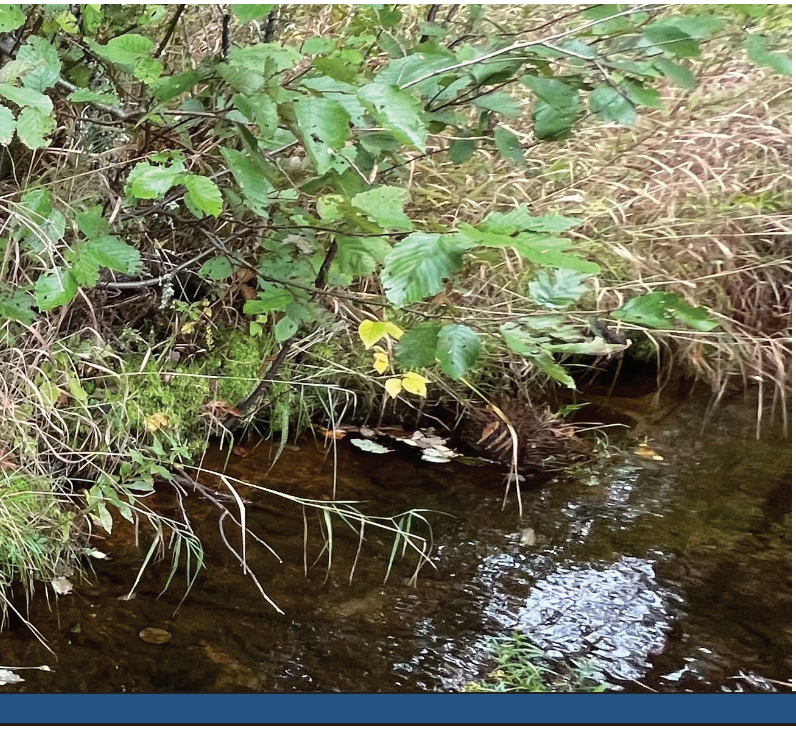
Kelting, D.L., Laxson, C.L., and Yerger, E.C. 2012. A regional analysis of the effect of paved roads on sodium and chloride in lakes. Water Research, 46(8):2749-2758.

Kennedy, E.J. 1984. Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3. US Government Printing Office. 50pp.

Kjensmo, J., 1997. The influence of road salts on the salinity and the meromictic stability of Lake Svinsjøen, southeastern Norway. Hydrobiologia, 347(1-3), pp.151-159.

Laxson, C.L., Yerger, E.C., Favreau, H.J., and Kelting, D.L. 2018. Blue Mountain Lake Watershed Monitoring Program, 2018 Report. Paul Smith's College Adirondack Watershed Institute.

Laxson, C.L., Yerger, E.C., Regalado, S.A., and D.L. Kelting. 2019. Adirondack Lake Assessment Program: 2018 Report. Paul Smith's College Adirondack Watershed Institute. Paul Smiths, NY USA.



Makarewicz, J.C., Lewis, T.W., Bosch, I., Noll, M.R., Herendeen, N., Simon, R.D., Zollweg, J. and Vodacek, A., 2009. The impact of agricultural best management practices on downstream systems: Soil loss and nutrient chemistry and flux to Conesus Lake, New York, USA. Journal of Great Lakes Research, 35, 23-36.

Martin, M.R. 1994. The limnological condition of Blue Mountain Lake: Final report of the 1993 monitoring program. Adirondack Watershed institute of Paul Smith's College.

Ragalado, S.A., Kelting, D.L. 2015. Landscape level estimate of land and water impacted by road runoff in the Adirondack Park of New York State. Environmental Monitoring and Assessment 187(8): 510.

Schindler, D.W. 1974. Eutrophication and recovery in experimental lakes: implications for lake management. Science, 184(4139), pp.897-899.

Strock, K. E., Nelson, S.J., Kahl, J.S., Saros, J.E., & McDowell, W.H. (2014). Decadal trends reveal recent acceleration in the rate of recovery from acidification in the Northeastern US. Environmental Science & Technology, 48(9), 4681-4689.

Sutherland, J.W., Norton, S.A., Short, J.W. and Navitsky, C., 2018. Modeling salinization and recovery of road salt-impacted lakes in temperate regions based on long-term monitoring of Lake George, New York (USA) and its drainage basin. Science of The Total Environment, 637, pp.282-294.

Turnipseed, D.P. and Sauer, V.B. 2010. Discharge Measurements at gauging stations: US Geological Survey Techniques and Methods, chapter A8, 87p. ISBN 978-1-4113-2969-0

Wetzel, R.G. 2001. Limnology, Lake and River Ecosystems, 3rd Edition. Academic Press, New York. 1006pp.

Wiltse, B,. Yerger, E.C., and Laxson, C.L. 2019. A reduction in spring mixing due to road salt runoff entering Mirror Lake (Lake Placid, NY). Lake and Reservoir Management, 36:1-13.

Yerger, E.C., Treibergs, L.A., Laxson, C.L. & Wiltse, B. 2021. Adirondack Lake Assessment Program: 2020 Update. Adirondack Watershed Institute, Paul Smiths, NY USA.

For more information concerning this report please contact:

Brendan Wiltse
Senior Research Scientist
Paul Smith's College Adirondack Watershed Institute
(518) 327-6460
bwiltse@paulsmiths.edu

Daniel L. Kelting
Executive Director
Paul Smith's College Adirondack Watershed Institute
(518) 327-6213
dkelting@paulsmiths.edu

About Us

The Adirondack Watershed Institute is a component of Paul Smith's College that conducts work broadly focused on conserving and protecting natural resources in the Adirondack region. The mission of the AWI is to create scientifically-sound knowledge about terrestrial and aquatic ecosystems and human relationships with the environment, enhance educational opportunities available for undergraduate students, and to engage the Adirondack Community in ways that facilitate the stewardship of our natural resources.

To find out more about the AWI, visit **www.adkwatershed.org**

PAUL SMITH'S
COLLEGE