International Watershed Initiative: Nutrient Monitoring on the St. Croix

Prepared by ECCC for
International St. Croix River Watershed Board and the International Joint Commission

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Acronyms & Abbreviations

cBOD- Carbonaceous Biological Oxygen Demand

CCME- Canadian Council of Ministers of the Environment

CRI – Canadian Rivers Institute

ECCC – Environment and Climate Change Canada

ESTL- Environmental Science Testing Laboratories

HUC(12)- Hydrological Unit Code (12-digit)

IJC – International Joint Commission

IQR – Interquartile Range

ISCRWB – International St. Croix River Watershed Board

IWI – International Watershed Initiative

km- Kilometer

KW- Kruskal Wallis

Maine DEP- Maine Department of Environmental Protection

mg/L- milligram per litre

MK- Mann Kendall

MLR – Multiple Linear Regression

NBDELG – New Brunswick Department of Environment and Local Government

NO_3- Nitrate

SE- Standard Error

SCIWC- St. Croix International Waterway Commission

TN- Total Nitrogen

TOC – Total Organic Carbon

TP- Total Phosphorus

TRI – Toxic Release Inventory

TSS- Total Suspended Solids

USGS – United States Geological Survey

WSI – Watershed Stressor Index

Executive Summary

The purpose of this report is to analyze nutrient concentrations throughout the St. Croix watershed, prompted by the Trends Analysis Water Quality Data 2007-2018 report (ECCC, 2019) that found increasing nitrogen levels and elevated phosphorus concentrations in its lower reaches. This raised questions about the source of these nutrients and concerns about continuous increases, which could result in more algal biomass in the river and the receiving Passamaquoddy Bay waters. Grab samples were collected at 23 sites throughout the watershed over a 3-year period (from 2022 to 2024) and analyzed for nutrients as well as other water quality parameters. Two of these sites (Forest City and Milltown) contained data spanning 2006 to 2023. Total nitrogen and total phosphorus data were examined on an upstream to downstream basis to determine sub-watershed contributions and potential sources. Total nitrogen levels have increased since 2006 in the lower portion of the watershed, however concentrations were still below mesotrophic levels – a threshold which could result in algal proliferation. Total phosphorus showed no increasing trend despite several samples above the New Brunswick Department of Environment and Local Government (NBDELG) objective of 0.03 mg/L. Recent land cover data (2017 to 2024) shows a decrease in canopy cover throughout the watershed likely resulting from increased forestry activities and contributing to an increase in nutrient run-off, particularly nitrogen, which is highly water soluble and less likely to be deposited in the sediments of lakes and head ponds.

The 2022-2024 sampling period of this project highlights the confounding effects of environmental conditions on nutrient concentrations with hot dry conditions having elevated nutrient levels compared to wet conditions. Continuing changes in summer temperatures and precipitation raises the concern for the potential development of harmful algal blooms in the watershed. The findings of this report have provided important insight into nutrient dynamics in the St. Croix watershed. While nutrient concentrations have not reached critical limits, total nitrogen is trending upward in the lower portion of the watershed. Land use activities that may be contributing to an increase in nutrients should be investigated and additional sampling effort could be implemented midstream to supplement long-term data at Forest City and Milltown.

Background

Environment & Climate Change Canada (ECCC) has a well-established water quality monitoring presence on the St. Croix River along with other government and non-government organizations. The current long term sampling sites are Milltown, located in the lower watershed and Forest City, an unimpacted reference site located in the uppermost watershed at the outflow of East Grand Lake. Both have routinely been sampled by ECCC for nearly 20 years. Since 2006, ECCC provides water quality data from grab samples collected at these two sites. In addition, automated real time data is collected at Forest City and through a collaboration with the United States Geological Survey (USGS) following the decommissioning of the Milltown dam in 2023, automated real time data continues to be collected year-round at Milltown.

In 2019, a report titled Trends Analysis Water Quality Data 2007 to 2018 was provided by ECCC to the International St. Croix River Watershed Board (ISCRWB) (ECCC, 2019). The report identified several differences in water quality parameters between Forest City and Milltown and highlighted significant trends at each of these locations. The Forest City station is located on the true right bank, the state of Maine riverside, below East Grand Lake and the Forest City Dam, and monitors the upstream and headwater portion of the watershed. It is a clean, low impacted site and showed decreasing trends in 10 water quality parameters including: total organic carbon (TOC), dissolved chloride, total calcium, total sodium, total magnesium, total nickel, total dissolved sulphate, total titanium, pH (field) and specific conductance (field). Comparatively, aluminum, total manganese and turbidity demonstrated increasing trends. Although not statistically significant, total nitrogen seemed to be trending downwards. No trend analysis was possible on phosphorus due to the consistently low or at detection limit values.

Milltown is located within the limits of the Town of St. Stephen, New Brunswick, and Calais, Maine, and receives effluent from upstream industry, municipal wastewater including storm or combined sewer run-off in addition to treated effluent, and run-off from any land clearing activities, such as forestry. The Milltown hydro-electric dam, where the real time monitoring station was located, was decommissioned between July 2022 and October 2024. The 2019 ECCC report indicated there were 3 water quality parameters that were trending downwards at this site, total chromium, total titanium and total vanadium. Conversely, total nitrogen was trending upwards. There was no significant trend for total phosphorus identified at Milltown, however the median concentrations were shown to be increasing in recent years with concentrations, at times, above the NB Department of Environment and Local Government's (NBDELG) guideline of 0.03 mg/L. Overall, most metals, major ions and nutrients were higher in Milltown than Forest City (ECCC, 2019).

As a result of the findings from the ECCC report (ECCC, 2019) and a general increase in nutrient-related impacts in neighboring watersheds (CRI, 2011), the ISCRWB requested funding from the International Joint Commission (IJC) for further study to be conducted through the International Watershed Initiative (IWI) to understand and report on the state of nutrients in the St. Croix including:

- Monitoring and assessing nutrient concentrations and contributions to the St. Croix River mainstem and tributaries,
- Identifying stressors affecting water quality in the watershed,
- Determining the effect of seasonality on nutrient concentrations, and
- Performing trend analyses on total nitrogen and phosphorus at Forest City and Milltown.

Description of St. Croix Watershed

The St. Croix River, also traditionally known as the Skutik by First Nations, comprises a 185 km portion of the Canada-United States border between New Brunswick and Maine and has an approximate drainage basin of 4,235 km^2 (CRI, 2021), making it the fourth largest basin in New Brunswick and the seventh largest basin in Maine (IJC, 2011). The river ultimately drains into Passamaquoddy Bay before reaching the Bay of Fundy and is culturally significant to Passamaquoddy First Nations and current residents and visitors. Historically, the river facilitated the movement between communities, was a source of hydro-electric power, had abundant fish populations, and was a location for various recreational activities. Over the years, various land uses influenced water quality including agriculture, forestry, industries such as pulp and paper, cotton mill, mining, ship building, municipal wastewater treatment facilities and other anthropogenic stressors such as the construction of multiple dams throughout the watershed (Loring et al., 1998 & Passamaquoddy Tribe at Pleasant Point, 2018). Most of the land cover in the watershed is forest (76.9%), water (12.0%), rangeland (7.47%) and a very small percentage of urban development (0.4%), which is mostly located in the lower portion of the watershed (Figure 1).

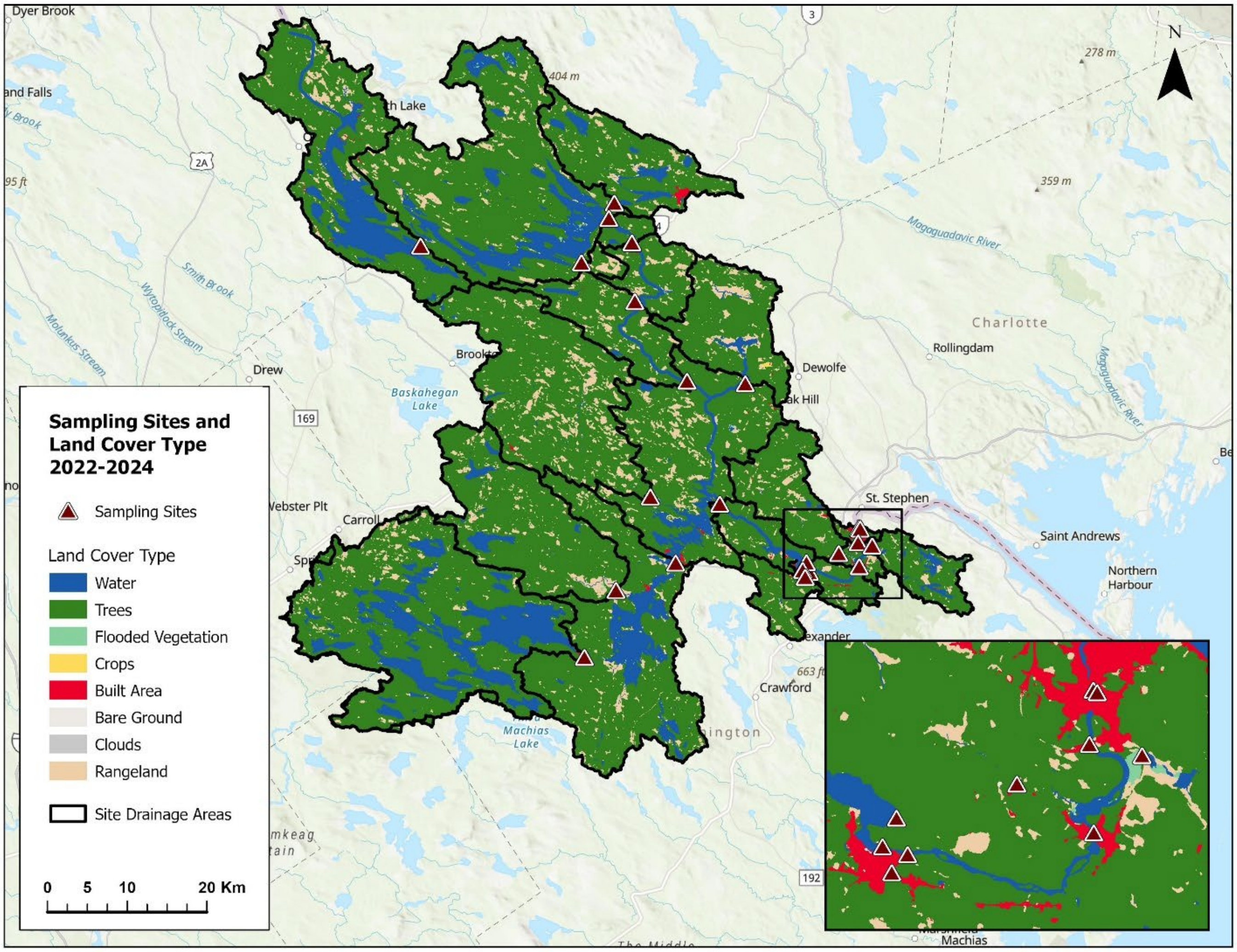


Figure 1: Land cover type throughout the St. Croix watershed. See Appendix A for land cover type definitions. *Footnote: Rangeland is defined as open areas covered in homogeneous grasses with little to no taller vegetation. For the purposes of this report, we are also including loss of canopy area in the definition.

Watershed Stressors

A watershed stressor index (WSI) was created for the St. Croix watershed in a 2021 report by applying different geospatial layers that could impact water quality (CRI, 2021). Twelve potential stressors were analyzed with more impactful stressors attributed to urban development, aquatic barriers (i.e., impoundments/dams, etc.), urban/developed area, and clearcut areas. Of the 50 sub-watersheds within the St. Croix, 45 were classified with low stress levels and 5 with elevated stress (CRI, 2021). The 5 sub-watersheds that experienced higher levels of stress were primarily in the lower portion of the watershed where there is a higher proportion of urbanized area including St. Stephen on the Canadian side and Calais on the American side.

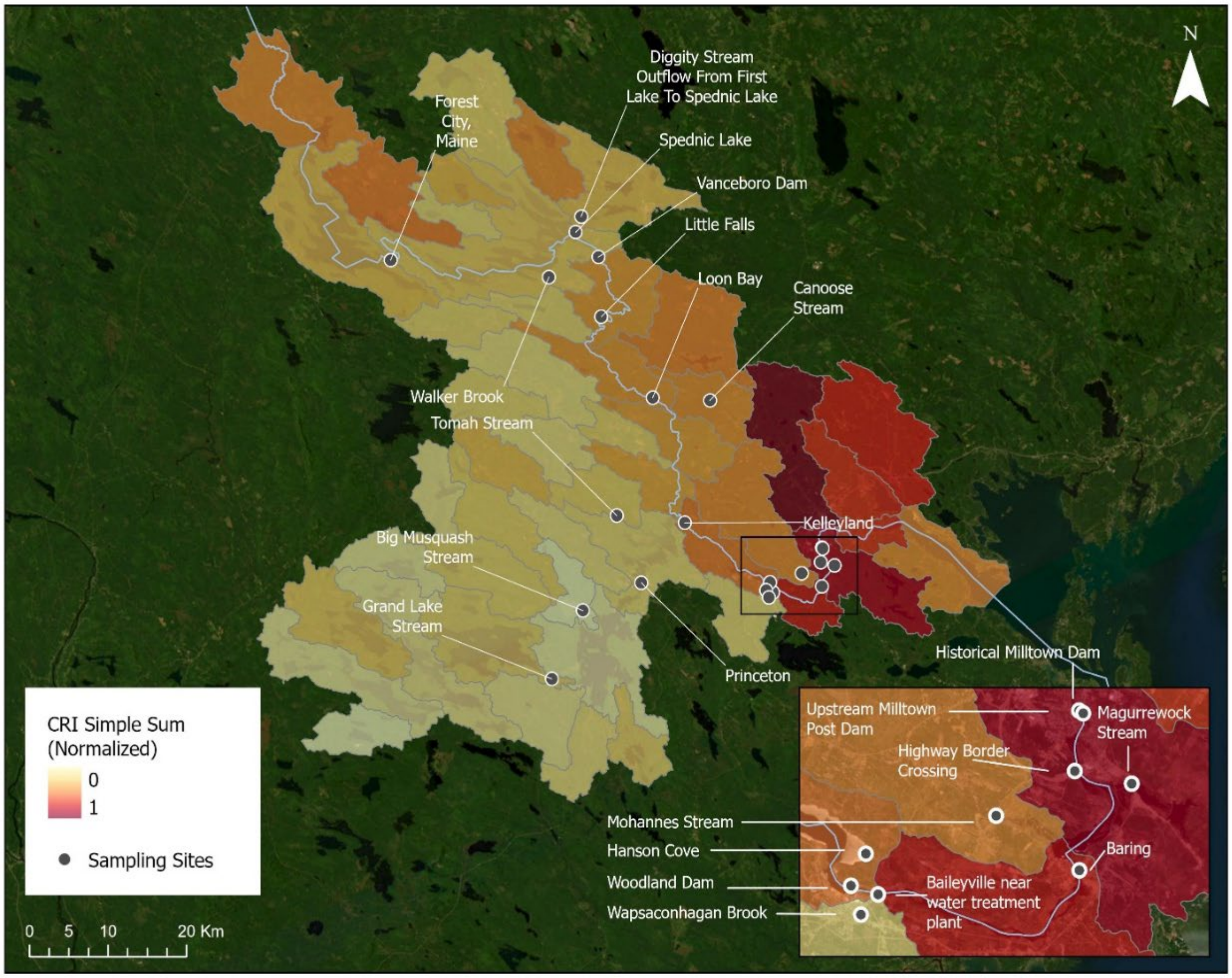


Figure 2: Simple sum watershed stressor index (WSI) from CRI St. Croix watershed stressor index pilot project report. The index is a sum of the normalized scores from the 12 stressor factors (CRI, 2021). Each HUC12 sub-watershed was assigned a colour based on their score with increasing values changing from yellow to red. Overlayed on the WSI are the sampling sites for the nutrient monitoring project.

Methods

Data Collection and Analysis

Sample sites for water quality monitoring throughout the watershed were selected in consultation with the St. Croix Water Quality Technical Advisory Committee (Figure 2). Twenty-three sites were selected based on general knowledge of the area, accessibility, monitoring of major tributaries, identification of known point sources of contamination and referencing the St. Croix watershed stressor index pilot report (CRI, 2021). Samples were collected by the St. Croix International Waterway Commission (SCIWC) using standard collection practices (Direction de la qualité de l'eau, 1983) between May 2022 and December 2024 and were analyzed at the accredited ECCC Environmental Science Testing Laboratories (ESTL). A full list of water quality parameters is listed in Appendix C. The complete data set for the enhanced nutrients monitoring can be accessed on Atlantic Data Stream: https://atlanticdatastream.ca.

Geospatial procedures and analyses

Sampling locations and median concentration maps for total nitrogen and total phosphorus were delineated in ArcGIS Pro 3.3.5. Drainage basin delineation was generated using the Create Watersheds tool at a resolution of 30 m from open-source DEM tiles (https://www.hydrosheds.org/). Grand Lake Stream contained large, flat lake areas and needed to be delineated using fine resolution DEM tiles downloaded from USGS at a resolution of 10 m.

Ideally, nutrient loadings (e.g., kg/year) would have been determined for the tributaries and sections throughout the main stem river. Nutrient loadings are important to consider because they reflect the potential impact of nutrients relative to the volume of water in the water body during a given period and inform water resource managers on excess nutrient situations. Nutrient contributions from point sources (e.g., wastewater discharges) and nonpoint sources (e.g., runoff from land clearing) vary with storms, seasons, and land use.

To determine nutrient contributions across the watershed, we developed a simple and cost-effective proxy method to estimate the proportion of nutrients from tributary and mainstem sites using nutrient concentrations from grab samples combined with the contributing area of each sample site. To achieve this, the upstream portions of land that drains each sample site were delineated. In some cases, monitoring sites covered an entire sub-watershed or tributaries, but in other cases, such as sites along the mainstem, the site was isolated from the adjacent upstream site(s) to ensure contributions were not overestimated. A land area proportion (*Pro*) value for each sampling site was calculated based on the area in km^2 of the drainage basin divided by the full drainage area of the watershed (3,766.07 km^2). If there was no drainage basin overlap for a site, the full drainage area (*fd*) in km^2 was used for the calculation. If there was drainage basin overlap for a site, the isolated drainage *(id)* in km^2 was used.

Proportion calculation with no drainage basin overlap: $Pro = fd / 3766.07\ km^2$
Proportion calculation with drainage basin overlap: $Pro = id / 3766.07\ km^2$

The contribution of each nutrient was calculated by multiplying the median concentration at the sampling site with the proportion value enabling comparisons of nutrients across sites on a common scale. The contribution was mapped on a relative minimum to maximum scale:

Contribution mg/L = *Pro* * [median nutrient concentration in mg/L]

This approach allowed for a better understanding of site nutrient output and comparison of sites with different drainage areas and flows. It also provided a comprehensive perspective for sites where nutrients were low with a high drainage area to sites with high nutrients and low drainage area.

Caution should be exercised when interpreting this study as the Milltown dam was decommissioned and removed during the three-year sampling project. This resulted in the creation of two unique data sets at Milltown, years prior to the dam removal (Milltown pre-dam prior to May 2023) and post dam (Milltown post-dam June 2023-present).

Watershed Stressor Index (WSI)

The final scores of the WSI (normalized) via the simple sum method were mapped using the Hydrologic Unit Code (HUC) at the highest watershed resolution level (12)). Refer to the Canadian Rivers Institute report (2021) for detailed WSI methodology.

Land Cover estimates

Landcover types (Table 1) were calculated in ArcGIS Pro using ESRI Sentinel 2 30 m land cover dataset (https://livingatlas.arcgis.com/landcoverexplorer). Canopy cover change between 2017 and 2024 was calculated using land-use landcover Geo-tiff file and was imported for both 2017 and 2024 from the Land Cover Explorer. They were projected to Canada Lambert Conformal Conic and then the Tabulate Area tool was used to calculate (in meters) the area of each land cover type for both full site drainage areas and isolate areas.

Assessing the effects of human activities on the nitrogen increase

The relationship of forestry related land use changes over time, with and without factoring water discharge, and ammonia and nitrate releases from point sources above Baring to median nitrogen concentrations (mg/L) were tested using multiple linear regression (MLR). The model included tree loss (kHa) + time (years) + ammonia (tons) + nitrogen (tons) + discharge (m^3/s).

The test found that only forest loss and time were relevant factors, and all others weakened the model. As a result, the additional factors were removed and only forestry related land use changes over time (formula = median nitrogen concentrations (mg/L) ~ tree loss (kHa) + time (years)) was included over the 2006 to 2023 period at Milltown to determine their influence on surface water nitrogen concentrations by MLR analyses using RStudio 4.3.1 via packages *corrplot, ppcor, car,* and *ggplot2* (R Core Team, 2023). Tree loss data was obtained from Global Forest Watch website (Global Forest

Watch, 2014). Preliminary testing and diagnostic testing such as plotting pairwise relationships, correlation matrices, partial correlations, multicollinearity, and measuring Cooks Distance for the MLR are in the appendices, while the model summary and observed vs. predicted plots are included in the results section. Such diagnostic testing was required when computing the MLR to ensure no statistical assumptions of the test were violated, and that outliers or influential points were reasonable or handled clearly. In such case, preliminary diagnostic testing indicated that row 16 (or year 2021) was an outlier. Upon further inspection, this year contained 3 samples and was then removed for clarity. For transparency, both the initial MLR (including row 16) and final MLR (which removed row 16) diagnostics and their results have been included in appendices E & F.

Total nitrogen & total phosphorus distributions

Total nitrogen and total phosphorus data for the watershed were preliminarily investigated and visualized using box and whisker plots (Figure 3 and Figure 4).

Correlations with streamflow

Visualizations and assessments of potential correlations were investigated where stream gauges and water quality grab samples coincided. Total nitrogen and total phosphorus concentrations were compared at four sites with discharge data (Forest City, Vanceboro, Grand Lake Stream and Baring) using *car* and *dplyr* packages. Various years of data were available per each site and included in the analyses. Normality of each dataset was tested via Shapiro-Wilk (W) test to determine the subsequent correlation analyses type to be used based on the p-value (if <0.05, were determined as not normally distributed, and correlations were computed via non-parametric analyses). In each case, water discharge rate was non-normally distributed therefore, the non-parametric Spearman’s Rank Correlation Coefficient was used.

Seasonal patterns and visuals

Total nitrogen and total phosphorus concentrations were tested to examine potential temporal trends at Forest City and Milltown Pre-dam removal sites. Seasonality and monotonic trends were evaluated using *trend* and *Kendall* packages in RStudio version 4.3.1 (R Core Team, 2023). Only the long-term water quality sites (Milltown Pre-Dam Removal and Forest City) were included in the analyses due to the data requirement of a monitoring period greater than 5 years, which is required for the seasonal Mann Kendall results to be considered powerful. A table reporting trend assessment data for all monitoring sites in this study is available in Appendix D. Results from all other sites should be interpreted with caution due to the lack of data in and between years. Seasonality was assessed using the Kruskal Wallis test (KW test) to determine if season influenced nutrient concentrations. Seasons were grouped based on the previous report’s findings of seasonal water discharge trends (January to March (winter), April to June (spring), July to September (summer), October to December (fall) (ECCC, 2019); if the KW p-value was <0.05, the effect of seasonality was present and subsequently the modified seasonal Mann Kendall test was used. If the KW p-value was >0.05, the effect of seasonality was not present, and the unmodified Mann Kendall test was used.

Since seasonality was a factor for both nitrogen and phosphorus at Forest City and Milltown Pre-Dam, the seasonal Mann Kendall test was used. A summary table of the results was created and included the KW p-value, tau, MK p-value, Sen Slope (unit/year), and direction of the trend (table 4). If the MK p-value was <0.05, a significant trend in nutrient concentrations was determined to be present. Depending on the value of tau, the trend may be increasing (positive) or decreasing (negative) at various strength levels. Sen slope was computed to provide context regarding the magnitude of the rate change to the monotonic trend (in mg/L per year). A table with all sites was created, however; only Milltown Pre-Dam Removal and Forest City are reported in the results.

Following the seasonal Mann Kendall, sites were plotted as scatter plots and average concentrations per season per year using the *tidyverse* and *lubridate* packages in RStudio software (R Core Team, 2023). For Forest City and Milltown, a regression line and R^2 were created using the scales package to highlight the line of best fit between concentration and time, to predict the direction of nutrient concentrations at these sites, and to determine the variability of the water quality dataset.

Results

Nitrogen

Beginning at the headwaters, following downstream on the mainstem, the median concentration of nitrogen is lowest at Forest City (0.19 mg/L), the most northern point in the watershed. Concentrations gradually increase until Woodland Dam (0.37mg/L) (Figure 3). Less than 1 km downstream from Woodland dam in Baileyville, the concentration of total nitrogen increased 12-fold to 4.52 mg/L. It should be noted that the sampling site for Baileyville is located roughly 100 meters from a paper manufacturing discharge outfall. Downstream, approximately 7.5 km from Baileyville to Baring, the total nitrogen concentration decreased to 0.59 mg/L. Lastly, in the lowest portion of the watershed that remains freshwater, total nitrogen concentration at the Milltown post-dam removal site reached 0.46 mg/L and the Milltown pre-dam site showed a similar concentration at 0.45 mg/L.

Several tributaries had elevated median concentrations of total nitrogen when compared to 0.19 mg/L at Forest City (Figure 3, Table 1). Two northern tributaries, Walker Brook and Canoose, had median concentrations of 0.76 mg/L and 0.75 mg/L, respectively, and ranked second and third highest in total nitrogen concentration for the entire watershed. Other tributaries in the northern portion of the watershed ranged from

0.20-0.44 mg/L. In the central portion of the watershed, the median concentrations for Tomah Stream and Princeton were lower at 0.525 mg/L and 0.31 mg/L, respectively. Finally, downstream of Woodland dam in the lower portion of the watershed, total median concentrations ranged from 0.44-0.54 mg/L (Figure 3, Table 1).

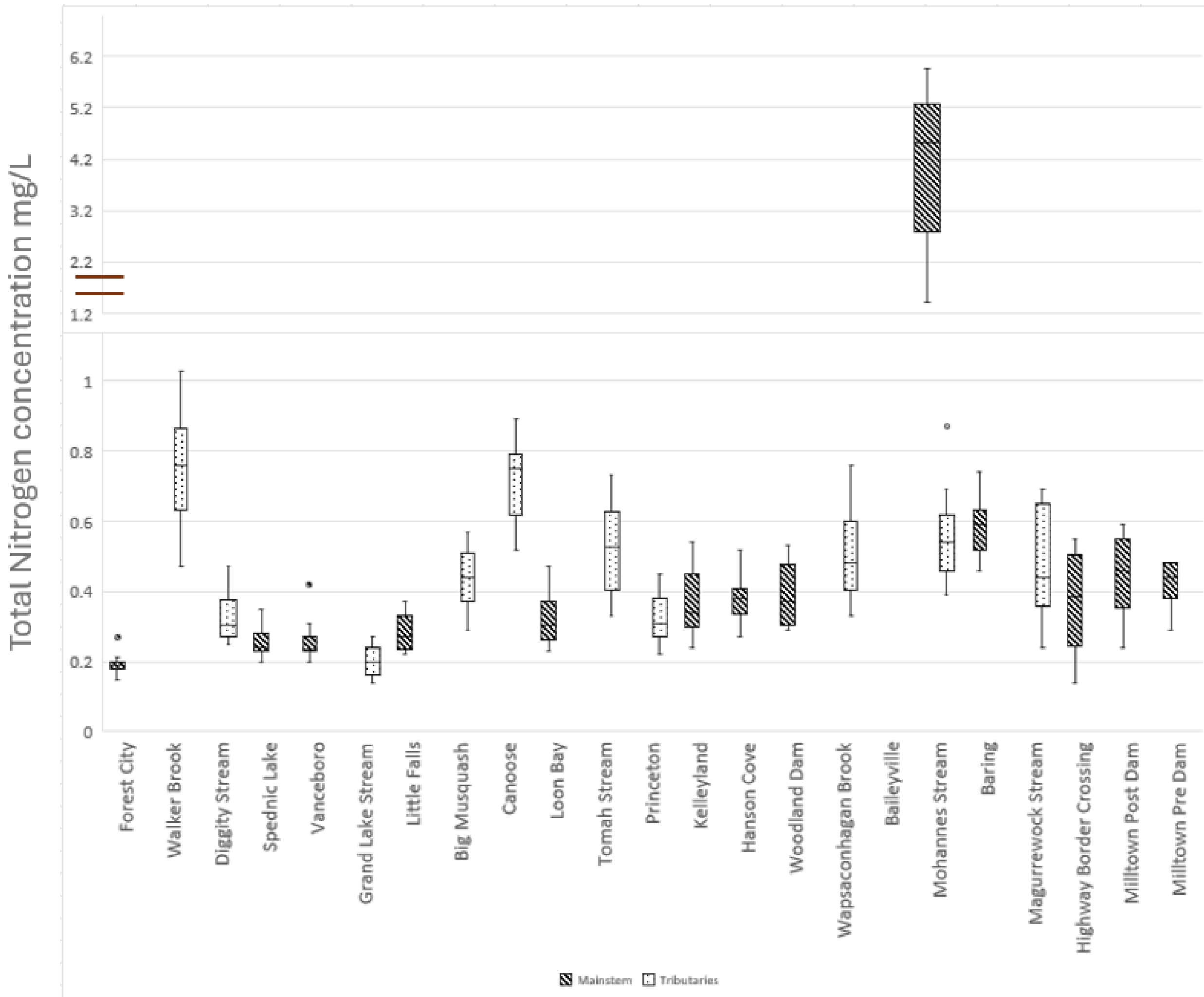
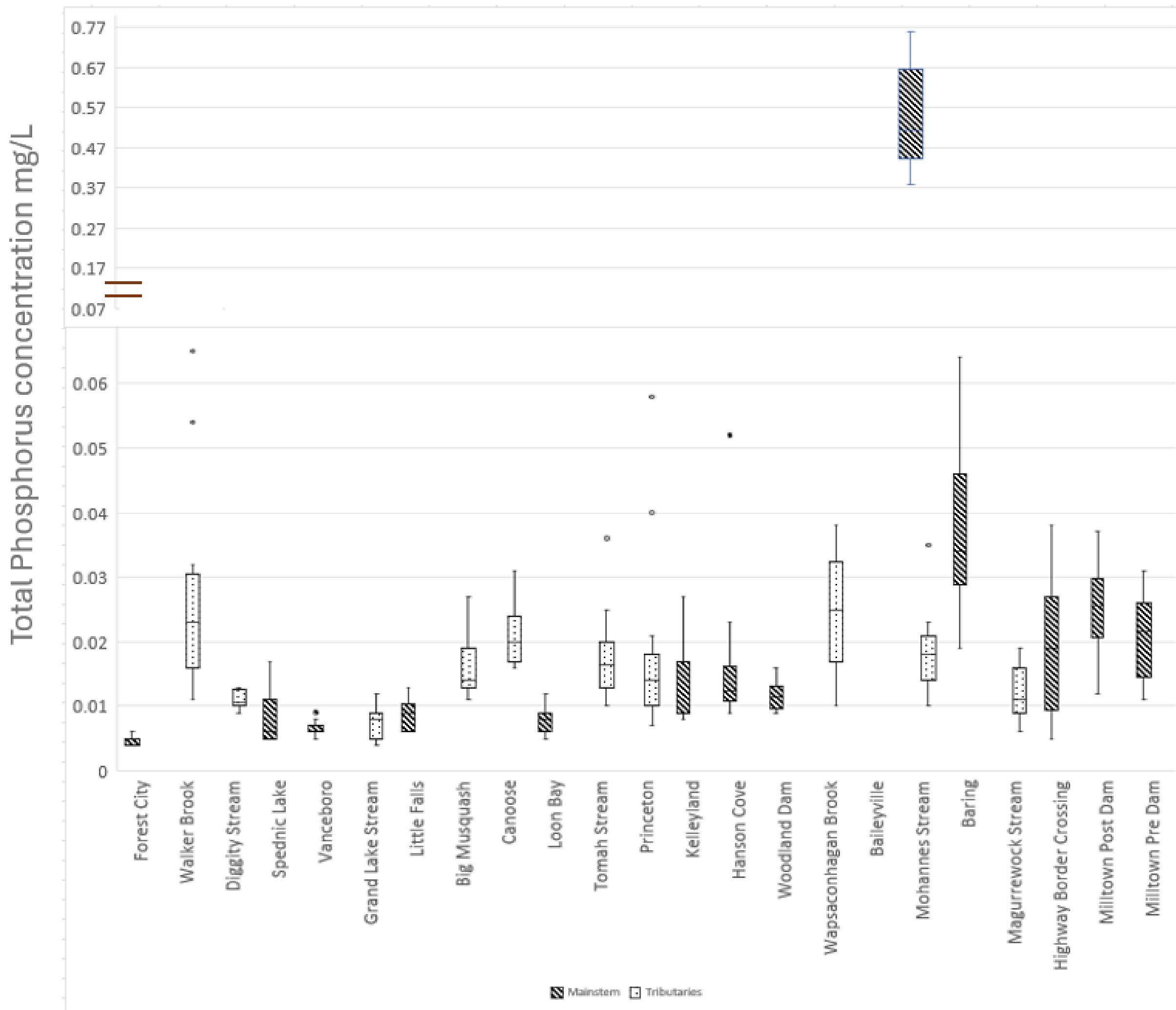


Figure 3: Box and whisker plot of total nitrogen concentrations in mg/L along the St. Croix River oriented from upstream (left) to downstream (right). The sites on the mainstem are shown in black and sites along tributaries are shown in white. The box represents the interquartile range (IQR) which is the 25th to 75th percentile and the vertical line through the box is the median value. The lower bar represents the 10th percentile, and the upper bar is the 90th percentile. Any data points beyond the whiskers are considered outliers.

Phosphorus

On the mainstem from Forest City to Woodland, the median concentration of phosphorus ranged from 0.004 to 0.013 mg/L (Figure 4, Table 1). At Baileyville, there was a substantial increase to 0.52 mg/L, which exceeded the NBDELG objective of 0.03 mg/L for eutrophication (NBDELG, 2019) by 17-fold. Downstream at Baring, the concentration of total phosphorus decreased to 0.034 mg/L but remained above the NBDELG objective. In the lowest portion of the watershed, between the Highway Border Crossing site and Milltown, median concentrations were between 0.019-0.021 mg/L, respectively.

Three tributaries in the northern portion of the watershed had higher median concentrations of total phosphorus. Walker Brook (0.023 mg/L), Canoose (0.02 mg/L) and Tomah stream (0.017 mg/L) also had elevated total phosphorus concentrations compared to 0.004 mg/L at Forest City (Figure 4 and Table 1). Beyond Woodland, Wapsaconhagan Brook had a median concentration of 0.025 mg/L, however the site contained some results that exceeded the NBDELG objective (Figure 4). Mohannes and Magurrewock streams had lower median phosphorus concentrations at 0.018 and 0.011 mg/L, respectively.



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St. Croix Watershed Land Use Types

The watershed was mostly comprised of water, forest, rangeland (cleared land, including clear cutting for forestry), and a small percentage of agriculture and urban development (Table 2). Based on the geographical location of each monitoring site's drainage area, the percentage of land types varied, however tree cover and water were consistently the most dominant classifications. Throughout the drainage basin of individual sampling sites (Table 2), tree cover ranged from 88-65.1%, the percentage of water is between 24.9-0.0 %, deforested area had the highest variability from 32.0-<0.01% and built area ranged from 12.6-0.02%.

Land use & nutrient contribution from the St. Croix mainstem

The 23 sample sites were delineated to characterize the drainage basin (km^2), land cover (%), and the approximate contribution of nutrient from each site (Table 1 & Table 2). The largest delineated drainage basins on the mainstem were Vanceboro, Kelleyland and Forest City once drainage overlap was removed (see methods). In addition, each of these sites also have a dam that could affect nutrient concentrations and contributions; Vanceboro Dam, Grand Falls Dam at Kellyland and one at the outfall of Grand Lake in Forest City. Vanceboro and Forest City are used primarily as storage dams, controlling the water level in Spednic Lake and East Grand Lake, respectively, while Grand Falls dam is a hydroelectric facility.

The refence site at Forest City had a drainage basin of 355 km^2 and represented 9.04% of the watershed. The median concentration of total nitrogen and total phosphorus in Forest City were relatively low (Table 1) which resulted in a low-moderate contribution of total nitrogen and a low contribution of total phosphorus (Figure 7 & Figure 9). The largest drainage basin, Vanceboro (548 km^2) in the northeast portion of the watershed accounted for 14% of the overall watershed when upstream drainage area overlap was removed (Table 1). Built area was responsible for 0.08% of land use in the basin, and primarily captured Spednic Lake, the presence of a hydroelectric dam and limited residential development (Table 2). The calculated contribution of total nitrogen was the third highest in the watershed at 0.033 mg/L while the total phosphorus contribution was moderately high at 0.0008 mg/L (Table 1). Downstream at Kelleyland, the drainage basin represented 8.68% of the watershed and included 0.49% of built area and 7.63% less canopy coverage, which suggested increased forestry activity (Table 2 & Figure 5A). As a result of the larger drainage basin size (341 km^2), the contribution of both total nitrogen and total phosphorus were moderate (Figure 7 & Figure 9).

Table 1: Median total nitrogen and total phosphorus concentrations with associated calculated contribution based on site drainage area. (*) Indicates sites with upstream drainage area overlap removed. Mainstem sampling sites are highlighted in bold**.** Spednic Lake, Woodland Dam and Highway Border Crossing were omitted from land use calculation as they represent very small areas post-overlap removal. See Appendix A for land cover type definitions.

Sample Site	Drainage basin area (km^2)	Area of watershed (%)	Median TN (mg/L)	Median TP (mg/L)	Calculated Contribution of TN (mg/L)	Calculated Contribution of TP (mg/L)
Forest City	354	9.04	0.19	0.004	0.017	0.0004
Walker Brook	14.8	0.38	0.76	0.023	0.003	<0.0001
Diggity Stream	180	4.59	0.305	0.011	0.014	0.0005
Spednic Lake	N/A	N/A	0.24	0.006	N/A	N/A
***Vanceboro Dam**	548	14.0	0.235	0.006	0.033	0.0008
Grand Lake Stream	599	15.3	0.2	0.008	0.031	0.0012
***Little Falls**	79.0	2.01	0.27	0.009	0.005	0.0002
Big Musquash Stream	283	7.21	0.44	0.014	0.032	0.001
Canoose Stream	165	4.20	0.75	0.02	0.032	0.0008
***Loon Bay**	129	3.30	0.305	0.008	0.010	0.0003
Tomah Stream	385	9.80	0.525	0.017	0.051	0.0016
*Princeton	417	10.6	0.31	0.014	0.033	0.0015
***Kelleyland**	341	8.68	0.34	0.009	0.029	0.0008
***Hanson Cove**	58.3	1.49	0.38	0.013	0.006	0.0002
Woodland Dam	N/A	N/A	0.37	0.012	N/A	N/A
Wapsaconhagan Brook	53.7	1.37	0.48	0.025	0.007	0.0003
***Baileyville**	57.9	1.48	4.52	0.52	0.067	0.0076
Mohannes Stream	125	3.19	0.54	0.018	0.017	0.0006
***Baring**	38.0	0.97	0.59	0.034	0.006	0.0003
Magurrewock Stream	69.3	1.77	0.44	0.011	0.008	0.0002
Highway Border Crossing	N/A	N/A	0.385	0.019	N/A	N/A
***Milltown Post Dam**	28.3	0.72	0.46	0.021	0.004	0.0002
***Milltown Pre Dam**	0.14	<0.01	0.45	0.021	<0.001	<0.0001
Total Watershed	3,766					

Table 2: Land use by sampling site drainage areas. Sites with upstream drainage area overlap removed are indicated with (*). Mainstem sampling sites are highlighted in bold. Spednic Lake, Woodland Dam and Highway Border Crossing were omitted from land use calculation as they represent very small areas once overlap is removed. See Appendix A for land cover type definitions.

Sample Site	Drainage basin area (km^2)	% of watershed	Water (%)	Trees (%)	Flooded (%)	Crops (%)	Built area (%)	Bare ground (%)	Rangeland (%)
Forest City	354	9.04	22.2	67.2	0.02	0.05	0.23	0	7.07
Walker Brook	14.8	0.38	0	65.1	0	0	0	0	32.0
Diggity Stream	180	4.59	9.47	78.2	0.04	0	1.25	0	8.22
Spednic Lake	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
***Vanceboro Dam**	548	14.0	17.2	74.0	0.14	0	0.08	0	<0.01
Grand Lake Stream	599	15.3	24.9	68.0	0.1	0	0.03	0	3.91
***Little Falls**	79.0	2.01	2.14	81.0	0.08	0	0.96	0.02	12.8
Big Musquash Stream	283	7.21	4.62	85.1	0.1	0	0.02	<0.01	7.00
Canoose Stream	165	4.20	3.04	81.9	0.02	0.30	0.05	0	11.6
***Loon Bay**	129	3.30	3.39	84.0	0	0	0.03	0	9.56
Tomah Stream	385	9.80	0.55	84.4	<0.01	0	0.08	<0.01	11.9
*Princeton	417	10.6	13.5	77.2	0.07	<0.01	0.25	0	5.60
***Kelleyland**	341	8.68	8.20	78.5	0.11	<0.01	0.49	0	9.55
***Hanson Cove**	58.3	1.49	9.53	80.5	0.03	0	0.82	0	5.89
Woodland Dam	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Wapsaconhagan Brook	53.7	1.37	0.18	88.0	<0.01	0	1.78	<0.01	6.71
***Baileyville**	57.9	1.48	1.08	84.7	<0.01	<0.01	4.57	0.03	6.27
Mohannes Stream	125	3.19	0.85	86.6	<0.01	<0.01	0.44	0.2	8.87
***Baring**	38.0	0.97	4.18	84.1	<0.01	<0.01	2.39	0	5.89
Magurrewock Stream	69.3	1.77	10.7	78.6	0.35	0	0.12	0	6.93
Highway Border Crossing	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
***Milltown Post Dam**	28.3	0.72	5.13	69.7	1.73	0	12.6	<0.01	7.52
***Milltown Pre Dam**	0.14	<0.01	0	0.87	0	0	93.6	0	2.33
Total Watershed	3,766								

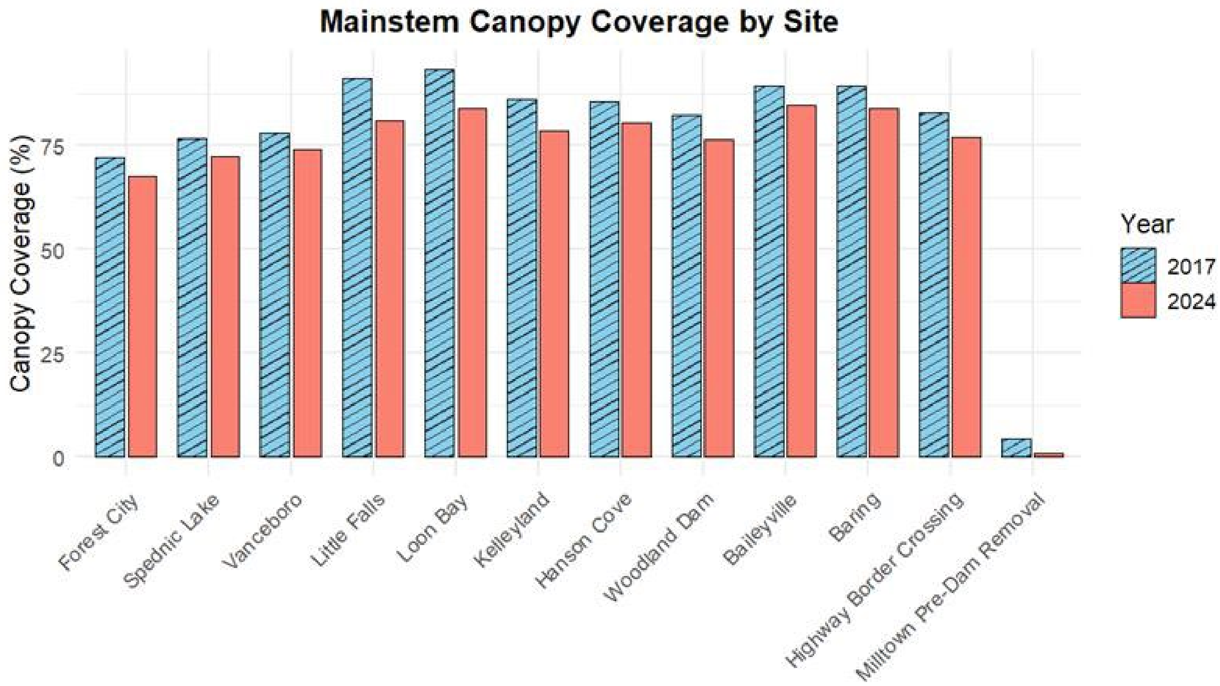

Figure 5A: Change in canopy cover between 2017 and 2024 of sampling sites on the mainstem of the St. Croix, ordered upstream to downstream with drainage area overlap removed.

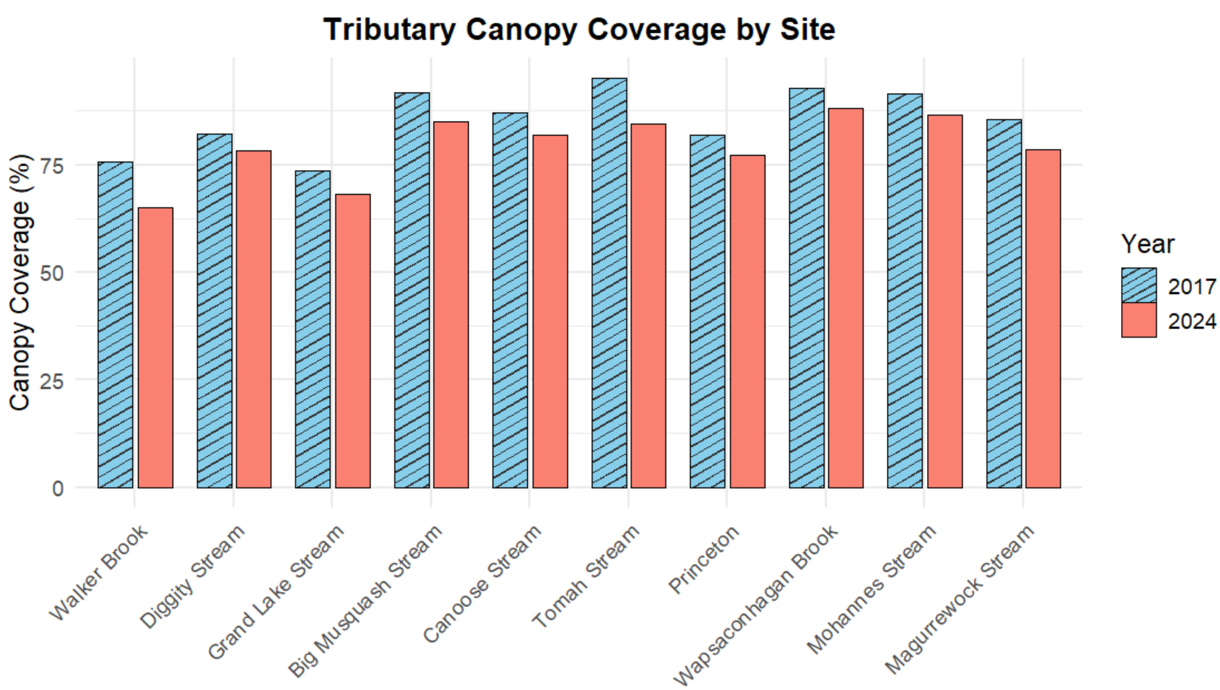

Figure 5B: Change in canopy cover between 2017 and 2024 of the St. Croix tributaries, ordered upstream to downstream.

On the mainstem in the lower portion of the watershed, several point sources and stressors exist, such as dams, pulp and paper manufacturing and municipal wastewater. Specifically, nutrient concentrations in and around the Woodland dam, Baileyville and Milltown were most heavily influenced. Downstream of Baileyville in Baring, the concentrations of total nitrogen and total phosphorus were greatly reduced through dilution. The reduction in nutrient concentration in addition to a small non-overlapped drainage basin (38 km^2) resulted in a low contribution of nutrients to the watershed at this site (Figure 7 & Figure 9). The most downstream site, Milltown, is located near the southern border of the watershed and provides an estimate of the overall health of the river as it captures the input from all major tributaries and encompasses the majority of the mainstem before it begins to drain into Passamaquoddy Bay. Both Milltown-Pre Dam and Milltown Post Dam had low-moderate concentrations of total nitrogen and total phosphorus and very small drainage basins when removing upstream overlap resulting in overall low nutrient contributions to the watershed.

Land use & nutrient contribution from the St. Croix tributaries

Ten major tributaries of the St. Croix were sampled throughout the course of the project. Walker Brook had some of the highest total nitrogen and total phosphorus levels but as one of the smallest drainage basins (14.8 km^2), contributed minimal amounts of nutrients overall (Figure 7 & Figure 9). Walker Brook had a high proportion of wetland cover and the second largest change in canopy cover at 10.5% when the years 2017 and 2024 were compared (Figure 5B). Furthermore, Diggity Stream had a small drainage basin (180 km^2) and represented 4.59% of the watershed. While a small portion of the basin was categorized as built area (1.25%), it included developments such as the town of McAdam and several manufacturing plants. The median concentration of total nitrogen and total phosphorus were low at Diggity, as were nutrient contributions (Figures 7 & Figure 9). Big Musquash Stream (283 km^2) and Grand Lake Stream (599 km^2) had low concentrations of total nitrogen and moderate levels of total phosphorus (Figure 6 & Figure 8) which resulted in a moderate contribution of total phosphorus. Both areas also had a decrease in canopy coverage between the years of 2017 to 2024, though Big Musquash Stream experienced a greater loss (6.72%) when compared to Grand Lake Stream (5.58%) (Figure 5B). Canoose drainage basin represented only 4.20% of the total watershed yet had moderate nutrient contribution due to elevated median concentrations of both total nitrogen and total phosphorus (Figure 6 & Figure 8). The Canoose sampling site had the highest proportion of crop land (0.3%) in the watershed and exhibited 5.10% canopy cover decrease between 2017-2024 (Figure 5B). Tomah was a major tributary with a drainage basin of 385 km^2 that primarily consisted of trees (84.4%); however, canopy coverage decreased by 10.7% between 2017-2024 (Figure 5B). The median concentration of total nitrogen and total phosphorus were 0.525 and 0.017 mg/L, respectively. Due to the moderate concentration levels of both nutrients and the size of the drainage basin, Tomah exhibited some of the highest nutrient contribution levels in the watershed (Figure 7 & Figure 9). Princeton had the second largest drainage basin (417 km^2), after upstream overlap was removed. The dominant land types were trees (77.2%), deforested land (5.60%) and built area (0.25%) (Table 2). The median concentrations of total nitrogen and total phosphorus were 0.31 and 0.014 mg/L, respectively (Table 1). The overall nutrient contribution was moderate for both total nitrogen and total phosphorus (Figure 7 & Figure 9).

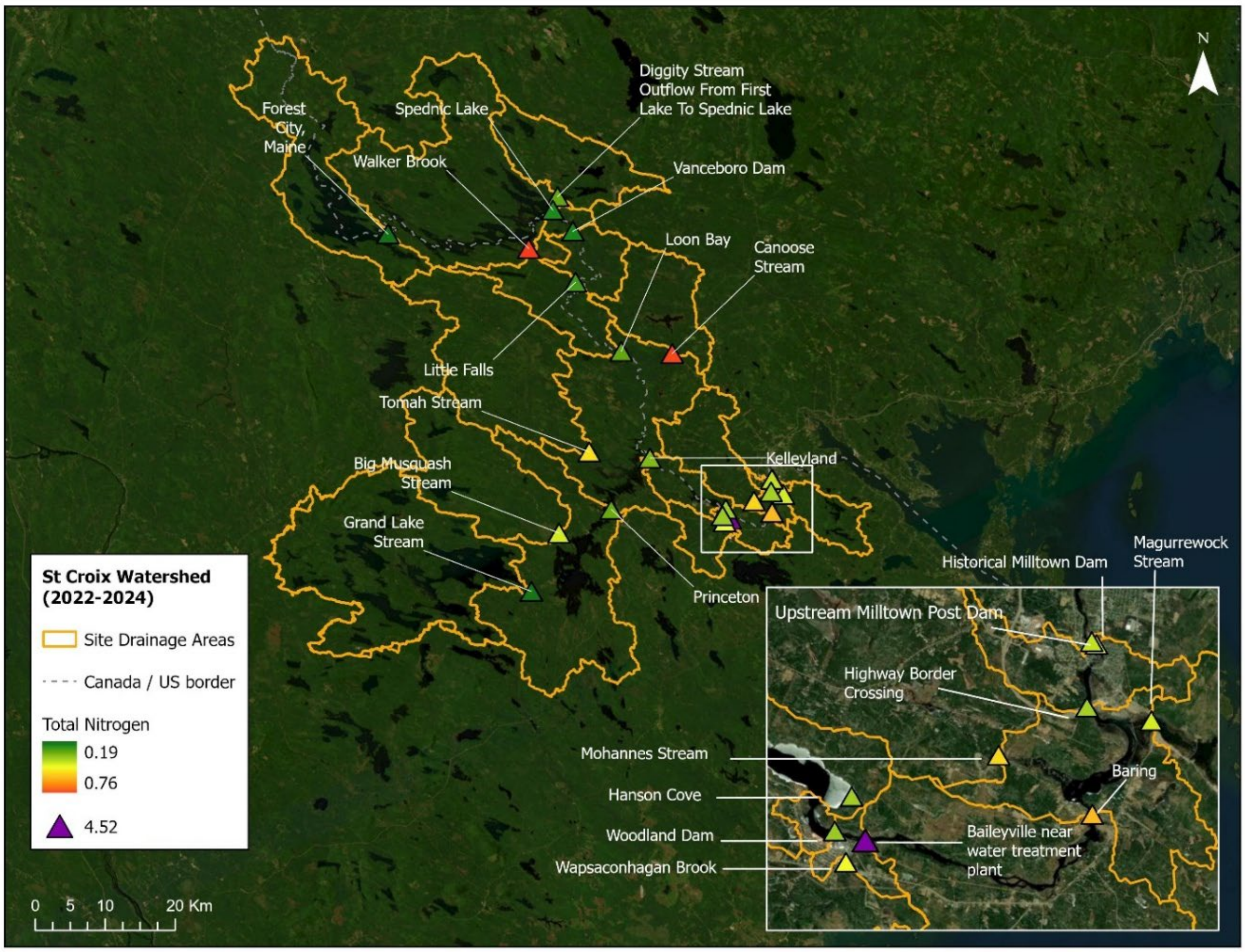

Figure 6: Median total nitrogen concentration (mg/L) at each sampling site between 2022-2024. The heat index represented the gradient of median total nitrogen from low (green) to high (red/purple).

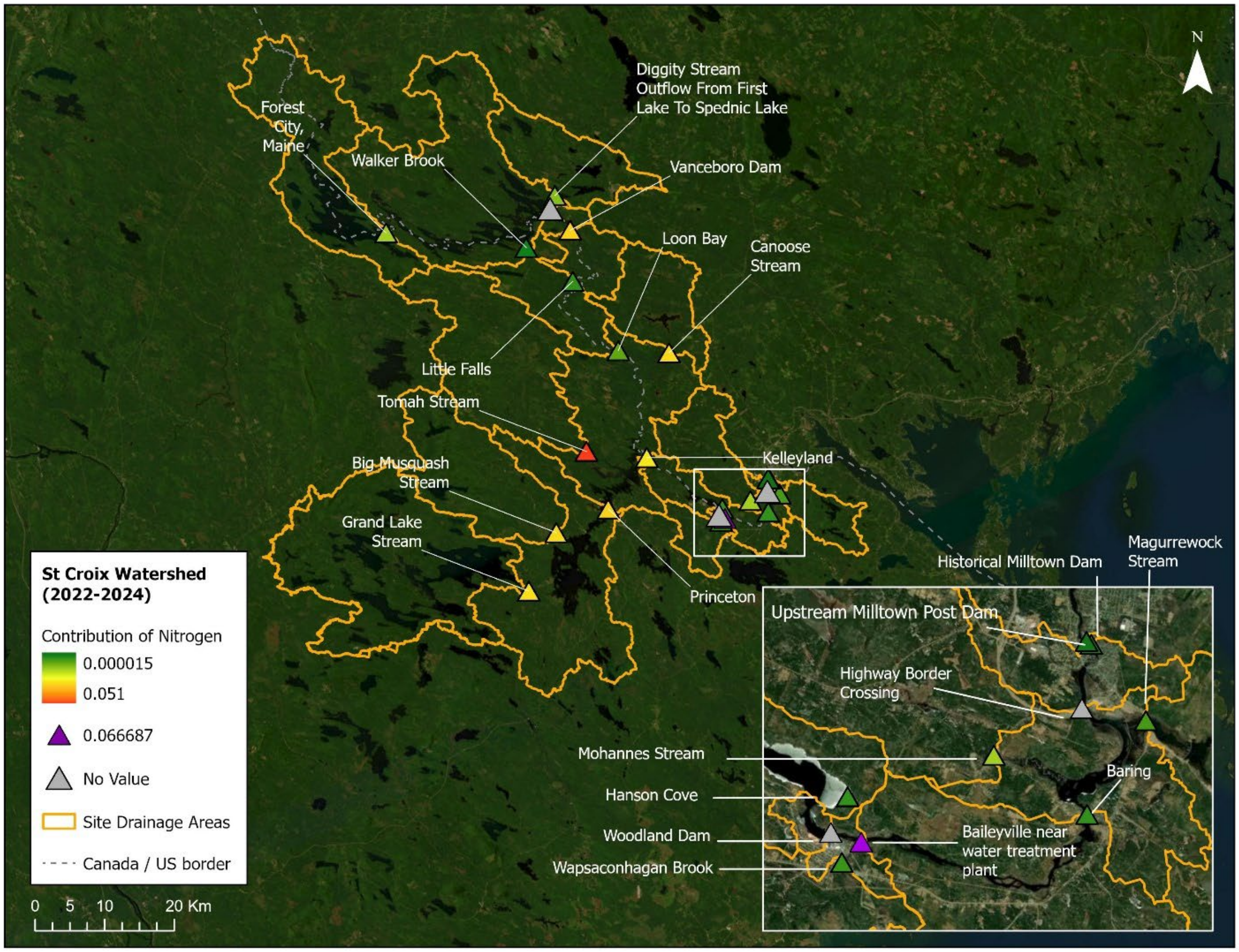

Figure 7: Calculated contribution of total nitrogen from each drainage basin in the St. Croix watershed. Median total nitrogen concentration (mg/L) were multiplied by the proportion of the drainage basin. The heat index represented the gradient of median total nitrogen contribution from low (green) to high (red/purple).

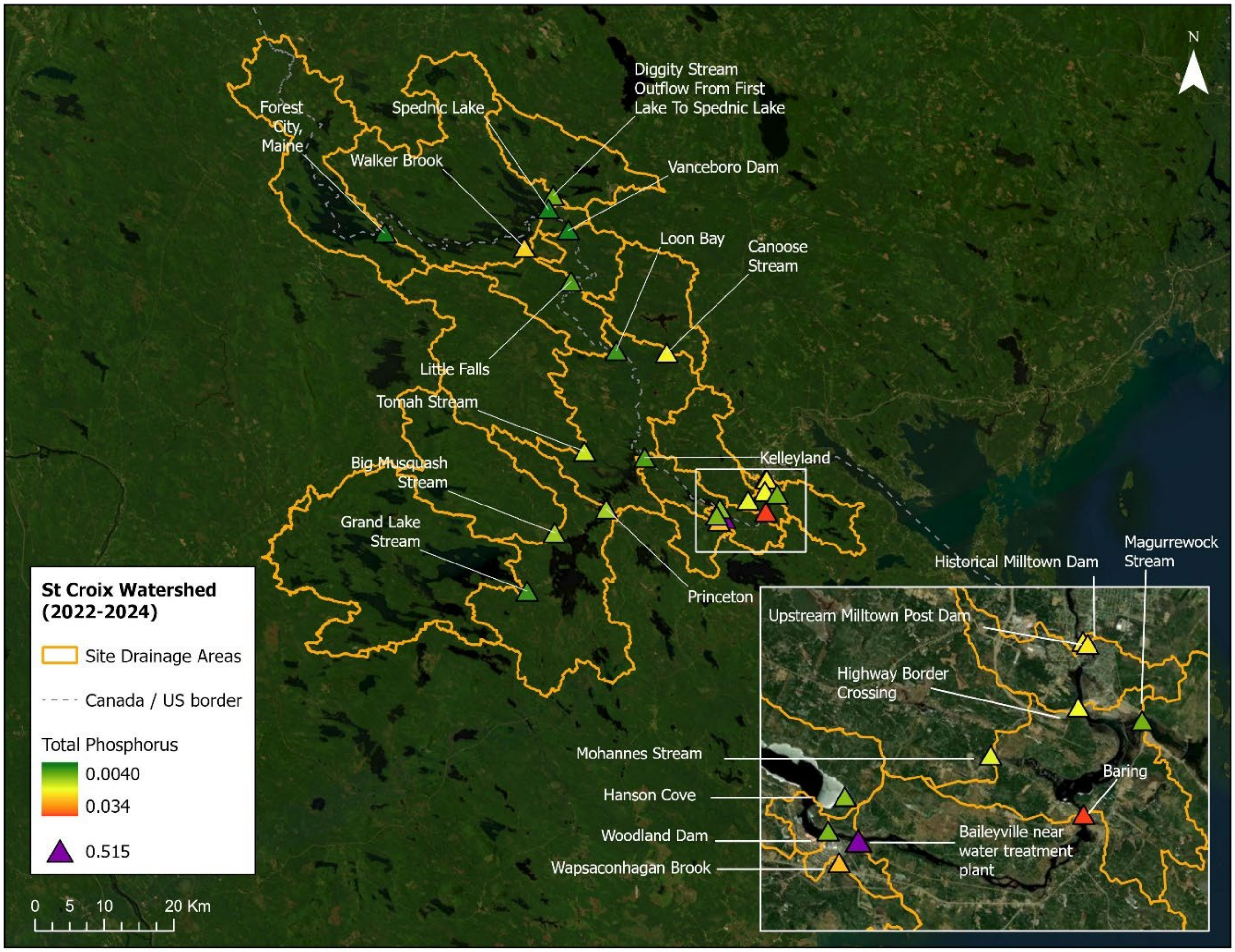

Figure 8: Median total phosphorus concentration (mg/L) at each sampling site between 2022-2024. The heat index represented the gradient of median total phosphorus from low (green) to high (red/purple).

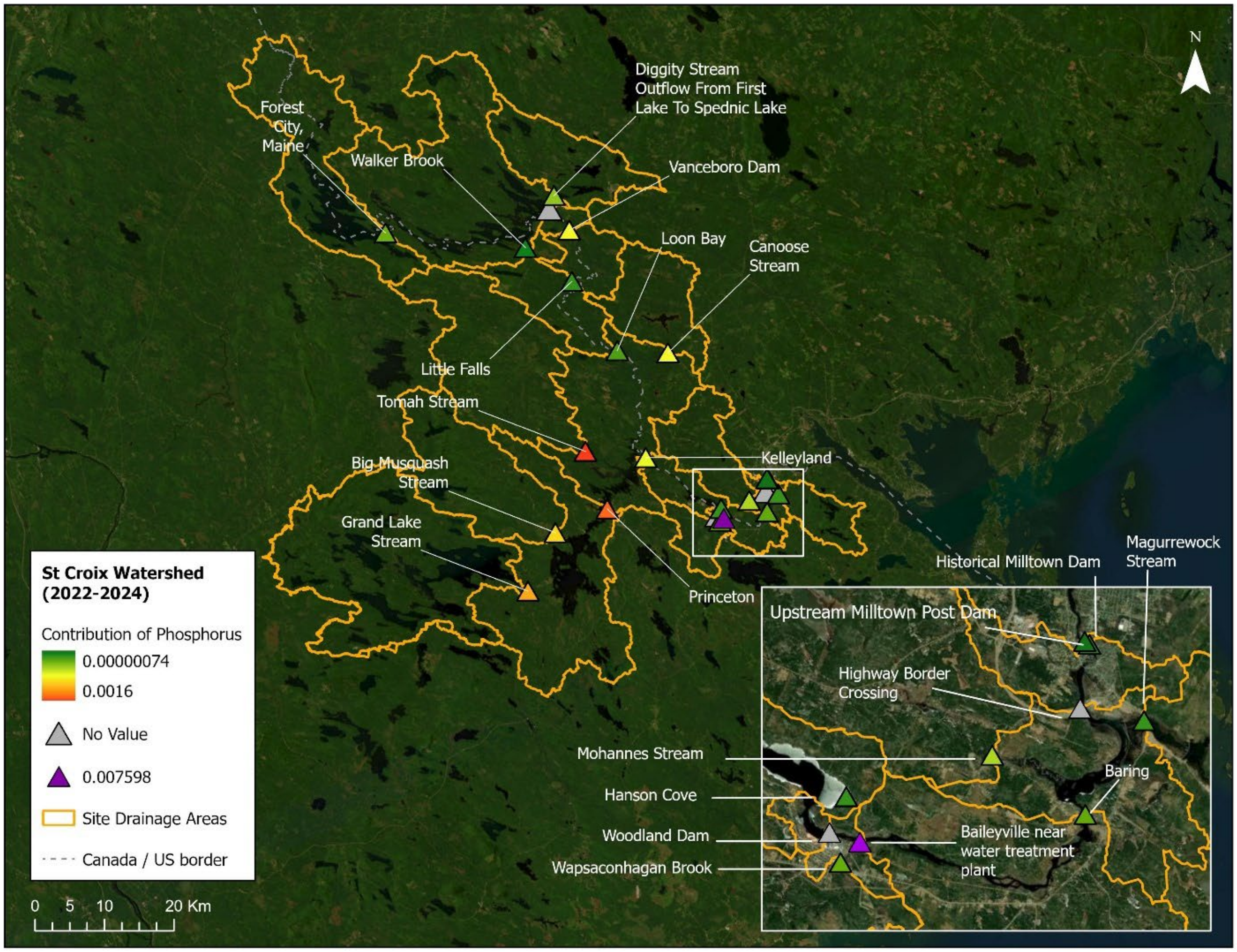

Figure 9: Calculated contribution of total phosphorus from each drainage basin in the St. Croix watershed. Median total phosphorus concentration (mg/L) were multiplied by the proportion of the drainage basin. The heat index represented the gradient of median total phosphorus contribution from low (green) to high (red/purple).

Tree Loss and Time on Median Nitrogen Concentrations

Loss in canopy coverage was tested with respect to natural variations over time to determine their influence on surface water nitrogen concentrations. A multiple linear regression (MLR) indicated that a strongly positive relationship was found when the influence of tree loss and year against surface water nitrogen concentrations were tested F (2,14) = 17.95, $p < 0.001$ and explained 72% of variance ($R^2 = 0.72$) (Table 5). While the year did not significantly predict median nitrogen concentrations (p = 0.150), tree loss was found to be significantly associated with nitrogen concentrations in the watershed (Table 3, Figure 10).

Table 3. Summary of MLR coefficients results.

Variable	B	SE	T-Value	P-Value
Intercept	-4.49	3.20	-1.404	0.182
Tree Loss (kHa)	**0.03**	**0.008**	**3.476**	**0.004**
Year	0.002	0.002	1.522	0.150

Note[1]. R^2 = 0.720, Adjusted R^2 = 0.679, F (2,14): 17.95, *P-value* = 0.0001, N = 17, *Residual SE* = 0.0256.

Note[2]. *Diagnostic tests found in the Appendices.*

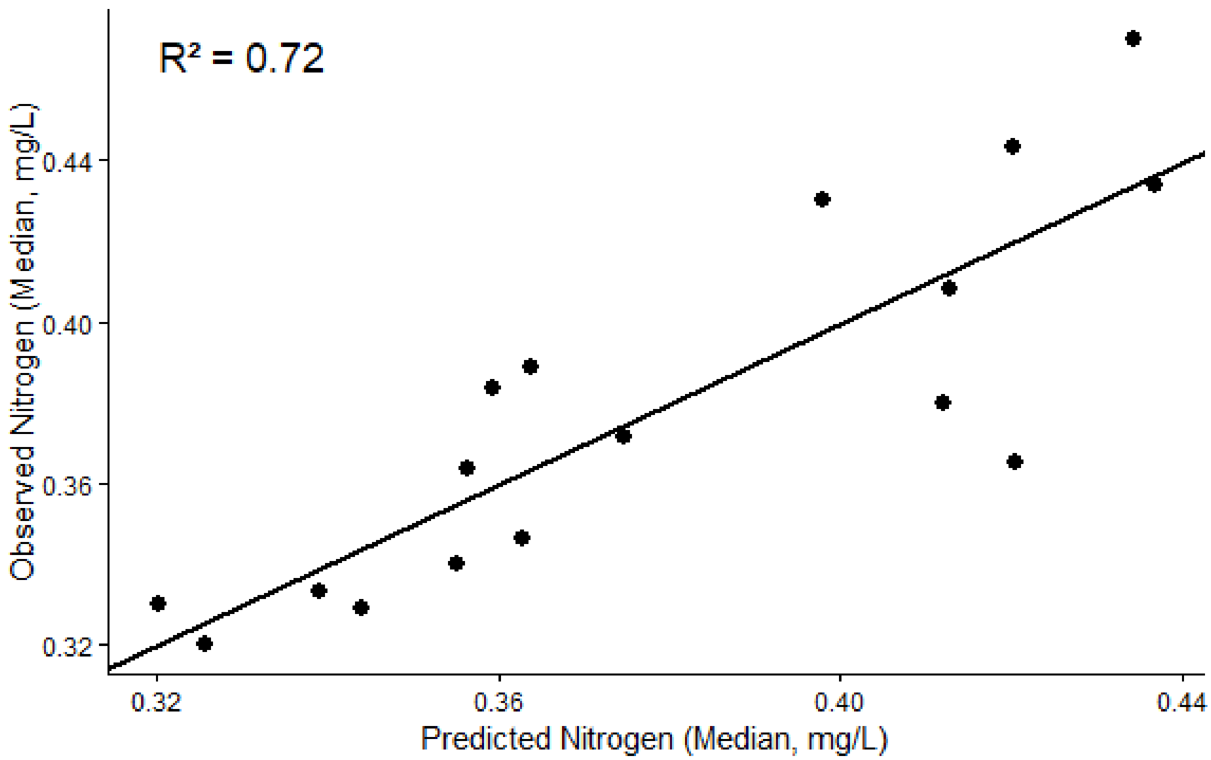

Figure 10. Predicted (x-axis) vs. Observed (y-axis) average nitrogen concentrations.

Correlation of nutrient concentration and discharge

Spearman's Rank Correlation Coefficient was used to assess and identify moderate to strong negative correlations between both nitrogen and phosphorus concentration and discharge rates at Baring (Figure 11 A & B; Table 3), while phosphorus concentrations had a weak negative correlation with discharge at Forest City (Table 3). No correlations between nutrient concentrations and discharge were identified at either Vanceboro or Grand Lake Stream. The Baring stream gauge represented the association between low flow conditions and elevated nutrient concentrations.

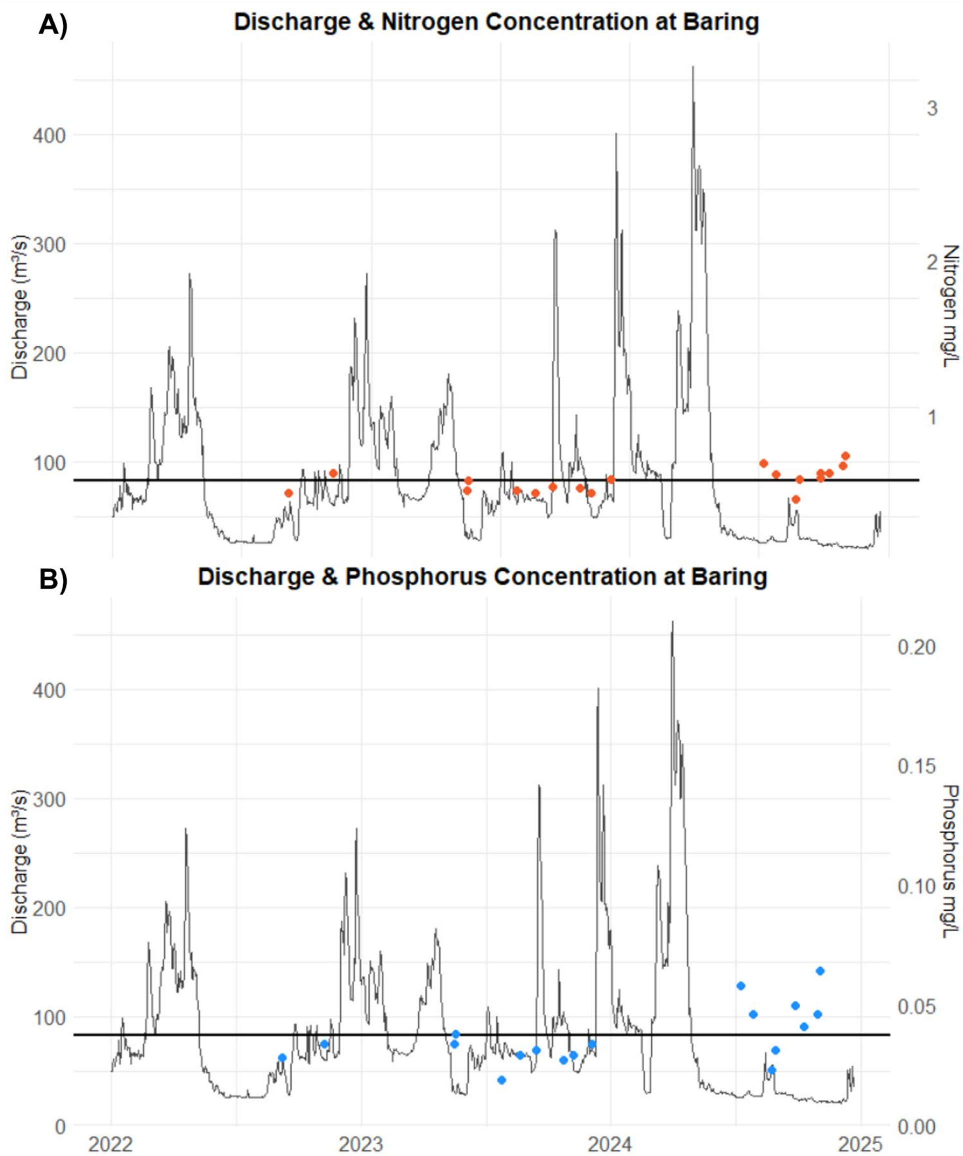

Figure 11 (A & B). A hydrograph of total nitrogen (A) and total phosphorus (B) concentrations at Baring paired with discharge data over the water quality sampling period.

Table 4. Spearman's Rank Correlation test results for all four sites with concentration and discharge data available during the study period.

Site	Nutrient	Spearman's Rho	Sample Size (n)	P-value
Baring	TN	-0.65	19	**0.003**
	TP	-0.8	19	**0.000**
Vanceboro	TN	0.04	14	0.903
	TP	0.07	14	0.816
Grand Lake Stream	TN	0.31	15	0.262
	TP	0.05	15	0.852
Forest City	TN	-0.07	115	0.457
	TP	-0.20	115	**0.016**

Nutrients over time and seasons

The total nitrogen concentrations found at Forest City between 2022-2024 were consistently below mesotrophic levels of 0.7 mg/L (Dodds et al., 1998) (Figure 12 A) when analyzing seasonal nutrient patterns. The long-term total nitrogen and total phosphorus data from 2006-2024 indicated that seasonal differences are present and significant at this site, though no monotonic trend was present (Figure 12 B & Table 5). Total phosphorus levels were below the NBDELG threshold of 0.03 mg/L between 2022-2024 and the long-term data also indicated the effect of seasonality on total phosphorus concentration level (Figure 12 B & Table 5).

Nutrient concentrations examined mid-stream in Baring (2022-2024) showed annual differences in concentrations that relate to weather conditions experienced during the monitoring period (Figure 11 & Figure 13). Total nitrogen and phosphorus concentrations were lower in 2023, a year that had elevated precipitation when compared to elevated nutrient concentrations during the hot and dry year of 2024 (Figure 11 & Figure 13). Additionally, sample collection routinely missed the spring freshet indicated by the lack of samples between April-June and limited samples collected in 2022. Throughout the sampling period, there were several instances of total nitrogen that exceeded 0.7 mg/L and total phosphorus that exceeded 0.03 mg/L, which may signal increased biological activity in this area.

Finally downstream in Milltown, total nitrogen concentrations were below mesotrophic levels during both pre-dam and post-dam removal. Long term data from 2006-2023 indicated a seasonal effect and an upward monotonic increasing trend in total nitrogen over 17-year period at a rate of 0.008 mg/L/year (Figure 14 A & B; Table 5). Total phosphorus had several exceedances of the NBDELG threshold of 0.03 mg/L for the proliferation of algal biomass (NBDELG, 2019) in both pre-dam and post dam sites, however the long-term data for total phosphorus between 2006-2023 did not indicate a trend but it did show effect of seasonality.

Table 5. Seasonal Mann Kendall results for sites with long-term water quality data.

Site	Nutrient	Seasonality Present?	Tau	MK P-value	Sen Slope (unit/year)	Trend
Forest City	Total Nitrogen	Yes	0.108	0.237	0.000	N
Forest City	Total Phosphorus	Yes	-0.051	0.588	0.000	N
Milltown Pre Removal	**Total Nitrogen**	**Yes**	**0.431**	**0.000**	**0.008**	**UP**
Milltown Pre Removal	Total Phosphorus	Yes	0.070	0.460	0.000	N

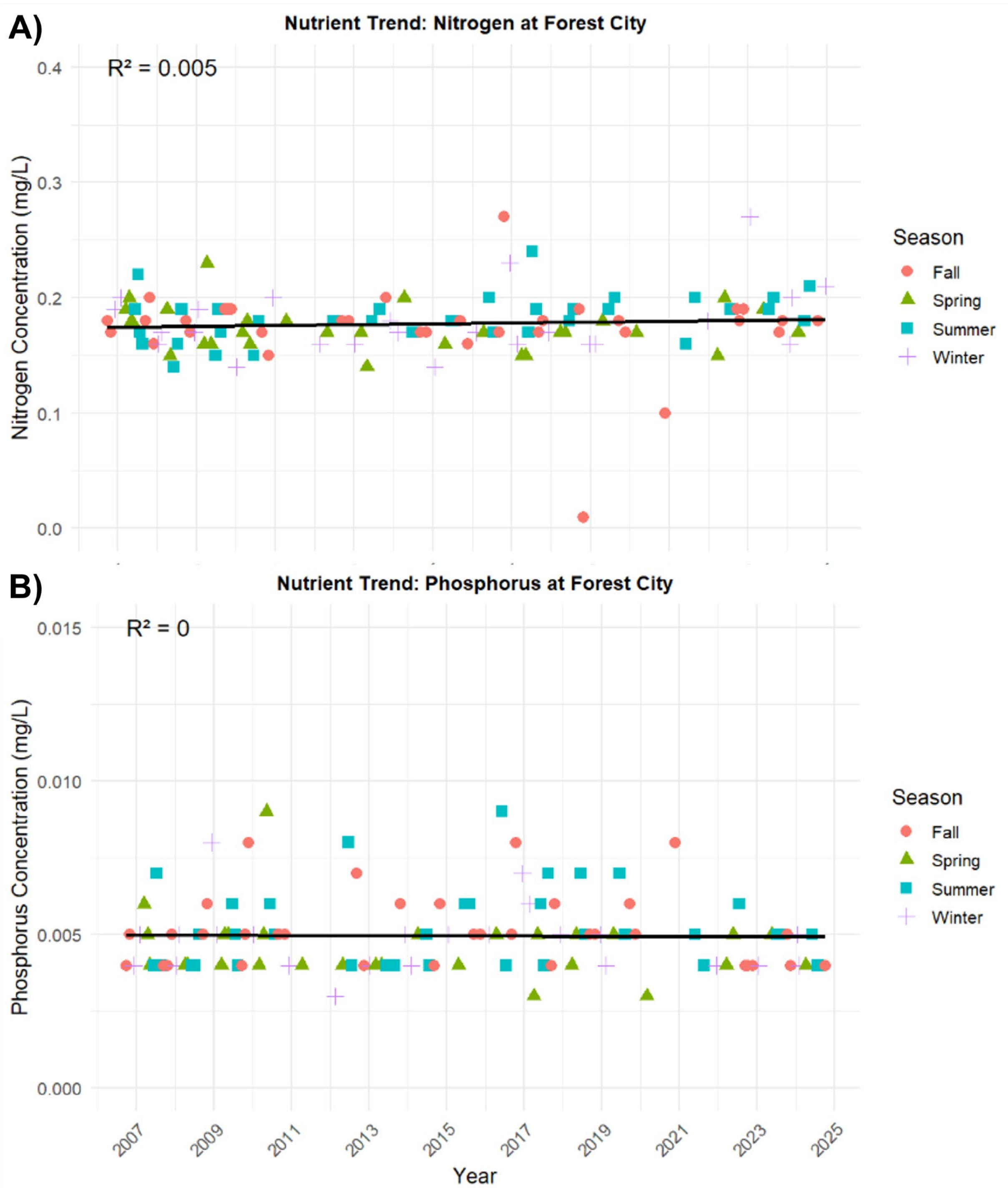

Figure 12 (A & B): Total nitrogen (A) and total phosphorus (B) concentrations at Forest City between 2006-2024 sub-classified by season.

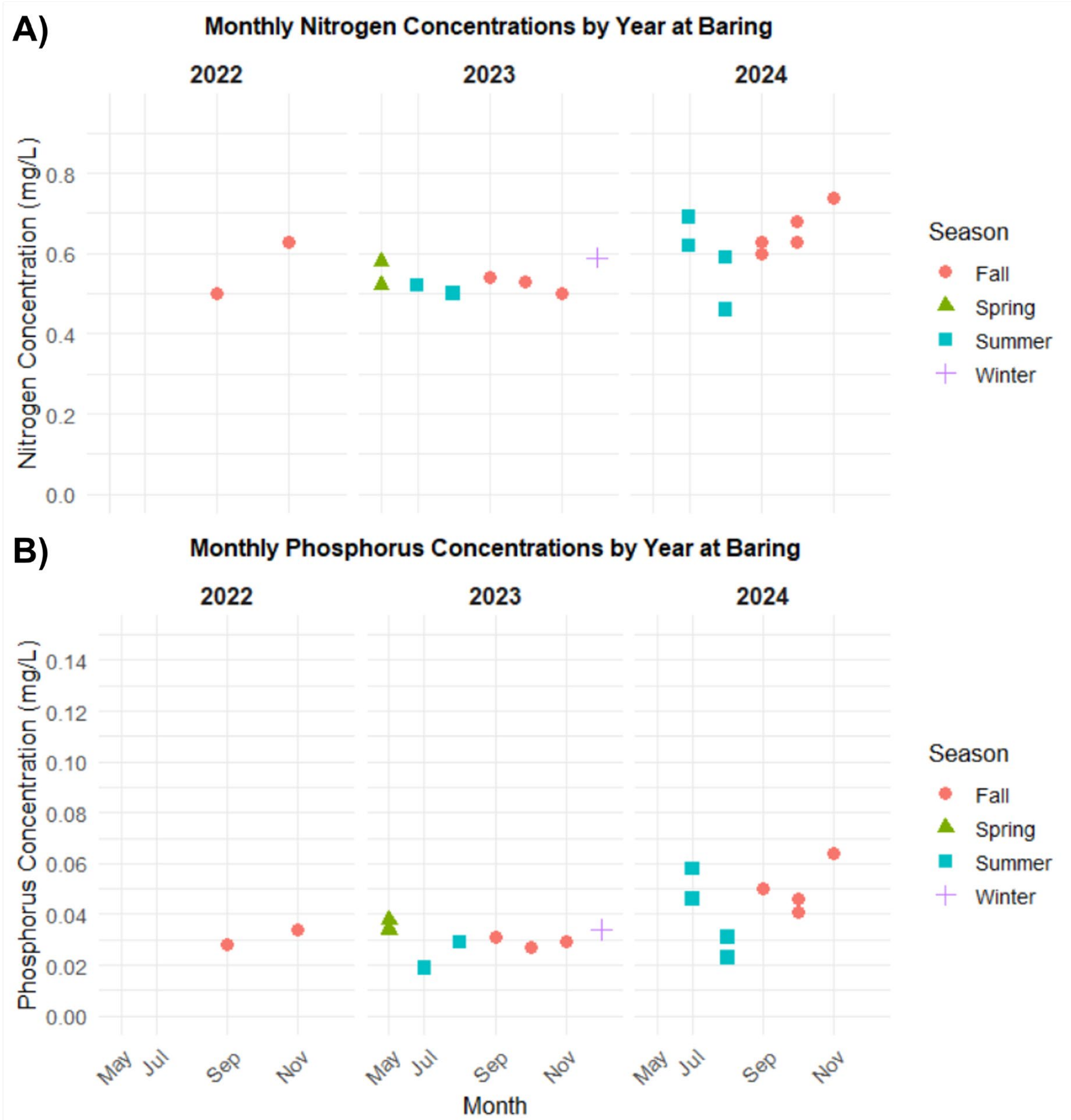

Figure 13 (A & B): Total nitrogen (A) and total phosphorus (B) concentrations at Baring between 2022-2024 sub-classified by season.

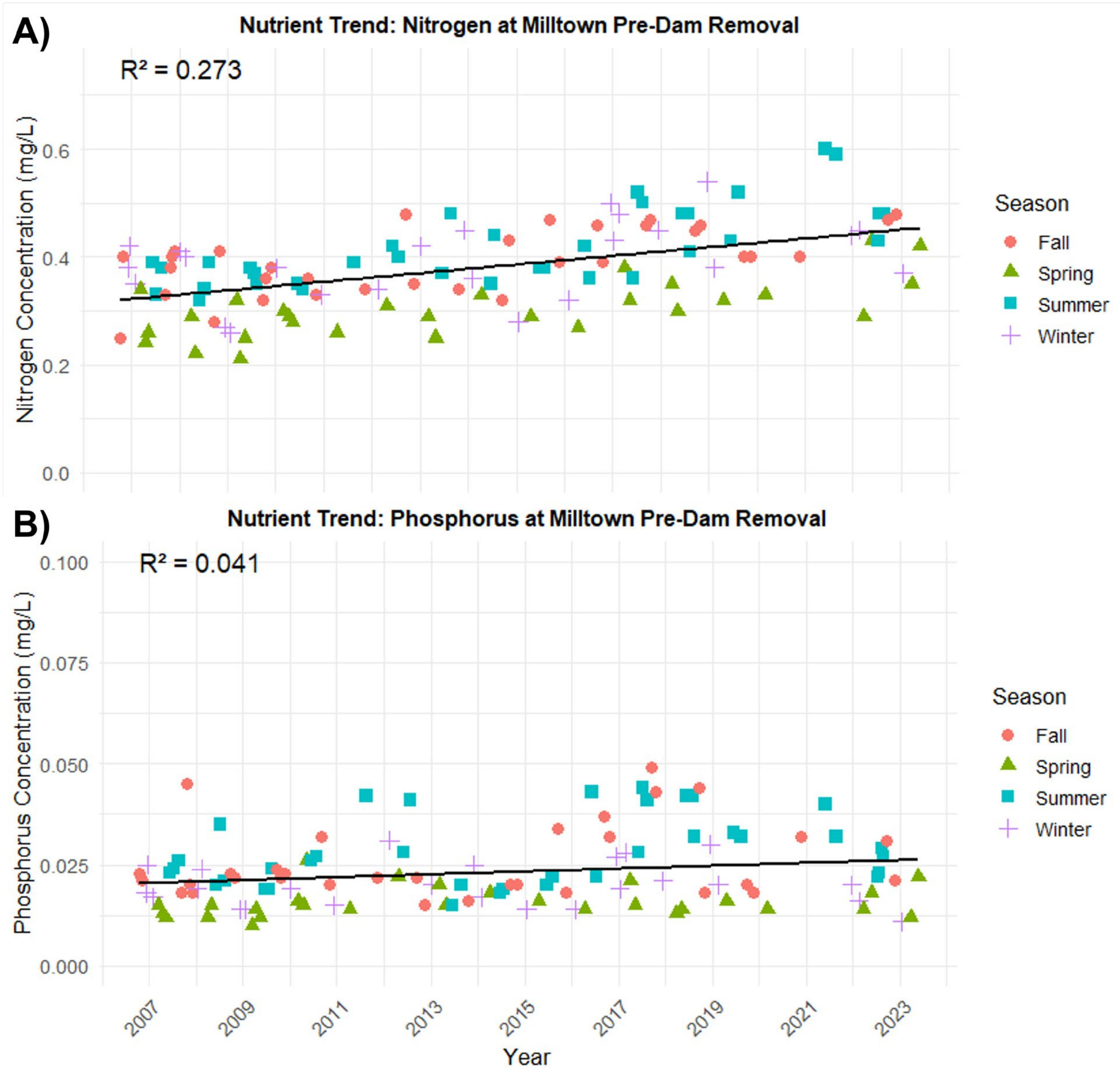

Figure 14 (A & B): Total nitrogen (A) and total phosphorus (B) concentrations at Milltown Pre-Dam Removal site between 2006 to 2023 sub-classified by season.

Discussion

A previous report from ECCC (2019) identified an increasing trend in nutrient concentrations on the St. Croix and warranted further investigation. Throughout the 23 sites sampled across the watershed from 2022 to 2024, the median nitrogen concentrations showed a strong upstream–downstream gradient, while phosphorus demonstrated a more subtle upstream to downstream gradient, with both factors tied to land use and point sources. Dodds et al. (1998) proposed a trophic level classification system based on total nitrogen, total phosphorus concentrations and algal biomass concentrations, that was used to describe nutrient conditions within the watershed. The drainage basin at Milltown encompassed much of the St. Croix watershed and had median total nitrogen and phosphorus concentrations of 0.45 and 0.021 mg/L respectively; indicating the area was most recently in an oligotrophic state.

Table 6: Trophic level classification of rivers and streams based on total nitrogen and total phosphorus concentrations (Dodds et al., 1998).

Nutrient	Oligotrophic	Mesotrophic	Eutrophic
Nitrogen	0-0.7 mg/L	0.7-1.5 mg/L	>1.5 mg/L
Phosphorus	0.025 mg/L	0.075 mg/L	>0.075 mg/L

On average, the upper portion of the watershed, dominated by forested headwaters, exhibited lower nitrogen and phosphorus levels from Forest City, Spednic Lake, Diggity Stream and Vanceboro. Transitioning to the mid-watershed, several sites such as Tomah Stream, Big Musquash Stream and Canoose had elevated canopy loss, suspected to be a result of forestry activities, as well as elevated median nutrient levels. Global Forest Watch (www.globalforestwatch.org) provided public satellite imagery of forest loss and forest gain starting from 2001. Despite a change in methodology in 2015, forest loss was noticed throughout the central portion of the watershed. Analysis of land use data extracted from ESRI Sentinel 2 with 30 m resolution further supports the increase in forestry practices in the watershed as a decrease in canopy coverage was detected between 2017 and 2024. It has been well documented that forestry activities near rivers and streams decrease water and nutrient uptake by soils, while also creating optimal environments for mineralization and nitrification as soils temperatures increase (Palviainen et al., 2004 & Kreutzweiser et al., 2008, Mellander et al., 2018, Finér et al., 2021). Less vegetation results in decreased potential for nutrient uptake, greater soil instability, and increased soil saturation and can result in enhanced potential for water entry via runoff events (Shah et al., 2022). Nutrient enrichments in clear-cut catchments are often short lived and can be detected between 1-5 years after clearing, though many instances exist where the effects on water quality continue to be measured beyond 5 years (Kreutzweiser et al., 2008 & Shah et al., 2022).

Along the main stem, median total nitrogen concentrations further increased but remain below mesotrophic levels of < 0.7 mg/L (Dodds et al., 1998) in Loon Bay, Kellyland, Hanson Cove and Woodland Dam which reflected a gradual enrichment from cumulative tributary inputs. Baileyville, located approximately 100 m below the Wooldland Pulp Outflow, exhibited the greatest nutrient enrichment in the watershed. The lower portion of the watershed had exceedances of the 0.03 mg/L phosphorus water quality objective for the prevention of algal blooms (NBDELG, 2019) in samples collected at Baileyville, Baring and Milltown, which could result in enhanced potential for harmful algal blooms to occur. Collectively, these patterns suggest that, while headwater streams maintained oligotrophic conditions, anthropogenic stressors such as forestry, urbanization and industrial processes elevate total nitrogen and to a lesser extent, total phosphorus downstream. Continued nutrient enrichment could lead to proliferation of algae and cause an overall decrease in ecosystem health that may impact fish and riverine benthic invertebrates (Mao et al., 2023 & Rolton et al., 2022).

Other factors associated with nutrient retention and accumulation could be dams or impoundments particularly those located on the mainstem. Dammed reservoirs affect nutrient levels differently because nitrogen is typically more soluble in the water column while phosphorus adsorbs to soil and sediment (Maavara et al., 2020) and is more likely to accumulate in head ponds. All portions of the watershed contained dams of various uses and sizes that can act as a sink for nutrients and sediments where nitrogen fixation can occur (Maavara et al., 2020). The magnitude of the dam (such as the height and reservoir size) can increase nutrient retention and unintended impacts on the river, such as impedance of fish migration (Schmutz & Moog, 2018). For example, the Milltown dam, one of the first hydroelectric dams in North America, was decommissioned in 2023-2024 due to its impacts on fish passage and abundance, particularly alewife, shad, and Atlantic salmon (Berry, 2024). Since all samples for Milltown (pre-2023) were reflective of the dam's presence, elevated nutrient concentrations could be partly attributed to the reservoir sink effect.

The ISCRWB reports annually on the status of point source pollution wastewater that is discharged in the St. Croix. There are 5 municipal wastewater treatment facilities, 3 in Canada that are regulated NBDELG and 2 in the United States that are regulated by Maine DEP. According to the 2022-2024 ISCRWB annual reports (ISCRWB 2023, ISCRWB 2024 & ISCRWB 2025) no wastewater discharge permit violations were reported at the City of Calais, Baileyville or town of McAdam wastewater treatment facilities. The facility in St. Stephen has been compliant, however has had several overflow events due to rain or snowmelt. Meanwhile, Evergreen Acres lagoon routinely had exceedances of carbonaceous biochemical oxygen demand (CBOD) and total suspended solids (TSS). While municipal wastewater is a known source of pollution, heavy regulations remain, and continued improvements have occurred since the 1970s as technology and analytical methods advanced. (Lofrano & Brown, 2010). Ammonia and other biological materials released in municipal effluent are contributing to baseline TN and TP concentrations, however the larger treatment facilities such as St. Stephen and Calais have discharge locations beyond our sampling site in Milltown and are therefore not captured by our samples. With no documented system failures or violations, we conclude that it is unlikely these upstream facilities were solely responsible for elevated nutrients levels in Milltown.

In addition to municipal wastewater treatment plant facilities, there were two industrial wastewater sources monitored by the ISCRWB: Champlain Industrial Park, and Woodland Pulp. Champlain had exceedances for CBOD and TSS (ISCRWB 2023, ISCRWB 2024 & ISCRWB 2025); however, the discharge location is below the sample site in Milltown and therefore not captured by the data used in this report. Woodland pulp had instances of unauthorized releases of chemicals in 2022, exceedances of copper and pH in discharges in 2023, and had no discharge violations in 2024 (ISCRWB 2023, ISCRWB 2024 & ISCRWB 2025). Although the discharge permit for Woodland pulp is regulated by Maine DEP, chemical releases must be submitted to the Toxic Release Inventory (TRI). Woodland Pulp total ammonia discharge records between 2006-2023 (Annex G) had the highest levels between 2006-2008 at a range of 237,900-259,000 tons. Levels drop significantly in 2009 to 99,100 tons and have since remained stable from 2010-2023, ranging from 46,700-83,800 tons. Despite the seemingly large amount of total ammonia being released by Woodland pulp, levels remained consistent over the past 10 years. The industrial effluent contributed to baseline nutrient concentrations but did not explain the on-going increase of total nitrogen detected within the St. Croix.

Relationships between nutrient concentration and local weather patterns were observed via hydrographs and in some instances, was supported with the Spearman's Rank analyses. Long term monitoring of temperature data at Forest City showed that the number of days above 20°C steadily increased from 64.9 days between 2007-2014 to 83.5 days between 2015-2024 (ISCRWB, 2025). Lower nutrient concentrations were noted during wetter and cooler portions of 2023 compared to elevated nutrient concentrations in the hot and dry year of 2024. These findings coincided with previous studies, where a dilution effect was noted in the seasons that are wetter, such as spring and fall (Zimmer et al., 2019). With the increased potential of extreme weather patterns, it is important to understand the impacts climate change will have on nutrient concentrations throughout this international and culturally significant watershed; a sentiment echoed by Costa et al. (2023) who highlights that climate change will have regional effects on nutrient dynamics. These warmer temperatures will also influence algal proliferation in addition to nutrient concentration. While seasonality tends to be a factor in larger datasets (Forest City and Milltown), these same patterns were not found at sites with limited datasets (Appendix D). However, the lack of pattern recognition does not mean the pattern is nonexistent. In addition, an upward trend of nitrogen at Milltown may indicate a change in nutrient inputs that exists in the mid-portion of the watershed as the nitrogen-based releases from the Baileyville area have not changed since 2011 (TRI, 2025). Further investigations in the mid-section of the watershed need to be conducted to determine baseline nutrient conditions and sources responsible for elevated nutrients. Longterm monitoring is also needed in this area to better understand water quality trends in this watershed.

Final Remarks

In conclusion, the results of this monitoring project confirmed earlier concerns of rising nitrogen concentrations and phosphorus levels in the lower portion of the watershed. The source of these elevated concentrations can likely be explained by a response to increased forest loss within the watershed. While nutrient concentrations in the upstream portion of the watershed remain low, the drivers of nutrient enrichment vary downstream and could indicate the sensitivity of the watershed to climate change. Compared to neighboring watersheds such as the Wolastoq (Saint John River), the level of activity and land use around the St. Croix is quite low and remains relatively unimpacted. Point sources of pollution continue to release effluent into the watershed under approved regulation and are contributing relatively consistent levels of nutrients to the watershed. However, the results from this study indicate that elevated samples of total nitrogen are likely due to deforestation practices such as clear-cutting. Seasonal and weather-related variability appeared to further influence nutrient dynamics, with higher concentrations observed during hot, dry conditions. Overall, these findings suggest the need for continued long-term monitoring, particularly at sites with limited data and where canopy coverage may have decreased over time, to address anthropogenic and climate-driven pressures on water quality in the St. Croix watershed.

Recommendations

ECCC recommends the following actions:

1. Investigating the effects of deforestation over long- and short-term periods, specifically clear cutting, by conducting sample collection in areas of high forestry activity. Ideally, this study would collect samples at regular intervals to better capture seasonal differences related to forestry activity.
2. Sampling above and below dams, as well as continued long-term sampling at Milltown may be useful for determining the impacts of these in-stream structures.
3. Algae analysis on rock surfaces could be conducted annually to monitor for changes of algae biomass, especially with consideration of cyanobacteria and harmful algal blooms.
4. Monitoring and/or assessing existing monitoring data downstream of Milltown in the estuary, capturing the added releases from Calais and St. Stephen, and determining whether there are areas with algal overabundance.
5. Further research on the effects of climate change on nutrient concentrations within this watershed should be considered with a focus surrounding baseline conditions in this watershed. Climate change and water modeling in the watershed could help better understand the long-term implications for nutrients.
6. The Board may want to consider adopting nutrient objectives as there is nothing to indicate that nutrient levels will stabilize or decrease in the future.

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Appendix

Appendix A: Definition of land cover legend

Water: areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.

Trees: Any significant clustering of tall (~15 feet or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).

Flooded: Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.

Crops: Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.

Built: Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.

Bare ground: Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.

Range land: Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees or other plants.

Appendix B: Sampling dates and number of samples collected between 2022-2024 used for statistical analyses.

Sampling Site	Latitude	Longitude	# of samples collected	Years
Baileyville	45.154306	-67.392454	9	2024
Baring	45.16549	-67.39028	19	2022-2024
Big Musquash	45.22618	-67.67976	15	2022-2024
Canoose Stream	45.37414	-67.35896	15	2022-2024
Diggity Stream	45.617342	-67.426342	12	2023-2024
Forest City	45.6641	-67.7336	123	2006-2025
Grand Lake Stream	45.1732	-67.7686	15	2022-2024
Hanson Cove	45.16549	-67.39028	14	2022-2024
Highway Border Crossing	45.16122	-67.30374	14	2022-2024
Kelleyland	45.26489	-67.47498	15	2022-2024
Little Falls	45.50845	-67.46245	14	2022-2024
Loon Bay	45.40388	-67.44052	14	2022-2024
Magurrewock			15	2022-2024
Milltown Pre-removal	45.17417	-67.29159	120	2006-2023
Milltown Post-removal	45.1686	-67.3006	8	2023-2024
Milltown US Dam	45.17417	-67.29159	13	2023-2024
Mohannes Stream	45.1596	-67.33838	15	2022-2024
Princeton	45.22603	-67.57677	15	2022-2024
Spednic Lake	45.60432	-67.44453	14	2022-2024
Tomah Stream	45.30441	-67.56922	14	2022-2024
Vaceboro	45.56901	-67.42765	14	2022-2024
Walker Brook	45.57251	-67.5133	14	2022-2024
Wapsaconhagan	45.151419	-67.401702	13	2023-2024
Woodland Dam	45.15956	-67.40062	10	2022-2024

Appendix C: Analytical parameters of St. Croix water quality samples

Parameter	
Major Ions	**Cations**
Alkalinity	Sodium
Chloride	Potassium
Sulphate	**Nutrients**
Bromide	Nitrate
Fluoride	Nitrite
Physical	Ammonia
pH	Total Nitrogen
Conductivity	Dissolved Nitrogen
Colour	Total Phosphorus
Turbidity	Dissolved Phosphorus
Cations	DOC/TOC
Calcium	Metals (29 elements)
Magnesium	

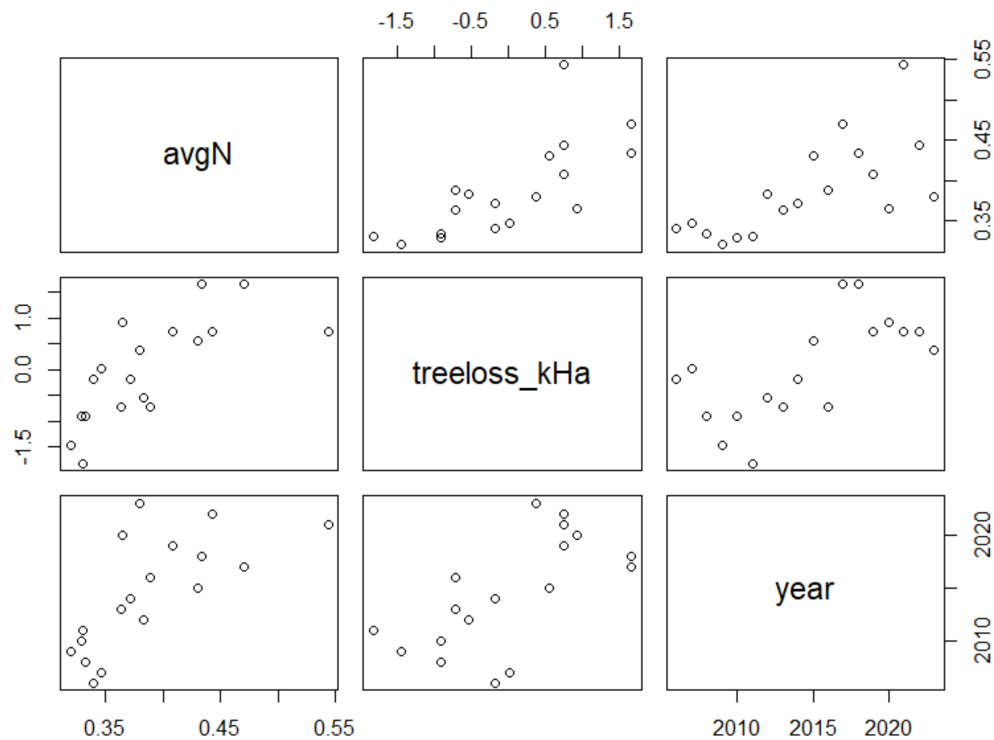
Appendix D: Kruskal Wallis and Mann Kendall test

Kruskal Wallis (seasonality) and (un)modified Mann Kendall test results for all sites over all available years of data. Rows that are blue and bold indicate a significant trend (MK P-value < 0.05), which is displayed under the trend column as either UP (increasing) or DOWN (decreasing), depending on the tau. N indicates no trend.

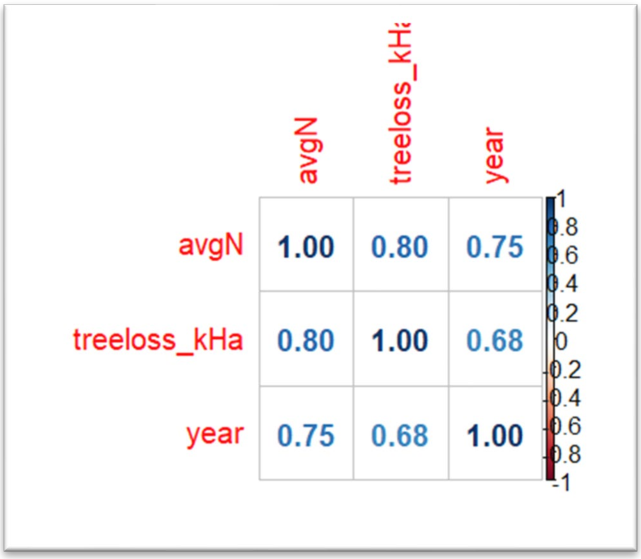
Site	Nutrient	KW P-value	Seasonality?	Tau	MK P-value	Sen Slope (unit/year)	Trend
Baileyville	Total Nitrogen	0.248	No	-0.600	0.221	-9.467	N
Baileyville	Total Phosphorus	0.564	No	-0.400	0.462	-0.763	N
Baring	**Total Nitrogen**	**0.349**	**No**	**0.457**	**0.008**	**0.070**	**UP**
Baring	**Total Phosphorus**	**0.847**	**No**	**0.407**	**0.018**	**0.011**	**UP**
Canoose Stream	Total Nitrogen	0.157	No	-0.010	1.000	0.000	N
Canoose Stream	Total Phosphorus	0.992	No	0.177	0.395	0.001	N
Diggity Stream	Total Nitrogen	0.064	No	0.202	0.407	0.028	N
Diggity Stream	Total Phosphorus	0.270	No	-0.137	0.613	0.000	N
Forest City	Total Nitrogen	0.007	Yes	0.108	0.237	0.000	N
Forest City	Total Phosphorus	0.044	Yes	-0.051	0.588	0.000	N
Grand Lake Stream	Total Nitrogen	0.549	No	-0.099	0.653	-0.010	N
Grand Lake Stream	Total Phosphorus	0.782	No	-0.091	0.687	0.000	N
Hanson Cove	Total Nitrogen	0.797	No	-0.343	0.108	-0.055	N
Hanson Cove	Total Phosphorus	0.797	No	-0.326	0.123	-0.002	N
Kelleyland	**Total Nitrogen**	**0.541**	**No**	**-0.483**	**0.015**	**-0.085**	**DOWN**
Kelleyland	Total Phosphorus	0.213	No	-0.270	0.198	-0.001	N
Little Falls	Total Nitrogen	0.448	No	0.000	1.000	0.000	N
Little Falls	Total Phosphorus	0.887	No	0.071	0.778	0.000	N
Loon Bay	Total Nitrogen	0.775	No	-0.291	0.169	-0.044	N
Loon Bay	Total Phosphorus	0.736	No	0.047	0.867	0.000	N
Magurrewock	Total Nitrogen	0.094	No	0.165	0.426	0.062	N
Magurrewock	Total Phosphorus	0.663	No	0.000	1.000	0.000	N
Milltown Pre Removal	**Total Nitrogen**	**0.000**	**Yes**	**0.431**	**0.000**	**0.008**	**UP**
Milltown Pre Removal	Total Phosphorus	0.000	Yes	0.070	0.460	0.000	N
Milltown Post Removal	Total Nitrogen	0.145	No	0.546	0.081	0.253	N
Milltown Post Removal	Total Phosphorus	0.359	No	0.571	0.063	0.013	N
Milltown U/S Dam	Total Nitrogen	0.136	No	-0.237	0.296	-0.036	N
Milltown U/S Dam	Total Phosphorus	0.099	No	0.123	0.618	0.001	N
Mohannes Stream	Total Nitrogen	0.087	No	-0.238	0.235	-0.056	N
Mohannes Stream	Total Phosphorus	0.174	No	-0.262	0.196	-0.003	N
Princeton	Total Nitrogen	0.103	No	-0.107	0.619	-0.011	N
Princeton	Total Phosphorus	0.843	No	-0.304	0.134	-0.006	N
Spednic Lake	Total Nitrogen	0.758	No	-0.104	0.656	-0.005	N
Spednic Lake	Total Phosphorus	0.497	No	0.370	0.091	0.001	N
Vanceboro	Total Nitrogen	0.314	No	0.141	0.536	0.010	N
Vanceboro	Total Phosphorus	0.276	No	0.271	0.243	0.000	N
Walker Brook	Total Nitrogen	0.063	No	0.303	0.152	0.109	N
Walker Brook	Total Phosphorus	0.057	No	0.344	0.099	0.007	N
Wapsaconhagan	Total Nitrogen	0.058	No	-0.219	0.328	-0.096	N
Wapsaconhagan	Total Phosphorus	0.553	No	0.359	0.100	0.009	N
Woodland Dam	Total Nitrogen	0.191	No	0.225	0.419	0.072	N
Woodland Dam	Total Phosphorus	0.513	No	0.322	0.239	0.002	N

Appendix E. Initial MLR results and diagnostic testing

1. Pairwise relationship exploration



2. Correlation plot



3. Partial Correlation controlling for year

Estimate	P-Value	Statistic	N	GP	Method
0.499	0.0416	2.23	18	1	Pearson

Model:

Variable	B	SE	T-Value	P-Value
Intercept	-8.05	4.71	-1.707	0.108
Tree Loss (kHa)	**0.03**	**0.012**	**2.228**	**0.042**
Year	0.004	0.002	1.789	0.094

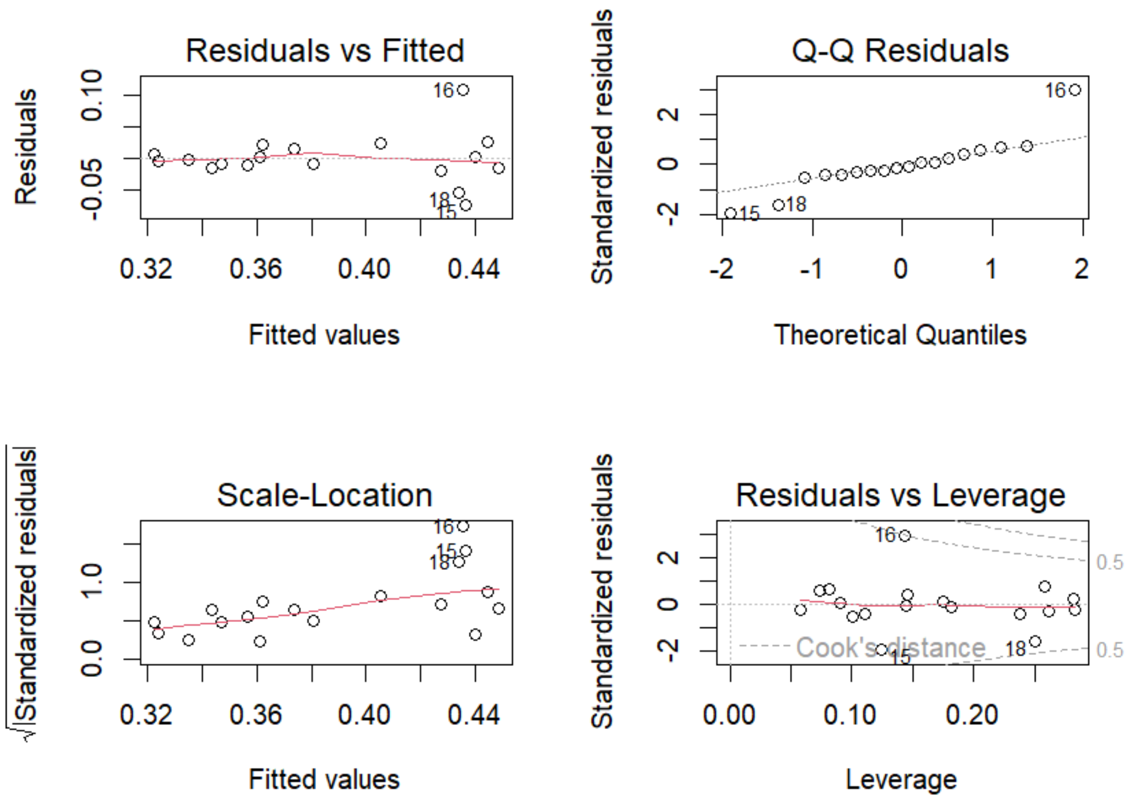
```
Residual standard error: 0.03888 on 15 degrees of freedom
Multiple R-squared:  0.6106,    Adjusted R-squared:  0.5587
F-statistic: 11.76 on 2 and 15 DF,  p-value: 0.0008473
```

4. Linear regression: median Nitrogen ~ tree loss + year

```
Call:
lm(formula = avgN ~ treeloss_kHa + year, data = df_std)

Residuals:
      Min        1Q    Median        3Q       Max
-0.071569 -0.013606 -0.003178  0.012970  0.107683

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
```

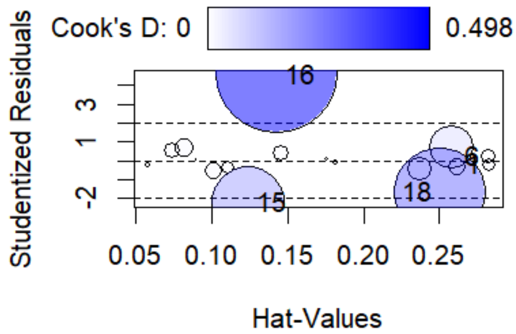
```
(Intercept)  -8.048720   4.714433  -1.707   0.1084
treeloss_kHa  0.027833   0.012493   2.228   0.0416 *
year          0.004188   0.002340   1.789   0.0937 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.03888 on 15 degrees of freedom
Multiple R-squared:  0.6106,    Adjusted R-squared:  0.5587
F-statistic: 11.76 on 2 and 15 DF,  p-value: 0.0008473
```

5. Diagnostics



Influence of individual points:

```
StudRes      Hat       CookD
1  -0.2145121 0.2830793 0.006467810
6   0.2269842 0.2816839 0.007189263
15 -2.2067881 0.1245347 0.183557835
16  4.5529218 0.1430674 0.498254233
18 -1.6961236 0.2506818 0.285134922
```



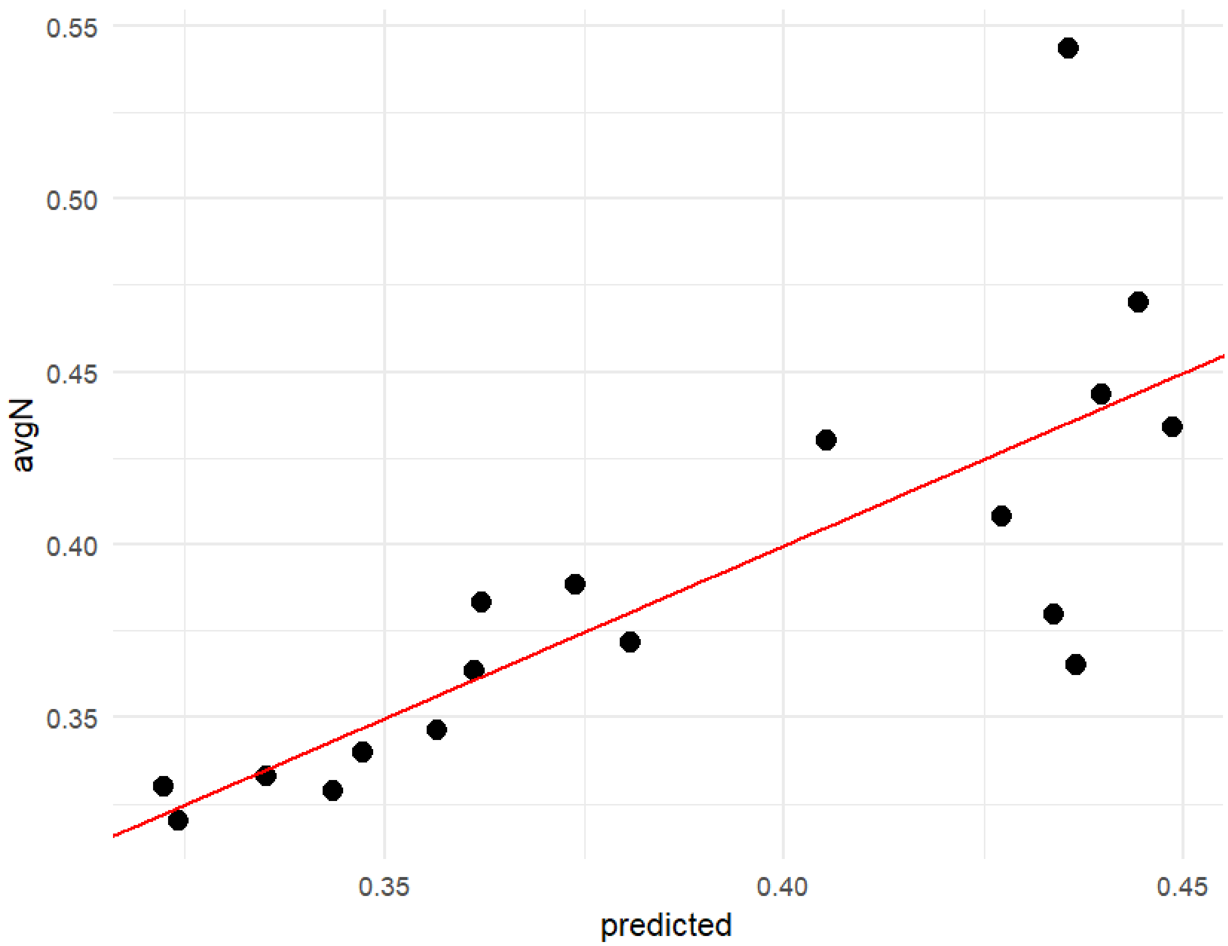
Normality test for residuals:

```
Shapiro-Wilk normality test

data:  residuals(reduced_model)
W = 0.86685, p-value = 0.0158
```

Multicollinearity check:

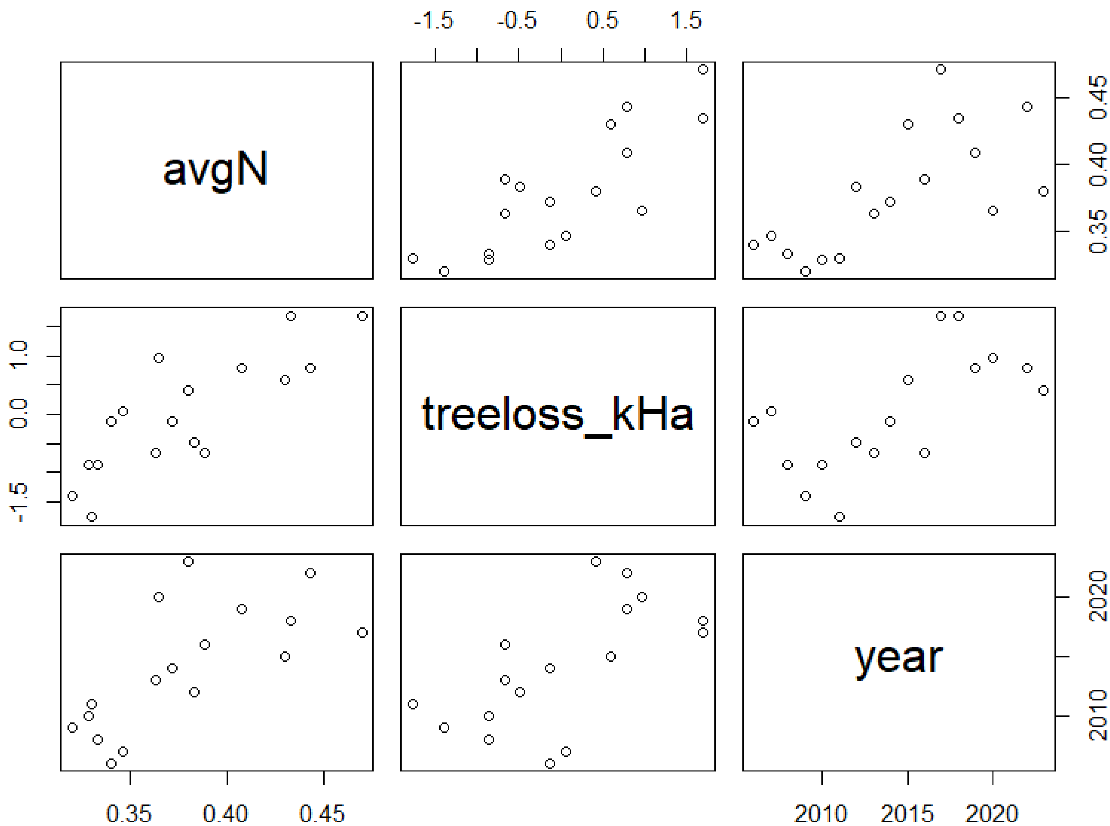
```
treeloss_kHa         year
    1.755678     1.755678
```

Predicted vs. Observed plot:



Appendix F – MLR with no extremely influential outlier (row 16)

1. Exploring Pairwise Relationships

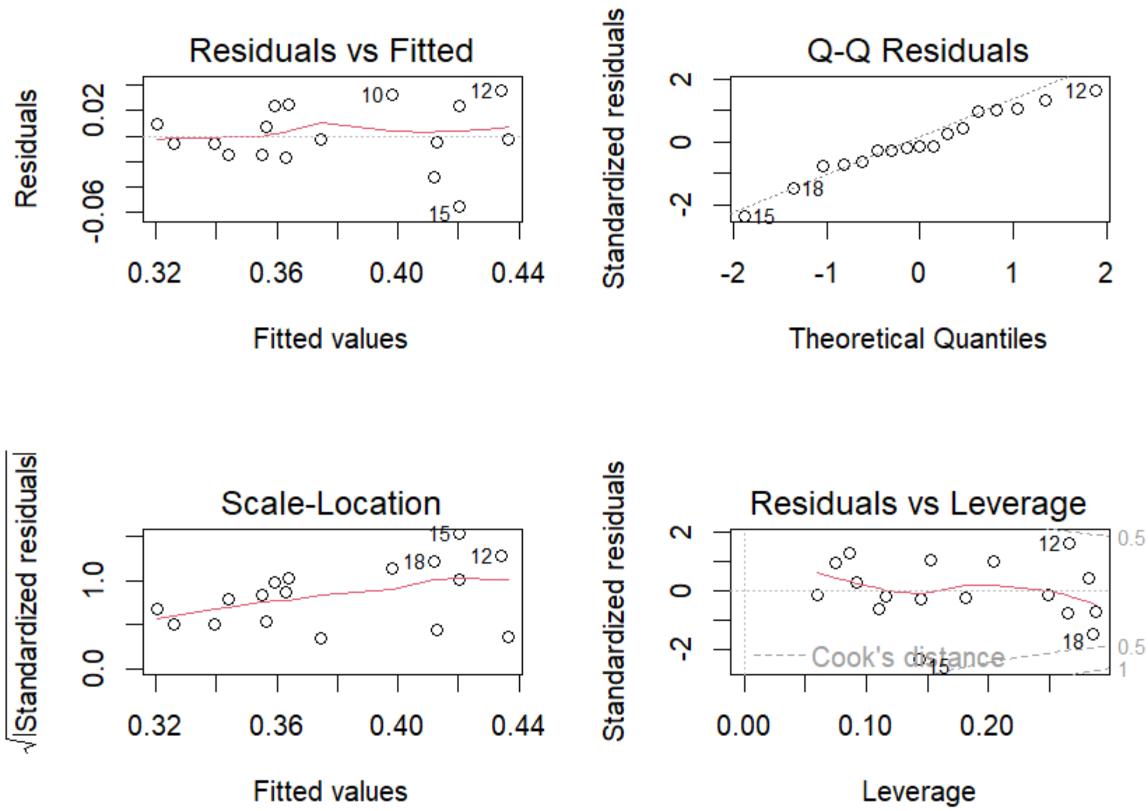


2. Correlation Plot

3. Partial correlation with control for year

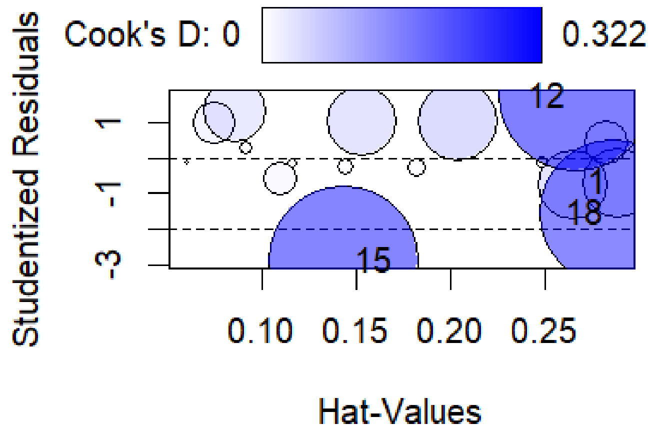
Estimate	P-Value	Statistic	N	GP	Method
0.681	0.004	3.48	17	1	Pearson

4. Diagnostics



Influence of Individual Points:

```
      StudRes       Hat      CookD
1  -0.6946817 0.2877696 0.06748851
12  1.7517894 0.2656274 0.32236237
15 -2.9041894 0.1436308 0.30798781
18 -1.5568299 0.2857523 0.29338701
```



Normality test of residuals:

```
Shapiro-Wilk normality test

data:  residuals(reduced_model)
W = 0.95168, p-value = 0.4837
```

5. Multicollinearity check

```
treeloss_kHa         year
    1.695737     1.695737
```

Annex G: Woodland Pulp nitrogen and ammonia discharge data reported to the Toxic Release Inventory between 2006-2023.

Year	Nitrogen Compound (tons)	Ammonia (tons)	Total N (tons)
2006	241,000	18,000	259,000
2007	228,000	17,000	245,000
2008	224,900	13,000	237,900
2009	91,100	8,000	99,100
2010	38,200	11,000	49,200
2011	31,700	15,000	46,700
2012	42,700	16,000	58,700
2013	38,500	23,000	61,500
2014	39,300	27,000	66,300
2015	63,800	20,000	83,800
2016	42,700	24,000	66,700
2017	42,600	28,000	70,600
2018	33,200	20,000	53,200
2019	33,200	17,000	50,200
2020	42,000	17,000	59,000
2021	43,400	14,000	57,400
2022	44,400	17,000	61,400
2023	34,400	15,000	49,400