Nitrogen Budgets for Mainstem Segments of the Lamprey River

A Report for the Lamprey River Advisory Committee

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Executive Summary

The Lamprey River is an important freshwater ecosystem that provides ecosystem services ranging from drinking water provision to recreation. Nutrient cycling is a key ecological function that contributes to river water quality and therefore a "fishable and swimmable" Lamprey River. Continued protection and restoration of water quality for the Lamprey River requires a full understanding of how nutrients, including nitrogen and phosphorus, are both transported and transformed within the river ecosystem. The objective of this project was to determine whether nitrogen inputs to the Lamprey River are conservative or reactive across varying time scales and whether they respond to phosphorus inputs. To achieve this goal, we examined water quality data for total dissolved nitrogen (TDN), dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), and orthophosphate (PO_4) across multiple sampling stations and years within the Lamprey River basin.

Spatial and temporal trends in nutrient loading and nitrogen budgets were examined at 21 sampling stations located throughout the Lamprey River watershed. Sampling stations included 10 mainstem stations along the Lamprey, along with 4 mid-sized and 7 small tributaries. Stations have been sampled at a monthly to weekly frequency for at least 4 years and capture the downstream progression of nutrients throughout the river network. The longest monitored station, LMP73, has been sampled weekly since 1999. Annual nutrient loads (mass/time) were calculated for each station using runoff-weighted mean concentrations and streamflow data. Decadal median loads for each site were used to determine nitrogen inputs and outputs for each segment of the Lamprey River. Estimates of the change in nitrogen storage within the river network were determined using a mainstem nitrogen budget. Annual N:P ratios were assessed using median TDN and PO_4 at each station, except for LMP73 where total nitrogen (TN) and total phosphorus data (TP) were also available.

Overall, median annual nitrogen loads (TDN, DIN, and DON) did not vary greatly between stations or over time, except for small tributaries. Stations with agricultural (BDC0.30) or suburban (WHB01; MLB01) land use had significantly higher mean annual TDN and DIN loads than all the other sampling stations. Among the 21 sampling stations, median TDN loads ranged from 0.37 to 8.04 kg N/ha/yr and median DIN loads ranged from 0.06 kg N/ha/yr to 5.4 kg N/ha/yr, accounting for 14 to 88% percent of TDN flux. Median DON loads ranged from 0.31 to 2.44 kg N/ha/yr. A total of 6 stations exhibited significant decreasing temporal trends in annual TDN and DIN loads and only 2 showed significant decreasing temporal trends for annual DON loads. Median annual PO_4 loads did not exhibit spatial variation between stations, except for BDC0.30, whose median load was an order of magnitude larger than all other sites. PO_4 loads showed more temporal variability, with 13 stations having significant increasing trends in annual loads over time.

Nitrogen inputs and outputs for segments of the Lamprey River were calculated on a decadal scale to assess changes in nitrogen storage. The nitrogen budget showed that TDN incremental loads ranged from -0.37 kg N/ha/yr to 11.93 kg N/ha/yr, DIN incremental loads ranged from -1.16 kg N/ha/yr to 9.17 kg N/ha/yr, and DON incremental loads ranged from 0.45 kg N/ha/yr to 2.91 kg/N/ha/yr. Most river segments had positive incremental loads, indicating that downstream nitrogen outputs were greater than nitrogen inputs upstream. Positive loads may indicate nitrogen production is happening in-situ through nitrogen fixation, or that there are additional inputs of nitrogen not quantified in this budget. LMP67 and LMP78 were the only two stations to show negative incremental nitrogen loads, indicating that outputs were less than nitrogen inputs. For LMP67, both DIN and TDN showed negative incremental loads in the second decade (water years 2010-2019). LMP78 only exhibited a negative incremental load for DIN in the first decade (water years 2000-2009). Negative loads indicate nitrogen is being transformed and either retained in-stream or lost to the atmosphere through denitrification. It is important to note that the positive incremental loads found between most stations indicate a net accumulation of N in the river. This does not mean that no N is removed from the water column, but instead means that any removal processes are more than offset by unmeasured inputs.

When apportioned by town, Epping and Raymond had the largest, provisional estimates of contributions to TDN and DIN loads. Between towns and across decades, TDN loads ranged from 1.05 to

3.99 kg N/ha/yr, DIN loads ranged from – 0.13 to 2.73 kg N/ha/yr, and DON loads ranged from 0.93 kg to 1.69 N/ha/yr. Towns with negative portions of the DIN load were positioned within the LMP67 or LMP78 watersheds, where DIN incremental loads were negative.

Introduction

The Lamprey River is an important freshwater ecosystem that provides wildlife habitat, supports recreational activities, and contributes to the local drinking water supply. Nutrient cycling is a key ecological function that contributes to river water quality and therefore a "fishable and swimmable" Lamprey River. In excess, nutrients like nitrogen and phosphorus can cause eutrophication within the river and downstream in Great Bay estuary. Eutrophication events contribute to algal blooms, anoxic waters, and declining water quality conditions, all of which can threaten the ecological function of both the river and the estuary. Documented nitrogen impairments for both the Lamprey and Great Bay are concerning due to the relationship between nutrient stimulated phytoplankton growth and light availability in the water column (Piscataqua Region Estuaries Partnership, 2018). Competing species of seaweed and phytoplankton, which thrive under nutrient rich conditions, shade out native eelgrass and contribute to its decline across New England estuaries (Short & Burdick, 1996). Future protection and restoration of water quality requires an understanding of the river ecosystem's ability to transport and transform inputs of nutrients both throughout the river network and downstream to the estuary.

Research and assessment of water quality for the Lamprey River has historically focused on one form of nitrogen, nitrate (NO_3^-), due to the scope of federal water quality regulations. National Primary Drinking Water Regulations, enforced by EPA, specify a maximum contaminant level (MCL) for nitrate in drinking water at 10 mg-N/L to protect human health (EPA, 2015). The Lamprey River is designated as nitrogen impaired for aquatic life integrity on the New Hampshire 303(d) list (Wood & Edwardson, 2020). This means nitrogen levels are high enough to impede the river's ability to fully support aquatic species. Nitrate is an important form of nitrogen, whose load can be managed through regulation of point sources like wastewater treatment plants. While it makes sense to monitor nitrate levels, expanding our purview to other forms of nitrogen allows us to assess the Lamprey River as an ecosystem and determine its ability to regulate the nitrogen cycle in the face of increasing anthropogenic pressure.

The dissolved portion of the nitrogen cycle includes both organic and inorganic forms of nitrogen in the water column. The summation of nitrate, nitrite (NO_2^-), and ammonium (NH_4^+) is referred to as the dissolved inorganic nitrogen (DIN) pool. Dissolved organic nitrogen (DON) refers to additional forms of nitrogen including complex organic molecules. The total dissolved nitrogen (TDN) pool is the summation of the DON and DIN pools. Previous work examined spatial and temporal trends in nitrate throughout the watershed and concluded that nitrate did not significantly vary across the 23 years of sampling (Kotowski, 2016). Across the entire watershed, DIN loads have been shown to respond to human inputs of nitrogen, whereas DON loads weakly correspond to natural landscape features like wetland cover (Daley et al., 2010). In-stream and terrestrial retention of nitrogen in the watershed was additionally shown to decrease with increasing nitrogen inputs, suggesting reduced nitrogen uptake efficiency and denitrification (Daley et al., 2010). As watershed nitrogen retention decreases, the Lamprey River is more likely to move excess nitrogen further downstream.

To better understand the ecological role of the Lamprey River in regulating inputs of nutrients, this report examined whether the river functions as a transporter or transformer of nitrogen. A transporter role indicates that nutrients flow conservatively downstream through an "unreactive pipe". A transformer role indicates that nutrients are produced or retained within the river as it flows downstream, effectively changing the amount present within the river. Determining whether the Lamprey River behaves as a transporter or transformer of nitrogen will help quantify the threshold of nitrogen inputs the river ecosystem can manage. The research objective of this project was to determine if nitrogen inputs are conservative or reactive within the Lamprey River at varying time scales, and whether they respond to phosphorus inputs. We asked the following questions:

1) How does the biogeochemical role of the Lamprey River change over spatial and/or temporal scales?
2) What is the biogeochemical role of the Lamprey River watershed as an ecosystem – is it a transporter or transformer of nitrogen?
3) How much of the overall Lamprey N load is attributable to sub-watersheds and towns within the river basin?

Methods

Site Description

The Lamprey River watershed drains 554 km^2 before entering Great Bay estuary (Coble et al., 2018). The watershed drains 479.2 km^2 at the sampling station LMP73, which is also the location of a USGS gauging site (site 01073500 waterdata.usgs.gov). Inputs of nitrogen and phosphorus to the watershed include both point and non-point sources. Two wastewater treatment plants, located in Epping and Newmarket, represent point-source pollution sources that discharge into the Lamprey River via traceable pipe outflows. The Epping wastewater treatment plant is located upstream of the monitoring station LMP51. Non-point sources of nitrogen and phosphorus are diffuse and less easily traced back their points of origin (US EPA, 2015). In the Lamprey River watershed, nonpoint sources of nitrogen pollution include septic systems, fertilizer use, animal waste, and atmospheric deposition (Trowbridge et al., 2014).

Discharge and Water Chemistry

Discharge is measured every 15 minutes by the U.S. Geological Survey at the gage located near Newmarket, NH (site 01073500, waterdata.usgs.gov). Mean daily discharge (cfs) was downloaded for the period of interest (Water Years 2000-2019) (Figure 1). Values were converted to cubic meters per second and scaled up to the time period of days. Discharge was then converted to a runoff estimate by dividing each measurement by the watershed area at that gaging station (water quality monitoring station LMP73).

Since September of 1999, the NH Water Quality Analysis Laboratory has monitored nutrient concentrations in the Lamprey River and its major tributaries. A total of 21 sites, ranging from the headwaters to the mouth of the Lamprey River, have been sampled at a monthly to weekly frequency (Figure 2). Sites included in this analysis have been monitored for at least 4 years (Table 1). The most frequently sampled site, located near the Packers Falls USGS gauging station, has 20 years of weekly data. All samples were analyzed for TDN, NO_3-N, NH_4-N and PO_4-P in the Water Quality Analysis Laboratory at the University of New Hampshire. Samples from LMP73 at Packers Falls were additionally analyzed for TN and TP. DON was calculated as the difference between TDN and DIN, which is the sum of nitrate and ammonium. 127 samples had a higher concentration of DIN than TDN. In those instances, samples were only retained for further analysis if the relative percent difference between DIN and TDN was less than 15%. Consequently, 34 samples were removed from the dataset prior to analysis. The number of samples taken per station over the 20-year period ranged from 111 to 1128 (mean: 322, median: 254).

Data Analysis

Annual loads were calculated using paired nutrient concentrations (mg/L) and streamflow (cubic feet/second) data at each site. Volume weighted mean annual concentrations were multiplied by annual runoff to determine annual loads (kg/ha/year) for each water year. A water year is defined as a 12-month period starting October 1st and continuing through to September 30th of the following year (USGS, 2016). For example, the water year 2019 runs from October 1st, 2018 to September 30th, 2019. Annual loads for each site were calculated for water years with a minimum of 10 collected water samples (Aulenbach et al., 2007). TDN:PO_4 ratios for all stations and TN:TP ratios for LMP73 were calculated by first converting flow-weighted nutrient concentrations to molar units. TDN:PO_4 ratios reflect the ratio of annual median TDN and PO4 runoff-weighted concentrations.

Incremental nitrogen loads, also known as Δ storage, were calculated between upstream and downstream monitoring stations using the basic mass balance equation:

$$Inputs + \Delta\, Storage = Output \qquad \text{[Eq. 1]}$$

Inputs refer to upstream stations and output refers to the downstream monitoring station. Incremental loads were only calculated between stations with a minimum 5% increase in incremental watershed area and if there were at least 5 years of monitoring data. To account for differences in sampling periods and frequency between stations, median annual nitrogen loads (kg/yr) were calculated by multiplying the runoff-weighted mean N concentration by median annual runoff for each of the two decades. Median annual runoff (USGS station 1073500) in decade 1 (WY 2000-2009) was 620 mm/year and 520 mm/year in decade 2 (WY 2010-2019). Incremental loads were calculated for TDN, DIN, and DON. An example incremental load calculation between mainstem monitoring stations LMP39 and LMP51 is shown below, where LMP39 and PWT10 are upstream of LMP51.

$$\frac{(LMP51\ TDN\ kg/yr - (LMP39\ TDN\ kg/yr\ +\ PWT10\ TDN\ kg/yr)}{[LMP51\ Area\ (ha) - \left(LMP39\ Area\ (ha) + PWT10\ Area\ (ha)\right)]} = \Delta\ storage\ kg\ TDN\ ha^{-1}\ year^{-1}$$

Nitrogen is considered conservative if there is no change in Δ nitrogen storage (i.e. 0 kg/ha/yr) between segments of the river. Nitrogen is considered reactive if there is a change in Δ storage, reflecting a transformation between river stations. Positive Δ storage values indicate a higher output nitrogen load than input nitrogen load for a given segment of the river network, reflecting the possibility of nitrogen production as water flows downstream. Negative Δ storage values indicate a smaller output than input nitrogen load, reflecting nitrogen retention within the river network. Negative values may also indicate removal of nitrogen from the dissolved portion of the nitrogen cycle via denitrification.

Town areas within each incremental watershed were determined by intersecting watershed and town boundary shapefiles in ArcGIS. TDN, DIN, and DON incremental loads were then apportioned based on incremental town areas. Incremental loads and town areas were summed to calculate the cumulative portion of nitrogen loading attributable to individual towns.

One-way analysis of variance (ANOVA) was used to detect differences in TDN, DIN, DON, and PO_4 annual loads among sampling sites (n=20). Annual loads were first log-transformed to improve assumptions of normality. SBM0.2 was excluded from univariate analysis due to its small sample size (<5 years of load estimates). Tukey's honest significance test for multiple comparisons was used as a post hoc test to determine which sampling stations differed in mean nitrogen and/or phosphorus annual load. Simple linear regression was used to assess trends in nutrient loads and N:P ratios over time for individual stations. All calculations and statistics were performed in R (version 3.6.3) and Microsoft Excel (2016).

Results

Nitrogen and Phosphorus Annual Loads

Median TDN loads ranged from 0.37 to 8.04 kg N/ha/yr across the 21 sampling stations, with the furthest upstream site (SMB0.2) having the smallest median TDN annual load (Table 1; Figure 3). Out of the 20 sampling stations retained for statistical analysis, LMP07 had the lowest median TDN load (Figure 3). Analysis of variance showed significant differences in mean TDN loads between the 20 sites ($p < 0.05$). Small tributaries with suburban or agricultural land uses tended to have higher mean TDN loads. Post hoc comparisons using the Tukey HSD test confirmed this difference, indicating that mean TDN loads for BDC0.30, WHB01, and MLB01 were significantly different from the 17 other sites ($p < 0.05$). Mainstem TDN loads were not significantly different from one another, except for LMP07. Tukey HSD test results indicated the LMP07 mean TDN load was significantly different from all other mainstem samplings stations ($p < 0.05$) except the next downstream station (LMP19).

Although TDN loads did not exhibit a clear, consistent spatial pattern from the headwaters to the river mouth, the river segment between stations LMP39 and LMP51 showed a sequentially increasing pattern in median TDN loads (Figure 3). Tukey HSD test results indicated that the Pawtuckaway River stations, PWT10 and the upstream station PWT03, were both significantly different from one another and from the downstream station LMP51 ($p < 0.05$). Most stations did not exhibit significant temporal trends in annual TDN loads (Figure 4). Out of the 21 sites analyzed with linear regressions, 6 showed significant decreasing trends in annual TDN loads ($p < 0.05$) (Appendix Table C1). Both tributary monitoring stations upstream of LMP51 (PWT03 and PWT10) were included in the 6 sites with significant trends ($R^2 = 0.45$; $R^2 = 0.54$).

Median DIN loads ranged from 0.06 kg N/ha/yr at SMB0.2 to 5.4 kg N/ha/yr at BDC0.30 (Table 1; Figure 5). DIN flux accounted for 14 to 88% of TDN flux (Table 1). Analysis of variance showed significant differences in mean DIN loads between the 20 sites ($p < 0.05$). Similar to TDN post hoc results, comparisons using the Tukey HSD test indicated that mean DIN load for the same three small tributaries (BDC0.30, WHB01, and MLB01) was significantly different from the other sites ($p < 0.05$). Tukey HSD tests results also indicated that mean DIN loads significantly differed between PWT03, PWT10, and LMP51 ($p < 0.05$). This spatial pattern of upstream tributaries having a significantly different DIN loads than the downstream receiving mainstem station also occurred between LMP51 and LMP59. Both NOR27 and its upstream tributary, DCF03, had significantly smaller ($p < 0.05$) DIN loads than LMP59. Most stations again did not exhibit significant temporal trends in annual DIN loads (Figure 6, Appendix Table C2). Only 6 stations had significant trends ($p < 0.05$), all of which showed a decrease in annual loads over time. Of those 6 stations, 4 showed decreasing trends in both TDN and DIN annual loads (LMP27, PWT10, WHB01, and LMP78).

Median nitrate, a main constituent of DIN, loads ranged from 0.08 to 4.91 kg N/ha/yr across the 20 sampling stations (excluding SMB0.2). Analysis of variance showed significant differences in mean NO_3 between the 20 sites ($p < 0.05$). Post hoc comparisons using the Tukey HSD test indicated that BDC0.30, WHB01, and MLB01 were not significantly different from one another in terms of mean nitrate load but were all significantly different from the 17 other sites ($p < 0.05$). LMP07 had a significantly lower nitrate load than all other mainstem sampling stations and LMP19 was significantly different LMP51. Similar to the TDN and DIN Tukey HSD results, PWT03, PWT10, and LMP51 were found to have significantly different mean nitrate loads. This spatial pattern repeats with DCF03, NOR27, and LMP59, which also showed significant differences in nitrate load. Only one station had a significant temporal trend in annual nitrate loads (Figure 8). WHB01, the suburban small tributary, showed a decreasing trend over time ($R^2 = 0.24$).

Median DON loads ranged from 0.31 to 2.44 kg N/ha/yr across all 21 sampling stations (Table 1, Figure 9). BDC0.30 consistently had the highest median load for all three forms of nitrogen. Analysis of variance showed significant differences in mean DON loads between the 20 sites ($p<0.05$). Unlike TDN and DIN, post hoc comparisons using the Tukey HSD test indicated that most sites did not have significantly different mean DON loads. BDC0.30 and MLB01 were the only two sites with significantly different mean DON loads ($p<0.05$. Those two sites were also significantly different from one another, as MLB01 has the lowest DON mean load (excluding SMB0.2) and BDC0.30 had the highest. Annual DON loads over time remained stable for almost all sites, except for PWT03 and PWT10 (Figure 10). Both sites showed significant, slightly decreasing temporal trends in annual DON loads (Appendix Table C3).

Median PO_4 loads had the smallest range, compared to nitrogen loads, amongst the sampling stations (Figure 11). BDC0.30 had the highest median load of 0.48 kg P/ha/yr (Table 1). Analysis of variance showed significant differences in mean PO_4 loads between sites ($p < 0.05$) and post hoc comparisons using Tukey indicated that BDC0.30 had a significantly different mean PO_4 load than all the other sites ($p < 0.05$). Post hoc Tukey HSD test results indicated that there was no significant difference in mean PO_4 loads between mainstem Lamprey stations. Most sites exhibited significant temporal trends in annual PO_4 loads (Figure 12). A total of 13 stations had significant increasing temporal trends in PO_4 loads (Appendix Table C4). DCF03 had the tightest temporal relationship ($R^2 = 0.84$) over the 7-year monitored period.

Nitrogen Budgets

Nitrogen inputs and outputs for segments of the Lamprey River ranged from 0.30 kg N/ha/yr to 11.93 kg N/ha/yr between sampling stations (Table 2). DIN inputs and outputs had the lowest median values of the three nitrogen forms across both decades (< 1 kg N/ha/yr). Stations during decade 2 exhibited larger ranges in TDN, DON, and DIN outputs of nitrogen than decade 1. This pattern is driven by the inclusion of the small tributary, BDC0.30, in the second decade, which had the largest output loads for TDN, DON, and DIN.

Incremental TDN loads ranged from -0.37 kg N/ha/yr to 11.93 kg N/ha/yr across the 15 sampling stations and 2 decades (Table 3). In decade 1 (WY 2000-2009), the median incremental TDN load for stations was 1.93 kg N/ha/yr. All stations had positive incremental loads that indicate downstream outputs were greater than upstream inputs. Two stations in decade 1 – LMP51 and MLB01 – had incremental loads more than 2 x greater (positive or negative) than the median incremental load. The median incremental load for stations was smaller in decade 2 (WY 2010-2019), at 1.78 kg N/ha/yr. LMP67 was the only station with a negative incremental load. Four stations in decade 2 also had incremental loads more than 2 x the median, including LMP51, BDC0.30, WHB01, and MLB01.

Incremental DON loads ranged from 0.45 kg N/ha/yr to 2.91 kg/N/ha/yr across the 15 stations and 2 decades (Table 3). DON incremental loads showed the smallest range amongst stations of the three nitrogen forms across both decades. No stations exhibited negative incremental loads in either decade. The median DON incremental load was greater in decade 1 (1.10 kg N/ha/yr) than in decade 2 (0.98 kg N/ha/yr). Only one station, BDC0.30 in decade 2, had an incremental load more than twice that of the median.

Incremental DIN loads ranged from -1.16 kg N/ha/yr to 9.17 kg N/ha/yr across the 15 stations and 2 decades (Table 3). The median incremental load between stations was less than 1 kg/ha/yr in both decades. LMP78 was the only station with a negative incremental load in decade 1 and LMP67 had the only negative incremental load in decade 2. Two stations, WHB01 and MLB01, had incremental loads more than twice the median incremental load in the first decade. Those two stations also had larger incremental DIN loads in the second decade. An additional three stations in decade 2 had incremental loads greater than 2 x the median load, with BDC0.30 having an incremental load more than 15 x larger.

Annual N:P Ratios

Median annual TDN:PO_4 molar ratios ranged from 56.28 to 340.92 across the 20 sampling stations (excluding SBM0.2) (Figure 13). The mainstem stations along the Lamprey River had the widest interquartile range (29 – 505), followed by the small tributaries (36-258). The mid-sized tributaries had the smallest interquartile range (228-387). Variation in TDN:PO_4 ratios was stronger over time than between stations, as evidenced by the large interquartile ranges. Median annual TDN:PO_4 ratios showed strong, decreasing temporal trends across 17 out of 20 sampling stations (Figure 14; Appendix Table C5). Declines in TDN:PO4 trends over time may be related to changes in the PO_4 measurement method that lowered the detection limit at which PO_4 is found. Measurement methods switched around 2009 in the UNH Water Quality Analysis Laboratory, resulting in a method detection limit drop from 2 µg/L PO_4-P to 0.5 µg/L PO_4-P.

Runoff-weighted TN annual concentrations at station LMP73 ranged from 0.15 mg/L to 0.50 mg/L (median 0.39) between water years 2006 and 2019 (Figure 15). TN concentrations (mg/L) significantly increased during the period of record ($p < 0.01$). Runoff-weighted TP concentrations at station LMP73 ranged from 0.01 mg/L to 0.03 mg/L (median 0.02) during the same period of record (Figure 15). TP concentrations showed no significant trend over the same 14-year period of record.

Annual TN:TP molar ratios at LMP73 ranged from 17.97 to 141.5 (median 42.33), with water year 2014 having the highest TN:TP ratio (Figure 16). TN:TP molar ratios had no significant trend over time.

Town Contributions to N Loads

Provisional estimates of individual town contributions to overall TDN loading ranged from 1.05 to 3.99 kg N/ha/yr, across both decades of study (Figure 17). DIN loads ranged from – 0.13 to 2.73 kg N/ha/yr, with the towns of Brentwood and Exeter tied for the lowest DIN load in decade 1. DIN loads for the town of Lee in decade 2 were negligible at -0.01 kg N/ha/yr. Epping and Raymond had the highest and second highest, respectively, TDN and DIN loads across both decades. DON loads showed the least variability amongst towns, ranging from 0.93 kg N/ha/yr for Deerfield in decade 2 to 1.69 kg N/ha/yr for both Brentwood and Exeter in decade 1. Town areas within the watershed ranged from 11.6 to 12416.2 hectares, with a median area of 2188.5 hectares for Newmarket (Table 4). No individual town accounted for a majority of the Lamprey's watershed area. Neither of the two largest towns (Nottingham and Deerfield) within the watershed contributed the highest loads of TDN, DIN, or DON. Notably, the BDC0.30 watershed which drains Burley-Demeritt Farm, fell completely within the town of Lee. The sampling site had the highest loads for all three forms of nitrogen yet comprised only 1% of the town's area.

Total nitrogen loads (mass/time) apportion by town showed similar patterns, with Epping having the largest provisional estimated total load for TDN (kg N/yr) and DIN (kg N/yr) for both decades (Table 5). Nottingham, which encompasses 22% of the Lamprey watershed, had the largest estimated DON load, totaling 14,937 kg N/yr in decade 1 and 13,047 kg N/yr in decade 2. When normalized for town areas, the highest DON loads were attributed to Exeter in decade 1 and Brentwood in decade 2 (Figure 17).

Conclusions

Spatial and Temporal Trends in Annual Nutrient Loads

Spatial trends in annual nitrogen and phosphate loads for tributaries and segments of the Lamprey River exhibit patterns driven by tributary size and possibly by sub-watershed land uses. Small tributaries, including BDC0.30, WHB01, and MLB01, had significantly different mean annual TDN and DIN loads from all other monitoring stations within the Lamprey River watershed. DIN loads accounted for 70%, 82%, and 88% of TDN loads, respectively, for those three tributaries (Table 1). This pattern is likely driven by higher nitrate loads, as nitrate usually dominates DIN loads under oxygen-rich conditions (Daley et al., 2010). Annual nitrate loads were the major contribution to DIN loads across all sites and years, accounting 83% of the DIN load on average (median 86%). This result is consistent with reported fluxes for the same stations between water years 2000-2009, with median DIN accounting for 91% of TDN loads at MLB01 and 81% at WHB01 (Daley et al., 2010). These two small tributaries have high reported population densities and sub-basin percent impervious surface cover, both of which have been described as key explanatory variables for DIN loading (Daley et al., 2010). BDC0.30 is an agriculturally dominated watershed that includes Burley-Demeritt Farm, a former beef and miniature swine rearing facility, now managed as an organic dairy farm. Dairy cattle produce the largest amounts of waste in comparison to other livestock, thus contributing to high nitrogen and phosphate stream loads through manure (Bilotta et al., 2007). Median annual phosphate loads showed no significant differences between stations, except for BDC0.30 and MLB01, which had the highest and lowest medians, respectively. This suggests that the Lamprey and its tributaries do not receive large inputs of phosphate and that phosphate moves through the river system at a consistent rate. Mainstem sampling stations did not exhibit clear spatial trends in either nitrogen or phosphate loads, as most were found to not be statistically different from one another.

Most sampling stations did not exhibit significant temporal trends in annual nitrogen loads. Other studies of the Lamprey River basin report similar findings of inorganic nutrient and DON fluxes remaining stable over time (Coble et al., 2018; Kotowski, 2016). The few sites with significant temporal trends all had decreasing annual nitrogen loads. Decreasing loads could be attributable to successful water quality management efforts within the watershed, including reduced point source pollution from upgraded municipal wastewater treatment facilities (Piscataqua Region Estuaries Partnership, 2018; Stets et al., 2020).

Annual PO_4 loads exhibited the opposite behavior of nitrogen loads, with most stations showing slight, but significant, increases over time. Increasing trends in phosphate loading across stations within the watershed, suggest new inputs of phosphorus are entering the river network. Sources of phosphate include agricultural land uses that add fertilizer and/or manure to the landscape and as well as sewage outflows (USGS, 2017). Soils can be another large source of phosphate for rivers, as soil erosion transports P from stream banks and adjacent landscapes (USGS, 2017). Legacy sources of phosphate bound to sediments have been identified as potentially new and unaccounted for inputs of PO_4 to river networks and lakes (Colborne et al., 2019). Mobilization of sediment-bound phosphate sources could explain the increasing PO_4 trends found in the Lamprey River watershed.

TDN:PO4 ratios for all but 3 stations showed significant decreasing trends over time. Increasing PO_4 loads and decreasing TDN:PO4 ratios could be the result of changing instruments for PO_4 analysis in 2009, which resulted in a lower detection limit. To test whether this change in measurement methods affected results, we compared median annual TDN:PO4 ratios across sites using PO_4 concentrations measured with discrete methods (higher method detection limits) to this report's results. The mean annual TDN:PO_4 ratio across sites using concentrations measured with the lower detection limit was 245. When discrete measurements were used instead, the mean was 258. The relative percent difference between the two means is 5.2%. Linear regression comparing the two measurement methods found a strong, positive relationship ($R^2 = 0.93$, $p < 0.01$; $Y = 0.90X + 12.5$, where Y represents TDN:PO4 ratios calculated with lower detection limit and X represents TDN:PO4 ratios calculated with higher (discrete) detection limit). Results suggest that switching measurement methods did not greatly affect PO_4 concentrations and therefore load and ratio estimates. Thus, the combination of decreasing TDN loads and/or increasing PO4 loads resulted in strong decreasing temporal trends for TDN:PO4 ratios.

Biogeochemical Role of the Lamprey River

Overall, the Lamprey River functions as a transformer of nitrogen as inputs and outputs did not balance throughout most of the river segments. Incremental loads were mostly positive, indicating output nitrogen loads are greater than input nitrogen loads. Consequently, nitrogen is either being produced as it flows downstream or there are unquantified sources entering the river flow path such as septic system leaks or groundwater inputs. Groundwater nitrate concentrations have been shown to be higher than reported river concentrations within the Lamprey (Daley et al., 2010). Groundwater connections to surface waters could facilitate additional nitrogen entering the river network.

Incremental loads at LMP67 were negative for TDN and DIN in decade 2 and DIN incremental loads were negative for LMP78 in decade 1. Negative loads indicate outputs of nitrogen were less than upstream inputs, suggesting retention or loss of nitrogen between sampling stations. Retention of nitrogen within a watershed can be temporary or permanent. Temporary pathways involve biotic uptake of nitrogen by stream organisms or burial in sediments (Bernot & Dodds, 2005). Permanent removal of nitrogen from river systems occurs via denitrification, when nitrate is converted to dinitrogen gas (Bernot & Dodds, 2005). Retention pathways may be enhanced by the input of dissolved inorganic nitrogen from the Epping wastewater treatment, located upstream of LMP51. LMP51 has a median annual DIN load of 1.04 kg N/ha/yr, which is higher than its neighboring upstream (LMP39 median 0.78) and downstream stations (LMP67 median 0.80). Additionally, the town of Epping had the highest contribution to overall TDN and DIN loads. Between LMP51 and LMP67, the river ecosystem may see higher biotic uptake of nitrogen and/or potentially higher denitrification, resulting in the removal/retention of nitrogen.

Table 1. Monitoring station characteristics, sampling frequencies, median nitrogen loads, and median phosphate loads within the Lamprey River watershed. Median loads calculated for water years shown. Stations are ordered by location, starting at the headwaters and moving to the mouth of the river.

Station ID	Station Characteristics			Median Annual Loads kg (N or P)/ha/yr				
	Area (km^2)	Water Years Sampled* (n)	Tributary Size	DON	DIN	TDN	% DIN	PO_4
SBM0.2	0.3	2013-2016 (4)	Small	0.31	0.06	0.37	16	0.02
LMP07	15.1	2003-2019 (17)	Mainstem	0.82	0.32	1.11	27	0.02
LMP19	80.1	2004-2019 (16)	Mainstem	0.88	0.60	1.54	38	0.02
NBR12	41.5	2004-2019 (16)	Mid-Size	1.07	0.41	1.47	31	0.03
LMP27	144.3	2004-2019 (16)	Mainstem	0.99	0.59	1.52	36	0.02
LMP39	197.9	2004-2019 (16)	Mainstem	1.01	0.78	1.93	44	0.02
PWT03†	2.6	2004-2019 (16)	Small	0.91	0.18	1.12	14	0.03
PWT10	25.5	2006-2017, 2019 (13)	Mid-Size	0.96	0.49	1.41	31	0.03
LMP51	251.7	2004-2019 (16)	Mainstem	1.05	1.04	2.10	46	0.03
RMB04	4.9	2004-2019 (16)	Small	1.21	1.18	2.50	50	0.05
DCF03†	7.0	2013-2019 (7)	Small	1.19	0.22	1.42	16	0.04
NOR27	128.9	2004-2019 (16)	Mid-Size	1.17	0.53	1.72	30	0.03
LMP59	396.6	2009-2019 (11)	Mainstem	0.99	0.75	1.74	43	0.03
BDC0.30	0.3	2011-2015, 2018 (6)	Small	2.44	5.37	8.04	70	0.48
LTR20	51.7	2004-2019 (16)	Mid-Size	1.07	0.58	1.60	35	0.03
LMP67	469.3	2004-2019 (16)	Mainstem	1.13	0.80	2.06	43	0.03
WHB01	1.0	2003-2019 (17)	Small	0.88	3.80	4.86	82	0.04
LMP72	476.9	2012-2019 (8)	Mainstem	1.20	0.81	2.03	39	0.04
LMP73	479.2	2000-2019 (20)	Mainstem	1.14	0.76	2.05	41	0.03
LMP78	548.1	2006-2019 (14)	Mainstem	1.18	0.88	2.03	44	0.04
MLB01	0.9	2009-2019 (11)	Small	0.50	3.49	3.95	88	0.03

*only years with a minimum of 10 samples were included †indicates site is directly upstream of the following site

Table 2. Median N inputs and outputs for the last two decades for 15 sampling stations within the Lamprey River watershed. Inputs are the summation of loads for upstream sampling stations (both mainstem and major tributaries). Outputs represent the downstream sampling station load. Dashes indicate no data was available or that no upstream sampling stations are present for some sites.

Station ID	Decade 1 (WY 2000-2009)						Decade 2 (WY 2010-2019)					
	N Inputs (kg N/ha/yr)			N Outputs (kg N/ha/yr)			N Inputs (kg N/ha/yr)			N Outputs (kg N/ha/yr)		
	TDN	DON	DIN	TDN	DON	DIN	TDN	DON	DIN	TDN	DON	DIN
LMP07	-	-	-	1.39	0.96	0.43	-	-	-	1.13	0.81	0.30
LMP19	1.39	0.96	0.43	1.78	0.94	0.85	1.13	0.81	0.30	1.40	0.86	0.51
NBR12	-	-	-	1.63	1.10	0.53	-	-	-	1.34	0.98	0.36
LMP27	1.73	1.00	0.74	1.84	1.06	0.78	1.38	0.90	0.46	1.44	0.91	0.52
LMP39	1.84	1.06	0.79	2.14	1.12	1.02	1.44	0.91	0.52	1.76	1.00	0.75
PWT10	-	-	-	1.48	1.01	0.48				1.28	0.93	0.35
LMP51	2.06	1.11	0.96	2.65	1.09	1.56	1.71	0.99	0.70	2.37	1.05	1.28
RMB04	-	-	-	2.47	1.31	1.16	-	-	-	2.09	1.13	0.96
NOR27	-	-	-	1.84	1.29	0.55	-	-	-	1.50	1.11	0.38
BDC0.30	-	-	-	-	-	-	-	-	-	11.93	2.91	9.17
LTR20	-	-	-	1.98	1.10	0.88	-	-	-	1.58	0.97	0.60
LMP67	2.33	1.15	1.18	2.27	1.17	1.10	2.02	1.06	0.94	1.86	1.06	0.80
WHB01	-	-	-	5.35	0.95	4.46	-	-	-	4.46	0.70	3.69
LMP78	2.28	1.17	1.11	2.17	1.24	0.93	1.87	1.06	0.80	1.89	1.13	0.75
MLB01	-	-	-	5.26	0.56	4.94	-	-	-	3.96	0.45	3.55
Median	**1.95**	**1.08**	**0.87**	**2.06**	**1.10**	**0.90**	**1.57**	**0.95**	**0.61**	**1.67**	**0.99**	**0.67**

Table 3. Median incremental N loads (change in N storage) for each segment of the Lamprey River across the last two decades. Dashes indicate no data was available for a given decade. Area represents incremental area between upstream and downstream stations.

Station ID	Decade 1 (WY 2000-2009)				Decade 2 (WY 2010-2019)			
	N Incremental Load (kg/ha/yr)				N Incremental Load (kg/ha/yr)			
	TDN	DON	DIN	Area (ha)	TDN	DON	DIN	Area (ha)
LMP07	1.39	0.96	0.43	1510.9	1.13	0.81	0.30	1510.9
LMP19	1.88	0.94	0.94	6498.7	1.46	0.87	0.56	6498.7
NBR12	1.63	1.10	0.53	4143.6	1.34	0.98	0.36	4143.6
LMP27	2.43	1.37	1.03	2274.5	1.78	0.97	0.87	2274.5
LMP39	2.93	1.28	1.65	5359.7	2.63	1.23	1.34	5359.7
PWT10	1.48	1.01	0.48	2544.8	1.28	0.93	0.35	2544.8
LMP51	7.33	1.00	6.31	2828.1	7.56	1.54	5.87	2828.1
RMB04	2.47	1.31	1.16	485.3	2.09	1.13	0.96	485.3
NOR27	1.84	1.29	0.55	12888.3	1.50	1.11	0.38	12888.3
BDC0.30	-	-	-	-	11.93	2.91	9.17	32.6
LTR20	1.98	1.10	0.88	5163.4	1.58	0.97	0.60	5163.4
LMP67	1.40	1.39	0.04	3213.9	-0.37	0.99	-1.16	3181.2
WHB01	5.35	0.95	4.46	101.8	4.46	0.70	3.69	101.8
LMP78	1.56	1.69	-0.13	7780.4	2.06	1.60	0.46	7780.3
MLB01	5.26	0.56	4.94	92	3.96	0.45	3.55	92

Table 4. Town areas (hectares) within the Lamprey River watershed, expressed as a percentage of total watershed area.

Town	Area (ha)	% of Watershed
Barrington	1737.2	3.17%
Brentwood	314.4	0.57%
Candia	4823.6	8.79%
Deerfield	10827.6	19.73%
Durham	1628.5	2.97%
Epping	6780.1	12.35%
Exeter	629.0	1.15%
Fremont	1232.7	2.25%
Lee	3212.7	5.85%
Newfields	1053.0	1.92%
Newmarket	2188.5	3.99%
Northwood	3055.2	5.57%
Nottingham	12416.2	22.62%
Raymond	4974.9	9.06%
Strafford	11.6	0.02%
Total	54885.1	100%

Table 5. Provisional estimates of total town contributions to N load within the Lamprey River watershed, apportioned by TDN, DON, and DIN for each of the two decades of record. Town load calculations assume N loads occur evenly across each incremental watershed.

	Decade 1 (WY 2000-2009)			Decade 2 (WY 2010-2019)		
Town	**TDN kg N/yr**	**DON kg N/yr**	**DIN kg N/yr**	**TDN kg N/yr**	**DON kg N/yr**	**DIN kg N/yr**
Barrington	3434.4	1929.8	1505.7	2748.0	1692.3	1029.0
Brentwood	492.1	530.4	-42.0	648.9	501.6	145.8
Candia	10047.5	5656.5	4385.6	8510.2	5082.5	3345.3
Deerfield	19861.5	11291.2	8621.8	15699.1	10077.1	5440.8
Durham	2544.5	2739.7	-213.6	3303.0	2583.3	716.6
Epping	27050.5	8515.6	18488.9	26156.1	9243.0	16656.6
Exeter	984.2	1060.9	-84.0	1298.0	1003.3	291.7
Fremont	2268.2	1978.8	277.8	2683.8	1874.6	789.3
Lee	5569.1	4396.8	1199.2	3374.4	3661.5	-41.2
Newfields	1612.5	1710.9	-103.6	1644.3	1547.9	134.8
Newmarket	3652.0	3379.8	292.2	3004.9	2965.7	171.8
Northwood	5146.0	3583.3	1561.5	4192.1	3079.4	1080.9
Nottingham	22755.1	14936.9	7817.6	18555.2	13047.2	5466.4
Raymond	14185.5	6411.9	7733.0	12287.8	5731.9	6412.2
Strafford	21.4	14.9	6.4	17.4	12.9	4.4

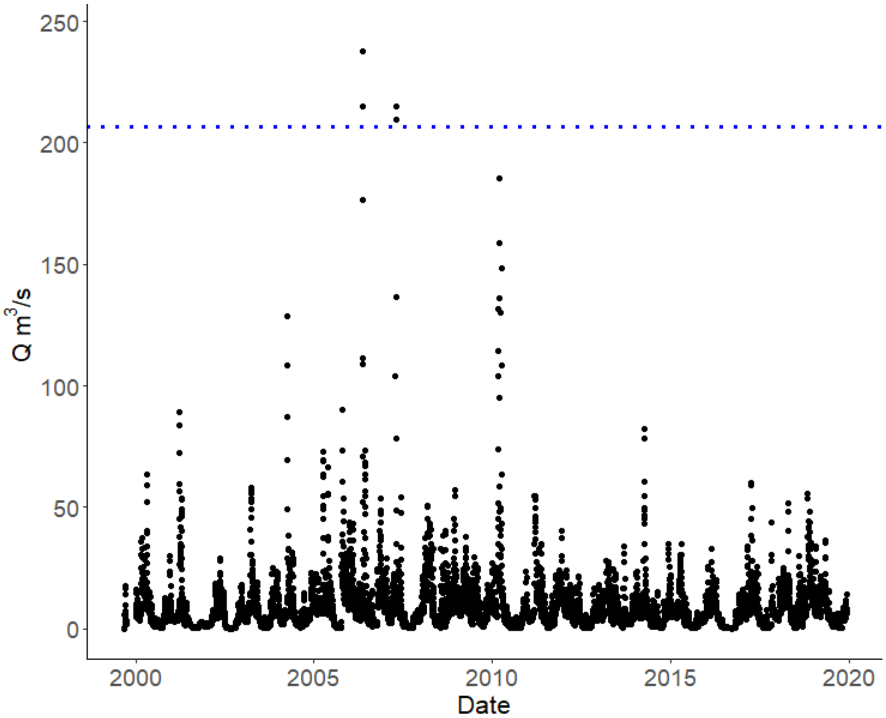

Figure 1. Instantaneous mean daily discharge for the Lamprey River, measured at USGS site 1073500. Dotted line indicates threshold flow that defines a 100-year flood event (FEMA, 2008).

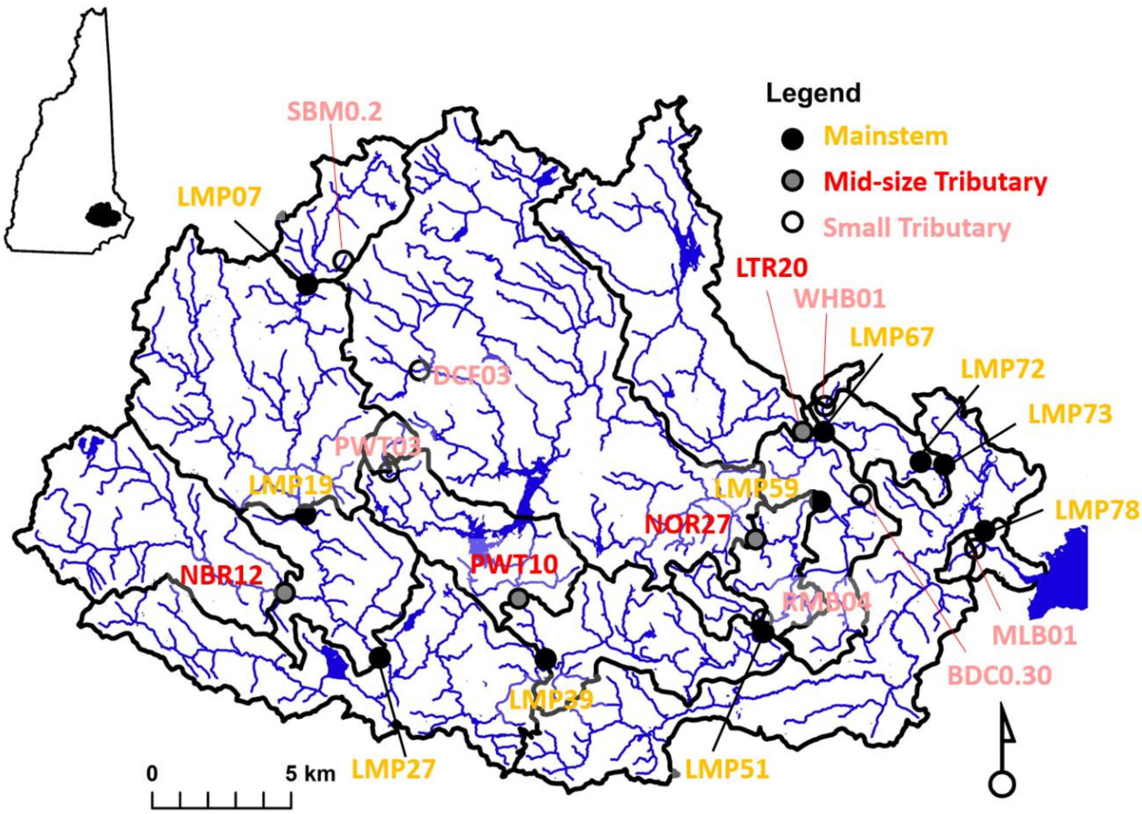

Figure 2. Map of the Lamprey River watershed, with sampling stations labeled. Stations are color-coded by tributary size.

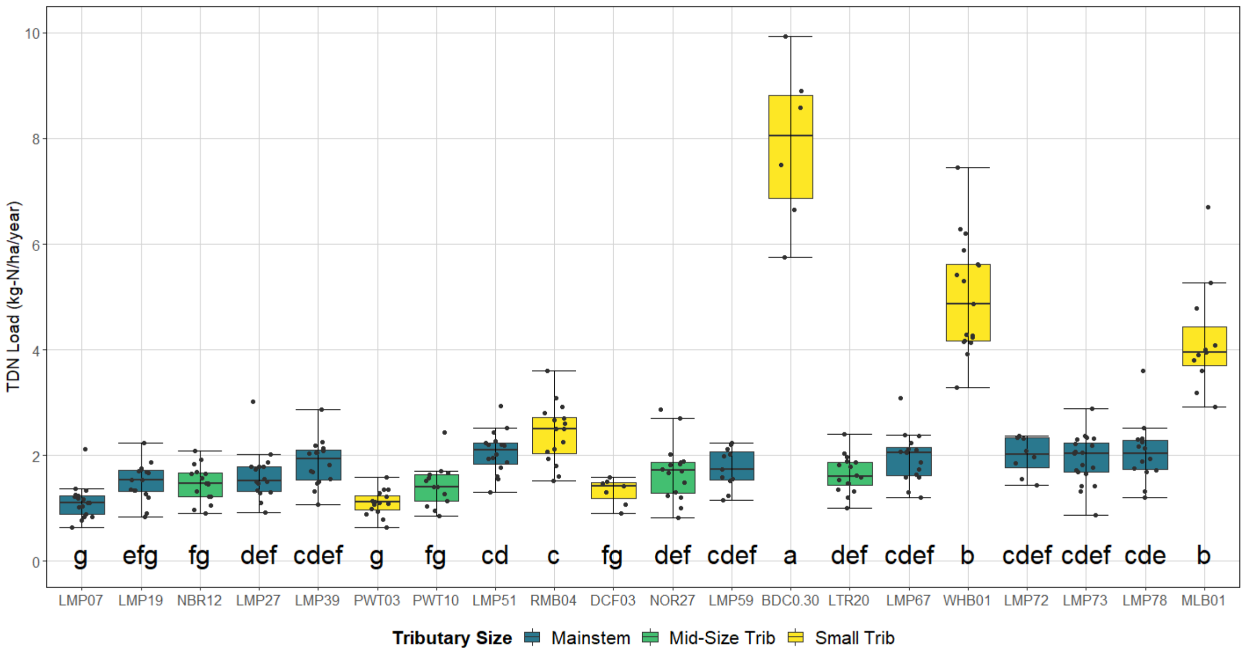

Figure 3. Annual total dissolved nitrogen loads (kg N ha^{-1} yr^{-1}) for 20 sampling stations within the Lamprey River. Sampling stations are ordered from headwaters (left) to mouth (right) of the Lamprey River. *Horizontal lines* mark the median annual load for each site, *box boundaries* indicate the first and third quantiles, the *whiskers* mark 1.5 times the interquartile range (relative to the smallest or largest observation within the interquartile range), and the *points* represent individual annual load estimates. Points are jittered along the x-axis to prevent overlap and points outside of the whiskers represent outliers. Lowercase letters represent results of post hoc Tukey test, where sites sharing the same letter(s) are not significantly different ($p > 0.05$).

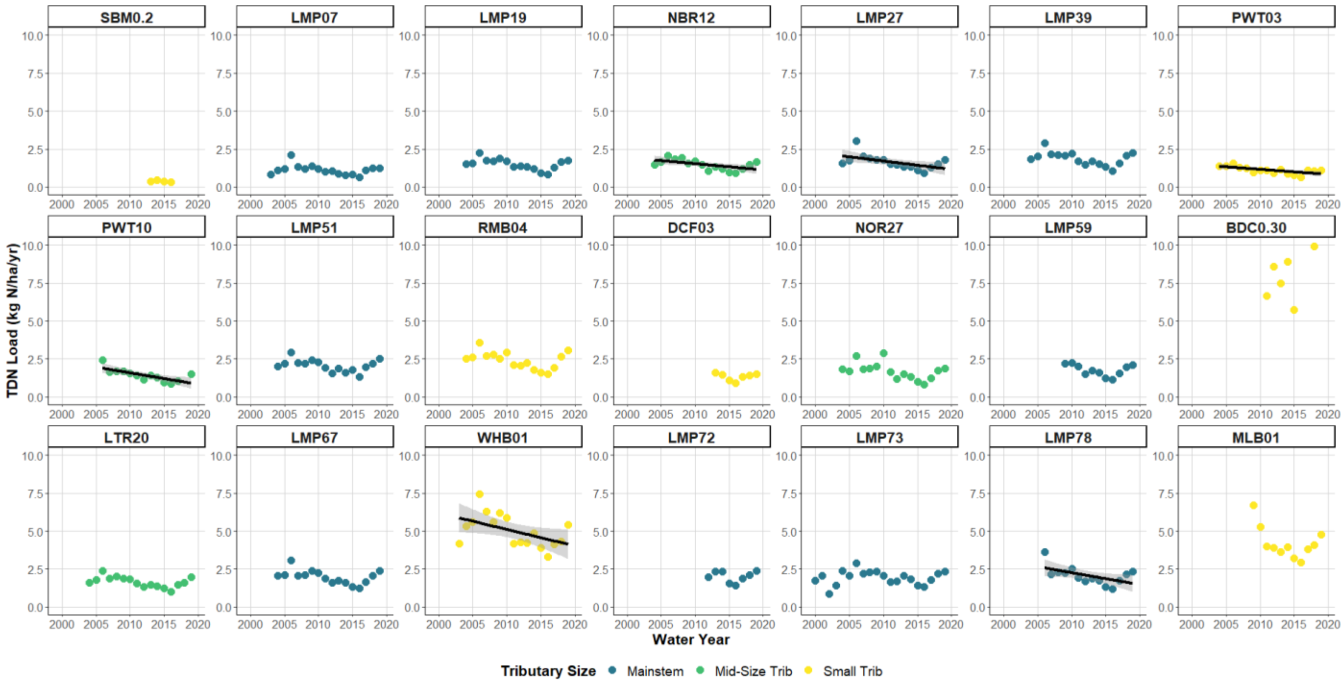

Figure 4. Median annual (water years) total dissolved nitrogen loads over time for 21 sampling stations within the Lamprey River basin. Stations are color coded based on tributary size and from headwaters to mouth (left to right; top to bottom). Solid lines represent significant (p<0.05), decreasing trends in TDN loads at 6 sites. Shading represents 95% confidence intervals.

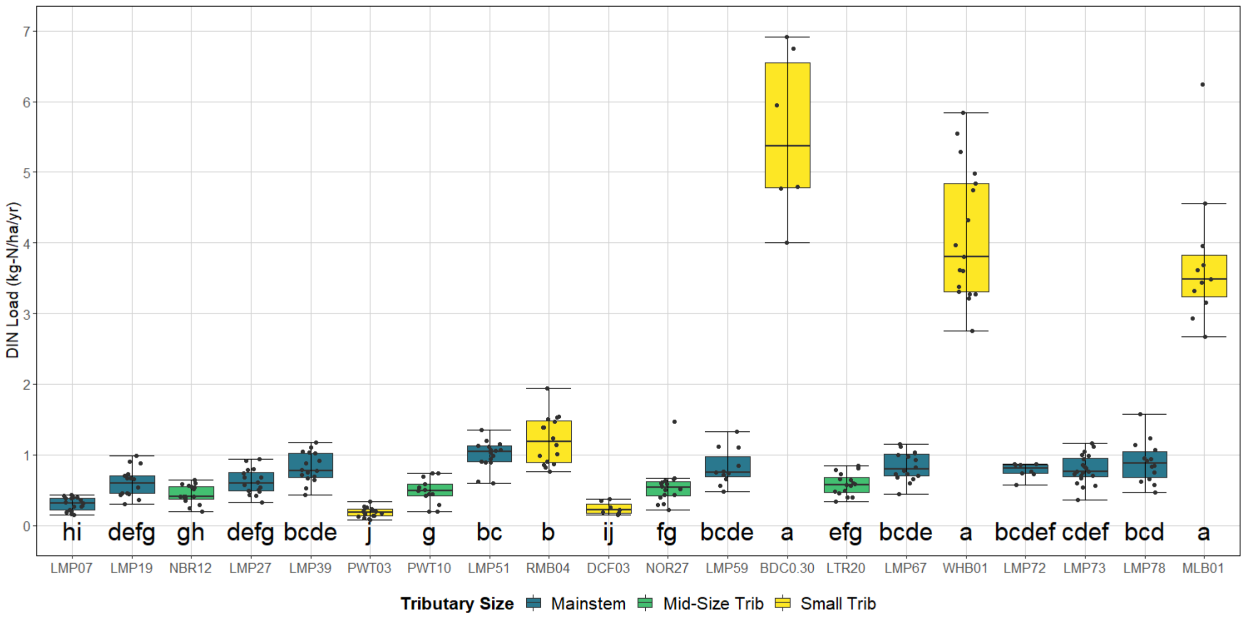

Figure 5. Annual dissolved inorganic nitrogen loads (kg N ha^{-1} yr^{-1}) for 20 sampling stations within the Lamprey River. Sampling stations are ordered from headwaters (left) to mouth (right) of the Lamprey River. *Horizontal lines* mark the median annual load for each site, *box boundaries* indicate the first and third quantiles, the *whiskers* mark 1.5 times the interquartile range (relative to the smallest or largest observation within the interquartile range), and *points* represent individual annual load estimates. Points are jittered along the x-axis to prevent overlap and those outside of the whiskers are outliers. Lowercase letters represent results of post hoc Tukey test, where sites sharing the same letter(s) are not significantly different ($p > 0.05$).

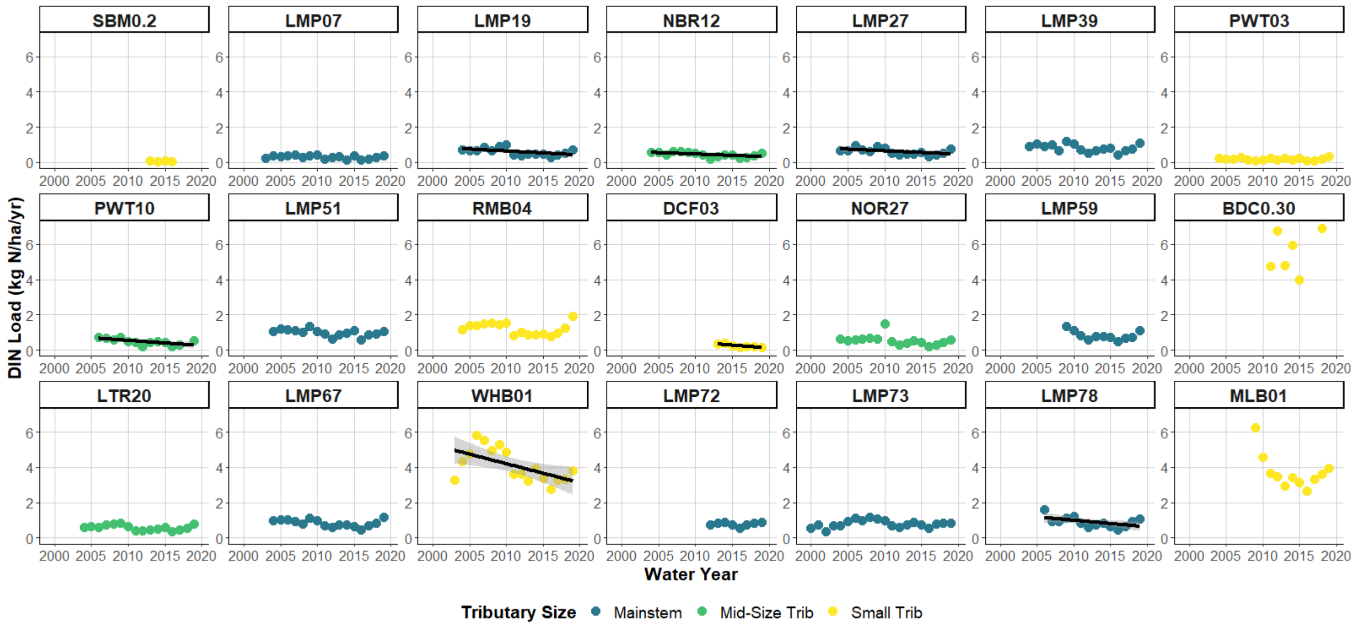

Figure 6. Median annual (water years) dissolved inorganic nitrogen loads over time at 21 sampling stations within the Lamprey River basin. Stations are color coded based on tributary size and from headwaters to mouth (left to right; top to bottom). Solid lines represent significant ($p<0.05$), decreasing trends in DIN loads at 6 sites. Shading represents 95% confidence intervals.

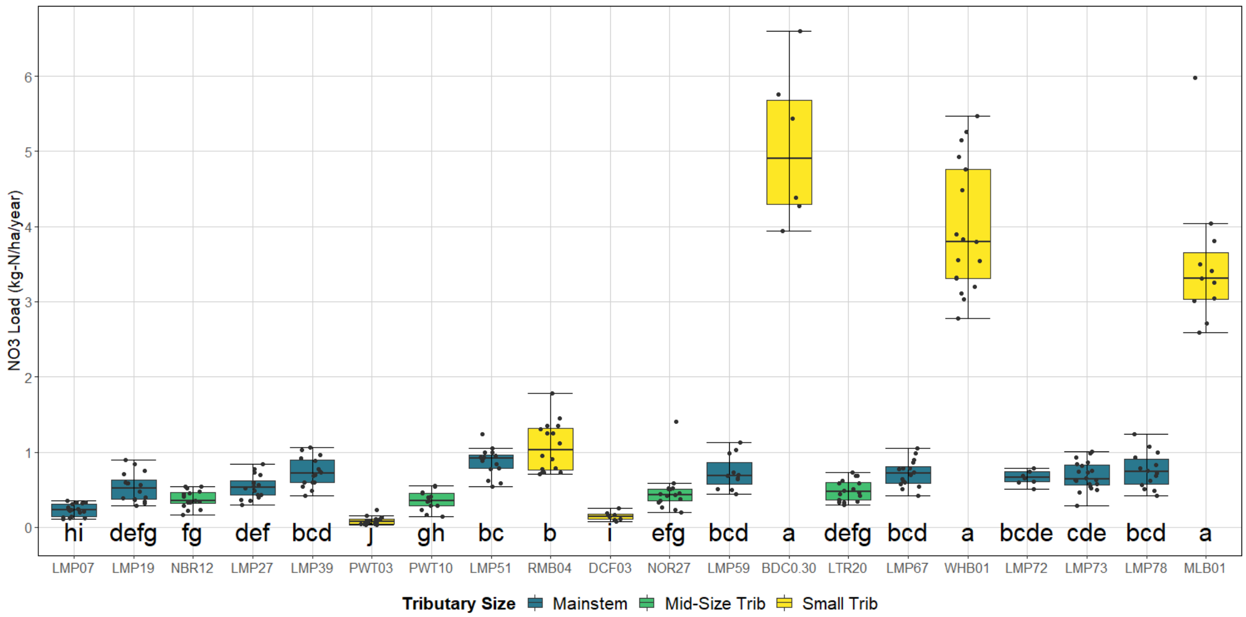

Figure 7. Annual nitrate loads (kg N ha^{-1} yr^{-1}) for 20 sampling stations within the Lamprey River. Sampling stations are ordered from headwaters (left) to mouth (right) of the Lamprey River. *Horizontal lines* mark the median annual load for each site, *box boundaries* indicate the first and third quantiles, the *whiskers* mark 1.5 times the interquartile range (relative to the smallest or largest observation within the interquartile range), and the *points* represent individual annual load estimates. Points are jittered along the x-axis to prevent overlap and those outside of the whiskers represent outliers. Lowercase letters represent results of post hoc Tukey test, where sites sharing the same letter(s) are not significantly different ($p > 0.05$).

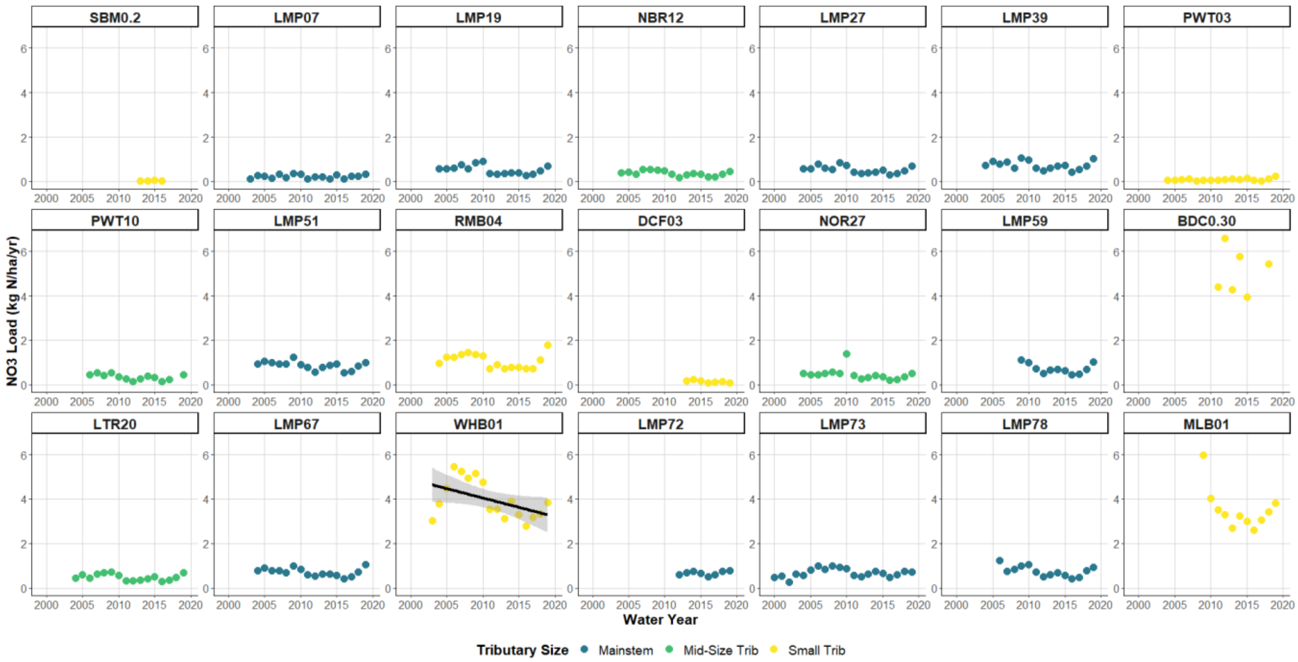

Figure 8. Median annual (water years) nitrate loads over time at 21 sampling stations within the Lamprey River basin. Stations are color coded based on tributary size and organized from headwaters to mouth (left to right; top to bottom). Solid line represents a significant ($p<0.05$), decreasing trend in nitrate loads. Shading represents 95% confidence intervals.

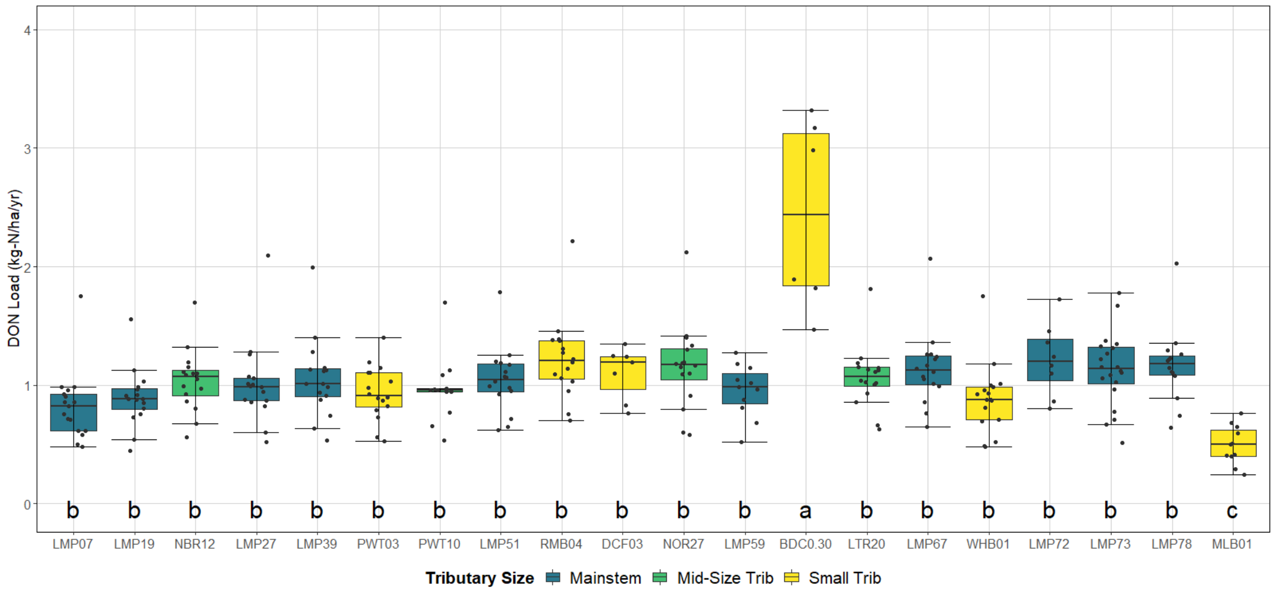

Figure 9. Annual dissolved organic nitrogen loads (kg N ha^{-1} yr^{-1}) for 20 sampling stations within the Lamprey River. Sampling stations are ordered from headwaters (left) to mouth (right) of the Lamprey River. *Horizontal lines* mark the median annual load for each site, *box boundaries* indicate the first and third quantiles, the *whiskers* mark 1.5 times the interquartile range (relative to the smallest or largest observation within the interquartile range), and the *points* represent individual annual load estimates. Points are jittered along the x-axis to prevent overlap and those outside of the whiskers represent outliers. Lowercase letters represent results of post hoc Tukey test, where sites sharing the same letter(s) are not significantly different ($p > 0.05$).

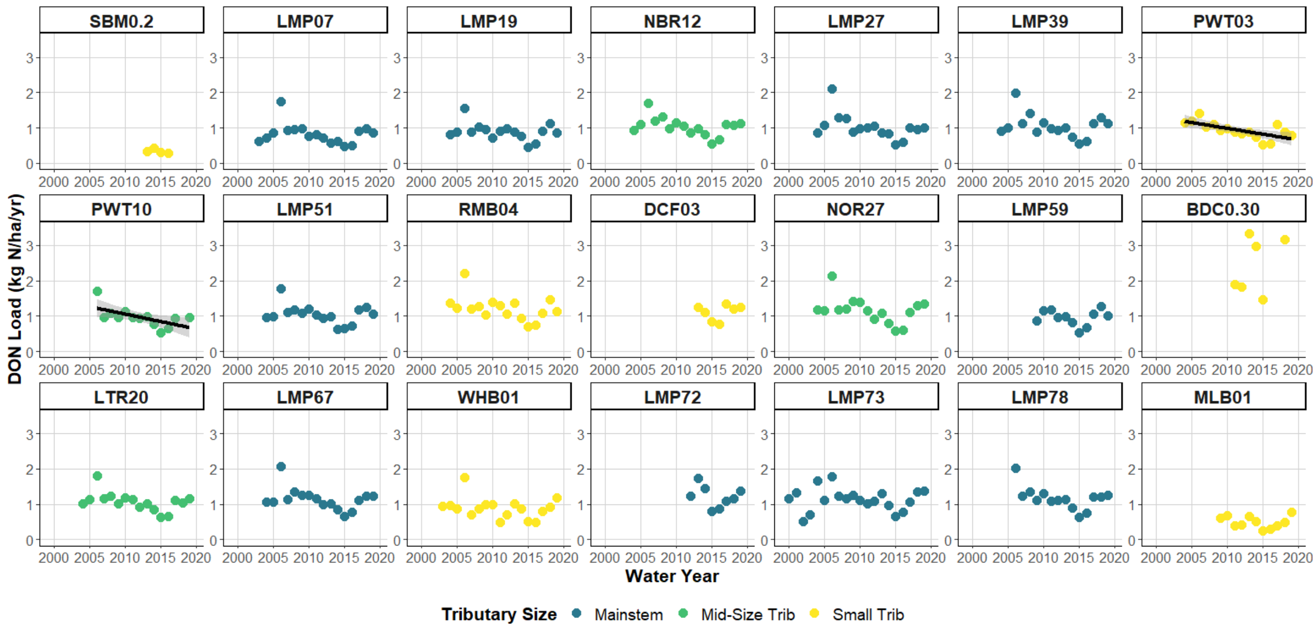

Figure 10. Median annual (water years) dissolved organic nitrogen loads over time at 21 sampling stations within the Lamprey River basin. Stations are color coded based on tributary size and organized from headwaters to mouth (left to right; top to bottom). Solid lines represent significant ($p<0.05$), decreasing trends in DON loads at 2 sites. Shading represents 95% confidence intervals.

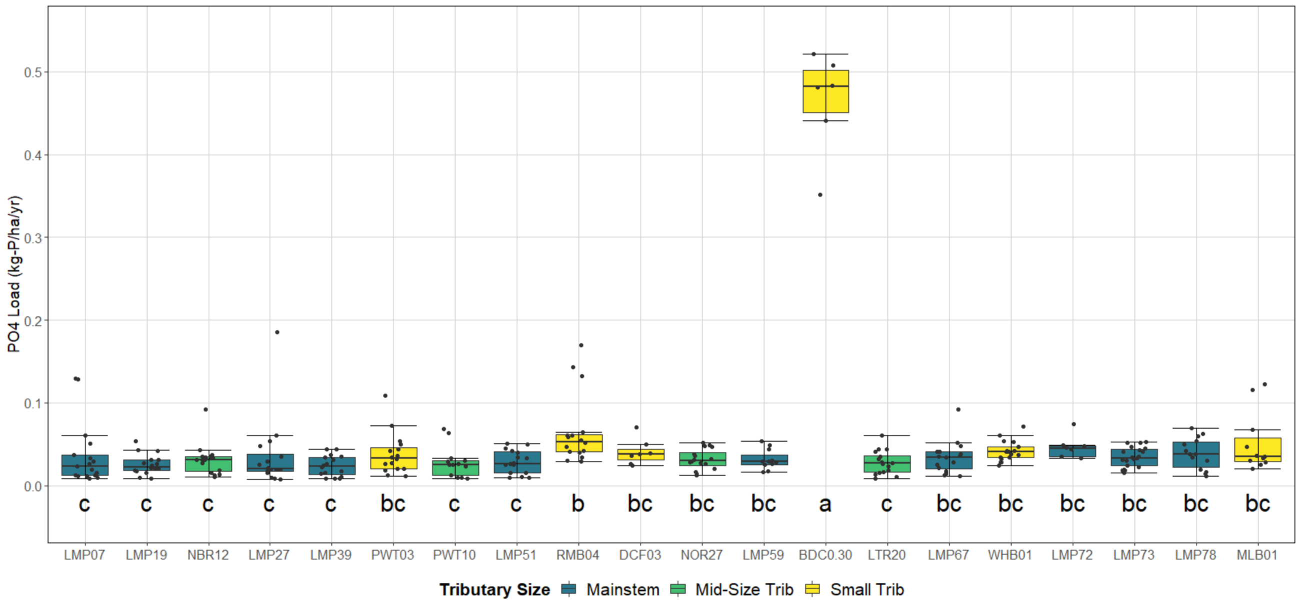

Figure 11. Annual phosphate loads (kg P ha^{-1} yr^{-1}) for 20 sampling stations within the Lamprey River. Sampling stations are ordered from headwaters (left) to mouth (right) of the Lamprey River. *Horizontal lines* mark the median annual load for each site, *box boundaries* indicate the first and third quantiles, the *whiskers* mark 1.5 times the interquartile range (relative to the smallest or largest observation within the interquartile range), and the *points* represent individual annual load estimates. Points are jittered along the x-axis to prevent overlap and those outside of the whiskers represent outliers. Lowercase letters represent results of post hoc Tukey test, where sites sharing the same letter(s) are not significantly different ($p > 0.05$).

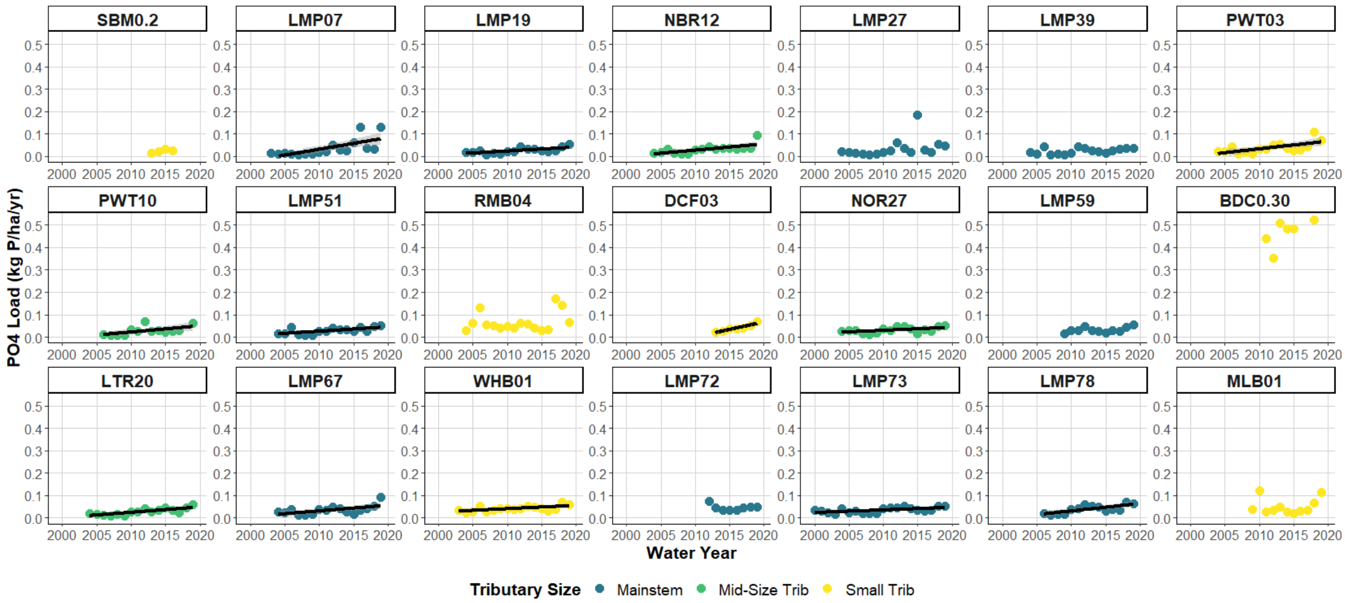

Figure 12. Median annual (water years) phosphate loads over time at 21 sampling stations within the Lamprey River basin. Stations are color coded based on tributary size. Solid lines represent significant ($p<0.05$), increasing trends in PO_4 loads at 13 sites. Shading represents 95% confidence intervals.

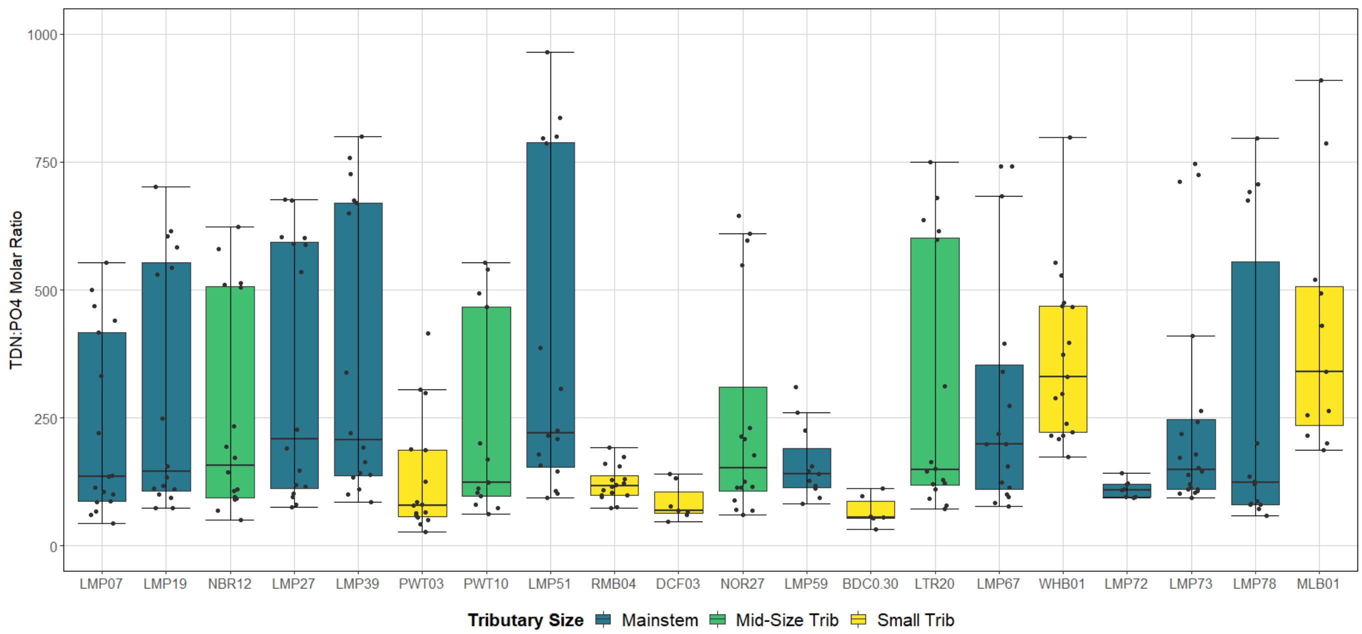

Figure 13. Median annual TDN:PO_4 molar ratios (mol:mol) for 20 sampling stations, ordered from headwaters to mouth (left to right) within the Lamprey River watershed. *Horizontal lines* mark the median annual TDN:PO_4 ratio for each site, *box boundaries* indicate the first and third quantiles, the *whiskers* mark 1.5 times the interquartile range (relative to the smallest or largest observation within the interquartile range), and the *points* represent individual median TDN:PO_4 ratios. Points are jittered along the x-axis to prevent overlap and those outside of the whiskers represent outliers.

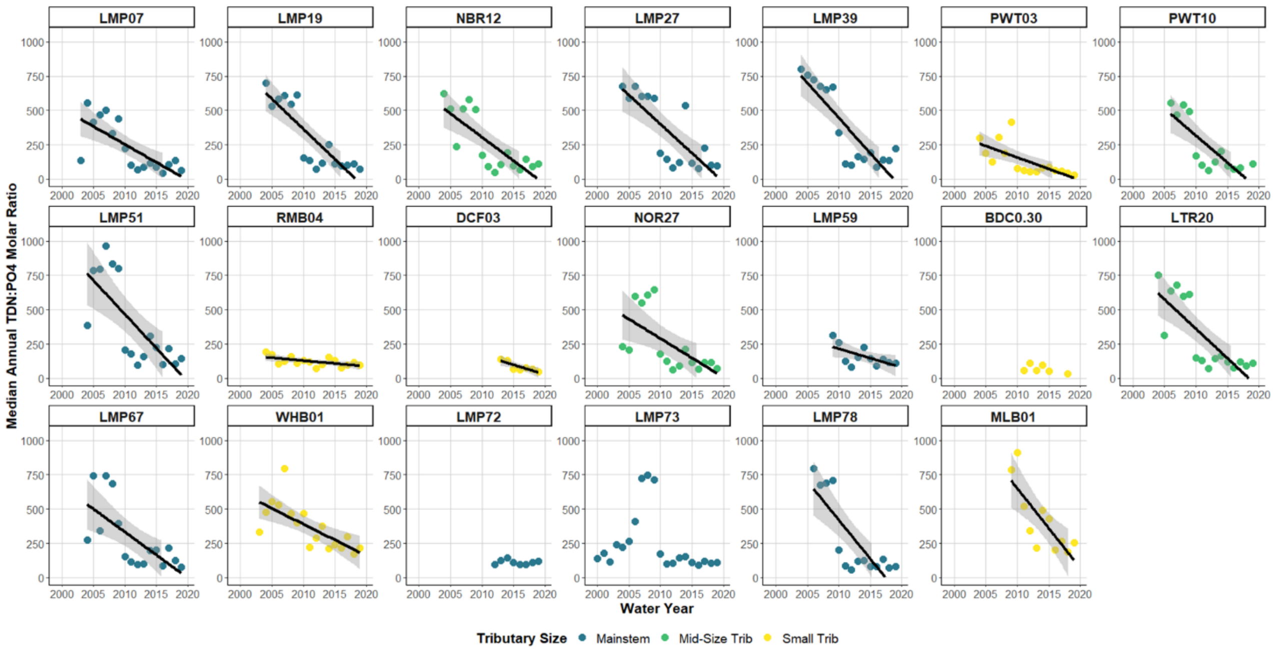

Figure 14. Median annual (water years) TDN:PO_4 ratios at 20 sampling stations within the Lamprey River basin over time. Ratios are calculated using median TDN and median PO_4 concentrations for each year. Stations are color coded based on tributary size and organized from headwaters to mouth (left to right; top to bottom). Solid lines represent significant ($p<0.05$), decreasing trends in ratios over time. Shading represents 95% confidence intervals.

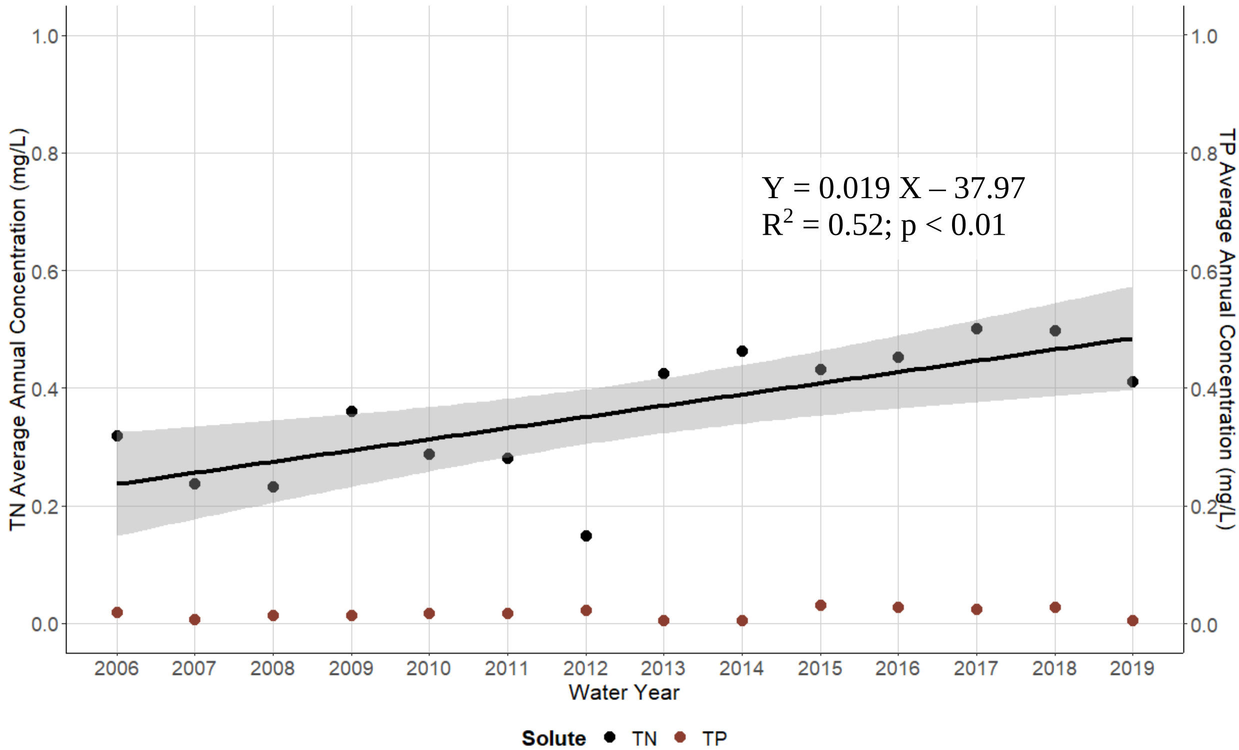

Figure 15. Runoff-weighted median annual concentrations of total nitrogen (TN) and total phosphorus (TP) at LMP73. Regression line shows significant, increasing trend for TN concentrations over time. Shading represents 95% confidence interval for linear regression.

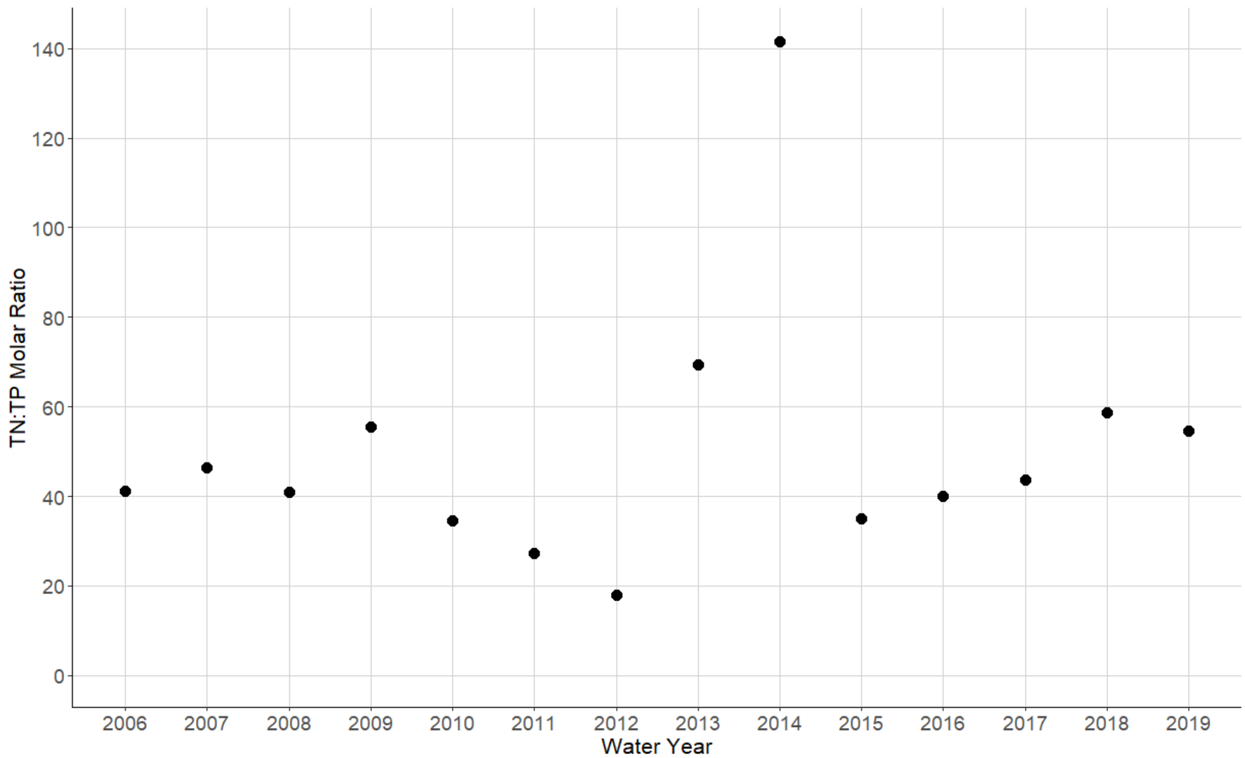

Figure 16. Median annual molar TN:TP ratios at LMP73 from water years 2006 to 2019.

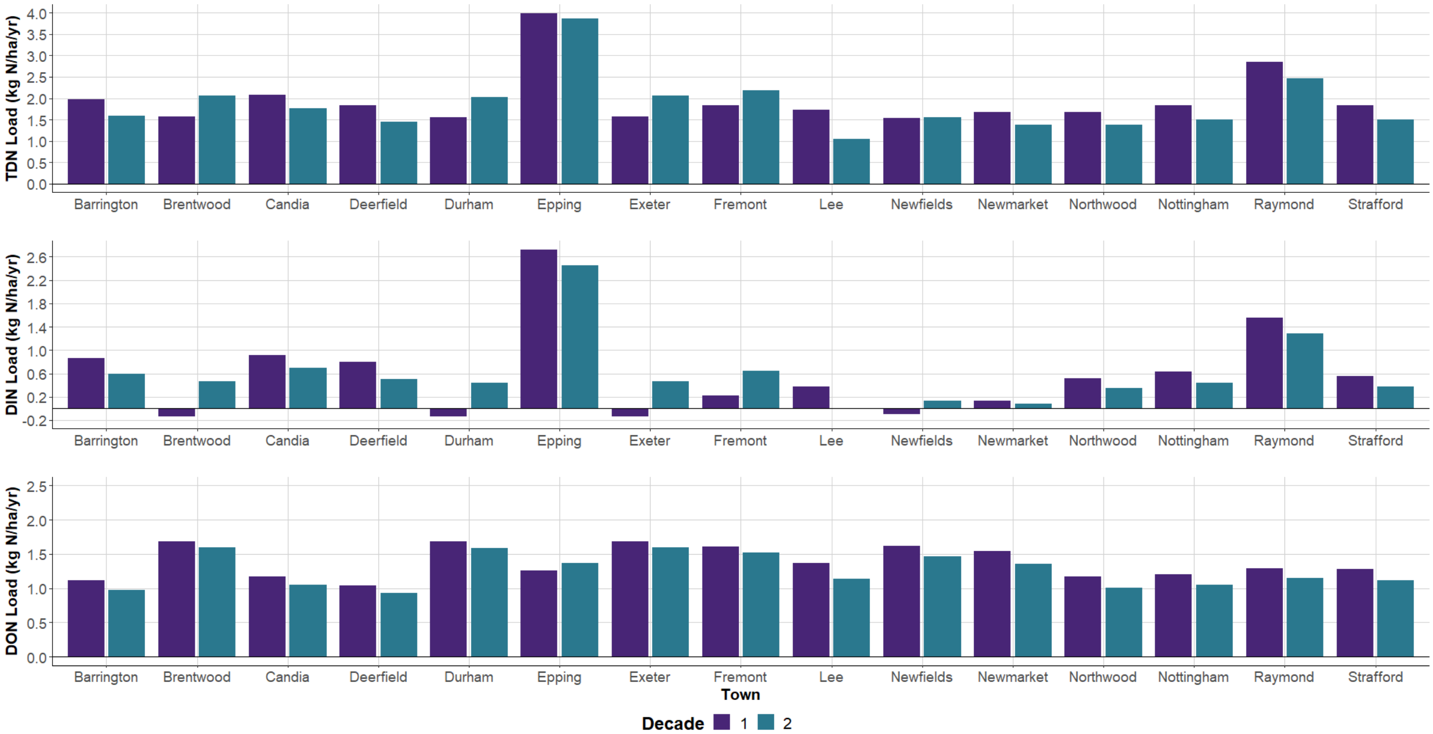

Figure 17. Provisional estimates of the portions of the overall TDN (top panel), DIN (middle panel), and DON (bottom panel) load (kg N/ha/yr) attributable to individual towns within the Lamprey River watershed. Town loads are shown separately for decade 1 (WY 2000-2009) and decade 2 (WY 2010-2019).

Appendices

Appendix A: Additional Site Map with Town Boundaries

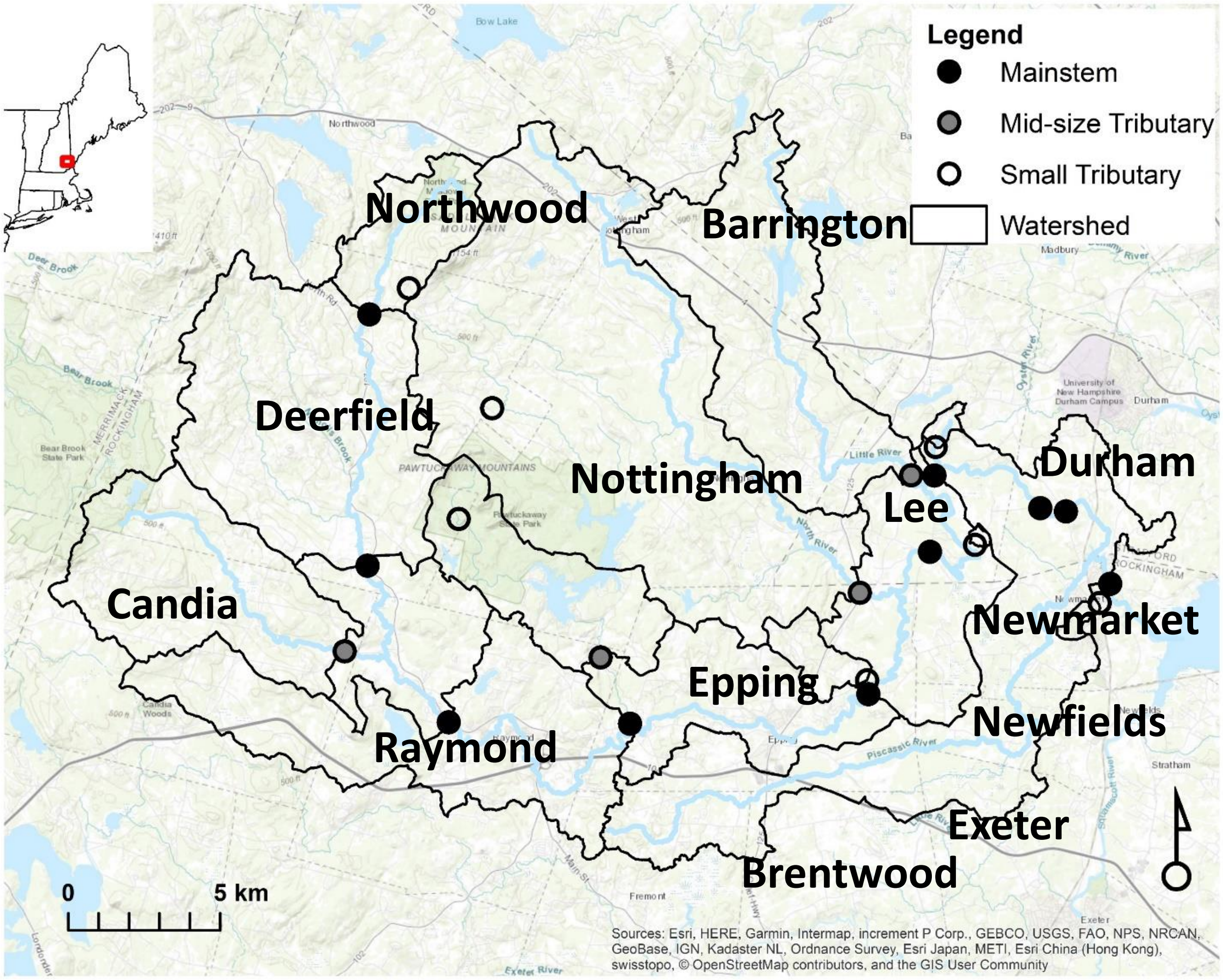

Figure A. Site map of the Lamprey River watershed. Bold lines highlight sub-watershed boundaries. Towns and mainstem sampling stations are labeled. Town loads are shown separately for decade 1 (WY 2000-2009) and decade 2 (WY 2010-2019).

Appendix B: Nutrient Loading Data

Table B1. Average annual nutrient loads (kg/year) for mainstem sampling stations along the Lamprey. Stations are organized from the headwaters to the river mouth and then by water year.

Station ID	Water Year	TDN kg N/yr	DON kg N/yr	DIN kg N/yr	NO3 kg N/yr	NH4 kg N/yr	PO4 kg P/yr
LMP07	2003	1261.5	932.9	328.6	185.1	143.5	19.3
LMP07	2004	1670.6	1071.2	599.4	405.1	201.1	17.4
LMP07	2005	1779.7	1293.3	484.5	363.4	121.1	23.2
LMP07	2006	3200.8	2648.3	574.7	222.0	352.7	16.6
LMP07	2007	2028.8	1395.7	634.6	489.2	145.3	12.6
LMP07	2008	1838.5	1444.7	399.0	293.4	105.6	18.1
LMP07	2009	2078.8	1487.1	598.3	533.3	65.0	14.3
LMP07	2010	1795.6	1147.8	650.8	495.0	155.8	28.7

Station ID	Water Year	TDN kg N/yr	DON kg N/yr	DIN kg N/yr	NO3 kg N/yr	NH4 kg N/yr	PO4 kg P/yr
LMP07	2011	1550.3	1241.1	303.6	178.0	125.6	34.8
LMP07	2012	1577.6	1082.6	421.7	324.6	97.1	76.8
LMP07	2013	1351.7	878.3	477.1	322.5	154.6	43.7
LMP07	2014	1171.5	927.5	244.4	167.3	77.4	39.5
LMP07	2015	1271.5	722.4	546.7	472.6	74.1	91.6
LMP07	2016	974.7	753.7	220.3	196.6	23.7	194.2
LMP07	2017	1672.8	1366.0	273.5	353.7	76.7	56.0
LMP07	2018	1898.7	1483.5	402.2	351.8	57.3	49.9
LMP07	2019	1877.3	1290.7	572.9	506.6	64.9	195.6
LMP19	2004	12273.8	6460.7	5813.9	4645.1	1168.8	148.4
LMP19	2005	12379.5	7082.6	5287.1	4517.4	769.8	138.6
LMP19	2006	17881.1	12497.5	5369.1	4789.4	579.7	214.2
LMP19	2007	14098.8	7096.5	7044.8	6034.3	1027.1	65.3
LMP19	2008	13586.5	8259.2	5335.8	4678.7	657.1	120.6
LMP19	2009	14969.0	7724.4	7254.4	6729.0	525.4	78.1
LMP19	2010	13656.4	5823.3	7900.4	7180.0	720.5	163.4
LMP19	2011	10776.7	7285.9	3490.1	2946.5	543.6	164.5
LMP19	2012	10864.0	7912.2	2924.5	2590.6	333.9	347.0
LMP19	2013	10687.8	7025.1	3662.7	2988.9	673.8	252.1
LMP19	2014	9673.2	6061.2	3610.6	3114.8	495.8	250.6
LMP19	2015	7265.3	3595.1	3681.3	3182.2	499.1	191.5
LMP19	2016	6752.9	4352.0	2423.5	2294.6	128.9	169.2
LMP19	2017	10224.6	7353.7	3587.1	2731.6	528.4	210.4
LMP19	2018	13424.9	9026.9	4287.2	3772.3	601.6	336.6
LMP19	2019	13973.4	6793.1	5595.4	5699.7	612.9	433.5
LMP27	2004	22319.2	12555.7	9771.6	8142.0	1629.6	301.4
LMP27	2005	25189.7	15442.6	9737.4	8471.0	1266.4	281.2
LMP27	2006	43618.6	30263.3	13472.4	11219.2	2253.2	218.5
LMP27	2007	29152.2	18519.2	10632.7	8606.8	2026.0	127.3
LMP27	2008	26952.9	18177.1	8733.1	7801.9	931.2	105.6
LMP27	2009	25811.3	12629.9	13222.3	12148.8	1073.5	136.2
LMP27	2010	25721.8	14193.9	11571.3	10522.8	1048.5	256.1
LMP27	2011	21653.5	14317.0	7317.4	6257.6	1059.8	368.0
LMP27	2012	21292.2	15260.0	6035.9	5292.5	743.4	871.4
LMP27	2013	19261.2	12396.8	6863.3	5773.7	1089.6	502.7
LMP27	2014	18939.9	11918.0	7024.9	6276.7	748.2	281.4
LMP27	2015	15847.3	7536.4	8308.2	7473.0	835.2	2674.1
LMP27	2016	13391.7	8725.9	4703.4	4344.8	363.8	422.7
LMP27	2017	18613.8	14467.6	6178.6	5151.7	656.2	277.3
LMP27	2018	21591.1	13625.7	7782.3	7061.0	801.6	778.4
LMP27	2019	25793.7	14580.9	11253.8	10103.8	1145.5	696.4
LMP39	2004	36083.0	18004.8	18075.5	14662.8	3412.8	345.8
LMP39	2005	40436.9	20042.5	20408.4	18095.0	2313.4	212.3
LMP39	2006	56901.6	39445.1	17445.8	15303.4	2142.4	873.9
LMP39	2007	42388.5	22155.3	20242.5	17479.8	2762.7	159.5
LMP39	2008	41366.6	27807.5	13605.1	11755.3	1849.8	174.7
LMP39	2009	40582.7	17402.1	23154.9	21015.9	2139.0	160.7
LMP39	2010	43417.7	22676.2	20742.2	19044.1	1698.1	312.4
LMP39	2011	33635.1	19444.3	14171.5	11876.4	2295.1	873.3
LMP39	2012	29030.1	18627.7	10386.9	9540.9	846.0	737.5
LMP39	2013	33290.6	20045.3	13234.5	11863.1	1371.5	483.5
LMP39	2014	29855.6	14636.7	15217.0	13869.0	1348.0	439.2
LMP39	2015	26215.6	10620.5	15591.5	14349.4	1242.1	280.9
LMP39	2016	21070.3	12505.0	8545.3	8263.1	282.2	526.3
LMP39	2017	30744.5	22432.3	12735.2	10694.1	1255.2	605.5
LMP39	2018	40779.2	25336.0	14930.8	13591.6	1541.2	684.7
LMP39	2019	44654.0	22252.7	21846.2	20384.7	1458.4	678.7
LMP51	2004	50896.9	23974.9	26846.0	23286.4	3559.6	389.4
LMP51	2005	55012.1	24991.6	30020.1	26550.2	3470.0	378.9
LMP51	2006	73886.5	44971.9	28909.8	25041.2	3868.6	1123.2
LMP51	2007	56263.1	28065.1	28184.4	23894.3	4290.1	260.8

Station ID	Water Year	TDN kg N/yr	DON kg N/yr	DIN kg N/yr	NO3 kg N/yr	NH4 kg N/yr	PO4 kg P/yr
LMP51	2008	55442.0	29603.4	25996.0	23779.1	2217.0	240.3
LMP51	2009	61157.3	27019.8	34081.1	31108.7	2972.4	229.1
LMP51	2010	57172.4	30258.8	26907.7	22975.0	3932.7	688.7
LMP51	2011	48652.7	25910.7	22823.1	19688.2	3134.9	626.3
LMP51	2012	39041.0	23311.5	15717.0	14627.2	1089.8	1009.8
LMP51	2013	46880.0	24563.3	22297.2	19531.7	2765.5	838.1
LMP51	2014	40277.0	15603.9	24677.8	22253.6	2424.3	850.3
LMP51	2015	44687.6	16352.8	28334.8	23290.7	5044.1	651.7
LMP51	2016	32941.6	18033.5	14908.1	13689.9	1218.2	1063.1
LMP51	2017	49255.8	29899.3	22429.7	15431.8	6123.1	641.7
LMP51	2018	55462.3	31617.3	23482.4	21236.2	2481.8	1239.6
LMP51	2019	63439.7	26828.4	26532.9	25012.1	2128.8	1272.7
LMP59	2009	87139.1	34740.1	52534.8	44851.3	7683.5	635.3
LMP59	2010	88931.6	45561.9	43527.9	39096.1	4431.8	1100.9
LMP59	2011	79842.3	46716.7	33353.1	28967.0	4386.1	1161.0
LMP59	2012	60412.5	38232.9	22211.9	20292.1	1919.8	1934.3
LMP59	2013	68863.2	39143.6	29749.5	25779.2	3970.3	1196.6
LMP59	2014	62733.8	32042.2	30394.2	27468.3	3023.1	988.4
LMP59	2015	49230.3	20706.2	28524.1	25501.9	3022.2	694.0
LMP59	2016	45653.3	26967.4	18770.5	17589.7	1180.8	1166.8
LMP59	2017	61306.8	41525.0	26112.9	19639.1	5478.1	1041.4
LMP59	2018	78524.3	50445.3	29235.2	27078.5	3394.7	1745.9
LMP59	2019	83793.1	40431.0	44102.2	40862.4	3397.5	2116.1
LMP67	2004	96251.0	49456.1	46794.9	36163.1	10631.8	1325.7
LMP67	2005	98571.3	50243.3	48282.9	41784.0	6498.8	1005.1
LMP67	2006	144980.4	96980.8	47939.1	36768.3	11170.8	1706.5
LMP67	2007	97126.2	53566.3	43488.4	36770.1	6718.3	588.0
LMP67	2008	99831.5	63841.0	36328.7	32608.7	3720.0	522.3
LMP67	2009	111101.6	59043.1	52164.5	46080.7	6083.8	668.7
LMP67	2010	105042.5	59050.6	45906.5	40210.5	5686.3	1763.5
LMP67	2011	87737.8	54809.9	32937.9	27887.5	5050.4	1637.5
LMP67	2012	74654.8	46547.4	28098.5	25580.7	2517.8	2250.9
LMP67	2013	81530.0	47573.2	33971.6	29025.5	4946.0	1896.1
LMP67	2014	74260.2	40213.8	34052.9	30037.2	4015.7	1182.9
LMP67	2015	61165.8	30553.4	30612.4	26797.8	3814.6	828.1
LMP67	2016	56775.0	35922.5	20867.9	19669.5	1199.2	1597.6
LMP67	2017	76944.2	52148.1	32091.3	24023.1	6108.5	1915.9
LMP67	2018	97399.0	58326.7	38647.7	34365.4	4306.8	2416.8
LMP67	2019	112074.6	57322.2	53961.9	49370.7	4840.1	4310.7
LMP72	2012	93776.1	59043.4	34746.9	28882.8	5864.1	3557.5
LMP72	2013	111657.3	82231.8	40831.3	32564.4	8266.9	2177.0
LMP72	2014	110938.3	69546.2	41396.5	35480.0	5917.0	1690.2
LMP72	2015	73939.3	38424.5	35436.9	31080.9	4624.0	1598.0
LMP72	2016	68263.0	41065.8	27175.8	24236.2	2581.0	1577.0
LMP72	2017	88446.4	52315.2	36120.0	28620.4	6659.8	2070.4
LMP72	2018	99697.8	55732.2	40868.2	35350.6	5735.7	2336.6
LMP72	2019	113223.4	65076.8	41425.9	37447.7	4013.0	2274.8
LMP73	2000	82300.0	55402.8	26880.4	22417.2	4463.2	1692.5
LMP73	2001	98736.2	63733.6	35037.7	25832.9	9199.8	1427.9
LMP73	2002	41893.0	24658.1	17235.2	13483.6	3751.7	1072.0
LMP73	2003	67952.1	34114.5	33826.9	30112.7	3714.2	746.1
LMP73	2004	113648.3	80165.6	33493.2	27744.3	5748.9	1937.1
LMP73	2005	97874.0	52888.5	44995.3	39281.2	5714.1	1175.4
LMP73	2006	138564.0	85370.8	53288.8	47135.1	6153.7	1468.7
LMP73	2007	106139.9	58538.1	47575.2	40090.2	7475.4	874.4
LMP73	2008	110780.8	55277.5	55516.3	48008.9	7507.4	903.2
LMP73	2009	111578.5	60620.1	50309.9	44591.9	5746.7	859.5
LMP73	2010	98150.8	53675.7	47247.4	41440.0	5846.2	1962.1
LMP73	2011	79562.4	49053.3	31943.0	27651.4	4182.7	2166.6
LMP73	2012	81082.4	52050.3	28614.4	24703.7	3910.6	2230.1
LMP73	2013	98927.1	63027.8	35907.7	30189.1	5718.6	2499.3

Station ID	Water Year	TDN kg N/yr	DON kg N/yr	DIN kg N/yr	NO3 kg N/yr	NH4 kg N/yr	PO4 kg P/yr
LMP73	2014	87444.8	46212.5	41223.6	36053.1	5170.5	2056.9
LMP73	2015	68026.1	31990.3	36308.5	31458.2	4896.7	1582.6
LMP73	2016	62945.3	37184.7	25699.3	23612.9	2153.3	1545.9
LMP73	2017	85081.9	50599.2	36734.6	29413.2	6255.7	1617.3
LMP73	2018	104921.8	64685.3	39630.8	35654.8	4407.7	2536.8
LMP73	2019	112031.9	65927.4	38942.0	34849.0	4127.8	2462.8
LMP78	2006	197763.5	111276.9	86569.7	68043.1	18526.6	1043.9
LMP78	2007	119157.2	67092.3	52014.7	41326.9	10687.8	636.2
LMP78	2008	125904.4	74315.5	51560.1	45617.2	5942.8	902.1
LMP78	2009	123473.5	61080.3	62321.5	54817.6	7503.9	803.7
LMP78	2010	138525.7	71024.1	67512.2	58535.1	8977.1	2070.9
LMP78	2011	105737.5	59048.5	46521.9	39587.7	6934.1	2293.4
LMP78	2012	92204.5	60584.5	31634.4	27565.5	4068.9	3248.7
LMP78	2013	103502.4	62659.5	40843.0	33669.4	7173.6	2957.5
LMP78	2014	94485.0	48678.1	45812.4	37423.0	8389.3	2740.7
LMP78	2015	72031.5	35290.2	34261.6	30874.4	4203.0	1653.9
LMP78	2016	66097.4	40599.6	25497.8	22947.4	2550.4	2082.7
LMP78	2017	96089.9	66334.2	35654.7	26478.5	7800.2	1888.5
LMP78	2018	117272.5	66629.7	50401.9	42911.3	7590.9	3788.9
LMP78	2019	127571.5	68927.0	58630.0	50814.9	8682.2	3449.8

Appendix C: Regression Outputs for Temporal Trends in Nutrient Loads

Table C1. Regression statistics, including the slope and intercept for the line of best fit, R^2 value, and p value for annual TDN loads over time at individual stations. Stations with a significant trend are bolded.

Station ID	**Slope**	**Intercept**	**R^2**	**p value**
BDC0.30	0.29	-566.50	0.21	0.361
DCF03	0.00	8.20	0.00	0.950
LMP07	-0.02	40.10	0.09	0.246
LMP19	-0.04	71.90	0.22	0.068
LMP27	**-0.06**	**113.00**	**0.31**	**0.026**
LMP39	-0.04	82.70	0.19	0.091
LMP51	-0.03	61.60	0.12	0.183
LMP59	-0.04	77.10	0.11	0.326
LMP67	-0.05	92.00	0.21	0.073
LMP72	0.00	0.40	0.00	0.990
LMP73	0.00	-2.70	0.00	0.901
LMP78	**-0.08**	**160.10**	**0.31**	**0.038**
LTR20	-0.04	73.90	0.24	0.056
MLB01	-0.16	320.70	0.25	0.122
NBR12	**-0.04**	**83.40**	**0.33**	**0.021**
NOR27	-0.06	114.60	0.24	0.055
PWT03	**-0.03**	**67.60**	**0.45**	**0.005**
PWT10	**-0.08**	**152.80**	**0.54**	**0.004**
RMB04	-0.05	100.80	0.17	0.112
SBM0.2	-0.03	54.10	0.31	0.447
WHB01	**-0.11**	**222.40**	**0.25**	**0.039**

Table C2. Regression statistics, including the slope and intercept for the line of best fit, R^2 value, and p value for annual DIN loads over time at individual stations. Stations with a significant trend are bolded.

Station ID	Slope	Intercept	R^2	p value
BDC0.30	0.15	-293.70	0.10	0.549
DCF03	**-0.03**	**66.80**	**0.64**	**0.030**
LMP07	-0.01	12.50	0.11	0.204
LMP19	**-0.02**	**45.10**	**0.27**	**0.040**
LMP27	**-0.02**	**38.80**	**0.25**	**0.048**
LMP39	-0.02	34.30	0.14	0.157
LMP51	-0.02	40.00	0.22	0.065
LMP59	-0.03	60.50	0.15	0.244
LMP67	-0.02	36.60	0.18	0.107
LMP72	0.01	-10.70	0.02	0.752
LMP73	0.00	-5.50	0.01	0.702
LMP78	**-0.04**	**76.80**	**0.29**	**0.048**
LTR20	-0.01	20.60	0.10	0.243
MLB01	-0.16	328.00	0.30	0.081
NBR12	-0.02	32.30	0.32	0.022
NOR27	-0.02	45.80	0.15	0.145
PWT03	0.00	-1.60	0.00	0.832
PWT10	**-0.03**	**59.30**	**0.41**	**0.019**
RMB04	-0.02	31.50	0.04	0.433
SBM0.2	-0.01	9.40	0.30	0.453
WHB01	**-0.11**	**221.90**	**0.34**	**0.014**

Table C3. Regression statistics, including the slope and intercept for the line of best fit, R^2 value, and p value for annual DON loads over time at individual stations. Stations with a significant trend are bolded.

Station ID	**Slope**	**Intercept**	**R^2**	**p value**
BDC0.30	0.13	-256.50	0.16	0.436
DCF03	0.03	-50.20	0.06	0.593
LMP07	-0.01	29.60	0.06	0.336
LMP19	-0.02	33.30	0.10	0.240
LMP27	-0.03	70.20	0.22	0.067
LMP39	-0.02	43.50	0.09	0.261
LMP51	-0.02	35.90	0.09	0.260
LMP59	0.00	4.90	0.00	0.932
LMP67	-0.03	51.50	0.15	0.145
LMP72	-0.04	71.30	0.08	0.503
LMP73	0.00	6.20	0.00	0.844
LMP78	-0.04	80.10	0.26	0.064
LTR20	-0.03	51.60	0.21	0.078
MLB01	-0.01	9.90	0.01	0.783
NBR12	-0.02	47.20	0.17	0.108
NOR27	-0.03	63.00	0.16	0.119
PWT03	**-0.03**	**67.30**	**0.47**	**0.004**
PWT10	**-0.04**	**85.70**	**0.39**	**0.023**
RMB04	-0.03	64.80	0.19	0.090
SBM0.2	-0.03	51.30	0.24	0.513
WHB01	-0.01	29.90	0.06	0.342

Table C4. Regression statistics, including the slope and intercept for the line of best fit, R^2 value, and p value for annual nitrate loads over time at individual stations. Stations with a significant trend are bolded.

Station ID	**Slope**	**Intercept**	**R^2**	**p value**
BDC0.30	0.00	-3.10	0.00	0.985
DCF03	-0.02	41.00	0.55	0.058
LMP07	0.00	-3.00	0.01	0.712
LMP19	-0.02	34.40	0.17	0.108
LMP27	-0.01	29.40	0.18	0.097
LMP39	-0.01	22.80	0.07	0.312
LMP51	-0.02	36.60	0.22	0.068
LMP59	-0.02	47.70	0.12	0.307
LMP67	-0.01	22.70	0.09	0.261
LMP72	0.01	-22.70	0.10	0.457
LMP73	0.01	-9.10	0.02	0.518
LMP78	-0.03	60.50	0.27	0.057
LTR20	-0.01	16.50	0.07	0.316
MLB01	-0.15	294.60	0.27	0.102
NBR12	-0.01	23.00	0.22	0.070
NOR27	-0.02	34.60	0.09	0.265
PWT03	0.01	-9.60	0.20	0.084
PWT10	-0.02	30.60	0.21	0.114
RMB04	-0.02	30.40	0.05	0.431
SBM0.2	0.00	-0.80	0.00	0.948
WHB01	**-0.08**	**172.90**	**0.24**	**0.046**

Table C5. Regression statistics, including the slope and intercept for the line of best fit, R^2 value, and p value for annual PO4 loads over time at individual stations. Stations with a significant trend are bolded.

Station ID	**Slope**	**Intercept**	**R^2**	**p value**
BDC0.30	0.016	-32.30	0.43	0.158
DCF03	**0.007**	**-13.50**	**0.84**	**0.004**
LMP07	**0.005**	**-10.40**	**0.48**	**0.002**
LMP19	**0.002**	**-3.50**	**0.45**	**0.004**
LMP27	0.004	-7.30	0.16	0.122
LMP39	0.001	-2.10	0.16	0.132
LMP51	**0.002**	**-3.90**	**0.43**	**0.006**
LMP59	0.002	-3.50	0.23	0.138
LMP67	**0.003**	**-5.00**	**0.37**	**0.013**
LMP72	-0.002	3.60	0.10	0.438
LMP73	**0.001**	**-2.30**	**0.33**	**0.008**
LMP78	**0.003**	**-6.60**	**0.55**	**0.003**
LTR20	**0.002**	**-4.80**	**0.65**	**0.000**
MLB01	0.002	-3.00	0.02	0.682
NBR12	**0.003**	**-5.50**	**0.48**	**0.003**
NOR27	**0.001**	**-2.70**	**0.26**	**0.043**
PWT03	**0.003**	**-6.90**	**0.43**	**0.005**
PWT10	**0.003**	**-5.50**	**0.35**	**0.033**
RMB04	0.003	-5.00	0.08	0.295
SBM0.2	0.005	-9.10	0.59	0.235
WHB01	**0.001**	**-3.00**	**0.37**	**0.010**

Table C6. Regression statistics, including the slope and intercept for the line of best fit, R2 value, and p value for median annual TDN:PO4 molar ratios over time at individual stations. Stations with a significant trend are bolded.

Station ID	**Slope**	**Intercept**	**R^2**	**p value**
BDC0.30	-6.49	13139	0.29	0.272
DCF03	**-14.05**	**28399**	**0.70**	**0.019**
LMP07	**-26.18**	**52866**	**0.54**	**0.001**
LMP19	**-43.89**	**88579**	**0.74**	**0.000**
LMP27	**-42.20**	**85215**	**0.64**	**0.000**
LMP39	**-51.36**	**103670**	**0.75**	**0.000**
LMP51	**-49.39**	**99751**	**0.54**	**0.001**
LMP59	**-13.76**	**27878**	**0.39**	**0.040**
LMP67	**-33.53**	**67719**	**0.46**	**0.004**
LMP72	-0.49	1098	0.01	0.867
LMP73	-9.91	20168	0.07	0.256
LMP78	**-56.54**	**114073**	**0.66**	**0.000**
LTR20	**-42.95**	**86700**	**0.64**	**0.000**
MLB01	**-58.07**	**117370**	**0.63**	**0.004**
NBR12	**-34.31**	**69268**	**0.61**	**0.000**
NOR27	**-28.26**	**57084**	**0.39**	**0.010**
PWT03	**-16.68**	**33685**	**0.48**	**0.003**
PWT10	**-39.32**	**79357**	**0.65**	**0.001**
RMB04	**-4.14**	**8447**	**0.34**	**0.018**
WHB01	**-22.93**	**46481**	**0.49**	**0.002**

Sources

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