Lake Champlain Basin Program

TECHNICAL REPORT NO. 86

Concentration, load, and trend estimates for nutrients, chloride, and total suspended solids in Lake Champlain tributaries,1990 – 2017

May 2019

Final Report

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For:
The Lake Champlain Basin Program and New England Interstate Water Pollution Control Commission

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NEIWPCC Job Code: 0100-323-002

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for the

Lake Champlain Steering Committee

Approved by the

Lake Champlain Basin Program Technical Advisory Committee

April 3, 2019

NEIWPCC
New England Interstate Water Pollution Control Commission

Lake Champlain Basin Program

Although the information in this document may have been funded by the International Great Lakes Fishery Commission through their contracts to NEIWPCC, it has not undergone review by the Commission, and no official endorsement of the content of the document should be inferred.

Cite as: Vaughan, M.C.H. (2019), Concentration, load, and trend estimates for nutrients, chloride, and total suspended solids in Lake Champlain tributaries, 1990 – 2017. Lake Champlain Basin Program Technical Report #86.
http://lcbp.org/techreportPDF/86_LC_Tributary_Loading_Report.pdf

First released May 30, 2019.

Revision released June 3, 2019. This version includes corrections to Tables 3-12 and some text that refers to trend results for first half of record.

Executive Summary

Purpose and scope

Lake Champlain is a treasured natural resource and the subject of several water quality restoration goals. Determining the amount of water, nutrients, and sediment delivered to the lake each year by major tributaries is critical to inform management objectives. This report compiles water quality and discharge data for 18 major tributaries to Lake Champlain to examine concentration, load, and trends for key water quality parameters: total phosphorus, dissolved phosphorus, total nitrogen, chloride, and total suspended solids. The influence of annual water flux variability was reduced with a flow-normalization technique. Trends in flow-normalized concentration and load were considered for three time periods for all parameters: full record, and the first and second halves of record. Model biases were generally within acceptable limits for all constituents besides total suspended solids, where concentrations and loads were often over-estimated. Models and results were generated using custom automated programming code using R statistical software, which will reduce the time and cost required for future iterations of this report to be generated for Lake Champlain Basin stakeholders.

Total phosphorus

The Winooski and Missisquoi Rivers, Lake Champlain's two largest tributaries, each contributed roughly 100 to 300 metric tons of phosphorus to the lake most years. In 10 out of the 18 tributaries, no trends in flow-normalized total phosphorus load were found for any time period. Flow-normalized total phosphorus load decreased in the Little Ausable River throughout the period of record. Flow-normalized loads decreased sharply in the first half of the record for the LaPlatte River, but no trends were found in the second half of the record. Lewis and Little Otter Creeks showed significant increases in flow-normalized load for entire record. For the Missisquoi and Poultney Rivers and Putnam Creek, increasing trends were only found in the second half of the record.

Dissolved phosphorus

Dissolved phosphorus loads ranged from roughly 20 to 80 metric tons per year for the Missiquoi River and Otter Creek, and roughly 10 to 40 metric tons per year for the Winooski and Pike Rivers. Seven out of the eighteen tributaries showed no trend in flow-normalized dissolved phosphorus load for all of the three trend periods considered. The LaPlatte River showed a significant decrease in flow-normalized load throughout record, and Otter Creek and Winooski River showed a significant decrease for the first half of the record and full-record trend periods, but not for the second half of record. There were significant increases in flow-normalized load for several tributaries in the first half of record and full record trend periods, including: Ausable, Boquet, Salmon, and Saranac Rivers and Putnam Creek. Of these, only the Putnam Creek continued to increase in flow-normalized load in the second half of record; no trend in the second half of record was observed for the others.

Total nitrogen

The Winooski and Missisquoi Rivers each delivered roughly 750 to 2,000 metric tons of nitrogen to Lake Champlain most years. The Pike River annual flow-normalized total nitrogen yield often exceeded that of other tributaries by a factor of two and Pike River annual mean total nitrogen concentrations were much higher than other tributaries. Trends, mostly downward, in flow-normalized load were found for at least one trend period for all but three tributaries. Flow-normalized total nitrogen load significantly decreased for all three trend periods in the Saranac River. Six tributaries decreased in flow-normalized total nitrogen load for the full record trend period: the LaPlatte, Mettawee, Saranac, and Salmon Rivers, and Otter and Putnam Creeks. The Ausable, Boquet, and Little Chazy Rivers showed no trend for the first half of record, then had significant decreases in the second half of the record. Significant increases in flow-normalized load for the second half of record were found in the Great Chazy River and the Little Otter Creek.

Chloride
The Winooski River delivered roughly 15,000 to 45,000 metric tons of chloride to Lake Champlain each year; its loads and yields often exceeded those of other tributaries. The LaPlatte River had the highest flow-normalized chloride concentration for much of the record, though this decreased significantly and was similar to the Winooski and Mettawee Rivers in 2017. Full-record significant increases in flow-normalized chloride load were observed in all but two tributaries, the LaPlatte and Pike Rivers, where decreasing trends were found. For six tributaries that had significant first half and full record increases, there was no trend or a decreasing trend in flow-normalized chloride load for the second half of record: Ausable, Boquet, Missisquoi, and Winooski Rivers, and Lewis and Otter Creeks.

Total suspended solids
Winooski and Missisquoi Rivers had the highest annual total suspended solids loads, at times exceeding an estimated 200,000 metric tons per year. Five tributaries had significantly increasing trends in flow-normalized total suspended solids load for the full record: LaPlatte, Missisquoi, and Pike Rivers, and Lewis and Little Otter Creeks. Of these, only Little Otter Creek had an increasing trend in the second half of record; the others had no trend. The Lamoille River was the only tributary to show a decreasing trend in flow-normalized total suspended solids load for the full record trend period. The Little Ausable and Little Chazy Rivers had relatively low chloride loads and yields, and both decreased significantly in the second half of record.

Water
Annual water fluxes for Lake Champlain tributaries were closely related to contributing watershed area, and larger watersheds generally had greater runoff per land area. The Winooski and Missisquoi Rivers delivered roughly one to three billion cubic meters of water to Lake Champlain most years. There were no trends in water flux for the full record or for the first half record for any tributary. For the second half of record, the Boquet, Mettawee, Otter, and Poultney Rivers and Putnam Creek showed significant decreases in annual water flux.

Introduction

Purpose of study

Lake Champlain is a treasured natural resource situated in the US states of New York and Vermont, and the Canadian Province of Québec (Figure 1). Its tributaries deliver water, nutrients, sediment, and pollutants to the lake from a drainage basin that is roughly 18 times the size of the water body. The lake and its tributaries are the subject of several restoration efforts. To inform these restoration efforts, the Lake Champlain Basin Program supports the Long-term Water Quality and Biological Monitoring Program for Lake Champlain (LTMP) in collaboration with New York and Vermont Departments of Environmental Conservation and the New England Interstate Water Pollution Control Commission. This program has collected extensive water quality and aquatic community data since 1990, including 22 Lake Champlain tributary monitoring stations where key water quality parameters are measured several times per year. In addition, the U.S. Geological Survey has recorded estimates of discharge on many of these major Lake Champlain tributaries every 15 minutes over the same time period.

The Lake Champlain Basin Program LTMP and US Geological Survey datasets provide the opportunity to consider historical records, variability, and changing trends of the delivery of water, nutrients, sediment, and chloride delivery to the lake since 1990. This analysis is central to *Opportunities for Action: An Evolving Plan for the Future of the Lake Champlain Basin*, which calls for the assessment of progress toward established water quality targets. Secondly, it informs the Lake Champlain Basin Program's *State of the Lake and Ecosystem Indicators Report*, which disseminates the latest scientific knowledge in a document accessible to all stakeholders in the Lake Champlain Basin.

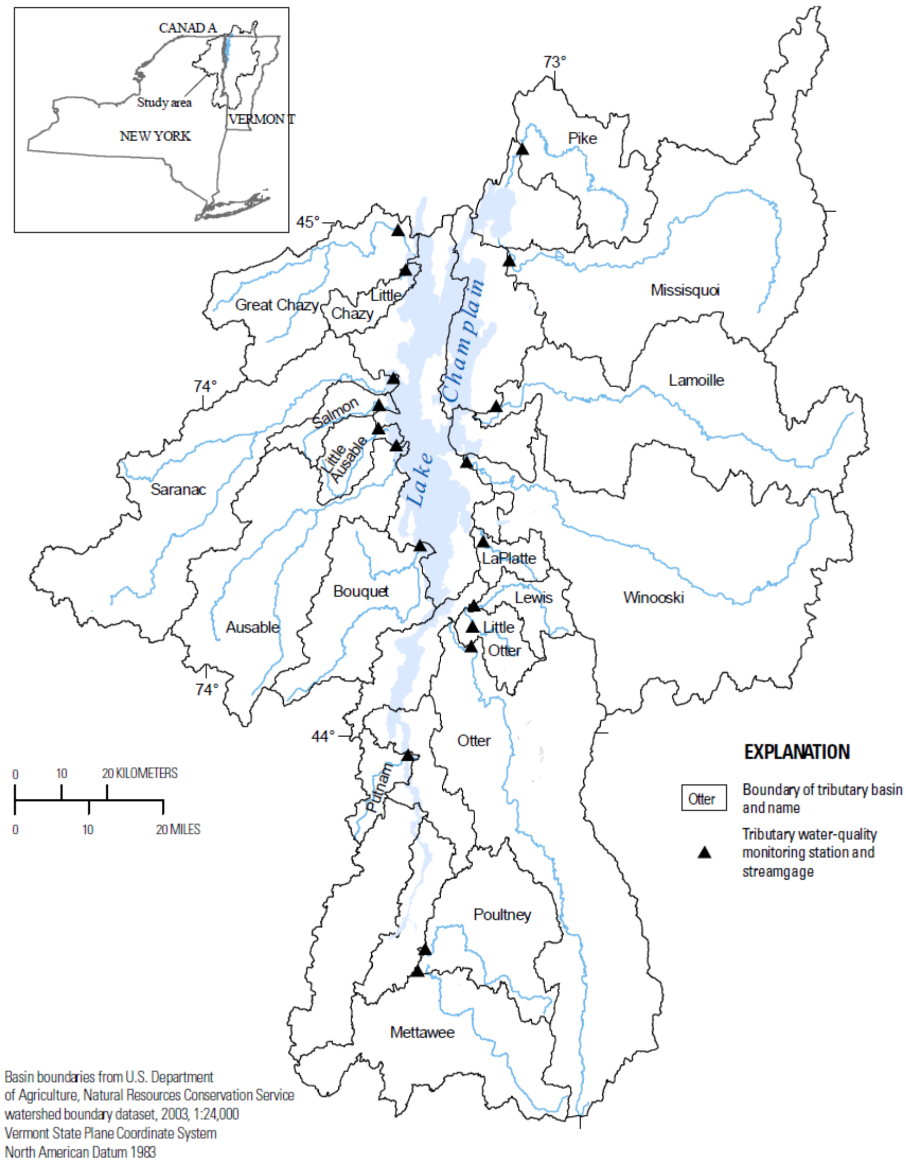


Figure 1. Map of Lake Champlain, its drainage basin, major tributaries, and co-located long-term monitoring and stream gauge stations (Medalie 2016).

Summary of past efforts to estimate Lake Champlain tributary loads

Several past efforts have calculated concentrations, loads, and trends for Lake Champlain tributaries. The Lake Champlain Diagnostic-Feasibility Study (1997) was the first major effort to document tributary concentrations and loads of total phosphorus, dissolved phosphorus, and chloride. At that time, water samples and continuous discharge measurements were collected at 31 tributaries of Lake Champlain. Also among the earliest efforts was Medalie and Smeltzer (2004), where tributary total phosphorus concentrations were summarized, and loads were calculated for 18 major tributaries using the U.S. Army Corps of Engineers FLUX program

(Walker 1987; Walker 1996). In this study, trends were determined using two separate methods, including the ESTIMATOR program (Cohn et al. 1992) and a time-series moving average approach (Vecchia 2000). In Smeltzer and Simoneau (2008), phosphorus loads were estimated for tributaries of Missisquoi Bay from 2002 – 2005 using the FLUX program. This was also the first study to incorporate laboratory phosphorus measurements from the LTMP and the Québec Ministère du Environnement et Lutte contre les changements climatiques (MELCC) to estimate phosphorus load for the Pike River, which flows through the two nations. Although methodological differences likely caused results from the two labs to be significantly different, a linear regression model was used to adjust the data for inclusion into the FLUX model.

Medalie et al. (2012) was the first to estimate load trends for 18 of Lake Champlain's major tributaries using the weighted regression on time, discharge, and season (WRTDS) model. This method was then repeated and updated with iterative improvements in Medalie (2013), Medalie (2014), and Medalie (2016). The latest effort considered data from 1990 – 2014, included uncertainty estimates for the first time, and omitted estimates for the winter season. In addition, Patoine (2017) used the same model to estimate phosphorus loads from 2009 to 2012 for all MELCC monitored streams in Québec, including the Pike River.

Phosphorus load estimates for Lake Champlain have been made in the development of Total Maximum Daily Load (TMDL) determinations for the states of New York (New York and Vermont DECs, 2002) and Vermont (EPA, 2016). Both efforts were based on the BATHTUB modeling program (Walker 1987) and Lake Champlain Basin Program LTMP data. The Vermont TMDL for Lake Champlain segments also incorporated the Soil and Water Assessment Tool (SWAT) model to determine phosphorus loads from areas that are outside of monitored tributary watersheds.

Goals of this work

The goals of this work are to consider available data for discharge, phosphorus, nitrogen, chloride, and suspended sediment for the major tributaries of Lake Champlain to determine

1. annual mean concentration estimates for each constituent;
2. annual load estimates for each constituent; and
3. mid-term and long-term trends in concentration and load estimates with associated uncertainties.

Among many factors, annual constituent tributary loads and concentrations are driven by precipitation and annual water flux, which are highly variable in the Lake Champlain Basin's humid climate. Flow-normalization by the WRTDS model is a method to reduce the influence of annual variability in water flux and determine water quality trends that may be attributed to watershed restoration efforts and/or environmental stressors.

Methods

The LTMP collects water samples and tributary data at 22 tributary sites; 18 of these sites have sufficient records for the WRTDS analysis (Table 1). Available records began in 1990 for total phosphorus, dissolved phosphorus, and chloride. For total nitrogen and total suspended solids, records began in 1992. Detailed methods on sample collection can be found in the LTMP Quality Assurance Project Plan (Appendix A). These concentration measurements were paired with measurements of discharge by the U.S. Geological Survey at 17 of the 18 sites, and by the MELCC at the Pike River.

Estimates and trends for concentration and loads for water quality parameters were calculated using WRTDS models generated with the EGRET package in R (Hirsch et al. 2010; R Core Team 2015). This flexible statistical method is intended to provide estimates of actual concentrations and fluxes, and artificial estimates that reduce the influence of annual water flux variability. Its regression to predict concentration values for any given day is based on a model that weights time, discharge, and season. This regression takes the basic form

$$\ln(c) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \varepsilon \,, \quad (1)$$

where c is the estimated concentration, β values are fitted coefficients, t is the time of the estimate in fractional years, Q is daily mean discharge on the day of estimate, and ε is a residual term. The fitted coefficients are determined using weights that correspond to the multi-dimensional "distance" of the estimate from known sample concentrations. This is determined by the equation

$$w = \begin{cases} (1 - (d/h)^3)^3 & \text{if } |d| \leq h \\ 0 & \text{if } |d| > h \end{cases} \,, \quad (2)$$

where w is the weight used for regression, d is the "distance" from the estimate point to the known sample concentration point, and h is the half-window width, a user-specified input. This function approximates a normal distribution with a flat top of the bell curve and tails equal to zero past the half-window width, rather than asymptotic tails. More detail on how these weights determine regression coefficients can be found in Hirsch et al. (2010).

Flow-normalized estimates are intended to reduce the influence of annual variability in water flux. These estimates are computed in a similar way as actual estimates, though instead of using the actual daily mean discharge for each estimate, the algorithm uses the mean of estimates using all discharge measurements observed at each site on the date of estimate. For example, if estimating concentration on May 1, 2000, the model computes estimates using discharges for each observed May 1 on record, then calculates the mean of these estimates.

WRTDS models and all results were generated using custom R programming code that automated calculations, compilation, and graphical presentation. User-specified parameters were identical to Medalie (2016) and most water quality and discharge data was retrieved automatically through online databases and incorporated into model calculations. This programming infrastructure will reduce the time and cost required for future iterations of this report to be generated for Lake Champlain stakeholders. All resulting data generated from this report, including daily and annual estimates of concentration and load for all parameters and tributaries, can be found in Appendix B.

One notable difference from Medalie (2016) is that annual estimates were generated for full years rather than non-winter periods only. Although winter water quality sample data is sparse and including the winter period may introduce uncertainty to estimates, watershed managers and other stakeholders have expressed a preference for full-year estimates in order to compare results to nutrient load targets and regulations.

A second notable difference from Medalie (2016) is the addition of Québec MELCC phosphorus concentration data to Pike River total phosphorus concentration estimates from the LTMP. From the earliest record until March 2009, MELCC total and dissolved phosphorus concentrations were determined by automated colorimetric method using ammonium molybdate. From April 2009 until the present, these concentrations were determined by acid-persulfate digestion, as with LTMP samples. Where appropriate, a conversion factor was applied to MELCC laboratory results based on the correlation demonstrated by Smeltzer and Simoneau (2008).

The discharge gauging stations for the Little Chazy River was discontinued on September 30, 2014, and then resumed operation on October 1, 2015. In order to generate estimates and calculate trends, the missing year of record was estimated using a linear correlation of available daily mean discharge values at Little Chazy River gauge with the nearby Great Chazy River gauge. The linear model incorporated 9,406 days of data and was highly significant ($p < 0.001$) with an adjusted R^2 of 0.81.

Table 1. Tributary information and dates used in the analysis. Note that the tributaries are sorted in descending order by watershed area. The Pike River gauge number corresponds to the MELCC gauge network. The mean annual water flux is for years considered in this report.

Tributary	Watershed area (km^2)	Mean annual water flux (10^9 m^3)	USGS gage number	STORET station number	Date of first estimate for TP, TDP, Cl	Date of first estimate for TN, TSS	Date of last estimate for all parameters
Winooski	2704	1.80	4290500	501903	1990-03-01	1992-06-01	2017-11-30
Missisquoi	2201	1.63	4294000	500505	1990-03-01	1992-06-01	2017-11-30
Lamoille	1777	1.27	4292500	501794	1990-03-01	1992-06-01	2017-11-30
Otter	1627	1.02	4282500	500509	1990-03-01	1992-06-01	2017-11-30
Saranac	1575	0.91	4273500	500491	1990-03-01	1992-06-01	2017-11-30
Ausable	1155	0.73	4275500	500500	1990-03-01	1992-06-01	2017-11-30
Bouquet	699	0.34	4276500	500498	1990-03-01	1992-06-01	2017-11-30
Great Chazy	629	0.32	4271500	500492	1990-03-01	1992-06-01	2017-11-30
Pike	584	0.33	30424	500512	1990-03-01	1992-06-01	2017-11-30
Poultney	484	0.25	4280000	500578	1990-03-01	1992-06-01	2017-11-30
Mettawee	433	0.25	4280450	500508	1990-03-01	1992-06-01	2017-11-30
Lewis	200	0.10	4282780	500503	1990-03-01	1992-06-01	2017-11-30
Little Ausable	176	0.05	4273800	500501	1991-10-01	1992-06-01	2017-11-30
Salmon	164	0.06	4273700	500502	1990-03-01	1992-06-01	2017-11-30
Little Otter	148	0.06	4282650	501371	1990-03-01	1992-06-01	2017-11-30
Putnam	134	0.07	4276842	500495	1990-03-01	1992-06-01	2014-09-30
Little Chazy	130	0.06	4271815	500490	1990-03-01	1992-06-01	2017-11-30
LaPlatte	116	0.05	4282795	501594	1990-03-01	1992-06-01	2017-11-30

Annual concentration estimates and uncertainties

Annual concentration estimates were calculated in three ways: (1) time-weighted mean concentration, (2) flow-weighted mean concentration, and (3) flow-normalized concentration. The time-weighted mean concentration for a given year is the arithmetic mean of all estimated daily concentration values for each tributary and year. Flow weighted concentration is given by the equation,

$$C_{FWM} = \frac{\sum c_i q_i t_i}{\sum q_i t_i}, \quad (3)$$

where C_{FWM} is the annual flow-weighted mean concentration, c_i is the daily concentration on the i^{th} day of the year, q_i is the daily discharge on the i^{th} day of the year, and t_i is the time duration of the i^{th} day of the year. This results in the equivalent of the total mass flux divided by the total flux volume of water. In other words, if the tributary hypothetically flowed into a bucket that was well mixed at the end of the year, its concentration would equal the flow-weighted mean concentration. The difference between the flow-weighted and time-weighted concentrations indicates the importance of high discharge events (storms and snowmelt) on the bulk concentration of water delivered to Lake Champlain. The annual flow-normalized concentration was found by calculating the arithmetic mean of all daily flow-normalized concentration values for each tributary and year. Confidence intervals (95%) for annual flow-normalized concentration values were generated using the EGRETci package in R.

Annual load estimates and uncertainties

Annual loads for each site were estimated by multiplying daily concentration estimates by daily mean discharge estimates, then summing each of these daily load estimates to attain a total load for each year. Annual flow-normalized load was calculated in a similar way, but using flow-normalized concentrations rather than actual concentration estimates. Confidence intervals (95%) for annual flow-normalized load estimates were generated in the same way as those for flow-normalized concentration estimates. Annual yield estimates were calculated by dividing the annual load estimates by the contributing watershed area for each tributary. Similarly, annual water yield estimates were calculated by dividing the annual water flux estimates by the contributing watershed area for each tributary, and converting units to millimeters.

The flux bias statistic is a dimensionless diagnostic metric that indicates the difference between modeled and observed loads for each WRTDS model. It is calculated by the difference of the mean predicted flux and the mean observed flux, divided by the mean observed flux. Flux bias values outside of the range of −0.1 to +0.1 (representation a range of ±10% error) may indicate that the model has an unacceptable level of uncertainty (Hirsch 2014; Medalie 2016).

Trends and uncertainties

Trends and associated uncertainties were calculated for three different time periods at each site and parameter: the full record, beginning of record to 2004 (hereafter “first half”), and 2004 to the end of record (hereafter “second half”). Records used for trends in total phosphorus, dissolved phosphorus, and chloride begin in 1991 for all tributaries besides Little Ausable River, which began in 1992. Records used for trends in total nitrogen and total suspended solids began in 1993 for all tributaries. The last year of record used for trend analyses was 2017 for all tributaries besides Putnam Creek, where 2013 was used as the final year due to discharge data availability.

The probability of a statistically significant trends in flow-normalized concentration and load was determined using the EGRETci R package, which uses a bootstrap test using Monte Carlo simulations to estimate the probability of detecting a trend when a trend is not present. Model parameters replicated those of Medalie (2016) (100 bootstrap replicates, 40 or more replicates, and 200 days in a bootstrap block). Trends were determined to be significant if their probability of being different from zero was greater than or equal to 90%. Changes from the first year of trend to the last year of trend are reported, as well as the annualized percent change provided by the equation:

$$c_a = \left(\frac{v_f}{v_i}\right)^{\frac{1}{y}} - 1 \,, \quad (4)$$

where c_a is the annualized percent change, v_f is the final value in the trend period, v_i is the first value in the trend period, and y is the duration of the trend period in years. Note that this metric differs from previous reports on Lake Champlain tributary trends and reflects the annual percent change expected from year to year.

Monotonic trends in annual water flux were determined by the nonparametric Mann-Kendall test, and rates of change were determined by Sens slope estimator, which is equivalent to the median of the slopes of all pairs of data used in each test (Helsel and Hirsch 2002).

Results and discussion

Model performance

Flux bias statistics for each model (Table 2) indicate that most models were validated within an acceptable amount of prediction error. For total phosphorus, models were acceptable for 16 out of 18 tributaries. Flux bias statistics for Putnam Creek and Saranac River were less than -0.1, indicating that total phosphorus concentrations and loads may be underpredicted. All models predicting dissolved phosphorus concentrations and loads were acceptable besides that for Saranac River, which tended to underpredict concentrations and loads. All WRTDS models for total nitrogen and chloride were validated with acceptable flux bias statistics.

Of the 18 WRTDS models for total suspended solids, only six were validated with an acceptable flux bias statistic value. Of 12 others that had large errors, 10 tended to overpredict total suspended solids concentrations and loads, and two tended to overpredict them. Total suspended solids often have a nonlinear relationship with discharge, and these relationships may not be adequately captured by the WRTDS method (Hirsch et al. 2010; Medalie 2016).

Table 2. Flux bias statistics (unitless) for each WRTDS model. Values less than -0.1 and greater than +0.1 are outlined and shown in **bold**.

Tributary	Total phosphorus	Dissolved phosphorus	Total nitrogen	Chloride	Total suspended solids
Ausable	0.007	-0.041	-0.044	-0.022	**0.221**
Boquet	0.058	0.075	0.057	-0.028	**0.371**
Great Chazy	-0.014	-0.005	-0.001	-0.014	**0.129**
Lamoille	-0.058	0.024	-0.007	-0.020	**-0.138**
LaPlatte	0.063	0.084	0.011	0.000	**0.130**
Lewis	0.007	-0.091	-0.013	-0.004	**0.109**
Little Ausable	-0.069	-0.025	0.013	-0.018	**0.118**
Little Chazy	-0.019	-0.006	0.001	-0.009	0.015
Little Otter	-0.008	-0.002	0.014	-0.009	0.037
Mettawee	0.071	0.009	0.000	-0.001	**0.217**
Missisquoi	-0.017	0.005	-0.027	-0.016	0.063
Otter	-0.016	0.008	-0.017	-0.013	0.006
Pike	-0.003	0.026	-0.034	-0.009	0.035
Poultney	0.007	-0.005	-0.011	-0.004	**0.116**
Putnam	**-0.138**	-0.028	-0.043	-0.035	-0.013
Salmon	-0.035	-0.072	-0.014	0.015	**0.117**
Saranac	**-0.216**	**-0.170**	-0.013	-0.020	**-0.686**
Winooski	0.012	-0.020	-0.010	-0.017	**0.133**

Total phosphorus

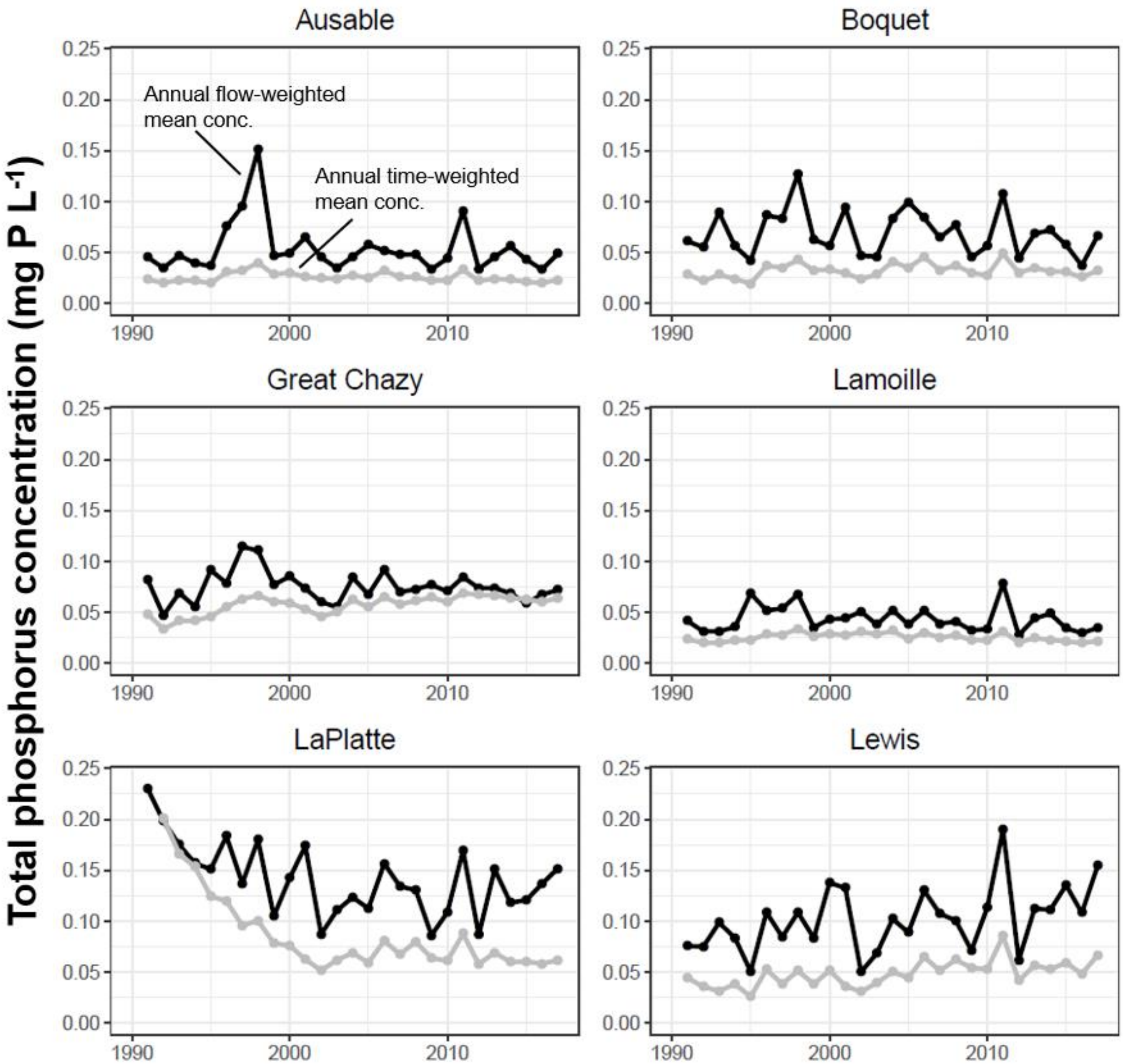
Annual time- and flow-weighted mean total phosphorus concentrations demonstrate the influence of annual hydrologic variability on phosphorus concentration (Figure *3*). Flow-weighted mean concentrations tend to be higher than time-weighted mean concentrations for total phosphorus because total phosphorus trends to increase with higher discharge.

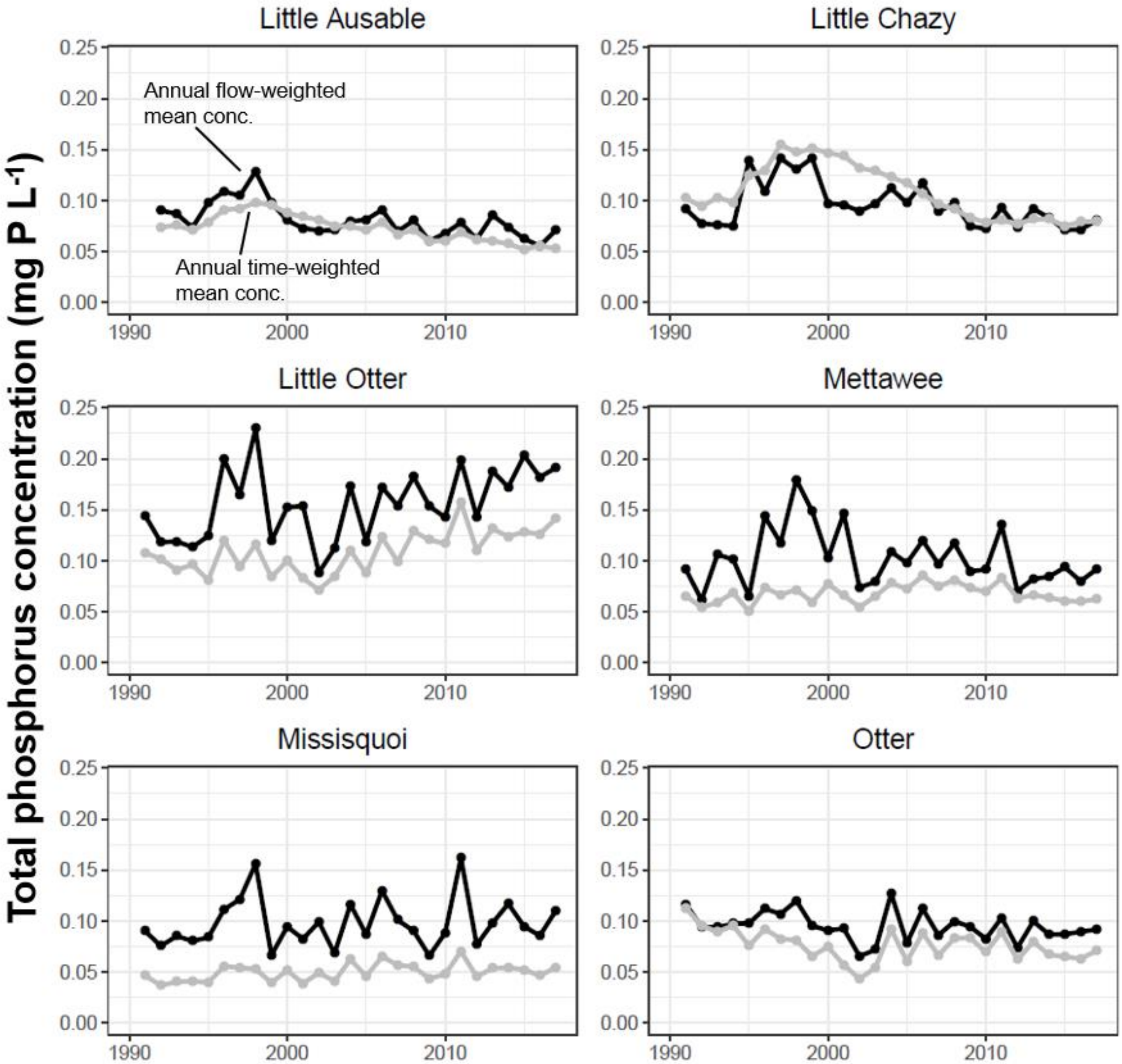
Monte Carlo simulations revealed that there were no trends in total phosphorus concentration during any of the three trend periods for 7 out of the 18 tributaries (Figure *3*, Table *3*). The LaPlatte and Pike Rivers and Otter Creek showed significant flow-normalized concentration decreases in the first half of the record, but these trends were not found in the second half of the record. Lewis, Little Otter, and Putnam Creeks all increased in flow-normalized concentration for full record and second half trend periods. Finally, the flow-normalized concentration in the

Missisquoi River increased slightly for the full record timeframe, but no significant trends were found for half record timeframes.

Annual total phosphorus loads were also influenced by hydrologic variability and this effect was artificially reduced in annual flow-normalized loads for trend analyses (Figure *4*). Although the largest tributaries generally had the highest loads (e.g., Winooski and Missisquoi Rivers), the Pike River had the highest flow-normalized total phosphorus yield (load per watershed area) for the entire record (Figure 5). The Little Ausable, Saranac, and Salmon Rivers and Putnam Creek were among the tributaries with the lowest annual flow-normalized total phosphorus yields.

In 10 out of the 18 tributaries, no trends in flow-normalized total phosphorus load were found for any of the three trend periods (Table 4). Flow-normalized loads decreased strongly in the first half of the record for the LaPlatte River and over the full record timeframe, but no trends were found in the second half of the record. Lewis and Little Otter Creeks showed significant increases in flow-normalized load for full and second half trend periods. For the Missisquoi and Poultney Rivers and Putnam Creek, trends were only found in the second half of the record, where trend probabilities were high (> 97%).


Total phosphorus concentration (mg P L-1)
Ausable
Annual flow-weighted mean conc.
Annual time-weighted mean conc.
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
0.25
0.20
0.15
0.10
0.05
0.00
1990
2000
2010


Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
Annual flow-weighted mean conc.
Annual time-weighted mean conc.
Total phosphorus concentration (mg P L-1)
0.25
0.20
0.15
0.10
0.05
0.00
1990
2000
2010

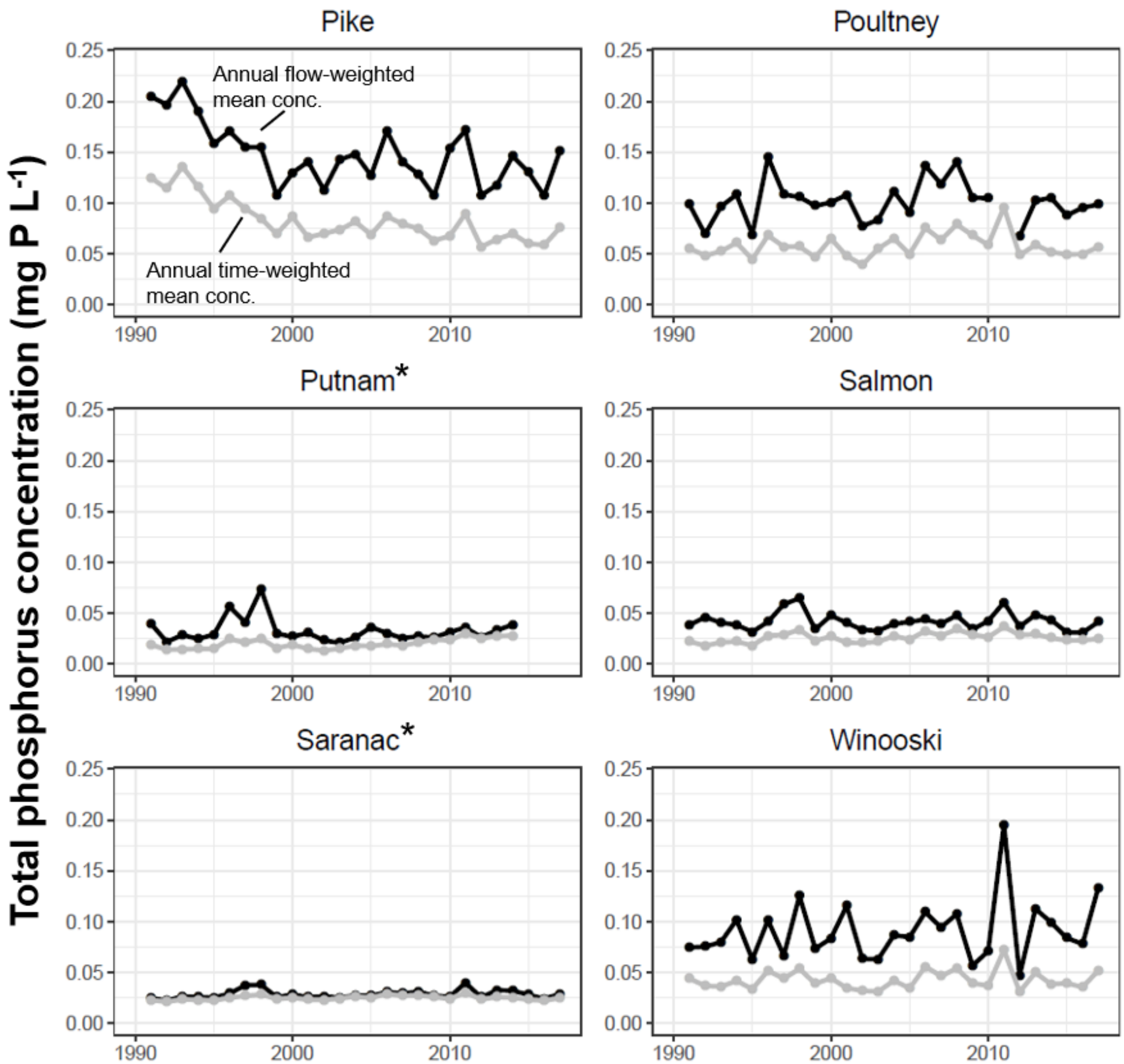


Figure 2. Estimated annual flow-weighted mean (black dots and lines) and time-weighted mean (grey dots and lines) total phosphorus concentrations for eighteen Lake Champlain tributaries. An asterisk (*) indicates that the flux bias statistic was outside of the acceptable range and that the results should be interpreted with care.

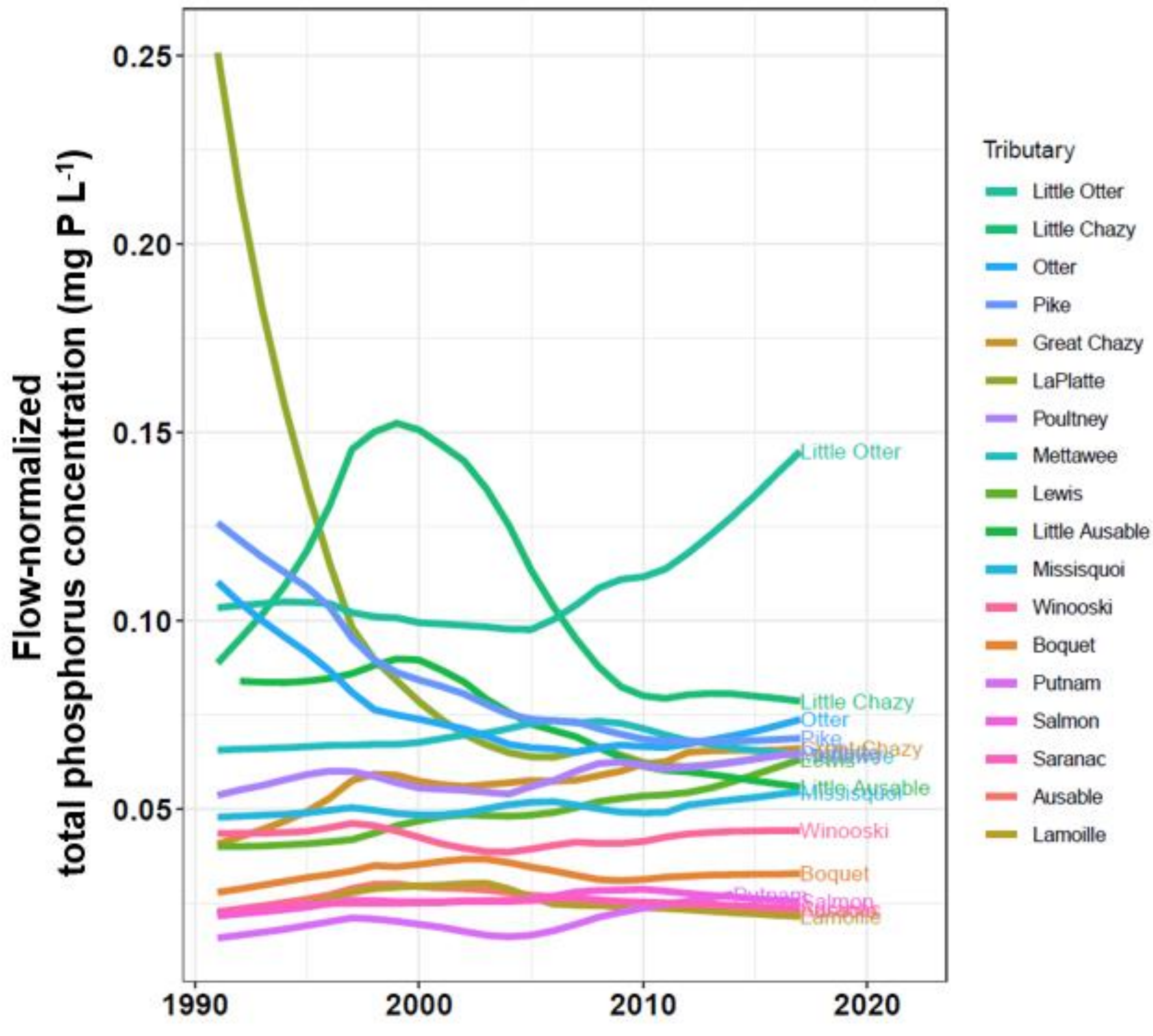
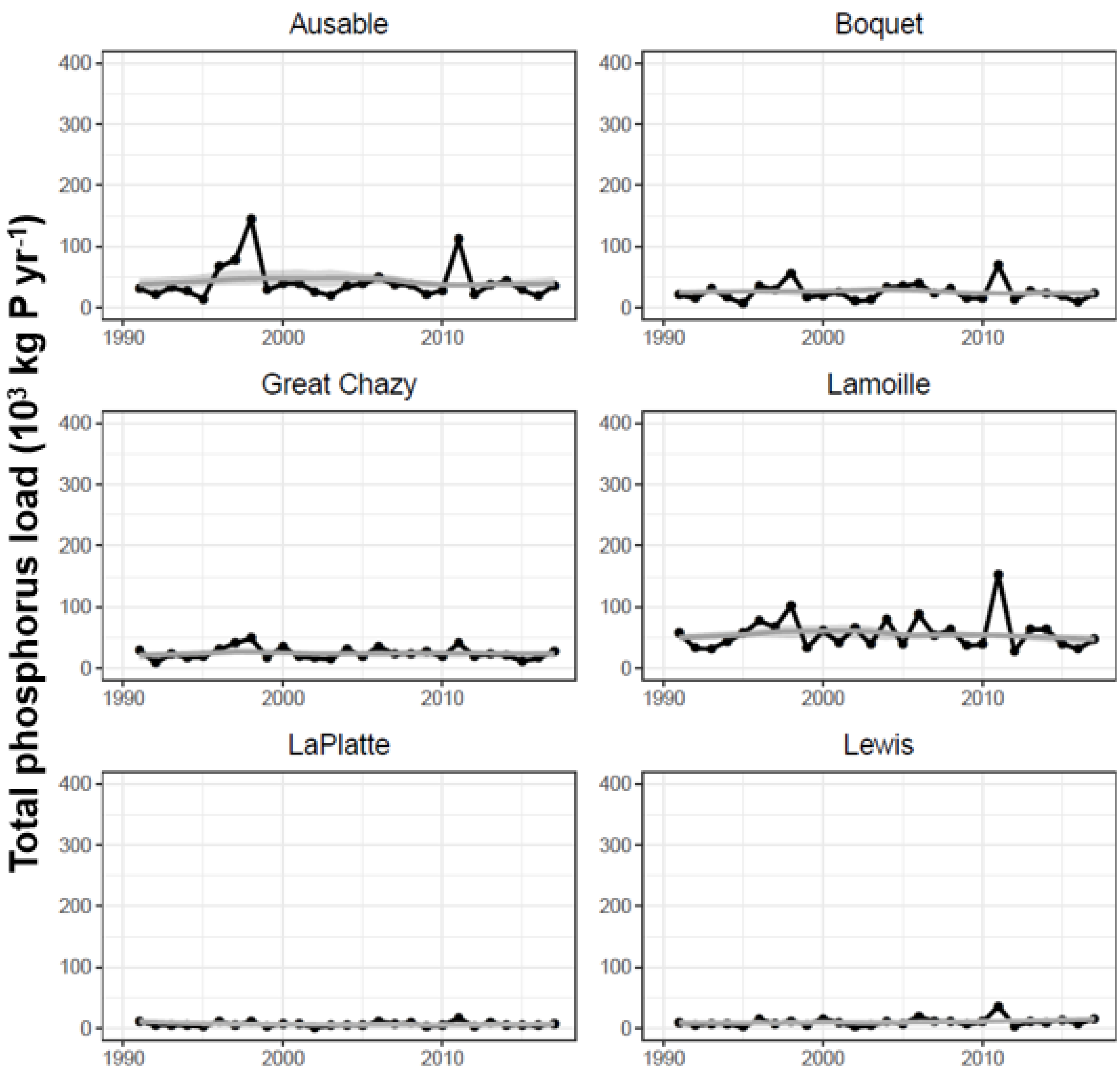
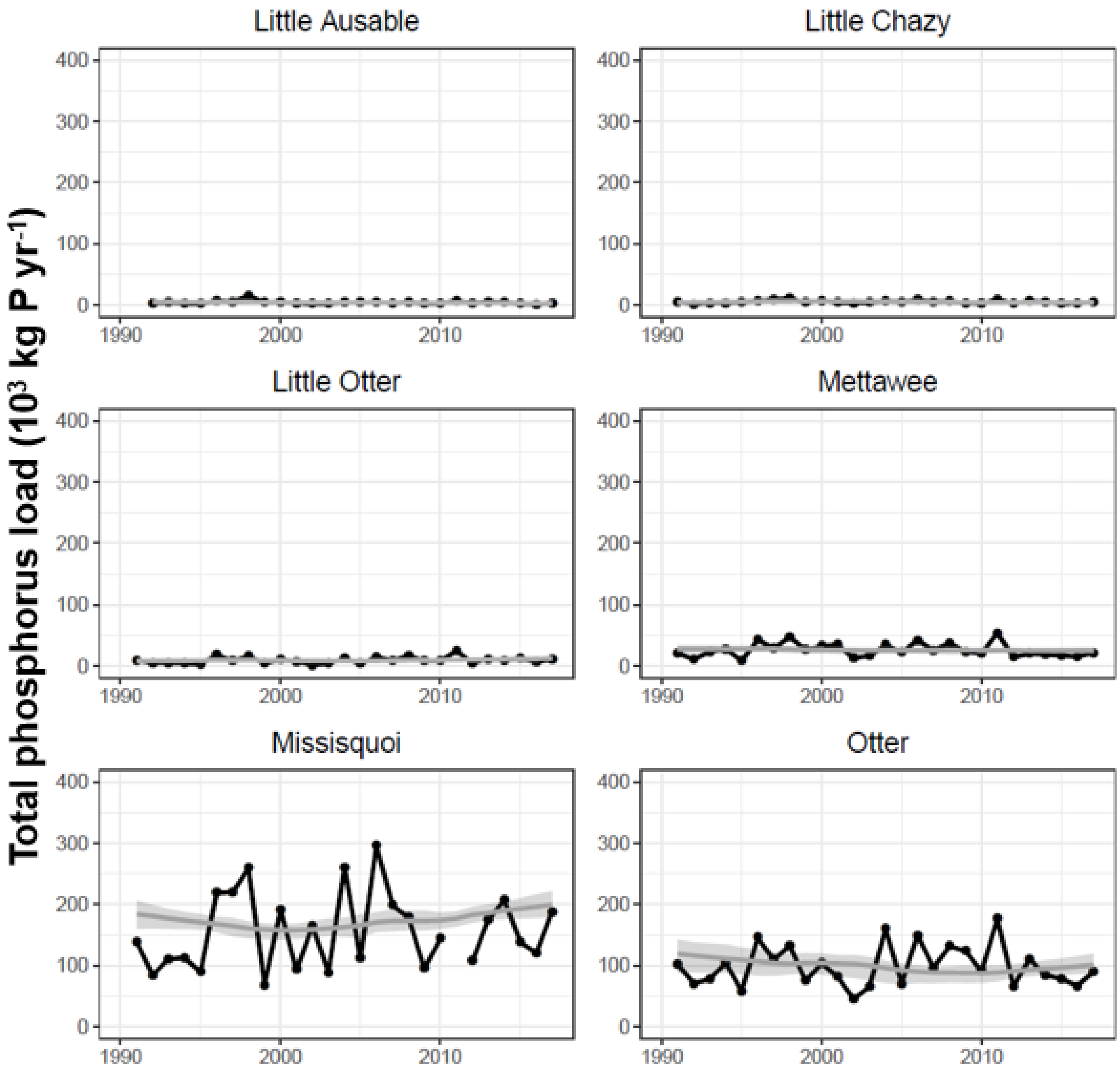


Figure 3. Plot of annual flow-normalized total phosphorus concentration estimates for eighteen Lake Champlain tributaries. The annual flow-normalized concentration is an estimate of the annual mean concentration with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

Table 3. Trend probabilities and magnitudes for **flow-normalized total phosphorus concentration** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for (*) Little Ausable River begin as early as 1993, and trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change
Ausable	**Increase**	**0.91**	0.005	1.6	No trend	0.62	0.000	0.1	No trend	0.82	-0.005	-1.4
Boquet	No trend	0.89	0.008	2.0	No trend	0.72	0.005	0.6	No trend	0.60	-0.003	-0.6
Great Chazy	**Increase**	**0.95**	0.016	2.6	No trend	0.87	0.025	1.9	No trend	0.65	0.009	1.1
Lamoille	No trend	0.77	0.007	2.0	No trend	0.72	-0.001	-0.1	No trend	0.74	-0.007	-2.2
LaPlatte	**Decrease**	**0.99**	-0.190	-9.8	**Decrease**	**0.99**	-0.190	-5.0	No trend	0.57	0.000	0.0
Lewis	No trend	0.82	0.008	1.4	**Increase**	**0.99**	0.023	1.8	**Increase**	**0.91**	0.015	2.1
Little Ausable*	No trend	0.70	-0.008	-0.9	**Decrease**	**0.97**	-0.028	-1.6	**Decrease**	**0.99**	-0.020	-2.3
Little Chazy	No trend	0.72	0.037	2.7	No trend	0.60	-0.010	-0.4	No trend	0.87	-0.047	-3.5
Little Otter	No trend	0.70	-0.006	-0.4	**Increase**	**0.99**	0.042	1.3	**Increase**	**0.99**	0.047	3.1
Mettawee	No trend	0.62	0.006	0.6	No trend	0.60	-0.001	-0.1	No trend	0.72	-0.007	-0.8
Missisquoi	No trend	0.60	0.003	0.5	**Increase**	**0.90**	0.007	0.5	No trend	0.79	0.003	0.5
Otter	**Decrease**	**0.97**	-0.043	-3.7	**Decrease**	**0.92**	-0.037	-1.5	No trend	0.67	0.007	0.7
Pike	**Decrease**	**0.99**	-0.051	-3.9	**Decrease**	**0.99**	-0.057	-2.3	No trend	0.89	-0.006	-0.7
Poultney	No trend	0.55	0.000	0.0	No trend	0.84	0.011	0.7	No trend	0.88	0.011	1.4
Putnam[a]	No trend	0.50	0.000	0.2	**Increase**	**0.97**	0.011	2.4	**Increase**	**0.99**	0.010	5.7
Salmon	No trend	0.89	0.004	1.3	No trend	0.82	0.004	0.6	No trend	0.57	0.000	-0.1
Saranac	**Increase**	**0.91**	0.003	0.9	No trend	0.72	0.001	0.2	No trend	0.62	-0.002	-0.6
Winooski	No trend	0.82	-0.005	-0.9	No trend	0.60	0.001	0.1	No trend	0.79	0.006	1.1


Total phosphorus load (10^3 kg P yr^{-1})
Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
400
300
200
100
0
1990
2000
2010


Total phosphorus load (10³ kg P yr⁻¹)
Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
0
100
200
300
400
1990
2000
2010

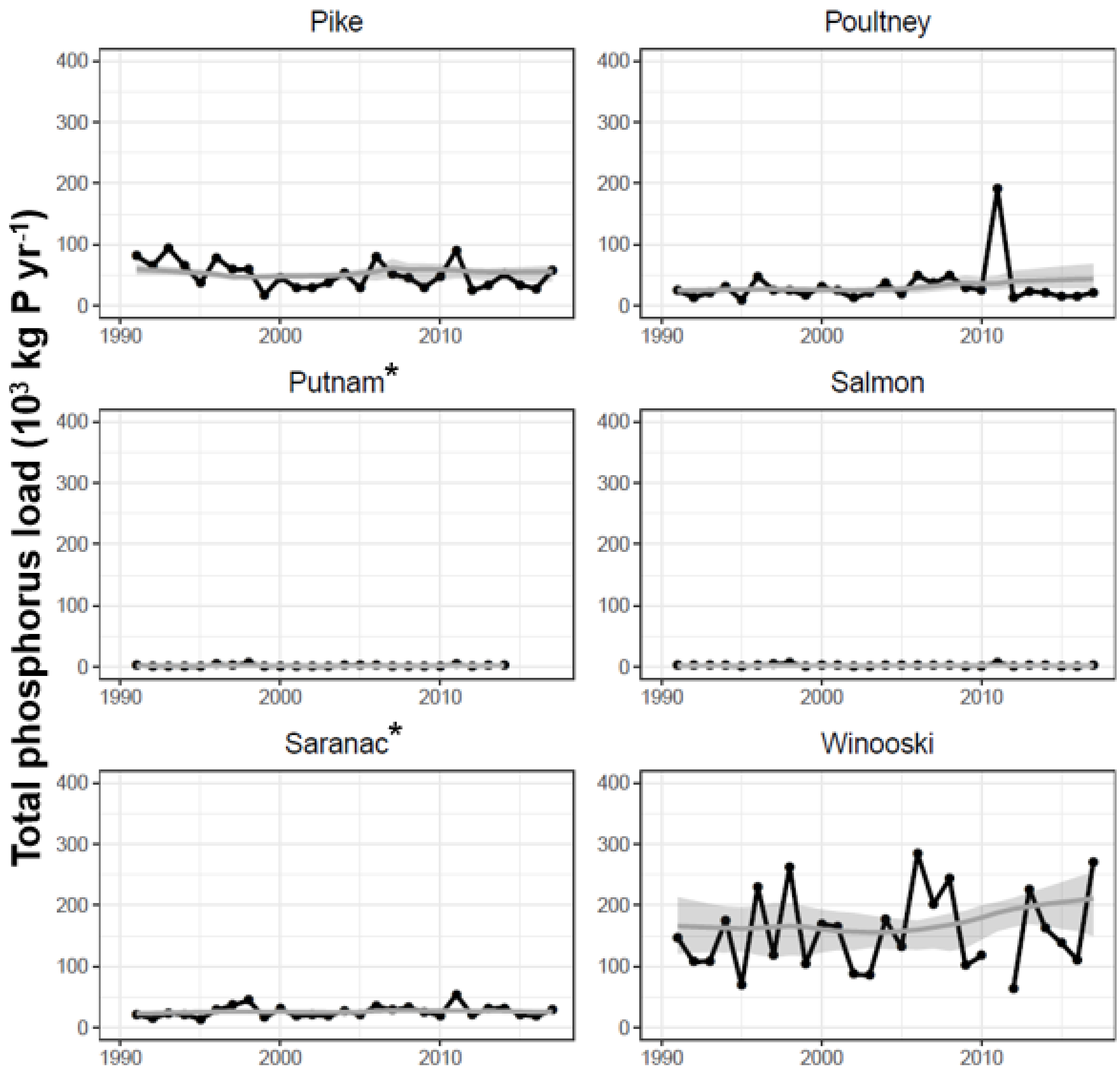


Figure 4. Estimated annual total phosphorus load (black dots and lines) and flow-normalized total phosphorus load (grey lines) with 95% confidence intervals (grey shaded areas) for eighteen Lake Champlain tributaries. An asterisk (*) indicates that the flux bias statistic was outside of the acceptable range and that the results should be interpreted with care.

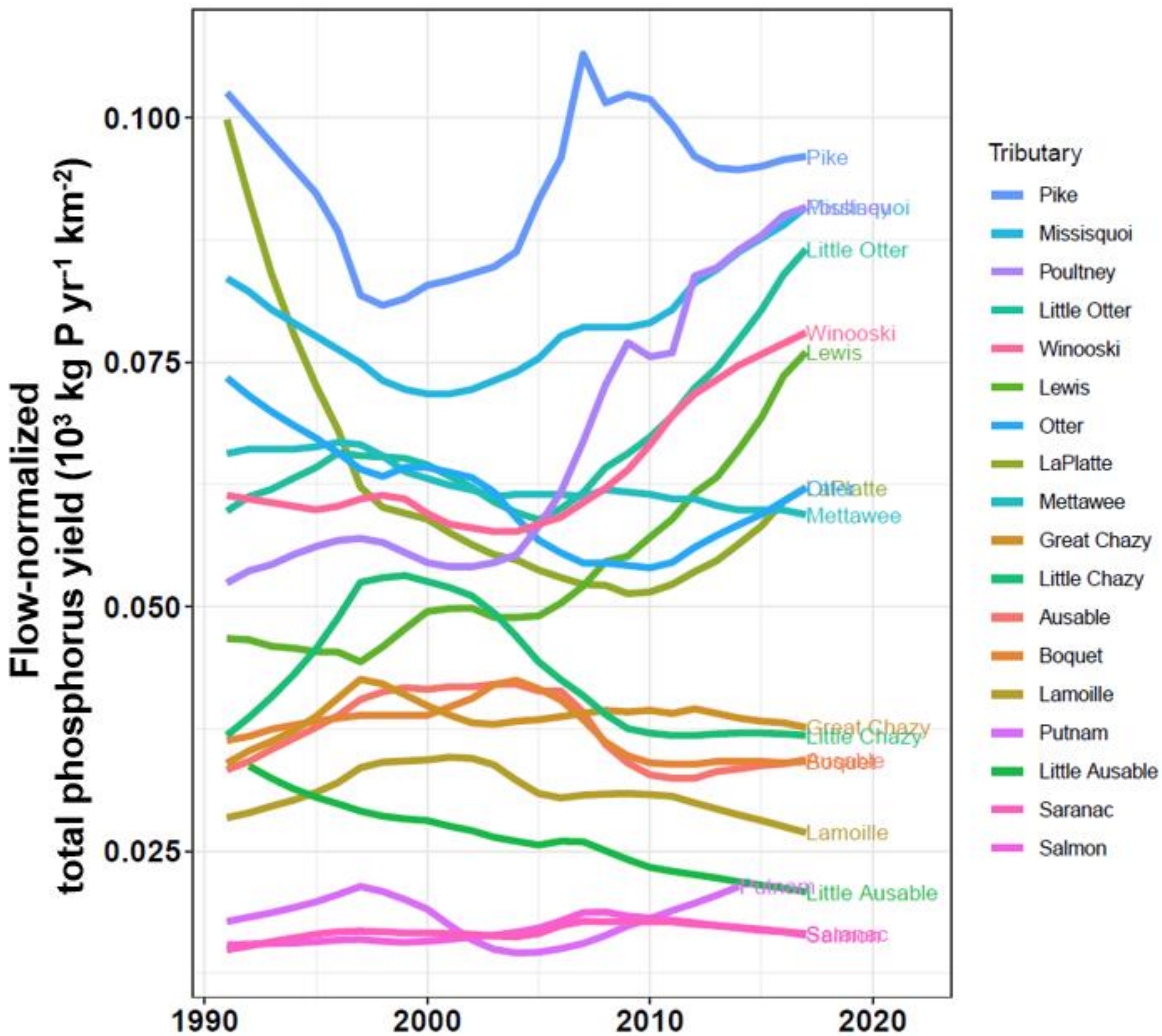


Figure 5. Plot of annual flow-normalized total phosphorus yield estimates for eighteen Lake Champlain tributaries. The flow-normalized yield is an estimate of load per watershed area, with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

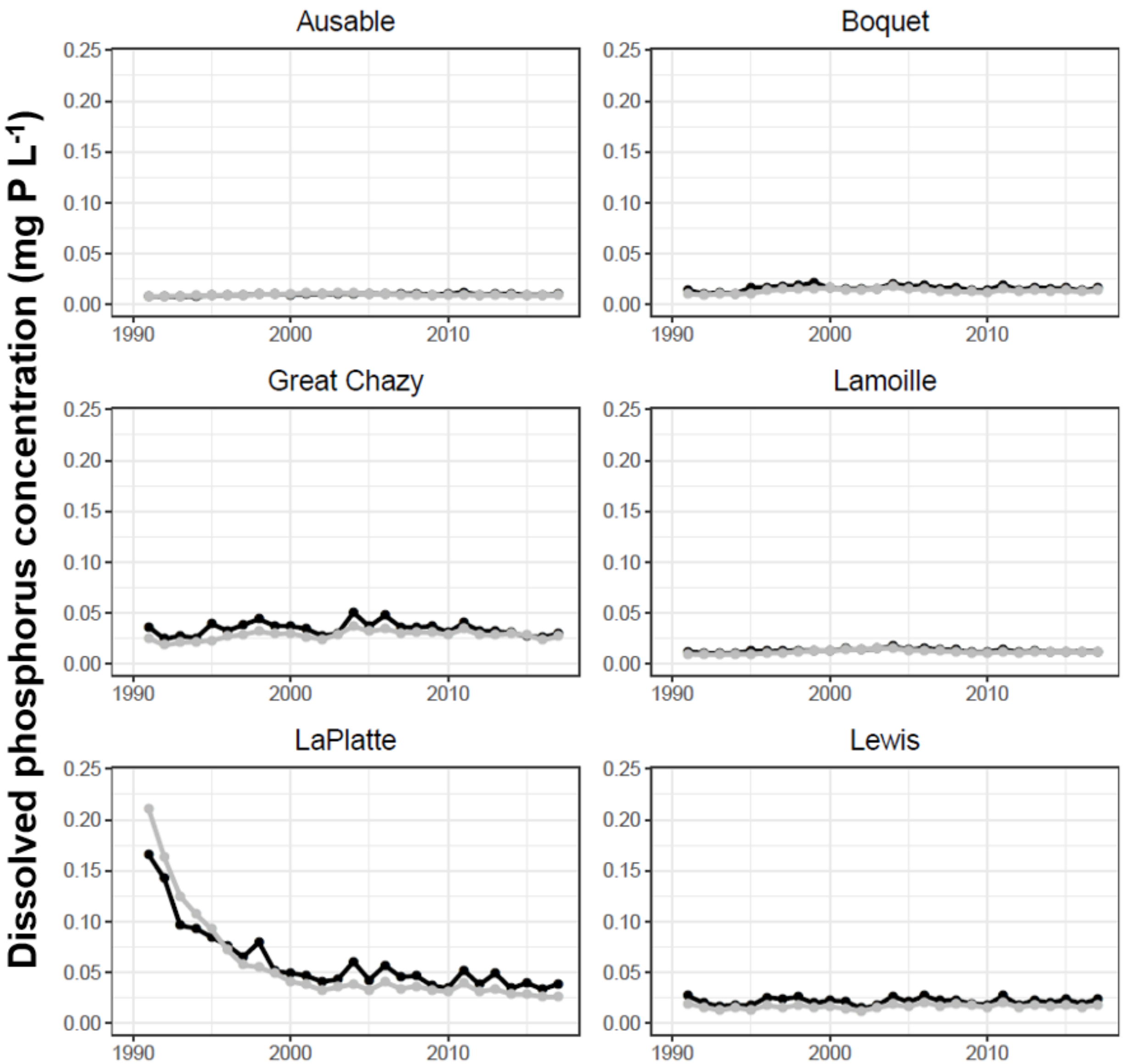
Table 4. Trend probabilities and magnitudes for **flow-normalized total phosphorus load** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for (*) Little Ausable River begin as early as 1993, and trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

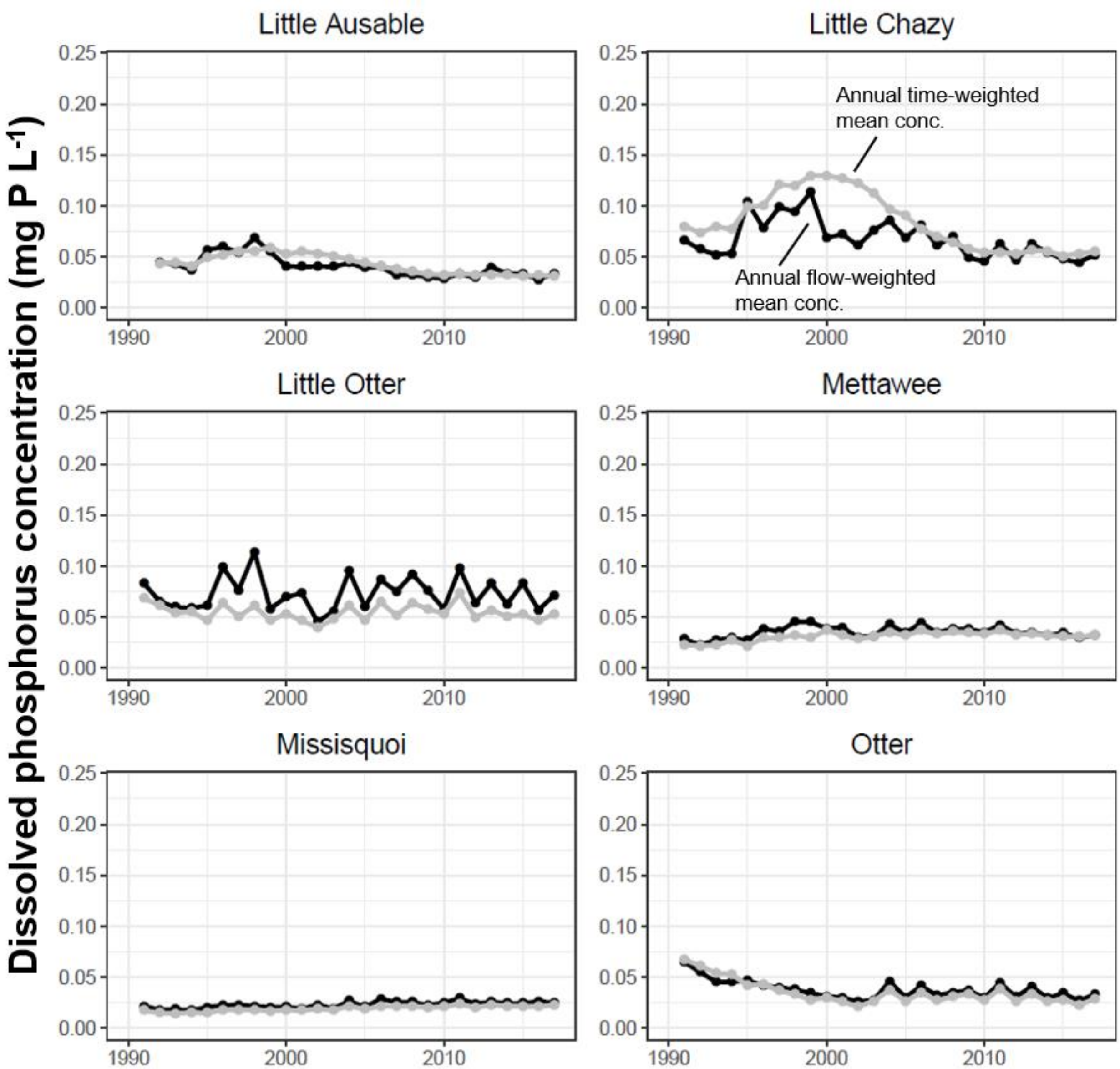
	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change
Ausable	No trend	0.89	10.0	1.8	No trend	0.65	1.1	0.1	No trend	0.70	-9.0	-1.5
Boquet	No trend	0.89	4.3	1.2	No trend	0.60	-1.5	-0.2	No trend	0.89	-5.8	-1.7
Great Chazy	No trend	0.75	2.7	0.9	No trend	0.72	2.3	0.4	No trend	0.65	-0.4	-0.1
Lamoille	No trend	0.82	6.9	1.0	No trend	0.77	-2.6	-0.2	No trend	0.77	-9.5	-1.4
LaPlatte	**Decrease**	**0.99**	-5.2	-4.5	**Decrease**	**0.99**	-4.4	-1.8	No trend	0.79	0.9	0.9
Lewis	No trend	0.70	0.4	0.3	**Increase**	**0.99**	5.9	1.9	**Increase**	**0.97**	5.4	3.4
Little Ausable*	No trend	0.84	-1.4	-2.2	**Decrease**	**0.99**	-2.3	-1.9	**Decrease**	**0.99**	-0.9	-1.7
Little Chazy	No trend	0.70	1.3	1.9	No trend	0.65	0.0	0.0	No trend	0.84	-1.3	-1.9
Little Otter	No trend	0.60	0.0	0.0	**Increase**	**0.99**	4.0	1.4	**Increase**	**0.99**	4.0	2.9
Mettawee	No trend	0.55	-1.8	-0.5	No trend	0.70	-2.7	-0.4	No trend	0.60	-0.9	-0.3
Missisquoi	No trend	0.87	-21.0	-0.9	No trend	0.86	15.0	0.3	**Increase**	**0.99**	36.0	1.5
Otter	No trend	0.82	-23.0	-1.7	No trend	0.70	-18.0	-0.6	No trend	0.70	5.1	0.4
Pike	**Decrease**	**0.91**	-9.5	-1.3	No trend	0.72	-3.7	-0.2	No trend	0.72	5.7	0.8
Poultney	No trend	0.62	1.5	0.4	No trend	0.89	19.0	2.2	**Increase**	**0.97**	17.0	3.9
Putnam[a]	No trend	0.60	-0.4	-1.5	No trend	0.60	0.4	0.6	**Increase**	**0.97**	0.8	3.9
Salmon	No trend	0.74	0.2	0.6	No trend	0.72	0.2	0.2	No trend	0.62	-0.1	-0.1
Saranac	No trend	0.86	2.2	0.7	No trend	0.87	2.7	0.4	No trend	0.57	0.5	0.2
Winooski	No trend	0.65	-10.0	-0.5	No trend	0.82	44.0	0.9	No trend	0.87	54.0	2.3

Dissolved phosphorus

Dissolved phosphorus concentrations were generally highest in Little Otter Creek, and the Pike and Little Chazy Rivers, and were similar and relatively lower for several tributaries (Figure *6* and Figure *7*). For 7 out of 18 tributaries, no trends in flow-normalized dissolved phosphorus concentration were found for any of the three trend periods (Table *5*). Flow-normalized concentration decreased in the Otter Creek and the LaPlatte River for the first half and full record trend periods, but these trends were not found in the second half of record. Conversely, flow-normalized concentration significantly decreased in the Little Ausable River for the second half of the record only. The Pike River showed significant flow-normalized concentration decreases for full record and second half trend periods. Full record significant increases in flow-normalized concentration were observed in the Mettawee, Missisquoi, and Saranac Rivers and Putnam Creek. Only Putnam Creek showed a significant increase in the second half of record.

Dissolved phosphorus loads were highest at Otter Creek and Missisquoi River, where loads were often above 40 metric tons of dissolved phosphorus per year (Figure *8*). Dissolved phosphorus yields were relatively high for Little Otter Creek, and the Pike and Little Chazy Rivers (Figure *9*). Seven out of the eighteen tributaries showed no trend in flow-normalized dissolved phosphorus load for any of the three trend periods considered (Table 6). The LaPlatte River was the only tributary to demonstrate a significant decrease in flow-normalized load for all three trend periods, and the Otter Creek and Winooski River showed a significant decrease for the first half of the record, but no trends for the second half. Significant increases in flow-normalized load were observed for several tributaries for the first half and full record trend periods, including: Ausable, Boquet, Salmon, and Saranac Rivers and Putnam Creek. Of these, only the Putnam Creek continued to increase in flow-normalized load in the second half of record; no trend was observed for all others.


Dissolved phosphorus concentration (mg P L-1)
Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
0.25
0.20
0.15
0.10
0.05
0.00
1990
2000
2010


Dissolved phosphorus concentration (mg P L-1)
Little Ausable
Little Chazy
Annual time-weighted mean conc.
Annual flow-weighted mean conc.
Little Otter
Mettawee
Missisquoi
Otter
0.25
0.20
0.15
0.10
0.05
0.00
1990
2000
2010

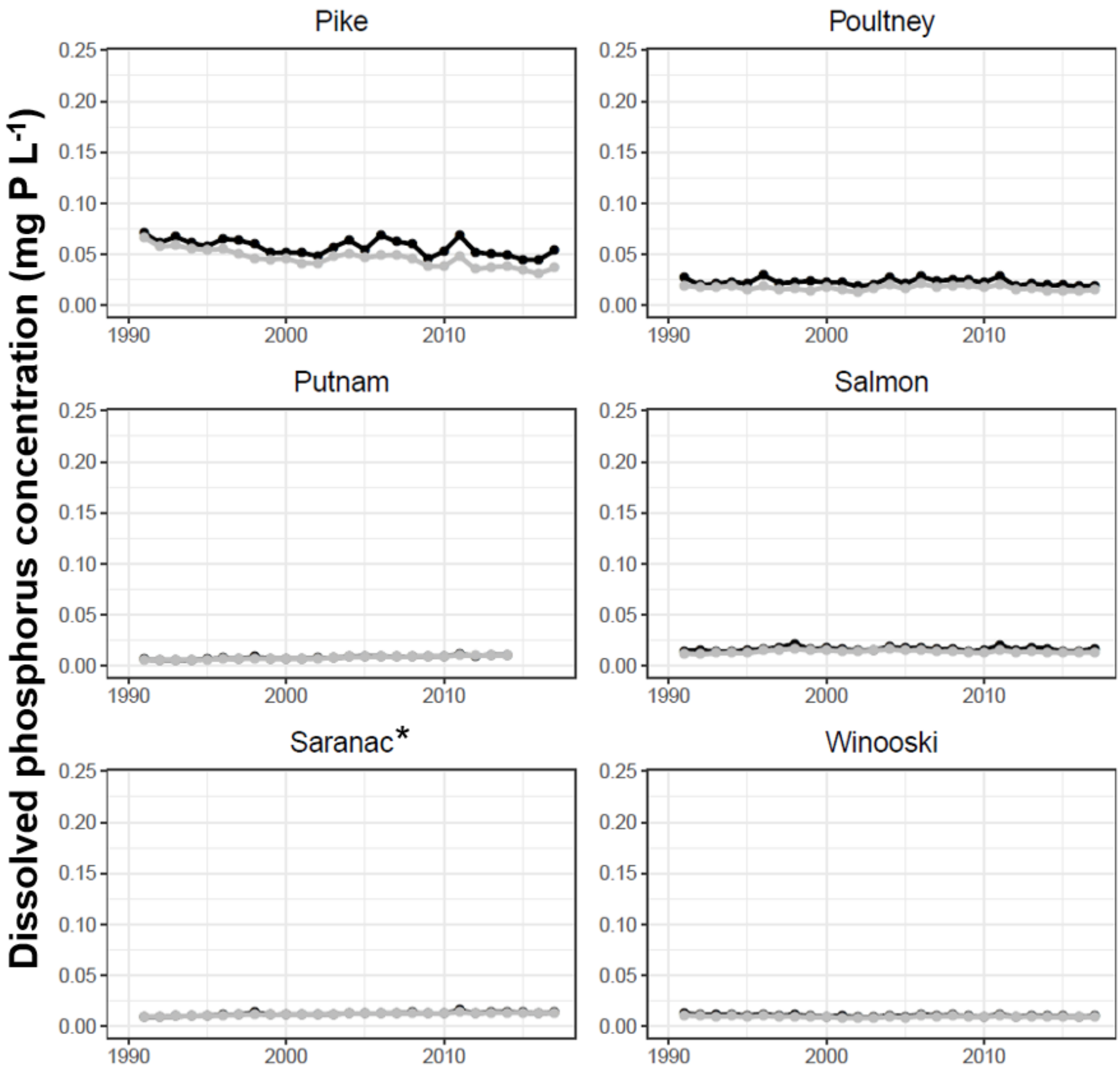


Figure 6. Estimated annual flow-weighted mean (black dots and lines) and time-weighted mean (grey dots and lines) dissolved phosphorus concentrations for eighteen Lake Champlain tributaries. An asterisk (*) indicates that the flux bias statistic was outside of the acceptable range and that the results should be interpreted with care.

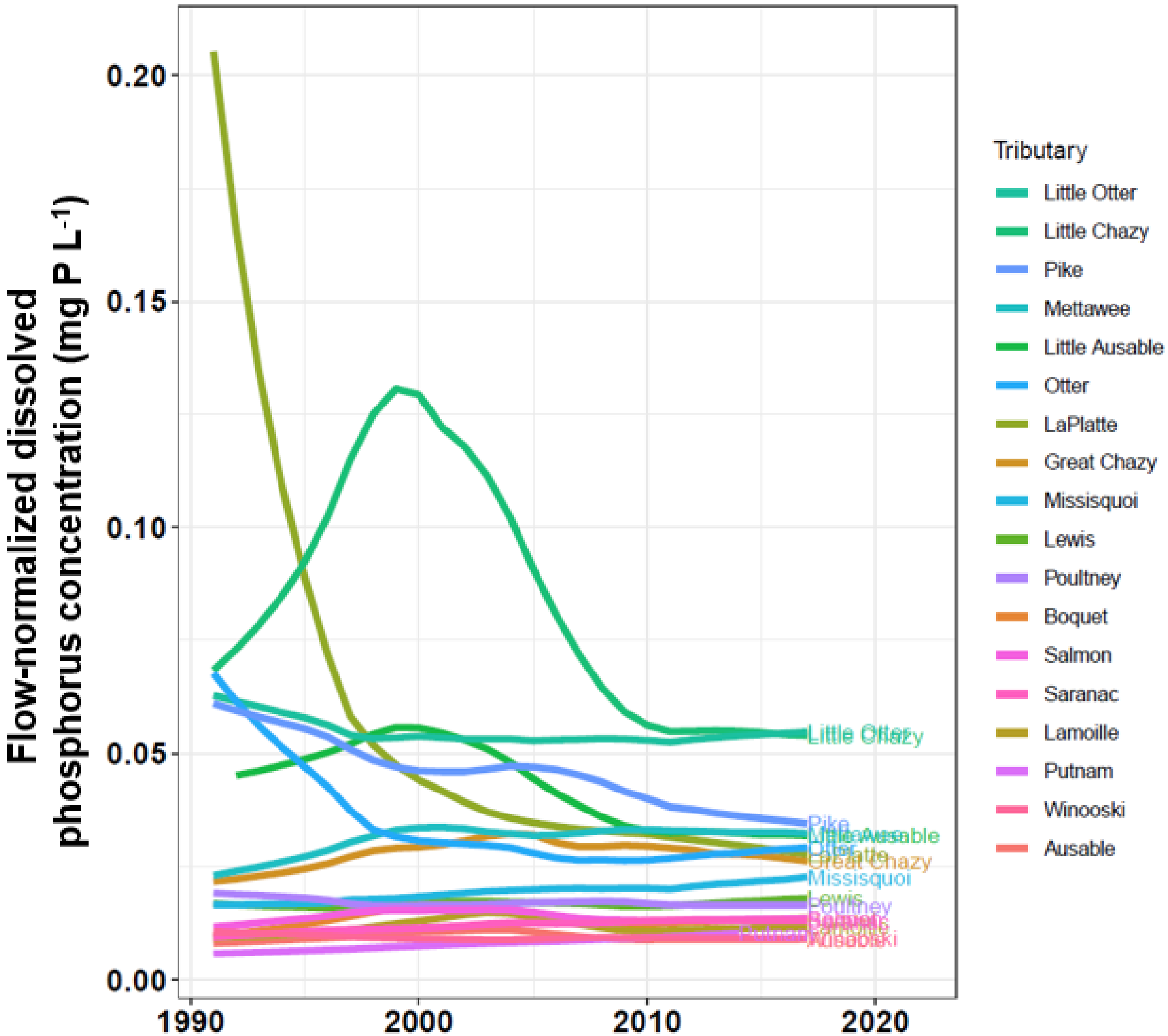
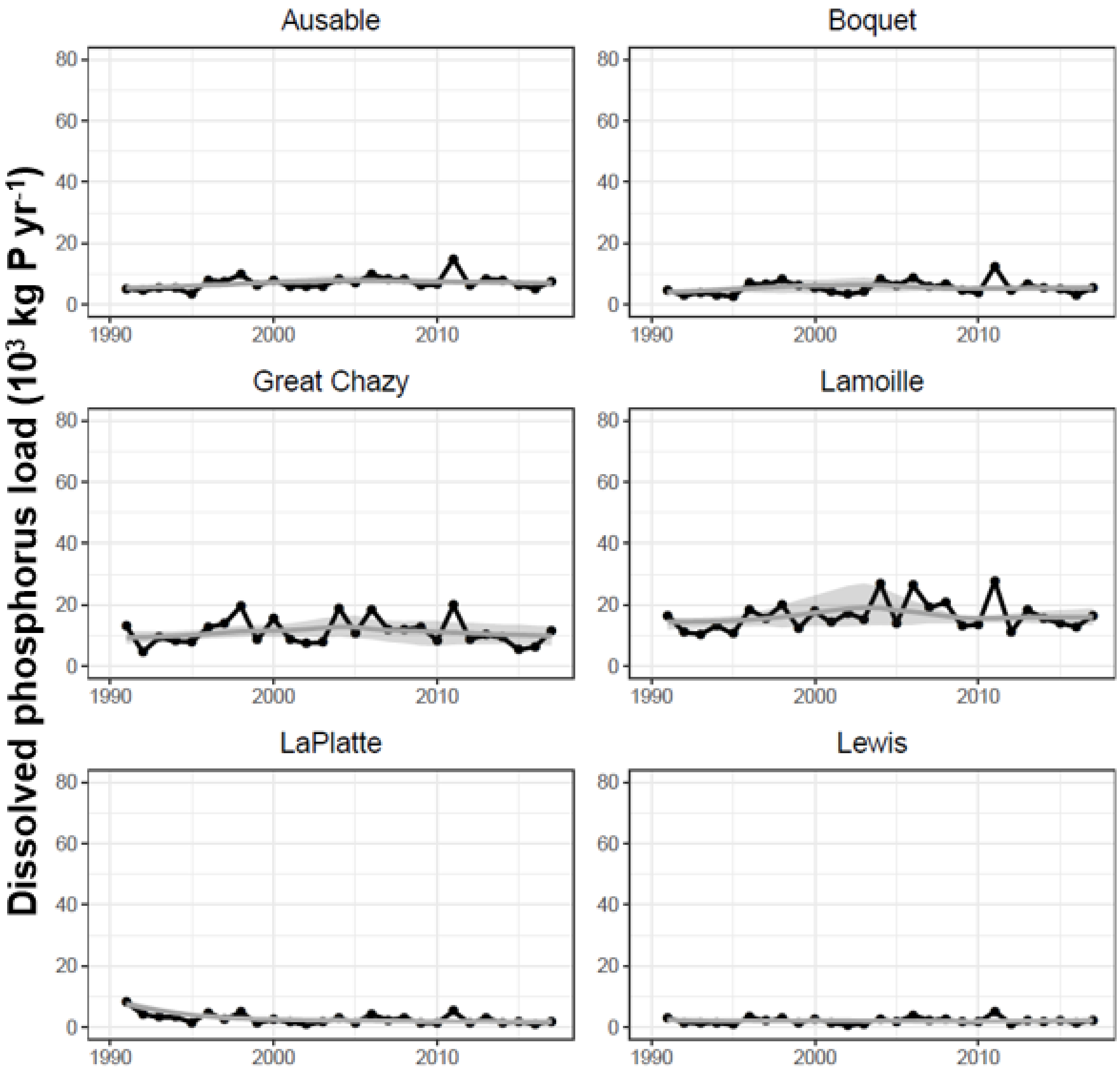
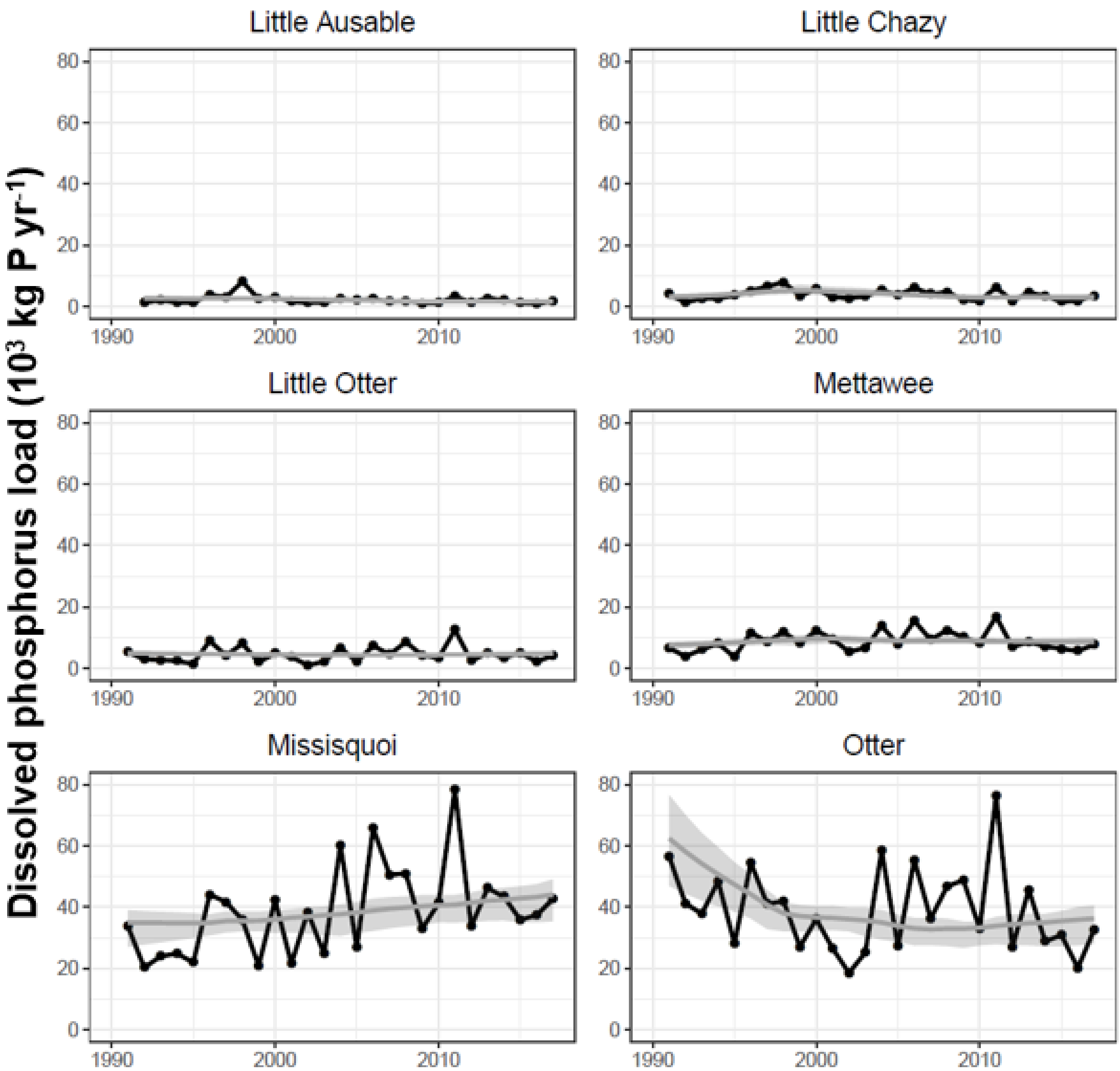


Figure 7. Plot of annual flow-normalized dissolved phosphorus concentration estimates for eighteen Lake Champlain tributaries. The annual flow-normalized concentration is an estimate of the annual mean concentration with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

Table 5. Trend probabilities and magnitudes for **flow-normalized dissolved phosphorus concentration** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for (*) Little Ausable River begin as early as 1993, and trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change ($mg\ L^{-1}$)	Annualized percent change	Direction	Probability of trend	Change ($mg\ L^{-1}$)	Annualized percent change	Direction	Probability of trend	Change ($mg\ L^{-1}$)	Annualized percent change
Ausable	**Increase**	**0.96**	0.0030	2.5	No trend	0.84	0.0009	0.4	No trend	0.84	-0.0021	-1.6
Boquet	No trend	0.88	0.0061	3.8	No trend	0.86	0.0040	1.3	No trend	0.55	-0.0022	-1.2
Great Chazy	No trend	0.77	0.0110	3.1	No trend	0.60	0.0045	0.7	No trend	0.79	-0.0061	-1.6
Lamoille	**Increase**	**0.91**	0.0053	3.5	No trend	0.89	0.0024	0.9	No trend	0.60	-0.0029	-1.7
LaPlatte	**Decrease**	**0.99**	-0.1700	-12.7	**Decrease**	**0.99**	-0.1800	-7.3	No trend	0.89	-0.0078	-1.9
Lewis	No trend	0.57	0.0003	0.1	No trend	0.77	0.0012	0.3	No trend	0.65	0.0009	0.4
Little Ausable*	No trend	0.84	0.0030	0.5	No trend	0.87	-0.0130	-1.4	**Decrease**	**0.99**	-0.0160	-3.1
Little Chazy	No trend	0.89	0.0340	3.1	No trend	0.57	-0.0140	-0.9	No trend	0.82	-0.0480	-4.8
Little Otter	No trend	0.82	-0.0097	-1.2	No trend	0.90	-0.0081	-0.5	No trend	0.67	0.0016	0.2
Mettawee	**Increase**	**0.99**	0.0092	2.6	**Increase**	**0.97**	0.0094	1.3	No trend	0.50	0.0002	0.0
Missisquoi	**Increase**	**0.94**	0.0032	1.4	**Increase**	**0.90**	0.0063	1.2	No trend	0.87	0.0031	1.1
Otter	**Decrease**	**1.00**	-0.0380	-6.3	**Decrease**	**0.99**	-0.0380	-3.2	No trend	0.52	0.0001	0.0
Pike	No trend	0.84	-0.0140	-2.0	**Decrease**	**0.99**	-0.0270	-2.1	**Decrease**	**0.97**	-0.0130	-2.4
Poultney	No trend	0.57	-0.0023	-1.0	No trend	0.67	-0.0027	-0.6	No trend	0.62	-0.0004	-0.2
Putnam[a]	**Increase**	**0.97**	0.0025	2.8	**Increase**	**0.99**	0.0043	2.5	**Increase**	**0.99**	0.0017	2.1
Salmon	**Increase**	**0.99**	0.0038	2.2	No trend	0.89	0.0018	0.6	No trend	0.74	-0.0019	-1.1
Saranac	**Increase**	**0.99**	0.0031	2.2	**Increase**	**0.99**	0.0036	1.2	No trend	0.67	0.0005	0.3
Winooski	No trend	0.86	-0.0018	-1.4	No trend	0.90	-0.0015	-0.6	No trend	0.60	0.0003	0.3


Dissolved phosphorus load (10³ kg P yr⁻¹)
Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
80
60
40
20
0
1990
2000
2010


Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
Dissolved phosphorus load (10³ kg P yr⁻¹)
0
20
40
60
80
1990
2000
2010

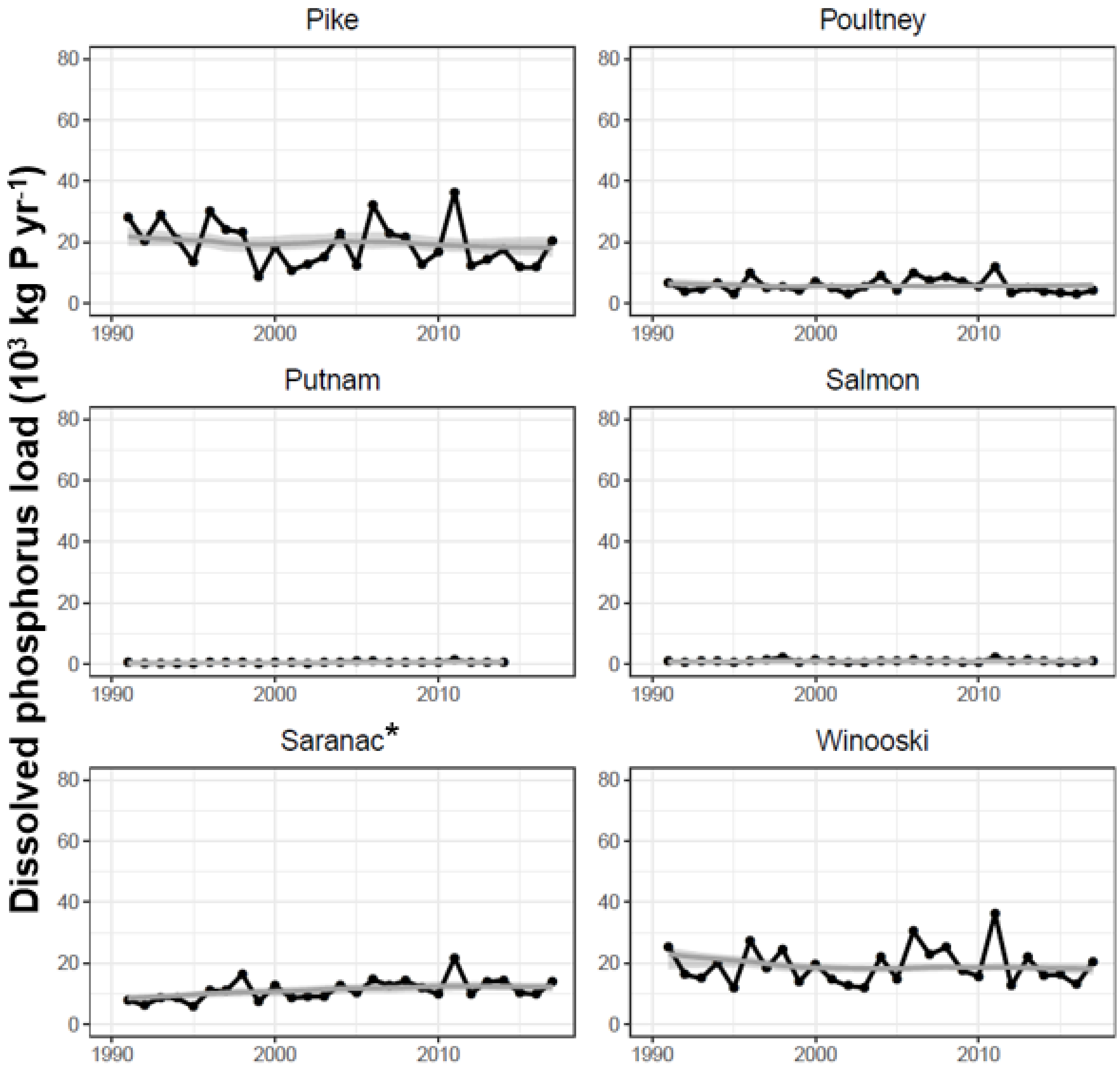


Figure 8. Estimated annual dissolved phosphorus load (black dots and lines) and flow-normalized dissolved phosphorus load (grey lines) with 95% confidence intervals (grey shaded areas) for eighteen Lake Champlain tributaries. An asterisk (*) indicates that the flux bias statistic was outside of the acceptable range and that the results should be interpreted with care.

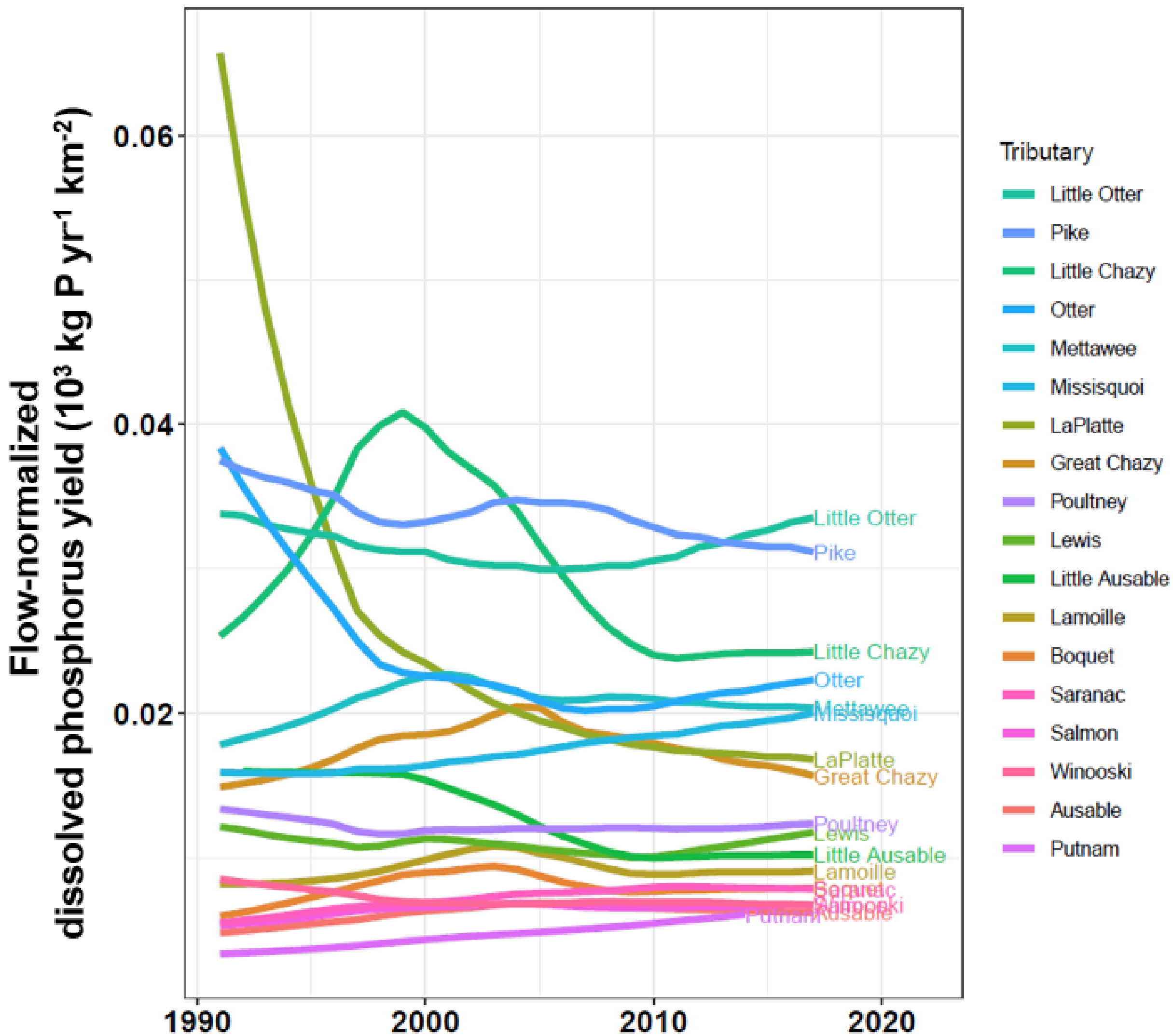


Figure 9. Plot of annual flow-normalized dissolved phosphorus yield estimates for eighteen Lake Champlain tributaries. The flow-normalized yield is an estimate of load per watershed area, with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

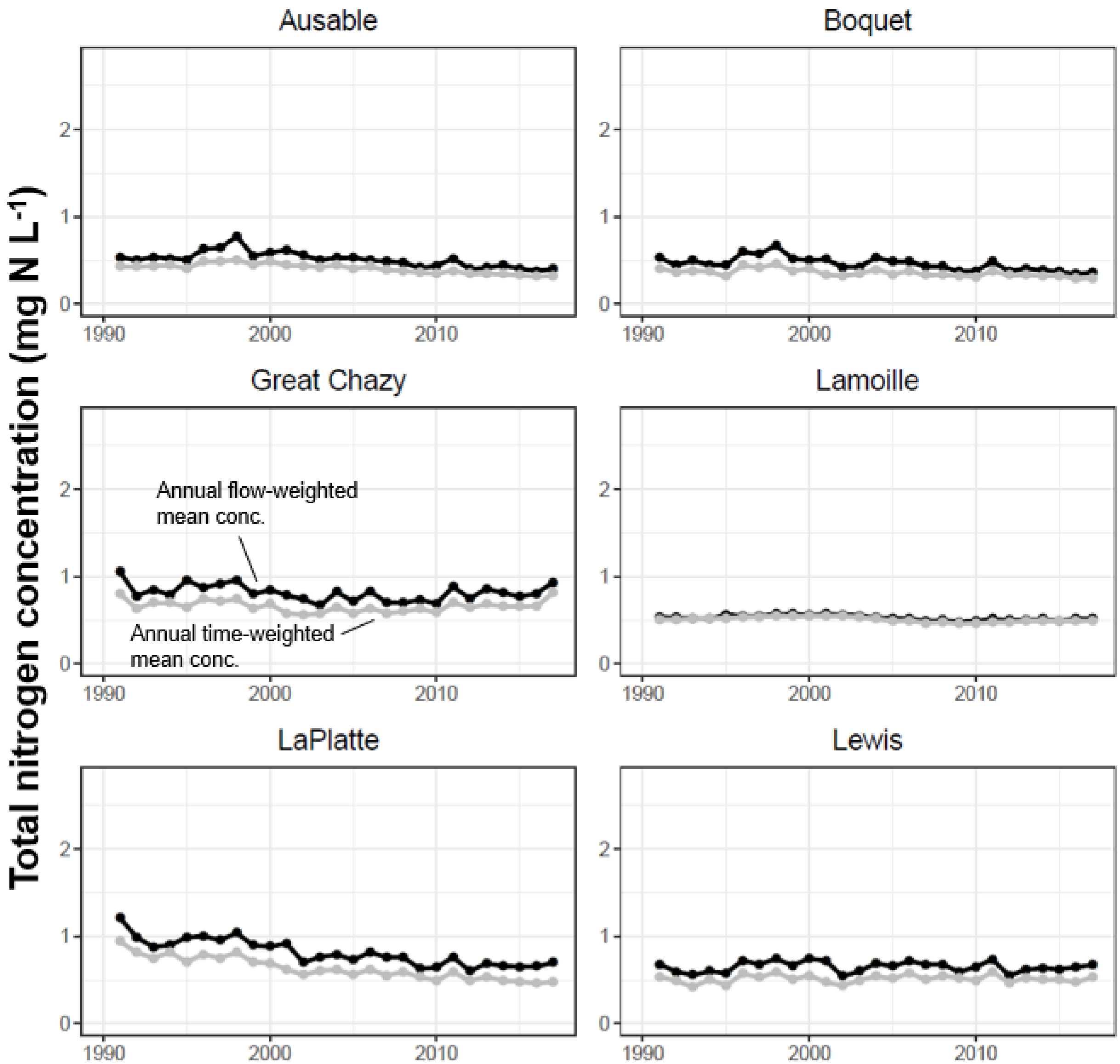
Table 6. Trend probabilities and magnitudes for **flow-normalized dissolved phosphorus load** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for (*) Little Ausable River begin as early as 1993, and trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

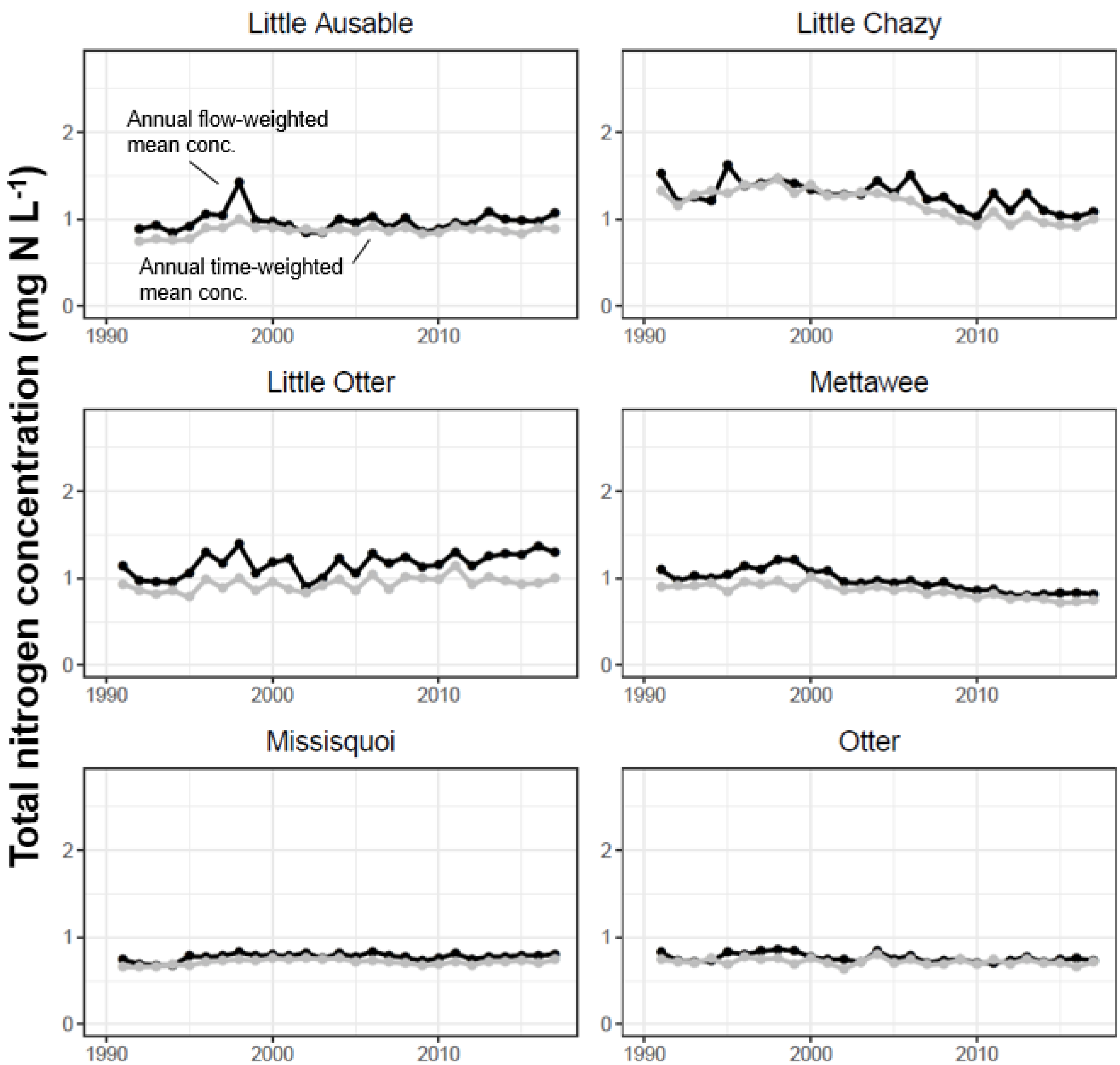
	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change
Ausable	**Increase**	**1.00**	2.4	2.8	**Increase**	**0.97**	1.6	1.0	No trend	0.84	-0.8	-0.8
Boquet	**Increase**	**0.91**	2.3	3.4	**Increase**	**0.91**	1.4	1.1	No trend	0.67	-0.9	-1.2
Great Chazy	No trend	0.84	3.5	2.5	No trend	0.57	0.5	0.2	No trend	0.87	-3.0	-2.0
Lamoille	No trend	0.84	4.5	2.1	No trend	0.79	1.5	0.4	No trend	0.67	-3.0	-1.3
LaPlatte	**Decrease**	**0.99**	-5.3	-8.6	**Decrease**	**0.99**	-5.7	-5.0	**Decrease**	**0.99**	-0.4	-1.4
Lewis	No trend	0.74	-0.3	-0.9	No trend	0.52	-0.1	-0.1	No trend	0.82	0.2	0.7
Little Ausable*	No trend	0.65	-0.5	-1.7	No trend	0.84	-1.0	-1.8	No trend	0.89	-0.5	-1.8
Little Chazy	**Increase**	**0.95**	1.1	2.3	No trend	0.70	-0.1	-0.2	No trend	0.89	-1.3	-2.6
Little Otter	No trend	0.87	-0.5	-0.9	No trend	0.50	0.0	0.0	No trend	0.89	0.5	0.8
Mettawee	**Increase**	**0.99**	1.6	1.4	No trend	0.81	1.1	0.5	No trend	0.70	-0.5	-0.4
Missisquoi	No trend	0.86	2.7	0.6	**Increase**	**0.90**	9.0	0.9	No trend	0.89	6.3	1.2
Otter	**Decrease**	**0.96**	-27.0	-4.4	**Decrease**	**0.99**	-26.0	-2.1	No trend	0.57	1.3	0.3
Pike	No trend	0.57	-1.5	-0.6	No trend	0.89	-3.6	-0.7	No trend	0.86	-2.1	-0.8
Poultney	No trend	0.60	-0.7	-0.8	No trend	0.62	-0.5	-0.3	No trend	0.55	0.2	0.2
Putnam[a]	**Increase**	**0.99**	0.2	2.7	**Increase**	**0.99**	0.3	2.6	**Increase**	**0.99**	0.2	2.4
Salmon	**Increase**	**0.99**	0.3	2.0	**Increase**	**0.94**	0.2	0.9	No trend	0.55	0.0	-0.1
Saranac	**Increase**	**0.97**	3.1	2.4	**Increase**	**0.99**	3.7	1.4	No trend	0.72	0.6	0.4
Winooski	**Decrease**	**0.90**	-4.7	-1.8	**Decrease**	**0.97**	-4.8	-0.9	No trend	0.57	-0.1	0.0

Total nitrogen

In general, the highest annual mean total nitrogen concentrations were observed at the Pike River, and the lowest concentrations were observed at the Putnam Creek (Figure 10 and Figure *11*). Although 8 of the 18 tributaries demonstrated no trend in flow-normalized concentration over any of the three trend periods, nine tributaries showed decreasing trends in flow-normalized concentration for at least one trend period (Table *7*). Significant full record flow-normalized concentration decreases were found for seven tributaries: Ausable, LaPlatte, Little Chazy, Mettawee, Salmon, and Saranac Rivers and Putnam Creek. Pike River demonstrated the only full record significant increase in flow-normalized concentration, though no trend was observed in the second half of record. The Winooski River demonstrated a significant increase in flow-normalized concentration for the first half of record and a significant decrease in the second half of record, resulting in no significant full record trend.

Although Lake Champlain's largest tributaries, the Winooski and Missisquoi Rivers, generally had the highest annual total nitrogen loads, the Pike River annual flow-normalized total nitrogen yield often exceeded that of other tributaries by a factor of two (Figure *13*). Flow-normalized total nitrogen yield was lowest in the Salmon and Boquet Rivers and Putnam Creek. Trends in flow-normalized load were found for at least one trend period for all but four tributaries (Table *8*). Six tributaries decreased in flow-normalized total nitrogen load for the full record trend period: the LaPlatte, Mettawee, Saranac, and Salmon Rivers, and Otter and Putnam Creeks. Several tributaries had trends that changed from the first half of the record to the second half. The Ausable, Boquet, Little Chazy, and Mettawee Rivers showed no trend for the first half of record, then had significant decreases in the second half of the record. The Winooski River demonstrated a significant increase in flow-normalized load for the first half of record and a significant decrease in the second half of record, resulting in no significant full record trend. In addition, full record significant increases in flow-normalized load were found in the Little Otter Creek (increased full record and second half only), Pike River (increased first half and full record only), Great Chazy River (increased second half only), and Missisquoi River (increased first half of record only).


Total nitrogen concentration (mg N L-1)
Ausable
Boquet
Great Chazy
Annual flow-weighted mean conc.
Annual time-weighted mean conc.
Lamoille
LaPlatte
Lewis
0
1
2
1990
2000
2010


Total nitrogen concentration (mg N L-1)
Little Ausable
Annual flow-weighted mean conc.
Annual time-weighted mean conc.
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
0
1
2
1990
2000
2010

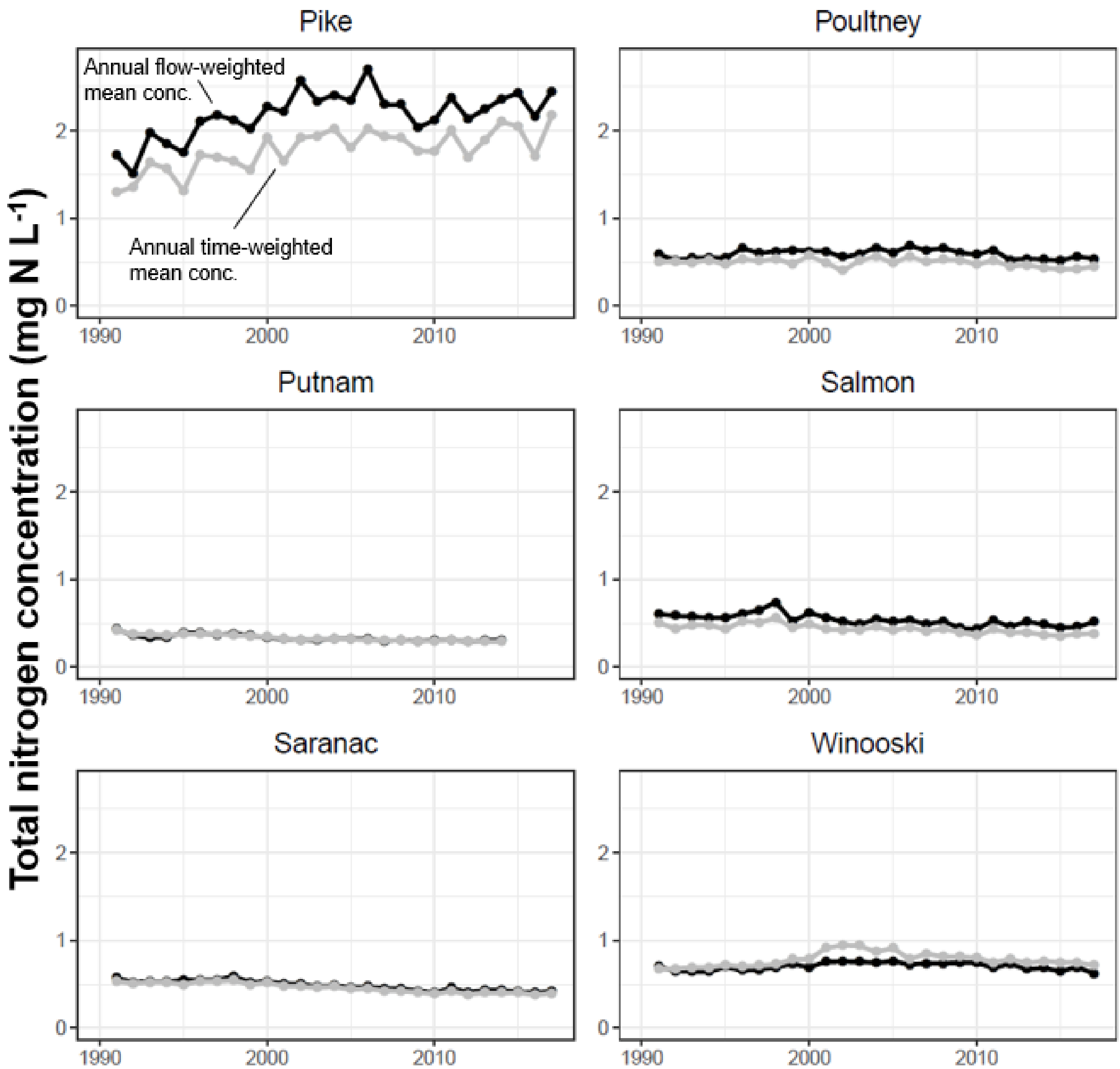


Figure 10. Estimated annual flow-weighted mean (black dots and lines) and time-weighted mean (grey dots and lines) total nitrogen concentrations for eighteen Lake Champlain tributaries.

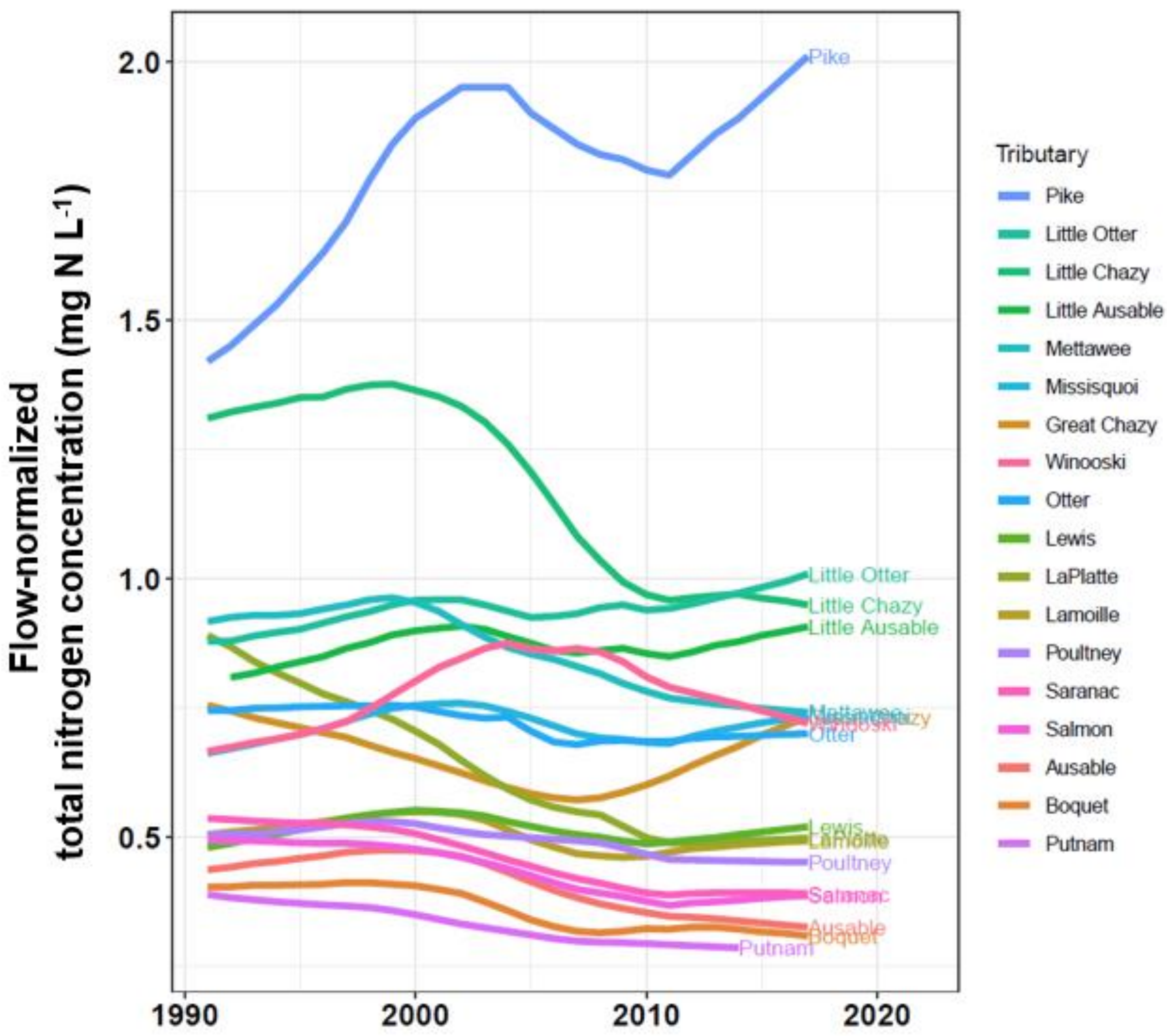
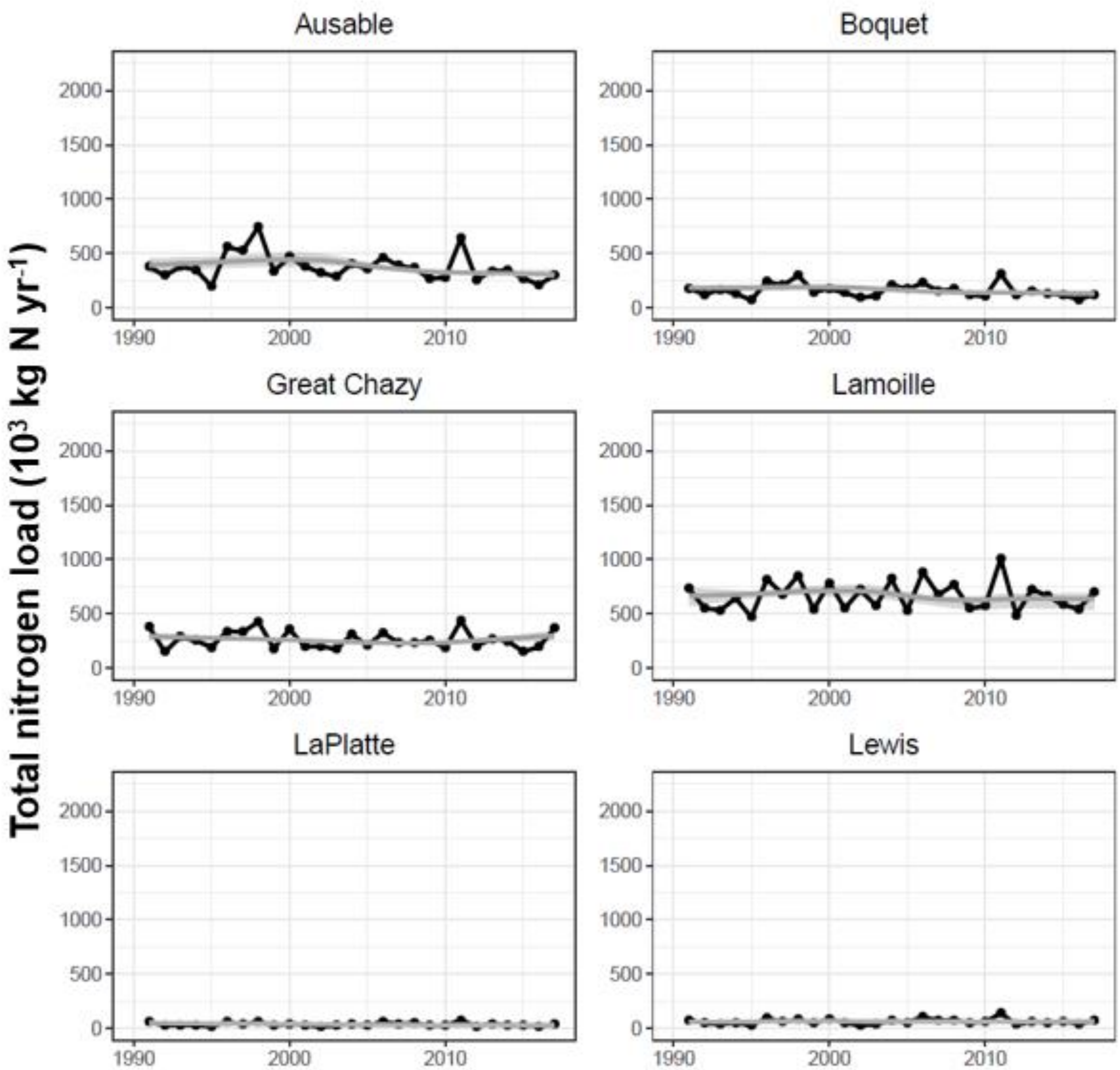
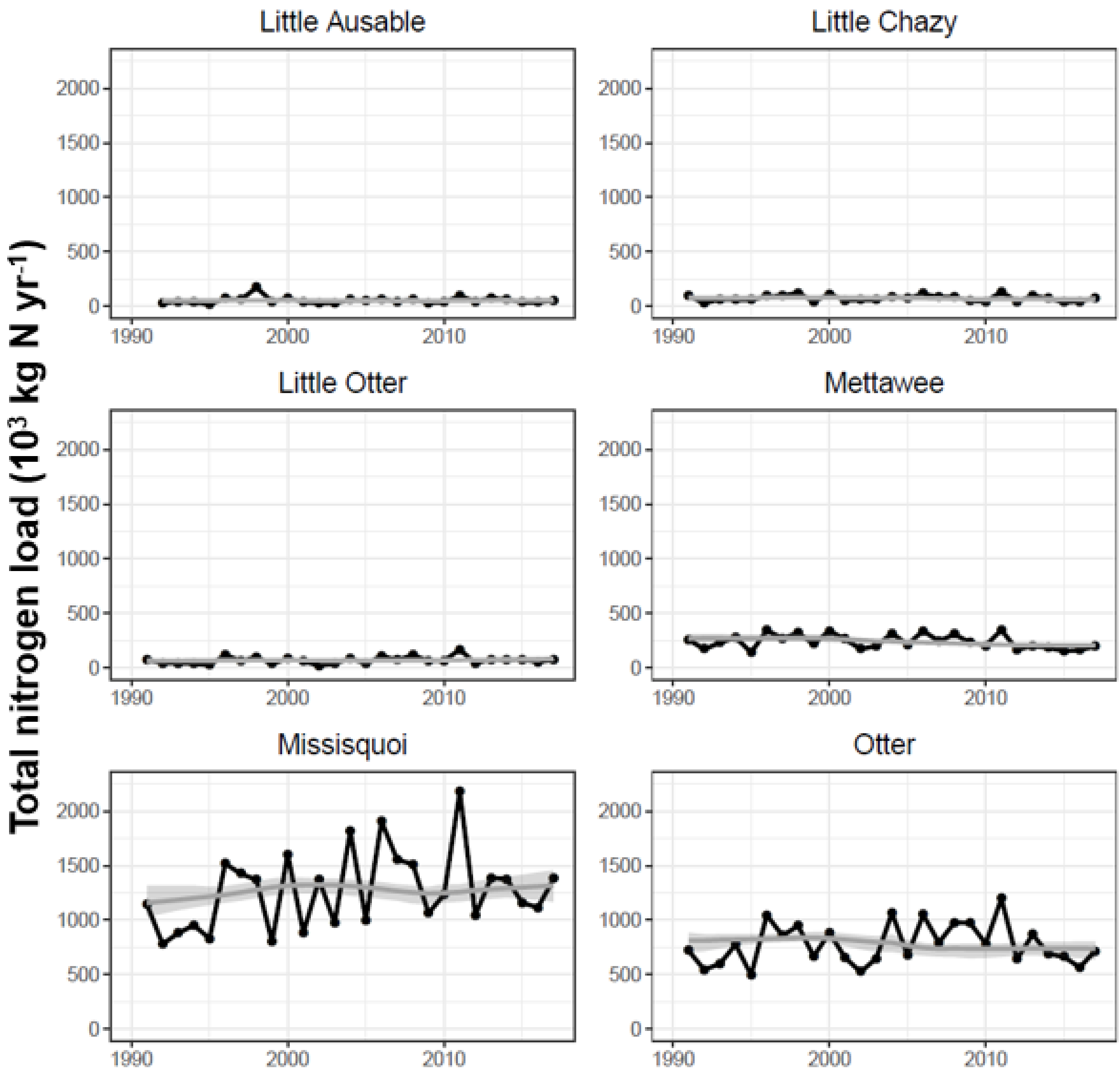


Figure 11. Plot of annual flow-normalized total nitrogen concentration estimates for eighteen Lake Champlain tributaries. The annual flow-normalized concentration is an estimate of the annual mean concentration with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

Table 7. Trend probabilities and magnitudes for **flow-normalized total nitrogen concentration** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

	First half (1993 to 2004)				Full record (1993 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change
Ausable	No trend	0.57	-0.02	-0.4	**Decrease**	**0.97**	-0.12	-1.3	**Decrease**	**0.99**	-0.11	-2.1
Boquet	No trend	0.89	-0.05	-1.2	No trend	0.87	-0.10	-1.1	No trend	0.74	-0.05	-1.2
Great Chazy	**Decrease**	**0.99**	-0.14	-1.9	No trend	0.52	0.00	0.0	No trend	0.88	0.14	1.6
Lamoille	No trend	0.60	0.00	0.0	No trend	0.50	-0.02	-0.2	No trend	0.65	-0.02	-0.3
LaPlatte	**Decrease**	**0.97**	-0.25	-3.1	**Decrease**	**0.97**	-0.34	-2.2	**Decrease**	**0.91**	-0.10	-1.3
Lewis	No trend	0.70	0.03	0.6	No trend	0.74	0.02	0.2	No trend	0.57	-0.01	-0.2
Little Ausable	No trend	0.84	0.07	0.8	No trend	0.87	0.09	0.4	No trend	0.60	0.02	0.2
Little Chazy	No trend	0.65	-0.07	-0.5	**Decrease**	**0.93**	-0.38	-1.4	No trend	0.86	-0.31	-2.2
Little Otter	No trend	0.62	0.05	0.5	No trend	0.87	0.12	0.5	No trend	0.72	0.07	0.6
Mettawee	No trend	0.62	-0.06	-0.6	**Decrease**	**0.97**	-0.19	-0.9	**Decrease**	**0.99**	-0.13	-1.2
Missisquoi	No trend	0.76	0.06	0.8	No trend	0.89	0.06	0.3	No trend	0.62	-0.01	-0.1
Otter	No trend	0.70	-0.02	-0.2	No trend	0.75	-0.05	-0.3	No trend	0.60	-0.03	-0.3
Pike	**Increase**	**0.97**	0.46	2.5	**Increase**	**0.97**	0.52	1.3	No trend	0.62	0.06	0.2
Poultney	No trend	0.50	0.00	-0.1	No trend	0.89	-0.06	-0.5	No trend	0.74	-0.05	-0.8
Putnam[a]	**Decrease**	**0.97**	-0.06	-1.6	**Decrease**	**0.99**	-0.09	-1.4	No trend	0.84	-0.03	-1.1
Salmon	**Decrease**	**0.95**	-0.05	-1.1	**Decrease**	**0.99**	-0.11	-1.0	**Decrease**	**0.96**	-0.05	-1.0
Saranac	**Decrease**	**0.97**	-0.08	-1.4	**Decrease**	**0.99**	-0.14	-1.2	**Decrease**	**0.99**	-0.07	-1.2
Winooski	**Increase**	**0.99**	0.19	2.3	No trend	0.67	0.04	0.2	**Decrease**	**0.99**	-0.15	-1.5


Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
Total nitrogen load (10^3 kg N yr^{-1})
0
500
1000
1500
2000
1990
2000
2010


Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
Total nitrogen load (10³ kg N yr⁻¹)
0
500
1000
1500
2000
1990
2000
2010

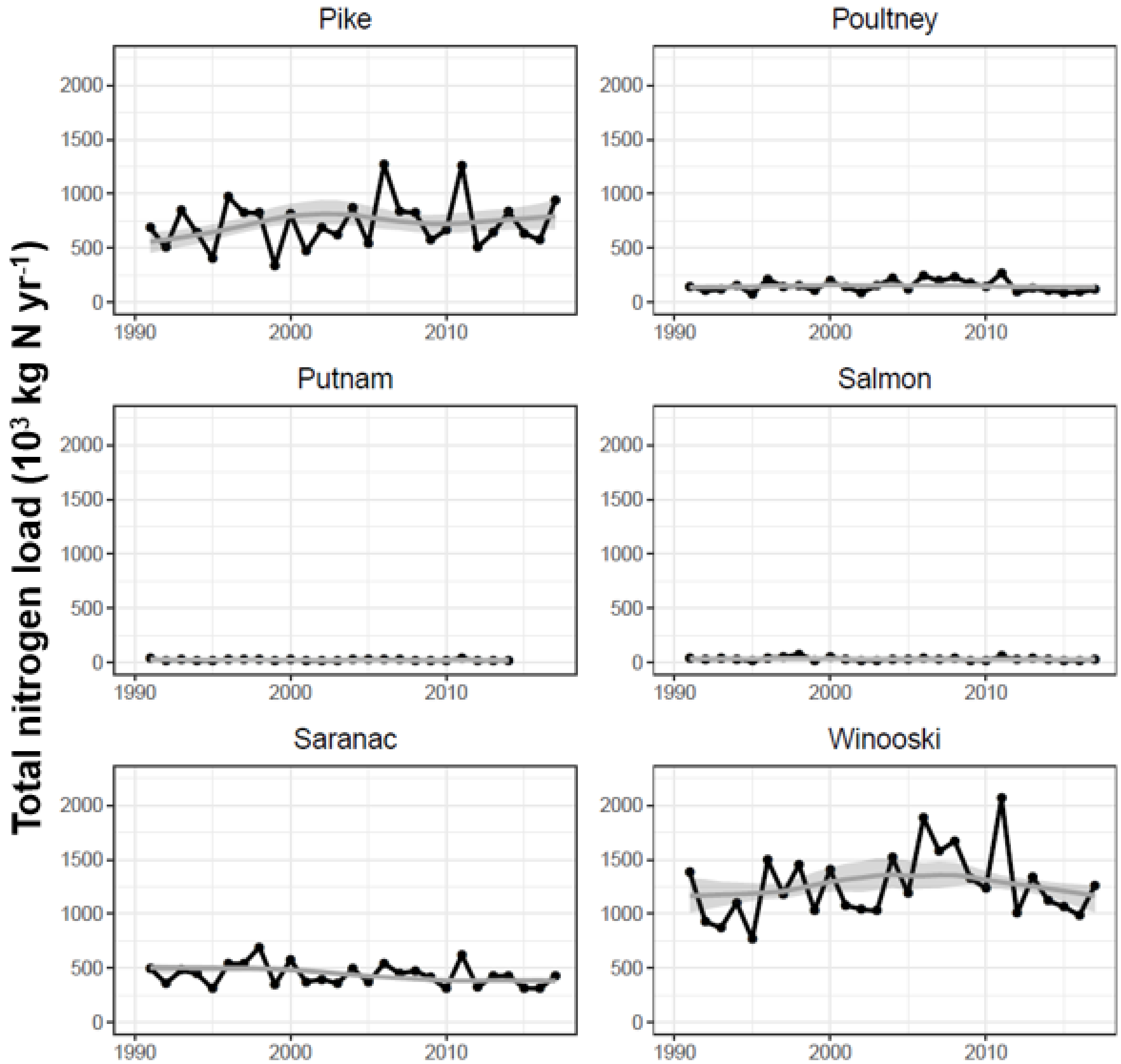


Figure 12. Estimated annual total nitrogen load (black dots and lines) and flow-normalized total nitrogen load (grey lines) with 95% confidence intervals (grey shaded areas) for eighteen Lake Champlain tributaries.

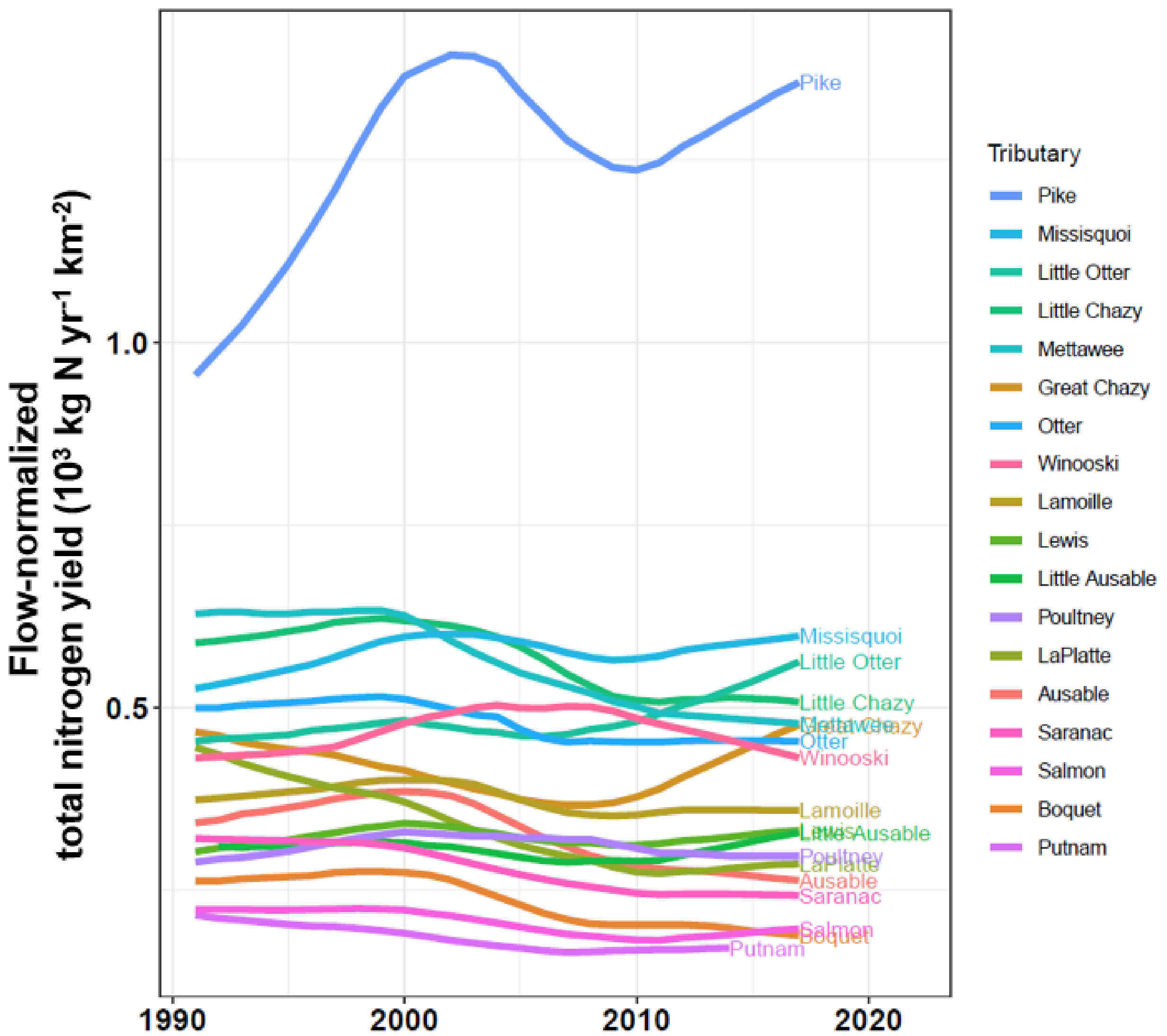


Figure 13. Plot of annual flow-normalized total nitrogen yield estimates for eighteen Lake Champlain tributaries. The flow-normalized yield is an estimate of load per watershed area, with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

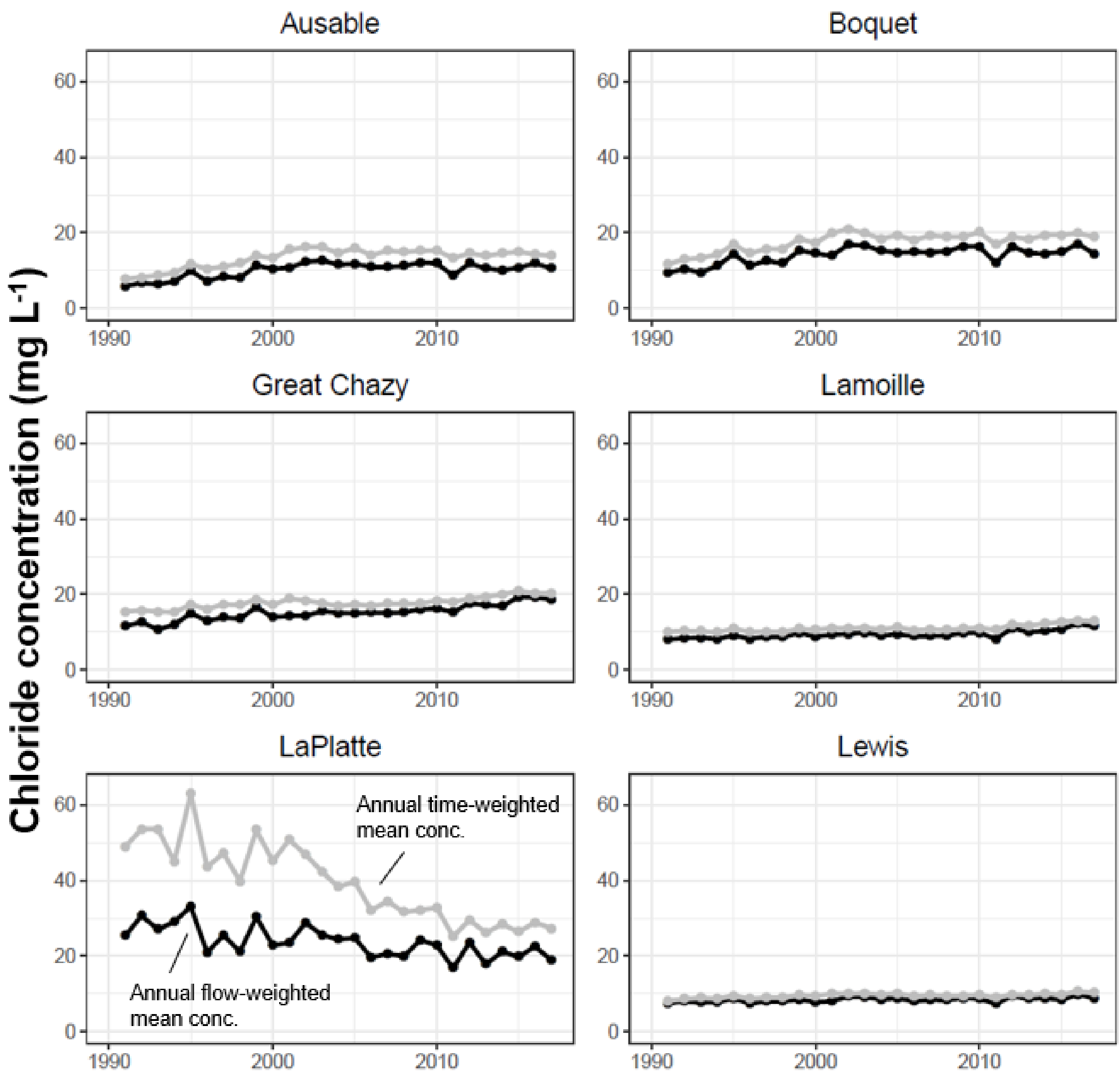
Table 8. Trend probabilities and magnitudes for **flow-normalized total nitrogen load** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

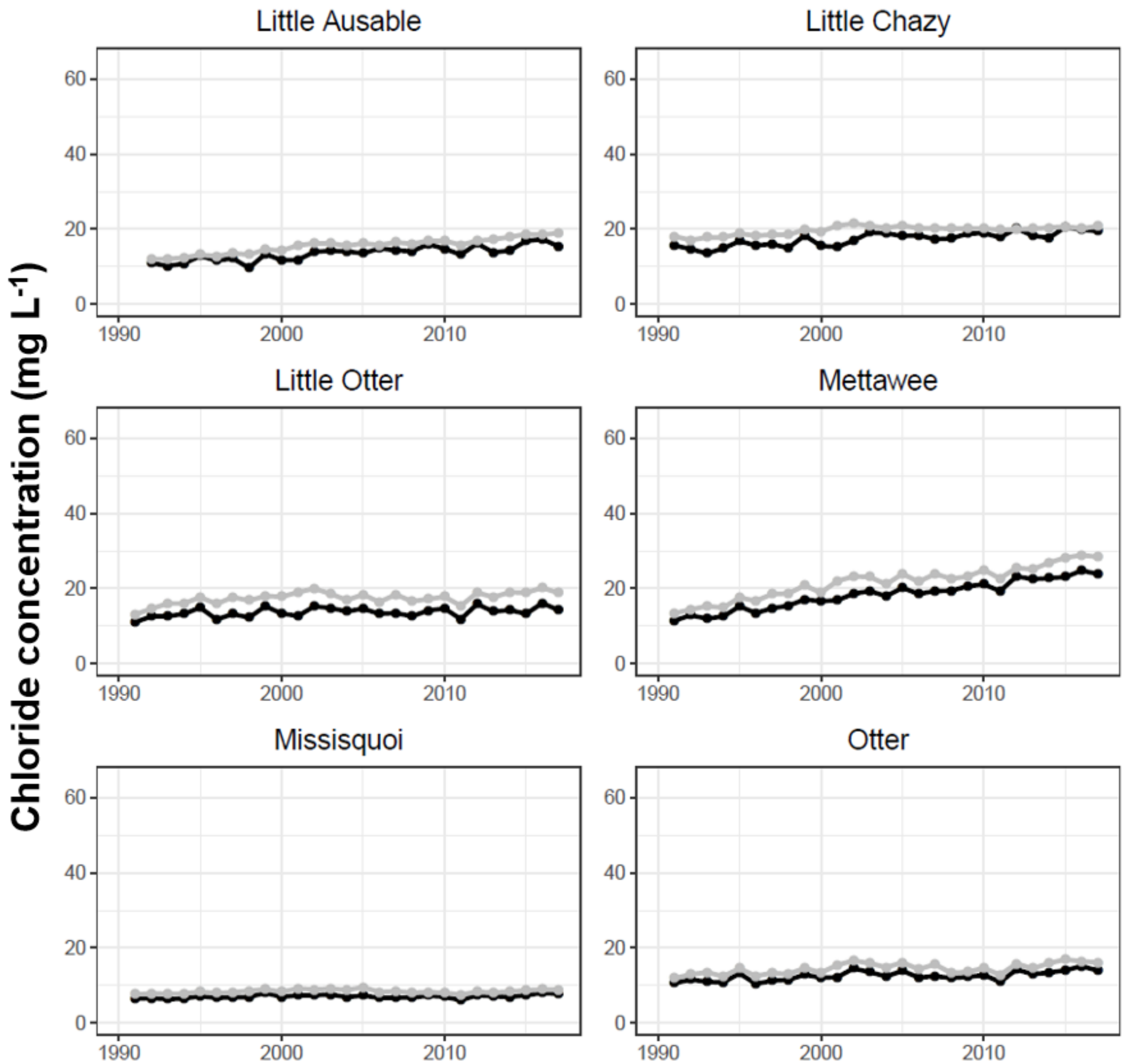
	First half (1993 to 2004)				Full record (1993 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change
Ausable	No trend	0.62	-1.7	0.0	No trend	0.90	-105.0	-1.2	**Decrease**	**0.99**	-103.0	-2.2
Boquet	No trend	0.82	-17.0	-0.9	No trend	0.84	-54.0	-1.4	**Decrease**	**0.99**	-37.0	-1.9
Great Chazy	**Decrease**	**0.97**	-44.0	-1.6	No trend	0.57	14.0	0.2	**Increase**	**0.94**	59.0	1.7
Lamoille	No trend	0.52	10.0	0.1	No trend	0.62	-35.0	-0.2	No trend	0.79	-46.0	-0.5
LaPlatte	No trend	0.90	-12.0	-2.5	**Decrease**	**0.98**	-16.0	-1.6	No trend	0.86	-4.1	-0.9
Lewis	No trend	0.62	3.4	0.5	No trend	0.65	4.2	0.3	No trend	0.55	0.8	0.1
Little Ausable	No trend	0.57	-1.4	-0.2	No trend	0.77	3.6	0.3	No trend	0.87	5.0	0.7
Little Chazy	No trend	0.67	0.2	0.0	No trend	0.85	-11.0	-0.7	**Decrease**	**0.91**	-12.0	-1.2
Little Otter	No trend	0.55	1.1	0.1	**Increase**	**0.99**	15.0	0.9	**Increase**	**0.97**	14.0	1.5
Mettawee	No trend	0.79	-30.0	-1.1	**Decrease**	**0.97**	-66.0	-1.1	**Decrease**	**0.97**	-36.0	-1.2
Missisquoi	**Increase**	**0.91**	126.0	1.0	No trend	0.89	130.0	0.4	No trend	0.67	4.6	0.0
Otter	No trend	0.74	-26.0	-0.3	**Decrease**	**0.92**	-80.0	-0.4	No trend	0.72	-55.0	-0.5
Pike	**Increase**	**0.99**	208.0	2.8	**Increase**	**0.99**	194.0	1.2	No trend	0.52	-14.0	-0.1
Poultney	No trend	0.89	14.0	0.9	No trend	0.55	0.6	0.0	No trend	0.79	-14.0	-0.7
Putnam[a]	**Decrease**	**0.96**	-4.6	-1.6	**Decrease**	**0.94**	-5.2	-1.0	No trend	0.62	-0.6	-0.3
Salmon	No trend	0.82	-3.0	-0.8	**Decrease**	**0.92**	-4.3	-0.5	No trend	0.76	-1.3	-0.3
Saranac	**Decrease**	**0.96**	-64.0	-1.3	**Decrease**	**0.99**	-120.0	-1.1	**Decrease**	**0.99**	-56.0	-1.1
Winooski	**Increase**	**0.97**	185.0	1.4	No trend	0.60	-9.6	0.0	**Decrease**	**0.99**	-195.0	-1.2

Chloride

In general, time-weighted mean chloride concentration values were higher than flow-weighted mean values, in contrast to these relationships for nutrients and total suspended solids (Figure 14). This is because baseflow chloride concentrations tended to be higher than chloride concentrations during storm events, when tributaries had more diluted concentrations. The LaPlatte River had relatively high chloride concentrations, and the largest difference between time- and flow-weighted annual mean concentrations. The LaPlatte River was the only tributary to demonstrate a significant decreasing trend in chloride concentration (Table 9). Nearly all (16) of the other tributaries showed significant increasing trends in flow-normalized chloride concentration for the full record trend period. Eight of these tributaries showed no trend in the second half of the record.

Annual chloride loads and yields in the Winooski River often exceeded those of all other tributaries, and the Mettawee River chloride yield was also relatively high (Figure 16 and Figure *17*). First-half and full-record significant increasing trends in flow-normalized chloride load were observed in all but two tributaries, where full record decreasing trends were found (Pike and LaPlatte Rivers; Table 10). Seven of these sixteen tributaries showed no trend in flow-normalized load in the second half of the record: the Ausable, Boquet, Mettawee, Missisquoi, and Winooski Rivers, and Lewis and Otter Creeks. Although the Putnam Creek increased in flow-normalized load for the full and first half of record, it showed a decrease for the second half of the record.


Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
Chloride concentration (mg L-1)
0
20
40
60
1990
2000
2010
Annual time-weighted mean conc.
Annual flow-weighted mean conc.


Chloride concentration (mg L-1)
Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
0
20
40
60
1990
2000
2010

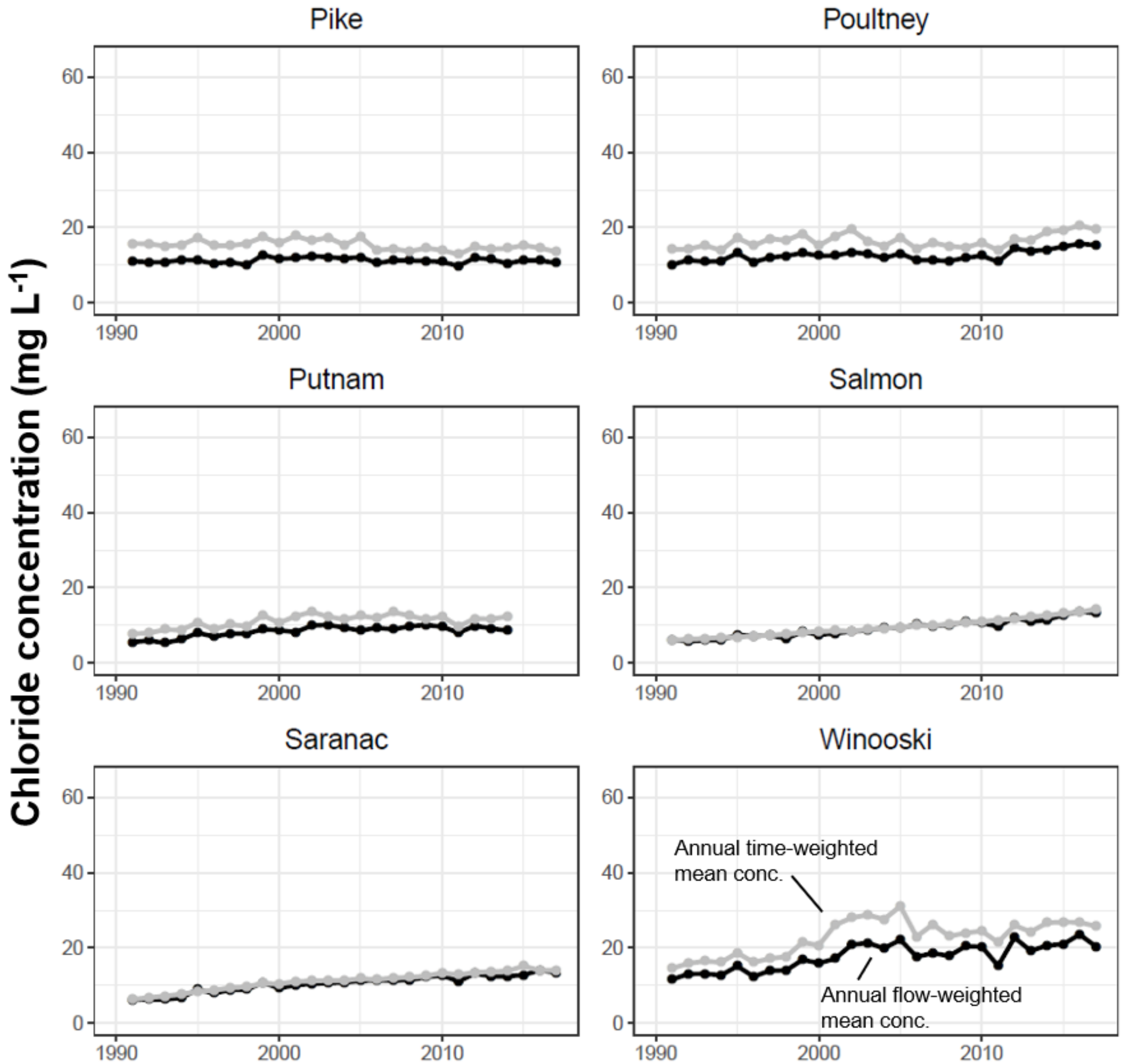


Figure 14. Estimated annual flow-weighted mean (black dots and lines) and time-weighted mean (grey dots and lines) chloride concentrations for eighteen Lake Champlain tributaries.

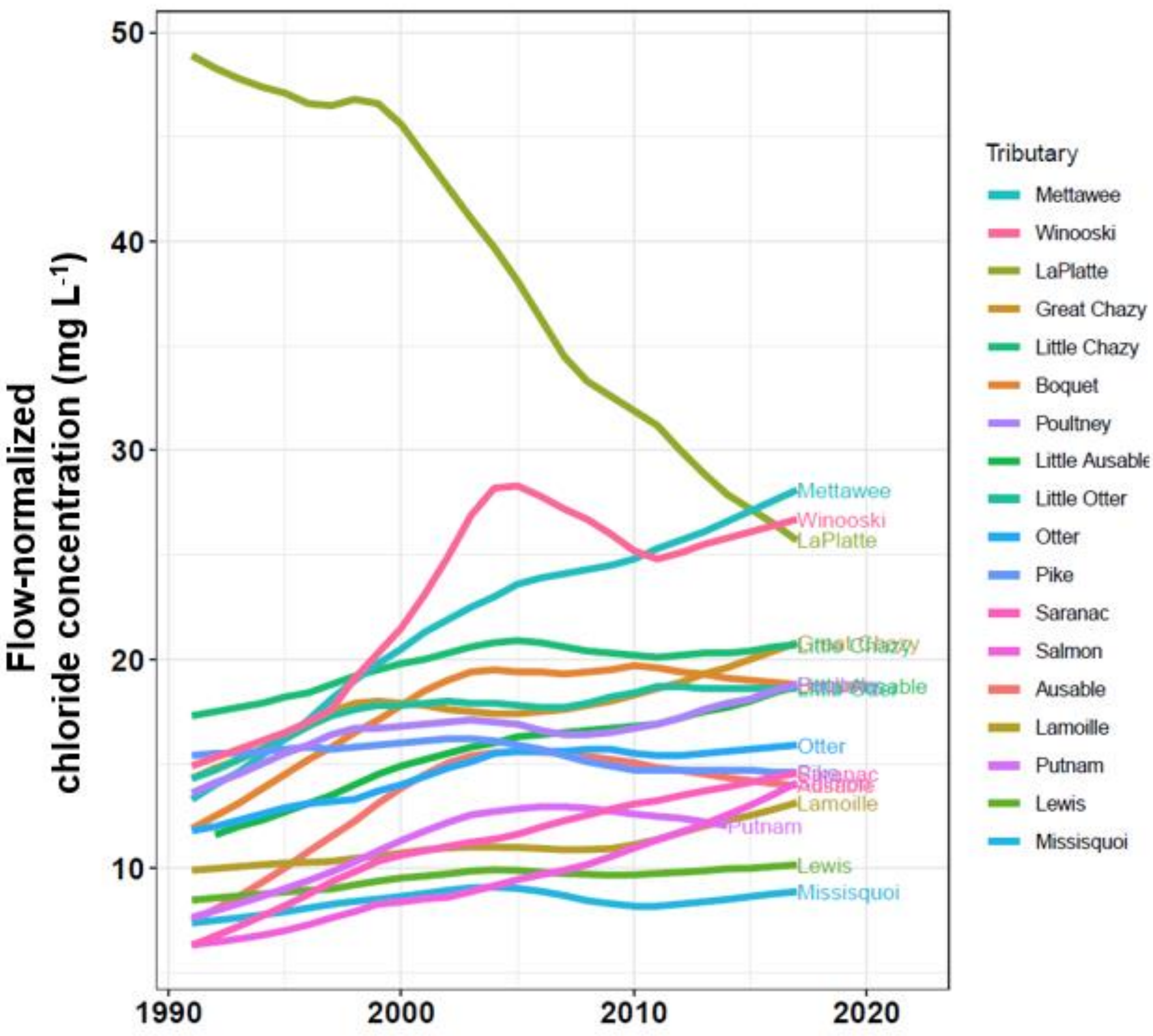
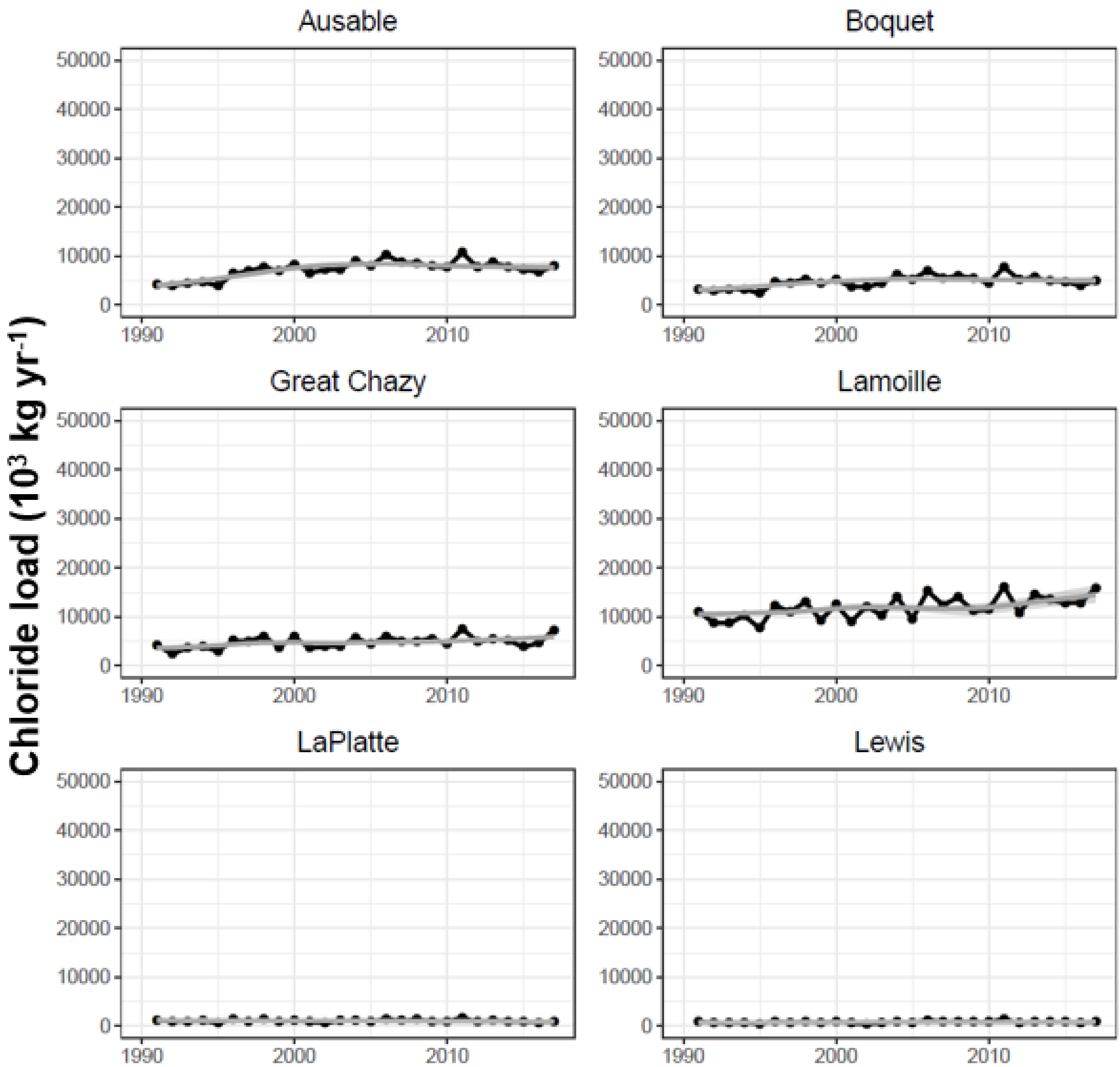
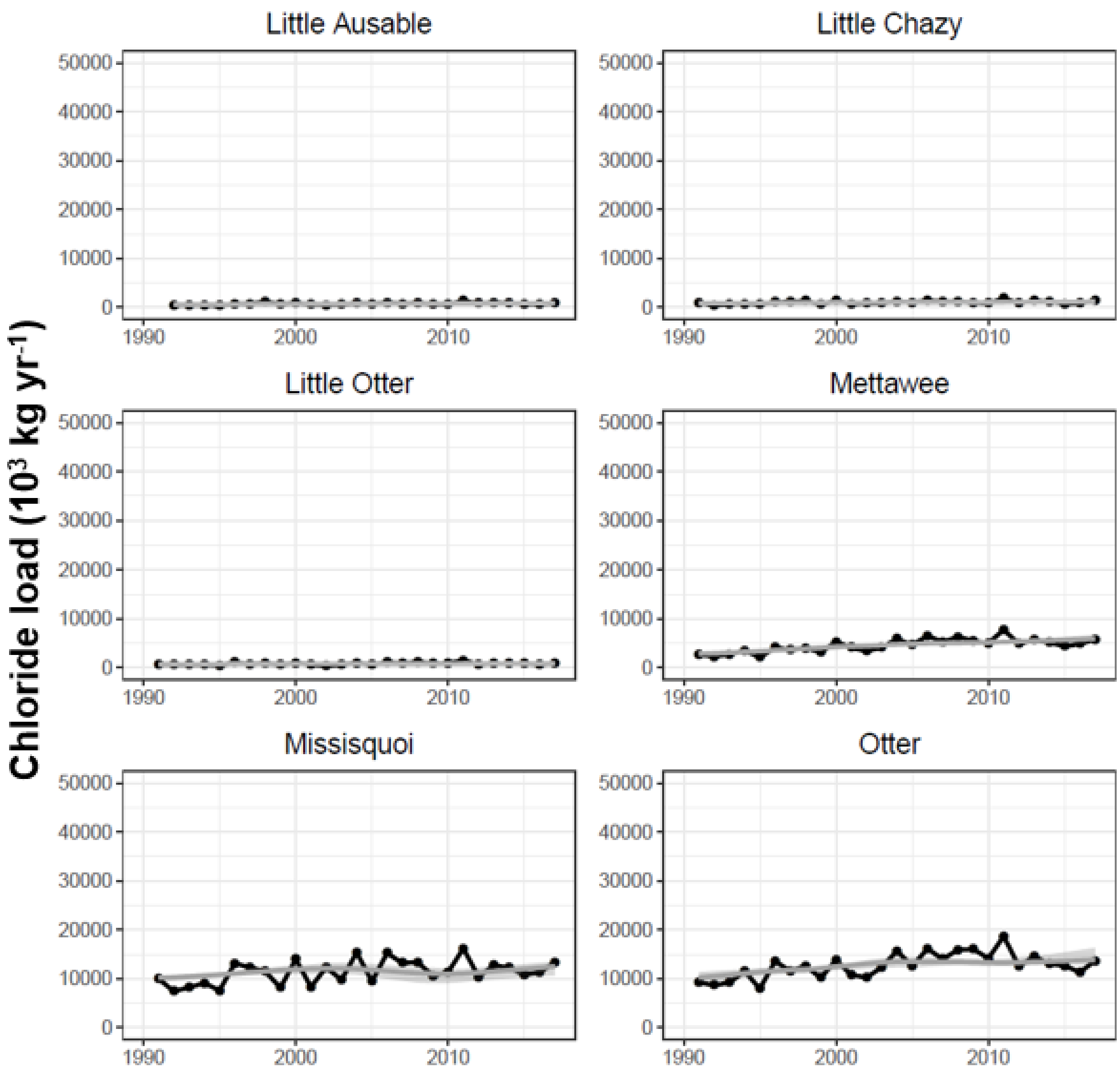


Figure 15. Plot of annual flow-normalized chloride concentration estimates for eighteen Lake Champlain tributaries. The annual flow-normalized concentration is an estimate of the annual mean concentration with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

Table 9. Trend probabilities and magnitudes for **flow-normalized chloride concentration** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for (*) Little Ausable River begin as early as 1993, and trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change
Ausable	**Increase**	**0.99**	8.1	5.8	**Increase**	**0.99**	6.5	2.4	No trend	0.90	-1.6	-0.8
Boquet	**Increase**	**0.99**	7.6	3.8	**Increase**	**0.99**	6.8	1.8	No trend	0.67	-0.7	-0.3
Great Chazy	**Increase**	**0.99**	3.1	1.5	**Increase**	**0.99**	6.5	1.5	**Increase**	**0.99**	3.5	1.4
Lamoille	No trend	0.88	1.1	0.8	**Increase**	**0.97**	3.2	1.1	**Increase**	**0.93**	2.1	1.3
LaPlatte	**Decrease**	**0.98**	-9.2	-1.6	**Decrease**	**0.99**	-23.0	-2.4	**Decrease**	**1.00**	-14.0	-3.3
Lewis	**Increase**	**0.99**	1.4	1.2	**Increase**	**0.97**	1.7	0.7	No trend	0.67	0.2	0.2
Little Ausable*	**Increase**	**0.99**	4.4	2.7	**Increase**	**0.99**	7.1	1.9	**Increase**	**0.99**	2.7	1.2
Little Chazy	**Increase**	**0.99**	3.6	1.5	**Increase**	**0.99**	3.4	0.7	No trend	0.52	-0.1	0.0
Little Otter	**Increase**	**0.99**	3.6	1.7	**Increase**	**0.99**	4.4	1.0	**Increase**	**0.96**	0.8	0.3
Mettawee	**Increase**	**0.99**	9.7	4.3	**Increase**	**0.99**	15.0	2.9	**Increase**	**0.99**	5.1	1.5
Missisquoi	**Increase**	**0.99**	1.7	1.6	**Increase**	**0.92**	1.5	0.7	No trend	0.70	-0.2	-0.2
Otter	**Increase**	**0.99**	3.8	2.2	**Increase**	**0.99**	4.2	1.2	No trend	0.74	0.4	0.2
Pike	No trend	0.70	0.7	0.3	No trend	0.80	-0.9	-0.2	No trend	0.90	-1.5	-0.8
Poultney	**Increase**	**0.99**	3.4	1.7	**Increase**	**0.99**	5.2	1.2	**Increase**	**0.97**	1.8	0.7
Putnam[a]	**Increase**	**0.99**	5.1	4.0	**Increase**	**0.99**	4.6	2.2	No trend	0.72	-0.5	-0.4
Salmon	**Increase**	**0.99**	2.8	2.9	**Increase**	**0.99**	7.7	3.1	**Increase**	**0.99**	4.9	3.4
Saranac	**Increase**	**0.99**	5.1	4.7	**Increase**	**0.99**	8.2	3.3	**Increase**	**0.99**	3.2	1.9
Winooski	**Increase**	**0.99**	13.0	5.0	**Increase**	**0.99**	12.0	2.3	No trend	0.74	-1.5	-0.4


Chloride load (10^3 kg yr^{-1})
Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
50000
40000
30000
20000
10000
0
1990
2000
2010


Chloride load (10^3 kg yr^{-1})
Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
50000
40000
30000
20000
10000
0
1990
2000
2010

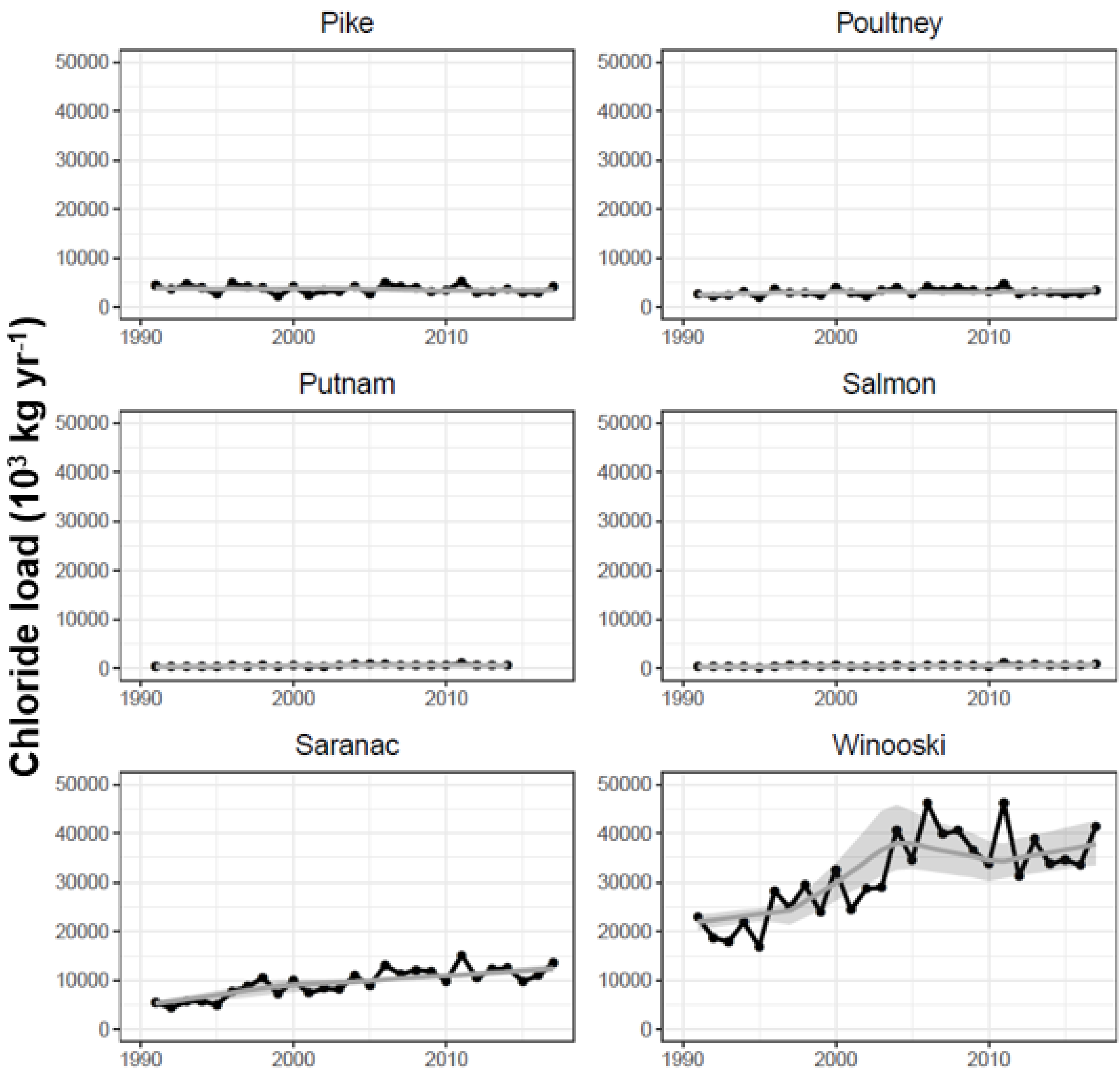


Figure 16. Estimated annual chloride load (black dots and lines) and flow-normalized chloride load (grey lines) with 95% confidence intervals (grey shaded areas) for eighteen Lake Champlain tributaries.

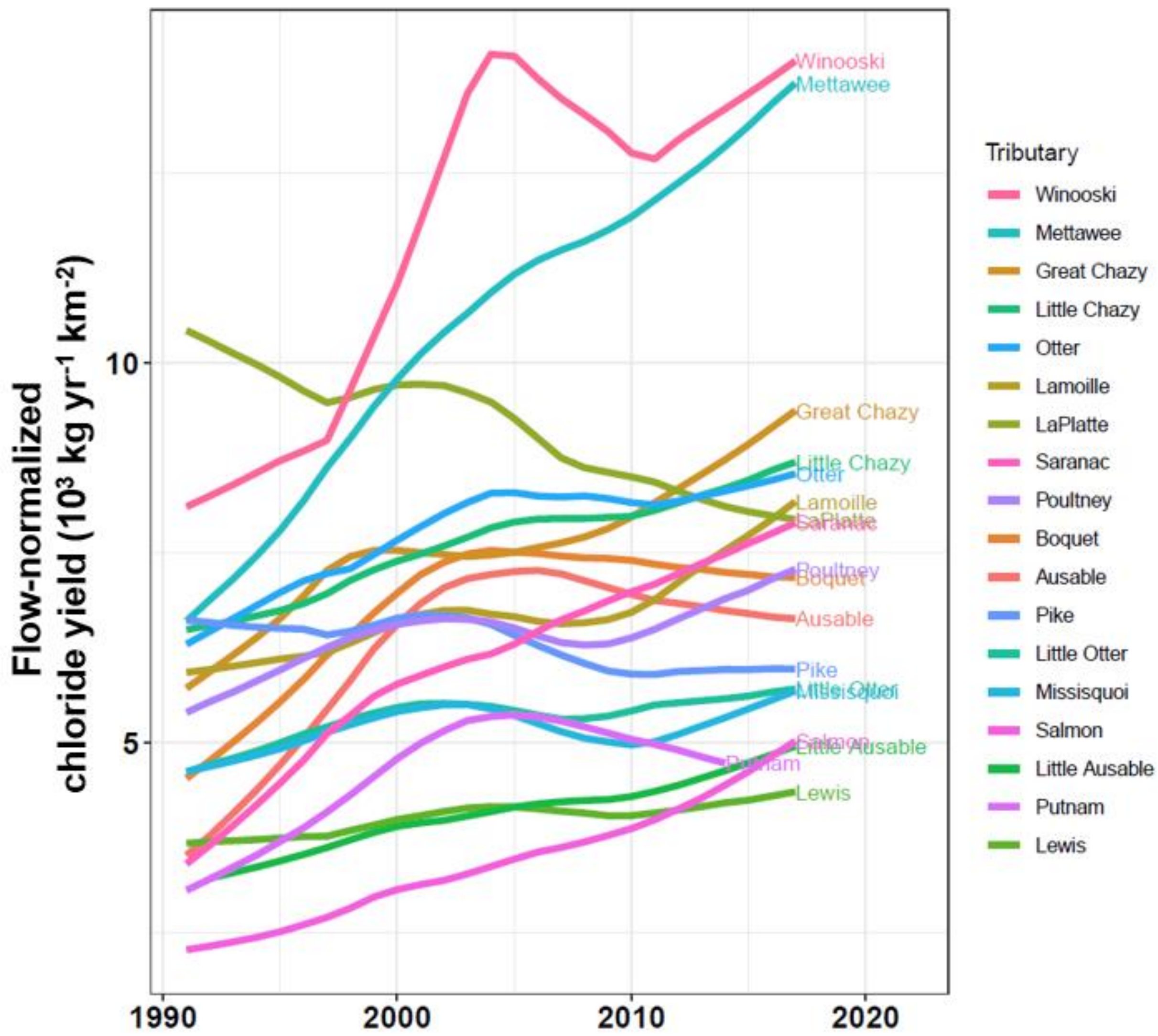


Figure 17. Plot of annual flow-normalized chloride yield estimates for eighteen Lake Champlain tributaries. The flow-normalized yield is an estimate of load per watershed area, with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

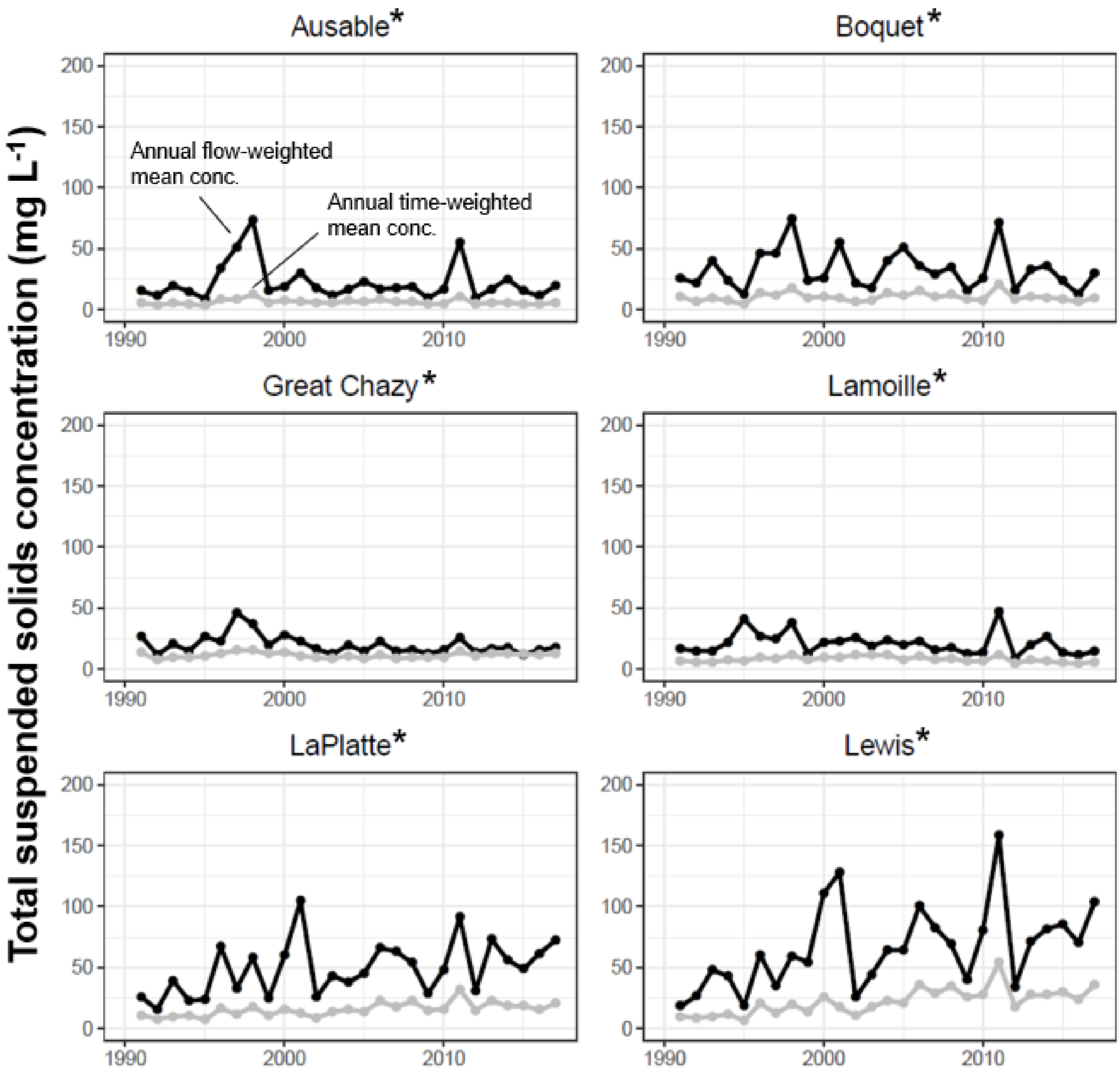
Table 10. Trend probabilities and magnitudes for **flow-normalized chloride load** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for (*) Little Ausable River begin as early as 1993, and trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability $\geq$ 0.90) are outlined and shown in **bold**.

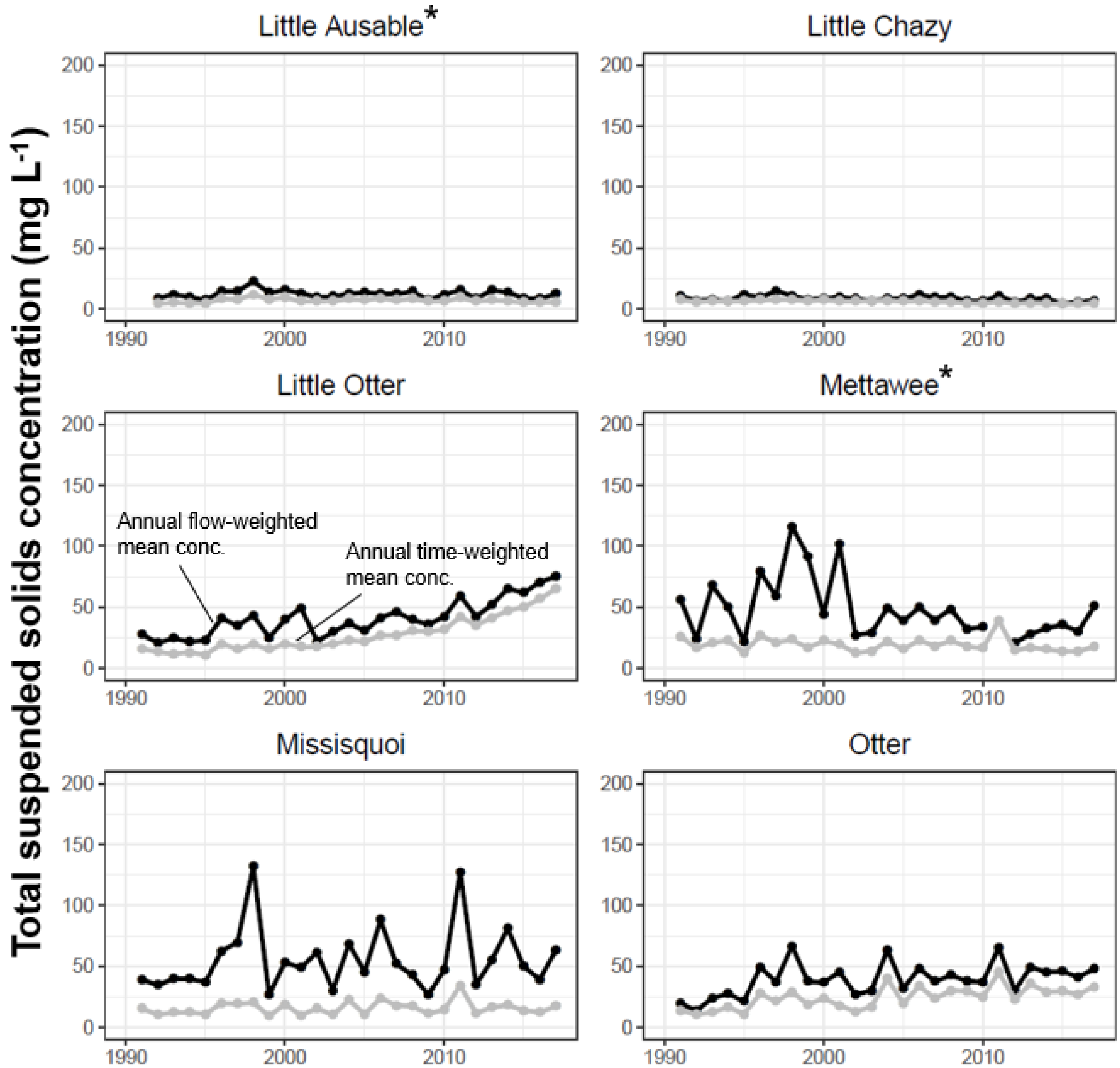
	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change
Ausable	**Increase**	**0.99**	4276	5.7	**Increase**	**0.99**	3601	2.5	No trend	0.85	-675	-0.6
Boquet	**Increase**	**0.99**	2099	4.0	**Increase**	**0.99**	1849	1.8	No trend	0.70	-250	-0.4
Great Chazy	**Increase**	**0.99**	1105	2.1	**Increase**	**0.99**	2302	1.9	**Increase**	**0.99**	1197	1.7
Lamoille	**Increase**	**0.97**	1365	0.9	**Increase**	**0.99**	3999	1.2	**Increase**	**0.97**	2634	1.5
LaPlatte	**Decrease**	**0.95**	-109	-0.7	**Decrease**	**0.99**	-288	-1.0	**Decrease**	**0.97**	-180	-1.3
Lewis	**Increase**	**0.99**	97	0.9	**Increase**	**0.97**	135	0.6	No trend	0.79	38	0.3
Little Ausable*	**Increase**	**0.99**	154	2.0	**Increase**	**0.99**	306	1.7	**Increase**	**0.99**	152	1.5
Little Chazy	**Increase**	**0.99**	175	1.5	**Increase**	**0.99**	289	1.1	**Increase**	**0.99**	114	0.8
Little Otter	**Increase**	**0.99**	129	1.3	**Increase**	**0.99**	162	0.8	**Increase**	**0.92**	34	0.3
Mettawee	**Increase**	**0.99**	1873	4.0	**Increase**	**0.99**	3066	2.8	**Increase**	**0.99**	1193	1.7
Missisquoi	**Increase**	**0.99**	1817	1.3	**Increase**	**0.98**	2336	0.8	No trend	0.82	519	0.3
Otter	**Increase**	**0.99**	3236	2.2	**Increase**	**0.99**	3654	1.2	No trend	0.74	417	0.2
Pike	No trend	0.57	-32	-0.1	**Decrease**	**0.91**	-375	-0.4	No trend	0.85	-343	-0.7
Poultney	**Increase**	**0.99**	578	1.5	**Increase**	**0.99**	914	1.2	**Increase**	**1.00**	337	0.8
Putnam[a]	**Increase**	**0.99**	305	4.4	**Increase**	**0.99**	234	2.1	**Decrease**	**0.91**	-71	-1.2
Salmon	**Increase**	**0.99**	180	3.1	**Increase**	**0.99**	451	3.1	**Increase**	**0.99**	271	3.1
Saranac	**Increase**	**0.99**	4356	4.7	**Increase**	**0.99**	7077	3.3	**Increase**	**0.99**	2721	1.9
Winooski	**Increase**	**0.99**	16126	4.4	**Increase**	**0.99**	15887	2.1	No trend	0.65	-239	0.0

Total suspended solids

Because validations showed that many of the models to predict total suspended solids concentration and load were biased (Table 2), results below should be interpreted with care and with the caveat that they have notable uncertainty. Annual flow-weighted mean total suspended solids concentrations were heavily influenced by annual discharge variability and were consistently higher than annual time-weighted mean values (Figure 18). For 8 out of 18 tributaries, no trends in flow-normalized total suspended solids concentration were found for any trend period (Table 11). Full record significant increases in flow-normalized concentration were found in the LaPlatte and Poultney Rivers and Lewis, Little Otter, and Otter Creeks. However, Lewis and Otter Creeks had no significant trends in the second half of record. In contrast, the Winooski River had no trend in flow-normalized concentration in the first half of record, but significantly increased in the second half of record.

Winooski and Missisquoi Rivers had the highest annual total suspended solids loads, at times exceeding an estimated 300,000 metric tons per year (Figure 20). In addition to these two tributaries, the Poultney River had relatively high annual flow-normalized total suspended solids yields (Figure 21). Although five tributaries had significantly increasing trends in flow-normalized load for the full record trend period (LaPlatte, Missisquoi, and Pike Rivers, and Lewis and Little Otter Creeks), only two had significantly increasing trends in the second half of record (Little Otter Creek and Winooski River) (Table 12). Three tributaries showed significant decreases in flow-normalized load: Lamoille River for the full record trend period, and Little Ausable and Little Chazy Rivers for the second half of record.


Total suspended solids concentration (mg L-1)
Ausable*
Annual flow-weighted mean conc.
Annual time-weighted mean conc.
Boquet*
Great Chazy*
Lamoille*
LaPlatte*
Lewis*
200
150
100
50
0
1990
2000
2010


Little Ausable*
Little Chazy
Little Otter
Mettawee*
Missisquoi
Otter
Total suspended solids concentration (mg L-1)
Annual flow-weighted mean conc.
Annual time-weighted mean conc.
200
150
100
50
0
1990
2000
2010

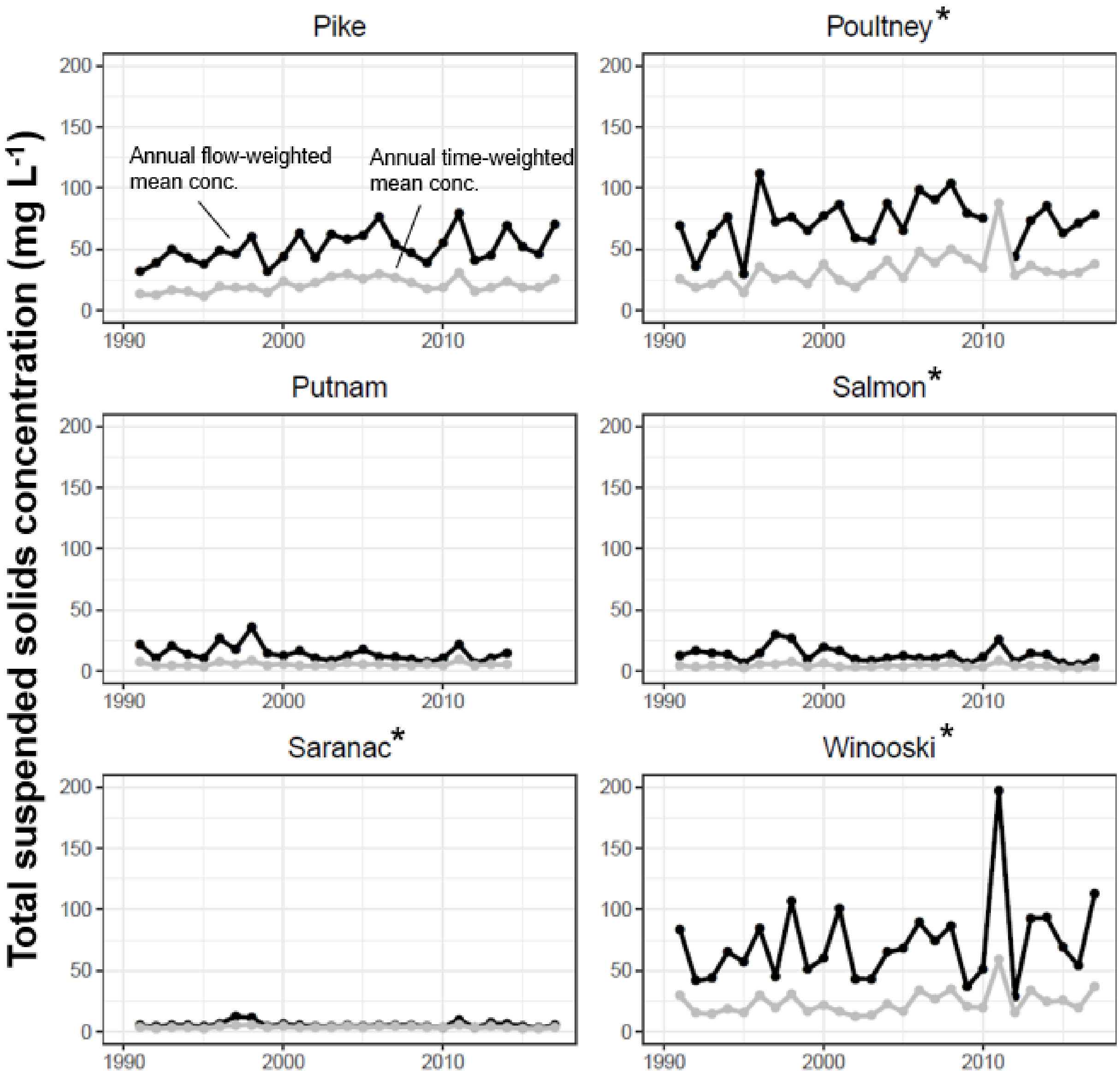


Figure 18. Estimated annual flow-weighted mean (black dots and lines) and time-weighted mean (grey dots and lines) total suspended solids concentrations for eighteen Lake Champlain tributaries. An asterisk (*) indicates that the flux bias statistic was outside of the acceptable range and that the results should be interpreted with care.

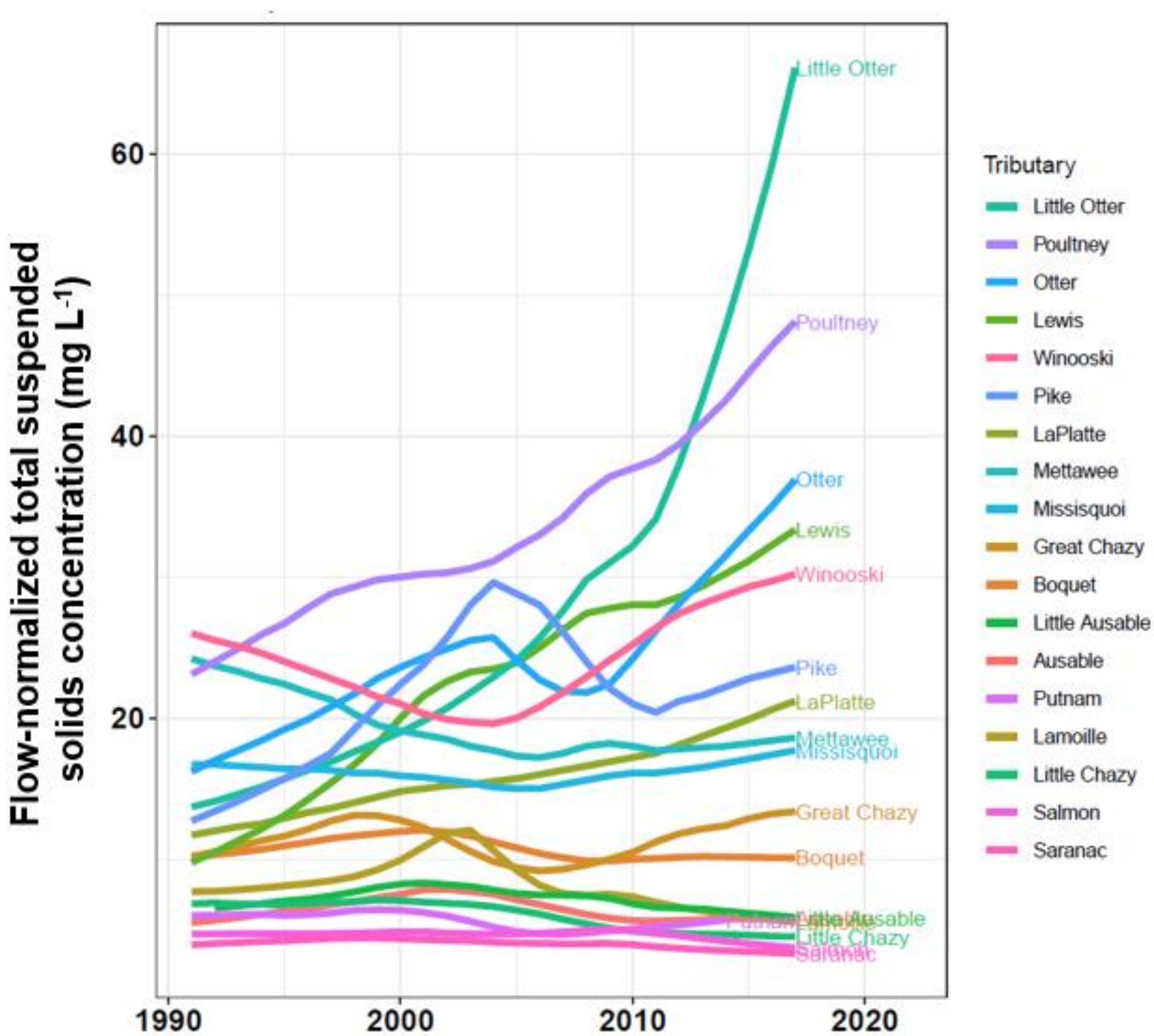
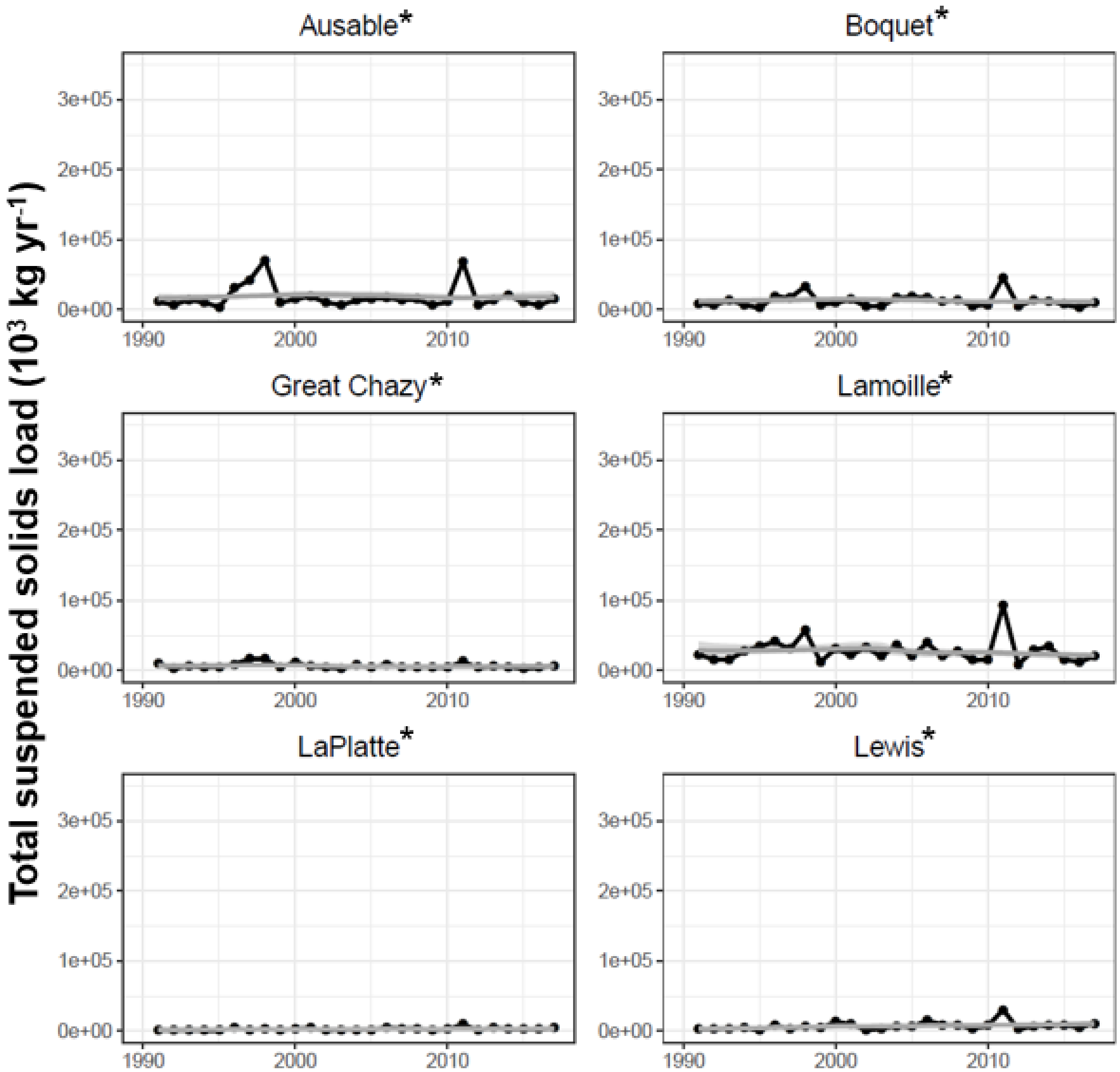
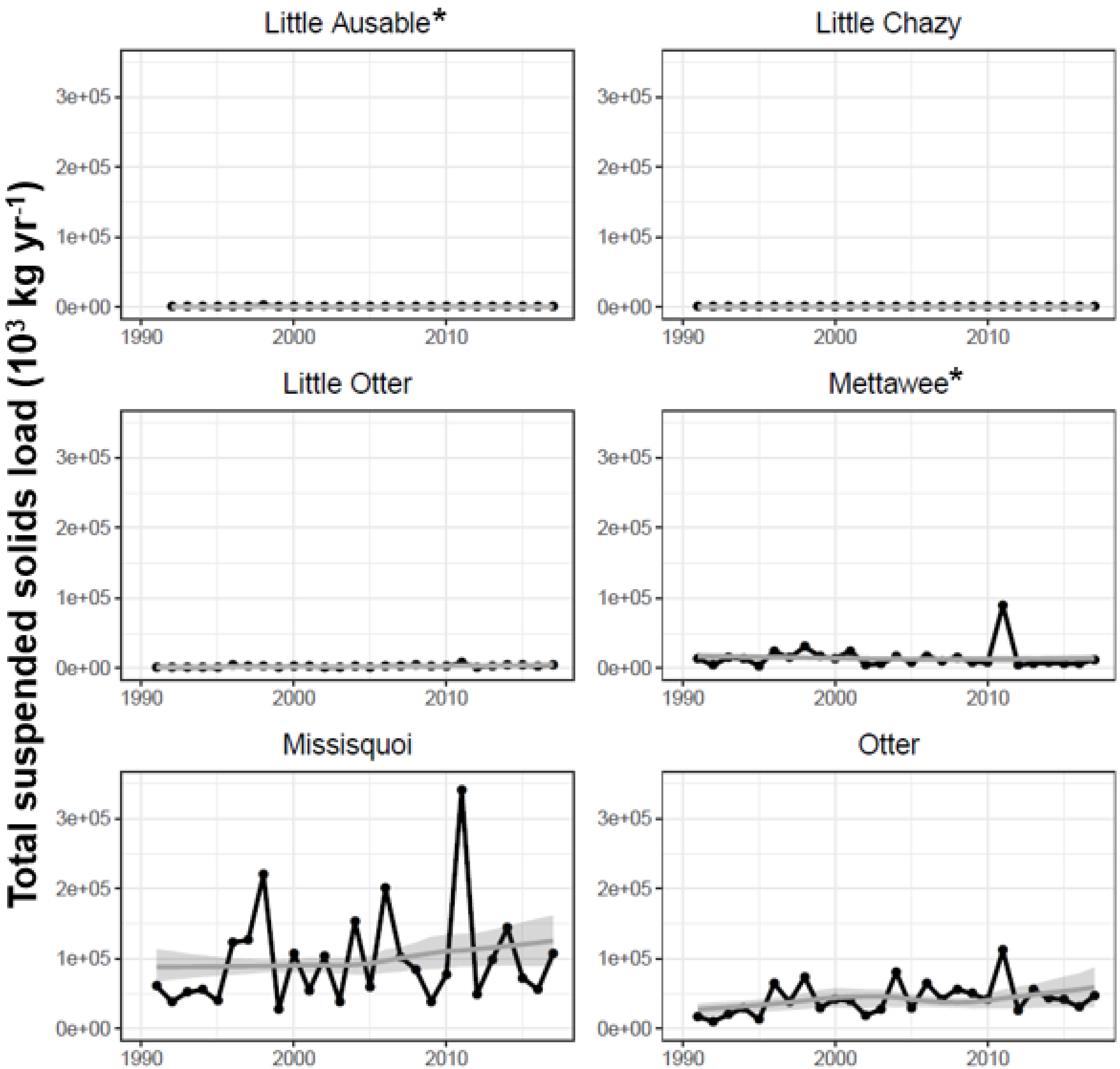


Figure 19. Plot of annual flow-normalized total suspended solids concentration estimates for eighteen Lake Champlain tributaries. The annual flow-normalized concentration is an estimate of the annual mean concentration with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

Table 11. Trend probabilities and magnitudes for **flow-normalized total suspended solids concentration** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

	First half (1993 to 2004)				Full record (1993 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change	Direction	Probability of trend	Change (mg L^{-1})	Annualized percent change
Ausable	**Increase**	**0.90**	1.7	2.3	No trend	0.65	0.0	0.0	No trend	0.89	-1.7	-2.0
Boquet	No trend	0.67	0.7	0.6	No trend	0.65	-0.4	-0.2	No trend	0.62	-1.1	-0.8
Great Chazy	No trend	0.55	-1.1	-0.9	No trend	0.70	2.5	0.9	No trend	0.60	3.5	2.4
Lamoille	No trend	0.65	2.8	2.8	No trend	0.89	-2.3	-1.4	No trend	0.74	-5.1	-4.9
LaPlatte	No trend	0.79	3.2	2.1	**Increase**	**0.97**	8.9	2.3	**Increase**	**0.99**	5.7	2.4
Lewis	**Increase**	**0.99**	12.0	6.9	**Increase**	**0.97**	22.0	4.6	No trend	0.87	9.9	2.7
Little Ausable	**Increase**	**0.92**	1.1	1.4	No trend	0.57	-0.8	-0.5	**Decrease**	**0.98**	-1.9	-2.2
Little Chazy	No trend	0.55	-0.2	-0.3	No trend	0.89	-2.3	-1.7	**Decrease**	**0.97**	-2.1	-2.9
Little Otter	No trend	0.84	8.3	4.1	**Increase**	**0.99**	51.0	6.5	**Increase**	**0.99**	43.0	8.5
Mettawee	No trend	0.74	-5.6	-2.5	No trend	0.84	-4.7	-0.9	No trend	0.62	0.9	0.4
Missisquoi	No trend	0.79	-1.4	-0.8	No trend	0.65	1.1	0.3	No trend	0.89	2.6	1.2
Otter	No trend	0.85	8.0	3.4	**Increase**	**0.91**	19.0	3.1	No trend	0.74	11.0	2.8
Pike	**Increase**	**0.96**	16.0	7.0	No trend	0.88	9.5	2.2	No trend	0.79	-6.0	-1.7
Poultney	**Increase**	**0.91**	6.2	2.0	**Increase**	**0.97**	23.0	2.8	**Increase**	**0.95**	17.0	3.4
Putnam[a]	No trend	0.50	-0.9	-1.5	No trend	0.50	-0.6	-0.5	No trend	0.74	0.3	0.7
Salmon	No trend	0.52	0.0	-0.1	No trend	0.72	-1.0	-1.0	No trend	0.84	-1.0	-1.8
Saranac	No trend	0.55	0.0	0.0	No trend	0.74	-0.8	-0.9	No trend	0.87	-0.8	-1.7
Winooski	No trend	0.82	-5.4	-2.2	No trend	0.90	5.1	0.8	**Increase**	**0.96**	11.0	3.4


Total suspended solids load (10^3 kg yr^{-1})
Ausable*
Boquet*
Great Chazy*
Lamoille*
LaPlatte*
Lewis*
3e+05
2e+05
1e+05
0e+00
1990
2000
2010


Total suspended solids load (10^3 kg yr^{-1})
Little Ausable*
Little Chazy
Little Otter
Mettawee*
Missisquoi
Otter
3e+05
2e+05
1e+05
0e+00
1990
2000
2010

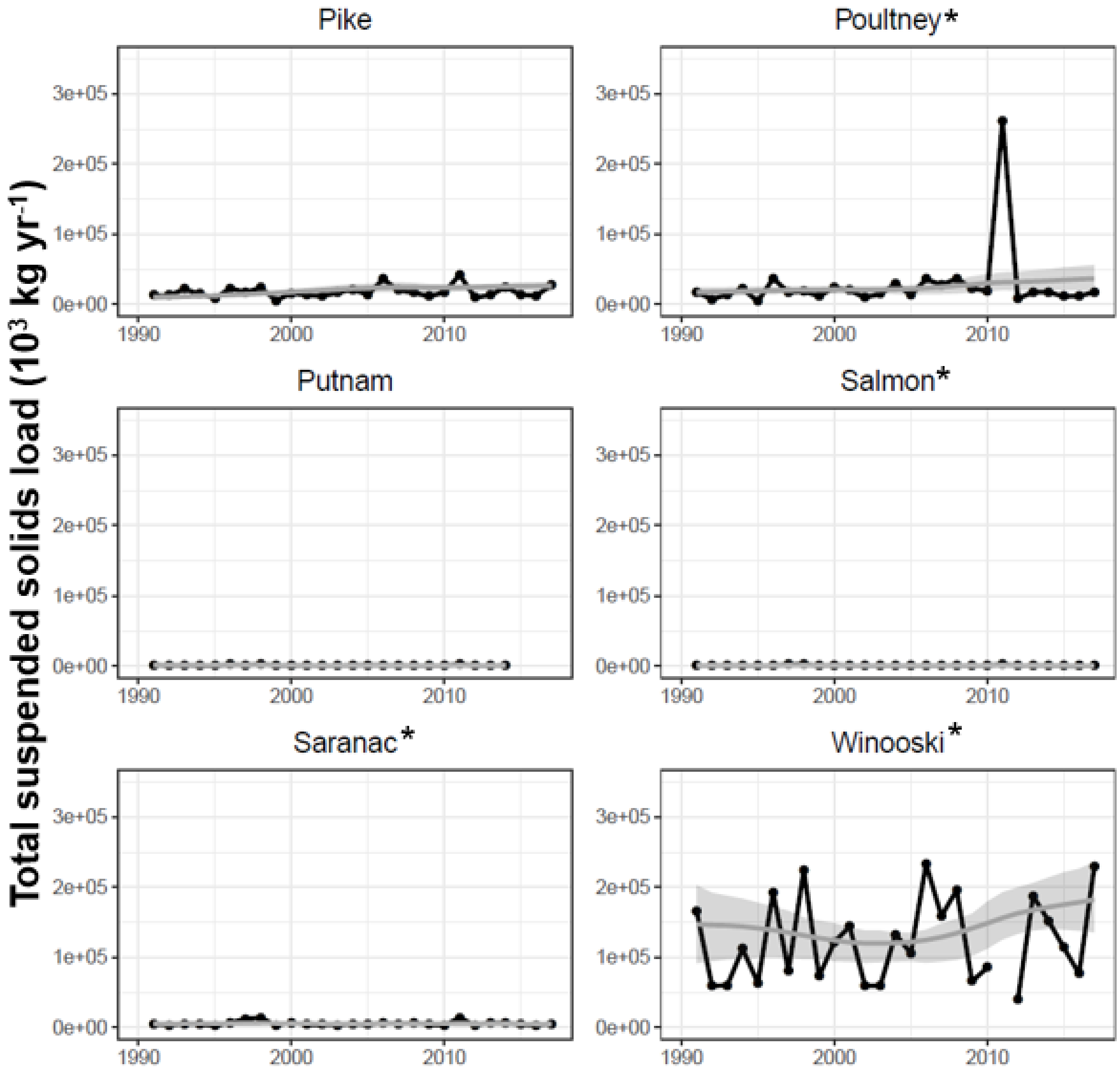


Figure 20. Estimated annual total suspended solids load (black dots and lines) and flow-normalized total suspended solids load (grey lines) with 95% confidence intervals (grey shaded areas) for eighteen Lake Champlain tributaries. An asterisk (*) indicates that the flux bias statistic was outside of the acceptable range and that the results should be interpreted with care.

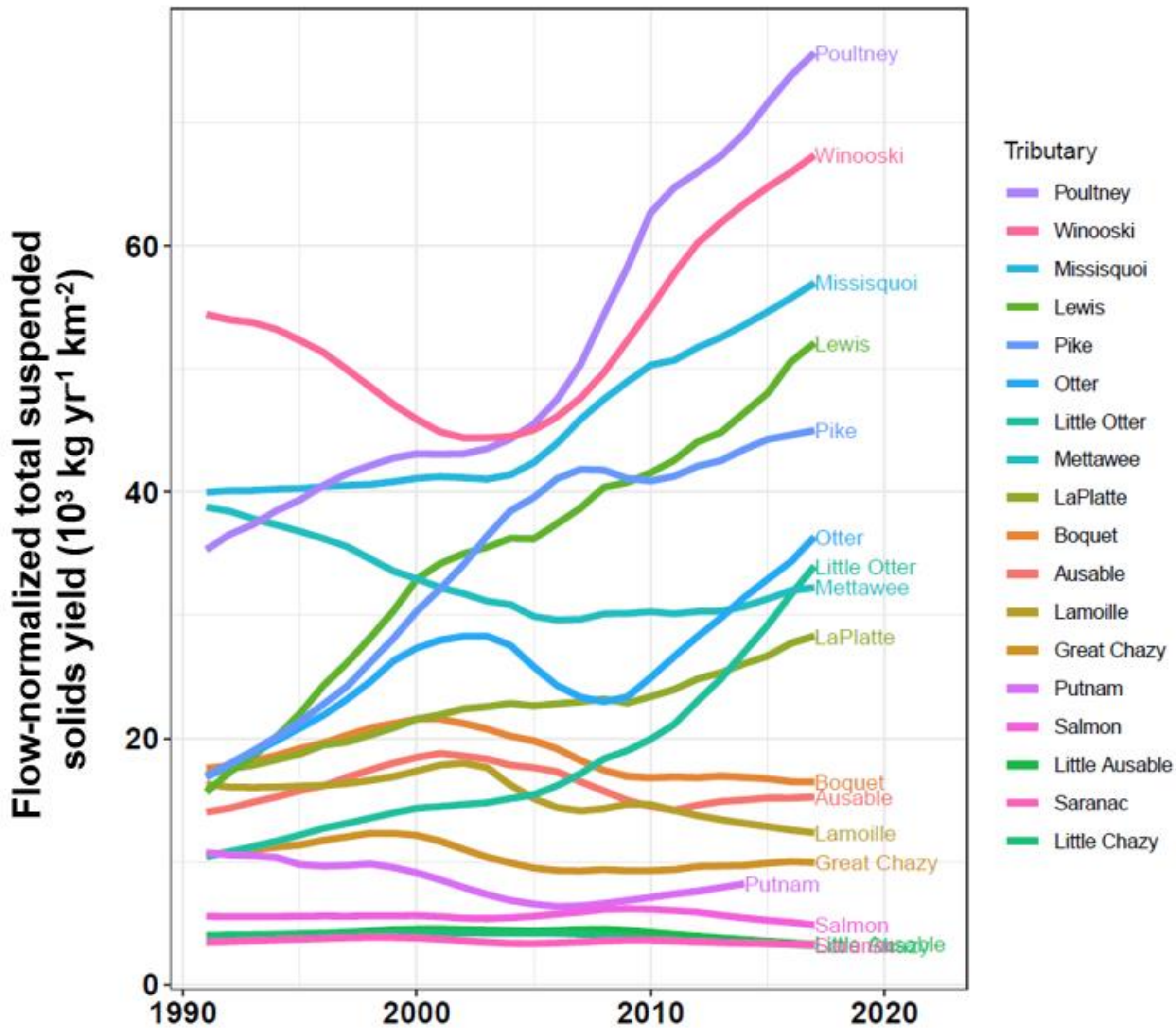


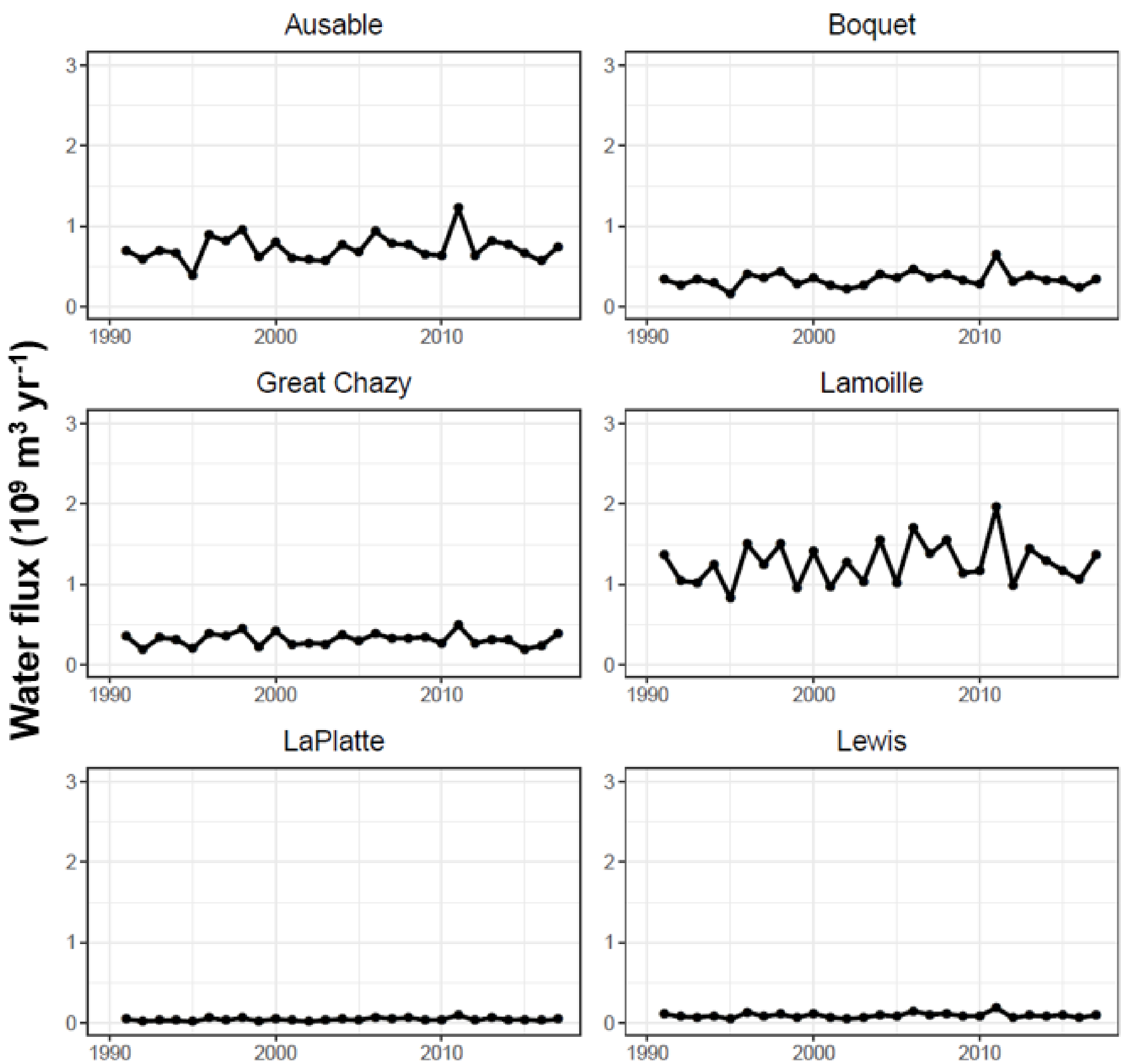
Figure 21. Plot of annual flow-normalized total suspended solids yield estimates for eighteen Lake Champlain tributaries. The flow-normalized yield is an estimate of load per watershed area, with the influence of annual water flux variability reduced. Note that the legend is in descending order by the latest value for each tributary.

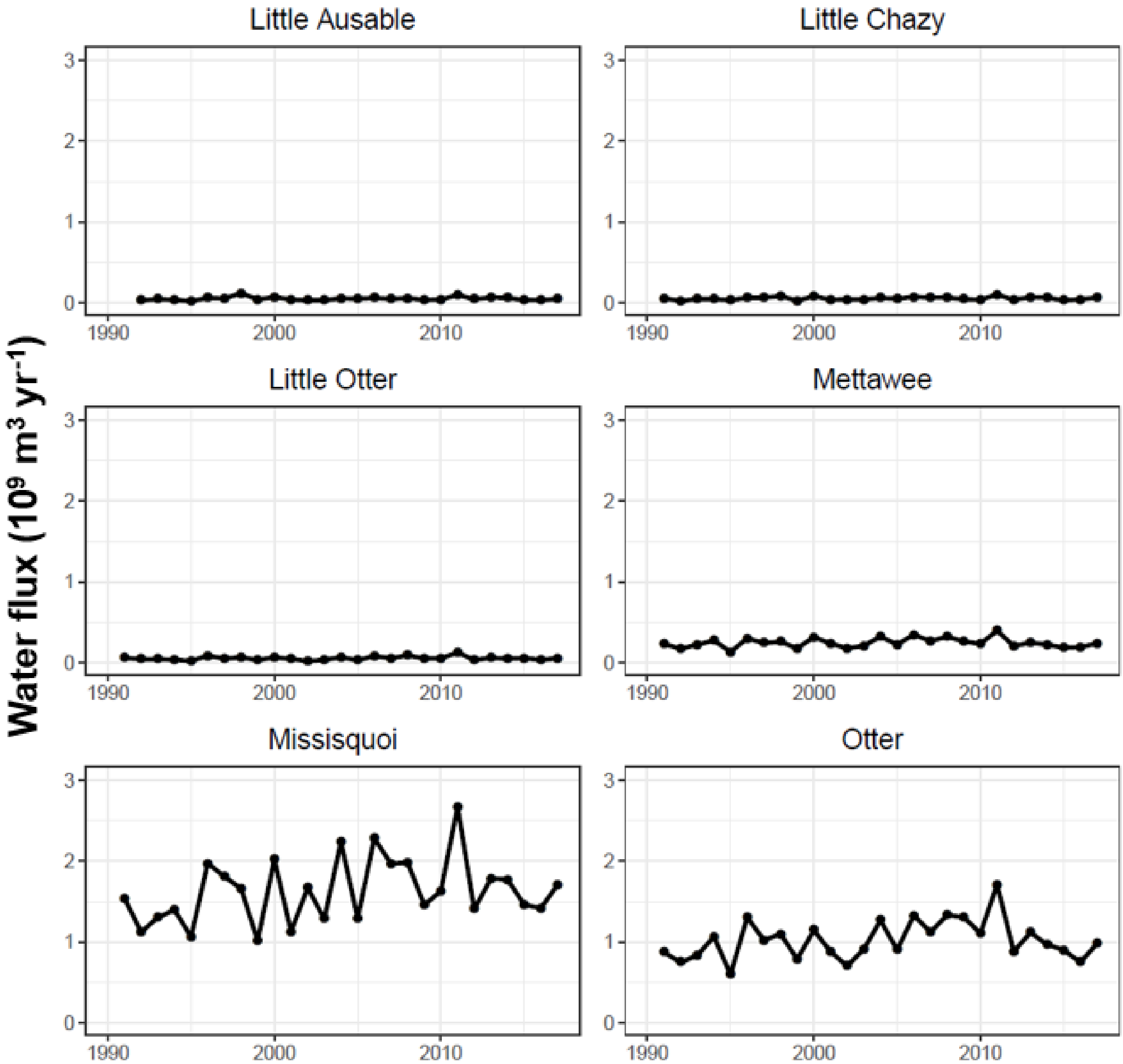
Table 12. Trend probabilities and magnitudes for **flow-normalized total suspended solids load** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for ([a]) Putnam Creek end as late as 2013. Significant trends (probability ≥ 0.90) are outlined and shown in **bold**.

	First half (1993 to 2004)				Full record (1993 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change	Direction	Probability of trend	Change (10^3 kg yr^{-1})	Annualized percent change
Ausable	No trend	0.70	3461	1.7	No trend	0.79	479	0.1	No trend	0.67	-2982	-1.2
Boquet	No trend	0.72	1399	1.0	No trend	0.52	-1191	-0.4	No trend	0.70	-2591	-1.5
Great Chazy	No trend	0.60	-671	-0.9	No trend	0.60	-652	-0.4	No trend	0.65	19	0.0
Lamoille	No trend	0.52	349	0.1	**Decrease**	**0.91**	-6543	-1.1	No trend	0.84	-6892	-2.1
LaPlatte	No trend	0.82	581	2.3	**Increase**	**0.94**	1213	2.0	No trend	0.87	632	1.7
Lewis	**Increase**	**0.99**	3537	6.3	**Increase**	**0.97**	6709	4.4	No trend	0.89	3172	2.8
Little Ausable	No trend	0.64	60	0.7	No trend	0.79	-137	-0.9	**Decrease**	**0.97**	-197	-2.3
Little Chazy	No trend	0.55	19	0.3	No trend	0.89	-111	-1.0	**Decrease**	**0.97**	-130	-2.1
Little Otter	No trend	0.89	578	2.8	**Increase**	**0.99**	3370	4.7	**Increase**	**0.97**	2792	6.4
Mettawee	No trend	0.72	-3020	-1.8	No trend	0.65	-2420	-0.7	No trend	0.62	600	0.3
Missisquoi	No trend	0.60	2808	0.3	**Increase**	**0.92**	37110	1.5	No trend	0.89	34303	2.5
Otter	**Increase**	**0.92**	14117	3.5	No trend	0.87	28442	2.8	No trend	0.65	14325	2.2
Pike	**Increase**	**0.99**	11392	6.6	**Increase**	**0.97**	15211	3.7	No trend	0.60	3820	1.2
Poultney	No trend	0.75	3360	1.6	No trend	0.78	18556	3.0	No trend	0.87	15196	4.2
Putnam[a]	No trend	0.70	-485	-3.8	No trend	0.60	-348	-1.4	No trend	0.84	137	1.6
Salmon	No trend	0.55	-17	-0.2	No trend	0.74	-115	-0.6	No trend	0.77	-98	-0.9
Saranac	No trend	0.65	-348	-0.6	No trend	0.62	-526	-0.4	No trend	0.55	-178	-0.3
Winooski	No trend	0.79	-25022	-1.7	No trend	0.90	36760	0.9	**Increase**	**0.96**	61782	3.2

Water

Annual water fluxes for Lake Champlain tributaries were closely related to contributing watershed area (Table *1*, Figure *22*). The highest observed water flux was from the Winooski River in 2011, when 3.0 billion cubic meters of water were delivered to the Lake. There were no trends in water flux for the full record or for the first half record for any tributary. For the second half of record, the Boquet, Mettawee, Otter, Poultney Rivers and Putnam Creek showed significant decreases in annual water flux (Table 13). Plotting mean annual water yield vs. contributing watershed area shows that tributaries with larger watersheds generally had greater runoff per land area (Figure 24).




Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
Water flux (10⁹ m³ yr⁻¹)
0
1
2
3
1990
2000
2010

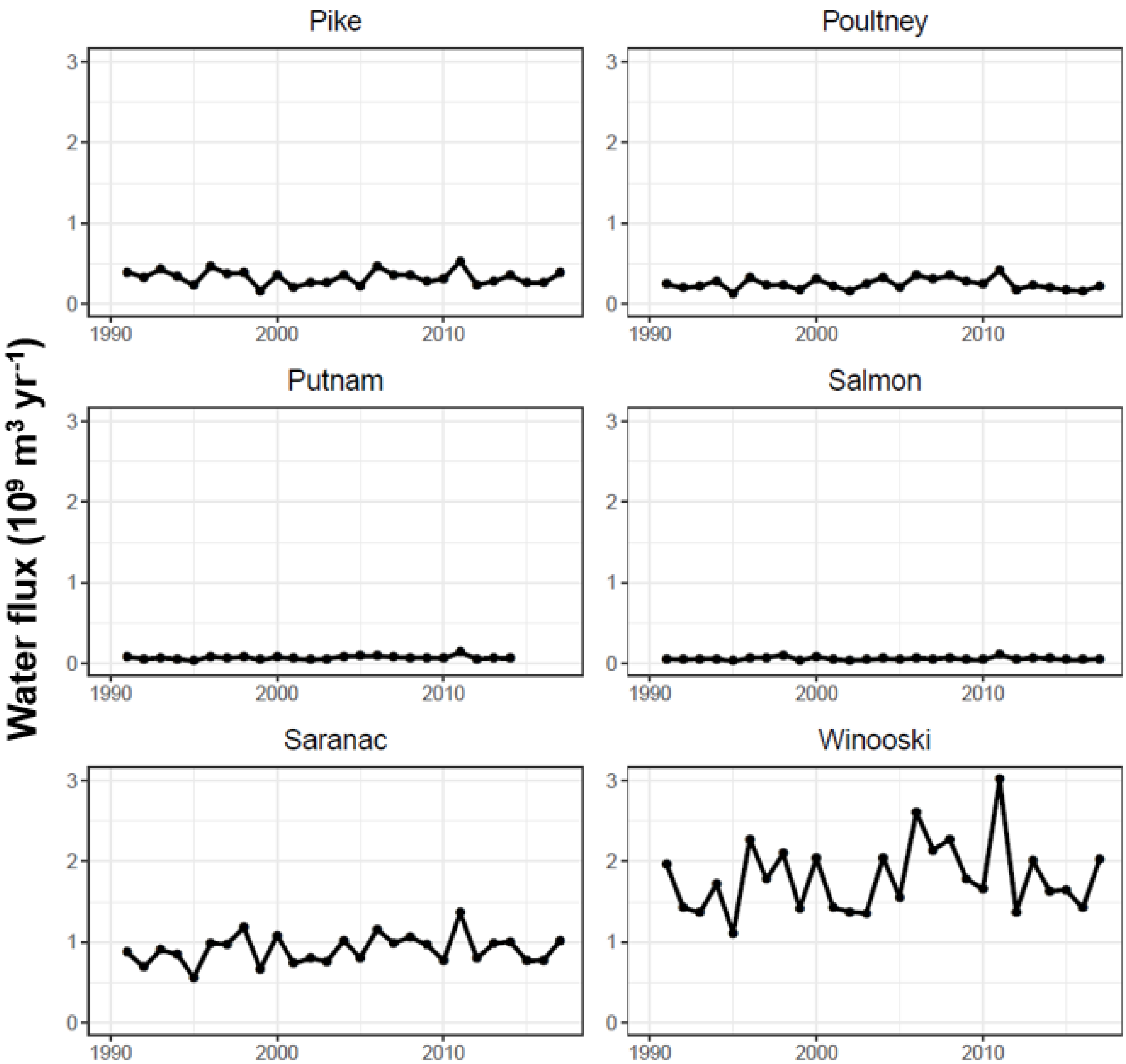
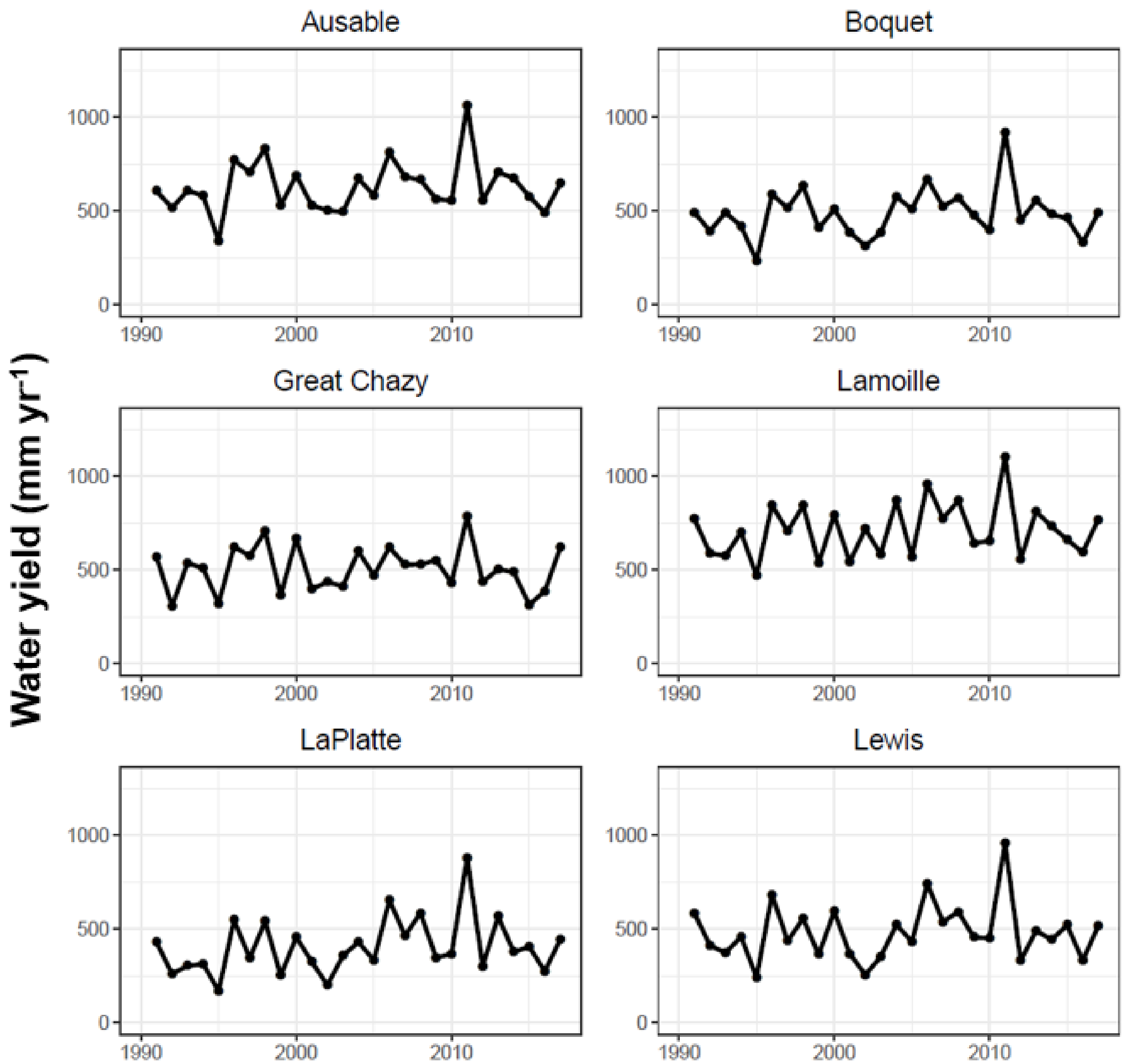
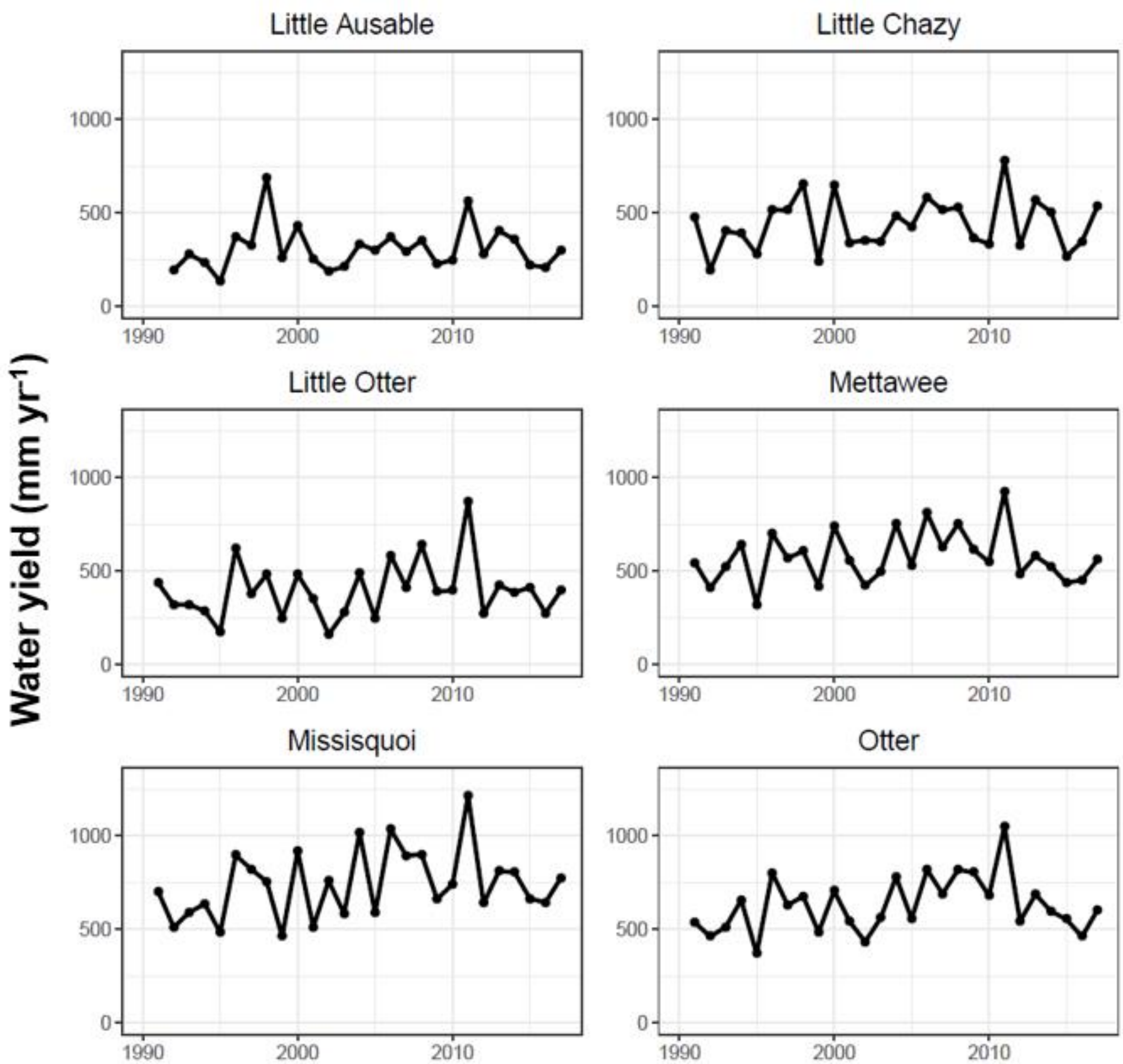


Figure 22. Estimated annual water flux for eighteen Lake Champlain tributaries.


Ausable
Boquet
Great Chazy
Lamoille
LaPlatte
Lewis
Water yield (mm yr-1)
1000
500
0
1990
2000
2010


Little Ausable
Little Chazy
Little Otter
Mettawee
Missisquoi
Otter
Water yield (mm yr^{-1})
0
500
1000
1990
2000
2010

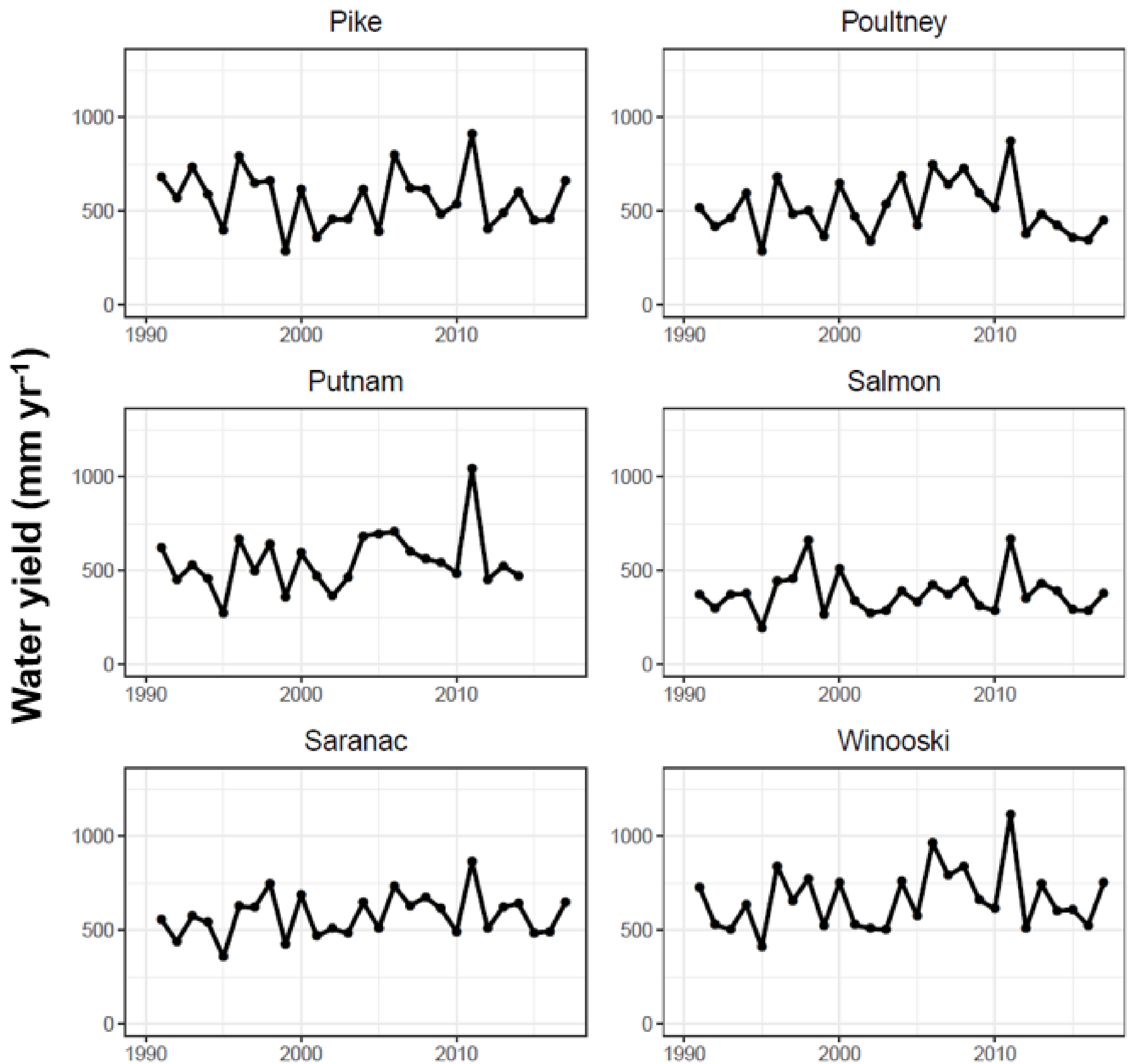


Figure 23. Estimated annual water yield for eighteen Lake Champlain tributaries.

Table 13. Results of Mann-Kendall tests and Sens slope estimator calculations for **annual water flux** over three trend periods for eighteen Lake Champlain tributaries. Note that trend periods for ([a]) Putnam Creek end as late as 2014, and trend periods for ([*]) Little Ausable River begin as early as 1992. Significant trends ($p \leq 0.10$) are outlined and shown in **bold**.

	First half (1991 to 2004)				Full record (1991 - 2017)				Second half (2004 to 2017)			
Tributary	Direction	p value	Sen slope (10^6 m^3 yr^{-1})	Ratio of Sens slope to mean value (%)	Direction	p value	Sen slope (10^6 m^3 yr^{-1})	Ratio of Sens slope to mean value (%)	Direction	p value	Sen slope (10^6 m^3 yr^{-1})	Ratio of Sens slope to mean value (%)
Ausable	No trend	0.66	-5.8	-0.8	No trend	0.90	1.1	0.2	No trend	0.27	-9.8	-1.3
Boquet	No trend	0.83	-1.0	-0.3	No trend	0.77	0.9	0.3	**Decrease**	**0.08**	-7.3	-2.0
Great Chazy	No trend	0.58	4.5	1.4	No trend	0.93	-0.2	0.0	No trend	0.23	-7.0	-2.1
Lamoille	No trend	0.58	6.1	0.5	No trend	0.40	5.3	0.4	No trend	0.38	-19.0	-1.4
LaPlatte	No trend	0.66	0.4	0.9	No trend	0.12	0.5	1.1	No trend	0.58	-0.6	-1.1
Lewis	No trend	0.44	-1.1	-1.2	No trend	0.80	0.3	0.3	No trend	0.32	-1.6	-1.5
Little Ausable*	No trend	0.76	0.6	1.1	No trend	0.66	0.3	0.5	No trend	0.32	-1.0	-1.9
Little Chazy	No trend	0.74	0.9	1.7	No trend	0.59	0.3	0.5	No trend	0.51	-1.0	-1.6
Little Otter	No trend	1.00	-0.2	-0.3	No trend	0.50	0.4	0.7	No trend	0.44	-0.9	-1.4
Mettawee	No trend	0.38	3.4	1.4	No trend	0.68	0.5	0.2	**Decrease**	**0.03**	-9.3	-3.5
Missisquoi	No trend	0.32	33.7	2.2	No trend	0.16	13.6	0.8	No trend	0.27	-34.7	-1.9
Otter	No trend	0.38	14.6	1.5	No trend	0.20	5.9	0.6	**Decrease**	**0.08**	-31.8	-2.8
Pike	No trend	0.23	-6.8	-2.1	No trend	0.50	-1.8	-0.5	No trend	0.58	-3.1	-0.9
Poultney	No trend	0.51	3.3	1.4	No trend	0.80	-0.5	-0.2	**Decrease**	**0.02**	-13.1	-5.0
Putnam[a]	No trend	0.91	0.1	0.1	No trend	0.47	0.3	0.4	**Decrease**	**0.03**	-3.5	-4.2
Salmon	No trend	0.74	0.3	0.4	No trend	1.00	0.0	0.0	No trend	0.44	-0.7	-1.1
Saranac	No trend	0.58	10.9	1.3	No trend	0.26	4.6	0.5	No trend	0.38	-6.0	-0.6
Winooski	No trend	0.83	-1.7	-0.1	No trend	0.50	7.7	0.4	No trend	0.23	-36.2	-1.9

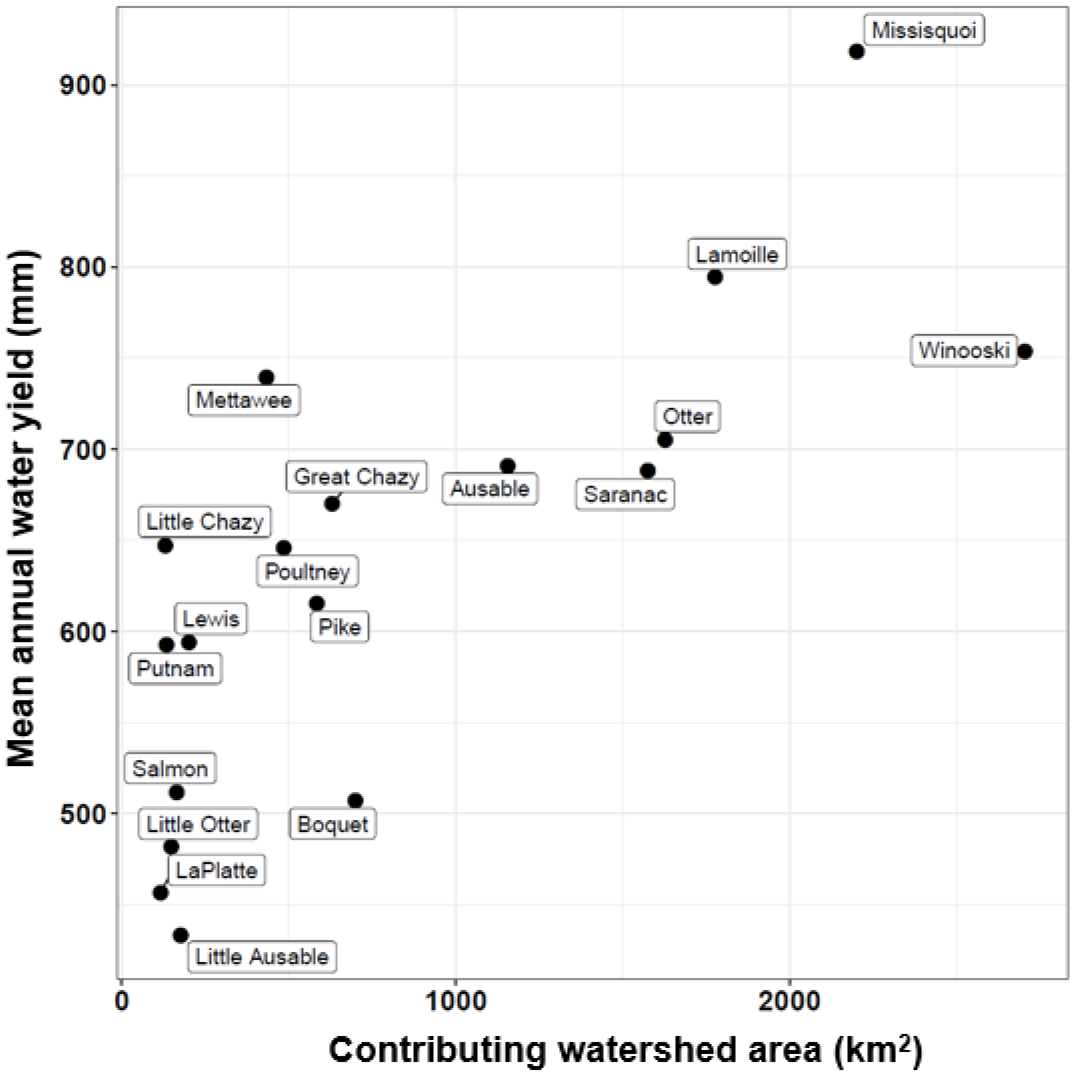


Figure 24. Plot of the mean annual water yield for all years considered in this report versus the contributing watershed area for 18 Lake Champlain tributaries.

Conclusion

Determining tributary concentrations and loads for key water quality parameters will continue to be important as Lake Champlain managers and stakeholders face water quality challenges and work toward shared goals. This report represents observed conditions and trends over the period of record; they do not necessarily represent a trajectory into the future. As in the past, the future delivery of water, nutrients, chloride, and sediment to Lake Champlain will depend on several factors, including climate conditions, pollution reduction practice implementation, management decisions, river geomorphic function, and changes in watershed land use and land cover.

The results of this report demonstrate the tremendous value of the Lake Champlain Long-term Monitoring Program in determining the state of the Lake Champlain ecosystem and changes in this system over time. The Lake Champlain Basin Program plans to continue its support for this monitoring in partnership with New York and Vermont Departments of Environmental Conservation and the New England Interstate Water Pollution Control Commission.

Acknowledgements
This work greatly benefited from conversations with Laura Medalie (USGS), Jennifer Murphy (USGS), Jamie Shanley (USGS), and the Lake Champlain Basin Program team.

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