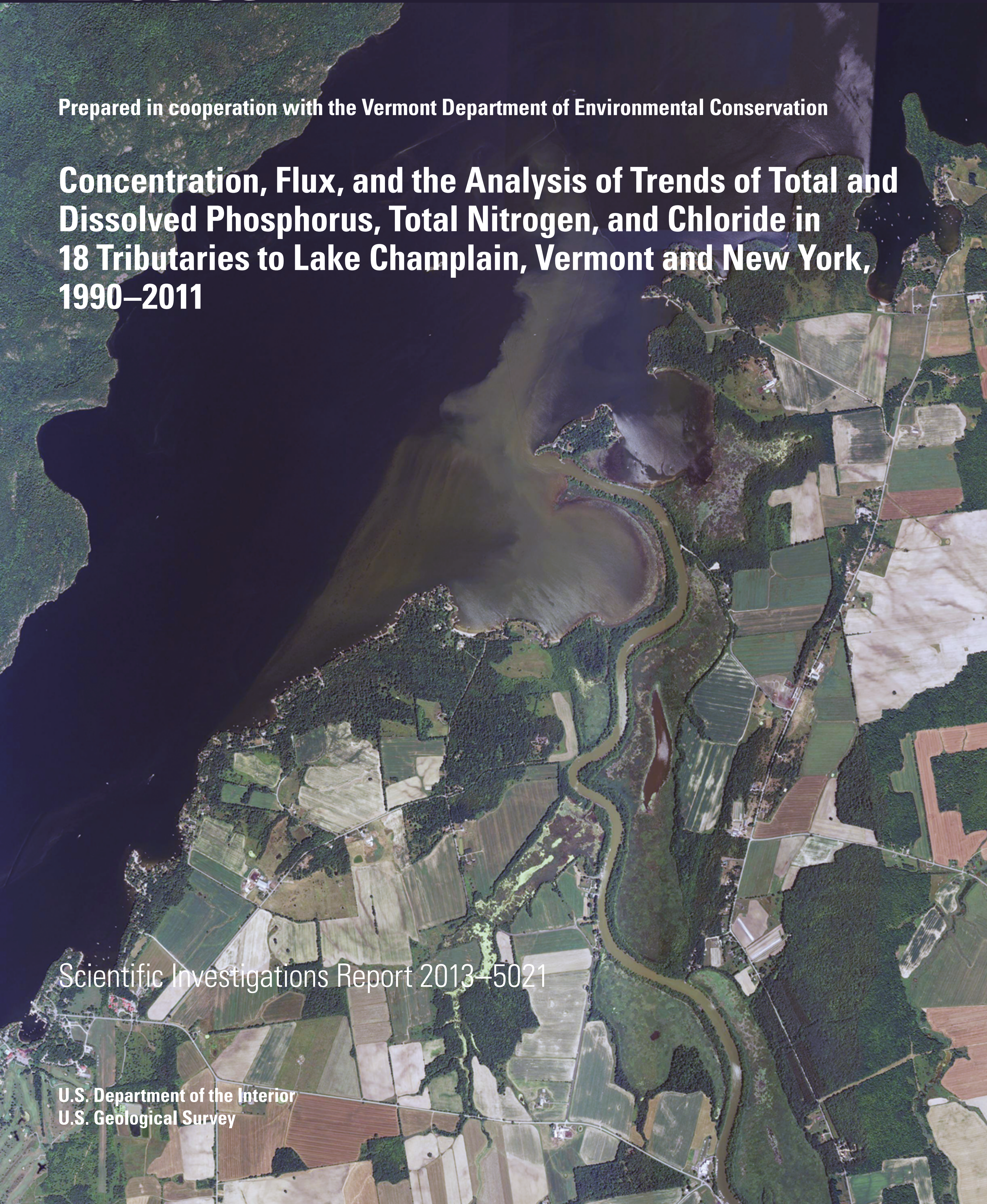

Prepared in cooperation with the Vermont Department of Environmental Conservation

Concentration, Flux, and the Analysis of Trends of Total and Dissolved Phosphorus, Total Nitrogen, and Chloride in 18 Tributaries to Lake Champlain, Vermont and New York, 1990–2011

Scientific Investigations Report 2013–5021

U.S. Department of the Interior
U.S. Geological Survey

Cover. Aerial photograph of Otter Creek outlet into Lake Champlain, western Vermont. Photograph by the U.S. Department of Agriculture, Farm Service Agency.

Concentration, Flux, and the Analysis of Trends of Total and Dissolved Phosphorus, Total Nitrogen, and Chloride in 18 Tributaries to Lake Champlain, Vermont and New York, 1990–2011

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

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Contents

Figures

Tables

Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
short ton per day per square mile [(ton/d)/mi^2]	0.3503	megagram per day per square kilometer [(Mg/d)/km^2]
short ton per year (ton/yr)	0.9072	metric ton per year

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

BMP	best-management practice
CSUB	county/subbasin area
HUC	hydrologic unit code
LTMP	long-term water quality and biological monitoring project
t	metric tons
NYSDEC	New York State Department of Environmental Conservation
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VTDEC	Vermont Department of Environmental Conservation
WRTDS	weighted regression on time, discharge, and season

Concentration, Flux, and the Analysis of Trends of Total and Dissolved Phosphorus, Total Nitrogen, and Chloride in 18 Tributaries to Lake Champlain, Vermont and New York, 1990–2011

By Laura Medalie

Abstract

Annual concentration, flux, and yield for total phosphorus, dissolved phosphorus, total nitrogen, and chloride for 18 tributaries to Lake Champlain were estimated for 1990 through 2011 using a weighted regression method based on time, tributary streamflows (discharges), and seasonal factors. The weighted regression method generated two series of daily estimates of flux and concentration during the period of record: one based on observed discharges and a second based on a flow-normalization procedure that removes random variation due to year-to-year climate-driven effects. The flow-normalized estimate for a given date is similar to an average estimate of concentration or flux that would be made if all of the observed discharges for that date were equally likely to have occurred. The flux bias statistic showed that 68 of the 72 flux regression models were minimally biased. Temporal trends in the concentrations and fluxes were determined by calculating percent changes in flow-normalized annual fluxes for the full period of analysis (1990 through 2010) and for the decades 1990–2000 and 2000–2010.

Basinwide, flow-normalized total phosphorus flux decreased by 42 metric tons per year (t/yr) between 1990 and 2010. This net result reflects a basinwide decrease in flux of 21 metric tons (t) between 1990 and 2000, followed by a decrease of 20 t between 2000 and 2010; both results were largely influenced by flux patterns in the large tributaries on the eastern side of the basin. A comparison of results for total phosphorus for the two separate decades of analysis found that more tributaries had decreasing concentrations and flux rates in the second decade than the first.

An overall reduction in dissolved phosphorus flux of 0.7 t/yr was seen in the Lake Champlain Basin during the full period of analysis. That very small net change in flux reflects substantial reductions between 1990 and 2000 from eastern tributaries, especially in Otter Creek and the LaPlatte and Winooski Rivers that largely were offset by increases in the Missisquoi and Saranac Rivers in the second decade (between 2000 and 2010). The number of tributaries that had increases in dissolved phosphorus concentrations stayed constant at 13 or 14 during the period of analysis.

Total nitrogen concentration and flux for most of the monitored tributaries in the Lake Champlain Basin have decreased since 1990. Between 1990 and 2010, flow-normalized total nitrogen flux decreased by 386 t/yr, which reflects an increase of 440 t/yr between 1990 and 2000 and a decrease of 826 t/yr between 2000 and 2010. All individual tributaries except the Winooski River had decreases in total nitrogen concentration and flux between 2000 and 2010. The decrease in total nitrogen flux over the period of record could be related to the decrease in nitrogen from atmospheric deposition observed in Vermont or to concurrent benefits realized from the implementation of agricultural best-management practices in the Lake Champlain Basin that were designed primarily to reduce phosphorus runoff.

For chloride, large increases in flow-normalized concentrations and flux between 1990 and 2000 for 17 of the 18 tributaries diminished to small increases or decreases between 2000 and 2010. Between 1990 and 2010, flow-normalized flux increased by 32,225 t/yr, 78 percent of which (25,163 t) was realized during the first decade, from 1990 through 2000. The five tributaries that had decreasing concentration and flux of chloride between 2000 and 2010 were all on the eastern side of Lake Champlain, possibly related to reductions since 1999 in winter road salt application in Vermont.

Positive correlations of phosphorus flux and changes in phosphorus concentration and flux in tributaries with phosphorus inputs to basins from point sources, suggest that point sources have an effect on stream phosphorus chemistry. Several measures of changes in agricultural statistics, such as agricultural land use, acres of land in farms, acres of cropland, and acres of corn for grain or seed, are positively correlated with changes in phosphorus concentration or flux in the tributaries. Negative correlations of the amount of money spent on agricultural best-management practices with changes in phosphorus concentration or flux in the tributaries, suggest that best-management practices may be an effective

tool, along with point-source reductions, in making progress towards management goals for phosphorus reductions in Lake Champlain.

Introduction

High concentrations of phosphorus from tributary inputs and the ensuing eutrophication in Lake Champlain are identified in the 2010 Lake Champlain management plan (Lake Champlain Steering Committee, 2010) as a serious environmental problem. The plan specifies that reducing phosphorus inputs to Lake Champlain is one of eight highest priority goals needed to meet the vision for the lake, and one that has been specified in every version of that plan since it was first published in 1996. Nine out of 13 segments of Lake Champlain were included on the 2000 Vermont list of impaired waters submitted to the U.S. Environmental Protection Agency under section 303(d) of the Clean Water Act due to phosphorus pollution (Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 2002). In 1992, the Lake Champlain long-term water-quality and biological monitoring project (LTMP) formalized an ongoing plan of data collection in 18 tributaries to the lake and at 15 lake stations (Lake Champlain Management Conference, 1996) to supplement collection of continuous records of streamflow on the 18 tributaries at streamgages operated by the U.S. Geological Survey (USGS).

The LTMP collects water samples in tributaries that are analyzed for 23 chemical constituents and field parameters (Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 2012). Although monitoring for total phosphorus was the principal effort and concern, the samples also were analyzed for constituents that were judged by the Lake Champlain Basin Program Technical Advisory Committee to be the most meaningful for assessing the long-term effects of management actions and other changes in the environment.

Earlier investigators have analyzed trends for various subsets of the water-quality data: total phosphorus concentrations in the lake and concentrations and fluxes in tributaries during 1990–2000 (Medalie and Smeltzer, 2004); total phosphorus concentrations in the lake and loading from tributaries during 1990–2008 (Smeltzer and others, 2009); 11 physical, chemical, and biological properties in the lake generally during 1990–2009 (Smeltzer and others, 2012); and total phosphorus and total nitrogen concentrations and fluxes in the tributaries during 1990–2009 (Medalie and others, 2012).

Except for the last study mentioned in the preceding paragraph, estimates of fluxes and trends in water-quality data from tributaries have relied on regression-based statistical models like ESTIMATOR (Cohn, 2005) or Load Estimator (LOADEST; Runkel and others, 2004) that estimate constituent concentrations or flux on the basis of factors that may include discharge, time, season, or the squares of these terms. Concentrations or flux estimated using these models, which have been utilized for many years, may have been adjusted to remove the random effects of discharge ("flow-adjusted concentrations"). In 2010, the USGS developed a new method (WRTDS—Weighted Regressions on Time, Discharge, and Season) for estimating constituent concentrations and fluxes and for detecting trends in long-term water-quality datasets (Hirsch and others, 2010). WRTDS was designed to overcome shortcomings of traditional methods of regression analysis related to inflexible model constraints and to increase the amount of information that can be derived from long-term datasets. A recent publication that compared results from WRTDS with those from ESTIMATOR found that WRTDS provides estimates of concentration and flux that are more accurate and less biased than does ESTIMATOR; WRTDS also has an enhanced ability to determine changes in flux over time as a result of human activities in the basin (Moyer and others, 2012).

To address the need to evaluate environmental water-quality changes with a flexible, state-of-the-art regression model, the USGS, in cooperation with the Vermont Department of Environmental Conservation, applied the WRTDS method to 21 years of streamflow and concentration data for total phosphorus, dissolved phosphorus, total nitrogen, and chloride in water samples collected from 18 tributaries to Lake Champlain. One purpose of this study was to provide annual estimates of concentrations and flux of total phosphorus, dissolved phosphorus, total nitrogen, and chloride for the Lake Champlain tributaries for calendar years 1990 through 2011. This was accomplished by aggregating daily estimates of concentrations and flux for dissolved phosphorus and chloride and by updating estimated concentrations and flux of total phosphorus and total nitrogen previously published in Medalie and others (2012). A second purpose was to statistically relate basin characteristics to total phosphorus concentrations, flux, and trends.

This report provides analysis of 2 more years of data than did a previous investigation of concentrations and flux of total phosphorus and total nitrogen (Medalie and others, 2012); includes statistical analysis for two new parameters (concentrations and flux of dissolved phosphorus and chloride); provides new interpretations regarding model bias and seasonal effects on concentrations and flux of total phosphorus; and describes results of tests of correlation between estimated annual phosphorus concentration, flux, and changes in concentration or flux during several time periods with a set of selected basin characteristics to determine whether any of those characteristics could be statistically related to the phosphorus data. Trends are presented as net changes in concentration and flux between 1990 and 2000 (decade I), between 2000 and 2010 (decade II), and between 1990 and 2010 (the full period of analysis). Note that the "period of analysis" from 1990 through 2010, selected for even decadal time intervals, differs slightly from the "period of record" (of available data) from 1990 to 2011. The first year for analyzing and reporting results of concentrations for total nitrogen was 1992. Categories of basin characteristics that were examined include physical and demographic properties, point sources of phosphorus, land use, and best-management practices (BMPs). The streamflow and surface-water quality of about 74 percent of the area of the Lake Champlain Basin is monitored by the data collected at 18 streamgages and water-quality sampling stations (fig. 1). Use of the term “basinwide” in the report refers to the 74 percent of the total drainage area that is monitored.

Study Methods

Original data that may have been reported and (or) were stored in various formats and units in many cases required modifications in order to be useful for exploring water-quality trends at two subbasin scales within the Lake Champlain Basin. As described below, some digital geodatasets were combined or overlain and intersected using ArcMap software.

Assembling and Modifying Data

Water-quality data were collected, analyzed, and posted online by the Vermont Department of Environmental Conservation (VTDEC) as part of the Lake Champlain Long-Term Water Quality and Biological Monitoring Project (Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 2012). The number of samples collected at each monitoring station ranged from approximately 14 to 19 samples per year that were analyzed for total phosphorus and from 5 to 16 samples per year that were analyzed for the other constituents. Streamflow at the 18 Lake Champlain tributary stations has been gaged continuously by the USGS, in cooperation with the VTDEC and the New York State Department of Environmental Conservation (NYSDEC), and is part of the National Water Information System network. Streamflow records at 10 of the streamgages, where data collection began on March 1, 1990, were extended 2 months back in time, and the record at one additional station was extended back 21 months, as previously described in Medalie and others (2012), to complete the 1990 calendar year record.

Data on basin characteristics were assembled from many different sources (table 1). Spatial data on populations by census block from the U.S. Census Bureau were intersected with subbasin boundaries in ArcMap to reformulate as populations by subbasins. A 2011 consultant’s report (Stone Environmental, Inc., 2011) indicated that hydrologic soil group, in particular group C and D soils (Natural Resources Conservation Service, 2007), was one of the top three factors driving the magnitude of phosphorus export (in both total and dissolved species) and the incidence of critical source areas. A general hypothesis, of whether the relation of the percent of agricultural land in the subbasin to phosphorus flux could be strengthened by combining it with hydric soils (saturated with water), was formulated from that report. This hypothesis was tested in a gross manner across the Lake Champlain Basin by creating a spatial layer from an overlay of the two types of information (land use is equal to agricultural and soil hydrologic group equal to C or D).

Statistical data that profile agricultural activities across the United States are reported at the county level by the U.S. Department of Agriculture (USDA) census of agriculture. The transformation of county-level census data to a dataset applicable to subbasins involved first a disaggregation of county data into pixels of agricultural land use and then an aggregation of pixels into subbasin areas. For the first step of disaggregation, a polygon spatial layer of all unique county/subbasin (CSUB) areas was created by overlaying the county spatial layer with the gaged subbasin spatial layer. A spreadsheet was then created that listed the number of pixels of agricultural land from the 1992 and 2001 land-use datasets in each CSUB area. The ratio of agricultural land in the CSUB area to agricultural land in the county was multiplied by the county census statistic. The agricultural statistics data, transformed to a CSUB basis, were aggregated up to subbasin areas by adding all values for the CSUB areas that belonged to each particular subbasin.

Spreadsheets with data on agricultural best-management practices (BMPs) were obtained from the New York State Department of Agriculture and Markets and the Vermont Agency of Agriculture. Both states provided itemized lists of BMPs that included information about BMP type, implementation date, total cost, and subbasin location. Although different types and scales of BMPs would have different effects on the amount of phosphorus in runoff, substantiated information to quantify these effects is not available. Many other factors, including but not limited to proximity to streams, slope, and soil type, also contribute to BMP performance. Thus, associations between phosphorus trends and BMPs are provided for just two unambiguous measures of BMPs: the number implemented and the money spent on implementation (not including upkeep). Subbasin locations from the state agency data were provided at the HUC11[1] scale for New York State and the HUC14 scale for Vermont, and where possible, the data were reassigned to the HUC8 and HUC12 scales used in this report. BMP datasets were grouped by implementation date into two periods for correlation analysis—the entire period of available data (from 1995 through 2010) and the years before 2000—to test whether there might be a delayed or lag effect between BMP implementation and water-quality response in the streams.

[1]The USGS developed a system of nested hydrologic unit codes (HUCs) to organize hydrologic data across the United States into successively smaller basins, called “hydrologic units.” The designation HUC8, for example, means the 8-digit code used for hydrologic units at the subbasin level. As the HUC number increases, the size of the basin decreases. For example, HUC8 scale basins are larger than HUC12 scale basins.

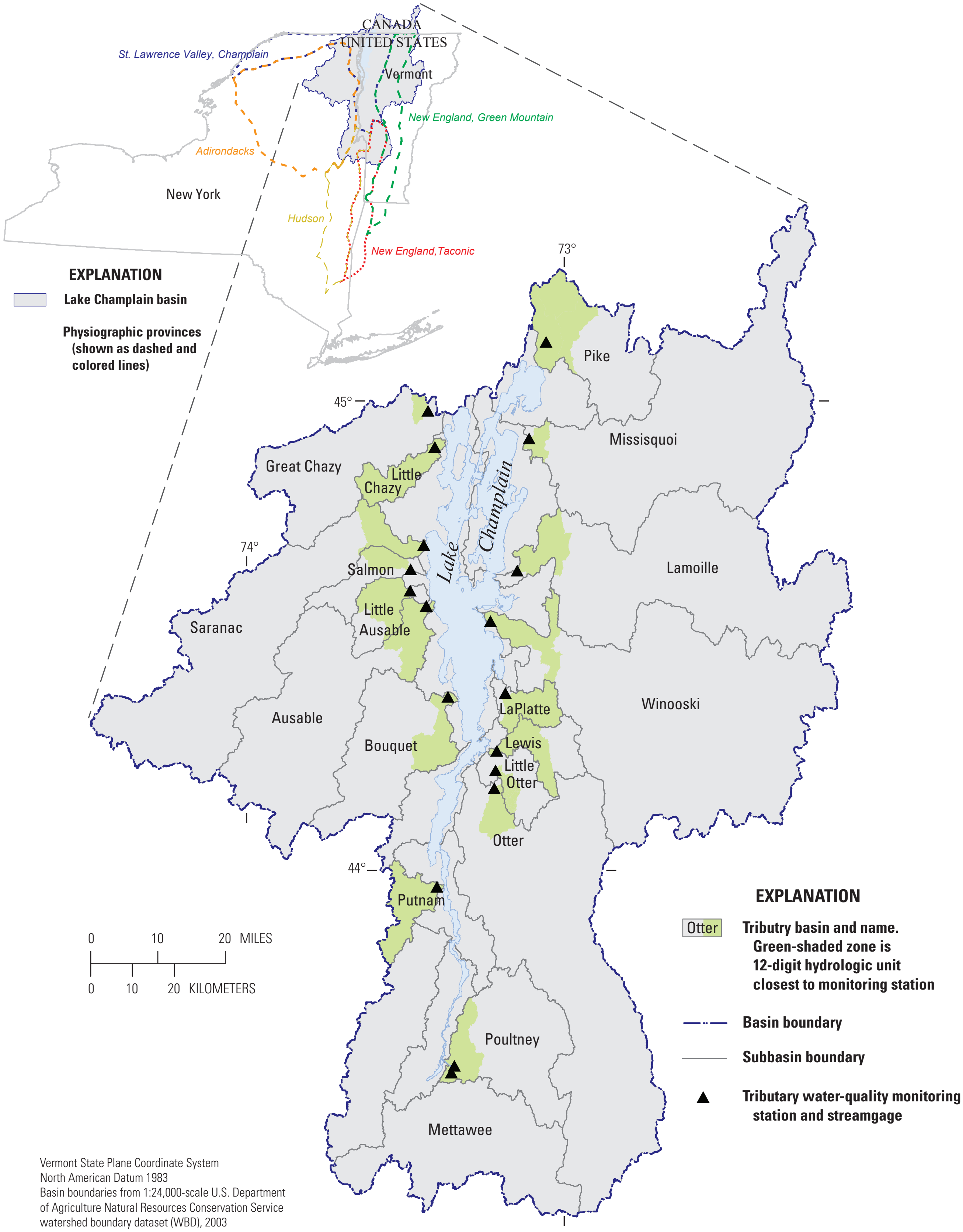

Figure 1. Lake Champlain Basin, physiographic provinces (inset), water-quality monitoring stations, tributary boundaries, and parts of tributaries that include only the 12-digit hydrologic unit closest to the monitoring station.

Table 1. Sources of data for basin characteristics that were tested for correlation with concentration and flux of total phosphorus for tributaries to Lake Champlain.

[km^2, square kilometers]

Basin characteristic	Source of data and citation for basin characteristic
Physical and demographic	
Physiographic province	Fenneman and Johnson, 1946
Population density, people per km^2	U.S. Census Bureau (2001; Jen McCormick, written commun., June 11, 2012); Vermont Center for Geographic Information, 2012
Change in population density, people per km^2	
Point sources	
Phosphorus flux from point sources	Vermont Department of Environmental Conservation (Eric Smeltzer, written commun., June 7, 2012)
Percent change in phosphorus flux from point sources	
Land use	
Percent or percent change in:	
Urban land use including open land	University of Vermont Spatial Analysis Laboratory, 2007
Agricultural land use	
Agricultural land in basin that intersects hydric soils (type C or D)	University of Vermont Spatial Analysis Laboratory, 2007 and soils data (Natural Resources Conservation Service, variously dated)
Acres of land in farms	U.S. Department of Agriculture Census of Agriculture, 1987; 1992 and 1997 (U.S. Department of Agriculture, 1999); 2002 and 2007 (U.S. Department of Agriculture, 2009)
Acres of cropland	
Acres of corn for grain or seed	
Acres of corn for silage	
Acres of commercial fertilized	
Number of milk cows	
Best-management practices	
Number of agricultural best-management practices implemented	Vermont Agency of Agriculture (Jeffrey Cook, written commun., October 29, 2010) and New York State Department of Agriculture and Markets (Bob Brower, written commun., August 2, 2011)
Money spent on agricultural best-management practices, dollars	

Estimating Annual Average Concentration, Annual Flux, and Trends

The WRTDS method was used to estimate annual average concentrations of constituents and their annual flux (movement on a mass basis) and to determine trends in those factors (Hirsch and others, 2010). The method was developed by USGS to improve upon previous regression-based methods of estimating concentration and flux from a set of water-quality observations and continuous streamflow records for datasets that span at least 20 years. WRTDS has been applied to datasets from the Chesapeake Bay (Hirsch and others, 2010; Moyer and others, 2012), the Mississippi River Basin (Sprague and others, 2011), and the Lake Champlain Basin for data through 2009 (Medalie and others, 2012).

The WRTDS weighted regression model provides daily estimates of constituent concentration and flux in two ways (Hirsch and others, 2010). First, the software creates a 3-dimensional matrix (with dimensions of time in years, time in months, and equal log-space increments of discharge) of weighted regression results that cover the time and stream discharge continuum of the dataset and then applies bilinear interpolation between matrix results to estimate concentration for every day in the entire period based on the given time and observed discharge. At each estimation point in the matrix, weights are assigned to every combination of observed concentration and discharge based on distance (in terms of time, season, and discharge) to the time and discharge at the estimation point. The idea is that observations close in time and with similar discharges to the estimation point will be weighted heavily, and observations that are very different in either time or discharge will have little or zero weight. The daily estimate of flux is calculated by multiplying the estimated concentration by the observed discharge (times a unit conversion factor). Estimates produced in this way (based on the observed daily discharge) are estimates of actual concentration or flux that occurred on a given day.

The second method of estimating concentrations calculates, for every day in the record, the mean of 20 (this number represents the number of years of record; this example is for a 20-year record) interpolated estimates of concentration. The 20 estimates for a specified date, for example July 1, 2001, are made with the 20 different observed discharges for that date (July 1) and the given date as the time variable (July 1, 2001). The rationale is that any of those 20 July 1st discharges are equally likely to have occurred during the years of record. The mean of the 20 results provides the "flow-normalized" estimate of concentration for that day. The estimate of flow-normalized flux for each day is the mean of the 20 estimates of flux generated by multiplying the 20 interpolated estimates of concentration times discharge. Flow normalizing provides estimates of concentration and flux that remove natural climate-related variability. Because it offers a depiction of water-quality conditions that is not obstructed by random noise, flow-normalized estimates can be used as a tool to evaluate progress and effectiveness (or lack thereof) of basin restoration activities. Daily estimates of concentration are averaged during a month or year to provide monthly or annual estimates, and daily estimates of flux are aggregated to form monthly or annual estimates.

Trend results from WRTDS are presented in terms of percent change for a user-defined period of time rather than a hypothesis test for significance. While many traditional multiple linear regression approaches (ESTIMATOR, LOADEST, FLUX (Walker, 1996)) allow for the determination of a trend and associated statistical significance, the ability of those trends to fully describe water-quality changes over time is limited because the forms are fixed and the trend models are monotonic. The weighting scheme used by WRTDS results in a flexible model that maximizes relevancy of information. For example, in traditional approaches, concentrations are predicted on the basis of solutions to equations that assign equal weights to all streamflow observations in the prediction window; in WRTDS, the models to predict concentrations are constructed using unequal weights of discharge, with greater weights assigned to discharge values closer in time (in years), discharge, and season to values to be estimated. Flexibility afforded by the weighted regression approach of WRTDS models the full range of observed discharges, which is not possible with traditional linear or log-linear regression models. In addition, the inability of traditional approaches to decouple concentration from flux trend (Moyer and others, 2012) artificially constrains those models. The WRTDS model was designed specifically to overcome these and other limitations.

A limitation of the WRTDS model was identified for two of the tributaries (Little Ausable and Poultney Rivers) where the sampled dataset did not include samples collected at the extremely high discharges that occurred during the period of record. Because concentrations at very high flows typically are among the highest in the water-quality record and can inordinately influence annual estimates, model results based on extrapolations far above the sampled range of discharge cannot be substantiated and therefore should not be used. For the Little Ausable and Poultney Rivers, estimated concentrations and fluxes were calculated using only the mean (concentration) or sum (flux) of daily values where the daily discharge was less than some designated value (near the highest discharge that was sampled: 530 cubic feet per second (ft^3/s) for the Little Ausable River and 2,470 ft^3/s for the Poultney River). Days with discharges above this designated value simply were omitted from the annual calculations for concentration and flux. Because high discharges were targeted for the collection of samples, the number of days with discharge that exceeds the designated discharge is very small (0.6 percent for the Little Ausable River and 0.3 percent for the Poultney River), and these exceeded discharges correspond to total flow volumes of about 10 percent for the Little Ausable River and 4 percent for the Poultney River of the total discharge over the period of record. For the Little Ausable and Poultney Rivers, annual estimates of concentration and flux for years with at least one daily discharge above the designated value are represented as "greater than" the value listed in appendix 1. This adjustment only affects the estimates of actual concentration, flux, or yield; since the flow-normalized estimates are based on discharge values integrated over the 21 years of record, a very high discharge in one particular year would have minimal impact on the smoothed estimates. This approach is predicated on the idea that the data do not provide any reliable means for estimating concentrations or fluxes on these extreme high-discharge days. Any attempt to do so would be a substantial extrapolation beyond the data. Thus, the results reported simply describe inferences about water-quality conditions that have taken place below that discharge threshold.

Another tool available as part of WRTDS to enhance model representation of the sample data is the ability to adjust weights of the variables in the regression. Weights are assigned to every combination of observed concentration and discharge based on distance (of time, season, and discharge) to the time and discharge at each estimation point. In WRTDS, weights are a function of the user-assigned half-window width. Although the default half-window widths of 10 years for time, 2 logarithm cycles for discharge, and 0.5 year for season are adequate in most situations, diagnostic tools available as part of the WRTDS software have pointed to some cases in the Lake Champlain dataset where better model representations could be achieved by widening the half-window widths (appendix 2). Half-window widths that are widened result in greater weights for more observations, which has the effect of smoothing results and decreasing the magnitudes of the trends.

Decisions about widening the windows were based on a subjective analysis using various graphical means to determine how much wider they needed to be to produce relatively smooth representations of relations between concentration and discharge (for a given time) or relations between concentration and time (for a given discharge). Thus, results produced by widening the half-window widths are conservative and serve to reduce the possibility of identifying a sizeable upward or downward trend when there is a paucity of data to support the trend.

Determining the Relation Between Trends and Basin Characteristics

Many of these datasets were evaluated in two ways: as applicable to the whole subbasin (HUC8) and as applicable to just that part of the subbasin nearest the monitoring station (HUC12) to determine whether there were better relations for areas within the immediate vicinity of data collection. Basin characteristics were analyzed for correlations with total phosphorus concentrations and flux (appendix 6). The significance level of statistical tests was established as $\alpha = 0.10$. Correlation for most analyses was calculated using jmp software (SAS Institute, Inc., 2010) by use of the nonparametric Kendall's tau correlation coefficient, which was selected for its resistance to outliers (Helsel and Hirsch, 2002). Physiographic province, the only categorical (nonnumeric) independent variable, was evaluated using the nonparametric Kruskal-Wallis test (Helsel and Hirsch, 2002). For this test, each of the 18 major subbasins was assigned to one of three physiographic provinces and sections (appendix 6) in the Appalachian Highlands division: St. Lawrence Valley, Champlain; New England, Taconic; and New England, Green Mountain. For most of the correlation tests, there was no need to normalize flux by land area (by calculating yield) because the datasets consisting of percentages were already normalized.

Calculating Flux Bias

WRTDS model fit is examined for each constituent of interest (dissolved and total phosphorus, total nitrogen, and chloride) for each tributary by plots of observed versus estimated concentration (appendix 4) and flux (appendix 7). Plots include the 1:1 reference lines, which would occur if all observed values were perfectly represented by the modeled, or estimated, values. Table 2 shows the flux bias statistic associated with appendix 7, computed as (mean (predicted flux) – mean (observed flux)) / mean (observed flux). A model that has no bias would have a flux bias statistic of 0. Using total phosphorus in the Great Chazy River as an example, the mean of the predicted fluxes is about 0.7 percent lower than the mean of the observed fluxes. Three of the models for total phosphorus (Saranac, Little Ausable, and Putnam) and one for dissolved phosphorus (Saranac) are moderately biased as indicated by a flux bias statistic of at least 10 percent (±0.1). The remaining 68 WRTDS models have minimal flux bias.

Table 2. Flux bias statistic comparing WRTDS[1] regression model estimates with observed water-quality observations for total phosphorus, dissolved phosphorus, total nitrogen, and chloride for tributaries to Lake Champlain.

Tributary	Total phosphorus	Dissolved phosphorus	Total nitrogen	Chloride
Great Chazy	-0.007	0.027	-0.002	-0.018
Little Chazy	-0.014	-0.011	-0.013	-0.012
Saranac	-0.281	-0.142	-0.024	-0.032
Salmon	-0.052	0.012	-0.035	0.022
Little Ausable	-0.100	-0.097	0.014	-0.017
Ausable	0.069	-0.037	-0.036	-0.016
Bouquet	0.087	0.068	0.085	-0.041
Putnam	-0.133	-0.026	-0.066	-0.046
Poultney	0.023	-0.002	-0.020	-0.015
Mettawee	0.086	0.023	-0.009	-0.004
Otter	-0.002	0.007	-0.038	-0.023
Little Otter	0.011	0.020	0.007	-0.026
Lewis	-0.036	-0.083	-0.013	-0.008
LaPlatte	0.053	0.072	0.001	-0.003
Winooski	0.016	-0.003	-0.014	-0.028
Lamoille	-0.082	0.015	-0.017	-0.023
Missisquoi	0.027	0.021	-0.025	-0.027
Pike	0.006	0.009	-0.062	-0.016

[1]WRTDS is Weighted Regression on Time, Discharge, and Season.

Annual Average Concentration, Annual Flux, and Trends

Estimated annual average concentration, flux, and yield (flux divided by drainage area) for total phosphorus, dissolved phosphorus, total nitrogen, and chloride in tributaries to Lake Champlain from 1990 to 2011 are presented in appendix 1. The three types of estimates (concentration, flux, and yield) are shown for the two types of WRTDS output: those based on observed discharges and those based on flow-normalized data. The flow-normalized data listed in appendix 1 are shown as plots in appendixes 3 (concentration) and 8 (yield) for individual subbasins. Temporal trends are presented as changes in flow-normalized concentrations and flux for three time periods (decade I, decade II, and the period of analysis) in tables 3 and 4. Figures 2 (flow-normalized concentrations) and 3 (flow-normalized flux) illustrate annual percent changes listed in tables 3 and 4 for the two decades. For purposes of assigning tributaries to the eastern or western group, the Mettawee River is considered an eastern tributary because it is closest hydrologically to other tributaries in the eastern group.

Table 3. Net change in flow-normalized concentrations of total phosphorus, dissolved phosphorus, total nitrogen, and chloride in the

[mgL, milligrams per liter; %/yr, percent per year; No., number]

Tributary name (and group)[1]	Change, 1990–2000		Change, 2000–2010		Change, 1990–2010		Change, 1990–2000		Change, 2000–2010		Change, 1990–2010	
	mg/L	%/yr	mg/L	%/yr	mg/L	%/yr	mg/L	%/yr	mg/L	%/yr	mg/L	%/yr
	Total phosphorus						Dissolved phosphorus					
Great Chazy (W)	0.008	1.8	0.006	1.2	0.014	1.7	0.005	2.3	0.006	2.2	0.011	2.6
Little Chazy (W)	0.010	1.0	0.005	0.4	0.015	0.8	0.013	1.6	0.009	0.9	0.022	1.4
Saranac (W)	0.003	1.2	0.002	0.7	0.005	1.0	0.003	2.6	0.003	2.2	0.005	2.8
Salmon (W)	0.003	1.1	0.002	0.8	0.005	1.0	0.002	2.0	0.002	1.2	0.004	1.8
Little Ausable (W)	0.012	1.9	-0.008	-1.1	0.004	0.3	0.015	4.2	-0.014	-2.6	0.001	0.2
Ausable (W)	0.002	0.9	0.000	0.1	0.003	0.6	0.002	2.1	0.002	1.6	0.003	2.1
Bouquet (W)	0.008	2.6	-0.002	-0.5	0.006	1.0	0.004	4.3	0.002	1.8	0.006	3.6
Putnam (W)	0.002	1.0	-0.000	-0.3	0.001	0.4	0.002	3.0	0.003	3.8	0.005	4.2
Poultney (E)	-0.000	-0.0	-0.003	-0.5	-0.003	-0.3	0.000	0.1	0.002	1.0	0.002	0.6
Mettawee (E)	0.004	0.6	-0.004	-0.5	0.000	0.0	0.011	5.0	0.002	0.5	0.013	3.0
Otter (E)	-0.026	-2.3	-0.018	-2.2	-0.044	-2.1	-0.033	-4.8	-0.004	-1.1	-0.037	-2.8
Little Otter (E)	0.003	0.3	-0.004	-0.3	-0.001	-0.0	-0.007	-1.1	0.002	0.3	-0.005	-0.4
Lewis (E)	0.003	0.6	0.004	0.7	0.006	0.7	0.001	0.3	0.002	0.9	0.002	0.7
LaPlatte (E)	-0.225	-6.7	-0.025	-2.8	-0.249	-3.9	-0.168	-6.6	-0.031	-4.5	-0.199	-4.1
Winooski (E)	-0.004	-0.8	-0.001	-0.2	-0.005	-0.5	-0.001	-0.9	0.000	0.2	-0.001	-0.4
Lamoille (E)	0.007	3.0	-0.003	-1.0	0.004	0.9	0.001	1.2	0.002	2.0	0.004	1.8
Missisquoi (E)	-0.001	-0.1	0.000	0.0	-0.000	-0.0	0.002	1.2	0.004	2.1	0.006	1.9
Pike (E)	-0.017	-1.5	-0.010	-1.0	-0.027	-1.2	-0.010	-1.6	-0.006	-1.1	-0.016	-1.3
No. of no change	1		3		3		0		0		0	
No. of decreases	5		11		5		5		4		5	
No. of increases	12		6		10		13		14		13	

[1]Tributaries are assigned to the western (W) or eastern (E) group, based on hydrologic connection.

[2]The first year that samples were analyzed for total nitrogen was 1992.

monitored Lake Champlain tributaries for three time periods.

Change, 1992–2000[2]		Change, 2000–2010		Change, 1992–2010		Change, 1990–2000		Change, 2000–2010		Change, 1990–2010	
mg/L	**%/yr**	**mg/L**	**%/yr**	**mg/L**	**%/yr**	**mg/L**	**%/yr**	**mg/L**	**%/yr**	**mg/L**	**%/yr**
		Total nitrogen						Chloride			
-0.08	-1.1	-0.07	-1.0	-0.15	-1.0	3.9	2.7	0.2	0.1	4.2	1.5
-0.01	-0.0	-0.05	-0.4	-0.05	-0.2	3.0	1.6	0.5	0.2	3.5	1.0
-0.01	-0.2	-0.14	-2.6	-0.15	-1.4	4.3	6.9	2.1	1.9	6.4	5.4
0.00	0.0	-0.14	-2.7	-0.14	-1.4	1.6	2.4	3.0	3.4	4.6	3.5
0.10	1.2	-0.08	-0.8	0.02	0.1	3.8	3.2	2.6	1.6	6.4	2.8
0.06	1.2	-0.15	-2.8	-0.09	-1.0	6.5	8.1	2.2	1.4	8.7	5.6
0.01	0.3	-0.15	-3.4	-0.13	-1.7	6.0	4.7	3.7	1.9	9.8	4.0
-0.05	-1.2	-0.08	-2.1	-0.12	-1.6	3.4	4.3	3.2	2.7	6.6	4.3
0.04	0.7	-0.08	-1.5	-0.04	-0.4	2.2	1.5	-0.4	-0.2	1.8	0.6
0.06	0.6	-0.22	-2.2	-0.16	-0.9	7.3	5.4	5.0	2.3	12.3	4.7
0.05	0.6	-0.13	-1.7	-0.09	-0.6	2.6	2.1	0.5	0.4	3.1	1.3
0.08	0.8	-0.03	-0.3	0.04	0.2	3.5	2.3	1.1	0.6	4.6	1.6
0.03	0.6	-0.05	-0.9	-0.02	-0.2	0.9	1.0	0.3	0.3	1.2	0.7
-0.15	-1.7	-0.26	-3.4	-0.41	-2.3	-6.5	-1.2	-18.5	-3.8	-25.0	-2.3
0.10	1.4	0.07	0.8	0.17	1.2	5.5	3.3	4.5	2.0	10.0	3.2
0.00	0.1	-0.04	-0.8	-0.04	-0.4	0.2	0.2	-0.2	-0.1	0.1	0.0
0.08	1.1	-0.09	-1.1	-0.01	-0.1	1.2	1.5	-0.6	-0.6	0.7	0.4
0.19	1.1	-0.03	-0.2	0.16	0.5	0.7	0.4	-2.8	-1.6	-2.1	-0.7
2		0		0		0		0		0	
4		17		14		1		5		2	
12		1		4		17		13		16	

Table 4. Net change in flow-normalized fluxes of total phosphorus, dissolved phosphorus, total nitrogen, and chloride in the monitored

[mt/yr, metric tons per year; %/yr, percent per year; No., number]

Tributary name (and group)[1]	Change, 1990–2000		Change, 2000–2010		Change, 1990–2010		Change, 1990–2000		Change, 2000–2010		Change, 1990–2010	
	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr
	Total phosphorus						Dissolved phosphorus					
Great Chazy (W)	1.0	0.4	-0.3	-0.1	0.7	0.1	1.6	1.4	2.0	1.6	3.7	1.7
Little Chazy (W)	0.4	0.6	0.0	0.0	0.4	0.3	0.5	1.1	0.1	0.3	0.6	0.7
Saranac (W)	3.1	1.2	2.6	0.9	5.7	1.1	2.7	3.0	3.3	2.8	5.9	3.5
Salmon (W)	0.1	0.3	0.2	0.5	0.3	0.5	0.2	1.8	0.1	1.1	0.3	1.6
Little Ausable (W)	0.3	0.7	-0.5	-1.0	-0.2	-0.2	0.3	1.2	-0.8	-2.9	-0.5	-1.1
Ausable (W)	4.6	1.1	-2.3	-0.5	2.4	0.3	1.9	3.2	2.3	2.9	4.2	3.7
Bouquet (W)	2.0	0.7	-2.0	-0.7	-0.0	-0.0	1.7	3.9	1.1	1.8	2.8	3.3
Putnam (W)	0.1	0.3	-0.1	-0.6	-0.1	-0.1	0.1	2.5	0.2	3.2	0.3	3.4
Poultney (E)	0.7	0.2	0.6	0.2	1.3	0.2	0.0	0.0	0.3	0.5	0.3	0.3
Mettawee (E)	0.7	0.2	-3.2	-1.0	-2.5	-0.4	2.1	2.5	-0.3	-0.3	1.8	1.1
Otter (E)	-13	-1.1	-18	-1.6	-32	-1.3	-20	-3.3	-3.6	-0.9	-24	-2.0
Little Otter (E)	1.1	1.3	0.2	0.2	1.3	0.8	-0.1	-0.1	0.2	0.4	0.1	0.1
Lewis (E)	0.3	0.3	0.7	0.7	1.0	0.5	0.0	0.0	0.1	0.4	0.1	0.2
LaPlatte (E)	-5.6	-4.1	-1.2	-1.6	-6.8	-2.6	-4.9	-5.5	-1.1	-3.2	-6.0	-3.5
Winooski (E)	-11	-0.6	2.1	0.1	-9.2	-0.2	-3.1	-1.2	-0.5	-0.2	-3.6	-0.7
Lamoille (E)	10	1.8	-5.7	-0.8	4.7	0.4	1.3	0.8	3.0	1.7	4.3	1.4
Missisquoi (E)	-13	-0.6	3.8	0.2	-9.4	-0.2	1.8	0.5	9.5	2.3	11	1.5
Pike (E)	-2.7	-0.6	3.3	0.9	0.6	0.1	-0.7	-0.5	-0.3	-0.2	-1.0	-0.3
Total	-21	-0.2	-20	-0.2	-42	-0.3	-15	-0.7	16	0.7	0.7	0.0
West total	12	0.8	-2	-0.2	9	0.3	9	2.3	8.4	1.7	17	2.3
East total	-33	-0.5	-18	-0.3	-51	-0.4	-24	-1.3	7.4	0.4	-17	-0.5
No. of no change	0		1		1		2		0		0	
No. of decreases	5		9		7		5		6		5	
No. of increases	13		8		10		11		12		13	

[1]Tributaries are assigned to the western (W) or eastern (E) group, based on hydrologic connection.

[2]The first year that samples were analyzed for total nitrogen was 1992.

Lake Champlain tributaries for three time periods.

Change, 1992–2000[2]		Change, 2000–2010		Change, 1992–2010[2]		Change, 1990–2000		Change, 2000–2010		Change, 1990–2010	
mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr	mt/yr	%/yr
		Total nitrogen						Chloride			
-35	-1.0	-39	-1.3	-73	-1.1	1,388	3.7	117	0.2	1,505	2.1
-0.7	-0.1	-4.4	-0.5	-5.1	-0.3	137	1.5	62	0.6	199	1.1
-5.9	-0.1	-120	-2.3	-126	-1.2	3,883	7.4	1,644	1.7	5,527	5.5
1.5	0.4	-9.7	-2.4	-8.2	-1.1	105	2.4	134	2.5	240	2.9
2.2	0.4	-7.4	-1.2	-5.2	-0.5	151	2.5	72	0.9	224	1.9
71	1.7	-138	-2.8	-67	-0.8	3,674	8.4	1,042	1.2	4,716	5.6
16	0.8	-68	-3.2	-52	-1.4	1,608	4.7	975	1.9	2,584	3.9
-3.4	-1.1	-5.4	-2.0	-8.9	-1.5	223	5.2	133	2.0	356	4.4
24	1.5	-20	-1.1	3.6	0.1	446	1.5	-52	-0.1	394	0.7
9.3	0.3	-69	-2.4	-60	-1.1	1,444	4.7	917	2.0	2,361	4.0
77	1.0	-178	-2.0	-100	-0.7	2,433	2.2	52	0.0	2,486	1.2
3.7	0.5	-4.8	-0.6	-1.1	-0.1	124	1.7	10	0.1	134	0.9
4.8	0.7	-4.3	-0.6	0.5	0.0	66	0.8	26	0.3	91	0.6
-7.1	-1.3	-15	-3.1	-22	-2.1	-93	-0.7	-315	-2.5	-408	-1.6
56	0.4	41	0.3	97	0.4	7,095	2.9	4,626	1.4	11,722	2.5
10	0.1	-59	-0.8	-49	-0.3	710	0.6	-448	-0.4	261	0.1
131	1.0	-106	-0.7	24	0.1	1,834	1.7	-1,296	-1.0	538	0.3
86	1.8	-20	-0.3	67	0.7	-66	-0.2	-639	-2.1	-706	-1.2
440	0.8	-826	-1.1	-386	-0.3	25,163	2.8	7,062	0.6	32,225	1.9
46	0.3	-391	-2.2	-345	-1.2	11,170	5.8	4,180	1.3	15,350	4.2
394	0.9	-435	-0.8	-41	-0.0	13,993	2.0	2,882	0.3	16,875	1.2
0		0		0		0		0		0	
5		17		13		2		5		2	
13		1		5		16		13		16	

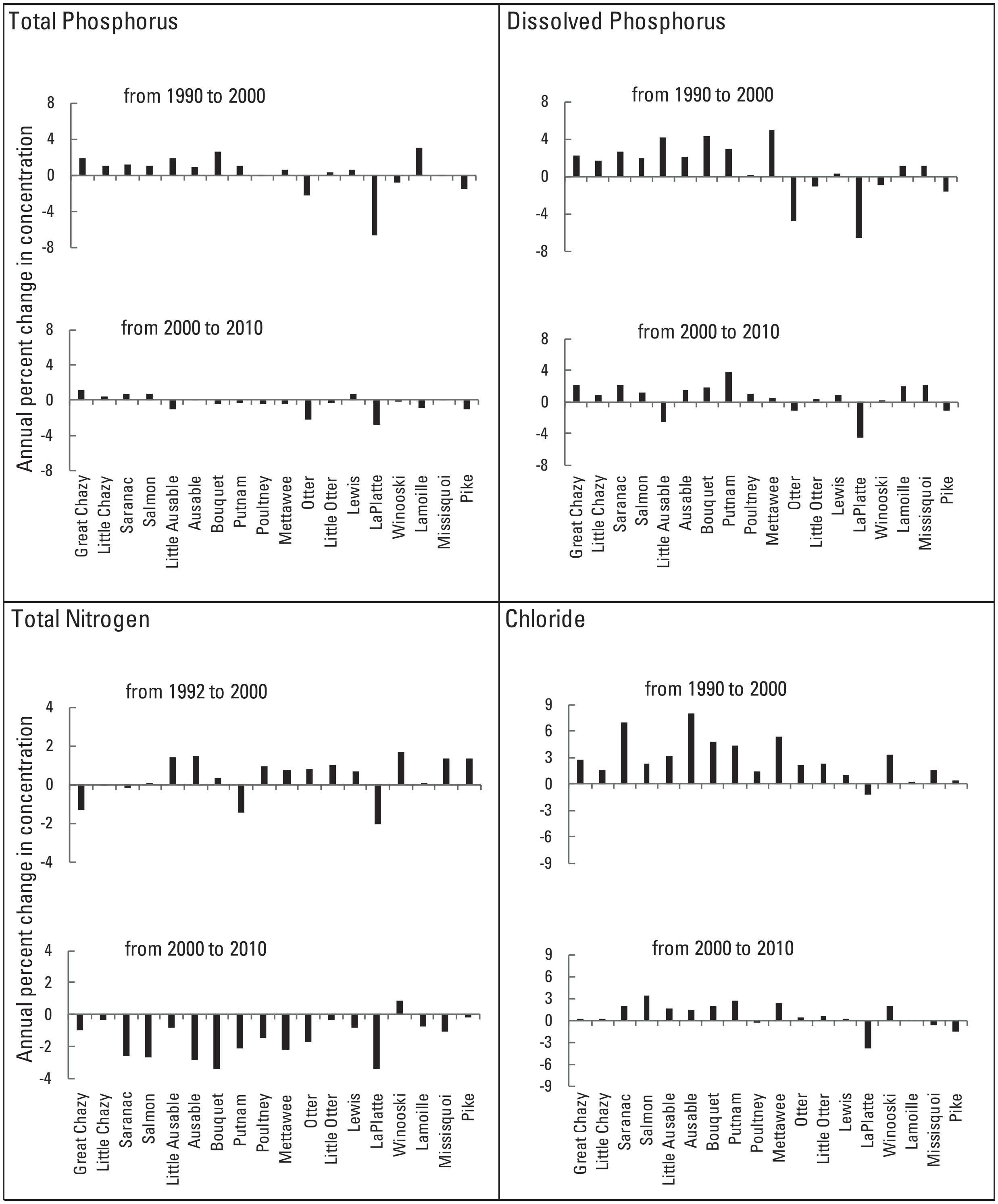

Figure 2. Annual percent changes in flow-normalized concentrations of total phosphorus, dissolved phosphorus, total nitrogen, and chloride between 1990 and 2000 and between 2000 and 2010.

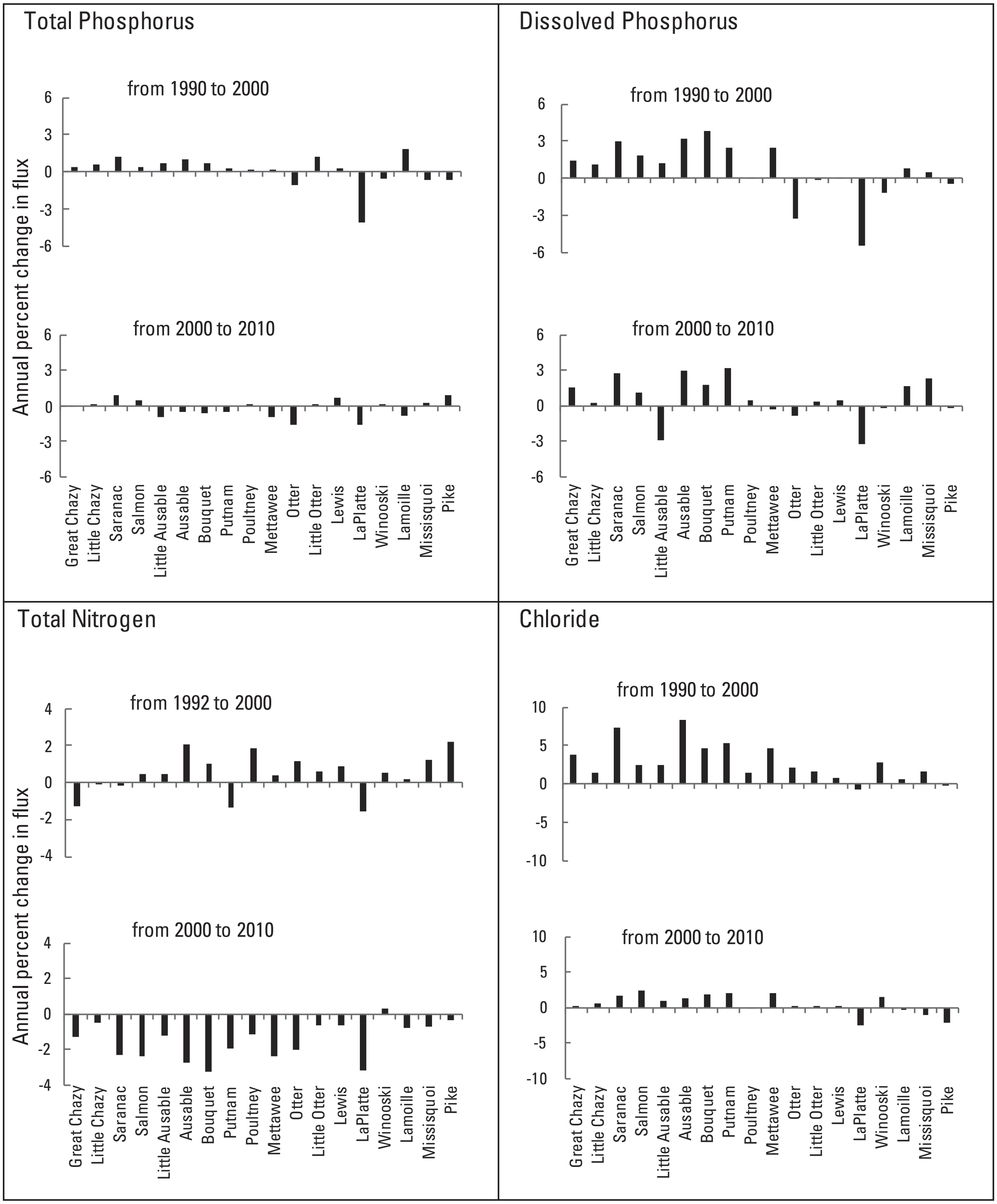

Figure 3. Annual percent changes in flow-normalized fluxes of total phosphorus, dissolved phosphorus, total nitrogen, and chloride between 1990 and 2000 and between 2000 and 2010.

The graphs in appendix 8 illustrate the benefits of flow normalization in removing year-to-year variations in streamflow for assessing long-term trends in water quality. Extremely high streamflows occurred in 2011 throughout the basin; for instance, in the Winooski River, the annual mean streamflow for water year 2011 was the highest on record for the period from 1929 to 2011 (3,380 ft^3/s in 2011 compared to the long-term average of 1,801 ft^3/s) (U.S. Geological Survey, 2012). Because of these high streamflows, the 2011 estimates of actual yield (circles in the graphs in appendix 8) based on observed streamflows were all either the highest or among the highest of yields since 1990 for all four constituents. However, the solid lines of flow-normalized yields in the graphs, whose endpoints and mid-point were the values used in the trend calculations (for differences between 1990, 2000, and 2010), in most cases do not show a sharp upturn near the latter part of the record because of the effects of the flow normalization. It is useful to see it both ways: that estimates of actual loads (appendix 1) or yields (appendixes 1 and 8) were extremely high in 2011, as expected because of the extreme weather, and to see loads and yields in the context of long-term trends that are uninfluenced by extreme events.

Total Phosphorus

For decade I, concentrations of total phosphorus increased in 12 tributaries, decreased in 5 tributaries, and did not change in 1 tributary (fig. 2; table 3; appendixes 1 and 3). Those numbers almost completely reversed in decade II, when concentrations increased in 6 tributaries, decreased in 11 tributaries, and did not change in 1 tributary. Improvements seen in the second decade did not compensate entirely for the larger increases during the 1990s; for the overall period of analysis, concentrations decreased in 5 tributaries, increased in 10 tributaries, and did not change in 3 tributaries. The patterns, or directions, of change in total phosphorus flux were similar to those for concentration (fig. 3; table 4; appendixes 1 and 8). For decade I, flux decreased in 5 tributaries and increased in 13 tributaries. For decade II, flux of total phosphorus decreased in nine tributaries, increased in eight tributaries, and did not change in one tributary. For the entire period of analysis, flux decreased in 7 tributaries, increased in 10 tributaries, and did not change in 1 tributary.

On a mass basis, each time period that was examined showed a basinwide decrease in flux of total phosphorus. The total annual decrease in total phosphorus flux for decade I was 21 metric tons (t). For decade II, the total annual decrease was 20 t, and for the entire period of analysis, the total annual decrease was 42 t (table 4). The flux of total phosphorus for the whole basin was dominated by flux from tributaries on the eastern side. For example, the reduction in flux in decade I primarily reflects flux decreases in Otter Creek and Missisquoi and Winooski Rivers (of 13, 13, and 11 metric tons per year (t/yr), respectively), all on the eastern side of Lake Champlain. Decade II saw slight reversals (increases) in flux in two of those tributaries, Missisquoi and Winooski Rivers. However, since these increases were very small, and Otter Creek continued with a large decrease in combination with decreases in several tributaries (that had shown increases in decade I), the net effect was a decrease in flux in decade II. Adding the effects over the two decades, the period of record showed a net decrease of 42 t/yr, composed of a 51 t/yr decrease from the eastern tributaries and a 9 t/yr increase from the western tributaries.

Normalizing the changes in concentration and flux (by expressing in terms of percent changes) provides a sense of the relative magnitude of change among the tributaries. Most of the annual changes in concentration and flux of total phosphorus for tributaries over the period of analysis were less than 1 percent (tables 3 and 4). The largest relative changes in flux in decade I were decreases in the LaPlatte River (6.7 and 4.1 percent per year for concentration and flux, respectively) and increases in the Lamoille River (3.0 and 1.8 percent per year for concentration and flux, respectively). In decade II, the largest relative changes in flux were decreases in the LaPlatte River (2.8 and 1.6 percent per year for concentration and flux, respectively) and Otter Creek (2.2 and 1.6 percent per year for concentration and flux, respectively). The net change of all gaged tributaries for the period of record was a 0.3 percent per year decrease in flux.

Dissolved Phosphorus

The pattern of increases and decreases between decades did not shift as much for concentration or flux of dissolved phosphorus as it did for total phosphorus. More tributaries had increases than had decreases in concentrations and flux of dissolved phosphorus for all of the time periods. In decade I, concentrations of dissolved phosphorus decreased in 5 tributaries and increased in 13 tributaries (table 3; fig. 2; and appendixes 1 and 3); in decade II, concentrations decreased in 4 tributaries and increased in 14 tributaries; and for the entire period, concentrations decreased in 5 tributaries and increased in 13 tributaries. The number of tributaries with flux that decreased was five for decade I and for the overall period of analysis (fig. 3; table 4; appendix 8). For decade II, flux decreased in 6 tributaries and increased in 12 tributaries. Thirteen tributaries had changes in concentrations that did not vary by more than 0.005 milligrams per liter between decades I and II.

In decade I, the total annual decrease in dissolved phosphorus flux was 15 t; this decrease was entirely offset in decade II with a total annual increase of 16 t, resulting in a total annual increase of 0.7 t from 1990 through 2010 (table 4). The decade I decrease in flux of dissolved phosphorus was dominated by decreases in flux from tributaries on the eastern side of Lake Champlain, in particular, from Otter Creek (a decrease of 20 t/yr). Small relative increases in flux from all of the western tributaries had minimal effect on basin-wide flux. In decade II, increases and decreases in dissolved phosphorus flux were distributed among tributaries on both sides of the lake, with the largest increases seen in Missisquoi and Saranac Rivers (9.5 and 3.3 t/yr). Throughout the period of analysis, tributaries on the western side of the lake collectively increased by 17 t/yr, and tributaries on the eastern side collectively decreased by 17 t/yr, led by Otter Creek and the LaPlatte and Winooski Rivers (decreases of 24, 6.0, and 3.6 t/yr, respectively). The effect of this net decrease was diminished by increases of 11 t/yr in the Missisquoi River and of 5.9 t/yr in the Saranac River.

While the magnitudes of many of the large annual percent changes in concentration and flux of dissolved phosphorus seen in decade I were diminished in decade II (tables 3 and 4), the number of increasing changes still was greater than those for decreasing changes. In decade I, the largest annual percent increase in concentration was in the Mettawee River. The largest increase in flux was in the Bouquet River, and the largest decrease in concentration and flux was in the LaPlatte River. In decade II, the largest annual percent increases in concentration and flux were seen in Putnam Creek, and the largest decrease was again in the LaPlatte River.

Total Nitrogen

Concentrations of total nitrogen in decade I showed no change in 2 tributaries, decreasing concentrations in 4 tributaries, and increasing concentrations in 12 tributaries (fig. 2; table 3; appendixes 1 and 3). An almost complete reversal in this pattern was seen in the data for decade II, when concentrations decreased in 17 tributaries and increased in just one. Concentration changes for the period of analysis showed 14 tributaries with decreasing concentrations of total nitrogen and 4 with increasing concentrations. The numbers of tributaries with either upward or downward trends in the flux of total nitrogen for the three time periods was similar to the pattern in the trends for concentration, with the flux in 17 of the 18 tributaries (all except Winooski) decreasing during decade II (fig. 3; table 4; appendixes 1 and 8). For the period of analysis, 13 tributaries showed decreases (table 4; appendix 8) in nitrogen flux.

On a mass basis, the total annual increase in the flux of total nitrogen for decade I was 440 t. For decade II, the total annual decrease was 826 t, and for the period of analysis, the total annual decrease was 386 t (table 4). The largest increases in flux in decade I were in the Missisquoi and Pike Rivers (131 and 86 t/yr, respectively). The largest decreases in mass flux in decade II were in Otter Creek and the Ausable River (178 and 138 t/yr, respectively). In decade II, flux of total nitrogen decreased in all of the tributaries from the western side of Lake Champlain; the largest mass decreases were seen in the Saranac, Great Chazy, Ausable, and Bouquet Rivers on the western side, and also in Otter Creek and the Mettawee River on the eastern side of Lake Champlain.

All of the increasing concentrations and fluxes of total nitrogen in decade I were relatively small; only five were more than 1 percent per year (but less than 2 percent per year). Percent changes in decade II were larger; the concentration in seven tributaries and the flux in eight tributaries decreased at least 2 percent per year. On a normalized basis, the largest increases in flux in decade I were in the Ausable and Pike Rivers (1.7 and 1.8 percent per year, respectively). The largest decreases in flux in decade II were in the Bouquet and LaPlatte Rivers (3.2 and 3.1 percents per year, respectively).

Chloride

For decade I, concentrations of chloride decreased in 1 tributary and increased in 17 tributaries. For decade II concentrations decreased in 5 and increased in 13 tributaries, and for the period of analysis, concentrations decreased in 2 and increased in 16 tributaries (fig. 2; table 3; appendixes 1 and 3). The summary for numbers of tributaries that had decreasing and increasing chloride flux and associated rates of change in flux (fig. 3; table 4; appendixes 1 and 8) is almost identical to the summary for chloride concentration.

On a mass basis, the two tributaries with decreases in chloride for decade I and for the period of analysis were LaPlatte and Pike Rivers; for decade II, tributaries with the largest mass decreases were Missisquoi and Pike Rivers (table 4), and those with the largest normalized decreases were LaPlatte and Pike Rivers. For all three time periods, the largest contributors to the mass increase in chloride flux were the Winooski and Saranac Rivers. For decade I, the total annual increase in chloride flux was 25,163 t. For decade II, the total annual increase was 7,062 t, and for the period of analysis, the total annual increase was 32,225 t. Seventy-eight percent of the annual flux increase during the period of analysis was realized during decade I. The five tributaries that had decreasing concentration and flux of chloride between 2000 and 2010 were all on the eastern side of Lake Champlain. Decreasing chloride fluxes were not seen in any tributaries on the western side of the lake for any of the three time periods analyzed.

Eleven of the increasing concentrations for decade I increased at rates greater than 2 percent per year. The highest rates of decrease of concentration and flux for both the separate decades and for the period of analysis were in the LaPlatte River. For decade II, the rates of increase generally decelerated; concentrations in only four of the tributaries with increasing concentrations increased at least 2 percent per year, and for the period of analysis, the greatest rates of increase, over 5 percent per year, were seen in the Ausable and Saranac Rivers.

Discussion of Trends

Because of the emphasis in the Lake Champlain Management plan on the goal of reducing phosphorus flux to the lake, the following discussion focuses on the trends in concentrations and flux of total and dissolved phosphorus.

An important question is how to interpret the data in terms of measuring progress toward meeting the phosphorus reduction goals. A tool that provides information about the influence of particular seasons and discharges on positive and negative changes in total phosphorus concentrations between two selected years is illustrated and discussed. Additional discussion topics are the significance of the ratios of total phosphorus to dissolved phosphorus and trends in concentrations and fluxes of nitrogen and chloride.

Is Progress Being Made in Reducing Phosphorus?

Examination of data on the concentrations and flux of total phosphorus for the overall period of analysis showed that more tributaries had increasing than had decreasing concentration and flux. When the datasets for the two separate decades of record are compared, however, decade II shows that concentrations improved compared to those in decade I, in that a greater number of tributaries showed decreasing concentrations (10 decreases in decade II compared to 5 decreases in decade I; fig. 2; table 3). The flux picture is more complex. As with concentrations, the number of tributaries with downward trends in flux was greater in decade II than in decade I (9 decreases in decade II and 5 in decade I) (fig. 3 and table 4); however, basinwide flux is an additive property, unlike concentration, and the tendency for flux from a small number of tributaries to dominate the basinwide picture is important to note. In particular, although trends from two of the largest tributaries, Winooski and Missisquoi, have decreased over 21 years, they have increased in the most recent 11-year period. While the annual percent changes from these tributaries has been very small, their large areas translate to a large overall contribution on a mass basis.

To put things in perspective, many of the changes in concentration and flux of these Lake Champlain tributaries have been very small, less than 1 percent per year. While most tributaries had increasing concentration and flux over the period of record, improvements were seen for a greater number of individual tributaries in decade II compared to decade I. In decade I, most of the western tributaries had increasing flux, and the eastern tributaries had decreasing flux, but the larger tributaries in the east dominated the basinwide decrease. In decade II, all of the western tributaries improved in both concentrations and flux compared to decade I, except Salmon River, whose flux increased. Flux in tributaries on the eastern side of the basin continued to decrease in decade II, although at a lower rate of change compared to decade I.

Influence of Season and Discharge on Changes in Total Phosphorus

The USGS software package that includes WRTDS[2] offers additional tools that can be used to improve our understanding of water-quality responses to ecosystem and land-based processes. One such tool is the contour plot shown in figure 4 that depicts the difference in estimated total phosphorus concentrations for four representative rivers between two selected years, during the range of seasons and discharges, in order to demonstrate how the combination of various discharges and seasons influence the annual estimates. Similar plots of estimated total phosphorus concentrations for all 18 tributaries are in appendix 5. In figure 4 and appendix 5, pink areas show times of the year and discharges for which estimates of total phosphorus concentration increased between 1994 and 2010, with darker shades of pink indicating greater increases. Likewise, areas of blue shading indicate combinations of times of the year and discharges for which estimates of the concentrations of total phosphorus decreased, with darker shades showing greater decreases. Figure 4A shows that for the Saranac River, total phosphorus concentrations increased at all discharges during the spring and summer and at very low discharges through the winter. In the fall and winter at all but the lowest discharges, the concentrations decreased. Thus, concentrations of total phosphorus that increased in the Saranac River throughout the period of analysis were dominated by increases that occurred primarily in the spring and summer, especially at very high discharges in June and July and at very low discharges between March and June. Increased concentrations during periods of low flow throughout the year provide evidence of increases in point-source or groundwater sources of phosphorus, and increases during summer high flows suggest new or additional sources of seasonal nonpoint contamination. Even this kind of general information that provides some guidance on where the phosphorus in observed concentrations is coming from can be helpful to managers who are charged with designing treatments for reducing phosphorus inputs to tributaries or to Lake Champlain.

For the Mettawee River (fig. 4B), decreases and increases in estimated total phosphorus concentrations were evenly distributed throughout the year, but large decreases were estimated at very high discharges (generally above the 95th percentile of flow) for most parts of the year. Concentrations in Otter Creek (fig. 4C) decreased across all seasons and discharges except for increases during summer months at very high discharges (generally above the 95th percentile of flow). For the Missisquoi River (fig. 4D), decreases and increases in estimated total phosphorus concentrations were relatively evenly distributed throughout

[2]WRTDS is one component of an Exploration and Graphics for River Time-Series (EGRET) toolkit, a utility in R programming language to analyze long-term changes in water quality and streamflow (https://github.com/USGS-CIDA/WRTDS/blob/master/README.md).

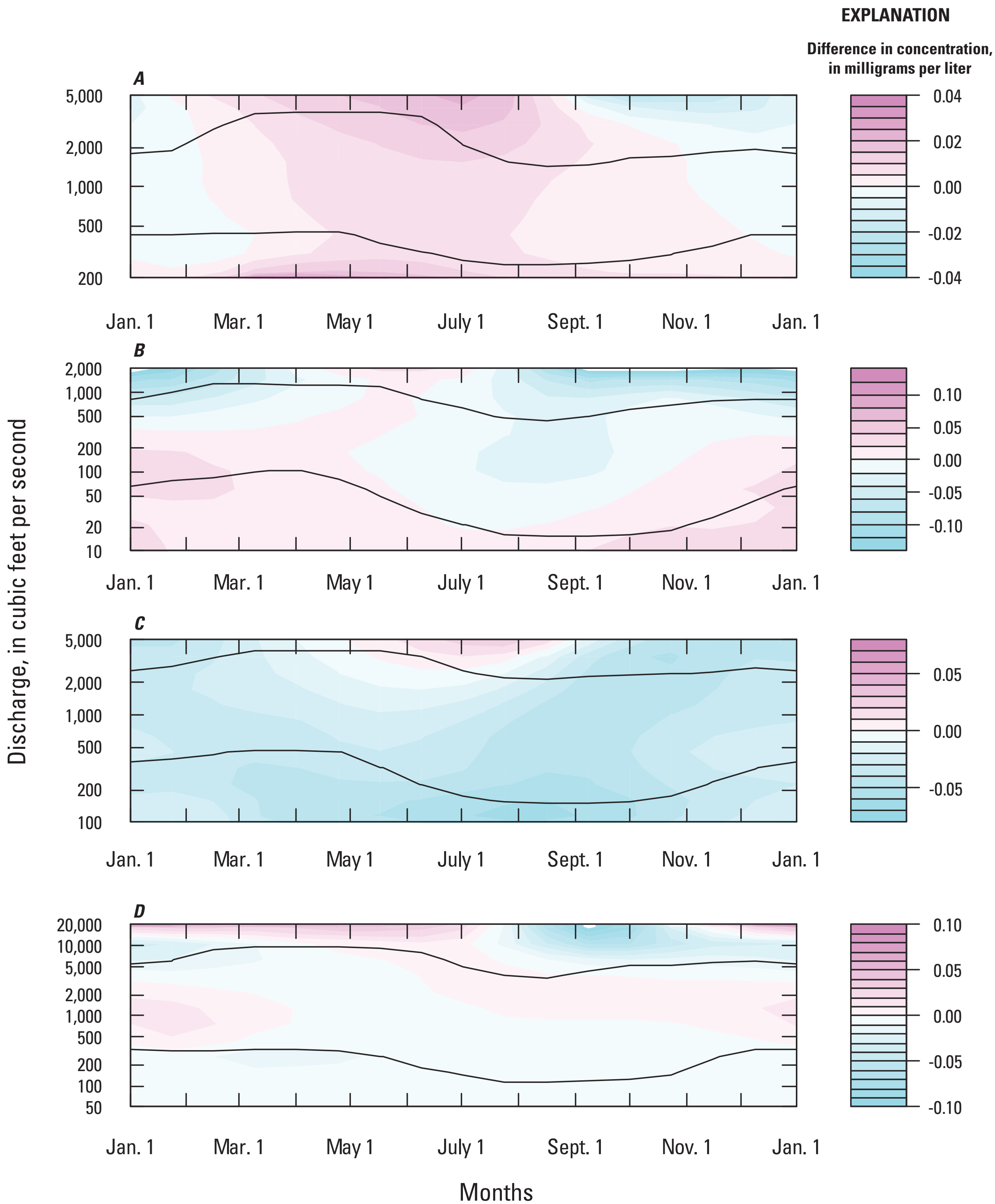

Figure 4. The seasonal differences in estimated total phosphorus concentrations between 1994 and 2010 in the *A,* Saranac River, *B,* Mettawee River, *C,* Otter Creek, and *D,* Missisquoi River.

the year. The largest increases or decreases occurred at very high discharges, those above the 95th percentile, through most of the year. Graphs in appendix 5 show that increases and decreases in concentrations of total phosphorus between 1994 and 2010 in all of the monitored Lake Champlain tributaries follow similar patterns as those described in figure 4: patterns in all the New York tributaries (Great Chazy, Little Chazy, Salmon, Little Ausable, Ausable, Bouquet, and Putnam) were similar to those in the Saranac River. The Lamoille River was similar to the Mettawee River, the Poultney and LaPlatte Rivers were similar to Otter Creek, and the Winooski River was similar to the Missisquoi River. The Pike River had a slight, fairly uniform decrease in concentrations of total phosphorus during most discharges and seasons, except for large increases at very high discharges in fall and winter. Little Otter and Lewis Creeks were characterized by increases in concentrations during the summer and fall and decreases during parts of the winter and spring.

Ratios of Dissolved to Total Phosphorus Concentration and Flux

Examination of the ratios of concentrations of dissolved to total phosphorus may provide some insight to the movement of phosphorus in the tributaries to Lake Champlain. Ratios of dissolved to total phosphorus concentration and flux for the tributaries essentially fall into one of three groups: the majority of phosphorus is in the dissolved state (the ratio is greater than 0.5), the minority of phosphorus is in the dissolved state (the ratio is less than 0.5), or about half of the phosphorus is dissolved. The fraction of total phosphorus that is not dissolved is in a particulate form. Examples from each of these groups are shown as graphs of concentration (fig. 5A) or flux (fig. 5B) of dissolved versus total phosphorus. Although some similar patterns of the ratios among tributaries are seen in figure 5, the similarities appear unrelated to geography or to have any other simple explanation. The interaction of several different processes that may influence this ratio makes it difficult to trace the evolution of any particular pattern. Areas saturated with orthophosphate (the degrees of saturation are indicated in fig. 5 by the distance that blue points plot below the 1:2 reference line), the primary dissolved form of phosphorus, as a result of over application of manure or other fertilizers can show increases in dissolved relative to total phosphorus, except in the presence of clays or iron oxides, which lead to adsorption or calcium carbonate, which in turn leads to mineralization (Domagalski and Johnson, 2012). In addition to soil chemistry reactions, some of the other processes that might increase the concentration of total phosphorus relative to that of dissolved phosphorus include plant uptake of dissolved phosphorus, streambank erosion, and erosion away from streams in areas dominated by overland flow.

Trends in Total Nitrogen

Total nitrogen concentration and flux for most individual tributaries have decreased since 1990. What could be causing these large and fairly uniform decreases in total nitrogen? Some of the decrease could be related to the decrease in inorganic nitrogen loading from atmospheric deposition by about 0.08 kilograms per hectare per year between 1990 and 2010, which has been documented at an observation station in the Lake Champlain Basin (National Atmospheric Deposition Program, 2012). There also could be some concurrent benefit from the implementation of agricultural BMPs in the Lake Champlain Basin, such as cattle exclusion from streams, erosion control, and waste storage. Although these BMPs are designed primarily to reduce phosphorus flux into the lake by runoff processes, and thus target the total rather than dissolved fraction of phosphorus, the focus on runoff could concomitantly be helping to reduce total nitrogen flux to streams. These BMPs also might be particularly effective in areas with impermeable soils and impermeable bedrock that contribute only small amounts of nitrate-containing groundwater to base flow (Spahr and others, 2010). In areas with greater groundwater contributions to base flow, such as agricultural areas with permeable soils, it is possible that BMPs or other processes that directly or indirectly induce denitrification have been effective in reducing nitrogen input to streams. Denitrification occurs in any setting where groundwater flow paths intersect reducing environments (those containing little or no free oxygen), including upland parts of aquifers, riparian (near stream) zones, and hyporheic (interface between groundwater and surface water along a stream) zones (Puckett, 2004).

Trends in Chloride

Trends in concentrations and fluxes of chloride in the tributaries to Lake Champlain correspond, in most cases, with in-lake data for chloride concentrations presented in Smeltzer and others (2012). The only in-lake data that does not reflect inputs from its closest major contributing tributary is that for Shelburne Bay, which shows no overall trend in chloride concentration and flux between 2001 and 2011, while the LaPlatte River, which drains into Shelburne Bay, has a pronounced downward trend in chloride for that period, possibly related to a wastewater-treatment facility upgrade (Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 1998). Smeltzer and others (2012) suggest that the 30 percent decrease in winter road salt application in Vermont since 1999 could feasibly account for the downward trends in chloride concentrations and flux in those parts of Lake Champlain that receive inflow primarily from tributaries draining from Vermont. The temporal and spatial pattern of decreasing chloride concentration and flux appears to support that hypothesis because in general, the chloride concentrations

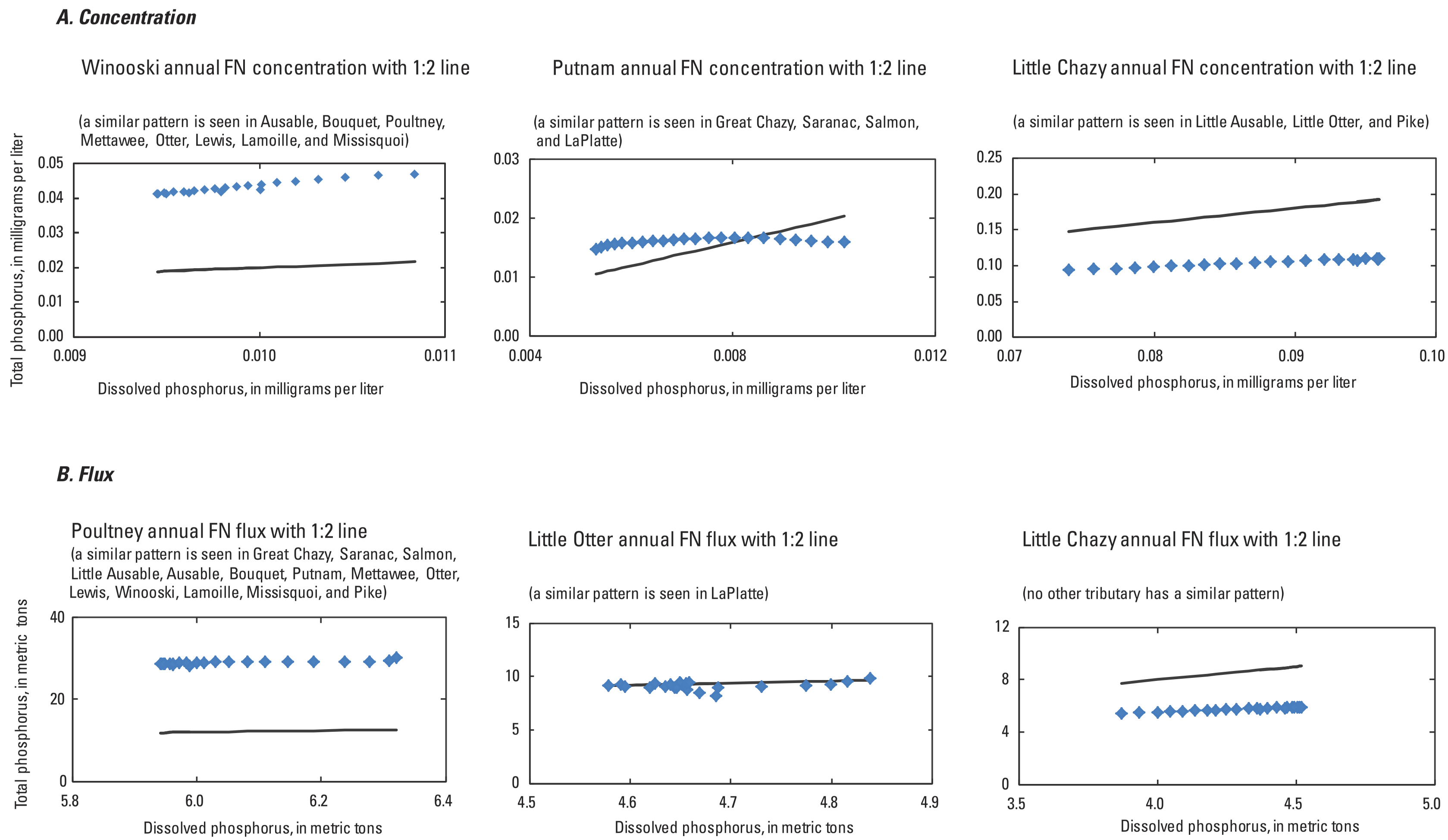

Figure 5. Patterns of the ratio of *A,* concentration and *B,* flux of flow-normalized dissolved phosphorus to flow-normalized total phosphorus for tributaries to Lake Champlain, from 1990 through 2011.

in Vermont tributaries (eastern side of Lake Champlain) are decreasing and in the New York tributaries (western side) are increasing in decade II[3]. Note, however, that the New York tributaries have clearly improved in both chloride concentration and flux in decade II compared to decade I; that is, the increases in concentration in decade II are much less than the increases in decade I.

Relating Trends in Total Phosphorus to Basin Characteristics

A variety of basin characteristics were tested at two spatial scales for correlations with total phosphorus concentration and with flux. One scale was HUC8, which represents the entire subbasin for the major tributary (such as Winooski or Ausable), and the other was HUC12, the scale that represents a nested subdivision of the subbasin that was closest to the water-quality and streamflow monitoring station (fig. 1). Results of the correlation tests are presented in table 5. For most of the correlation tests, the time periods of the two data sets that were tested are the same or nearly the same, except for the category of BMPs where possible lag effects were tested. The lack of strong trends in total phosphorus for most of the tributaries over the time periods that were analyzed should be kept in mind during this discussion.

Physical and Demographic Factors

Physiographic province had a significant relation with phosphorus concentration and flux (table 5). As a static measure, population density was positively correlated with phosphorus flux at the HUC12 scale. The change in population density was not correlated with the change in phosphorus concentration or flux at any scale or time period.

Point Sources of Phosphorus

Fluxes of total phosphorus from point sources decreased in all tributaries (except Bouquet River, where the Willsboro wastewater-treatment plant began operations in 1995) that reported fluxes between 1991 and 2011 (fig. 6). The largest point-source fluxes of total phosphorus in 1991 and 2000 were in Otter Creek and the Winooski River (64.0 and 24.3 t, respectively, in 1991 and 13.9 and 16.1 t, respectively, in 2000), but by 2011, the largest fluxes were in the Winooski and Saranac Rivers (7.7 and 3.7 t, respectively). During the 1991 to 2011 time period, all tributaries except the Bouquet River saw point-source total phosphorus flux decreases of between 58 (Saranac) and 99 percent (LaPlatte). Phosphorus flux decreased in the Bouquet River by 43 percent from 2000 to 2011. Because locations of point sources were identified only to the HUC8 subbasin, correlations were not tested at the finer HUC12 scale. The decreases in point source fluxes from 1991 to 2011 correlated with decreases in phosphorus concentrations and flux in the tributaries for the same period (table 5). Fluxes from point sources in 2000 and in 2010 were strongly correlated with phosphorus flux in tributaries for the same years.

Given these reductions in point-source discharges in many of the Lake Champlain subbasins between 1991 and 2011, it is worth assessing whether the reductions appear related to concurrent changes in concentrations of dissolved phosphorus, the form of phosphorus with greatest bioavailability (Ekholm and Krogerus, 1998), in the tributaries. Figure 7 shows that 38 percent of the variation in the changes of flow-normalized flux of dissolved phosphorus in tributaries is related to the variation in changes in total phosphorus flux from point sources. The point in the lower left corner of the graph represents data from the LaPlatte River Basin.

Land Use and Agricultural Statistics

Runoff from agricultural land and urban land is estimated to contribute about 56 and 37 percent, respectively, of the nonpoint source of total phosphorus flux to Lake Champlain (Hegman and others, 1999). As a result, several State and Federal agricultural and stormwater initiatives are aimed at reducing runoff from these types of land uses. The collective effectiveness of these programs is an elusive metric at the basin scale because of complexities associated with multiple sources of phosphorus with different hydrological controls (Sharpley and others, 2009). Another difficulty with matching tributary concentrations of phosphorus with agricultural activities on the land is that many of the measures of activities are reported on a county rather than basin basis.

Yet, the countywide USDA census of agriculture data (U.S. Department of Agriculture, 2012) presents a comprehensive, detailed, consistent, and well documented picture of farming across the country every 5 years—all important characteristics of datasets if they are to be useful in exploring relations to trends. The agricultural statistics that were selected for exploring correlation tests against total phosphorus in the tributaries to Lake Champlain were acres of land in farms, acres of harvested cropland, acres of corn for grain or seed, acres of corn for silage or green chop, acres of land with applications of commercial fertilizer, and number of dairy cows in the tributary basins.

Several land-use and agricultural statistics for the basins of the tributaries to Lake Champlain showed significant correlations with the phosphorus concentration or flux data (table 5). The percentages of agricultural land and of agricultural land that intersected hydric soils in year 2001 were positively correlated with year 2001 phosphorus

[3]Tributaries in figures 2 and 3 are listed in downstream order number; the first eight tributaries are in New York, the next two drain area in both states, the next six are entirely in Vermont, the next drains areas in both Vermont and the Province of Quebec, and the last is entirely in Quebec.

Table 5. Basin characteristics that were tested for correlation with total phosphorus concentration and flux, and correlation test results for tributaries to Lake Champlain.

[Supporting data are in appendix 6; HUC8, data pertain to drainage area from streamgage to entire 8-digit hydrologic unit basin; HUC12, data pertain to drainage area from streamgage to adjacent 12-digit hydrologic unit subbasin; τ, Kendall's tau; --, not applicable; km², square kilometers; **bold** values signify statistical significance for $\alpha = 0.10$]

Watershed characteristic	Year or range of years	Phosphorus concentration and flux	Statistical test result for phosphorus concentrations and part of watershed				Statistical test result for phosphorus flux and part of watershed			
		Year or range of years[1]	HUC8		HUC12		HUC8		HUC12	
			Kendall τ	p-value	Kendall τ	p-value	Kendall τ	p-value	Kendall τ	p-value
Physical and demographic										
Physiographic province[2]	--		ChiSquare = 4.8	**0.092**	--	--	ChiSquare = 6.2	**0.045**	--	--
Population density, people per km²	2000	2000	0.217	0.211	0.092	0.620	0.085	0.622	-0.417	**0.024**
Change in population density, people per square kilometer[3]	1990–2010	1990–2011	-0.072	0.677	-0.167	0.368	-0.046	0.791	0.050	0.787
	2000–2010	2000–2011	-0.111	0.520	-0.233	0.207	-0.150	0.384	-0.167	0.368
Point sources										
Phosphorus flux from point sources	2000	2000	-0.143	0.420	--	--	0.683	**0.000**	--	--
	2010	2010	-0.014	0.939	--	--	0.597	**0.001**	--	--
Percent change in phosphorus flux from point sources	1991–2011	1991–2011	0.462	**0.028**	--	--	0.487	**0.020**	--	--
	2000–2011	2000–2011	0.026	0.903	--	--	0.180	0.393	--	--
Land use										
Percent or percent change in:										
Urban land use including open land[3]	2001	2001	0.275	0.111	-0.147	0.402	0.146	0.403	-0.203	0.252
Agricultural land use[3]			0.555	**0.001**	0.409	**0.019**	0.535	**0.002**	0.428	**0.015**
Agricultural land in basin that intersects hydric soils (type C or D)[3]			0.573	**0.002**	0.400	**0.026**	0.526	**0.004**	0.420	**0.021**
Acres of land in farms	1987–2007	1990–2007	0.338	**0.053**	0.244	0.174	0.298	**0.087**	0.362	**0.043**
	1997–2007	1997–2007	0.020	0.910	0.044	0.805	0.163	0.344	0.206	0.249
Acres of cropland	1987–2007	1990–2007	0.320	**0.064**	0.237	0.187	0.216	0.211	0.267	0.137
	1997–2007	1997–2007	0.236	0.172	0.199	0.266	-0.066	0.705	-0.111	0.536
Acres of corn for grain or seed	1987–2007	1990–2007	0.373	**0.031**	0.598	**0.001**	0.294	**0.088**	0.376	**0.036**
	1997–2007	1997–2007	0.300	0.105	0.260	0.180	-0.033	0.857	-0.048	0.804
Acres of corn for silage	1987–2007	1990–2007	0.026	0.880	0.007	0.967	0.013	0.940	-0.022	0.902
	1997–2007	1997–2007	0.137	0.426	0.185	0.303	-0.242	0.161	-0.244	0.174
Acres of commercial fertilized	1987–2007	1990–2007	0.137	0.426	0.081	0.650	0.033	0.850	0.037	0.837
	1997–2007	1997–2007	-0.020	0.910	-0.059	0.742	0.177	0.307	0.044	0.805
Number of milk cows	1987–2007	1990–2007	0.112	0.519	0.118	0.510	0.086	0.622	0.074	0.680
	1997–2007	1997–2007	0.177	0.307	0.191	0.284	-0.203	0.240	-0.206	0.249

Table 5. Basin characteristics that were tested for correlation with total phosphorus concentration and flux, and correlation test results for tributaries to Lake Champlain.—Continued

[Supporting data are in appendix 6; HUC8, data pertain to drainage area from streamgage to entire 8-digit hydrologic unit basin; HUC12, data pertain to drainage area from streamgage to adjacent 12-digit hydrologic unit subbasin; τ, Kendall's tau; --, not applicable; km^2, square kilometers; **bold** values signify statistical significance for $\alpha = 0.10$]

Watershed characteristic	Year or range of years	Phosphorus concentration and flux	Statistical test result for phosphorus concentrations and part of watershed				Statistical test result for phosphorus flux and part of watershed			
			HUC8		HUC12		HUC8		HUC12	
		Year or range of years[1]	Kendall τ	p-value	Kendall τ	p-value	Kendall τ	p-value	Kendall τ	p-value
Best-management practices										
Number of agricultural best-management practices constructed or implemented	1995–1999	1990–2011	-0.231	0.201	0.184	0.469	-0.245	0.173	0.138	0.587
		2000–2011	-0.275	0.127	-0.230	0.365	-0.290	0.107	-0.368	0.148
	1995–2010	1990–2011	-0.229	0.201	0.200	0.421	-0.126	0.483	0.156	0.531
		2000–2011	-0.170	0.343	-0.244	0.325	-0.170	0.343	-0.289	0.245
Money spent on agricultural best-management practices, dollars	1995–1999	1990–2011	-0.339	**0.070**	-0.291	0.152	-0.390	**0.037**	-0.268	0.186
		2000–2011	-0.271	0.148	-0.358	**0.078**	-0.203	0.278	-0.156	0.441
	1995–2010	1990–2011	-0.332	**0.064**	-0.332	0.100	-0.214	0.232	-0.199	0.324
		2000–2011	-0.229	0.201	-0.155	0.443	-0.185	0.303	0.044	0.826

[1]When a range of years is denoted, the variable tested for correlation was percent change between the range of years.

[2]This is the only watershed characteristic which, because the variable is nominal (non-continuous), uses the Kruskal-Wallis statistical test instead of Kendall's tau for correlation.

[3]Correlation tests are with phosphorus yield rather than flux.

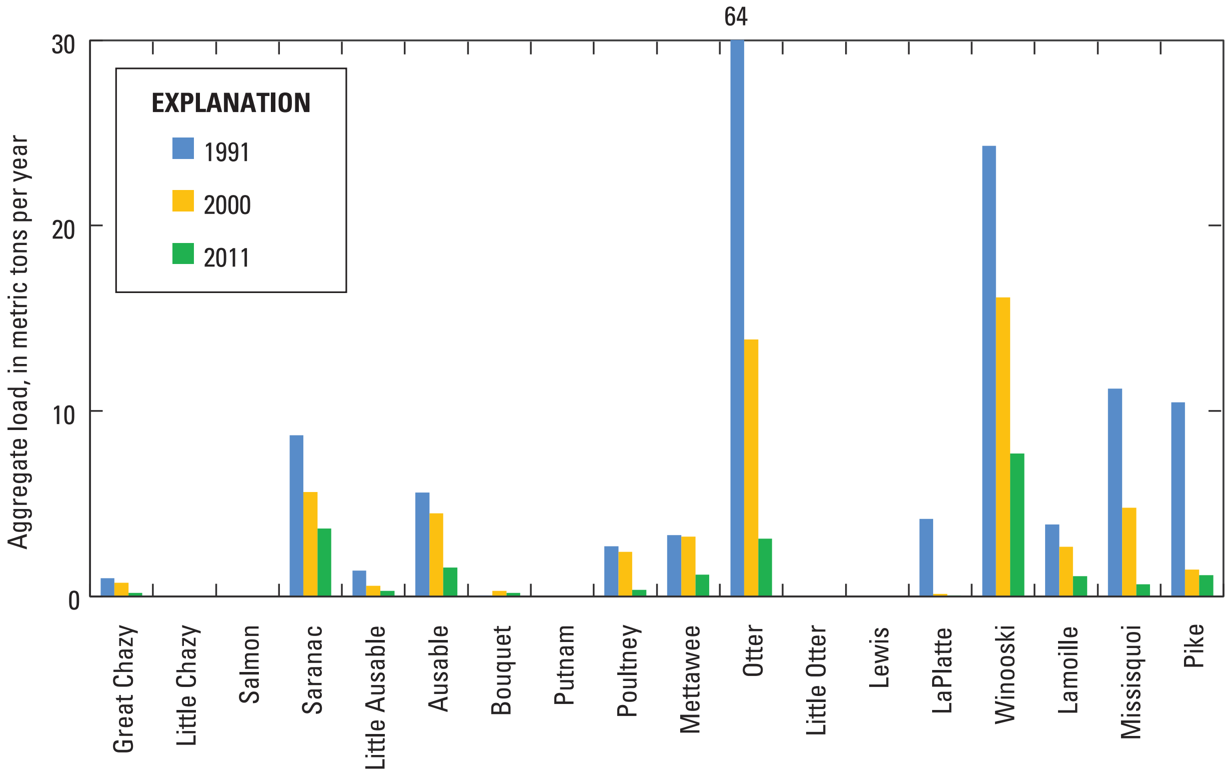

Figure 6. Aggregate reported point-source fluxes of total phosphorus for the 18 monitored Lake Champlain tributaries in 1991, 2000, and 2011.

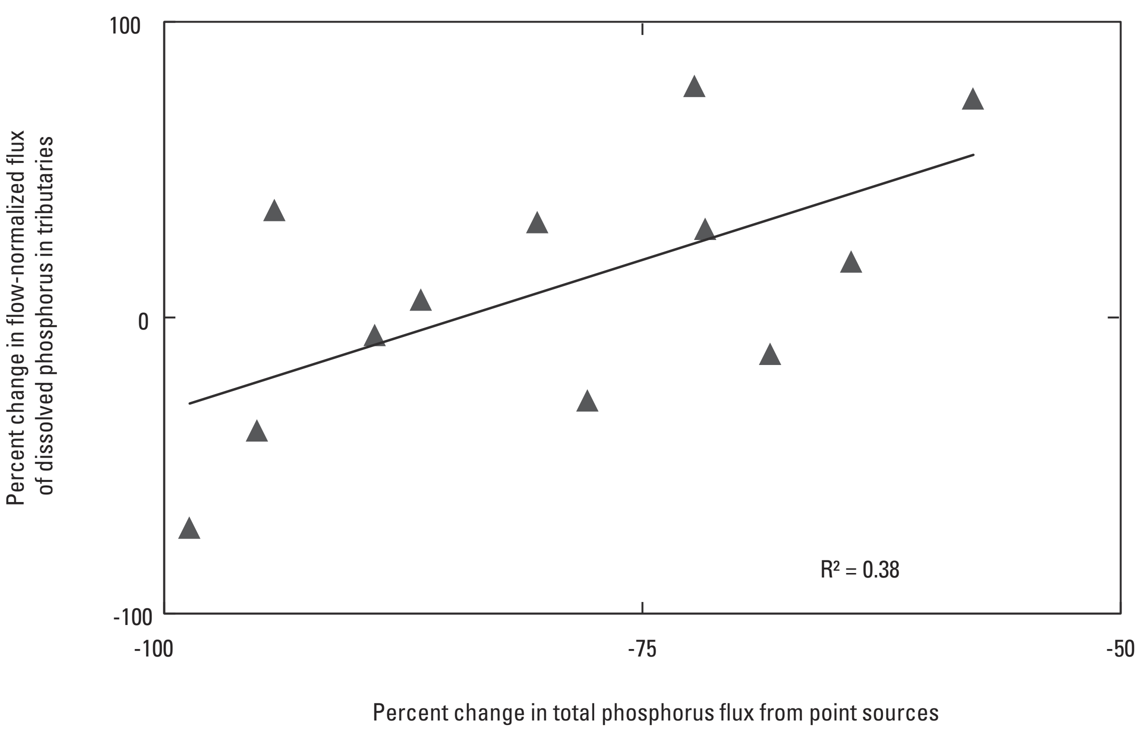

Figure 7. The relation between changes in flux of total phosphorus from point sources and in dissolved phosphorus from Lake Champlain tributaries from 1991 to 2011.

concentrations and yield at both the HUC8 and HUC12 scales. The change in acres of land in farms between 1987 and 2007 was positively correlated with the change in phosphorus concentration at the HUC8 scale and with the change in phosphorus flux at the HUC8 and the HUC12 scales. At the HUC8 scale, the change in acres of cropland between 1987 and 2007 was positively correlated with changes in phosphorus concentration. At all scales and over a 20-year time period, the change in acres of corn for grain or seed was positively correlated with changes in phosphorus concentrations and yields.

Best-Management Practices

Several significant negative correlations (and no positive correlations) were found between money spent on agricultural BMPs and changes in phosphorus concentration and flux (table 5). A negative correlation (for example, an increase in money spent on agricultural BMPs relates to a decrease in percent change of phosphorus concentration or flux) indicates a beneficial outcome that occurred synchronously with BMP implementation. Just as with other results presented, however, this does not necessarily demonstrate that BMPs are causing the reduction in phosphorus. Although the two metrics of agricultural BMP effectiveness used in this study (the number of BMPs implemented and the money spent on BMPs) are related, the finding of a number of significant results for money spent on BMPs and no significant results for the number of BMPs implemented indicates that projects that cost more money are more strongly related to a reduction in phosphorus (suggesting that perhaps money is well spent).

At the HUC8 scale, the change in phosphorus concentration during the period of record was negatively correlated with money spent on agricultural BMPs from 1995 to 1999 and from 1995 through 2010. Also at the HUC8 scale, the change in phosphorus flux during the period of record was negatively correlated with money spent on BMPs from 1995 to 1999. The only significant correlation between phosphorus concentration or flux and BMPs at the HUC12 scale was negative for concentration from 2001 to 2010 and money spent from 1995 to 1999. This latter correlation in addition to the incidence of several negative correlations for BMPs from 1995 to 1999 and changes in phosphorus concentration and flux during the longer time period suggests perhaps a possible delay between the time of BMP implementation and observed phosphorus reductions in Lake Champlain tributaries.

Summary and Conclusions

The second decade of the record (from 2000 through 2010) saw improvement (a decrease) in flow-normalized total phosphorus concentration and flux for most individual tributaries in the Lake Champlain Basin compared to the first decade (from 1990 through 2000). During the entire period of analysis (from 1990 through 2010), however, total phosphorus concentrations increased in most of the tributaries (10 increases and 5 decreases); similarly, the number of flux increases and decreases were 10 and 7, respectively. From 1990 through 2000, the total change in flow-normalized total phosphorus flux was a decrease of 21 metric tons (t). From 2000 through 2010, the total change was a decrease of 20 t, and overall from 1990 through 2010, the total change in flux was a decrease of 42 t. The basinwide flux picture across the two decades was first dominated by decreases in flux for Otter Creek and the Winooski and Missisquoi Rivers in decade I followed by the continued decrease in Otter Creek in decade II.

Basinwide, dissolved phosphorus flux in the Lake Champlain Basin increased by 0.7 metric tons per year (t/yr) during the period of analysis (from 1990 through 2010). Flux of dissolved phosphorus decreased in decade I, primarily because of the large decrease in Otter Creek of 20 t/yr. In decade II, large increases seen in Missisquoi and Saranac Rivers (9.5 and 3.3 t/yr) contributed to the basinwide increase in flux of dissolved phosphorus of 16 t/yr. Throughout the period of analysis, tributaries on the western side of the lake collectively increased by 17 t/yr, and tributaries on the eastern side collectively decreased by 17 t/yr. The effect of this net decrease was diminished by increases of 11 t/yr in the Missisquoi River and of 5.9 t/yr in the Saranac River.

Total nitrogen concentrations and flux for most individual tributaries and for the aggregate Lake Champlain Basin improved during the period of analysis. Between 1992 and 2010, flow-normalized total nitrogen flux decreased by 386 t (increase of 440 t between 1992 and 2000 and decrease of 826 t between 2000 and 2010); concentrations decreased in 14 tributaries, and flux decreased in 13 tributaries, with greater percent and absolute decreases generally for the western side of the lake. Between 2000 and 2010, decreases in concentration and flux were seen in 17 of the tributaries (Winooski was the exception), with the largest mass decreases in flux in Otter Creek and the Ausable River (-178 and -138 t/yr).

Large increases in flow-normalized chloride concentrations and flux that occurred between 1990 and 2000 shrank to small increases or decreases for individual tributaries between 2000 and 2010. Between 1990 and 2010, total flow-normalized chloride flux increased by 32,225 t, with 78 percent of that increase realized during the first decade. During the 21-year period of analysis, decreases in concentrations and flux of chloride were seen in two tributaries, the LaPlatte and Pike Rivers, both on the eastern side of the basin. During the 11-year period between 2000 and 2010, decreases were seen in five of the tributaries for both concentration and flux, in all cases from tributaries on the eastern side of Lake Champlain, although the total flux increase had contributions from both sides of the lake. Chloride trend results are in general agreement with published in-lake chloride concentration data and may be reflecting a decrease in winter road salt applications in Vermont since 1999.

Contour plots were used to demonstrate how various combinations of discharges and seasons influenced the difference between two selected years (a measure of trend) of annual estimates of total phosphorus concentrations. Contour plots of the differences between 1994 and 2010 of estimated daily phosphorus concentrations showed that many of the New York or western tributaries to Lake Champlain had the greatest increases in total phosphorus during the summer at all discharges and the greatest decreases in total phosphorus during the fall and winter at medium or high discharges. Tributaries on the eastern side of the lake lacked a uniform pattern for any of the seasons.

Significant correlations were found between physiographic province and concentration and flux of phosphorus but not between any of the measures of population density and phosphorus. The decreases in point source fluxes from 1991 to 2011 correlated positively with decreases in phosphorus concentrations and fluxes for the same period. Fluxes from point sources in 2000 and in 2010 were positively correlated with phosphorus flux for the same years. The percents of agricultural land and of agricultural land that intersected hydric soils in 2001 were positively correlated with 2001 phosphorus concentrations and yield at the HUC8 scale, as well as at the finer HUC12 scale. The change in acres of land in farms between 1987 and 2007 was positively correlated with the change in phosphorus concentration at the HUC8 scale and with the change in phosphorus flux at the HUC8 and the HUC12 scales. At the HUC8 scale, the change in acres of cropland between 1987 and 2007 was positively correlated with changes in phosphorus concentration. At all scales between 1987 and 2007, the change in acres of corn for grain or seed was positively correlated with changes in phosphorus concentrations and yields.

There were no significant correlations between the number of best-management practices (BMPs) and phosphorus concentration or flux in the Lake Champlain tributaries. The change in phosphorus concentration during the period of record was negatively correlated with money spent on implementation of BMPs from 1995 through 1999 and from 1995 through 2010 at the HUC8 scale. Also at the HUC8 scale, the change in phosphorus flux during the period of record was negatively correlated with money spent on BMPs from 1995 to 1999. The finding that there are some significant results for money spent on BMPs and no significant results for the number of BMPs suggests that costlier projects might be related to a greater reduction in phosphorus. Significant negative correlations between BMP measures from 1995 to 1999 and reductions in phosphorus concentration or flux during the period of record suggest a possible delay between the time of BMP implementation and observed phosphorus reductions in Lake Champlain tributaries.

References Cited

Cohn, T.A., 2005, Estimating contaminant loads in rivers—An application of adjusted maximum likelihood to type 1 censored data: Water Resources Research, v. 41, no. 7, W07003, doi:10.1029/2004WR003833.

Domagalski, J.L., and Johnson, Henry, 2012, Phosphorus and groundwater—Establishing links between agricultural use and transport to streams: U.S. Geological Survey Fact Sheet 2012–3004, 4 p. (Also available at http://pubs.usgs.gov/fs/2012/3004/.)

Ekholm, P., and Krogerus, K., 1998, Bioavailability of phosphorus in purified municipal wastewaters: Water Research, v. 32, no. 2, p. 343–351.

Fenneman, N.M., and Johnson, D.W., 1946, Physiographic divisions of the conterminous U.S.: U.S. Geological Survey water resources NSDI node, accessed June 12, 2012, at http://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml.

Hegman, William, Wang, Deane, and Borer, Catherine, 1999, Estimation of Lake Champlain basinwide phosphorus export: Grand Isle, Vermont, Lake Champlain Basin Program Technical Report 31, 81 p., accessed December 27, 2012, at http://www.lcbp.org/techreportPDF/31_NPS_phosphorus.pdf.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 510 p.

Hirsch, R.M., Moyer, D.L., and Archfield, S.A., 2010, Weighted regressions on time, discharge, and season (WRTDS) with an application to Chesapeake Bay river inputs: Journal of the American Water Resources Association, v. 46, no. 5, October, p. 857–880.

Lake Champlain Management Conference, 1996, Opportunities for action—An evolving plan for the future of the Lake Champlain Basin: Lake Champlain Basin Program, 132 p.

Lake Champlain Steering Committee, 2010, Opportunities for action, an evolving plan for the future of the Lake Champlain Basin, accessed July 10, 2012, at http://www.lcbp.org/PDFs/OpportunitiesForAction2010.pdf.

Medalie, Laura, Hirsch, R.M., and Archfield, S.A., 2012, Use of flow-normalization to evaluate nutrient concentration and flux changes in Lake Champlain tributaries, 1990–2009: Journal of Great Lakes Research, v. 38, supplement 1, p. 58–67.

Medalie, Laura, and Smeltzer, Eric, 2004, Status and trends of phosphorus in Lake Champlain and its tributaries, 1990–2000, *in* Manley, T.O., Manley, P.L., and Mihuc, T.B., eds., Lake Champlain—Partnership and research in the new millennium: New York, Kluwer Academic/Plenum Publishers, p. 191–219.

Moyer, D.L., Hirsch, R.M., and Hyer, K.E., 2012, Comparison of two regression-based approaches for determining nutrient and sediment fluxes and trends in the Chesapeake Bay watershed: U.S. Geological Survey Scientific Investigations Report 2012–5244, 118 p. (Also available online at http://pubs.usgs.gov/sir/2012/5244/.)

National Atmospheric Deposition Program, 2012, Annual data for site VT99 (Underhill): National Atmospheric Deposition Program, accessed November 6, 2012, at http://nadp.sws.uiuc.edu/nadpdata/annualReq.asp?site=VT99.

Natural Resources Conservation Service, [variously dated], Soil survey geographic (SSURGO) database for [various] count[ies], Vermont: Natural Resources Conservation Service, accessed December 15, 2010, at http://SoilDataMart.nrcs.usda.gov/.

Natural Resources Conservation Service, 2007, Hydrologic soil groups, chap. 7 *of* Hydrology: Natural Resources Conservation Service National Engineering Handbook, pt. 6, 14 p.

Puckett, L.J., 2004, Hydrogeologic controls on the transport and fate of nitrate in ground water beneath riparian buffer zones—Results from thirteen studies across the United States: Water Science and Technology, v. 39, no. 3, p. 47–53.

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load estimator (LOADEST)—A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods, book 4, chap. A5, 69 p.

SAS Institute, Inc., 2010, JMP, version 9.0.0: SAS Institute, Inc., accessed October 30, 2012, at http://www.jmp.com/software/.

Sharpley, A.N., Kleinman, P.J.A., Jordan, P., Bergström, L., and Allen, A.L., 2009, Evaluating the success of phosphorus management from field to watershed: Journal of Environmental Quality, v. 38, no. 5, p. 1981–1988.

Smeltzer, Eric, Dunlap, Fred, and Simoneau, Marc, 2009, Lake Champlain phosphorus concentrations and loading rates, 1990–2008: Lake Champlain Basin Program Technical Report No. 57, 41 p., accessed December 27, 2012, at http://www.lcbp.org/techreportPDF/57_Phosphorus_Loading_1990-2008.pdf.

Smeltzer, Eric, Shambaugh, A.D., and Stangel, Pete, 2012, Environmental change in Lake Champlain revealed by long-term monitoring: Journal of Great Lake Research, v. 38, supplement 1, p. 6–18.

Spahr, N.E., Dubrovsky, N.M., Gronberg, J.M., Franke, O.L., and Wolock, D.M., 2010, Nitrate loads and concentrations in surface-water base flow and shallow groundwater for selected basins in the United States, water years 1990–2006: U.S. Geological Survey Scientific Investigations Report 2010–5098, 39 p. (Also available at http://pubs.usgs.gov/sir/2010/5098/.)

Sprague, L.A., Hirsch, R.M., and Aulenbach, B.T., 2011, Nitrate in the Mississippi River and its tributaries, 1980 to 2008: Are we making progress?: Environmental Science & Technology, v. 45, no. 17, p. 7209–7216.

Stone Environmental, Inc., 2011, Identification of critical source areas of phosphorus within the Vermont sector of the Missisquoi Bay basin, Final report to the Lake Champlain Basin Program, accessed August 7, 2012, at http://www.lcbp.org/techreportPDF/63_Missisquoi_CSA.pdf, 242 p.

University of Vermont Spatial Analysis Laboratory, 2007, Generalized landcover/use for Champlain basin—SAL 2001 (LandLandcov_LULCLCB01): University of Vermont, accessed January 7, 2011, at http://www.vcgi.org/dataware/default.cfm?layer=LandLandcov_LCLULCB01.

U.S. Census Bureau, 2001, DemoCensus_BLCK2000, accessed December 12, 2008, at http://www.vcgi.org/dataware/?page=./search_tools/search_action.cfm&query=theme&theme_id=016-00402001.

U.S. Department of Agriculture, 1989, 1987 Census of Agriculture: Vermont State and County Data Volume 1 Geographic Area Series Part 45, U.S. Department of Agriculture AC87-A-45, 192 p. (Also available at http://agcensus.mannlib.cornell.edu/AgCensus/getVolumeOnePart.do?year=1987&part_id=107&number=45&title=Vermont).

U.S. Department of Agriculture, 1999, 1997 Census of Agriculture: Vermont State and County Data Volume 1 Geographic Area Series Part 45, U.S. Department of Agriculture AC97-A-45, 227 p. (Also available at http://www.agcensus.usda.gov/Publications/1997/Vol_1_National,_State_and_County_Tables/Vermont/index.asp).

U.S. Department of Agriculture, 2009, 2007 Census of Agriculture: Vermont State and County Data Volume 1 Geographic Area Series Part 45, U.S. Department of Agriculture AC-07-A-45, 337 p. (Also available at http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_2_County_Level/Vermont/).

U.S. Department of Agriculture, 2009, About the Census, accessed January 2, 2013, at http://www.agcensus.usda.gov/About_the_Census/index.php.

U.S. Geological Survey, 2012, 04290500 Winooski River near Essex Junction, VT: U.S. Geological Survey Water-Data Report 2011, accessed November 5, 2012, at http://wdr.water.usgs.gov/wy2011/pdfs/04290500.2011.pdf.

Vermont Agency of Natural Resources and New York State Department of Environmental Conservation, 2002, Lake Champlain phosphorus TMDL: Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 133 p. (Also available at http://www.vtwaterquality.org/lakes/docs/lp_lctmdl-report.pdf.)

Vermont Center for Geographic Information, 2012, 2010 census block boundaries and stats (DemoCensus_BLCK2010): Vermont Center for Geographic Information, accessed June 6, 2012, at http://www.vcgi.org/dataware/?page=./search_tools/search_action.cfm&query=theme.

Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 1998, Long-term water quality and biological monitoring project for Lake Champlain—cumulative data report for project years 1992–1996: Grand Isle, Vermont, Lake Champlain Basin Program Technical Report 26.

Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 2012, Lake Champlain long-term water quality and biological monitoring program—Program description: Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, accessed August 7, 2012, at http://www.anr.state.vt.us/dec/waterq/lakes/docs/lcmonitoring/lp_lclongtermprogdesc.pdf.

Walker, W.W., 1996, Simplified procedures for eutrophication assessment and prediction—User manual: U.S. Army Corps of Engineers Instruction Report W–96–2, September, 239 p. (Also available at https://wiki.umn.edu/pub/Nieber/WebHome/FLUX-Bathtub_MANUAL_IR-W-96_2.pdf.)

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Appendixes 1–8

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