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Lake Champlain Phosphorus Concentrations and Loading Rates, 1990-2008

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Cover photo by Angela Shambaugh

Abstract

Data from the Lake Champlain Basin Program's Long-Term Water Quality and Biological Monitoring Program were analyzed to determine the status and trends in lake phosphorus concentrations and tributary loading rates during 1990-2008. Phosphorus concentrations and loading rates were compared with the applicable water quality criteria and loading targets.

Lake phosphorus concentrations remained above the criteria values during all or nearly all years in five lake segments. Levels were below the targets during nearly all years in two lake segments, and the remaining six lake segments had borderline conditions where the mean phosphorus concentrations varied frequently above and below the criteria values. Four lake segments had significant increasing linear trends in phosphorus concentrations over the 1990-2008 time period, while no significant decreasing phosphorus trends were observed in any lake segment.

Phosphorus loading rates remained above the total loading capacities established in the Lake Champlain Phosphorus TMDL in all but two lake segments. There were no statistically significant linear trends either upward or downward in phosphorus loads for any individual tributary over the 1991-2008 time period, except for a marginally significant upward loading trend in the Winooski River and a marginally significant downward trend in the Pike River.

Wastewater phosphorus loads from facilities in Vermont, New York, and Québec declined by 75% over the 1990-2008 period and are currently below the limits specified in the Lake Champlain Phosphorus TMDL for all lake segment watersheds, with one exception. The wastewater portion of the total basinwide phosphorus loading rate declined from about 25% in 1991-1992 down to only 5% in 2007-2008.

Vermont contributed 60-70% of the total basinwide phosphorus loading to Lake Champlain during 1991-2008, with New York contributing 20-30% and Québec adding about 10%. Flow-weighted mean nonpoint source phosphorus concentrations were generally higher in the Vermont and Québec tributaries than in the New York rivers, indicating a higher density of nonpoint sources in Vermont and Québec watersheds.

While overall progress in reducing phosphorus in Lake Champlain has been disappointing, there were some positive signs in the results. Phosphorus loads and flow-weighted mean phosphorus concentrations in the inflows to most regions of the lake were stable or decreasing during 1991-2008 in spite of ongoing land use conversion and development in the watershed. Substantial reductions in wastewater phosphorus loading along with implementation of agricultural and urban nonpoint source controls may have offset new phosphorus sources created by land development.

Further insights are expected from a study in progress by the U.S. Geological Survey for the Lake Champlain Basin Program. This study will employ the most current statistical methods to account for the effects of hydrologic variations and phosphorus management efforts on trends in phosphorus loading to Lake Champlain.

Introduction

The Lake Champlain Basin Program has identified phosphorus reduction as one of the highest environmental management priorities for the lake[1]. Lake monitoring data have shown that phosphorus concentrations in the lake are higher than the allowable water quality criteria in many lake segments, resulting in algal blooms and other water quality impairments[2].

The Lake Champlain Phosphorus Total Maximum Daily Load (TMDL)[3] document prepared by the States of Vermont and New York and approved by the U.S. Environmental Protection Agency in 2002 established total phosphorus loading capacities for each lake segment watershed, and allocated those maximum capacities among the various jurisdictions and source categories. The Province of Québec and the State of Vermont signed a water quality agreement for Missisquoi Bay in 2002[4] that established maximum loading capacities and a division of responsibility for phosphorus reduction within Québec and Vermont portions of that watershed.

There has been a concerted effort for many years to reduce phosphorus loading to Lake Champlain. Vermont accelerated the funding of upgrades to wastewater treatment facilities during the 1990s in order to achieve statutory limits on the allowable phosphorus concentration in wastewater effluent. To date, over $40 million has been spent specifically on phosphorus removal upgrades for 35 treatment facilities throughout the basin in Vermont. A major funding initiative known as the Vermont Clean and Clear Action Plan[5] has provided nearly $100 million in state and federal funds since 2004 to support a wide range of water quality programs aimed primarily at reducing nonpoint sources of phosphorus to Lake Champlain.

In New York, many of the wastewater treatment facilities were built during the U.S Environmental Protection Agency construction grants era in the early and mid-1970s and, until recently, had been operating well beyond their expected life spans. Aging infrastructure and worn out equipment were no longer capable of providing today's desired level of treatment. As a result, since the mid-1990s, nearly $85 million has been invested in capital improvements to wastewater infrastructure throughout the New York portion of the basin. The effort has resulted in brand new facilities where none existed before, complete reconstruction of some facilities, and substantial upgrades to others. Treatment for phosphorus has been included in the reconstruction effort. In the nonpoint source sectors, approximately $15 million of combined funds have gone toward implementation of best management practices on both agricultural and non-agricultural lands to reduce phosphorus loadings to surface waters draining to Lake Champlain.

In Québec, around $26 million has been invested for brand new wastewater treatment facilities since 1992. Seven wastewater treatment facilities have been constructed and are now serving nine of the eleven sewered municipalities discharging wastewater in the Missisquoi Bay watershed. Two private facilities have also been put into place to treat wastewater originating from a ski resort area and a camp and trailer park. Two facilities, whose construction began in 2009, will allow treatment of the remaining sewered municipalities. Finally, a municipality whose dwellings currently rely on individual septic systems to treat their wastewaters will have both a sewer system and a wastewater plant in the near future. In addition to building new facilities, funding has been put aside to upgrade the existing wastewater treatment plants as part of the 2007-2017 Québec Action Plan on Blue-Green Algae. In this plan, the Québec Government recommends, among other things, that phosphorus from municipal point sources discharging into sensitive surface waters be further reduced. Over the past ten years, approximately $10 million of combined funds were invested to reduce phosphorus discharge to Missisquoi Bay from agricultural nonpoint sources.

With these significant efforts being made to reduce phosphorus in Lake Champlain, it is important to measure the results of these programs in a variety of ways. The ultimate measure of success will be attainment of the lake segment phosphorus concentration criteria established as management goals for the lake by New York, Québec, and Vermont[6]. The vast majority of phosphorus entering Lake Champlain is delivered by its tributaries rivers[7], and another key measure of progress is the extent to which the rate of phosphorus loading to the lake from these rivers is being reduced over time. The Lake Champlain Long-Term Water Quality and Biological Monitoring Program[8] was established by the Lake Champlain Basin Program in 1992 to provide a consistent set of monitoring data on the lake and its tributaries for purposes including phosphorus loading assessment. Data from this monitoring program are available to document in-lake phosphorus concentrations and tributary phosphorus loading rates, and to support the analysis of trends over time.

A previous study by the U.S. Geological Survey (USGS) and the Vermont Department of Environmental Conservation (DEC) on the status and trends of phosphorus in Lake Champlain analyzed lake phosphorus concentrations and tributary loadings over the period of 1990-2000[9]. That study found that phosphorus loads were consistently higher for most rivers than the targets established in the Lake Champlain Phosphorus TMDL. Statistical analysis of trends in flow-adjusted concentrations in the 18 monitored rivers found significant downward (improving) trends in two rivers, increasing concentration trends in six rivers, and no significant change in the remaining ten rivers. A similar analysis using data updated through 2004[10] found downward trends in flow-adjusted phosphorus concentrations in seven of these rivers, and increasing trends in three tributaries. However, phosphorus loading rates remained above the allowable amounts in all but one watershed.

Another collaborative study by the Vermont DEC and the Québec Ministry of Sustainable Development, Environment, and Parks (MDDEP) combined data from the Lake Champlain Long-Term Monitoring Program with tributary sampling results from the MDDEP to analyze phosphorus loading rates from multiple sub-basins within the Missisquoi Bay watershed in Québec and Vermont[11]. This analysis found statistically significant declines in phosphorus concentrations in the Pike River between the base period of 1990-1992 and the more recent monitoring period of 2001-2005, at equivalent flow rates. No changes occurred in the Missisquoi River, however. An updated analysis of phosphorus loading trends in Missisquoi Bay tributaries is planned in the near future.

Concentrations of phosphorus in a river are strongly influenced by the flow rate existing at the time of sampling, as well as anthropogenic factors such as land use activities, wastewater discharges, and other environmental modifications. Since loading rates are the product of the concentration and the flow, variations in precipitation and stream flow rates as a result of natural weather events or climate change can influence phosphorus loading rates and trends, independent of human impacts and management efforts in the watershed. Thus, in order to present a complete picture, it is informative to show concentrations and loads both in the actual state and with adjustments for flow. The U.S. Geological Survey (USGS) has developed a variety of statistical techniques to compensate for the influence of flow variability on trends in stream nutrient concentrations and loads[12]. These techniques have been further developed and applied in the Chesapeake Bay watershed[13] and nationally[14].

The purpose of the present report is to update the in-lake phosphorus concentration results and the estimates of phosphorus loading to Lake Champlain with data collected through 2008, using methods employed by the previous studies. Results will be documented for each of the lake segments, monitored tributaries, and lake segment watersheds. Current phosphorus concentrations and loading rates will be compared with the in-lake water quality criteria and the lake segment watershed loading targets established in the Lake Champlain Phosphorus TMDL. However, statistical analysis of loading trends over time will be limited to a simple examination of the actual loads during the period of 1991-2008.

More in-depth analysis of loading trends will be deferred to a study in progress by the USGS on Phosphorus Trend Analysis and Interpretation in the Lake Champlain Basin, in cooperation with the Lake Champlain Basin Program. The objectives of this USGS project are to (1) provide an analysis of changes in total phosphorus concentrations and flux from 1990-2009 for Lake Champlain tributaries and major lake stations, and (2) evaluate the role of watershed variables, including land use, demographics, point sources, and agricultural factors in total phosphorus trends. The project will bring national expertise within the USGS to assist with the Lake Champlain Basin analysis. A report is expected at the end of 2011.

Methods

Lake Sampling

The Lake Champlain Long-Term Water Quality and Biological Monitoring Program includes the core set of 15 lake stations shown in Figure 1. These lake stations have been sampled consistently during the entire monitoring period since 1992, with the exception of lake stations 9 and 16 which were added in 2001, and station 51 which was added in 2006. The lake stations were sampled for total phosphorus and several other variables using Kemmerer or Van Dorn water bottle devices, with discrete depth samples combined to form vertical water column composites. The lake stations were sampled approximately biweekly between May and early November each year. When thermal stratification existed, composite samples (composed of 2-3 discrete-depth samples) were obtained from both the epilimnion and hypolimnion layers. However, the phosphorus data used in the analysis for this report were limited to those obtained from the epilimnion layer or during unstratified conditions only. The data were supplemented for this analysis with comparable results obtained during 1990-1991 from a previous study[15].

Total phosphorus samples were immediately placed without filtration or preservation into 75 ml borosilicate glass test tubes. The phosphorus samples were then analyzed at the Vermont Department of Environmental Conservation (DEC) Laboratory using acid-persulfate digestion in their original containers followed by colorimetric analysis using the ascorbic acid method[15,16].

Tributary Sampling

The Lake Champlain long-term tributary sampling network includes the 21 rivers shown in Figure 1. The tributary sampling stations were located as near to the river mouths as possible where access by road bridges is available. Eighteen of these sites have been sampled at the same locations using consistent methods since 1990 as part of the Lake Champlain Long-Term Monitoring Program (1992-2008), or during a previous phosphorus loading assessment (1990-1992). More recently added tributary stations on the Rock River, Stevens Brook, and Jewett Brook were not included in this analysis because of the limited monitoring record available.

Samples for analysis of total phosphorus and a number of other water quality parameters were obtained manually from bridges using depth and velocity-integrating sampling devices. An effort was made to obtain as high a proportion of samples as possible during high flow conditions in order to improve the precision of tributary annual mass loading estimates. Beginning in 2006, four collections during base flow conditions were added to the program. The number of phosphorus samples obtained annually at each site ranged from 13-72 (median = 31) during the initial 1990-1991 period of more intensive monitoring, and from 4-29 (median = 14) during 1992-2008. Laboratory total phosphorus analyses were conducted using the same methods as for lake samples.

The Québec MDDEP has operated a water quality sampling station on the Pike River since 1979 (Station no. 03040015) at the same location as the site sampled by the Lake Champlain Long-Term Monitoring Program. Total phosphorus concentration results from the Québec program[17] during the period of water years 1991-2008 were added to the data from the Lake Champlain Long-Term Monitoring Program to supplement the dataset available for the Pike River. Differences in laboratory analytical methods required an adjustment to the Québec total

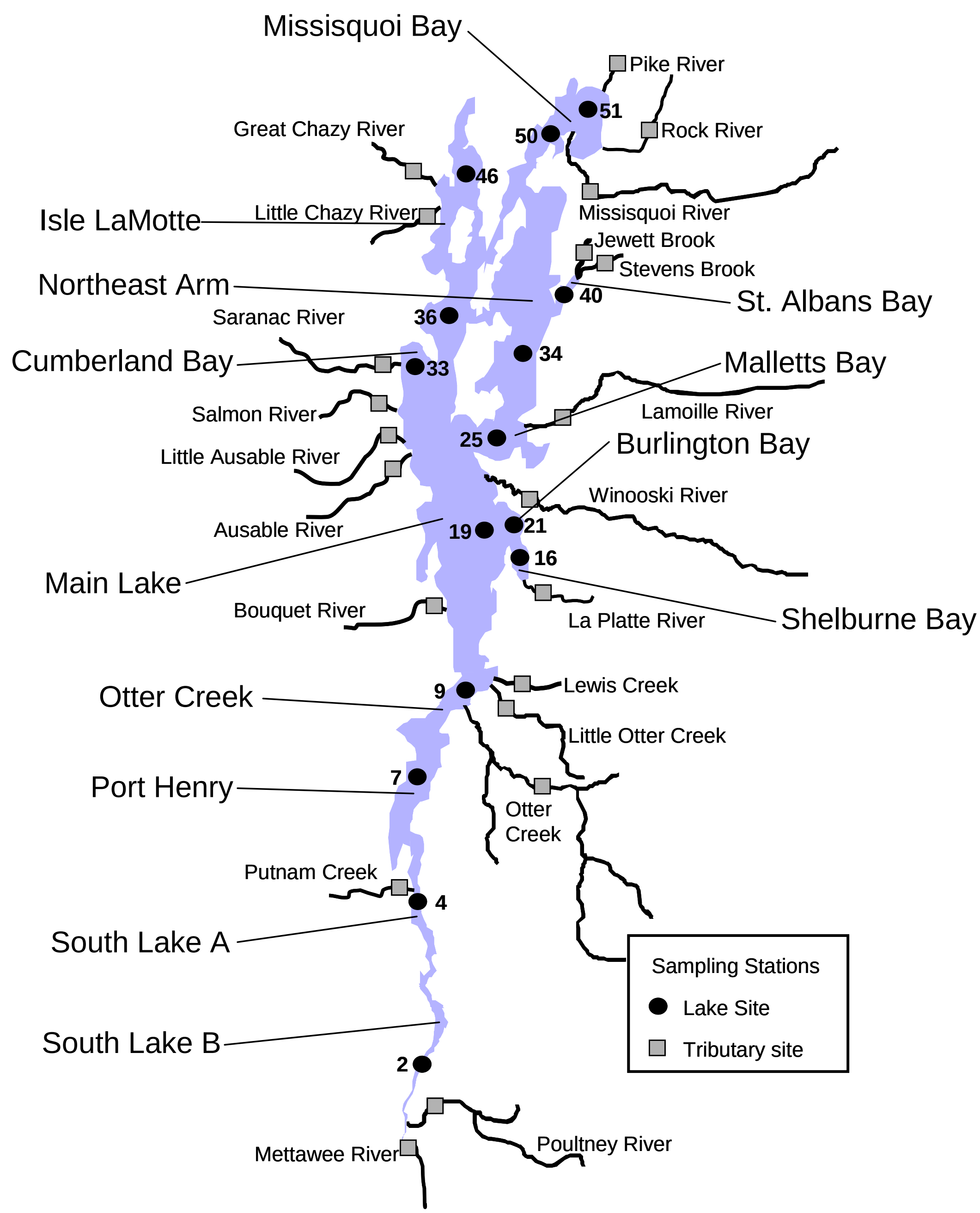

Figure 1. Lake Champlain phosphorus management segments and lake and tributary sampling stations.

phosphorus results in order to make them consistent with the data produced by the Vermont DEC Laboratory.

Tributary Flow Measurements

Each of the 18 tributary monitoring stations used in this analysis is located on a river having one or more long-term, continuous flow gages operated by the USGS or the Québec MDDEP. The flow gage stations used for this analysis are listed in Table 1. Collectively, these flow gage stations capture 76% of the total 19,881 km^2 watershed area of Lake Champlain. At their mouths, these rivers drain 87% of the total lake watershed. Phosphorus loading estimates were made using final, approved data on average daily flows for water years 1991-2008, available from USGS websites or from the Québec MDDEP.

Wastewater Phosphorus Loads

Loads of phosphorus were estimated annually for all wastewater treatment facilities in the Lake Champlain Basin. There are currently 60 facilities in Vermont, 29 facilities in New York, and 9 facilities in Québec, although these numbers have varied over time as new treatment plants were constructed or facilities were consolidated. Wastewater phosphorus loading estimates were based on annual averages of the monthly effluent total phosphorus concentrations and the monthly flows at these facilities, as reported by the facility operators to the state or provincial regulatory agencies. Laboratory analyses of total phosphorus concentrations were done according to approved methods and quality assurance procedures[18]. The wastewater phosphorus loading data were compiled annually on a calendar year basis from government records as part of the Lake Champlain Long-Term Monitoring Program.

Requirements to monitor wastewater effluent for phosphorus were phased in gradually over the 1991-2008 period. Where effluent phosphorus concentration measurements were lacking for some facilities, results for the same facility obtained during subsequent years were used to replace the previous missing values in cases where the level of treatment had not changed. Wastewater phosphorus concentrations and loads were estimated for all facilities in the Lake Champlain Basin during 1991 as part of a previous study. No wastewater phosphorus data were compiled during 1992-1994. For the purposes of this analysis, it was assumed that the 1991 loads applied during the 1992-1994 period as well.

Tributary Phosphorus Load Estimation

Phosphorus loads in Lake Champlain tributary rivers were estimated using the U.S. Army Corps of Engineers FLUX program[19,20]. The FLUX program has been used to estimate tributary phosphorus loading to Lake Champlain in several previous applications[7,9,11,21].

The FLUX program was used to examine the log-scale relationships between the phosphorus concentration and the average daily flow at the corresponding gage on the dates sampled. When more than one sample was obtained on the same date, the concentration results were composited into a single day average. In cases where statistically significant ($p<0.10$) regression relationships existed between concentration and flow, and residuals were randomly distributed, loading estimates were derived from these regressions by multiplying the predicted concentrations times the mean daily flows (FLUX Method 6). When the regression residuals were found to be dependent on flow (not randomly distributed), separate regression relationships were established for different flow strata in order to eliminate the residual dependence. For

Table 1. List of Lake Champlain Basin stream flow gages used for tributary phosphorus load estimation.

Tributary	Gage Location	Site No.	Agency	Drainage Area at Gage (km^2)	Drainage Area at Mouth (km^2)
Ausable	Au Sable Forks, NY	04275500	USGS	1155	1328
Bouquet	Willsboro, NY	04276500	USGS	699	704
Great Chazy	Perry Mills, NY	04271500	USGS	629	773
Little Ausable	Valcour, NY	04273800	USGS	176	189
Little Chazy	Chazy, NY	04271815	USGS	130	138
Mettawee	Middle Granville, NY	04280450	USGS	432	1097
Putnam	Crown Point Center, NY	04276842	USGS	134	160
Salmon	S. Plattsburgh, NY	04273700	USGS	164	175
Saranac	Plattsburgh, NY	04273500	USGS	1574	1591
Pike	Bedford, QC	030420	MDDEP	404	667
Lamoille	E. Georgia, VT	04292500	USGS	1776	1872
LaPlatte	Shelburne Falls, VT	04282795	USGS	115	137
Lewis	N. Ferrisburg, VT	04282780	USGS	200	210
Little Otter	Ferrisburg, VT	04282650	USGS	148	189
Missisquoi	Swanton, VT	04294000	USGS	2201	2240
New Haven[a]	Brooksville, VT	04282525	USGS	298	
Otter	Middlebury, VT	04282500	USGS	1626	2444
Poultney	Fair Haven, VT	04280000	USGS	484	681
Winooski	Essex Jct., VT	04290500	USGS	2703	2753

[a] The New Haven River is a tributary to the Otter Creek that is not sampled, but is included in the gage network to supplement the hydrologic coverage for the Otter Creek watershed. Average daily flows in the New Haven River were added to the average daily flows at the Otter Creek gage for use in estimating phosphorus loads in Otter Creek.

tributaries where no significant concentration-flow relationships existed, load estimates were derived from the flow-weighted mean concentration, using the mean flow for the entire averaging period (FLUX Method 2). An error-analysis procedure in the FLUX program was used to estimate the coefficient of variation (CV) for the mean loads and their 95% confidence intervals.

Mean phosphorus loading rates from each tributary were calculated for two-year intervals based on water years (ending September 30 of the indicated year). Combining two water years was necessary in order to obtain a sufficient sample size and acceptable precision in the mean loading estimates for each time interval. Separate concentration-flow relationships were developed for each two-year interval using the phosphorus concentration results and the stream flows measured at the gage stations during that interval.

The loading estimates produced by the FLUX program were adjusted to represent the phosphorus loads delivered at the river mouths. This adjustment involved (1) subtracting the wastewater loads discharged upstream of the monitoring stations during the corresponding time interval from the initial FLUX loading estimates, (2) multiplying the remaining "nonpoint source" loads by the ratio of the river drainage area at the mouth to the drainage area at the flow gage (Table 1), and then (3) adding the upstream wastewater load to the total nonpoint source load at the river mouth.

An alternative method for calculating constituent loads in rivers is provided by the USGS LOADEST program[22]. LOADEST is a multiple-parameter regression model that predicts concentrations as various functions of streamflow, decimal time, and additional user-specified data variables. Concentration prediction estimates in LOADEST can incorporate the effects of both stream flow and seasonality, and both FLUX and LOADEST handle potential bias resulting from transforming estimates from the log-regression back into original units[12,19].

In order to check whether the additional parameters and model options provided by the LOADEST program produced load estimates that were different or more precise than those obtained from FLUX, loading estimates for two Lake Champlain tributaries were calculated using LOADEST methods with the same data set employed for the FLUX program estimates. LOADEST estimates of mean phosphorus loads in the Winooski River and Lewis Creek for each two-year water year interval were based on the concentrations and the corresponding average daily flow measurements within each time interval (L. Medalie, USGS, personal communication, 6/2/09). Automated procedures within the LOADEST program were used to select the optimum regression model for each time interval.

Flow rates in this report are expressed in units of cubic hectometers per year (1 $hm^3/yr = 10^6$ m^3/yr). Phosphorus loading rates are expressed in units of metric tons per year (1 mt/yr = 1,000 kg/yr) as total phosphorus (P).

Results

Lake Phosphorus Concentrations

Annual mean total phosphorus concentrations at each sampling station during 1990-2008 are shown in Figure 2. Each of the lake segments for which phosphorus concentration criteria and watershed loading targets have been established includes at least one sampling station (Figure 1). Data from stations 36 and 46 were averaged to represent conditions in the Isle LaMotte segment. Data from station 51 in Missisquoi Bay were not included in the analysis because of the short monitoring record at that station. The results are shown in comparison with the in-lake total phosphorus concentration criteria established for each lake segment by New York, Québec, and Vermont.

Annual mean phosphorus concentrations exceeded the target values during all or nearly all years of the monitoring period in five lake segments, including South Lake A, Main Lake, Northeast Arm, St. Albans Bay, and Missisquoi Bay. Phosphorus levels remained below the applicable criteria during nearly all years in Burlington Bay and Cumberland Bay. The remaining lake segments had borderline conditions where the mean phosphorus concentrations varied frequently above and below the criteria values.

The statistical significance of trends in lake phosphorus concentrations over time was determined by testing the null hypothesis that the slope of the simple linear regression of the annual mean concentrations vs. year was equal to zero. Four lake segments had significant increasing linear trends in phosphorus concentrations over the 1990-2008 time period, including the Port Henry, Malletts Bay, Northeast Arm, and St. Albans Bay segments (Figure 2). No significant decreasing phosphorus trends were observed for any lake segment.

Tributary Phosphorus Loads

The phosphorus loading results for each tributary and two-year interval are listed in Table 2 and shown in Figure 3. Variations in mean loading rates over time were strongly related to variations in the mean flows during each time interval, as would be expected. The upstream wastewater portions of the total loads declined over the 1990-2008 time period in all tributaries where such discharges were present.

Comparison with LOADEST Estimates

The comparison of loading estimates produced by the FLUX and LOADEST programs for the Winooski River and Lewis Creek are shown in Figure 4. These loading estimates were made without adjustment for downstream watershed areas. The mean phosphorus loading estimates produced from the same data set by the FLUX and the LOADEST programs were similar in both magnitude and precision. No bias was apparent between the results from the two programs. This comparison suggests that FLUX and LOADEST could be used interchangeably with this data set for the purpose of calculating annual mean phosphorus loads from Lake Champlain tributaries.

Wastewater Phosphorus Loads

The annual wastewater phosphorus loads from each facility were summed by lake segment and listed in Table 3 for each two-year calendar year interval during 1991-2008. The total wastewater phosphorus load delivered to Lake Champlain has declined by 75% over this time period. The

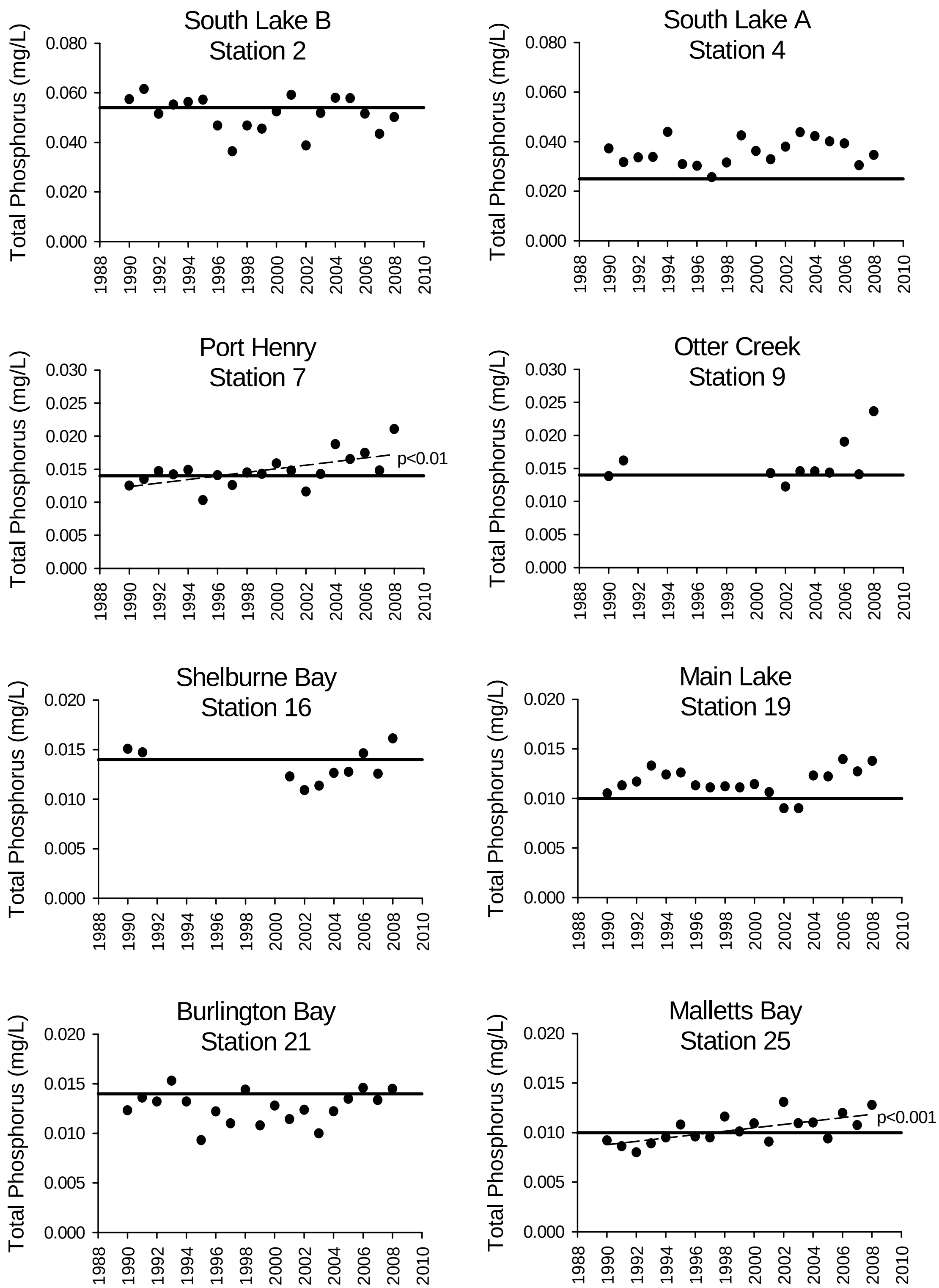

Figure 2. Annual mean total phosphorus concentrations in Lake Champlain segments during 1990-2008 in comparison with the applicable water quality criterion (solid horizontal lines). Dotted lines indicate significant linear trends ($p<0.05$). Note that the scales vary.

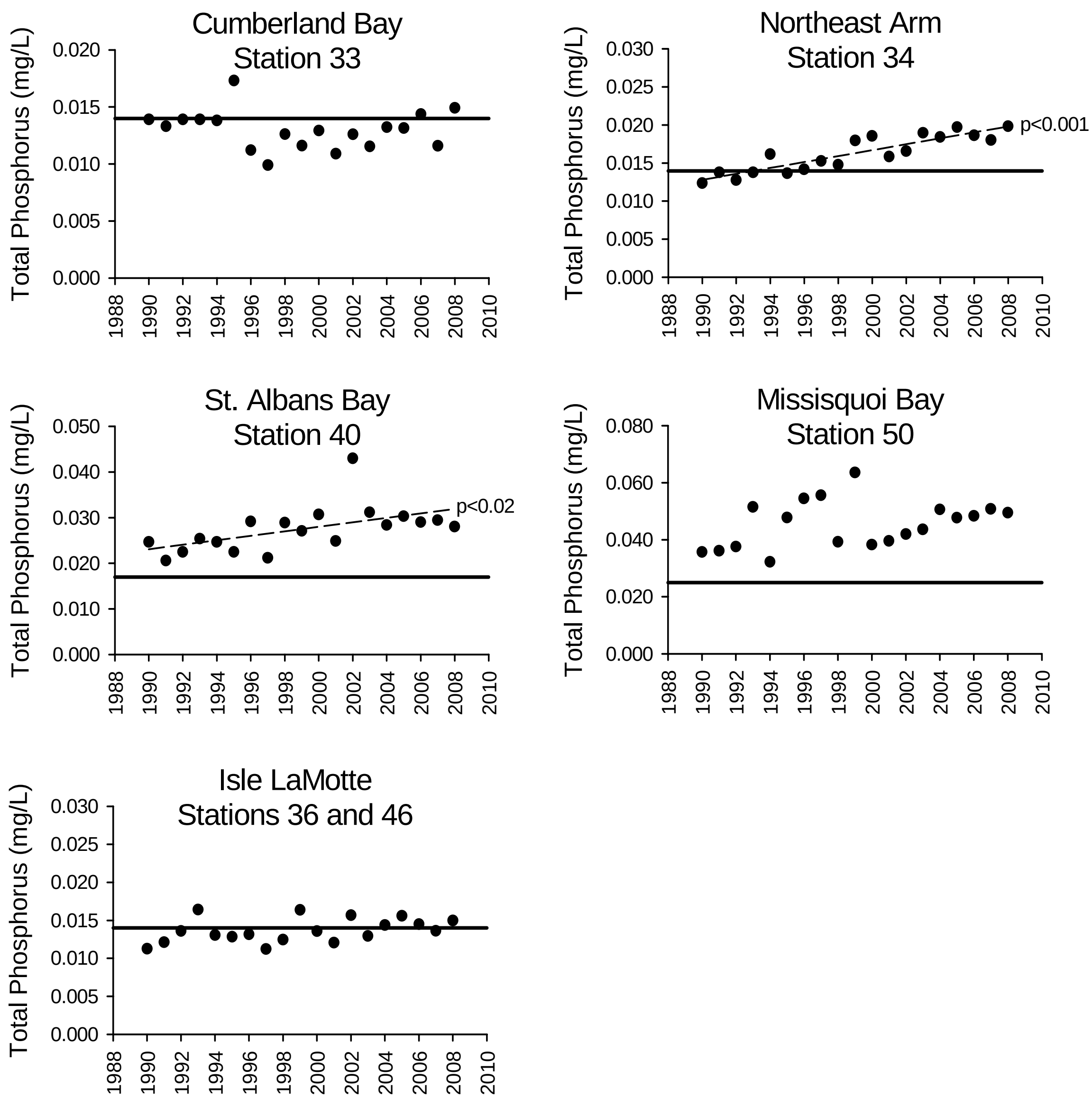

Figure 2 (cont.). Annual mean total phosphorus concentrations in Lake Champlain segments during 1990-2008 in comparison with the applicable water quality criterion (solid horizontal lines). Dotted lines indicate significant linear trends ($p<0.05$). Note that the scales vary.

Table 2. Tributary mean phosphorus load estimation results.

Tributary	Water Years	N[a]	FLUX Method[b]	Strata Bounds[c] (hm^3/yr)	Flow at Gage (hm^3/yr)	Load at Gage Station (mt/yr)	CV[d]	Upstream Wastewater Load[e] (mt/yr)	Nonpoint Load at Mouth (mt/yr)	Total Load at Mouth (mt/yr)
Missisquoi	1991-1992	48	6	1332	1332	106.5	0.102	11.206	97.0	108.2
Missisquoi	1993-1994	23	6		1351	109.5	0.148	11.206	100.1	111.3
Missisquoi	1995-1996	20	6		1515	109.9	0.138	8.066	103.6	111.7
Missisquoi	1997-1998	30	6	1736	1736	207.3	0.126	5.710	205.2	210.9
Missisquoi	1999-2000	23	6		1518	125.8	0.145	4.826	123.1	128.0
Missisquoi	2001-2002	30	6		1400	114.1	0.133	2.401	113.7	116.1
Missisquoi	2003-2004	36	6	1763	1763	159.9	0.115	2.158	160.6	162.7
Missisquoi	2005-2006	44	6	1787	1787	164.0	0.099	1.953	165.0	166.9
Missisquoi	2007-2008	40	6	3000	1973	167.0	0.123	1.299	168.7	170.0
Pike	1991-1992	67	6		251	59.6	0.156	10.479	81.1	91.6
Pike	1993-1994	45	6		266	40.2	0.128	10.479	49.1	59.6
Pike	1995-1996	31	6	239	239	37.6	0.134	1.630	59.4	61.1
Pike	1997-1998	44	6	498	498	69.8	0.076	1.223	113.3	114.5
Pike	1999-2000	39	6		194	24.2	0.119	1.438	37.6	39.0
Pike	2001-2002	50	6	164	164	17.7	0.115	1.476	26.8	28.3
Pike	2003-2004	63	6		217	26.6	0.105	1.391	41.6	43.0
Pike	2005-2006	67	6	241	241	32.6	0.111	1.314	51.7	53.0
Pike	2007-2008	48	6		238	22.5	0.081	1.453	34.8	36.2
Lamoille	1991-1992	47	6	1000	1207	39.6	0.088	3.892	37.6	41.5
Lamoille	1993-1994	24	6	1200	1135	32.3	0.046	3.892	29.9	33.8
Lamoille	1995-1996	19	6	1200	1167	35.7	0.069	3.474	34.0	37.4
Lamoille	1997-1998	31	6	2000	1377	84.4	0.179	2.841	85.9	88.7
Lamoille	1999-2000	25	6		1181	51.7	0.186	2.351	52.0	54.3
Lamoille	2001-2002	31	6	3000	1122	46.2	0.148	2.465	46.1	48.6
Lamoille	2003-2004	38	6	3000	1295	54.7	0.097	2.228	55.3	57.5
Lamoille	2005-2006	41	6	2000	1359	54.1	0.057	2.258	54.6	56.9
Lamoille	2007-2008	41	6		1460	57.2	0.135	1.621	58.6	60.2
Winooski	1991-1992	49	6	1500	1697	115.0	0.104	24.310	92.4	116.7
Winooski	1993-1994	24	6		1542	108.2	0.139	24.310	85.4	109.7
Winooski	1995-1996	19	6	1500	1688	137.1	0.218	20.484	118.7	139.2
Winooski	1997-1998	29	6		1937	178.9	0.137	17.623	164.2	181.8
Winooski	1999-2000	22	6		1726	151.4	0.177	15.517	138.4	153.9
Winooski	2001-2002	31	6		1402	95.7	0.119	14.531	82.7	97.2
Winooski	2003-2004	36	6	2000	1701	138.9	0.153	11.955	129.3	141.2
Winooski	2005-2006	42	6	2000	2081	179.6	0.157	10.672	172.0	182.7
Winooski	2007-2008	39	6		2202	231.2	0.121	8.761	226.5	235.3
LaPlatte	1991-1992	45	6		40	10.7	0.084	4.177	7.8	11.9
LaPlatte	1993-1994	36	2		36	5.7	0.157	4.177	1.8	6.0
LaPlatte	1995-1996	21	2		41	7.5	0.166	0.182	8.7	8.9
LaPlatte	1997-1998	30	6		51	7.2	0.108	0.082	8.5	8.6
LaPlatte	1999-2000	24	6		41	4.3	0.139	0.109	5.0	5.1
LaPlatte	2001-2002	30	6		30	4.6	0.139	0.088	5.4	5.4
LaPlatte	2003-2004	35	6		45	6.7	0.132	0.062	7.9	7.9
LaPlatte	2005-2006	42	6		57	6.5	0.118	0.060	7.7	7.7
LaPlatte	2007-2008	37	6	100	61	5.9	0.100	0.095	6.9	7.0

Tributary	Water Years	N[a]	FLUX Method[b]	Strata Bounds[c] (hm³/yr)	Flow at Gage (hm³/yr)	Load at Gage Station (mt/yr)	CV[d]	Upstream Wastewater Load[e] (mt/yr)	Nonpoint Load at Mouth (mt/yr)	Total Load at Mouth (mt/yr)
Lewis	1991-1992	47	6		99	7.7	0.110	0.000	8.1	8.1
Lewis	1993-1994	33	6		83	4.6	0.124	0.000	4.8	4.8
Lewis	1995-1996	18	6		92	6.2	0.170	0.000	6.6	6.6
Lewis	1997-1998	29	6		99	9.6	0.126	0.000	10.0	10.0
Lewis	1999-2000	24	6		96	10.6	0.178	0.000	11.2	11.2
Lewis	2001-2002	32	6		62	5.6	0.118	0.000	5.9	5.9
Lewis	2003-2004	31	6		87	9.0	0.137	0.000	9.5	9.5
Lewis	2005-2006	44	6		117	13.0	0.131	0.000	13.7	13.7
Lewis	2007-2008	36	6	100	113	8.6	0.069	0.000	9.0	9.0
Little Otter	1991-1992	48	6		56	7.3	0.078	0.000	9.3	9.3
Little Otter	1993-1994	28	6		45	5.5	0.165	0.000	7.1	7.1
Little Otter	1995-1996	21	6		59	7.4	0.081	0.000	9.5	9.5
Little Otter	1997-1998	29	6		64	12.0	0.130	0.000	15.4	15.4
Little Otter	1999-2000	24	6		54	7.1	0.120	0.000	9.1	9.1
Little Otter	2001-2002	31	6		38	4.6	0.136	0.000	5.9	5.9
Little Otter	2003-2004	30	6		57	8.2	0.117	0.000	10.5	10.5
Little Otter	2005-2006	44	6		62	8.5	0.096	0.000	10.9	10.9
Little Otter	2007-2008	36	6		78	9.4	0.095	0.000	12.0	12.0
Otter	1991-1992	55	2		977	118.9	0.125	63.950	69.8	133.8
Otter	1993-1994	29	2		1103	104.9	0.114	63.950	52.0	116.0
Otter	1995-1996	21	6		1128	88.8	0.114	14.975	93.8	108.8
Otter	1997-1998	30	6		1282	136.0	0.129	20.728	146.4	167.1
Otter	1999-2000	25	6		1145	87.1	0.126	18.774	86.8	105.6
Otter	2001-2002	31	6		939	58.6	0.122	4.837	68.3	73.1
Otter	2003-2004	30	6		1089	88.7	0.154	4.246	107.3	111.6
Otter	2005-2006	44	6		1340	102.0	0.078	4.466	123.9	128.4
Otter	2007-2008	36	6		1458	120.9	0.121	4.267	148.2	152.5
Poultney	1991-1992	40	6	100	226	21.5	0.198	2.701	26.4	29.1
Poultney	1993-1994	28	6		257	22.6	0.116	2.701	27.9	30.6
Poultney	1995-1996	18	6	150	234	23.1	0.170	2.977	28.3	31.2
Poultney	1997-1998	29	6	150	239	26.1	0.156	2.609	33.0	35.6
Poultney	1999-2000	25	6		245	25.3	0.131	2.254	32.4	34.7
Poultney	2001-2002	26	6	200	196	14.4	0.125	1.055	18.8	19.8
Poultney	2003-2004	32	6		296	27.6	0.159	0.355	38.3	38.7
Poultney	2005-2006	42	6	200	284	24.9	0.136	0.359	34.5	34.9
Poultney	2007-2008	30	6	100	331	23.5	0.084	0.303	32.6	32.9
Mettawee	1991-1992	43	6		207	15.8	0.131	3.305	31.7	35.0
Mettawee	1993-1994	29	6	400	253	25.2	0.145	3.305	55.5	58.8
Mettawee	1995-1996	23	6		221	24.3	0.169	3.244	53.4	56.6
Mettawee	1997-1998	32	6	400	254	35.3	0.182	3.343	81.2	84.6
Mettawee	1999-2000	25	6		251	22.4	0.074	3.225	48.6	51.8
Mettawee	2001-2002	27	6	400	102	8.4	0.152	2.955	13.8	16.8
Mettawee	2003-2004	33	6		270	24.6	0.179	3.099	54.6	57.7
Mettawee	2005-2006	42	6	300	290	25.1	0.090	2.539	57.3	59.8
Mettawee	2007-2008	30	6	200	298	24.7	0.125	1.500	58.9	60.4
Great Chazy	1991-1992	39	6		276	16.8	0.175	0.979	19.4	20.4
Great Chazy	1993-1994	20	6	200	330	22.7	0.172	0.979	26.7	27.7

Tributary	Water Years	N[a]	FLUX Method[b]	Strata Bounds[c] (hm^3/yr)	Flow at Gage (hm^3/yr)	Load at Gage Station (mt/yr)	CV[d]	Upstream Wastewater Load[e] (mt/yr)	Nonpoint Load at Mouth (mt/yr)	Total Load at Mouth (mt/yr)
Great Chazy	1995-1996	18	6		297	24.9	0.197	0.436	30.1	30.5
Great Chazy	1997-1998	18	6	400	403	32.6	0.344	0.455	39.5	39.9
Great Chazy	1999-2000	21	6		325	27.7	0.210	0.661	33.2	33.9
Great Chazy	2001-2002	34	6	500	263	15.6	0.162	0.553	18.5	19.0
Great Chazy	2003-2004	29	6		319	23.0	0.131	0.349	27.8	28.2
Great Chazy	2005-2006	32	6	400	344	18.8	0.095	0.265	22.8	23.0
Great Chazy	2007-2008	27	2		332	20.4	0.166	0.223	24.8	25.0
Little Chazy	1991-1992	43	2		44	4.5	0.252	0.000	4.8	4.8
Little Chazy	1993-1994	21	2		52	3.6	0.179	0.000	3.8	3.8
Little Chazy	1995-1996	18	2		52	5.3	0.210	0.000	5.6	5.6
Little Chazy	1997-1998	19	2		76	6.9	0.233	0.000	7.3	7.3
Little Chazy	1999-2000	23	2		58	8.0	0.350	0.000	8.4	8.4
Little Chazy	2001-2002	34	2		45	4.3	0.242	0.011	4.5	4.6
Little Chazy	2003-2004	29	2		54	6.1	0.243	0.016	6.5	6.5
Little Chazy	2005-2006	32	2		66	5.1	0.109	0.046	5.4	5.4
Little Chazy	2007-2008	28	6		68	4.5	0.133	0.045	4.7	4.8
Saranac	1991-1992	45	6		783	18.8	0.064	8.686	10.2	18.9
Saranac	1993-1994	24	6		878	25.5	0.077	8.686	17.0	25.6
Saranac	1995-1996	21	6		773	22.8	0.118	4.958	18.0	23.0
Saranac	1997-1998	20	6		1078	28.8	0.110	5.068	24.0	29.0
Saranac	1999-2000	23	6		874	24.5	0.075	5.178	19.5	24.7
Saranac	2001-2002	34	6		769	18.8	0.063	6.894	12.0	18.9
Saranac	2003-2004	29	2		888	25.6	0.074	5.633	20.2	25.8
Saranac	2005-2006	32	6		982	26.4	0.049	5.164	21.5	26.6
Saranac	2007-2008	27	6		1026	26.3	0.060	4.454	22.1	26.5
Salmon	1991-1992	42	6		55	2.2	0.190	0.000	2.4	2.4
Salmon	1993-1994	20	6		62	3.2	0.188	0.000	3.4	3.4
Salmon	1995-1996	21	6		52	2.0	0.170	0.000	2.2	2.2
Salmon	1997-1998	19	6		91	3.9	0.177	0.000	4.1	4.1
Salmon	1999-2000	23	6		64	3.1	0.163	0.000	3.3	3.3
Salmon	2001-2002	34	6		50	1.9	0.113	0.000	2.0	2.0
Salmon	2003-2004	30	6		56	2.3	0.107	0.000	2.5	2.5
Salmon	2005-2006	32	6		62	2.0	0.081	0.000	2.1	2.1
Salmon	2007-2008	28	6		67	2.2	0.093	0.000	2.4	2.4
Little Ausable	1991-1992	44	6		43	3.5	0.237	1.403	2.3	3.7
Little Ausable	1993-1994	19	6		45	4.7	0.321	1.403	3.6	5.0
Little Ausable	1995-1996	20	2		45	4.7	0.282	0.511	4.5	5.0
Little Ausable	1997-1998	19	2		89	7.1	0.297	0.593	7.0	7.6
Little Ausable	1999-2000	23	2		61	7.2	0.254	0.515	7.2	7.7
Little Ausable	2001-2002	32	2		39	2.8	0.125	0.762	2.2	3.0
Little Ausable	2003-2004	30	6		48	3.7	0.135	0.426	3.5	4.0
Little Ausable	2005-2006	32	2		59	4.8	0.146	0.525	4.6	5.1
Little Ausable	2007-2008	28	6		57	3.2	0.078	0.457	3.0	3.4
Ausable	1991-1992	45	6	600	648	25.1	0.201	5.608	22.4	28.0
Ausable	1993-1994	22	6		689	29.6	0.189	5.608	27.6	33.2
Ausable	1995-1996	21	6		642	56.7	0.298	3.272	61.5	64.8
Ausable	1997-1998	19	6		891	45.1	0.241	3.133	48.2	51.4

Tributary	Water Years	N[a]	FLUX Method[b]	Strata Bounds[c] (hm^3/yr)	Flow at Gage (hm^3/yr)	Load at Gage Station (mt/yr)	CV[d]	Upstream Wastewater Load[e] (mt/yr)	Nonpoint Load at Mouth (mt/yr)	Total Load at Mouth (mt/yr)
Ausable	1999-2000	23	6		705	39.5	0.220	4.085	40.8	44.8
Ausable	2001-2002	34	6	500	597	28.3	0.235	5.361	26.4	31.8
Ausable	2003-2004	29	6		672	27.1	0.157	4.932	25.5	30.4
Ausable	2005-2006	32	6	600	806	29.1	0.160	2.715	30.4	33.1
Ausable	2007-2008	26	6	1000	778	30.0	0.234	2.097	32.1	34.2
Bouquet	1991-1992	43	6	200	309	19.5	0.210	0.042	19.6	19.6
Bouquet	1993-1994	23	6		319	27.6	0.194	0.042	27.7	27.8
Bouquet	1995-1996	18	6		288	24.3	0.225	0.120	24.3	24.5
Bouquet	1997-1998	16	6		402	33.4	0.214	0.269	33.4	33.6
Bouquet	1999-2000	23	6		320	23.3	0.222	0.276	23.1	23.4
Bouquet	2001-2002	34	6		245	11.8	0.212	0.187	11.7	11.9
Bouquet	2003-2004	30	6		336	20.7	0.155	0.206	20.6	20.9
Bouquet	2005-2006	32	6		413	27.3	0.127	0.214	27.3	27.5
Bouquet	2007-2008	27	6		383	24.3	0.119	0.227	24.3	24.5
Putnam	1991-1992	26	6		72	2.0	0.299	0.000	2.4	2.4
Putnam	1993-1994	28	6		66	1.6	0.127	0.000	1.9	1.9
Putnam	1995-1996	14	2		63	4.3	0.531	0.000	5.1	5.1
Putnam	1997-1998	27	6		76	2.5	0.199	0.000	2.9	2.9
Putnam	1999-2000	25	6		64	1.6	0.139	0.000	1.9	1.9
Putnam	2001-2002	27	6		56	1.5	0.105	0.000	1.8	1.8
Putnam	2003-2004	33	6		76	2.2	0.112	0.000	2.6	2.6
Putnam	2005-2006	41	6		94	2.1	0.091	0.000	2.5	2.5
Putnam	2007-2008	30	6		78	1.9	0.140	0.000	2.3	2.3

[a] Number of phosphorus samples obtained during the time interval.
[b] Method 2 = flow-weighted mean concentration method; Method 6 = regression applied to individual daily flows.
[c] Upper bound of flow interval where concentration-flow relationships were developed for two flow strata.
[d] Coefficient of variation of the mean load. Errors were assumed to be log-normally distributed about the mean.
[e] Wastewater loads were compiled on a calendar year basis.

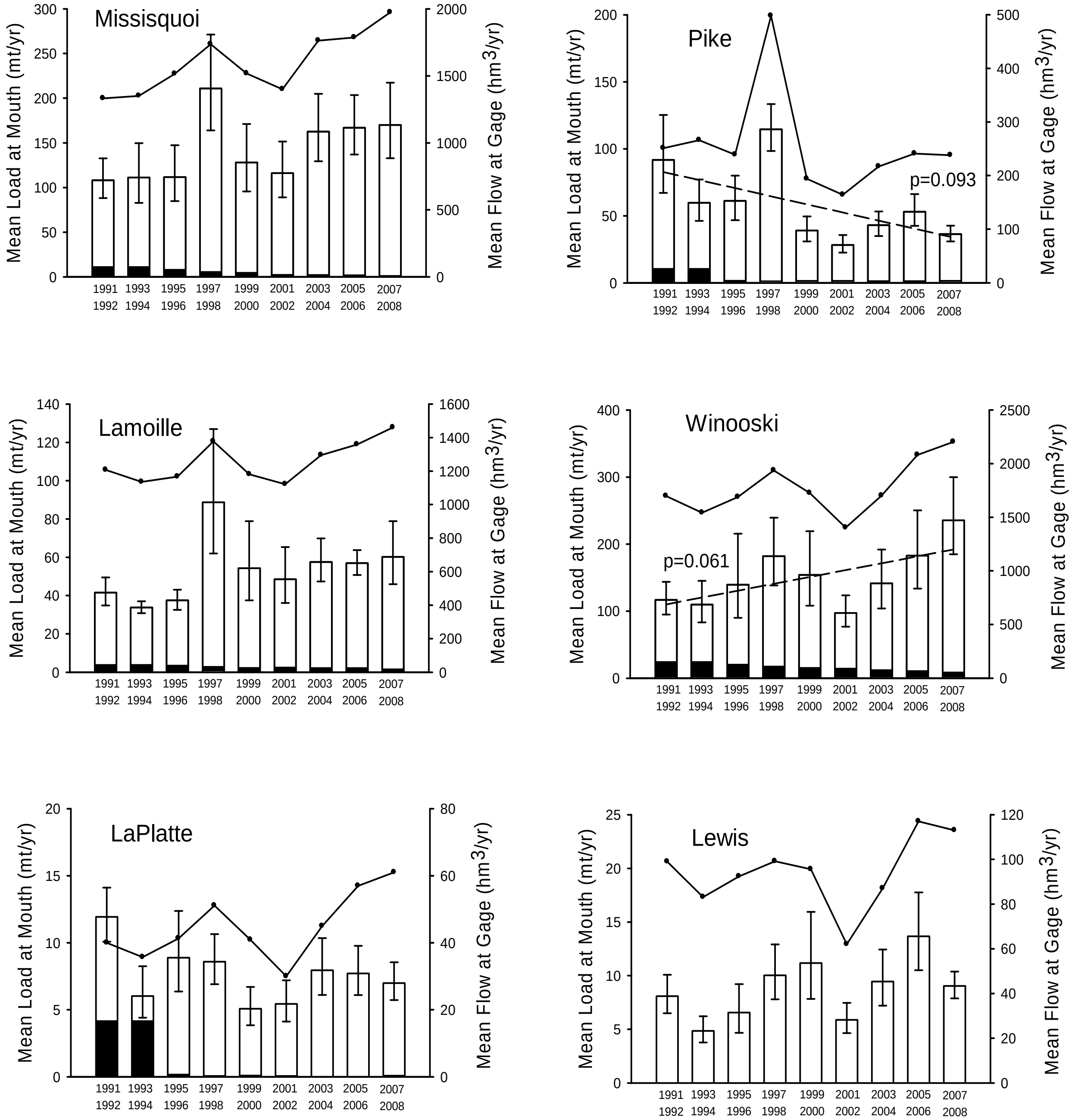

Figure 3. Mean total phosphorus loading rate (bars) and flow rates (points) from Lake Champlain tributaries for two-year intervals, 1991-2008 (water years). Solid fills show upstream wastewater portions of the total loads. Error bars are approximate 95% confidence intervals calculated from FLUX program procedures. Loads are adjusted for the additional drainage area downstream of the flow gage stations. Dotted lines indicate significant linear trends ($p<0.10$). Note that the scales vary.

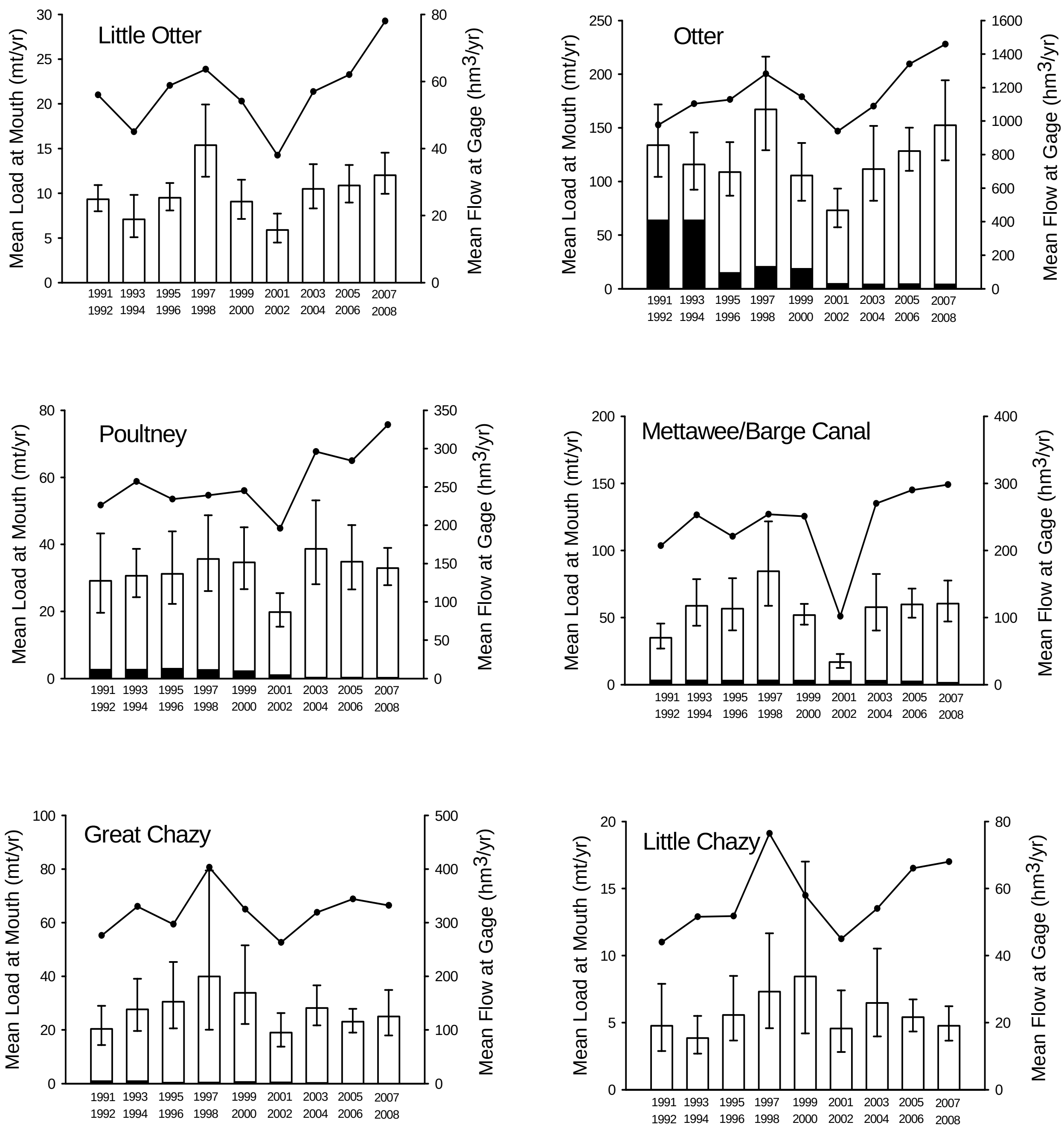

Figure 3 (cont.). Mean total phosphorus loading rate (bars) and flow rates (points) from Lake Champlain tributaries for two-year intervals, 1991-2008 (water years). Solid fills show upstream wastewater portions of the total loads. Error bars are approximate 95% confidence intervals calculated from FLUX program procedures. Loads are adjusted for the additional drainage area downstream of the flow gage stations. Note that the scales vary.

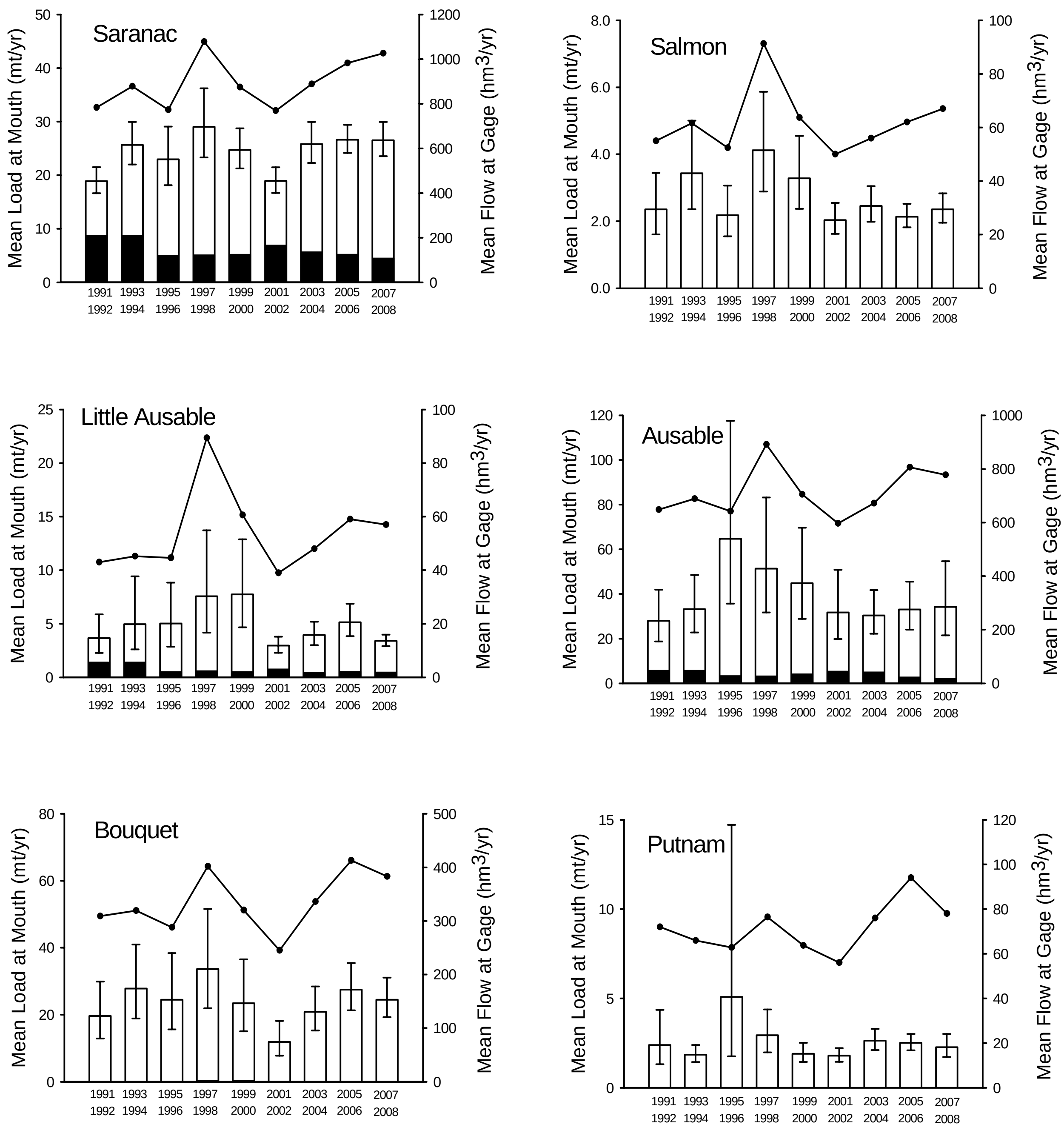

Figure 3 (cont.). Mean total phosphorus loading rate (bars) and flow rates (points) from Lake Champlain tributaries for two-year intervals, 1991-2008 (water years). Solid fills show upstream wastewater portions of the total loads. Error bars are approximate 95% confidence intervals calculated from FLUX program procedures. Loads are adjusted for the additional drainage area downstream of the flow gage stations. Note that the scales vary.

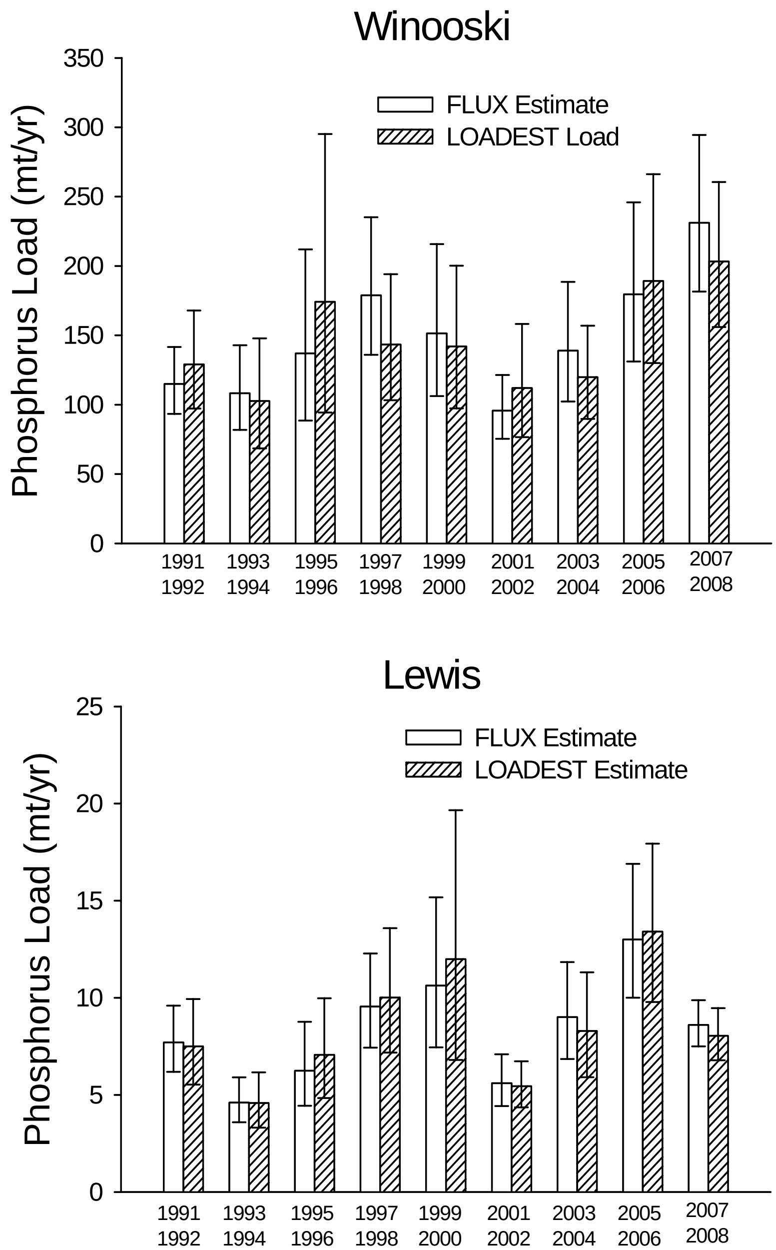

Figure 4. Comparison of FLUX and LOADEST program estimates of mean phosphorus loading in two Lake Champlain tributaries for two-year water year intervals. Error bars are approximate 95% confidence intervals for the mean loads.

Table 3. Mean wastewater phosphorus loads (mt/yr) to Lake Champlain segments for two-year calendar year intervals, 1991-2008. The wastewater phosphorus load allocation for each lake segment watershed as specified in the Lake Champlain Phosphorus TMDL (Vermont and New York discharges) is shown at right. The limit shown for Québec facilities was based on the permitted phosphorus concentrations at the design flows for each facility. Shading indicates values above the TMDL limit.

Lake Segment	1991-1992[a]	1993-1994[a]	1995-1996	1997-1998	1999-2000	2001-2002	2003-2004	2005-2006	2007-2008	TMDL Limit
New York										
South Lake B	3.167	3.167	3.155	3.245	3.126	2.857	2.972	2.426	1.369	1.940
South Lake A	9.595	9.595	7.140	6.517	8.180	8.683	7.779	6.978	5.574	7.900
Port Henry	1.764	1.764	2.161	2.228	2.269	1.723	2.311	2.127	1.523	0.890
Main Lake	7.070	7.070	3.906	4.001	4.899	6.359	5.579	3.472	2.791	4.220
Cumberland Bay	29.169	29.169	12.331	12.509	14.439	16.729	14.914	14.510	14.297	17.140
Isle LaMotte	7.314	7.314	2.221	1.939	2.066	2.392	2.560	2.132	1.966	3.430
New York Total	58.078	58.078	30.915	30.438	34.979	38.743	36.115	31.645	27.520	35.520
Québec										
Missisquoi Bay	16.573	16.573	5.271	4.752	4.959	2.601	2.139	1.957	2.174	3.124
Vermont										
South Lake B	2.840	2.840	3.066	2.706	2.352	1.153	0.482	0.473	0.434	1.624
South Lake A	0.108	0.108	0.101	0.089	0.081	0.068	0.034	0.169	0.095	0.228
Otter Creek	64.402	64.402	15.117	20.897	18.894	5.051	4.419	4.665	4.476	11.980
Main Lake	27.747	27.747	21.664	19.149	16.814	15.440	13.038	11.680	9.549	25.288
Shelburne Bay	5.312	5.312	0.825	0.924	0.838	0.738	0.626	0.618	0.568	1.998
Burlington Bay	11.245	11.245	2.499	3.054	2.987	2.967	3.009	2.838	2.448	4.392
Malletts Bay	3.895	3.895	3.400	2.767	2.346	2.462	2.228	2.257	1.605	3.242
St. Albans Bay	0.792	0.792	1.233	0.818	0.969	0.719	1.165	1.150	0.860	2.790
Missisquoi Bay	9.427	9.427	4.951	2.787	2.098	1.833	1.812	1.682	0.962	4.158
Isle LaMotte	0.003	0.003	0.004	0.002	0.001	0.003	0.003	0.004	0.002	0.108
Vermont Total	125.771	125.771	52.859	53.194	47.381	30.433	26.815	25.535	21.001	55.807
Total	200.422	200.422	89.045	88.384	87.318	71.777	65.069	59.137	50.694	94.451

[a] No data were compiled during 1992-1994. Loads estimated during 1991 were applied to the time intervals of 1991-1992 and 1993-1994.

loads during the most recent time interval of 2007-2008 were below the applicable limits specified in the Lake Champlain Phosphorus TMDL for all lake segments with the exception of the Port Henry segment in New York.

Lake Segment Loads in Relation to TMDL Total Loading Capacities

One of the important reasons for monitoring phosphorus loading to Lake Champlain is to evaluate compliance with the total loading capacities specified in the Lake Champlain Phosphorus TMDL for each lake segment watershed. There are a total of 13 segments of Lake Champlain (Figure 1) for which numeric phosphorus concentration criteria have been established in Vermont, New York, and Québec as water quality standards or joint management goals. Since many of these lake segments are shared between jurisdictions, the TMDL divided the total loading capacities among the various jurisdictions and established phosphorus loading limits for the 20 lake segment watersheds listed in Table 4.

Some of these lake segment watersheds include one or more of the 18 monitored tributaries for which long-term loading estimates are available (Table 2). However, some of the lake segment watersheds include no monitored tributaries, and loading estimates for these watersheds were not available. Two lake segment watersheds (South Lake B and Missisquoi Bay) include tributaries that cross jurisdictional boundaries, and it was not possible to separate their monitored loads by state or province. Table 4 lists the monitored tributaries located within each lake segment watershed. For lake segment watersheds that include monitored tributaries, these tributaries (at their mouths) represent 77-99% of the total drainage area of the lake segments to which they discharge.

The phosphorus loads to each lake segment watershed during 1991-2008 were calculated by adding the nonpoint source loads from each tributary within the watershed (Table 2), with a proportionate adjustment for the additional watershed area not drained by the tributaries, to the total wastewater load to each lake segment (Table 3). The lake segment loads are shown in Figure 5 in relation to the total loading capacities established in the Lake Champlain Phosphorus TMDL. Phosphorus loads have remained well above the total loading capacities for all lake segments, with the exception of Shelburne Bay in Vermont and South Lake A in New York where TMDL loading targets have been attained in recent years.

Combining the loading estimates into two-year intervals was necessary in order to obtain sufficient sample size for acceptable precision in the mean loads, but this procedure obscured some of the year-to-year variations that are relevant in comparing measured loads with the TMDL targets. For example, phosphorus loads were calculated on a single-year basis for the Winooski River using the same methods applied in calculating the two-year mean loads. The Winooski River drains about 98% of the Main Lake segment watershed in Vermont. As shown in Figure 6, there were several individual years during the 1991-2008 period for which the mean loads in the Winooski River were either below the TMDL target levels for the lake segment watershed, or had 95% confidence intervals that overlapped the targets. Annual flow rates strongly influenced whether the target loads were attained. The annual loads exceeded the TMDL loading targets during most years, but the pattern of non-attainment was not as consistent as suggested by the two-year averages shown in Figure 3.

Table 4. List of lake segment watersheds having total loading capacities assigned in the Lake Champlain Phosphorus TMDL, and monitored tributaries within each lake segment watershed.

Lake Segment Watershed	State/ Province	TMDL Total Loading Capacity (mt/yr)	Lake Segment Watershed Area (km^2)	Monitored Tributaries	Percent of Lake Segment Watershed Area at Tributary Mouths
South Lake B	NY	23.9	986	Poultney, Mettawee	90%
South Lake B	VT	20.8	1003		
South Lake A	NY	11.2	965	Putnam, LaChute[a]	89%
South Lake A	VT	0.6	174		
Port Henry	NY	3.4	239		
Port Henry	VT	0.1	32		
Otter Creek	NY	0.0	12		
Otter Creek	VT	56.1	2866	Otter, Lewis, Little Otter	99%
Main Lake	NY	33.7	2579	Bouquet, Ausable, Little Ausable, Salmon	93%
Main Lake	VT	76.6	2815	Winooski	98%
Shelburne Bay	VT	12.0	179	LaPlatte	77%
Burlington Bay	VT	5.8	14		
Malletts Bay	VT	28.6	2010	Lamoille	93%
Northeast Arm	VT	1.2	234		
Cumberland Bay	NY	25.2	1742	Saranac	91%
St. Albans Bay	VT	8.0	131		
Isle LaMotte	NY	22.3	973	Little Chazy, Great Chazy	94%
Isle LaMotte	VT	0.3	69		
Missisquoi Bay	VT	58.3	1809	Missisquoi, Pike	
Missisquoi Bay	QC	38.9	1316		93%

[a] LaChute River is a large (702 km^2) but unmonitored watershed draining Lake George. A constant load of 1.1 mt/yr was assumed for purposes of these calculations.

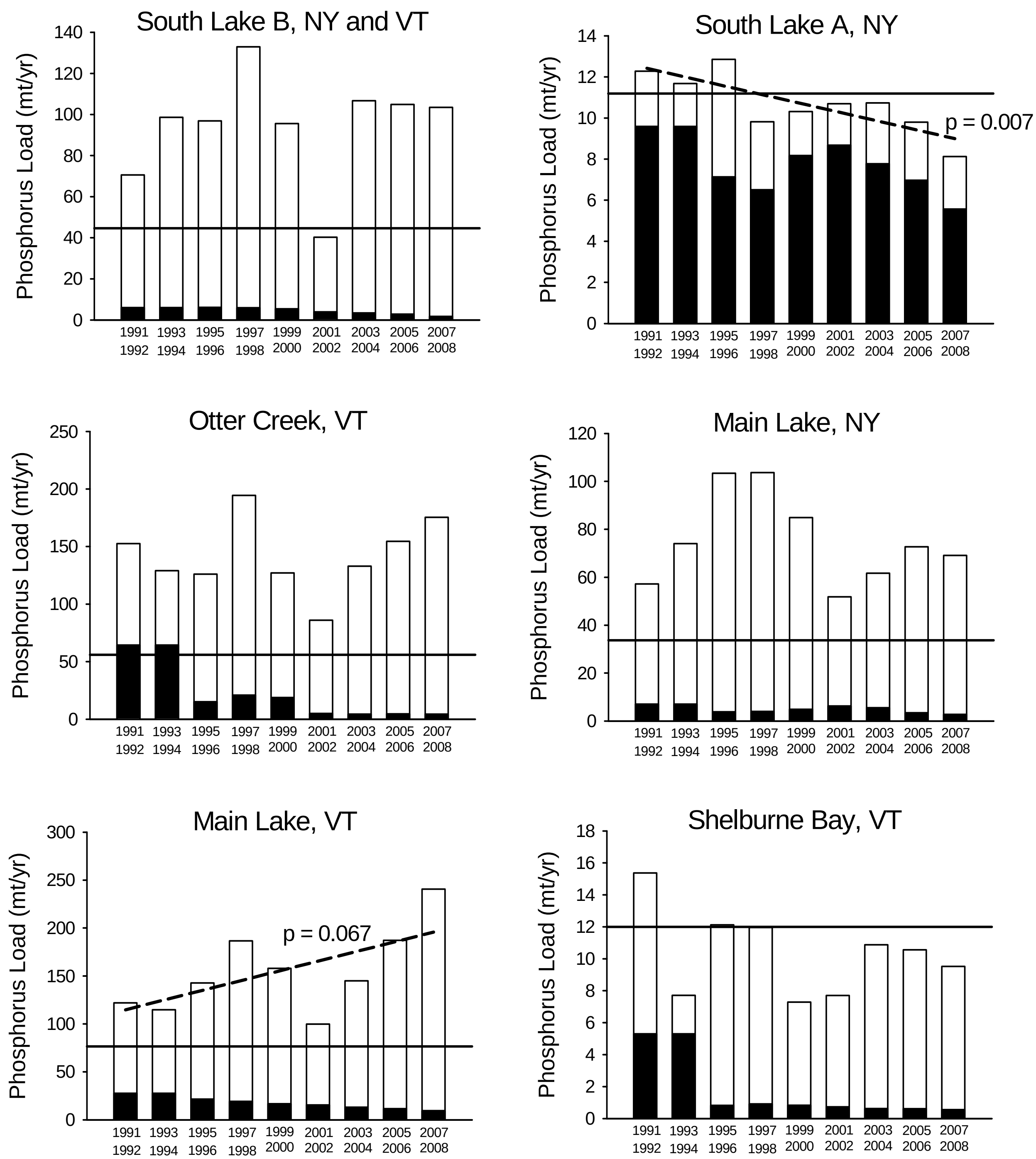

Figure 5. Two-year mean phosphorus loads from lake segment watersheds during 1991-2008 in comparison with the total loading capacities specified in the Lake Champlain Phosphorus TMDL (horizontal lines). Loads include inputs from all tributaries to the lake segment, adjusted for the additional drainage area outside of the tributary watersheds. Solid fills indicate wastewater portions of the total loads, including discharges direct to the lake. Dotted lines indicate significant linear trends ($p<0.10$). Note that the scales vary.

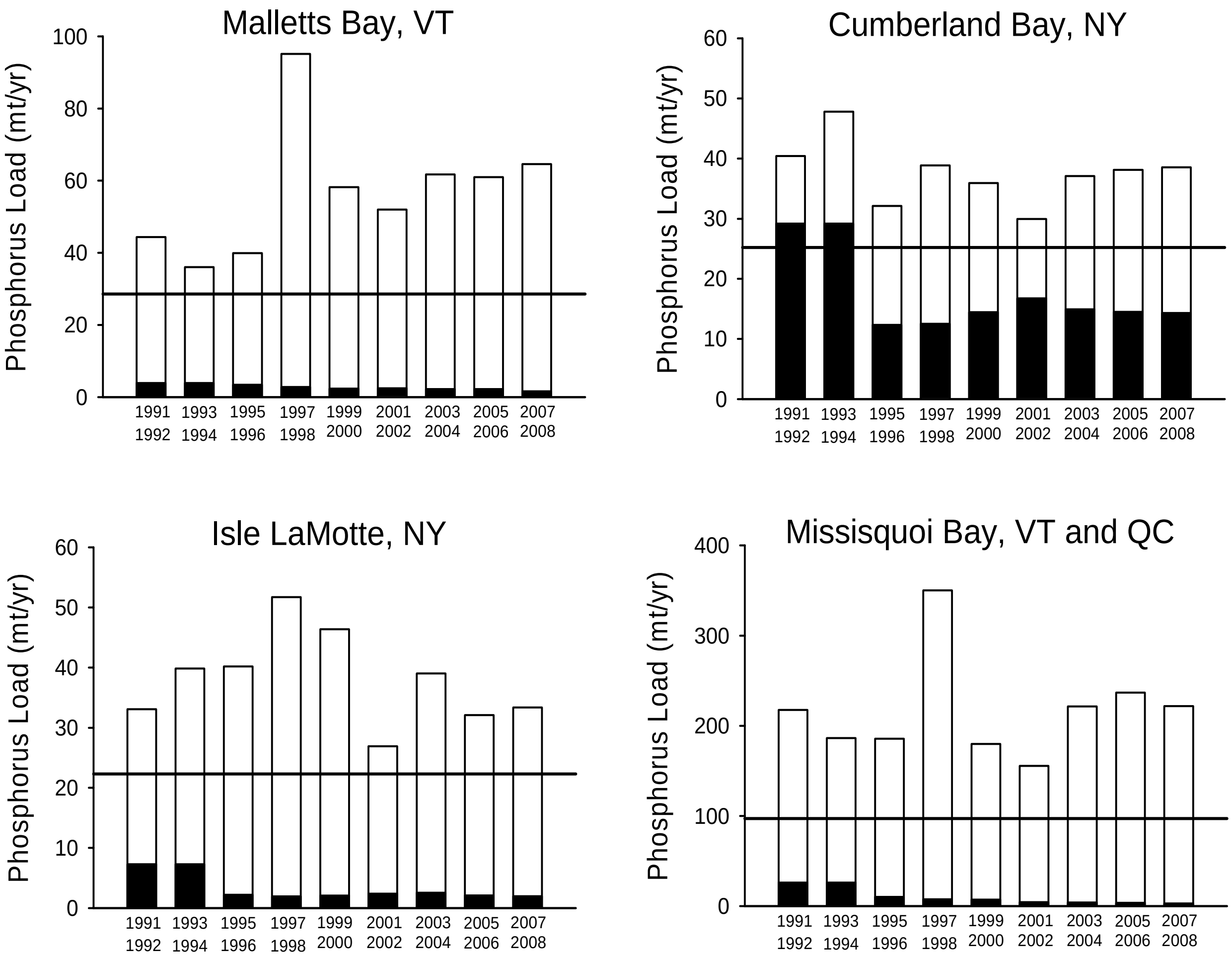

Figure 5 (cont.). Two-year mean phosphorus loads from lake segment watersheds during 1991-2008 in comparison with the total loading capacities specified in the Lake Champlain Phosphorus TMDL (horizontal lines). Loads include inputs from all tributaries to the lake segment, adjusted for the additional drainage area outside of the tributary watersheds. Solid fills indicate wastewater portions of the total loads, including discharges direct to the lake. Note that the scales vary.

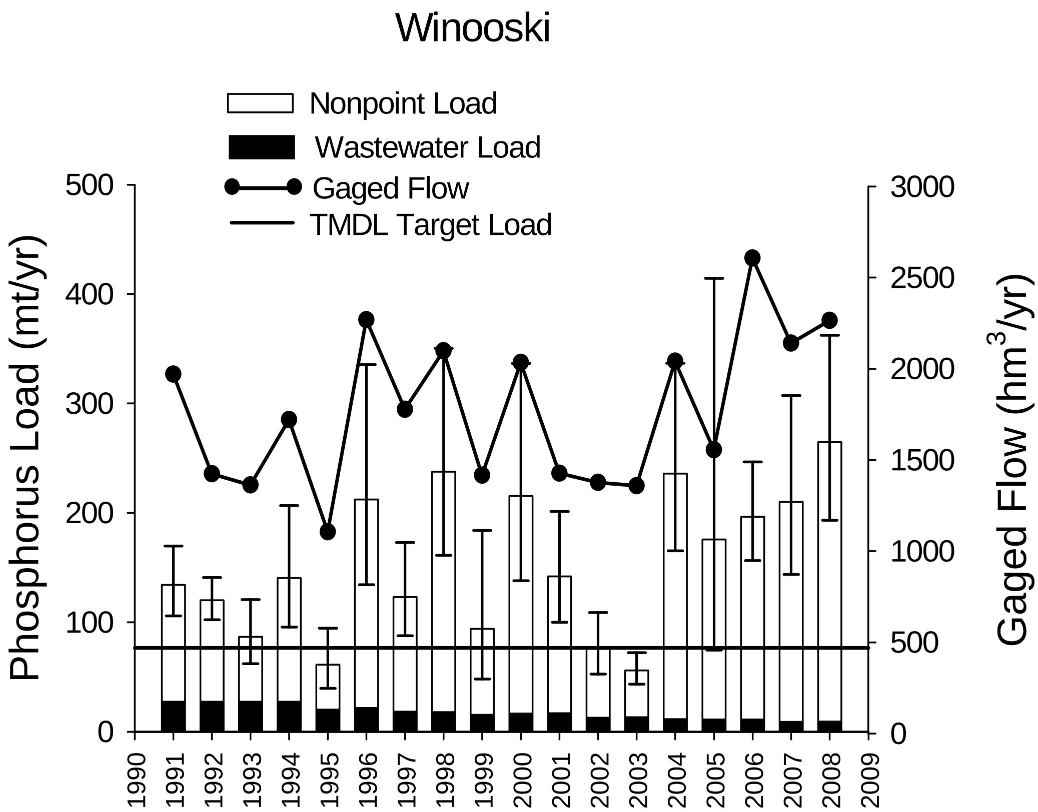

Figure 6. Annual mean phosphorus loads and gaged flows during water years 1991-2008 in the Winooski River, in comparison with the TMDL target load for the Main Lake, VT lake segment watershed. Error bars are approximate 95% confidence intervals for the annual mean loads.

Trends in Phosphorus Loads

As noted above, an in-depth analysis of trends in phosphorus loads to Lake Champlain as influenced by variations in river flows and watershed management practices over time will be deferred to a study in progress for the Lake Champlain Basin Program by the U.S. Geological Survey. However, a simple statistical analysis of the actual loads averaged over two-year intervals during 1991-2008 was used to gain an initial indication of any changes that have occurred.

This simple trends analysis was conducted without adjustment for flow effects by testing the null hypothesis that the slope of the simple linear regression of the two-year mean phosphorus loads vs. time for each of the monitored tributaries was equal to zero (Figure 3). There were no statistically significant ($p<0.05$) linear trends either upward or downward in the mean loads for any individual tributary over the 1991-2008 time period. However, a marginally significant ($p=0.06$) upward loading trend was seen in the Winooski River, and a marginally significant ($p=0.09$) downward trend was seen in the Pike River.

When the tributary loads and wastewater discharges direct to the lake were aggregated by lake segment watershed (Figure 5), the Main Lake segment watershed in Vermont showed a marginally significant ($p=0.07$) loading increase over this period, and the South Lake A segment watershed in New York showed a significant ($p<0.01$) decrease in loadings, due primarily to wastewater reductions which dominate in that watershed. Because the magnitude of the loading rates varied greatly among lake segments, the impact on the lake of a statistically significant loading trend is greater for those segments such as the Main Lake where the loading rates are higher.

Flow-Weighted Mean Inflow Phosphorus Concentrations

The phosphorus loading targets established in the Lake Champlain Phosphorus TMDL were based on a lake mass balance modeling analysis that used calendar year 1991 as a hydrologic reference year. Except for Otter Creek, the annual mean tributary flows during 1991 were fairly close to the medians of the annual mean flows recorded over the prior period of record (beginning in 1930 or earlier and ending in 1990) in six Lake Champlain Basin tributaries having long-term hydrologic records (Figure 7). However, annual mean flows have tended to be higher during the subsequent period of 1992-2007 than they were in 1991 in each of these rivers. Measured phosphorus loading rates have also been higher during most years since the 1991 base year[2,9]. Since annual mean phosphorus loading rates are highly correlated with mean flows (Figure 3), the elevated flows in recent years raise the possibility that the excessive phosphorus loading above TMDL targets (Figure 5) is due in part to higher precipitation and water runoff rates since 1991, as well as inadequate reductions in phosphorus sources.

Lake mass balance models[23,24] assume that in-lake concentrations are proportional to the ratio of the total mass loading rate to the total water inflow rate, which is the flow-weighted mean concentration in the inflow (equation 1). Higher mass loading rates can be tolerated if flows increase proportionately and flow-weighted mean inflow concentrations remain the same. Actual loading capacities, illustrated in Figure 5 as goal lines from the TMDL, are really moving targets dependent on the hydrologic conditions occurring each year. In this sense, flow-weighted mean inflow concentrations are a better indicator of phosphorus loading stress on the lake than mass loading rates alone.

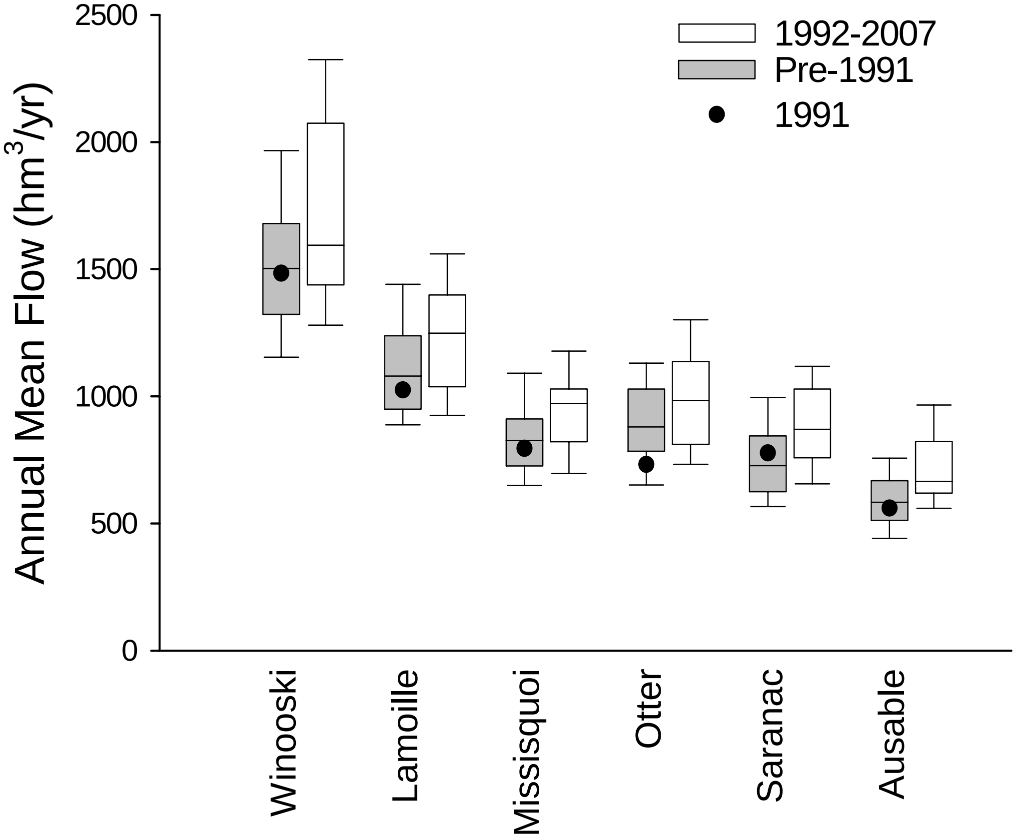

Figure 7. Annual mean river flows at six long-term USGS gages in the Lake Champlain Basin for pre-1991, 1991, and 1992-2007 calendar year periods. Annual statistics were compiled for the corresponding flow gage stations listed in Table 1, except that the Missisquoi River records were obtained from an upstream gage in East Berkshire, VT in order to provide a long-term record for that river. Box plots show medians (midlines), 25th and 75th percentiles (boxes), and 5th and 95th percentiles (endcaps) for the distributions of the annual mean flows.

$$C_{lake} \approx W / Q = C_{inflow} \tag{1}$$

Where,

C_{lake} = Phosphorus concentration in the lake water (mg/L)
W = Phosphorus loading rate (mt/yr)
Q = Water inflow rate (hm^3/yr)
C_{inflow} = Flow-weighted mean phosphorus concentration in the inflow (mg/L)

In order to provide additional perspective on the management implications of the elevated phosphorus loading rates shown in Figure 5, flow-weighted mean phosphorus concentrations in the inflow to each lake segment were calculated by dividing the total segment load by the total water inflow during each two-year time interval. The flow-weighted mean phosphorus concentrations in the total inflow to each lake segment during 1991-2008 are shown in Figure 8. Most lake segment watersheds had either no trend or a decreasing trend in flow-weighted mean phosphorus concentrations during 1991-2008, based on a linear regression of the two-year flow-weighted means over time. The one exception was the Main Lake watershed in Vermont which had a marginally significant ($p=0.07$) increasing trend. There was no overall lakewide trend in flow-weighted mean inflow phosphorus concentrations among all lake segments with monitored tributary inflows.

Flow-weighted mean phosphorus concentrations in the inflows from individual tributaries can also provide an indication of the relative density of nonpoint sources within these watersheds (Figure 9). The flow-weighted mean nonpoint source phosphorus concentrations shown in Figure 9 were calculated by dividing the nonpoint source component of the mean loads during each two-year interval (Figure 3) by the average flow rate for the interval, and then averaging these values over the entire 1991-2008 period.

For additional perspective, data from two other streams in the Lake Champlain Basin were included in Figure 9. Englesby Brook is a predominantly urban watershed in Vermont that has been the subject of a monitoring program conducted by the USGS[25]. A mean phosphorus loading rate of 0.15 mt/yr was reported for the Englesby Brook station during water years 2000-2005. This loading rate was divided by the mean flow rate of 0.53 hm^3/yr at the gage station to give a flow-weighted mean phosphorus concentration of 0.283 mg/L. No adjustment for additional drainage area at the mouth of the brook was necessary because the sampling station and the flow gage station were co-located very near the brook's outlet to Lake Champlain.

The Rock River is a predominately agricultural watershed shared by Québec and Vermont. The monitoring station on the Rock River (Figure 1) has been sampled as part of the Lake Champlain Long-Term Monitoring Program only since 2007, but continuous flow data are available from a gage station maintained by the Québec MDDEP which captures 48% of the drainage area of the Rock River. Using these data with the same load estimation methods employed in this report for the other tributaries, a mean phosphorus load of 15.7 mt/yr was calculated for the mouth of the Rock River for water years 2007-2008. This load was divided by the mean flow rate for this period adjusted to apply at the river mouth (79.8 hm^3/yr) to estimate a flow-weighted mean phosphorus concentration of 0.197 mg/L.

The streams having the highest flow-weighted mean nonpoint source phosphorus concentrations included Englesby (VT), Rock (QC and VT), Little Otter (VT), Pike (VT and QC), LaPlatte (VT), and Little Chazy (NY). The flow-weighted mean phosphorus concentrations were

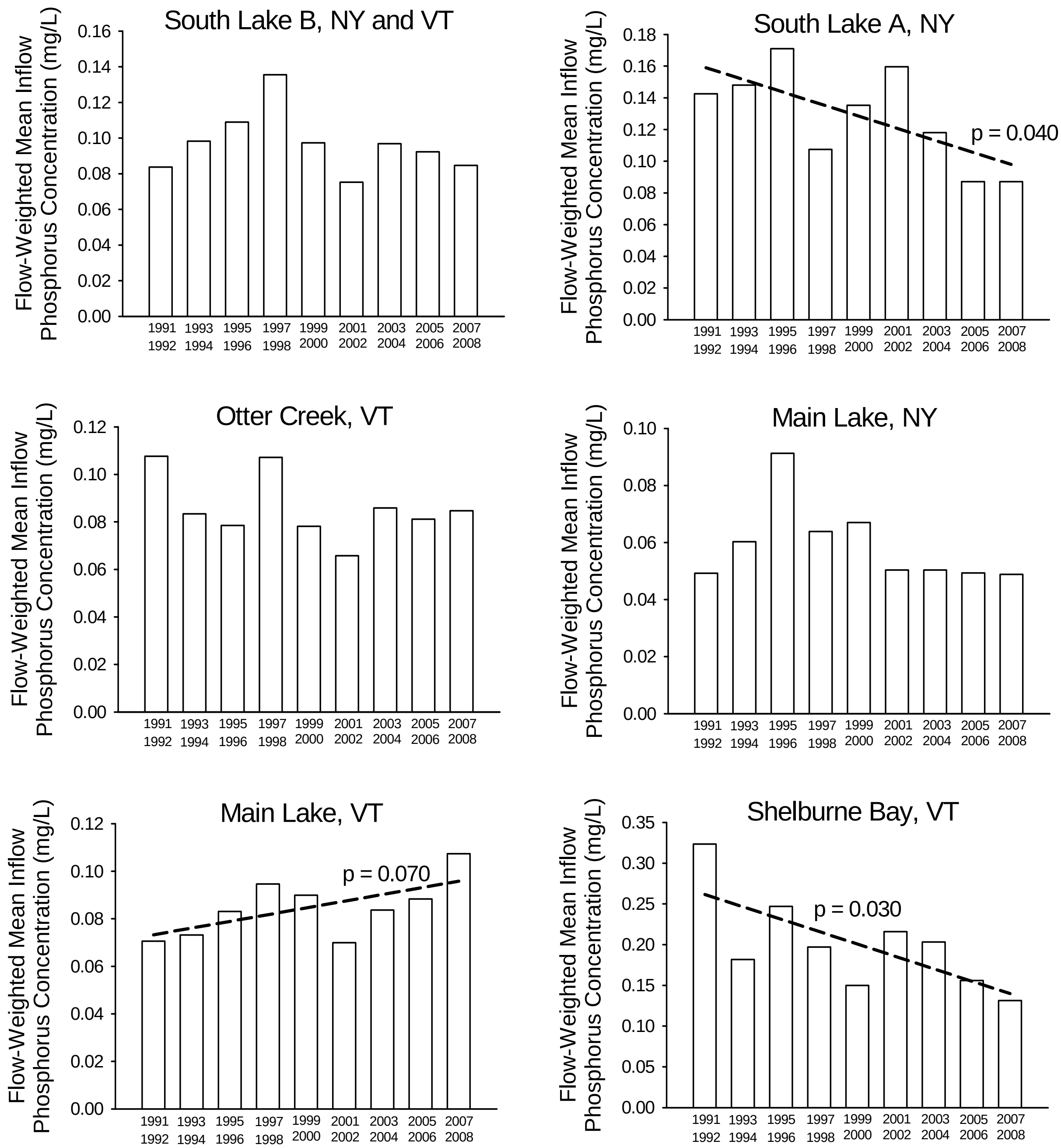

Figure 8. Flow-weighted mean phosphorus concentrations in the inflows to Lake Champlain segments during water years 1991-2008. Dotted lines indicate significant linear trends ($p<0.10$). Note that the scales vary.

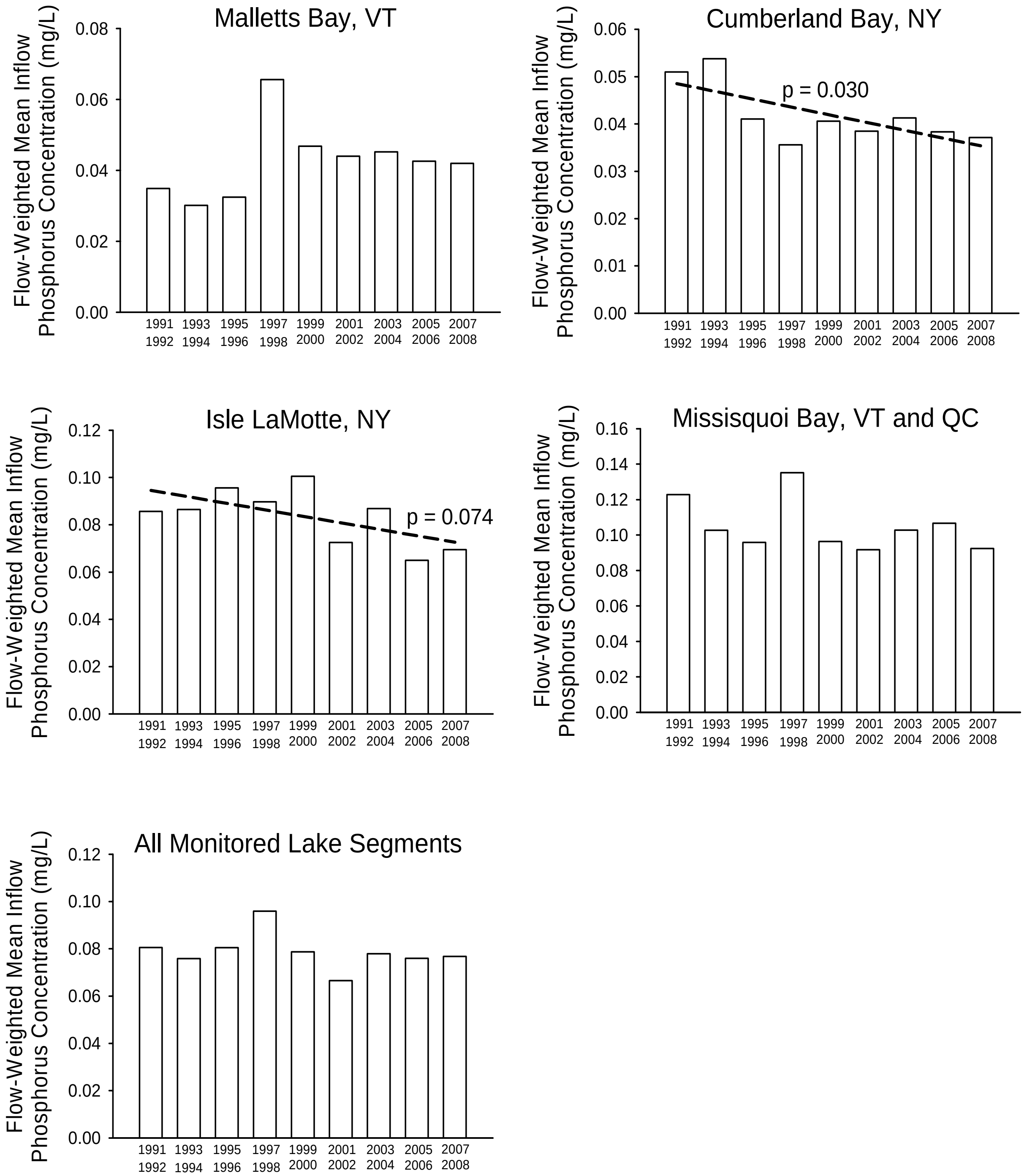

Figure 8 (cont.). Flow-weighted mean phosphorus concentrations in the inflows to Lake Champlain segments during water years 1991-2008. Dotted lines indicate significant linear trends ($p<0.10$). Note that the scales vary.

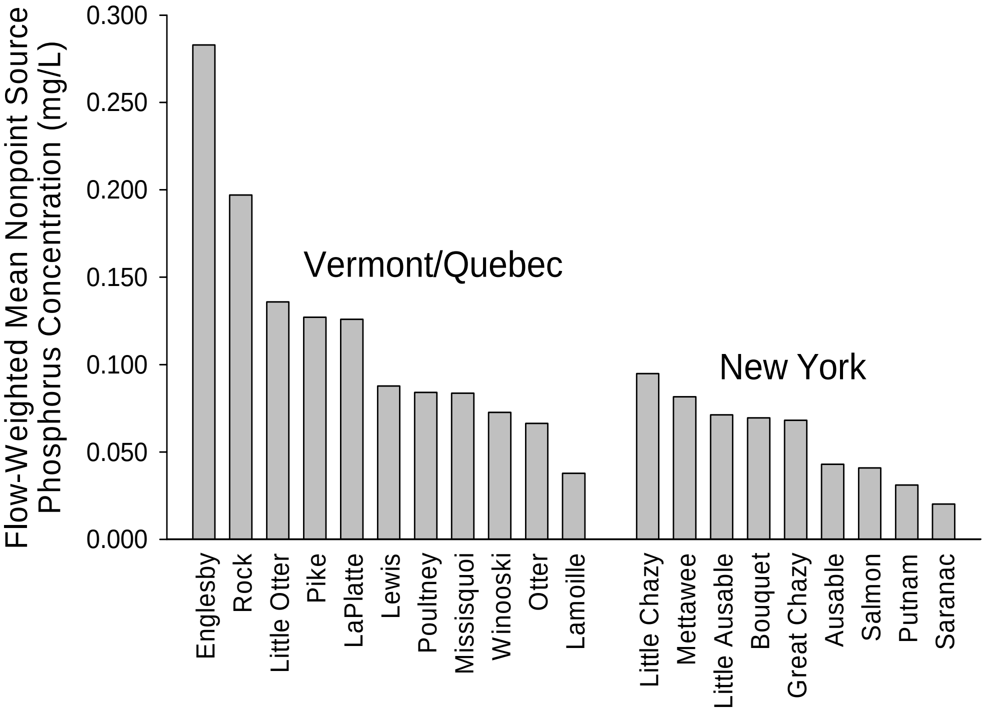

Figure 9. Comparison of flow-weighted mean nonpoint source phosphorus concentrations in Lake Champlain tributaries. Concentrations are averaged over the period of water years 1991-2008, except for Englesby Brook (2000-2005) and the Rock River (2007-2008). The Poultney and Mettawee River watersheds include areas in both Vermont and New York.

generally higher in the Vermont and Québec tributaries than in the New York rivers, indicating a higher density of nonpoint sources in Vermont and Québec watersheds. The very high levels found in Englesby Brook and the Rock River approach phosphorus concentrations discharged by some of the more advanced wastewater treatment facilities in the basin, which highlights the severity of the urban and agricultural nonpoint source impacts in those two watersheds.

Total Basinwide Loads

The total basinwide loads of phosphorus to Lake Champlain over the monitoring period have been presented in previous reports as a way of providing an overall summary picture of the status and trends in phosphorus loading to the lake[2,24]. An updated summary of total loads through 2008 is shown in Figure 10. The two-year mean phosphorus loading rates in Figure 10 were calculated by summing the wastewater and nonpoint loads for all lake segments (from Figure 5). The total nonpoint source loads were increased by 4% to account for loads from unmonitored lake segment watershed areas (Table 4). The wastewater loads shown in Figure10 include all discharges within the lake basin, including those direct to the lake and in unmonitored lake segment watersheds.

The total loads are compared in Figure 10 with the basinwide total loading capacity of 427 mt/yr established in the Lake Champlain Phosphorus TMDL, and with the total gaged water inflow rates during each two-year interval. Total loads to the lake remained well above the TMDL target level during 1991-2008. The two-year mean loads tracked closely with the total flow rates, but there was no statistically significant upward or downward trend in total loads over this period, based on a linear regression analysis of the two-year mean loads over time.

The wastewater portion of the total basinwide loads (Figure 11) has declined from about 25% in 1991-1992 down to only 5% in 2007-2008. Historically during the 1970s, nearly half of the total load of phosphorus to Lake Champlain came from wastewater discharges[26]. During the most recent time interval of 2007-2008, wastewater discharges contributed only 3% of the total load from Vermont, 13% of the total from New York, and 3% of the total from Québec.

The percentages of the total basinwide loads that were derived from each state or province are shown in Figure 12. For lake segment watersheds shared by two jurisdictions, the loads were partitioned based on land use modeling estimates[27] (South Lake B) or sub-basin monitoring (Missisquoi Bay). Figure 12 shows that Vermont has contributed 60-70% of the total phosphorus load to Lake Champlain during the 1991-2008 monitoring period, with New York contributing 20-30% and Québec contributing about 10%. These proportions have remained fairly constant over this time period.

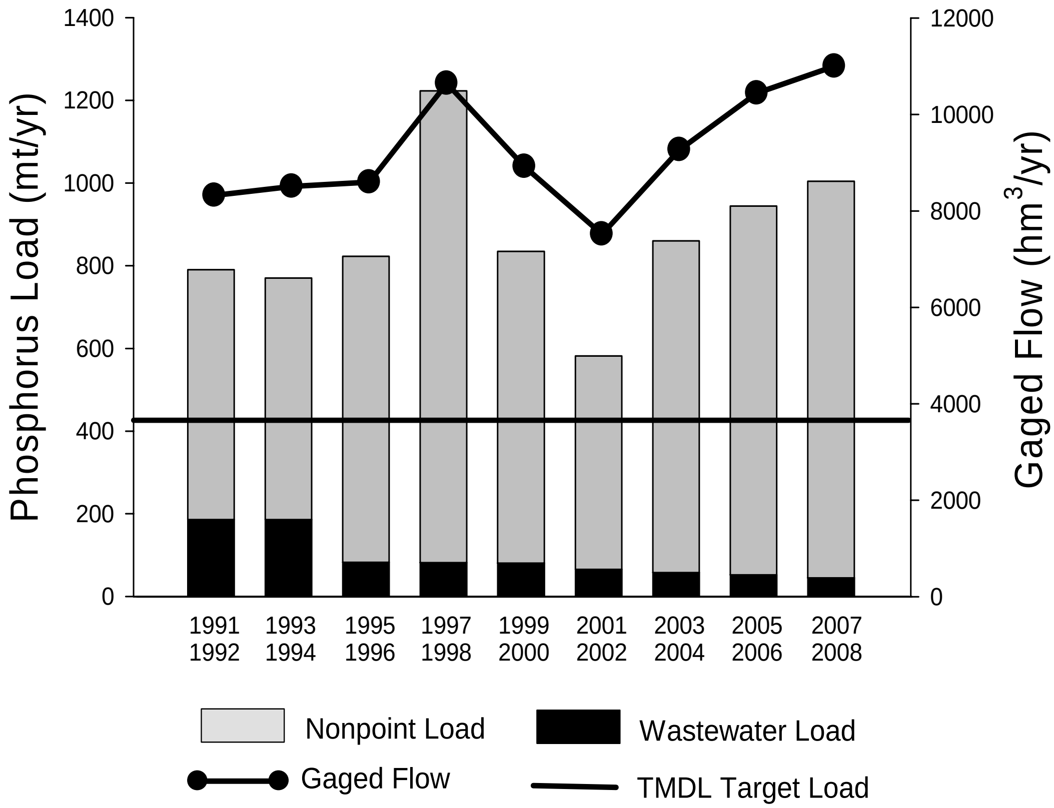

Figure 10. Total basinwide phosphorus loading rates to Lake Champlain during 1991-2008. Bars show two-year mean wastewater and nonpoint source loads, summed over all lake segment watersheds and adjusted for unmonitored drainage areas. Total loads are compared with the basinwide total loading capacity of 427 mt/yr established in the Lake Champlain Phosphorus TMDL, and with the total gaged tributary flow rates during each interval.

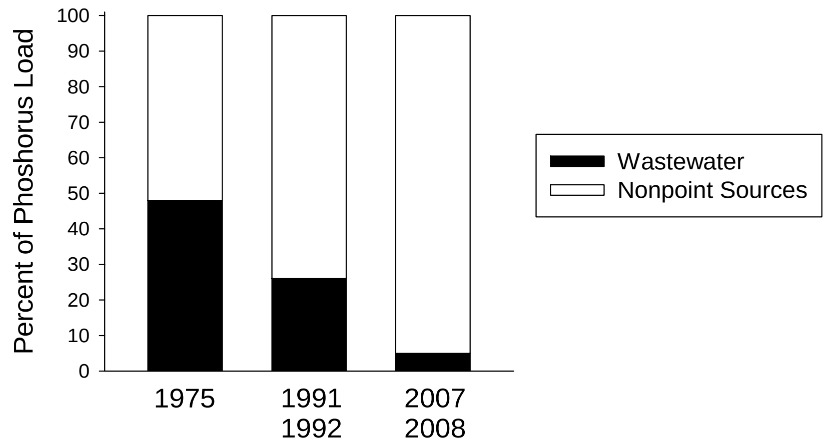

Figure 11. Proportions of the total basinwide phosphorus load to Lake Champlain derived from wastewater vs. nonpoint sources during 1975, 1991-1992, and 2007-2008. The ca. 1975 estimate is from Bogdan.

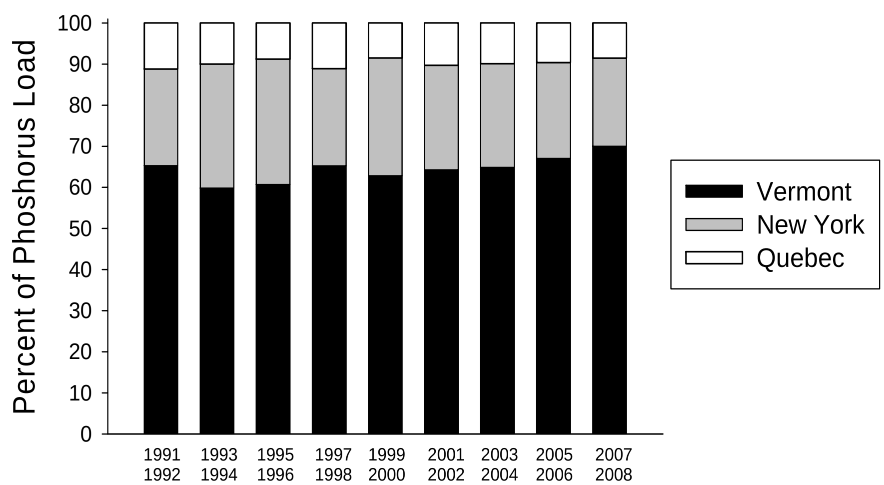

Figure 12. Proportions of the total basinwide phosphorus loads to Lake Champlain derived from Vermont, New York, and Québec during two-year water year intervals, 1991-2008.

Discussion

It is clear from this analysis that we have a long way to go to achieve our water quality goals for Lake Champlain in terms of in-lake phosphorus concentrations and loading rates from the lake's watershed. In most lake regions, in-lake phosphorus concentration criteria are not being consistently attained. No phosphorus concentration declines have been seen during 1990-2008 in any segment of the lake, and levels are increasing in several lake segments. Similarly, total phosphorus loading rates exceed the TMDL target levels for most lake segment watersheds.

It is important to recognize, however, that the excessive phosphorus loading rates above TMDL target levels are due in part to wetter weather and higher water runoff rates in recent years, in comparison with the 1991 base year conditions used for the TMDL loading allocations. It will be important to explore the relative importance of changing hydrologic conditions, as well as inadequate phosphorus source reduction, as reasons for the continued high phosphorus loading rates and the lack of downward trends in loadings. The USGS project on phosphorus trends analysis and interpretation in the Lake Champlain Basin will do this using advanced statistical techniques that compensate for the influence of flow variability on trends in stream phosphorus concentrations and loads.

A previous analysis of phosphorus loading rates from sub-basins in the Missisquoi Bay watershed used statistical techniques to account for the covariance of concentration and flow. A comparison of phosphorus concentration-flow relationships between the 1990-1992 reference period and the more recent 2001-2005 monitoring period revealed significant differences for the Pike River in both the low-flow and the high-flow range data, with generally lower phosphorus concentrations observed during 2001-2005 than during 1990-1992 at equivalent flow rates. The present analysis found only a marginally significant ($p=0.09$) downward trend in the actual phosphorus loading rates from the Pike River during 1991-2008 (Figure 3). The absence of a more highly significant loading trend for the Pike River was likely due to the confounding effects of flow variations, since the present analysis did not apply statistical trends methods that compensated for flow variability.

The statistical analysis of phosphorus trends in 13 lake segments and 18 tributaries presented in this report is subject to the problem of inflated Type 1 error rates (false positives) due to multiple comparisons. The true overall proportion of lake and tributary sites with significant trends is possibly less than reported here because no adjustment was made to the significance criterion (e.g., $p<0.05$) used to test the null hypotheses. However, a more stringent significance criterion would have resulted in a greater risk of Type 2 errors (failure to find a trend that existed) at individual sites, and this type of error was important to avoid as well[28].

Phosphorus loading rates to Lake Champlain did not increase significantly during the 1991-2008 monitoring period. This should be seen as a positive accomplishment, given the fact that land development has increased in the basin, creating new phosphorus sources. For example, a study of land use changes in the basin between 1992 and 2001 estimated that conversion of land into urban or developed uses could have added 26 mt/yr of new nonpoint source phosphorus loading on average, representing a 3% increase in ten years. Potential phosphorus loading increases in rapidly developing areas such as the Main Lake and Malletts Bay watersheds in Vermont were on the order of 6% over the ten-year period. The substantial reductions in wastewater phosphorus loading, along with possible benefits from implementation of a variety of agricultural and urban nonpoint source controls during this period, may have approximately offset the new phosphorus sources created by land development.

Another positive sign is that flow-weighted mean phosphorus concentrations increased in the inflow to only one lake segment during 1991-2008, with decreases seen in four other lake segment watersheds over this period. Since lake phosphorus mass balance modeling considerations indicate that flow-weighted mean inflow concentrations are more directly linked to in-lake phosphorus concentrations than mass loading rates alone, especially under changing hydrologic conditions, the generally stable or decreasing trends in this indicator are somewhat encouraging.

Summary of Findings

1. Data from the Lake Champlain Long-Term Water Quality and Biological Monitoring Program from 1990-2008 were analyzed to determine the status and trends in lake phosphorus concentrations and phosphorus loading rates from individual tributaries and lake segment watersheds in Vermont, New York, and Québec.
2. Lake phosphorus concentrations exceeded the applicable criteria values during most or all years of the 1990-2008 monitoring period in five lake segments, including South Lake A, Main Lake, Northeast Arm, St. Albans Bay, and Missisquoi Bay. Phosphorus levels remained below the targets during most, but not all years in Burlington Bay and Cumberland Bay. The remaining lake segments had borderline conditions where the mean phosphorus concentrations varied above and below the criteria values.
3. Four lake segments had significant increasing linear trends in phosphorus concentrations over the 1990-2008 time period, including the Port Henry, Malletts Bay, Northeast Arm, and St. Albans Bay segments. No significant decreasing phosphorus trends were observed for any lake segment.
4. Wastewater phosphorus loads from facilities in Vermont, New York and Québec declined by 75% over the 1990-2008 period. The wastewater loads during the most recent time interval of 2007-2008 were below the applicable limits specified in the Lake Champlain Phosphorus TMDL for all lake segment watersheds with the exception of the Port Henry segment in New York.
5. The total phosphorus loads from all sources have remained above the total loading capacities established in the TMDL in all lake segments, with the exception of Shelburne Bay in Vermont and South Lake A in New York where the TMDL loading targets have been attained in recent years.
6. There were no statistically significant linear trends either upward or downward in phosphorus loads for any individual tributary over the 1991-2008 time period, although a marginally significant upward loading trend was seen in the Winooski River and a marginally significant downward trend was seen in the Pike River.
7. There were no significant upward or downward trends during 1991-2008 in the aggregated phosphorus loading rates from any lake segment watershed, with the exception of a marginally significant increasing trend from the Main Lake watershed in Vermont and a significant decrease from the South Lake A watershed in New York (due primarily to reductions at a large wastewater treatment facility).
8. Annual mean tributary flows during the 1991 base year used for the Lake Champlain Phosphorus TMDL were similar to flows recorded over the prior long-term period of record in six Lake Champlain Basin tributaries, but flows during the subsequent period of 1992-2007 tended to be higher than they were in 1991 in each of these rivers. In situations where flow rates have changed, flow-weighted mean inflow phosphorus concentrations are a better indicator of phosphorus loading stress on the lake than mass loading rates alone.
9. Most lake segment watersheds had either no trend or a decreasing trend in flow-weighted mean inflow phosphorus concentrations during 1991-2008. The South Lake A (NY), Shelburne Bay (VT), Cumberland Bay (NY), and Isle LaMotte (NY) watersheds had

significant or marginally significant decreasing trends in flow-weighted mean inflow concentrations. Only one watershed (Main Lake, VT) had a marginally significant increasing trend in flow-weighted mean inflow phosphorus concentrations. There was no overall lakewide trend in flow-weighted mean inflow phosphorus concentrations.

10. Flow-weighted mean nonpoint source phosphorus concentrations were generally higher in the Vermont and Québec tributaries than in the New York rivers, indicating a higher density of nonpoint sources in Vermont and Québec watersheds. The streams having the highest flow-weighted mean nonpoint source phosphorus concentrations included Englesby (VT), Rock (VT and QC), Little Otter (VT), Pike (VT and QC), LaPlatte (VT), and Little Chazy (NY).

11. Vermont contributed 60-70% of the total basinwide phosphorus load to Lake Champlain during 1991-2008, with New York contributing 20-30% and Québec adding about 10%. The wastewater portion of the total basinwide loads declined from about 25% in 1991-1992 down to only 5% in 2007-2008.

12. While overall progress in reducing phosphorus in Lake Champlain has been disappointing, there were some positive signs in the results. Phosphorus loads and flow-weighted mean phosphorus concentrations in the inflows to most regions of the lake were stable or decreasing during 1991-2008 in spite of ongoing land use conversion and development in the watershed.

13. More in-depth analysis of tributary phosphorus loading trends will be deferred to a study in progress by the USGS on phosphorus trend analysis and interpretation in the Lake Champlain Basin, in cooperation with the Lake Champlain Basin Program. This project will bring national expertise within the USGS, and will employ the most current statistical methods to account for the effects of hydrologic variations and phosphorus management efforts on trends in phosphorus loading to Lake Champlain.

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