Phosphorus Management in Lake Champlain

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ABSTRACT

Eutrophication management in Lake Champlain has expanded over the past several years into a comprehensive approach involving the analysis of lakewide response to multiple point and nonpoint sources of phosphorus. A user survey analysis of the relationship between phosphorus levels and recreational use impairment was used to derive in-lake total phosphorus criteria for 13 segments of Lake Champlain. Annual water, chloride, and phosphorus loadings to the lake were measured by a field sampling program and used to support the development of a whole-lake phosphorus mass balance model. The model used a minimum-cost optimization procedure to identify the load reductions needed in each sub-watershed to attain the in-lake phosphorus criteria. Watershed phosphorus loading targets established by the model provided the basis for a Lake Champlain phosphorus reduction agreement negotiated by the States of Vermont and New York and the U.S. Environmental Protection Agency in 1996.

INTRODUCTION

Lake Champlain contains a diversity of environments with respect to phosphorus levels and trophic state (Figure 1). Lake regions such as Malletts Bay and the Main Lake have phosphorus concentrations in the low-mesotrophic range of 0.009-0.012 $mg \cdot L^{-1}$. Eutrophic conditions prevail in areas such as St. Albans Bay, Missisquoi Bay and the South Lake, where phosphorus levels are in the range of 0.024-0.058 $mg \cdot L^{-1}$. Water quality problems are most acute in these eutrophic bay areas. However, public concerns have been expressed at times throughout the lake for symptoms of eutrophication including algae blooms, reduced water clarity, and shoreline periphyton growth.

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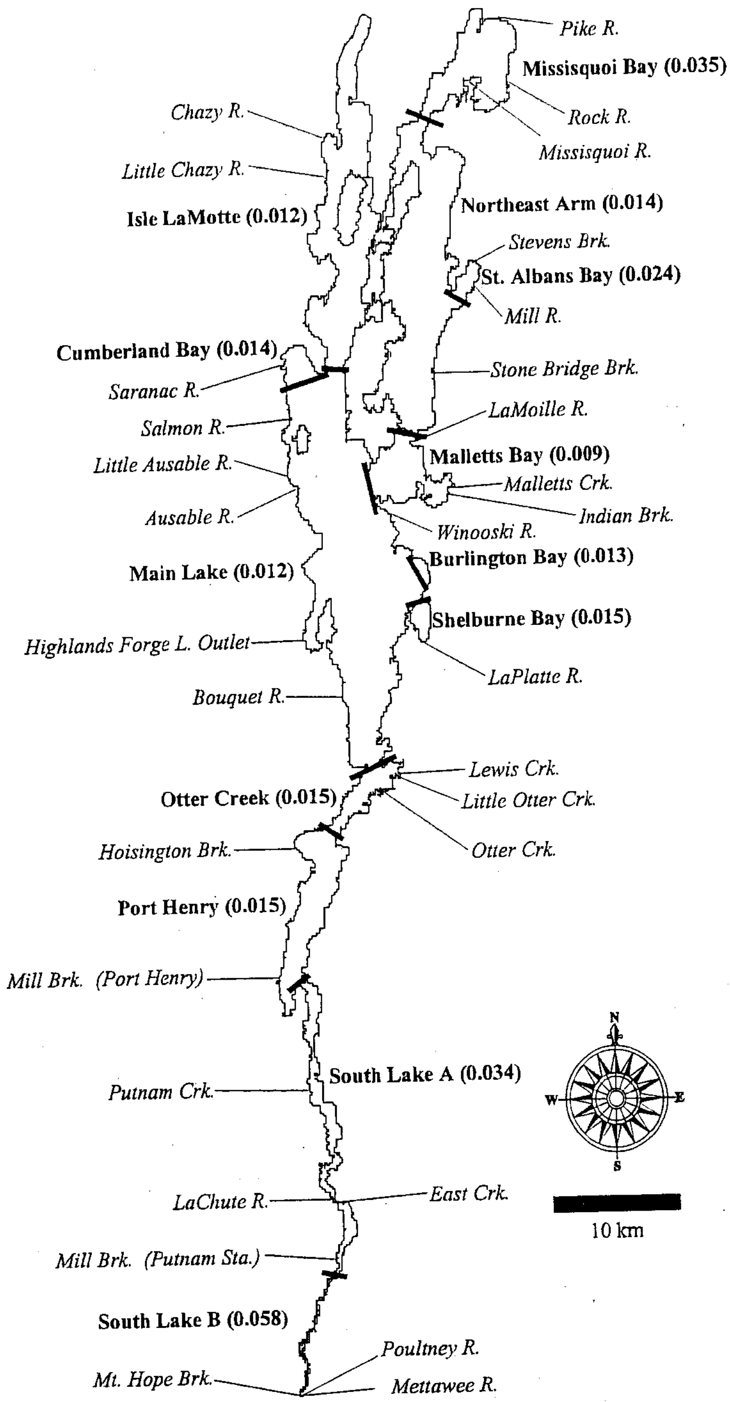

Figure 1. Map of Lake Champlain segments (bold) and tributaries (italics). Values in parentheses are 1991-1992 mean total phosphorus concentrations (mg·L^{-1}) in each lake segment [Vermont DEC and New York State DEC, 1997].

Phosphorus enrichment and eutrophication became a major water quality management issue in Lake Champlain during the 1970s. The first assessments of phosphorus sources to the lake [U.S. Environmental Protection Agency, 1974; Henson and Gruendling, 1977; Bogdan, 1978] estimated the total annual phosphorus load to the lake to be in the range of 536-804 $t{\cdot}yr^{-1}$, with approximately half of the total derived from point source discharges within the lake basin.

A comprehensive planning effort conducted in the 1970s [Lake Champlain Basin Study, 1979] recommended several management actions to hold constant or reduce phosphorus inputs to the lake until 1990. These actions included the continuation of phosphorus detergent bans in Vermont, New York, and Canada, the construction of advanced wastewater treatment facilities for phosphorus removal at a number of Vermont municipal treatment plants located near the lake, and the implementation nonpoint source best management practices in priority watersheds.

Even as these recommendations were pursued during the 1980s, it became apparent that management policies, and the limnological data to support sound policies, were inadequate to protect Lake Champlain from the cumulative effects of phosphorus loading [Vermont Agency of Natural Resources and New York State Department of Environmental Conservation (DEC), 1988]. Lake Champlain receives phosphorus inputs from more than 90 point source discharges throughout its basin and nonpoint source runoff from 31 major tributaries. However, no single phosphorus source is dominant on a lakewide basis. Numeric water quality standards were needed to define acceptable levels of phosphorus in the lake. Updated loading estimates and a lake phosphorus mass balance model were needed to establish finite limits for the cumulative phosphorus loading to each segment of the lake. Point and nonpoint source management programs in Vermont, New York, and Quebec needed to be structured to ensure attainment of the allowable phosphorus loads for Lake Champlain.

The purpose of this paper is to describe work done during the 1990s to address these phosphorus management needs for Lake Champlain. As a result of this work, a phosphorus reduction agreement was reached between the States of Vermont and New York and the U.S. Environmental Protection Agency and incorporated into a comprehensive basin plan [Lake Champlain Management Conference, 1996].

NUMERIC PHOSPHORUS CRITERIA

The first step in developing a phosphorus reduction plan for Lake Champlain was the establishment of numeric, in-lake phosphorus concentration criteria consistently between the various management jurisdictions. The total phosphorus criteria for each lake segment listed in Table 1 were incorporated into Vermont's state water quality standards in 1991 and subsequently endorsed as management goals by Vermont, New York, and Quebec in a Lake Champlain Water Quality Agreement signed in 1993 [Lake Champlain Phosphorus Management Task Force, 1993].

The criteria were derived, in part, from a lake user survey and an analysis of the relationship between phosphorus levels and recreational impairment of Lake Champlain [Heiskary and Walker, 1988; Smeltzer and Heiskary, 1990; North American Lake Management Society, 1992]. A user survey form was used in Lake Champlain from 1987-1991 as part of a citizen volunteer water quality monitoring program [Picotte, 1998]. Survey

TABLE 1. Lake Champlain total phosphorus concentration criteria.

Lake Segment	Existing Phosphorus Concentration[a] (mg·L^{-1})	Total Phosphorus Criterion[b] (mg·L^{-1})	Basis for Criterion[c]
Malletts Bay	0.009	0.010	Oligotrophic condition
Main Lake	0.012	0.010	
Port Henry	0.015	0.014	One percent time frequency of nuisance algal condition (from user survey analysis)
Otter Creek	0.015	0.014	
Shelburne Bay	0.015	0.014	
Burlington Bay	0.013	0.014	
Cumberland Bay	0.014	0.014	
Northeast Arm	0.014	0.014	
Isle LaMotte	0.012	0.014	
St. Albans Bay	0024	0.017	Expected response to advanced wastewater treatment
Missisquoi Bay	0.035	0.025	Moderate degree of eutrophication
South Lake A	0.034	0.025	
South Lake B	0.058	0.025	

[a]1991-1992 mean value [Vermont DEC and New York State DEC, 1997]
[b][Lake Champlain Phosphorus Management Task Force, 1993]
[c][Vermont DEC, 1990; Lake Champlain Basin Program, 1996]

questions asked the observers to rate the physical condition of the lake water and the recreational suitability at the same time samples were obtained for total phosphorus analysis.

The user survey results from over 900 individual observations distributed among 28 stations in Lake Champlain are illustrated in Figure 2. These results were used to quantify the instantaneous phosphorus levels at which critical transitions in user perceptions of water quality and recreational enjoyment occur in Lake Champlain. User descriptions such as "crystal clear" or "a little algae," and "beautiful" or "very minor problems" predominate when total phosphorus concentrations are below 0.025 mg·L^{-1}. Above 0.025 mg·L^{-1}, perceptions of "definite algal greenness" or "high algae," and "enjoyment slightly impaired" or "enjoyment reduced or impossible" represent the majority of responses. These results suggested that an instantaneous total phosphorus concentration of 0.025 mg·L^{-1} could be used to derive eutrophication criteria values for Lake Champlain.

Lake eutrophication criteria are best expressed as season or annual mean values, rather than as instantaneous "not to exceed" values [Walker, 1985a; North American Lake Management Society, 1992]. Cumulative frequency distributions for total phosphorus at Lake Champlain stations were used to evaluate the relationship between the mean phosphorus value and the frequency of the 0.025 mg·L^{-1} instantaneous nuisance criterion value [Walker, 1985a]. As shown in Figure 2, a mean value of 0.014 mg·L^{-1} represents a phosphorus level at which the 0.025 mg·L^{-1} nuisance condition would be exceeded only 1% of the time during the summer. A nuisance frequency of 1% (i.e. about one bad day per

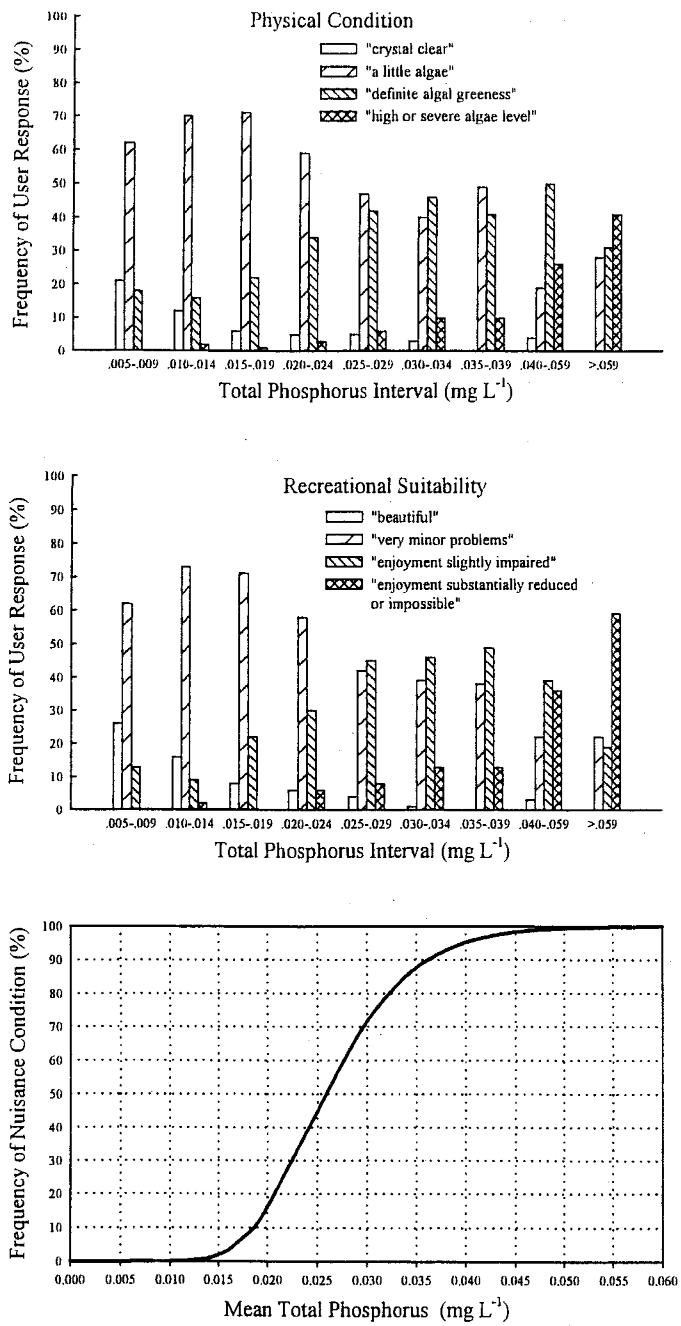

Figure 2. Results of Lake Champlain user survey analysis. The upper two graphs show the frequency of survey responses as a function of the instantaneous total phosphorus concentration measured at the time of observation. The lower graph shows the frequency (percent of time during the summer) of the 0.025 mg·L^{-1} nuisance algal condition as a function of the mean phosphorus value.

summer) was considered to be appropriately low for use in deriving nutrient water quality standards.

A mean total phosphorus criterion of 0.014 mg·L^{-1} was established for seven segments of Lake Champlain, as shown in Table 1. In other lake segments, higher or lower criteria values were established based on limitations of practical attainability, or to provide anti-degradation protection where existing phosphorus levels are below 0.014 mg·L^{-1} [Vermont DEC, 1990; Lake Champlain Basin Program, 1996]. The phosphorus criteria in Table 1 were used to guide the phosphorus modeling and load allocation studies described below.

WATER, CHLORIDE, AND PHOSPHORUS LOADS

A field study was conducted during 1990-1992 to quantify phosphorus loads to Lake Champlain from all major sources. The methods of sampling, data analysis, and results from the study are described in detail elsewhere [Vermont DEC and New York State DEC, 1997; Smeltzer and Quinn, 1996].

Hydrologic inputs were measured by a network of 31 tributary stream flow gages operated by the U.S. Geological Survey, representing 81% of the lake watershed area. Tributary samples (N = 36-115) were obtained near the mouth of each stream shown in Figure 1 and analyzed for total phosphorus, total dissolved phosphorus, and chloride. Sampling was conducted with an intentional bias toward high flow days to improve the precision of flow-stratified loading estimates [Verhoff et al., 1980]. Tributary annual mean mass loading rates were estimated using concentration vs. flow regression techniques provided by the FLUX program [Walker, 1987, 1990]. Other water and material budget terms were also estimated, including inputs from ungaged runoff, wastewater discharges, and direct precipitation, and losses by the Richelieu River outflow, water withdrawals, and evaporation [Vermont DEC and New York State DEC, 1997].

Mass loading rates are reported in this paper in units of metric tons per year (1 t·yr^{-1} = 1000 kg·yr^{-1}). Water flow rates are reported in units of cubic hectometers per year (1 hm^3·yr^{-1} = 10^6 m^3·yr^{-1}).

Water, chloride, and total phosphorus balances for Lake Champlain during the two-year sampling period are shown in Figure 3. Water and chloride inputs and losses balanced within statistical uncertainty limits. Residual budget errors were less than 2% for water and less than 4% for the conservative substance chloride. No attempt was made to account for groundwater inputs or losses, which were assumed to be minor. Net retention of phosphorus in the lake was estimated to be 80%.

Phosphorus loads from each tributary were estimated for calendar year 1991, which was defined as a hydrologic base year for phosphorus management purposes. Table 2 lists the base year flows and phosphorus loads from each tributary. Nonpoint source loading rates given in Table 2 were calculated by subtracting the loads discharged from all upstream point sources.

The total base year phosphorus loading rate to Lake Champlain was estimated to be 647 t·yr^{-1}, including inputs from monitored tributaries, unmonitored areas (estimated on a drainage area proportional basis relative to adjacent monitored tributaries), direct wastewater discharges to the lake, and precipitation direct to the lake surface. The 1991 value was within the range of 536-804 t·yr^{-1} estimated for the total phosphorus load to Lake Champlain during the 1970s [Bogdan, 1978], although the proportion of the total load derived from point sources (29%) was much lower in 1991 than in the 1970s.

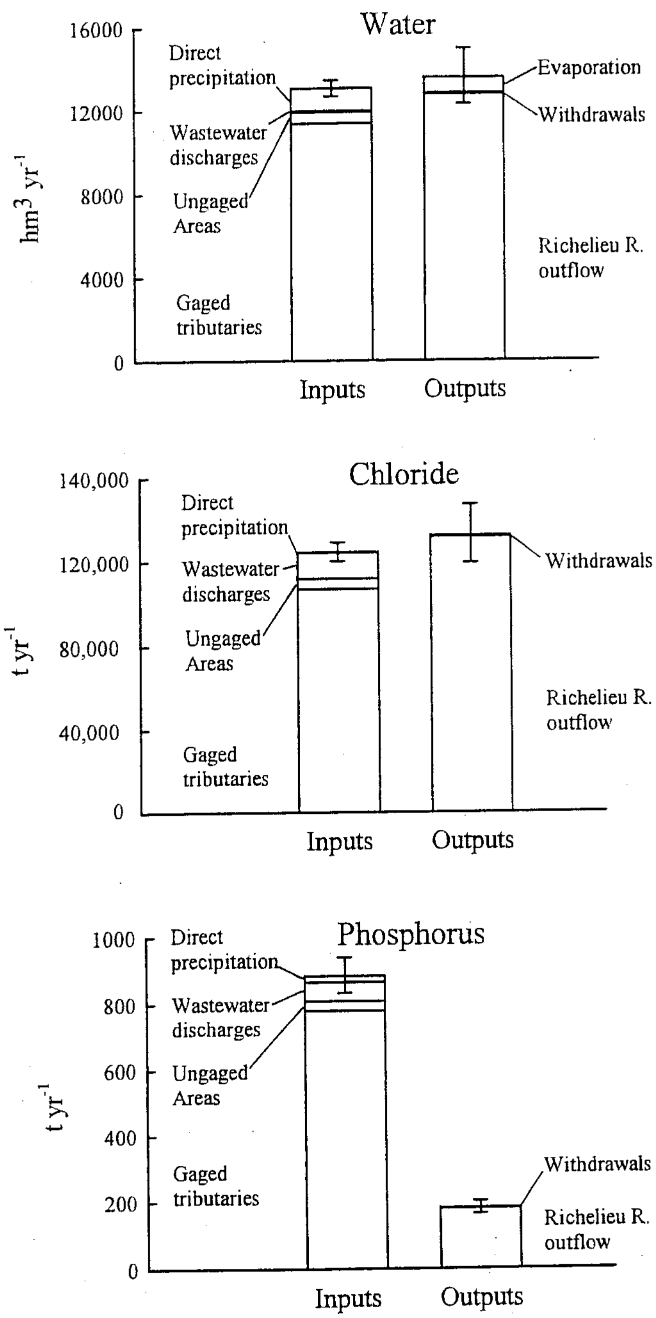

Figure 3. Water, chloride, and total phosphorus balances for Lake Champlain, March 1990 to February 1992. Error bars are 95% confidence intervals, calculated according to FLUX program procedures [Walker, 1987].

TABLE 2. Base year (1991) flows and phosphorus loading rates for Lake Champlain tributaries.

Tributary/Source	Drainage Area at Mouth (km^2)	Mean Flow ($hm^3 \cdot yr^{-1}$)	Total Load ($t \cdot yr^{-1}$)	Point Source Load ($t \cdot yr^{-1}$)	Nonpoint Source Load ($t \cdot yr^{-1}$)
Otter	2,462	1,119	109.7	62.3	47.4
Winooski	2,828	1,543	83.8	24.3	59.5
Missisquoi	2,223	1,307	82.1	7.0	75.1
Pike	517	296	50.3	5.9	44.4
Mettawee/Barge Canal	1,098	487	37.1	3.4	33.7
Lamoille	1,909	1,100	29.6	3.1	26.5
Rock	152	69	28.9	0.0	28.9
Great Chazy	769	320	17.7	1.1	16.6
Poultney	692	273	17.1	3.0	14.1
Ausable	1,323	639	16.8	5.6	11.2
Saranac	1,575	776	16.4	8.7	7.7
Bouquet	712	281	13.5	0.0	13.5
LaPlatte	137	44	11.8	4.2	7.6
Little Otter	185	55	5.4	0.0	5.4
Lewis	209	90	5.2	0.0	5.2
Little Ausable	189	89	5.2	1.4	3.8
Mill	59	26	3.5	0.0	3.5
Stevens	59	14	3.4	0.0	3.4
Little Chazy	139	44	3.2	0.0	3.2
Malletts	76	31	1.7	0.0	1.7
Salmon	175	55	1.7	0.0	1.7
East	81	24	1.3	0.1	1.2
Putnam	160	67	1.3	0.0	1.3
LaChute	702	273	1.1	0.0	1.1
Indian	31	13	0.9	0.0	0.9
Stone Bridge	32	10	0.8	0.0	0.8
Mill (Port Henry)	73	25	0.6	0.0	0.6
Hoisington	28	10	0.5	0.0	0.5
Mill (Putnam Sta.)	27	9	0.4	0.0	0.4
Highlands Forge Lake Outlet	30	9	0.1	0.0	0.1
Mt. Hope	30	13	0.1	0.0	0.1
Ungaged Areas	1,028	424	21.7	0.0	21.7
Direct Wastewater Discharges		52	58.4	58.4	0.0
Direct Precipitation	1,130	915	16.0	0.0	16.0
TOTAL	20,840	10,503	647.3	188.5	458.8

MASS BALANCE MODEL

A steady-state phosphorus mass balance model was developed for Lake Champlain to simulate the response of total phosphorus concentrations in each segment of the lake to changes in phosphorus loading rates. A steady-state approach was chosen because the in-lake criteria values established to guide the analysis (Table 1) were expressed as seasonal or annual mean values. The model employed the linear branching network of 13 lake segments illustrated in Figure 4. Each segment was modeled as a mixed-reactor, since vertical water column phosphorus concentration gradients were small in comparison with concentration differences between lake segments [Vermont DEC and New York State DEC, 1997].

The steady-state mass balance equation for an individual lake segment is given in Equation 1 [Chapra and Sonzogni, 1979; Chapra and Reckhow, 1983].

$$V_i\, dc_i/dt = 0 = W_i + \Sigma_j \{Q_{ji}c_j - Q_{ij}c_i + E_{ij}(c_j - c_i)\} - k_iV_ic_i^2 \qquad (1)$$

Where
V_i = volume of segment i (hm^3)
c_i = concentration in segment i ($mg \cdot L^{-1}$)
c_j = concentration in adjacent segment j ($mg \cdot L^{-1}$)
W_i = direct external mass loading to segment i ($t \cdot yr^{-1}$)
Σ_j = summation over all adjacent segments j
Q_{ji} = advective inflow to segment i from upstream segment j ($hm^3 \cdot yr^{-1}$)
Q_{ij} = advective outflow from segment i to adjacent downstream segment j ($hm^3 \cdot yr^{-1}$)
E_{ij} = bulk exchange flow between adjacent segments i and j ($hm^3 \cdot yr^{-1}$)
k_i = second-order sedimentation coefficient for segment i ($m^3 \cdot g^{-1} \cdot yr^{-1}$)

The flow routing scheme shown in Figure 4 was used to define the connections between adjacent lake segments. The advective inflow and outflow terms (Q_{ji} and Q_{ij}) in Equation 1 include the accumulated net sum of water inputs from monitored tributaries, ungaged watershed areas, wastewater discharges, direct precipitation, evaporation, and water withdrawals. One lake segment (Malletts Bay) required special two-dimensional treatment in the model. Advective and exchange flows from Malletts Bay were partitioned between adjacent lake segments according to field observations [Myer, 1977; Myer and Gruendling, 1979], with 86% of the flow routed to the Main Lake segment and the remainder going to the Northeast Arm.

Bulk exchange flow terms (E_{ij}) were evaluated using chloride loads and in-lake concentrations measured during the field study [Vermont DEC and New York State DEC, 1997]. Sedimentation rates (k_i) were assumed to be zero for the conservative substance chloride. Equation 1 was solved for the exchange flows at each segment boundary by direct linear matrix inversion, using a modified version of the BATHTUB program [Walker, 1987, 1992]. The values used for the chloride model terms for each lake segment and the calculated exchange rates are given in Table 3.

The second-order formulation for the phosphorus sedimentation term (k_i) in Equation 1 was found to provide a better empirical fit of the BATHTUB model to a U.S. reservoir data set than the more common first-order models [Walker, 1985b]. Use of a second-order decay term is consistent with the concept of poorer nutrient recycling efficiency in eutrophic environments, compared with oligotrophic lakes.

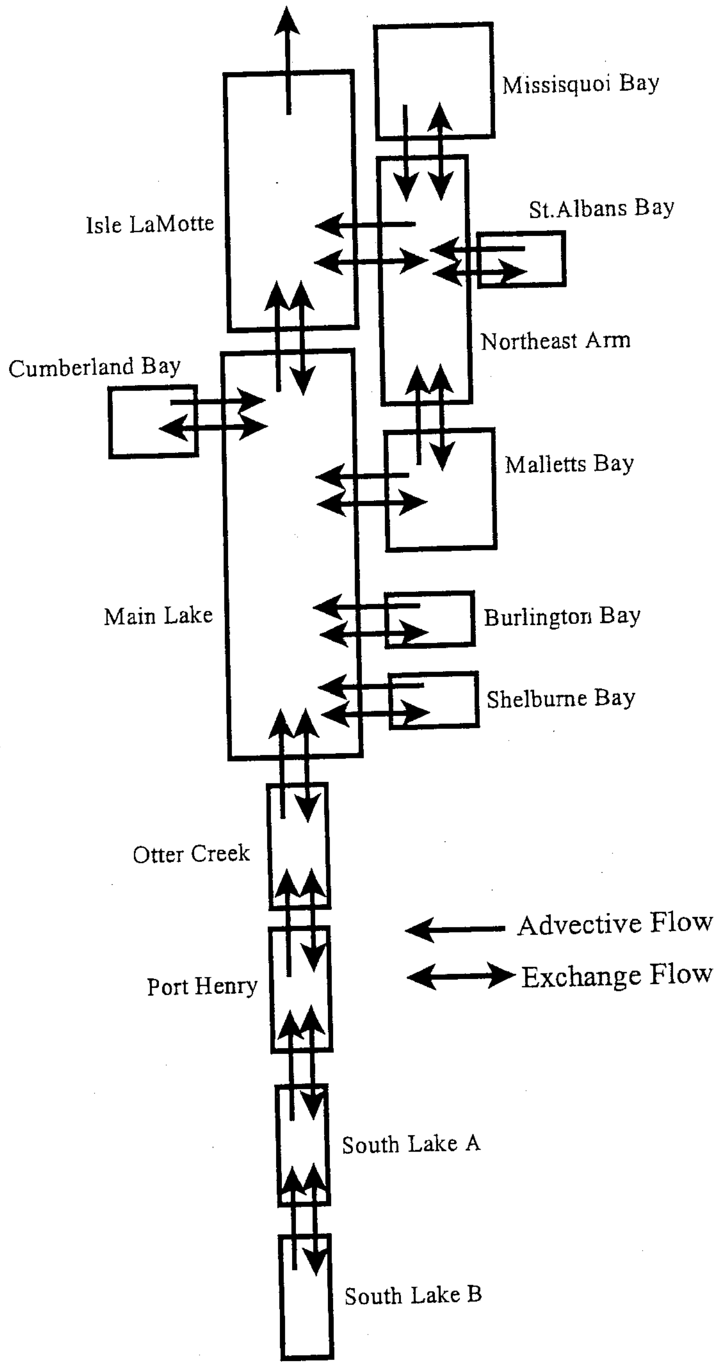

Figure 4. Lake Champlain mass balance model flow routing scheme.

TABLE 3. Chloride model terms for the period of March 1990 to February 1992.

Lake Segment	Segment Volume (hm^3)	Segment Area (hm^2)	External Inflow ($hm^3 \cdot yr^{-1}$)	Chloride Load ($t \cdot yr^{-1}$)	Chloride Conc. ($mg \cdot L^{-1}$)	Exchange Flow[a] ($hm^3 \cdot yr^{-1}$)
South Lake B	7.8	579	1,092	11,384	11.62	712
South Lake A	125	4,327	629	14,679	13.47	1,259
Port Henry	1,463	7,555	150	1,283	11.18	13,998
Otter Creek	955	2,849	1,648	15,769	10.72	49,427
Main Lake	16,787	41,414	3,530	38,250	10.61	8,861
Shelburne Bay	140	962	79	2,206	10.89	4,816
Burlington Bay	63	551	9	598	10.78	2,986
Cumberland Bay	63	1,075	950	5,941	10.18	8,672
Malletts Bay	722	5,506	1,529	14,098	9.43	272 (52[b])
Northeast Arm	3,380	24,825	130	997	9.29	1,968
St. Albans Bay	23	721	63	2,320	10.20	1,844
Missisquoi Bay	205	8,994	2,039	15,407	7.78	297
Isle LaMotte	1,892	18,559	514	4,931	10.33	

[a]At boundary with downstream lake segment.
[b]Value for the northern boundary of Malletts Bay with the Northeast Arm.

The optimal second-order sedimentation parameter estimate of 100 $m^3 \cdot g^{-1} \cdot yr^{-1}$, derived independently from the U.S. reservoir data set [Walker, 1985b], was applied without modification to ten of the 13 Lake Champlain segments [Smeltzer and Quinn, 1996; Vermont DEC and New York State DEC, 1997]. The sedimentation rates for two lake segments (Malletts Bay and Missisquoi Bay) were increased to 400 $m^3 \cdot g^{-1} \cdot yr^{-1}$ to improve the fit of model-predicted lake phosphorus concentrations to the observed Lake Champlain data. Calibration of the model for the St. Albans Bay segment required setting the phosphorus sedimentation rate to zero and adding an internal load of 8.6 $t \cdot yr^{-1}$ to the direct mass inputs in order to obtain an acceptable model fit. The non-linear phosphorus mass balance equations were solved by an iterative procedure in the BATHTUB program [Walker, 1987].

The values used for the phosphorus model terms and the phosphorus concentrations in each lake segment predicted by the calibrated model are given in Table 4. Figure 5 shows that a good overall calibration fit (root mean squared error = 0.034, $\log_{10}$ scale) was obtained between model-predicted phosphorus concentrations in each lake segment and the measured mean values. Uncertainty estimates for model input terms and model predictions (e.g. 95% confidence intervals, Figure 5) were derived from error analysis procedures in the FLUX and BATHTUB programs [Walker, 1987].

LOAD REDUCTION STRATEGY

The calibrated phosphorus mass balance model was used to evaluate alternative load reduction strategies to attain the in-lake criteria in each lake segment. A process for assigning phosphorus loading targets for point and nonpoint sources in each sub-watershed

TABLE 4. Phosphorus model terms for the 1991 base year.

Lake Segment	External Inflow ($hm^3 \cdot yr^{-1}$)	Phosphorus Load ($t \cdot yr^{-1}$)	Calibrated Sedimentation Coefficient ($m^3 \cdot g^{-1} \cdot yr^{-1}$)	Observed Phosphorus Conc. ($mg \cdot L^{-1}$)	Predicted Phosphorus Conc. ($mg \cdot L^{-1}$)
South Lake B	830	56.7	100	0.058	0.049
South Lake A	410	15.3	100	0.034	0.031
Port Henry	96	5.8	100	0.015	0.015
Otter Creek	1,283	121.3	100	0.015	0.014
Main Lake	2,708	133.0	100	0.012	0.012
Shelburne Bay	47	16.4	100	0.015	0.015
Burlington Bay	7	11.7	100	0.013	0.016
Cumberland Bay	828	38.1	100	0.014	0.015
Malletts Bay	1,176	33.0	400	0.009	0.009
Northeast Arm	66	6.5	100	0.014	0.014
St. Albans Bay	43	16.6[a]	0	0.024	0.022
Missisquoi Bay	1,720	167.9	400	0.035	0.035
Isle LaMotte	413	31.4	100	0.012	0.012

[a]Includes an internal load of 8.6 $t \cdot yr^{-1}$ added for model calibration.

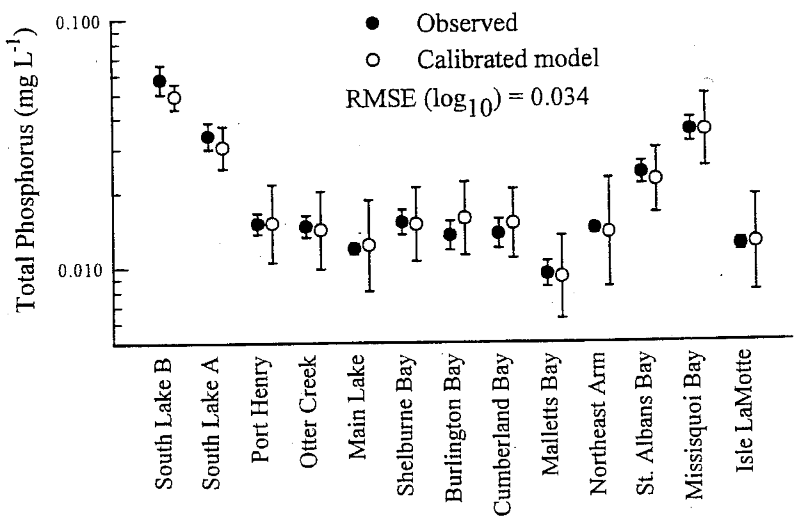

Figure 5. Phosphorus model calibration results, comparing the observed mean and model-predicted total phosphorus concentrations in each lake segment. Error bars are 95% confidence intervals.

TABLE 5. Base year (1991) phosphorus loads to Lake Champlain from Vermont and New York, and watershed target loads.

Lake Segment	1991 Load ($t \cdot yr^{-1}$)			Target Load ($t \cdot yr^{-1}$)		
	VT	NY	Total	VT	NY	Total
South Lake B	28.0	28.2	56.2	20.8	26.2	47.0
South Lake A	2.4	13.1	15.5	0.6	9.4	10.1
Port Henry	0.4	4.3	4.7	0.1	2.5	2.6
Otter Creek	121.7	0.1	121.8	56.1	0.0	56.2
Main Lake	88.0	38.9	126.9	76.6	35.0	111.6
Shelburne Bay	16.4	0.0	16.4	12.0	0.0	12.0
Burlington Bay	11.5	0.0	11.5	3.1	0.0	3.1
Cumberland Bay	0.0	38.0	38.0	0.0	25.5	25.5
Malletts Bay	32.9	0.0	32.9	28.6	0.0	28.6
Northeast Arm	3.2	0.0	3.2	1.2	0.0	1.2
St. Albans Bay	8.0	0.0	8.0	9.5	0.0	9.5
Missisquoi Bay[a]	167.3	0.0	167.3	109.7	0.0	109.7
Isle LaMotte	0.6	28.3	28.8	0.3	21.5	21.8
Direct Precipitation			16.0			16.0
TOTAL	480.4	150.9	647.3	318.6	120.2	454.9

[a]Includes loads from both Vermont and Quebec.

in each state was negotiated by the States of Vermont and New York and the U.S. Environmental Protection Agency [Lake Champlain Management Conference, 1996].

Point source loading targets were established for each sub-watershed before the phosphorus model was applied. Allowable point source loads (Table 5) were calculated by assuming an advanced treatment effluent total phosphorus concentration of 0.8 $mg \cdot L^{-1}$ at all wastewater treatment facilities larger than 200,000 $gal \cdot day^{-1}$ (757 $m^3 \cdot day^{-1}$) in permitted flow, exempting facilities using aerated lagoon processes.

The remaining nonpoint source phosphorus load reductions needed in each lake segment watershed were identified by the model using a minimum-cost optimization procedure [Chapra et al., 1983; Holmes and Artuso, 1995; Vermont DEC and New York State DEC, 1997]. Information on the cost and effectiveness of agricultural and urban phosphorus control practices specific to each sub-watershed was obtained from the U.S. Natural Resources Conservation Service and from an economic analysis [Holmes and Artuso, 1995]. The calibrated mass balance model equations and cost-effectiveness data were transferred to a commercial spreadsheet program. Numeric solution techniques in the spreadsheet program were used to find the least-cost distribution of nonpoint source load reductions among the sub-watersheds. The optimization procedure was constrained by the need to attain the in-lake phosphorus criteria values without exceeding the maximum potential nonpoint source load reduction considered possible in each sub-watershed.

The nonpoint source loading targets resulting from the optimization procedure are shown in Table 5. Compliance with the 0.025 $mg \cdot L^{-1}$ criterion for the South Lake B segment was

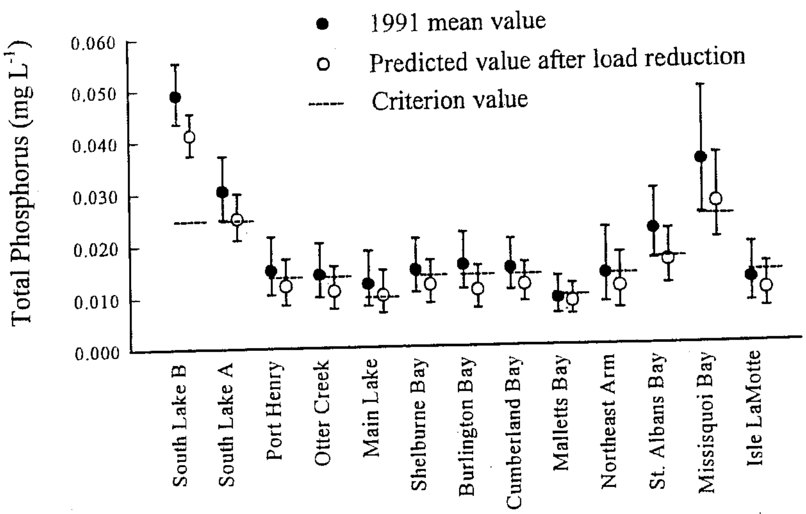

Figure 6. Phosphorus load reduction modeling results showing the observed 1991 mean total phosphorus concentration in each lake segment, and comparing the in-lake criteria values with the concentrations predicted after all watershed loading targets are achieved. Error bars are 95% confidence intervals for the observed mean and model-predicted values.

waived in the procedure because of the unrealistically large nonpoint source reductions needed to achieve that criterion. However, substantial reductions were still required in the South Lake B segment watershed (Table 5) in order to attain the 0.025 mg·L^{-1} criterion for the South Lake A segment downstream. The endpoint for the Missisquoi Bay segment was modified in the analysis from 0.025 mg·L^{-1} (Table 1) to 0.027 mg·L^{-1} for similar reasons. The load reduction analysis assumed that the 8.6 t·yr^{-1} internal load applied to the St. Albans Bay segment during the model calibration will decline to zero over time as excessive sediment phosphorus is gradually depleted in the bay [Martin et al., 1994].

The results of the load reduction analysis shown in Table 5 indicated that the total phosphorus load to Lake Champlain should be limited to 455 t·yr^{-1}, representing a net reduction of 192 t·yr^{-1} (30%) from the 1991 base year total load of 647 t·yr^{-1}. As shown in Figure 6, the model predicted that these load reductions will result in attainment of the in-lake criteria for most lake segments with a 50% or greater level of confidence.

The point and nonpoint source loading targets for each lake segment watershed derived from the modeling analysis (Table 5) were adopted as part of a comprehensive basin plan for Lake Champlain [Lake Champlain Management Conference, 1996]. The loading targets are to be achieved over a time period of 20 years.

DISCUSSION

Substantial progress was made during the 1990s in managing phosphorus in Lake Champlain. Agreements were reached between the various government jurisdictions on the desired in-lake water quality goals and on a division of responsibility for achieving the necessary phosphorus load reductions. Implementation of point and nonpoint source controls reduced phosphorus loading to the lake by 20% between 1991 and 1995 [Lake Champlain Management Conference, 1996]. The results of the analyses described in this paper contributed directly to the development of the water quality agreements and the formation of the comprehensive basin plan for Lake Champlain.

The relatively simple mass balance model used to derive the phosphorus loading targets for Lake Champlain has certain limitations that should be addressed by future research. By not accounting in detail for internal phosphorus cycling between the lake sediments and the water column, the model assumed a constant net sedimentation rate as external loadings change. However, studies in St. Albans Bay [Martin et al., 1994] and in other shallow lakes [Havens and James, 1997] have shown that sediment phosphorus storage may cause long response time lags that are not predicted by simple models.

Missisquoi Bay and the South Lake are two shallow, eutrophic regions of Lake Champlain where substantial loading reductions are planned. The sediment phosphorus release model applied to St. Albans Bay [Martin et al., 1994; Chapra and Canale, 1991] should be extended to these areas of Lake Champlain. Benthic phosphorus cycling research and modeling work in progress on Lake Champlain [HydroQual, Inc., 1998; Cornwell and Owens, 1998] should be used to refine predictions of the long-term water quality response of these regions to phosphorus management actions.

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