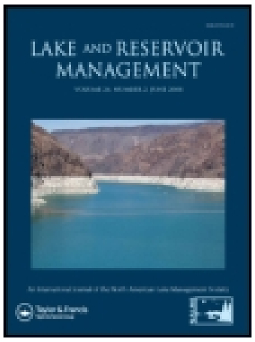

Taylor & Francis
Taylor & Francis Group

Lake and Reservoir Management

ISSN: 1040-2381 (Print) 2151-5530 (Online) Journal homepage: http://www.tandfonline.com/loi/ulrm20

A Phosphorus Budget, Model, and Load Reduction Strategy For Lake Champlain

Eric Smeltzer & Scott Quinn

Journal of Lake and Reservoir Management 12(3):381-393, 1996

A Phosphorus Budget, Model, and Load Reduction Strategy For Lake Champlain

Eric Smeltzer
Vermont Department of Environmental Conservation
103 South Main St., Bldg. 10 North
Waterbury, VT 05671-0408

Scott Quinn
New York State Department of Environmental Conservation
50 Wolf Rd.
Albany, NY 12233-3502

ABSTRACT

Smeltzer, E. and S. Quinn. 1996. A phosphorus budget, model, and load reduction strategy for Lake Champlain. Lake and Reserv. Manage. 12(3):381-393.

A phosphorus budget and mass balance model were developed for Lake Champlain in order to identify load reductions necessary to attain interim in-lake total phosphorus concentration criteria established in a water quality agreement between New York, Quebec, and Vermont. Total phosphorus loadings were measured from 31 tributaries, 88 wastewater discharges, and direct precipitation. Mean annual tributary loadings were estimated using the FLUX program (Walker 1987). The total base year phosphorus loading rate of 647 mt · yr^{-1} included 29% from point sources, 47% from cultural nonpoint sources, and 24% from natural sources. A mass balance model for 13 lake segments was developed and calibrated to the data using the BATHTUB program (Walker 1987). Exchange flows between lake segments were evaluated using a mass balance for chloride. The BATHTUB program error analysis procedure was used to evaluate model prediction uncertainty, based on variance estimates for all input data terms. The modeling results were used with a minimum-cost optimization procedure to determine that an overall phosphorus load reduction of 192 mt · yr^{-1} distributed among specifically targeted lake segment watersheds will be needed to attain the in-lake phosphorus criteria.

Key Words: phosphorus budget, phosphorus loading, modeling, FLUX, BATHTUB, standards, watershed targeting, Lake Champlain.

Lake Champlain is a 170 km-long natural lake shared by the States of Vermont and New York and the Province of Quebec. The lake holds a special place in North American history. Lake Champlain provided a military invasion route during the Colonial Wars, the American Revolution, and the War of 1812, and later became an important commercial waterway linking the northeastern U.S. with Canada. Historic battles were fought at Fort Ticonderoga, Valcour Island, and Plattsburgh.

Today, the Lake Champlain Basin supports a population of over 600,000. The major use of the lake is for recreation, although Lake Champlain also serves as a water supply for 180,000 people. Commercial fisheries on the lake are minor.

The unregulated outflow from the 19,881 km^2 watershed drains northward to the St. Lawrence River. The watershed includes nearly half the state of Vermont and large areas of northeastern New York and southern Quebec. Lake Champlain is morphologically complex with numerous bays and well defined segments as shown in Fig. 1. The lake has a surface area of 1,130 km^2 and a mean depth of 22.8 m.

A wide variety of limnological conditions exist within Lake Champlain with respect to trophic state, ionic composition, thermal and hydrodynamic features, and optical properties (Potash et al. 1969, Henson and Gruendling 1977, Myer and Gruendling 1979, Effler et al. 1991, Vermont DEC and New York State DEC 1994). Mesotrophic to near-oligotrophic conditions exist in the deep (122 m maximum depth) open-water regions along the main axis of the lake where a large amplitude internal seiche results in extensive mixing and weak spatial water quality gradients. Eutrophic conditions

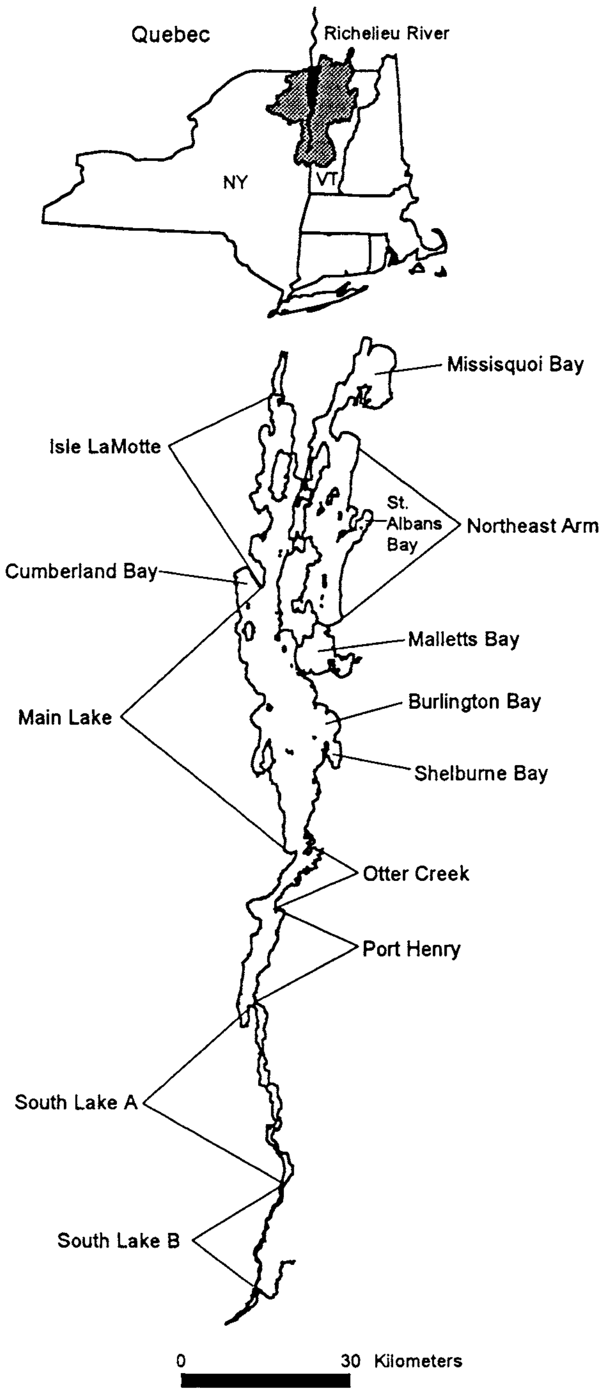

Figure 1.–Segments of Lake Champlain.

and strong chemical gradients prevail in shallow bays such as Missisquoi Bay, St. Albans Bay, and the South Lake region.

The problem of phosphorus and eutrophication is one of the key lake management issues being addressed in the Comprehensive Pollution Prevention, Control, and Restoration Plan prepared by the Lake Champlain Management Conference (1996) under the federal Lake Champlain Special Designation Act of 1990. Eutrophication in Lake Champlain is a problem of cumulative impacts from 88 municipal and industrial wastewater treatment plants in the basin and from nonpoint source phosphorus loading delivered by 31 major tributaries. Case-by-case management of phosphorus sources has proven inadequate to protect the lake as a whole from such cumulative impacts. A more comprehensive phosphorus reduction strategy is needed (Smeltzer 1992).

The first step in developing a phosphorus reduction strategy for Lake Champlain was the establishment of numeric, in-lake phosphorus concentration criteria consistently between the various management jurisdictions. Total phosphorus criteria for each lake segment were incorporated into Vermont's state water quality standards in 1991 and subsequently endorsed as interim management goals by Vermont, New York, and Quebec under an international water quality agreement on Lake Champlain signed in 1993 (Lake Champlain Phosphorus Management Task Force 1993). The phosphorus criteria for Lake Champlain are summarized in Table 1 and compared with the current levels in each lake segment. The criteria were derived, in part, from a user survey and analysis of the relationship between phosphorus levels and recreational impairment of Lake Champlain (Smeltzer and Heiskary 1990, North American Lake Management Society 1992).

The next step in the management process was the

Table 1.–Total phosphorus concentration criteria for Lake Champlain (Lake Champlain Phosphorus Management Task Force 1993), compared with current mean levels (this study).

	Total Phosphorus (mg · L^{-1})	
Lake Segment	**Criterion**	**Current Level**
Main Lake	0.010	0.012
Malletts Bay	0.010	0.009
Shelburne Bay	0.014	0.015
Burlington Bay	0.014	0.013
Cumberland Bay	0.014	0.014
Northeast Arm	0.014	0.014
Isle LaMotte	0.014	0.012
Otter Creek	0.014	0.015
Port Henry	0.014	0.015
St. Albans Bay	0.017	0.024
Missisquoi Bay	0.025	0.035
South Lake A	0.025	0.034
South Lake B	0.025	0.058

completion of a bi-state cooperative study to measure phosphorus loadings to the lake, develop a mass balance model, and use the model to identify load reductions needed to attain the criteria (Vermont DEC and New York State DEC 1994). This paper presents the results of the phosphorus study and describes how the results are being integrated into the policy and planning efforts for Lake Champlain by the States of Vermont and New York and the Lake Champlain Management Conference.

Methods

A complete description of the field and analytical methods and documentation of the project database can be found in Vermont DEC and New York State DEC (1994). A brief summary of methods is presented here.

Lake segment mean concentrations of total phosphorus and chloride were calculated from vertical water column composite samples obtained at 52 lake stations on a biweekly frequency during May to November, 1990-1991. Instantaneous samples for total phosphorus and chloride were obtained near the mouths of 31 tributaries using depth and velocity integrating sampling techniques (Edwards and Glysson 1988). Sample numbers ranged from 36 to 115 per tributary during the period of March 1990 to April 1992. The sampling effort was intentionally biased toward high flow days to improve the precision of flow-stratified load estimation methods (Verhoff et al. 1980).

Average daily flows in 31 tributaries to Lake Champlain and in the Richelieu River outflow for the period of March 1990 to April 1992 were measured at gage stations operated by the U.S. Geological Survey, the Quebec Ministry of the Environment, and Environment Canada. The gage sites incorporated 16,202 km² (81%) of the total 19,881 km² watershed area and were located on rivers which, at their mouths, represented 94% of the watershed area.

Mean annual tributary loadings of total phosphorus and chloride were estimated using concentration vs. average daily flow regression procedures provided by the FLUX program (Walker 1987, 1990, Method 6). Regression residuals were examined for dependence on flow or season, and the regression relationships were stratified appropriately to eliminate such residual dependence. Flows and loadings from the unmonitored portions of the watershed were estimated on a drainage area proportional basis using values from adjacent tributaries. Flows and loadings of total phosphorus and chloride from the 88 wastewater treatment plants in the basin were evaluated using plant operation records supplemented with monthly effluent sampling during 1990-1991 at 16 facilities discharging directly to Lake Champlain.

Precipitation volume inputs directly to the lake surface were estimated by averaging data from eight NOAA weather stations distributed around the lake. Total phosphorus and chloride deposition rates to the lake surface were calculated from volume-weighted mean concentrations in samples obtained at four precipitation sampling stations within the watershed. Pan evaporation measurements at one NOAA station within the watershed were used to estimate the annual mean evaporation rate from the lake surface by applying a regional pan-to-lake coefficient of 0.77 (Kohler et al. 1959).

Variances were estimated for all model input data terms and expressed as the coefficient of variation (CV) of the mean, following Walker (1987). Phosphorus and chloride concentration CV values for each lake segment were based on the variability between sampling intervals during the two year sampling period. Error estimates for most water balance terms were derived from Winter (1981), and were assumed to be 5% for continuously gaged tributaries and wastewater discharges, and 20% for ungaged or partially gaged tributary inflows and lake evaporation. The FLUX program (Walker 1987) provided tributary phosphorus and chloride loading error estimates using a jackknifing procedure. The observed variability among monitoring stations was used to estimate CV values for precipitation volumes and atmospheric deposition rates.

Chemical analyses were performed by the Vermont Department of Environmental Conservation Laboratory using procedures in APHA (1989) and USEPA (1983). Total phosphorus was analyzed on unfiltered samples using the ascorbic acid method following persulfate digestion. Chloride was measured using the ferric thiocyanate method.

Phosphorus Budget

Water, Chloride, and Phosphorus Balances

Water, chloride, and total phosphorus budget terms for Lake Champlain were calculated for the two-year monitoring period of March 1990 to February 1992. Budget input terms included flows and loadings from all monitored tributaries, ungaged areas, direct wastewater discharges, and direct precipitation. Outputs to the Richelieu River were estimated using the area-adjusted gage flow record with lake phosphorus and chloride concentrations measured near the lake

outlet. Other outputs included evaporation at a rate of 0.65 m · yr^{-1} and some minor municipal and industrial water withdrawals. Change-in-storage terms were derived from the observed net lake level decline of 0.62 m during the two-year monitoring period. Groundwater inputs and outputs were not measured and were assumed to be minor, pending the results of the water and chloride budget calculations.

Mass loading rates are reported in units of metric tons per year (1 mt = 1000 kg). Flow rates are reported in units of cubic hectometers per year (1 $hm^3 = 10^6 m^3$).

The budget results are shown in Table 2. Residual budget errors were less than 2% for water and less than 4% for the conservative substance chloride. Net retention of phosphorus was 81% during the two-year period.

Hydrologic Base Year Phosphorus Loadings

Tributary flows and phosphorus loadings were normalized to a hydrologic base year in order to better represent long term average conditions, as was done for the Great Lakes phosphorus management program (Thomas et al. 1980). Calendar year 1991 was chosen as a hydrologic base year for purposes of phosphorus source assessment and load reduction modeling, based on an examination of long-term flow gage records for ten rivers within the Lake Champlain Basin.

Tributary phosphorus loadings were calculated for the 1991 base year using the FLUX program methods described above. Base year inputs from atmospheric sources were estimated using the 1991 mean precipitation rate of 0.81 m · yr^{-1} and a phosphorus deposition rate of 13.6 mg · m^{-2} yr^{-1}.

The distribution of base year total phosphorus loadings among the 31 major tributaries to Lake Champlain is shown in Fig. 2. The total nonpoint source loads were calculated by subtracting the contributions of upstream wastewater discharges from the loadings measured at the river mouths. Nonpoint source phosphorus loading rates were strongly correlated with land use in the tributary watersheds (Fig. 3). The portions of the nonpoint source tributary loadings that resulted from measured concentrations higher than the estimated background level of 0.015 mg · L^{-1} (intercept, Fig. 3) were attributed to "cultural" nonpoint sources in Fig. 2. The "natural" background loadings estimated in this manner represent basin average values which could vary between individual tributaries as a result of differences in soil types or other geologic factors.

Table 2.–Water, chloride, and total phosphorus budgets for Lake Champlain measured during the period of March 1990 to February 1992. Coefficients of variation for the total input and output estimates are given in parentheses, estimated from BATHTUB program procedures (Walker 1987).

Source	Water ($hm^3 \cdot yr^{-1}$)	Chloride ($mt \cdot yr^{-1}$)	Phosphorus ($mt \cdot yr^{-1}$)
Inputs			
Gaged Tributaries	11,387	106,980	780
Ungaged Areas	552	4,838	29
Direct Wastewater Discharges	52	12,423	57
Direct Precipitation	1,085	312	18
Total Inputs	13,076	124,553	884
	(.015)	(.018)	(.030)
Outputs			
Outlet Flow	12,809	131,933	181
Withdrawals	46	549	1
Evaporation	735	0	0
Total Outputs	13,590	132,482	182
	(.049)	(.052)	(.053)
Change in storage	-350	-3,610	-5
Error/Retention	-164	-4,319	707

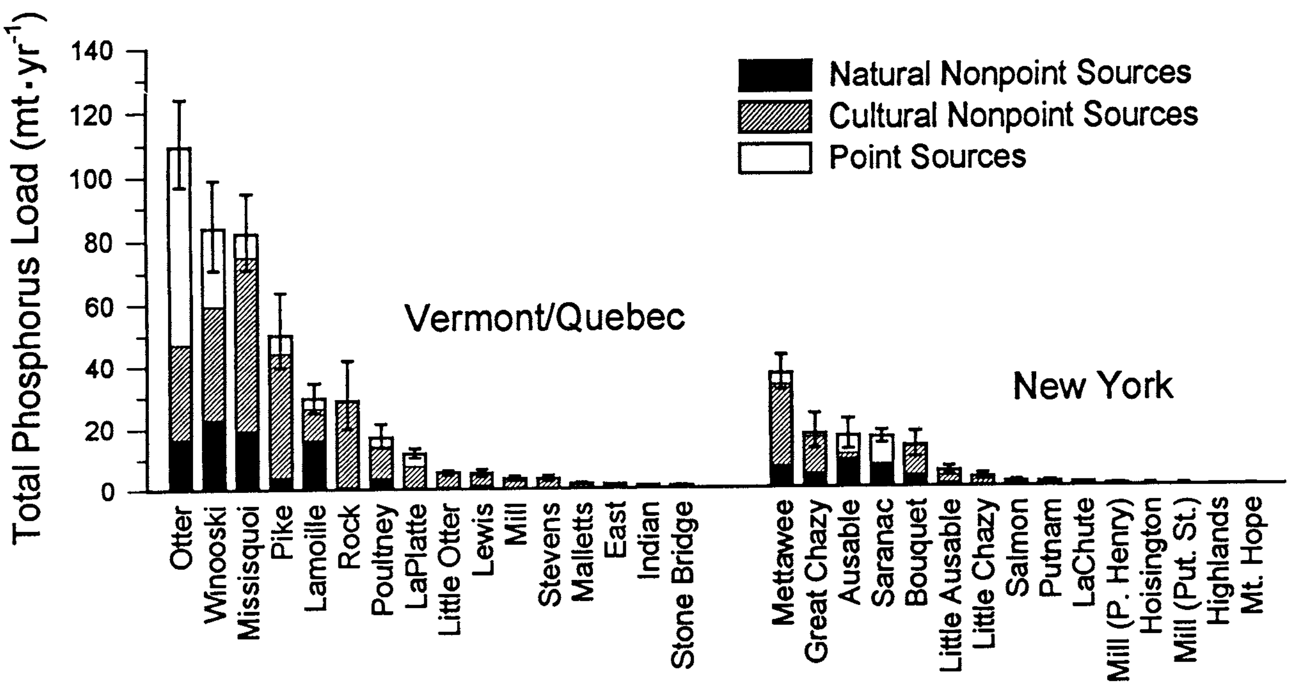

Figure 2.–Point and nonpoint source total phosphorus loadings from 31 major tributaries to Lake Champlain for the 1991 hydrologic base year. Error bars show 95% confidence intervals for the total loads, calculated using FLUX program procedures (Walker 1987).

Fig. 2 shows that most of the tributary phosphorus loading to the lake was derived from sources in Vermont and Quebec where most of the basin population resides and where agricultural and urban land uses are more prevalent than in the New York portion of the watershed. The total base year phosphorus loading rate to Lake Champlain was estimated to be 647 mt · yr^{-1}.

The distribution of the total phosphorus loading among source categories is summarized in Fig. 4. Point source discharges account for 29% of the total load. Cultural nonpoint sources are the largest category, contributing 47% of the total. Natural nonpoint sources including direct precipitation represent only 24% of the total. Apparently, human activities in the watershed have increased phosphorus loading to Lake Champlain four-fold over pre-development levels.

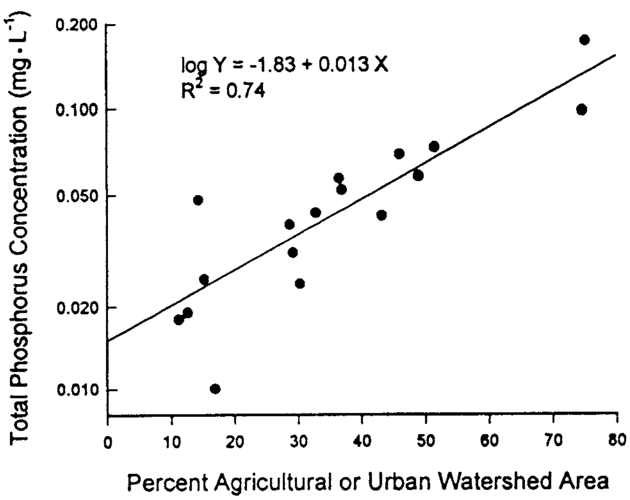

Figure 3.–Regression relationship between nonpoint source flow-weighted mean total phosphorus concentration and land use for 17 Lake Champlain tributaries. Land use data are from Budd and Meals (1994).

Model Development

Modeling Approach

The purpose of the modeling analysis was to determine the magnitude and locations of the

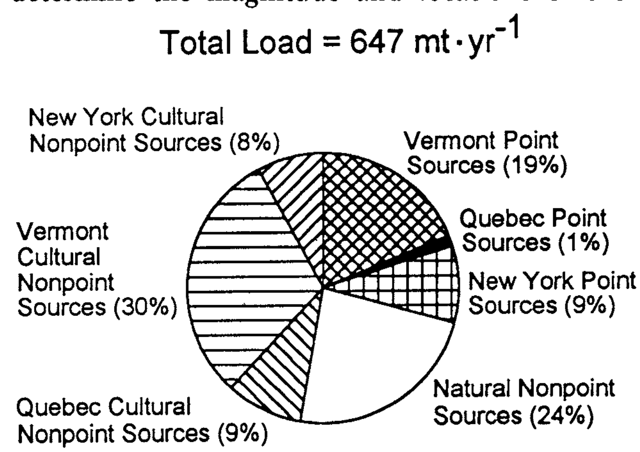

Figure 4.–Summary of total phosphorus sources to Lake Champlain for the 1991 base year.

phosphorus loading reductions needed to attain the in-lake criteria listed in Table 1. Since the existing water quality and the in-lake management targets differed greatly between lake segments, a model capable of simulating horizontal spatial concentration differences was required. Lake water column profile sampling for total phosphorus and chloride in Lake Champlain (Vermont DEC and New York State DEC 1994) indicated that vertical concentration gradients were small relative to the horizontal spatial gradients, and therefore each segment was modeled as a mixed reactor.

Significant seasonal differences in total phosphorus concentrations existed in some lake segments (Vermont DEC and New York State DEC 1994). However, a time-dependent modeling approach would have added considerable complexity, only to provide output that would need later statistical reduction for compatibility with the in-lake phosphorus criteria (Table 1) which are expressed as mean values. Therefore, a steady-state modeling approach was chosen as a way to simulate long term annual mean phosphorus concentrations.

The modeling approach used for this study was based on the steady-state mass balance equation for a lake segment given in Equation 1. A similar model was applied to the entire Great Lakes system by Chapra and Sonzogni (1979) to predict the response of each segment of the Great Lakes to phosphorus loading changes.

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

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 $mt \cdot yr^{-1}$)
Q_{ji} = advective inflow to segment i from adjacent 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} = diffusive exchange flow between adjacent segments i and j ($hm^3 \cdot yr^{-1}$)
k_i = second order net sedimentation coefficient for segment i ($m^3 \cdot g^{-1} \cdot yr^{-1}$)

The resulting system of simultaneous nonlinear mass balance equations was solved for the phosphorus concentration in each lake segment using an iterative procedure provided by the BATHTUB program (Walker 1987). The BATHTUB program was originally developed for modeling eutrophication in spatially segmented reservoirs and later modified by Walker (1992) to support application to Lake Champlain.

The 13-segment model for Lake Champlain based on Equation 1 is illustrated schematically in Fig. 5. The lake was represented as a linear branching network of segments with only one segment (Malletts Bay) requiring special two-dimensional treatment. The second order formulation of the net sedimentation term in Equation 1 was selected during the model calibration process described below.

Model Input Data

The BATHTUB program data requirements included estimates of mean flows and loadings for each tributary and direct wastewater discharge, as well as lakewide inputs from atmospheric sources. Variance (CV) estimates were provided for each flow or loading source to support an uncertainty analysis for the model predictions using procedures documented in Walker (1987). Errors were assumed to be lognormally distributed about the predicted values.

The measured water, chloride, and total phosphorus loadings from each source were grouped by lake segment in order to estimate the model terms in Equation 1. External inputs to each segment included the net sum of flows and loadings from monitored tributaries, ungaged areas, direct wastewater discharges, precipitation, evaporation, and withdrawals.

Advective inflows and outflows for each segment (Q_{ij} and Q_{ji} terms) were calculated from the cumulative net inflows routed through the system as shown in Fig. 5. Advective and exchange flows across the northern boundary of the Malletts Bay segment were specified to be 19% of the flows across the western boundary (Fig. 5), based on field measurements reported in Myer and Gruendling (1979).

An additional chloride load of 3,500 $mt \cdot yr^{-1}$ (3% of the total load) was added to the Main Lake segment data in order to satisfy a conservation of mass constraint on the exchange rate calibration procedure requiring the mean inflow concentration to be equal to the concentration in the outflow segment for this conservative substance. Municipal records indicated that road de-icing salt runoff from unmonitored urban areas adjacent to the Main Lake could have accounted for this amount of chloride, although the difference between the measured inputs and outputs was not statistically significant (Table 2) and could have resulted simply from measurement error.

The model input data are summarized in Table 3. Data from two time periods were used in developing the model. Flows and chloride loadings measured during the entire two-year monitoring period of March 1990 to February 1992 were used to calibrate the exchange rate terms (E_{ij}). Phosphorus sedimentation rates (k_i terms) were calibrated to the 1991 hydrologic

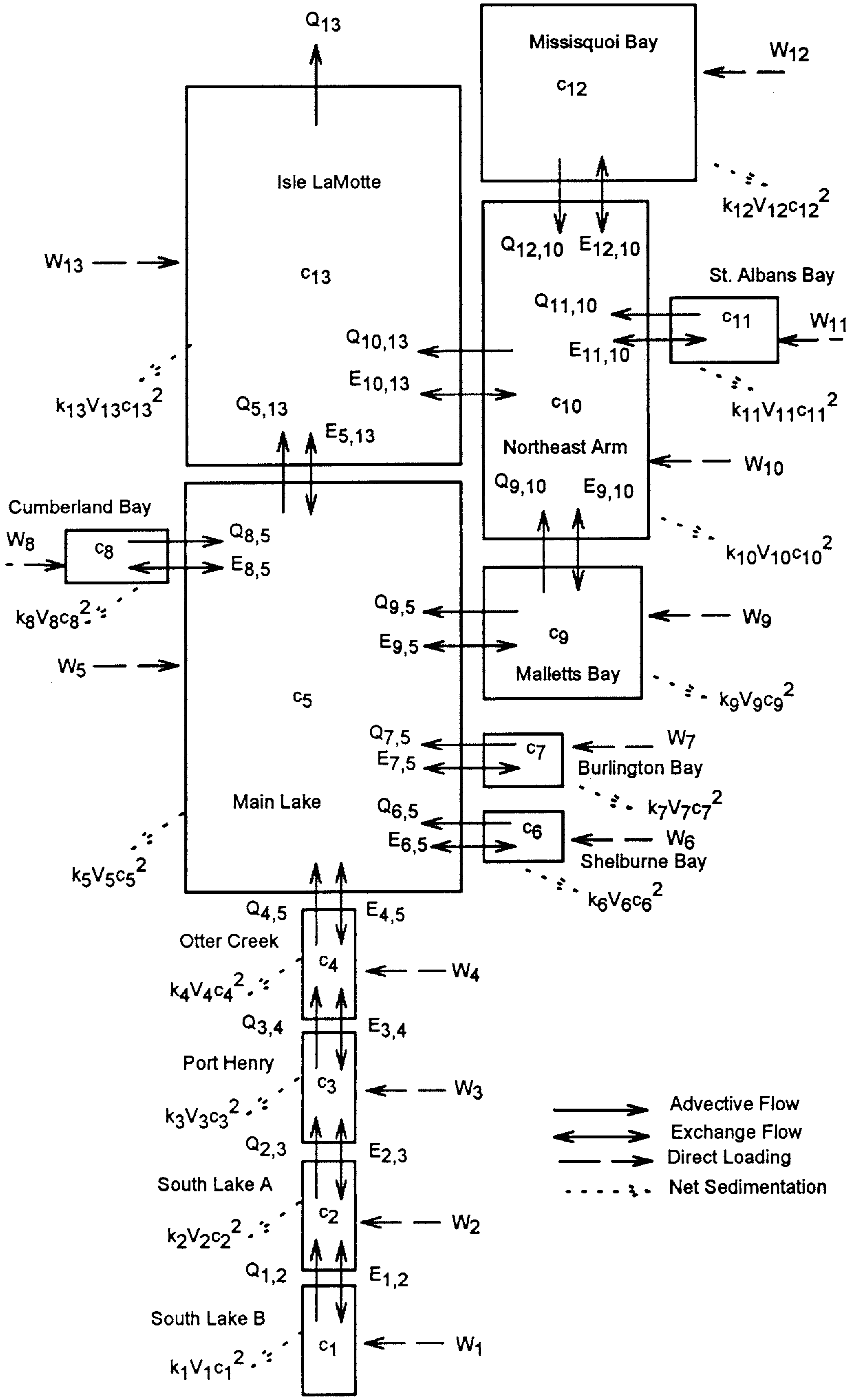

Figure 5.–Lake Champlain mass balance model diagram.

base year flows and loadings, on the rationale that time lags in lake response resulting from phosphorus residence time factors and sediment-water interactions probably make the measured lake phosphorus concentrations more reflective of long term average loading conditions.

Exchange Flow Rate Calibration

The linear chloride mass balance equations for each lake segment (Equation 1, all k_i=0) were solved for the exchange rates (E_{ij}) using the data in Table 3 and a direct matrix inversion procedure in the BATHTUB program (Walker 1992). The calibrated exchange rates for each segment are given in Table 4.

The segment interfaces shown in Figs. 1 and 5 include a broad range of hydrodynamic environments ranging from narrow causeway channels where exchange flows are constricted, to wide and deep open water situations where extensive mixing would be expected. The relationship between the calibrated exchange rates and the cross-sectional profile areas of the corresponding interfaces is shown in Fig. 6. The consistent, positive relationship demonstrated in Fig. 6 indicates that the chloride mass balance method of

Table 4.–Calibrated values for exchange flow rates and phosphorus net sedimentation coefficients.

Lake Segment	Exchange Flow Rate ($hm^3 \cdot yr^{-1}$)	Sedimentation Coefficient ($m^3 g^{-1} \cdot yr^{-1}$)
South Lake B	712	100
South Lake A	1,259	100
Port Henry	13,998	100
Otter Creek	49,427	100
Main Lake	8,861	100
Shelburne Bay	4,816	100
Burlington Bay	2,986	100
Cumberland Bay	8,672	100
Malletts Bay	272 (52[1])	400
Northeast Arm	1,968	100
St. Albans Bay	1,844	0
Missisquoi Bay	297	400
Isle LaMotte	—	100

[1]Value for the northern boundary of Malletts Bay with the Northeast Arm.

Table 3.–Model calibration data. External inflows and direct loads include the net sum from monitored tributaries, ungaged areas, wastewater discharges, precipitation, evaporation, withdrawals, and internal phosphorus loading to St. Albans Bay, and do not include inter-segment transport. Chloride data are mean values for the period of March 1990 to February 1992. Phosphorus flow and loading data are for the 1991 hydrologic base year.

		Chloride Model			Phosphorus Model		
Lake Segment	Segment Volume (hm^3)	Observed Cl^- Conc. ($mg \cdot L^{-1}$)	External Inflow ($hm^3 \cdot yr^{-1}$)	Direct Cl^- Load ($mt \cdot yr^{-1}$)	Observed P Conc. ($mg \cdot L^{-1}$)	External Inflow ($hm^3 \cdot yr^{-1}$)	Direct P Load ($mt \cdot yr^{-1}$)
South Lake B	7.8	11.62	1,092	11,384	.058	830	56.7
South Lake A	125	13.47	629	14,679	.034	410	15.3
Port Henry	1,463	11.18	150	1,283	.015	96	5.8
Otter Creek	955	10.72	1,648	15,769	.015	1,283	121.3
Main Lake	16,787	10.61	3,530	38,250	.012	2,708	133.0
Shelburne Bay	140	10.89	79	2,206	.015	47	16.4
Burlington Bay	63	10.78	9	598	.013	7	11.7
Cumberland Bay	63	10.18	950	5,941	.014	828	38.1
Malletts Bay	722	9.43	1,529	14,098	.009	1,176	33.0
Northeast Arm	3,380	9.29	130	997	.014	66	6.5
St. Albans Bay	23	10.20	63	2,320	.024	43	16.6
Missisquoi Bay	205	7.78	2,039	15,407	.035	1,720	167.9
Isle LaMotte	1,892	10.33	514	4,931	.012	413	31.4

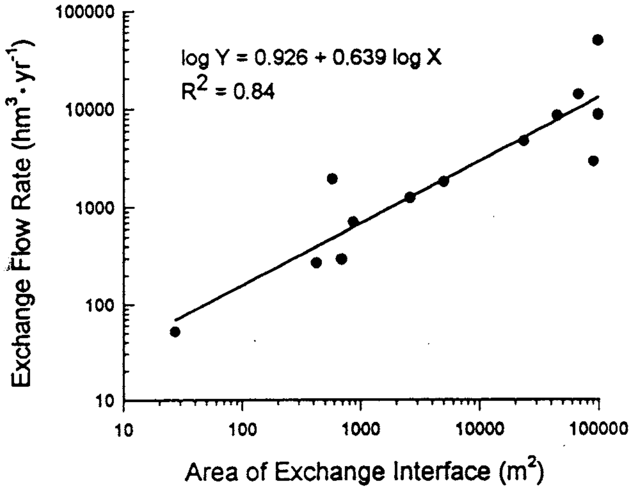

Figure 6.–Calibrated exchange flow rates vs. the cross-sectional area of the exchange interface for Lake Champlain segments.

calculating exchange rates produced realistic hydrodynamic values for Lake Champlain. The exchange rates given in Table 4 were used in all subsequent modeling analyses presented here.

Phosphorus Sedimentation Rate Calibration

The BATHTUB program (Walker 1987, 1992) provides a choice of several phosphorus sedimentation sub-models. The models considered for Lake Champlain included simple first or second order terms, as well as some second order models that partition the phosphorus loading into dissolved and particulate forms to account for differential sedimentation rates of these fractions once they enter the lake. Dissolved phosphorus loading data for Lake Champlain tributaries (Vermont DEC and New York State DEC 1994) were used to evaluate the load partitioning models.

The alternative phosphorus sedimentation models were evaluated through a global calibration procedure in the BATHTUB program in which a single sedimentation coefficient was fit to all lake segments using a least squares method (Walker 1992, Vermont DEC and New York State DEC 1994). The R^2 statistic for the log scale regression of predicted vs. observed phosphorus concentrations across all 13 lake segments was used as a basis for model comparison.

The second order phosphorus sedimentation models provided better predictions than the first order models, as was the case for the national reservoir data set evaluated by Walker (1987). Models incorporating phosphorus load partitioning had only marginally superior performance compared with the simple second order term used in Equation 1. Furthermore, lack of present knowledge about how inflow dissolved and particulate phosphorus fractions might change as a result of specific watershed management actions suggested that the phosphorus partitioning models would be impractical to apply in a predictive model for Lake Champlain. The simple second order model ($k_iV_ic_i^2$ term, Equation 1) was therefore selected.

A segment-specific calibration of the sedimentation coefficients was conducted using Walker's (1987) best fit value of k_i =100 $m^3 \cdot g^{-1} \cdot yr^{-1}$ from the national reservoir data set as a starting point for each lake segment. A good lakewide calibration was achieved by modifying k_i values for only three Lake Champlain segments.

St. Albans Bay is a special case where net internal loading from historically enriched lake sediments is known to occur, but is gradually declining in response to a 1986 wastewater treatment plant upgrade (Smeltzer et al. 1994, Martin et al. 1994). For model calibration purposes, an internal phosphorus load of 8.6 $mt \cdot yr^{-1}$ was included in the loading data in Table 3 for St. Albans Bay, and the sedimentation coefficient (k_i) was set to zero.

Calibration adjustments were also applied to the Malletts Bay and Missisquoi Bay segments where it was necessary to increase the sedimentation coefficients four-fold to 400 $m^3 \cdot g^{-1} \cdot yr^{-1}$ in order to achieve a close fit between observed and predicted phosphorus concentrations. The reason for the apparently greater phosphorus trapping efficiency of these two segments may be related to the fact that both bays are wholly confined by causeways with narrow openings to outer lake regions.

The calibrated phosphorus sedimentation coefficients for each lake segment are listed in Table 4. Observed and modeled phosphorus concentrations following calibration are compared in Fig. 7. A good overall calibration fit was obtained with a (log_{10} scale) root mean squared error of 0.034 between observed and modeled values.

Model Confirmation

Reckhow and Chapra (1983) discussed the need for confirmation of water quality models using a "severe" test involving conditions different than those used for calibration. However, the two-year monitoring period for which detailed phosphorus budget data were available was too short to allow for an independent test year data set for Lake Champlain with its mean hydraulic residence time of more than two years. Alternative forms of model confirmation were considered.

The exchange flow rates were calculated directly from the chloride mass balance data. Confidence in

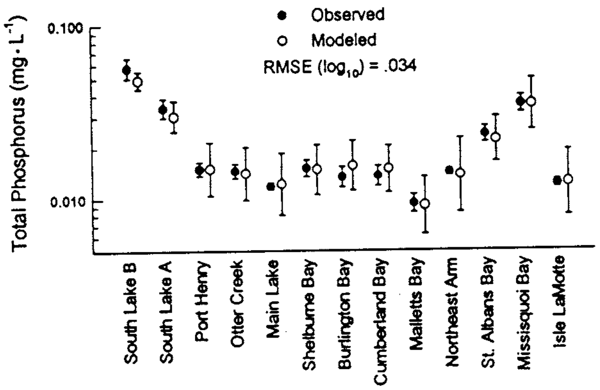

Figure 7.–Phosphorus model calibration results. Error bars show 95% confidence intervals for the observed and modeled mean total phosphorus concentrations in each lake segment following model calibration. The root mean squared error (RMSE) for the observed and modeled concentrations was calculated on log_{10} transformed values.

the exchange rate calibration can be derived from the demonstrated accuracy of the water and chloride budgets (Table 2), which were developed from independently estimated hydrologic and mass loading terms, and also from the physically realistic relationship shown between the exchange flows and lake segment morphometry (Fig. 6). Furthermore, annual average lake hydrodynamic features represented by the exchange flow terms are not likely to vary significantly between years.

A phosphorus sedimentation coefficient derived from Walker's (1987) analysis of a national reservoir data set was accurately applied without calibration to 10 of the 13 Lake Champlain segments. The independence of the Lake Champlain data from the calibration data set provides a form of confirmation for the phosphorus sedimentation term applied to those ten segments. Since no independent test of the segment-specific calibration applied to the other three segments is presently available, model predictions for St. Albans Bay, Malletts Bay, and Missisquoi Bay must be regarded as being relatively unconfirmed.

The use of a fixed net sedimentation term in the predicitve model assumes that the relative amounts of sedimentation and internal phosphorus release will remain constant as external loadings change. This assumption is likely to be valid in the deep water segments of Lake Champlain where internal phosphorus release appears to be minor, as evidenced by the lack of hypolimnetic anoxia or phosphorus accumulation (Vermont DEC and New York State DEC 1994). In shallow areas such as St. Albans Bay which have been subjected to heavy phosphorus loading, shifts in net sedimentation rates could occur in response to loading reductions, affecting model predictions over the short term.

A long-term sediment phosphorus modeling analysis by Martin et al. (1994) indicated that the effective internal loading rate to St. Albans Bay should decline to zero over several decades as sediment phosphorus concentrations reach a new equilibrium with the reduced external loadings. Application of the model for predicting future phosphorus concentrations in Lake Champlain will assume, conservatively, a net internal loading rate and a phosphorus sedimentation coefficient of zero for St. Albans Bay.

Phosphorus Load Reduction Strategy

A phosphorus management strategy is being pursued for Lake Champlain that is in many ways analogous to the phosphorus control efforts initiated for the Great Lakes in the 1970s (Chapra and Sonzogni 1979, Thomas et al. 1980, DePinto et al. 1986). Total phosphorus concentration objectives for each segment of the Great Lakes system were established by international treaty agreement. Phosphorus budgets and mass balance models for the system were developed and target load reductions to achieve the in-lake concentration objectives were established. Technology based effluent limits were applied to point source discharges, and the remainder of the needed loading reductions were sought from nonpoint sources.

Preliminary point source phosphorus loading targets for each watershed of Lake Champlain were negotiated between Vermont and New York by assuming an advanced treatment effluent phosphorus concentration of 0.8 mg · L^{-1} for facilities larger than 200,000 gal · day^{-1} (757 m^3 · day^{-1}) permitted flow, exempting aerated lagoon facilities. Comparable point source phosphorus controls are being implemented in Quebec as well.

The phosphorus model was used to identify the magnitude and watershed locations of the remaining nonpoint source load reductions needed to attain the in-lake phosphorus criteria listed in Table 1. The calibrated phosphorus mass balance model was transferred to a spreadsheet format and used with a minimum-cost optimization analysis, following approaches used by Chapra et al. (1983) and Holmes and Artuso (1995), to identify a least-cost watershed targeting strategy for nonpoint source reductions.

Information on the cost-effectiveness (dollars per kg P reduced) and maximum potential phosphorus load reductions from agricultural and urban best management practices in each sub-watershed of the Lake Champlain Basin were provided by the U.S. Natural Resources Conservation Service (R. Croft,

personal communication) and Holmes and Artuso (1995). Iterative solution techniques provided by the spreadsheet program (Novell, Inc. 1994) were used to find the least-cost combination of nonpoint source reductions in each lake segment watershed.

Constraints on the model optimization procedure were specified requiring the in-lake criteria to be attained without exceeding the maximum potential phosphorus load reductions from nonpoint sources. Compliance with the 0.025 mg · L^{-1} criterion for the South Lake B segment was not required in the analysis because of the unrealistically large nonpoint source reductions necessary to attain the criterion for that segment. The criterion for the Missisquoi Bay segment was also slightly relaxed in the analysis to 0.027 mg · L^{-1} for similar reasons.

Phosphorus loading targets for each watershed of Lake Champlain resulting from the minimum-cost optimization procedure are listed in Table 5 and compared with the measured 1991 loads. A total phosphorus load reduction of 192.4 mt · yr^{-1}, representing 30% of the 1991 base year loading rate of 647 mt · yr^{-1} (including direct precipitation), will be required to attain the water quality goals for Lake Champlain. Vermont must reduce its loading rate by 161.8 mt · yr^{-1} from 1991 levels, and the remaining 30.6 mt · yr^{-1} reduction will be sought in New York. In June 1996, the States of Vermont and New York and the Lake Champlain Management Conference agreed to the phosphorus loading targets listed in Table 5.

The states have agreed that point and nonpoint source phosphorus management policies and watershed target loads may be adjusted within each state as the planning process continues, provided that the model is used to ensure that any adjustments continue to comply with the in-lake criteria for each lake segment. Vermont will share responsibility with the Province of Quebec for load reductions in the Missisquoi Bay watershed.

Compliance with the criteria in the modeling analysis was judged using the mean of the predicted phosphorus concentration distributions for each lake segment following loading reductions. Attainment of the criteria at an upper (e.g., 90%) level of the predicted phosphorus distributions was not possible with any reasonable combination of point and nonpoint source reductions. A consequence of using the mean values to predict compliance is that the probability of full attainment of the criteria following implementation of the loading reductions specified in Table 5 is as low as 50% for some lake segments. The predicted segment phosphorus concentrations and their confidence intervals are shown in Fig. 8.

Table 5.–Phosphorus load reduction modeling results (mt · yr^{-1}), showing the 1991 base year loads, the preliminary target loads, and the load reductions required for each state and each lake segment watershed in order to attain the in-lake criteria. Values for Missisquoi Bay include both Vermont and Quebec components.

	1991 Base Year Load			Target Load			Load Reduction Required		
Lake Segment Watershed	VT	NY	Total	VT	NY	Total	VT	NY	Total
South Lake B	28.0	28.2	56.2	20.8	26.2	47.0	7.2	2.0	9.2
South Lake A	2.4	13.1	15.5	0.6	9.4	10.1	1.8	3.7	5.5
Port Henry	0.4	4.3	4.7	0.1	2.5	2.6	0.3	1.8	2.1
Otter Creek	121.7	0.1	121.8	56.1	0.0	56.2	65.5	0.0	65.6
Main Lake	88.0	38.9	126.9	76.6	35.0	111.6	11.4	3.9	15.3
Shelburne Bay	16.4	0.0	16.4	12.0	0.0	12.0	4.5	0.0	4.5
Burlington Bay	11.5	0.0	11.5	3.1	0.0	3.1	8.4	0.0	8.4
Cumberland Bay	0.0	38.0	38.0	0.0	25.5	25.5	0.0	12.4	12.4
Malletts Bay	32.9	0.0	32.9	28.6	0.0	28.6	4.3	0.0	4.3
Northeast Arm	3.2	0.0	3.2	1.2	0.0	1.2	2.0	0.0	2.0
St. Albans Bay	8.0	0.0	8.0	9.5	0.0	9.5	-1.4	0.0	-1.4
Missisquoi Bay	167.3	0.0	167.3	109.7	0.0	109.7	57.6	0.0	57.6
Isle LaMotte	0.6	28.3	28.8	0.3	21.5	21.8	0.3	6.8	7.1
TOTAL	480.4	150.9	631.3	318.6	120.2	438.9	161.8	30.6	192.4

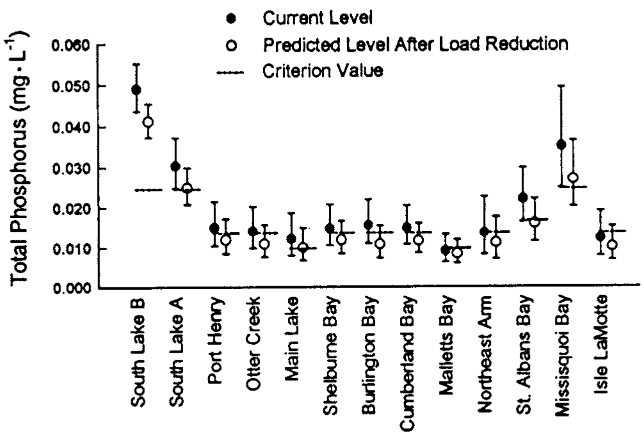

Figure 8.–Phosphorus load reduction modeling results. Predicted total phosphorus concentrations in Lake Champlain segments following planned loading reductions (Table 5) are compared with the 1991 measured levels and the in-lake water quality criteria. Error bars show 95% confidence intervals for the existing and predicted mean phosphorus concentrations in each lake segment.

Conclusions

A comprehensive phosphorus loading budget was developed for Lake Champlain based on a two-year field sampling program, and a relatively simple mass balance model for the lake was used to analyze basin-wide phosphorus load reduction strategies. The modeling analysis indicated that a total phosphorus load reduction of 192 mt · yr^{-1}, representing 30% of the 1991 base year loading, will be required to attain the in-lake water quality criteria for Lake Champlain with reasonable certainty for most lake segments. The mass balance model was used with a minimum-cost optimization procedure to establish phosphorus loading targets for each state and for each lake segment watershed. These loading targets have been accepted by the States of Vermont and New York and the Lake Champlain Management Conference as the basis for a division of responsibility for phosphorus reduction in Lake Champlain. Considerations of relative cost, technical reliability, and public acceptance of phosphorus management practices should now be used to develop fair and cost-effective strategies for meeting the load reduction targets assigned to each sub-watershed.

ACKNOWLEDGEMENTS: This study was funded by grants from the U.S. Environmental Protection Agency Clean Lakes Program to the States of Vermont and New York, with matching services provided by the two states. Cooperative assistance was provided by the U.S. Geological Survey. Field data collection and laboratory analyses were conducted with the assistance of Robert Bonham, John Donlon, Karen Hyde, Neil Kamman, James Kellogg, Daniel McAvinney, Joe Racette, James Swart, John Townsend, and Tamara Venne.

References

American Public Health Association. 1989. Standard methods for the examination of water and wastewater. 17th ed. Washington, DC.

Budd, L. F. and D. W. Meals. 1994. Lake Champlain nonpoint source pollution assessment. Prep. for Lake Champlain Management Conference. Lake Champlain Basin Program Tech. Rep. No. 6. Grand Isle, VT. 140 p.

Chapra, S. C. and W. C. Sonzogni. 1979. Great Lakes total phosphorus budget for the mid 1970s. J. Water Poll. Contr. Fed. 51:2524-2533.

Chapra, S. C., H. D. Wicke and T. M. Heidtke. 1983. Effectiveness of treatment to meet phosphorus objecives in the Great Lakes. J. Water Poll. Contr. Fed. 55:81-91.

DePinto, J. V., T. C. Young and L. M. McIlroy. 1986. Great Lakes water quality improvement. Environ. Sci. Technol. 20:752-759.

Edwards, T. K. and G. D. Glysson. 1988. Field methods for measurement of fluvial sediment. U.S. Geological Survey Open File Report 86-531. Reston, VA. 118 p.

Effler, S. W., M. Perkins and D. L. Johnson. 1991. Optical heterogeneity in Lake Champlain. J. Great Lakes Res. 17:322-332.

Henson, E. B. and G. K. Gruendling. 1977. The trophic status and phosphorus loadings of Lake Champlain. U.S. Environ. Prot. Agency. EPA-600/3-77-106. 142 p.

Holmes, T. P. and A. Artuso. 1995. Preliminary economic analysis of the draft plan for the Lake Champlain Basin Program. Prep. for Lake Champlain Management Conference. Lake Champlain Basin Program Tech. Rep. No. 12B. Grand Isle, VT. 172 p.

Kohler, M. A., T. J. Nordenson and D. R. Baker. 1959. Evaporation maps for the United States. Tech. Paper No. 37. U.S. Dept. Commerce Weather Bureau. Washington, DC. 12 p.

Lake Champlain Management Conference. 1996. Opportunities for action. An evolving plan for the future of the Lake Champlain Basin. Pollution prevention, control, and restoration plan. Draft June 1996. Grand Isle, VT.

Lake Champlain Phosphorus Management Task Force. May 14, 1993 report prepared for the Lake Champlain Steering Committee. New York State Department of Environmental Conservation, Adirondack Park Agency, Quebec Ministry of the Environment, and Vermont Agency of Natural Resources. 17 p.

Martin, S. C., R. J. Ciotola, P. Malla, N. G. Subramanyaraje Urs and P. B. Kotwal. 1994. Assessment of sediment phosphorus distribution and long-term recycling in St. Albans Bay, Lake Champlain. Prep. for Lake Champlain Management Conference. Lake Champlain Basin Program Tech. Rep. No. 7c. Grand Isle, VT. 202 p.

Myer, G. E. and G. K. Gruendling. 1979. Limnology of Lake Champlain. Prep. for New England River Basins Commission. Burlington, VT. 407 p.

North American Lake Management Society. 1992. Developing eutrophication standards for lakes and reservoirs. Report prep. by the Lake Standards Subcommittee. Alachua, FL. 51 p.

Novell, Inc. 1994. Quattro Pro™ user's guide. Version 6.0 for Windows™. Orem, UT. 752 p.

Potash, M., S. E. Sundberg and E. B. Henson. 1969. Characteristics of water masses of Lake Champlain. Verh. Internat. Verein. Limnol. 17:140-147.

Reckhow, K. H. and S. C. Chapra. 1983. Engineering approaches for lake management. Volume 1: Data analysis and empirical modeling. Butterworth. Boston. 340 p.

Smeltzer, E. 1992. Reducing phosphorus levels in Lake Champlain. P. 9-21. *In:* A clean lake for tomorrow: Procedings. Lake Champlain Committee. Burlington, VT.

Smeltzer, E. and S. A. Heiskary. 1990. Analysis and applications of lake user survey data. Lake and Reserv. Manage. 6:109-118.

Smeltzer, E., N. Kamman, K. Hyde and J. C. Drake. 1994. Dynamic mass balance model of internal phosphorus loading in St. Albans Bay, Lake Champlain. Prep. for Lake Champlain Management Conference. Lake Champlain Basin Program Tech. Rep. No. 7a. Grand Isle, VT. 43 p.

Thomas, N. A., A. Robertson and W. C. Sonzogni. 1980. Review of control objectives: New target loads and input controls. P. 61-90. *In:* Loehr, R.C. et al. (eds.). Phosphorus management strategies for lakes. Ann Arbor Science.

U.S. Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. EPA-600/4-79-020.

Verhoff, E. H., S. M. Yaksich and D. A. Melfi. 1980. River nutrient and chemical transport estimation. J. Environ. Eng. Div. A.S.C.E. 106:591-608.

Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation. 1994. A phosphorus budget, model, and load reduction strategy for Lake Champlain. Lake Champlain diagnostic-feasibility study draft final report, 7/1/94. Waterbury, VT and Albany, NY. 129 p.

Walker, W. W. 1987. Empirical methods for predicting eutrophication in impoundments. Report 4: Applications manual. Tech. Rep. E-81-9. Prep. for U.S. Army Corps Eng. Waterways Exp. Sta. Vicksburg, MS.

Walker, W. W. 1990. FLUX stream load computations. Version 4.4. Computer program prep. for U.S. Army Corps Eng. Waterways Exp. Sta. Vicksburg, MS.

Walker, W. W. 1992. BATHTUB empirical modeling of lake and reservoir eutrophication. Version 5.1 draft, updated December 1992. Computer program prep. for U.S. Army Corps Eng. Waterways Exp. Sta. Vicksburg, MS and Vermont Dept. Environmental Conservation. Waterbury, VT.

Winter, T. C. 1981. Uncertainties in estimating the water balances of lakes. Water Res. Bull. 17:82-115.