Vermont Department of Environmental Conservation

Expanded Lay Monitoring Program Studies

An Analysis to Determine the In-Lake Phosphorus Distribution and Estimate Phosphorus Loadings to Lake Carmi, Franklin, VT

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Introduction:

Lake Carmi, in Franklin, VT (Figure 1), has a history of water quality problems related to nutrients. Algae blooms, a result of excessive phosphorus enrichment, are an annual mid-summer occurrence on the lake. The Vermont Department of Environmental Conservation (VTDEC), through the Lay Monitoring Program, has a long record of phosphorus data which indicates that Lake Carmi is a eutrophic lake, with elevated phosphorus and chlorophyll-a concentrations, and reduced Secchi transparencies (Table 1).

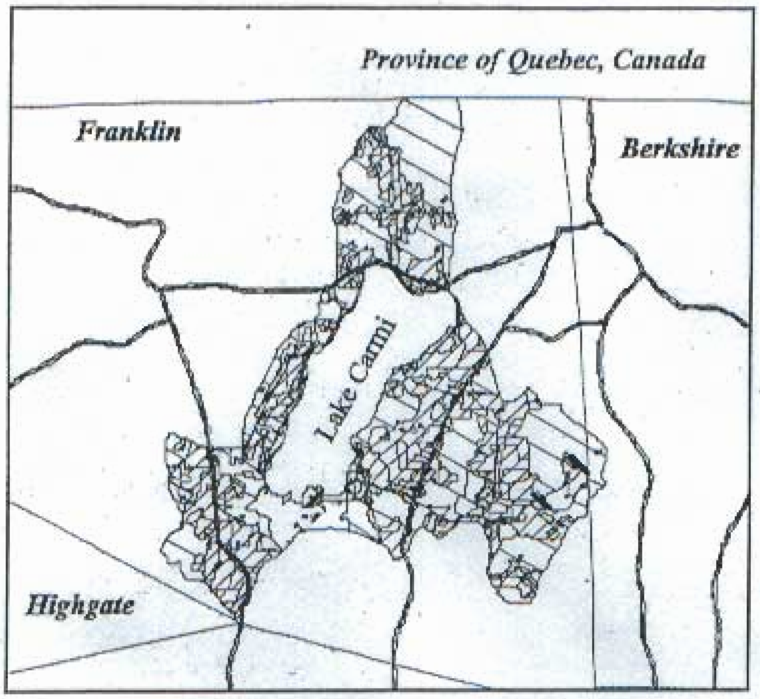

Figure 1. *Lake Carmi, Franklin, Vermont. Map showing watershed boundary, lake, major roads, town boundaries, and major land uses.*

The Lake Carmi watershed is primarily agricultural in nature, with some undisturbed forestland, and some portions of highly developed shoreline. The Lake Carmi State Park occupies 542 acres along the southeast shore of the lake, and attracts a large number of visitors and lake users every summer. A large wetland occupies the southern shore of the lake.

During the early 1980's, some efforts were made to implement agricultural best management practices on neighboring farms, but there has been little overall improvement in water quality as a result. For this reason, the Lake Carmi Campers Association approached the Vermont Department of Environmental Conservation seeking assistance in diagnosing the nature of water quality degradations in the lake.

During the summer of 1994, the VTDEC, through the Lay Monitoring Program (LMP), implemented a field survey of Lake Carmi to determine whether phosphorus loadings to the lake were affected by internal sediment-phosphorus recycling. That preliminary analysis indicated that external phosphorus loading processes were likely providing adequate phosphorus to Lake Carmi to account for degraded conditions, but noted that evidence of short-term and small scale internal phosphorus loading existed. Correspondingly, a second and third year of field sampling was recommended. This document presents a comprehensive overview of methods and results of the 1994-1996 field survey. In light of these data, a modeling analysis is presented which is used to determine whether phosphorus loadings to Lake Carmi are affected by internal processes, or dominated primarily by watershed nonpoint source runoff. The goal of this analysis is to provide the VTDEC and the Lake Carmi Campers Association information necessary to begin formulation of a management plan to control phosphorus in Lake Carmi.

Table 1. Water quality information and physical characteristics of Lake Carmi, Franklin, VT.

Lay Monitoring Program data: long-term average	Physical information:	
Total phosphorus (n=14) 30 ug/l	Mean depth/Max depth (m)	4.0m / 10.25m
Secchi transparency (n=16) 1.8 m	Area	5,831,000 m^2 (1402 ac)
Chlorophyll-a (n=16) 19.5 ug/l	Volume	21,650,000 m^3

Sampling Methods:

During 1994 through 1996, Lake Carmi LMP sampling station number one was visited biweekly from April through May and again from September through November. During June through August, sampling was conducted weekly. Biweekly sampling was conducted only during the summer and fall of 1996. In the field, the sampling station was located by triangulation from known landmarks. Water samples were collected at one meter intervals through the water column to a maximum depth of nine meters, using a Kemmerer sampler (method 2.2.3, VT DEC Field Methods Manual). A temperature profile and Secchi disk transparency were recorded for each sampling visit. A listing of parameters tested is provided in Table 2.

Table 2. Parameter table for Lake Carmi sampling.

Parameter	Frequency	Sample container	PQL - units	Hold time	Reference and method number
Total phosphorus	weekly	75 ml glass tube	0.003 mg/l	30 day	VT DEC Laboratory Methods Manual, 3.6.1.
Dissolved oxygen, Winkler titration	bi-weekly	300 ml BOD bottle	0.00 mg/l	8 hr	VT DEC Laboratory Methods Manual, 2.9.1.
Total iron (1994 only)	bi-weekly	500 ml plastic		6 mo	VT DEC Laboratory Methods Manual, 4.11.1.
Secchi transparency	weekly	NA	NA	in situ	VT DEC Field Methods Manual, Method 1.2.1.
Water temperature	bi-weekly	NA	NA	in situ	VT DEC Field Methods Manual, 1.1.2.

Sampling Results:

A summary of data collected throughout the monitoring period is presented in Table 3. Chemical parameters (Figures 2-4), and Secchi transparency (figure 5) are shown.

Table 3. Summary statistics for data collected on Lake Carmi during the 1994 -1996 field sampling seasons.

Parameter	Temperature, °C			Diss. oxygen, mg/l			Total phosphorus, mg/l*			Total iron, µg/l		Secchi depth, m		
	94	95	96	94	95	96	94	95	96	94	95	94	95	96
Number	216	200	106	142	197	109	214	200	110	142	200	24	20	11
Minimum	5.8	4.8	13.8	0.2	0	0	0.014	0.012	0.017	<50		1.4	1.2	.6
Maximum	25.5	26.2	24.9	10.7	12.9	13.0	0.119	0.240	0.324	836	2940	4	4	2.7
Mean	17.9	18.4	19.5	8.5	7.25	6.92	0.030	0.030	0.042	108.1	251.7	2.0	2.0	1.7

*Mean total phosphorus concentrations are reported as volume-weighted.

Thermal stratification developed only to a minor degree in Lake Carmi during 1994, between mid-July and mid-August (Figure 2). Since Lake Carmi is relatively shallow, stratification is easily broken down by frequent windy conditions (Vermont Agency of Environmental Conservation, 1976). As such, there may have been short time periods when stratification was established, but which were not detected by weekly sampling. By contrast, a prolonged period of thermal stratification developed during 1995 and 1996 (Figures 3 and 4).

Typically, release of phosphorus from lake sediments is triggered by anaerobic conditions at or near the sediment-water interface. During 1994, the deepest waters in Lake Carmi did show substantial but very short-term oxygen depletion during the period of maximum thermal stratification, and this was accompanied by somewhat elevated hypolimnetic phosphorus concentrations (Figure 2). The 1995 and 1996 stratification periods were characterized by episodic hypolimnetic anoxia (Figures 3 and 4). A concurrent dramatic increase in hypolimnetic total iron concentration indicates a dissociation of iron-bound compounds (including ferro-phosphate compounds) and suggests that there was at least some degree of sediment phosphorus release occurring during this time. The difference between the 1994, 1995, and 1996 stratification periods is readily noted by comparing hypolimnetic phosphorus concentrations between the years. Indeed, while phosphorus concentrations achieved 120 *ug*/l in 1994 for a one week period, they were nearly double and triple that amount for two months during 1995, and two discrete two-week periods during 1996, respectively (Table 3).

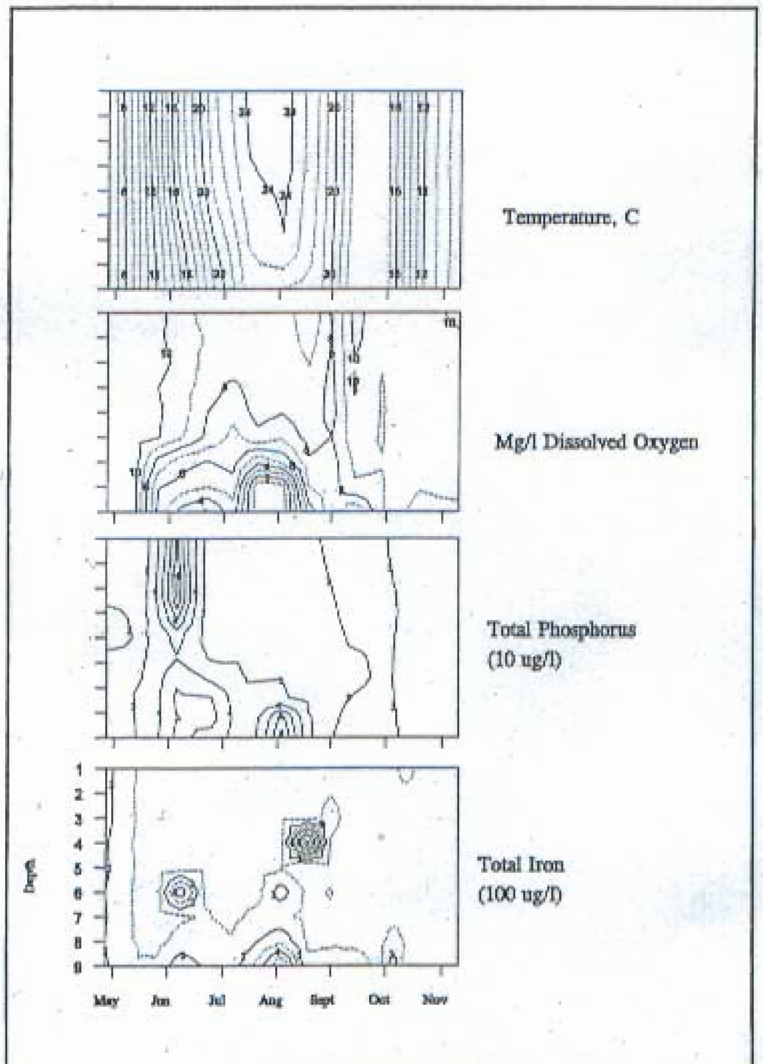

Figure 2. *Isopleth diagrams displaying results of water chemistry samples collected at Lake Carmi during 1994.*

Internal loading occurs when phosphorus, released from the sediments remains in the water column and is entrained into the lakes' epilimnetic layer. Determining whether internal loading occurred using the isopleth diagrams is tricky. The 1994 early-season total phosphorus 'pulse' observable in the middle depths of the lake is the likely result of a springtime runoff event. Overlooking this 'pulse', it is apparent that during 1994, there was no difference in phosphorus concentrations in the mixing-layer (all water above the thermocline, determined by this analysis as 7 meters) during the period following de-stratification as compared to the period preceding destratification. This was not the case in 1995 and 1996, where mixing-layer total phosphorus concentrations after destratification exceeded those noted before destratification.

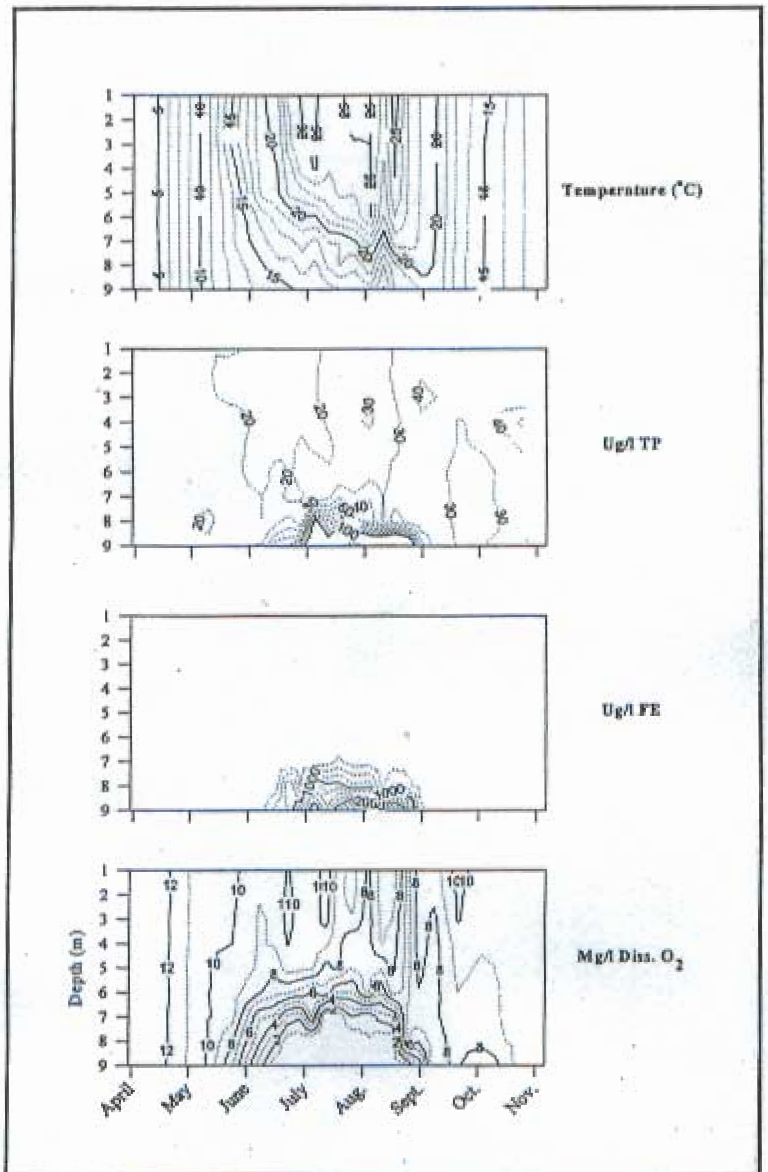

Figure 3. *Isopleth diagrams displaying results of water chemistry samples collected at Lake Carmi during 1995.*

One method of determining whether phosphorus released from the sediments is indeed resulting in an internal load to Lake Carmi is to compare the mass of phosphorus in the hypolimnion to the mass of phosphorus in the entire lake (Figure 5). These data presented that internal phosphorus loading during summer anoxia was not a major factor during 1994. The same, however, is not necessarily true of 1995 or 1996, when a hypolimnetic increase in phosphorus content was accompanied by a concurrent increase in the total in-lake phosphorus content. Moreover, the median total in-lake phosphorus mass observed after the 1995 and 1996 destratification was approximately 408 kg and 350kg higher (respectively) than that observed before the onset of stratification.

Water clarity, as measured by a Secchi disk reading, will vary in response to both inorganic turbidity and algal productivity. Since the greatest hydrologic inflows to the lake can be expected during spring runoff, along with generally windier conditions than during mid-summer, this is when non-algal turbidity should be at its maximum. Throughout the study period, Secchi transparencies reached a maximum during May, after which they declined steadily until late summer (Figure 5). The fact that Secchi transparencies are greatest during the spring runoff period suggests that in Lake Carmi, water clarity is affected primarily by algae, the growth of which is mediated by phosphorus.

Though the total 1995 post-mixing content of phosphorus was higher than that measured in 1994, secchi transparency was not different between the two years (Figure 5). Thus, while there was more phosphorus in Lake Carmi during the fall of 1995 than the fall of 1994, the lake did not have a worsened appearance. Such was clearly not the case in 1996, which was marked by serious cyanobacteria blooms which drastically reduced transparency during a one month period beginning August 20.

The degree to which internal loading was responsible for the increased phosphorus mass during 1995 and 1996 is confounded by the fact that the weather events which precipitated the destratification events for both years consisted of very large-scale floods which swept northern Vermont. It is conceivable that a total

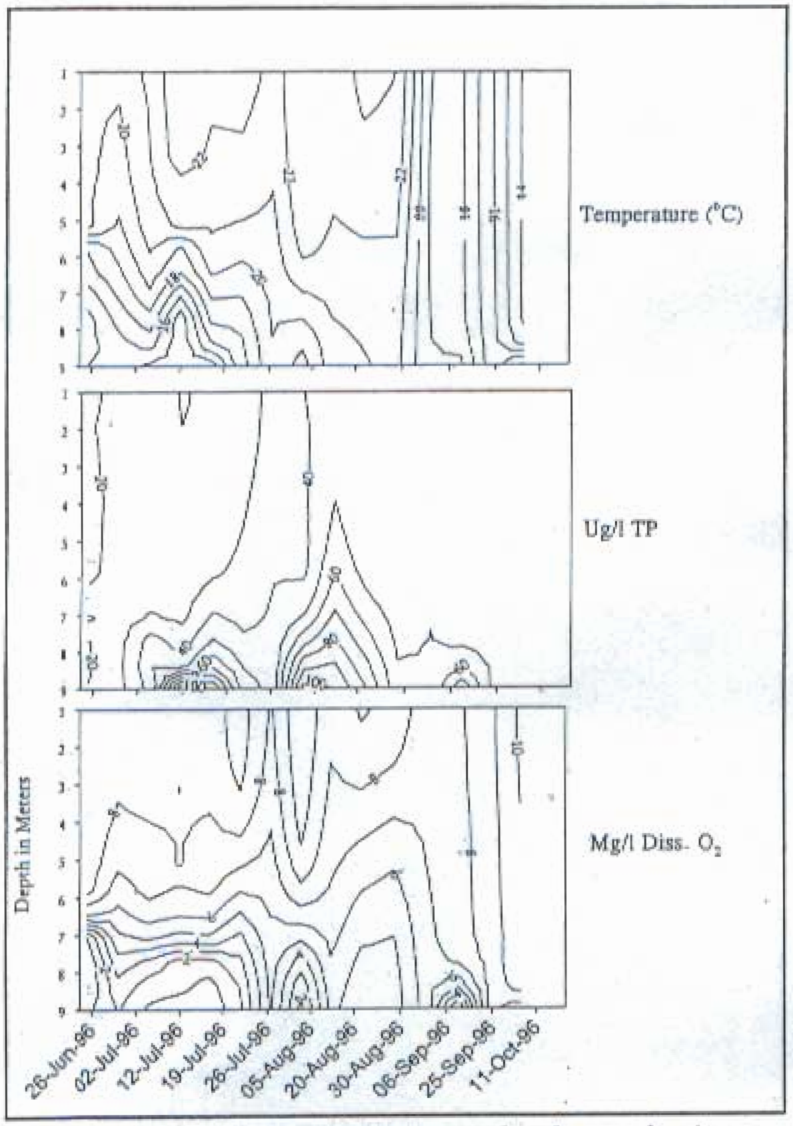

Figure 4. *Isopleth diagrams displaying results of water chemistry samples collected at Lake Carmi during 1996.*

load of approximately 400 kg could have entered Lake Carmi during the floods, resulting in increased total phosphorus concentrations in the lake from that point until ice-in. Tributary inflow data, lacking in this analysis, would be required to determine whether the loading process which resulted in elevated late-season phosphorus concentrations during 1995 and 1996 was internal or external. However, the fact that serious algal blooms occurred only in 1996, when stratification broke earlier in the summer, then reset, suggests that the 1996 blooms may have resulted from an internal loading pulse. It can thus be concluded that a significant increase in phosphorus mass was observed in Lake Carmi during the summers of 1995 and 1996. This increase can be attributed to either internal loading of phosphorus, to overland runoff from the great floods, or to a combination of both.

Internal phosphorus loadings can be reduced using a variety of costly mechanical or chemical options. However, for such treatments to be effective, external, watershed-based sources of phosphorus must first be controlled. In light of the cost of controlling internally-derived phosphorus, an important question arises: *is there sufficient external loading to account for the phosphorus concentrations which beget degraded water quality conditions in Lake Carmi?* The answer can be determined using the 1994-1996 volume-weighted mean phosphorus concentrations from this study, a mass phosphorus loading estimation approach, land use information, water inflow data, and a modeling framework.

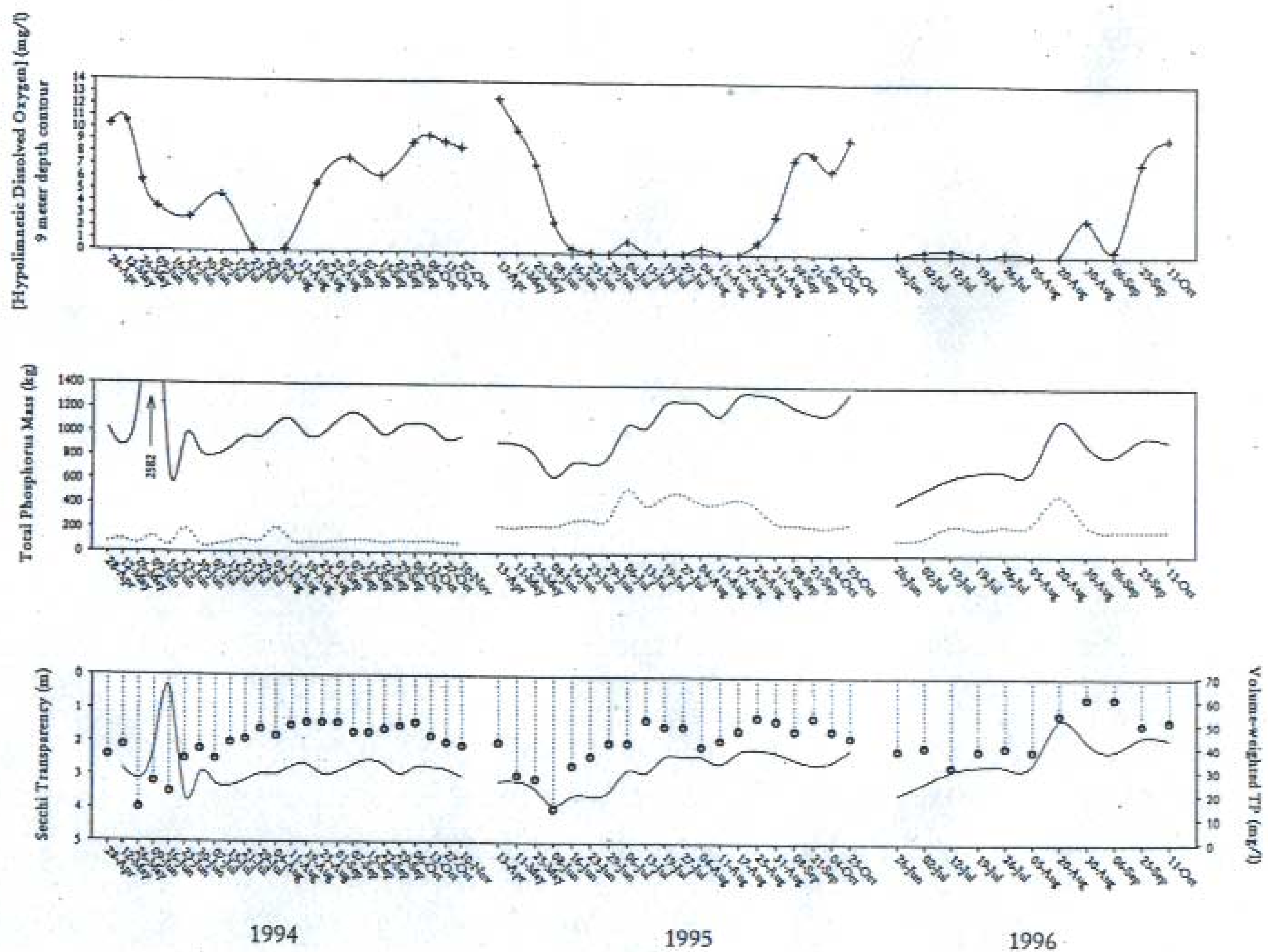

Figure 5. *Hypolimnetic dissolved oxygen, whole-lake (solid line) and hypolimnetic (dotted line; 7 meters and below) total phosphorus mass, Secchi transparency, and volume-weighted total phosphorus concentration for Lake Carmi during the 1994-1996 study period.*

Model Development:

Mass Phosphorus Load Estimation Approaches:

There are no current and only little historical data on tributary inflows or tributary phosphorus concentrations for the Lake Carmi watershed. For this reason, annual phosphorus loading estimates to Lake Carmi were derived using current land use information coupled with a load estimation procedure developed specifically for the Lake Champlain basin (Budd and Meals, 1994). Budd and Meals present two alternate methods for estimating loading from land use information. These are the *export coefficient method*, and the *load function method*. Both were applied to Lake Carmi.

Under *export coefficient* method, a phosphorus export coefficient (in kgP/Ha/yr) is selected for each land use type. These coefficients are then multiplied by the area of their respective land use types, resulting in an annual phosphorus load estimate for each land use category. Loads from each land use category are then summed to estimate total loading (kg/yr) to the lake. This method of estimating phosphorus loading is easy to implement and widely used, but has the major drawback of not incorporating between-year variations in rainfall, and as such can only estimate a long-term average condition.

A loading function is essentially the concentration of phosphorus in the runoff from a particular land use. Under the *load function* method, this concentration is multiplied by its corresponding volume of runoff to arrive at a mass phosphorus load from each land use. The loads attributable to each land use are then summed for all of the land uses in the watershed to calculate a total mass loading of phosphorus to a lake. For land use "k", this process can be described as:

$$LD_k = (Q_W \times A_k) \times C_k \qquad (1)$$

where:
LD_k = annual load from land use k (g/yr)
Q_W = annual runoff from watershed (m^3/yr)
A_k = percent of area of watershed in land use k
C_k = load function for land use k (g/m^3)

Budd and Meals (1994) provide an exhaustive literature survey of export coefficients and load functions taken from the world-wide literature. In the process of refining their basin-wide load estimates, the authors applied a range of these export coefficients and load functions (low, baseline, and high), and compared their results to phosphorus loadings measured by the Lake Champlain Diagnostic-Feasibility Study (VTDEC and NYSDEC, 1994). They found that a best-fit between estimated and observed loadings for the entire basin was achieved using the *load function* method, with 'low-end' loading functions. They acknowledged, however, that on a subwatershed basis, the 'low-end' load functions were underestimating actual loadings. The availability of detailed land use information for select subwatersheds allowed the authors instead to use 'baseline' loading functions.

Land Use Information:

Detailed land use information was compiled using a Geographic Information System by the Franklin County Regional Planning Commission (Microdata, 1994) using information from existing GIS files and recent ortho-photographs. The land use information presented in Table 4 was field checked and refined during the summer of 1994, and can be considered up-to-date as of then.

Water Flows and Resulting Phosphorus Loads to Lake Carmi:

Long-term annual average precipitation values and runoff coefficients by U.S.G.S. hydrologic-unit, for the entire Lake Champlain basin are provided by Budd and Meals (1994). The appropriate values for the hydrologic unit occupied by the Lake Carmi watershed were applied to estimate total water inflow (Q_w, Eq. 1) to the lake. Inflows calculated for each land use and for direct precipitation to the lake surface are presented in Table 4. Phosphorus loading to Lake Carmi was estimated using 'baseline' coefficients for both the *export coefficient* and *load function* methods. Phosphorus loads resulting from direct precipitation to the lake are included in the load estimates, based on data provided by VTDEC and NYSDEC (1992). No data exist on groundwater inflows to Lake Carmi, and these were considered negligible for this analysis. Total phosphorus loadings by land use category are presented in Table 4.

Table 4. Estimated phosphorus loadings to Lake Carmi derived using methods described by Budd and Meals(1994).

Land use Category: (Mean Annual Precip: **42.18** in) (Runoff Coefficient: **0.57**)	Area (ha)	Flow (m^3/yr)	Total Phosphorus Load, *Export Coefficient Method-baseline* (kg/yr)	Total Phosphorus Load, *Load Function Method-baseline* (kg/yr)
High Density Residential	27.68	169,046	27.7	59.2
Low Density Residential	43.14	263,454	33.7	92.2
Roadways	30.3	185,357	36.4	46.3
Waste Water Treatment Facility	1.54	9,391	2.5	2.4
Marina	0.61	3,707	NA[2]	
Campground	24.85	151,746	12.4	15.2
Cemetery	0.2	1,236	0.1	0.1
Row Crops	95.27	581,775	190.5	232.7
Pasture	365.57	2,232,443	164.5	446.5
Hay	482.6	2,947,181	482.6	648.4
Tree Farm	2.59	15,817	0.7	9.5
Farmstead	25.17	153,723	12.6	30.7
Shrub/Brush	186.77	1,140,565	46.7	68.4
Forest	1054.53	6,439,806	105.5	128.8
Wetland	121.77	1,304,655	NA[1]	
Open Water	583.13	6,247,515	106.2[2]	
Total	3045.77	20,542,762	1221.9	1886.6

[1] For this analysis, phosphorus is assumed to "flow through" wetlands.
[2] VTDEC and NYSDEC (1994).

Model Calibration:

Phosphorus loads estimated by the *export coefficient* method were 33% lower than those predicted using the *load function* method. In order to determine which estimate was most appropriate for Lake Carmi, a simple model (Chapra and Reckhow, 1983) was used to predict the in-lake phosphorus concentration based on annual loading. This model is structured such that it can directly assess if external phosphorus loadings are sufficient to account for the existing phosphorus concentration in Lake Carmi. Specifically, the model incorporates mass phosphorus loadings, water inflows, and phosphorus settling within Lake Carmi, in conjunction with the lakes' morphometry. The model takes the form:

$$P = W / [Q_w + (v_s A_s)] \qquad (2)$$

where:
P = long-term average volume-weighted phosphorus concentration (g/m^3)
W = annual phosphorus loading (g/yr)
Q_w = annual water loading from the watershed (m^3/yr)
v_s = apparent settling velocity (m/yr)
A_s = lake surface area

The annual phosphorus loads estimated by both methods were applied to this equation, setting P to the project-period volume-weighted mean phosphorus concentration of 0.030 g/m^3, and solving for v_s. Chapra and Reckhow, 1983, indicate that for north-temperate lakes, apparent settling velocities should range from 4.2 to 21.6 m/yr (mean of 9.52 $\pm$ 1 s.d.). When using loading estimates derived by the *export coefficient* method, a low out-of-range apparent settling velocity (2.5 m/yr) was required to accurately predict in-lake conditions. Using the loads estimated by the *load function* method, a more reasonable settling velocity was required (7 m/yr). This indicates that the 1,886 kg/yr load estimated with the *load function* method may be more realistic for Lake Carmi. Table 5 presents final model parameters and predicted in-lake phosphorus concentrations.

Table 5. *Model parameters necessary to predict in-lake phosphorus concentrations from external phosphorus loadings to Lake Carmi, Franklin, VT. A model prediction is also presented which assumes a pristine, uncut, forested watershed for purposes of assessing the extent of cultural eutrophication which has occurred since development began in the Lake Carmi watershed.*

<table>
<tr><th>Load Estimate Method:</th><th>Annual Phosphorus Loading (kg)</th><th>Annual water loading (m³)</th><th>Apparent settling velocity (m/yr)</th><th>Predicted phosphorus concentration (g/m³)</th></tr>
<tr><td>Export Coefficient-current conditions</td><td>1221.9</td><td rowspan="4">20,542,762</td><td rowspan="2">2.5</td><td>0.031</td></tr>
<tr><td>Export coefficient-pristine conditions</td><td>259</td><td>0.007</td></tr>
<tr><td>Load Function-current conditions</td><td>1886.6</td><td rowspan="2">7</td><td>0.031</td></tr>
<tr><td>Load Function-pristine conditions</td><td>249.2</td><td>0.004</td></tr>
</table>

Discussion

By using this model to solve for settling velocity, we are essentially investigating the effect of phosphorus retention by sediments on the total in-lake phosphorus concentration. Higher setting velocities indicate a more rapid deposition of phosphorus into the lake sediments. Conversely, as apparent settling velocity approaches 0, less 'settled' phosphorus is retained in the sediments of a lake. In a situation where internal loading is evident, settling velocity can achieve high negative values because the sediments are acting as a net source of phosphorus. A positive apparent settling velocity does not, however, prove that phosphorus is settling out of the water column every day of the year. Rather, it means that over the course of one year, some proportion of the phosphorus entering the lake will be retained. External loading estimates derived from both the *export coefficient* and *load function* methods (using baseline coefficients), coupled with measured in-lake phosphorus concentrations, yield a model with an apparent settling velocity which is greater than zero. Thus, on an annual basis, some proportion of the nutrient which enters Lake Carmi is sequestered into the sediments, and external phosphorus sources outweigh internal sources.

While the data and analysis presented here strongly suggest that phosphorus dynamics in Lake Carmi are controlled primarily by external sources, there remains the possibility that phosphorus release is from the sediments is occurring very slowly, on a daily basis. In order for this to happen, total external phosphorus loads to Lake Carmi would have to be less than 600 kg/yr, and the resulting apparent settling velocity less than zero. Without actual tributary phosphorus and flow measurements, it is impossible to determine if this is the case. Nevertheless, given the nature land use in the Lake Carmi watershed, it is unlikely that external phosphorus loads are that low. It can therefore be concluded that external sources of phosphorus are sufficient to account for the current long-term phosphorus mean concentration in Lake Carmi, and that internal loading was not likely the factor determining poor water quality conditions during 1994 and 1995. By contrast, an internal loading pulse during 1996 may have been a factor controlling the very strong cyanobacteria blooms noted during August of that year.

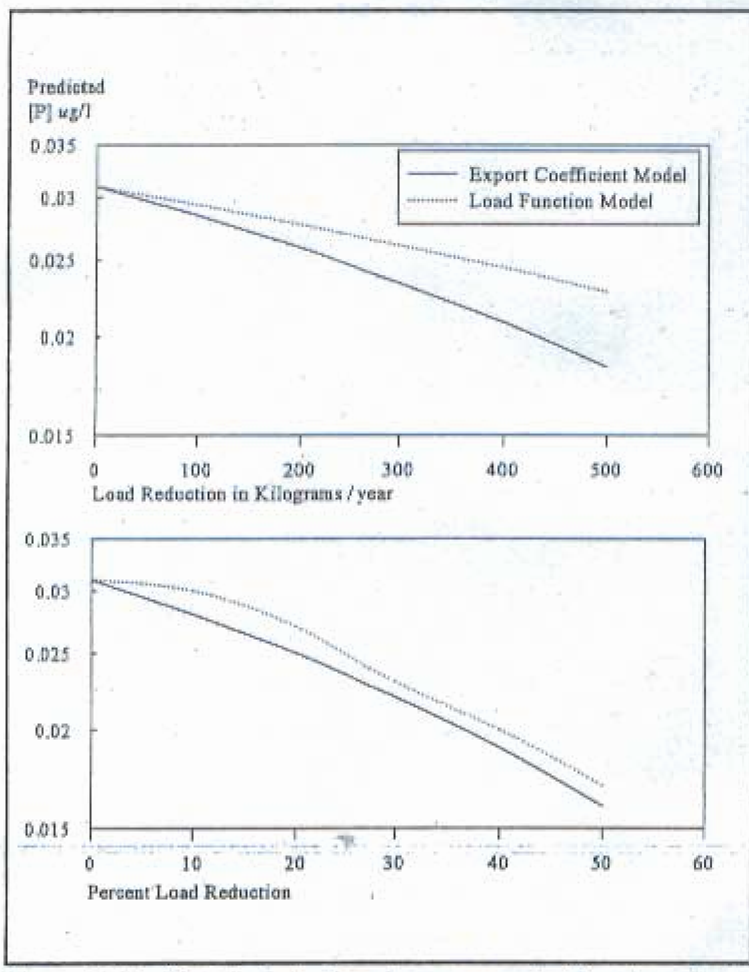

Figure 6. *Predicted in-lake phosphorus concentrations based on watershed phosphorus mass loading reductions and on watershed percent phosphorus loading reductions for Lake Carmi.*

The next use of this analysis is to determine if in-lake conditions can be improved by reducing phosphorus loadings from the Lake Carmi watershed. The model presented can predict, with a fair bit of uncertainty, the in-lake phosphorus concentrations which would result from non-point source load reductions, and these are presented for both load estimation methods in Figure 6. A major source of the uncertainty in the accuracy of these model predictions stems from the fact that a long period of cultural eutrophication has occurred in Lake Carmi since its original deforestation, and this may have resulted in a great deal of phosphorus being stored in the lake sediments. This is demonstrated in Table 5, which shows that with a fully forested and undisturbed watershed, Lake Carmi would probably be a pristine lake with in-lake phosphorus concentrations comparable to those in other oligotrophic Vermont lakes.

Large-scale reductions in external loading to a lake which has experienced cultural eutrophication can result in phosphorus-rich sediments becoming a phosphorus source to the water column, rather than a sink. This occurs when the ratio of water column to sediment phosphorus changes rapidly, a situation which over time will remediate itself. Indeed, remediation efforts in lakes with similar morphometric characteristics to Lake Carmi have been slow to result in water quality improvements. In St. Albans Bay, Lake Champlain, VT, it has been predicted that water quality conditions would take between 10 and 30 years to fully reflect changes in watershed phosphorus loading reductions (Martin et al., 1994 and Smeltzer et al., 1994). Further, in a worst-case scenario, a recovery time of 80 years was predicted for Shagwa Lake, MN (Martin et al., 1994). In both cases, the slow response time is a reflection of increased recycling of phosphorus from the sediments due to the water-sediment phosphorus imbalance created by reduced external loading.

Given the available data, it is not possible to estimate the time necessary for Lake Carmi to recover to a more reasonable, mesotrophic condition. One further unknown is that, without knowledge of the actual historical phosphorus concentration in Lake Carmi, it is difficult to determine a feasible in-lake phosphorus reduction target. Nonetheless, based on available data and this analysis, it can be concluded that over an unknown period of time of between 10 and 80 years, external phosphorus load reductions should indeed result in improvements to water quality in Lake Carmi.

Monitoring Recommendations:

- Continue supplemental Lay Monitoring on Lake Carmi.
- Refine the land-use map to verify that export coefficients or loading functions are accurately applied.
- Conduct a paleolimnological investigation do determine historical in-lake phosphorus concentrations.

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