Epilimnetic nutrient loading by metalimnetic erosion and resultant algal responses in Lake Waramaug, Connecticut

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Abstract

Phosphorus regeneration from lake sediments, and subsequent migration to trophogenic surface water, significantly contributes to the lake nutrient budgets and algal bloom conditions in some lake types. Decomposition of organic matter in deep water and sediments results in the accumulation of regenerated nutrients, alternate electron acceptors (reduced products of anaerobic respiration = COD), carbon dioxide, and depletion of dissolved oxygen (electron acceptor in aerobic respiration). Thermal stratification creates spatial segregation of trophogenic and tropholytic environments in the lake, resulting in gradients between sediments, hypolimnion, and the epilimnion. Exchange of oxygen, nutrients, and reduced alternate electron acceptors between the hypolimnion and epilimnion affects the productivity of a lake.

Secchi depth, temperature, and dissolved oxygen profiles were determined twice each week from May 1980 to October 1980 at each of five lake stations. Nutrient concentration profiles, including total soluble and total phosphorus, ammonium-N, nitrate, soluble Kjeldahl, and total Kjeldahl nitrogen were determined twice each month. Epilimnetic algal samples were collected twice each week using Kemmerer and water column 'straw' samplers. Cell counts of total, green, bluegreen, and diatom algae groups were made. Three methods were used to describe hypolimnetic-epilimnetic exchange, including coefficients of eddy diffusion (based on lake heat budget), a graphical method of defining thermocline location, and relative thermal resistance to mixing (RTRM, based on density differences). All three methods yeilded comparable estimates of net seasonal transport. The graphical and RTRM methods described events occurring at shorter intervals (greater resolution).

We find general agreement between the three methods of describing hypolimnetic–epilimnetic transport. The frequency of sampling resulted in increased resolution of thermal profiles (in time), allowing accurate estimation of short-term nutrient flux into epilimnetic waters. An algal bloom event occurred 5 to 12 days following erosion of the top of the metalimnion to below the aerobic–anaerobic interface. The lag time to peak algal concentration, following such events, decreased through the summer (June = 12 days, September = 5 days).

Introduction

Increased concentrations of phosphorus (P) in aquatic systems accelerates the eutrophication process and results in recurrent blooms of bluegreen algae during the summer. Such increases are the result of watershed and internal loading from a variety of sources. Internal sources of P, to the productive epilimnion, are suspect because hydrologic flow decreases markedly in the summer when blooms occur. However, Stauffer & Lee (1974) have demonstrated that periodic depression of the epilimnion boundary and thermocline, associated with meteorological events, can result in large in-

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puts of P to surface waters. Eddy diffusion coefficients calculated by McEwen's technique (Hutchinson 1941, 1957; Idso & Cole 1973; Rich 1979) are relatively high in Lake Waramaug (Rich, personal communication, UConn U-42, Storrs, Ct.) resulting in high estimates of steady-state epilimnetic P loading by vertical flux.

The major objective of this study was to determine the relative contributions of mixing, epilimnetic boundary migration, and external loading to algal bloom conditions through the summer. Thermal structure was monitored using relative thermal resistance to mixing (RTRM) (Vallentyne 1957), nutrient concentrations, algal abundance measured, and a vertical transport model (Stauffer & Lee 1974) was used to distinguish between watershed and in-lake epilimnetic P loading.

Materials and methods

Lake Waramaug covers 2.7 km^2, to a maximum depth of 13 m (mean depth = 7 m), in a 37 km^2 watershed (Fig. 1). Submerged and emergent vege-

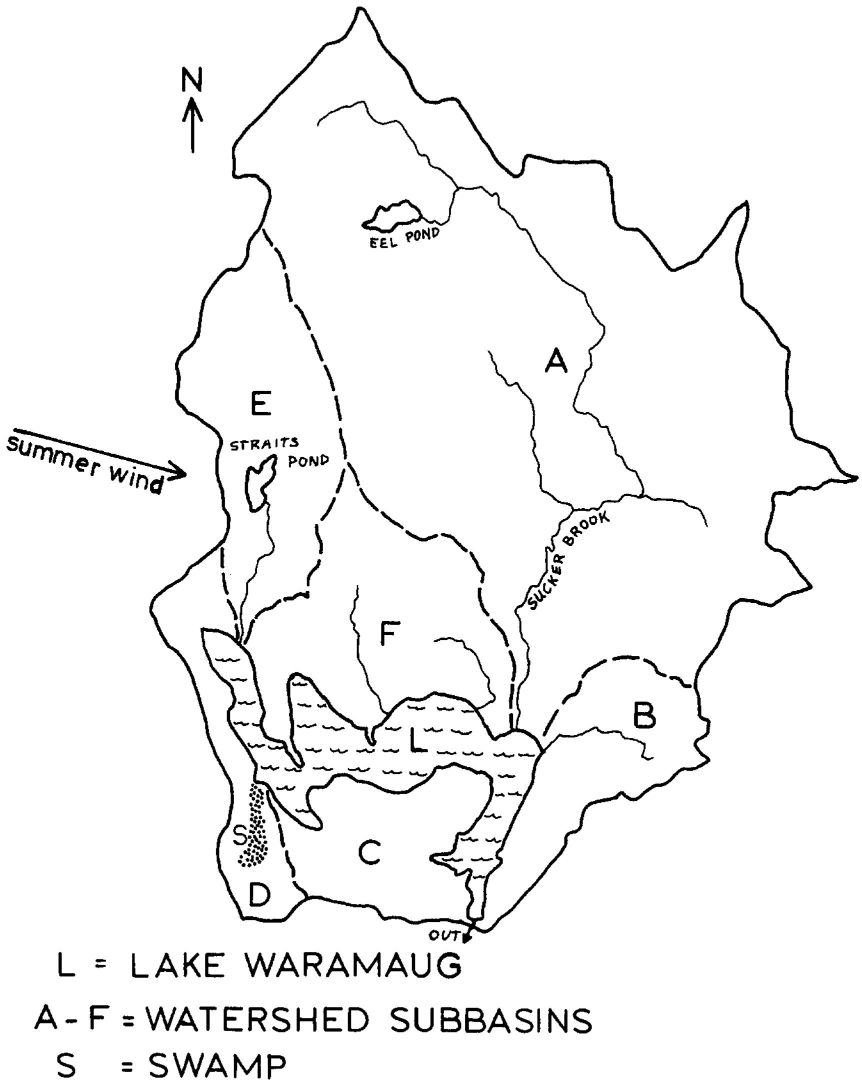

Fig. 1. Map of Lake Waramaug, and its watershed, showing major subbasins contributing to inflow, lake discharge (OUT), and direction of prevailing summer winds.

tation is scarce, except for localized patches of *Potamogeton robbinsii* and several less abundant aquatic macrophytes, due to the steep basin walls (U.S.G.S. 1980). Oxygen deficits greater than 1600 mg O_2 m^2 day^{-1} and phosphorus concentrations greater than 100 mg TP m^{-3} indicate that the lake is eutrophic (Rich, personal communication). Watershed TP loading, estimated in a land-use model, is about 1900 kg TP y^{-1} (Schiller *et al.* 1978). The retention time of flow through the lake is about 300 days. More than half of the total water budget is contributed by Sucker Brook (draining 20 km^2) on the northeast border of the lake (Fig. 1). This subbasin contains about 90% and 65% of the watershed agricultural and pasture lands, respectively. The lake perimeter is populated by both year-round and seasonal residents, vacation resorts, and a state park borders much of the northwest arm. All of this development uses on-site septic disposal systems which contribute an estimated 7% of the annual TP load (Schiller *et al.* 1978). The lake exhibits a typical seasonal algal succession, with recurrent blooms of bluegreen algae that are variable from year to year.

Light penetration (Secchi disk), dissolved oxygen and temperature (YSI Model 57 Meter), and epilimnetic algal abundance were monitored twice each week at five sampling sites. Algal samples were filtered and counted on grids at 150× after collection, using a weighted rubber tube that provided a 5-m core of water. Nutrient samples were collected at 2-m depth intervals at the deep station, using a Kemmerer sampler. Total and dissolved phosphorus concentrations (TP and TSP) were determined weekly by acid digestion, followed by molybdate colorimetry (A.P.H.A. 1971). Total soluble, total and ammonium-N nitrogen concentrations (SKN, TKN, NH_4^+-N) were determined by the Kjeldahl Method and Nesslerization, every 3 weeks (A.P.H.A. 1971).

The nitrogen and phosphorus content of the lake was obtained as the sum of the products of volume and concentration at each depth. Relative thermal resistance to mixing (RTRM) was obtained by converting temperature to density and calculating the ratio of density difference between two adjacent layers (1 m standard) to the density difference between water at 5 °C and 4 °C:

$$\text{RTRM} = \frac{\text{Upper layer density} - \text{Lower layer density}}{\text{Density at 5 °C} - \text{Density at 4 °C}}$$

(modified from Vallentyne 1957; Wetzel 1975).

An RTRM value equal to 30 (RTRM30) was chosen as a parameter estimate of the upper (and lower) metalimnetic boundary statistic (i.e. RTRM30 estimates D_e) after a comparison was made between temperature and RTRM depth profiles. RTRM accounts for the nonlinearity of density as a function of temperature and is a good indicator of stratification stability.

Estimates of eddy diffusion coefficients were determined by McEwen's technique (Hutchinson 1941, 1957).These coefficients were corrected for solar heating (Bachman & Goldman 1965). Eddy diffusion coefficients are based on an entire heating season and represent a seasonal estimate of steady-state flux. Geothermal heating, heat transferred by seiches, and diurnal effects are not accounted for (Powell & Jassby 1974; Miller & Reed 1975). Estimates of vertical transport between hypolimnetic and epilimnetic waters were obtained as the product of eddy diffusion coefficients and concentration difference.

Vertical transport due to epilimnetic expansion and short-term (not steady-state) mixing, induced by meteorologic events, was obtained by graphically determining metalimnetic boundaries and calculating mixing ratios (Stauffer & Lee 1974). The epilimnetic–metalimnetic boundary is taken to be that depth at which the second derivative (change in slope) of temperature, as a function of depth, is a minimum (= D_e). This statistic was also estimated by RTRM30. The metalimnetic–hypolimnetic boundary is taken to be that depth at which the second derivative of temperature, as a function of depth, is maximum. The thermocline is the depth at which temperature is midway between the temperatures associated with the lower and upper metalimnetic boundaries. Mixing ratios (R_z) between the epilimnion and each depth stratum below D_e were calculated as the ratio of change in temperature of the stratum ($T_2 - T_1$) and the difference between the average initial epilimnetic temperature ($\bar{T}_{e1}$), and final temperature, of the stratum (T_2):

$$R_z = (T_2 - T_1) / (\bar{T}_{e1} - T_2)$$

(modified from Stauffer & Lee 1974).

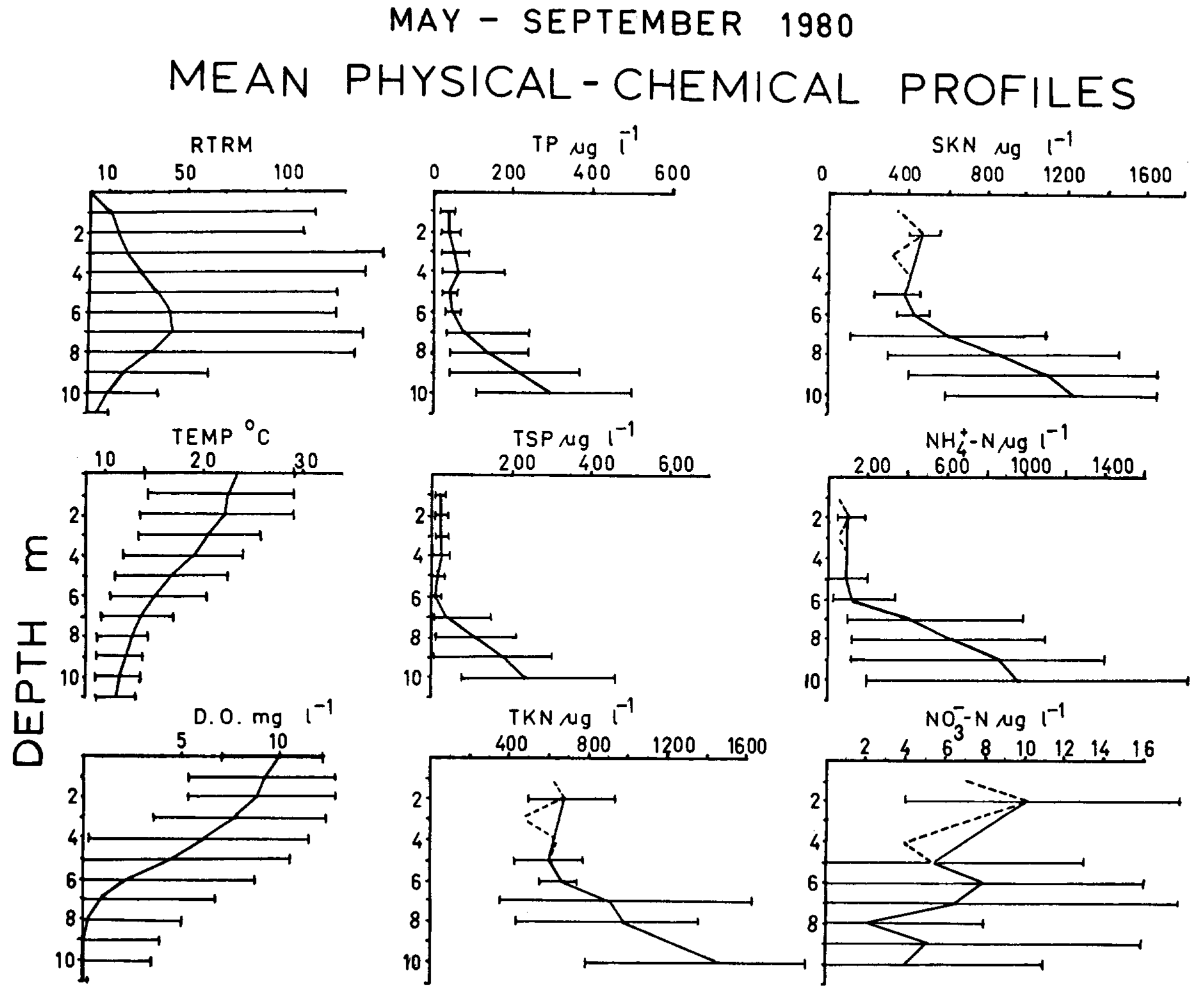

Fig. 2. Physical-chemical depth profiles from the deep station. Solid profiles indicate mean values during the May-September 1980 study. Horizontal bars indicate the range of values encountered. Dashed lines indicate trends based on a small sample size (i.e. not significant).

Total vertical transport during a meteorologic mixing event (F) was obtained as the sum of direct capture by epilimnion expansion (F_e), and the sum of the products of volume (V_z), concentration difference ($C_z - C_e$) and mixing ratio (R_z) associated with each depth stratum (z) below D_e:

$$F = F_e + \Sigma (V_z \times (C_z - C_e) \times R_z) \ldots$$

(modified fromStauffer & Lee 1974).

This vertical transport model was applied for each interval of downward migration of D_e, as identified by downward migration of RTRM30.

Results and discussion

Total phosphorus (TP), total soluble phosphorus (TSP), ammonium-N nitrogen (NH_4^+), soluble nitrogen (SKN), and total nitrogen accumulate in the hypolimnion as a result of decomposition and sediment nutrient release (Fig. 2). Concentrations of nitrate were low throughout the water column and were highly variable (0.0 to 17.0 mg m^{-3}). The molar nitrogen:phosphorus ratio varied between 11 and 67, with a mean value of 30. Nitrogen accumulated in the hypolimnion at a lower rate than phosphorus, resulting in a decreasing N:P ratio as a function of depth. The N:P ratios indicate that phosphorus, in general, is more limiting than nitro-

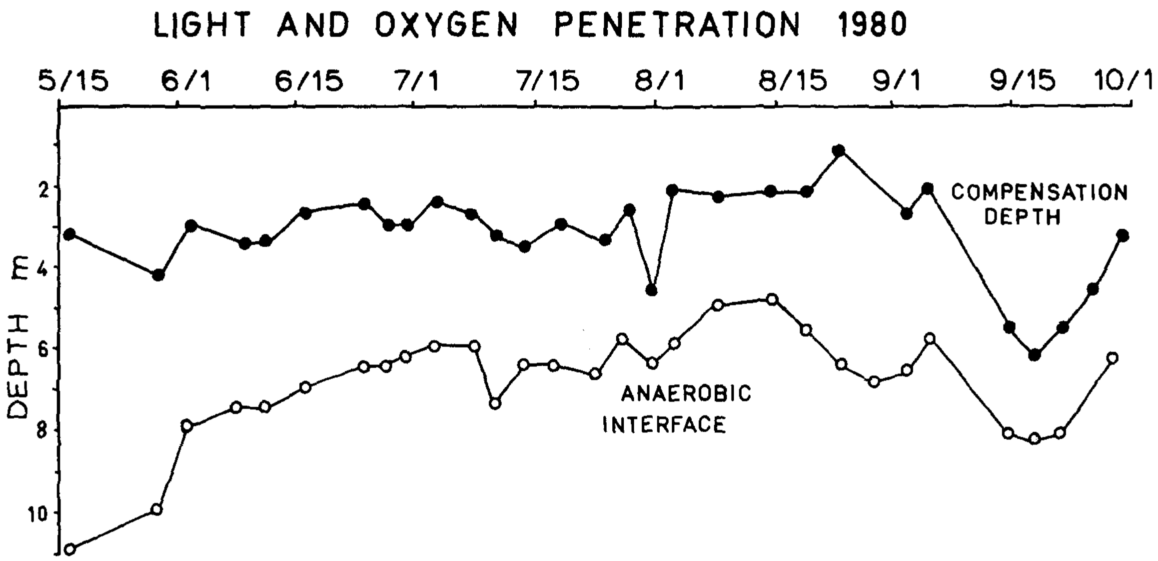

Fig. 3. Depth of 1% light penetration and its relationship to the anaerobic–aerobic interface.

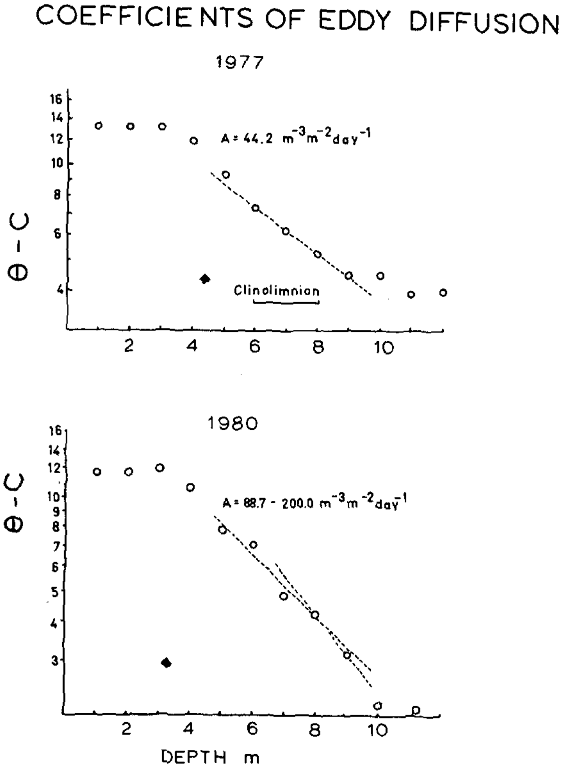

Fig. 4. McEwen analysis of heating in Lake Waramaug in 1977 and 1980. Diamonds indicate mean depth of 1% light penetration used in corrections for solar heating.

gen. Pearson correlations between all chemical and algal observations indicated that: 1) as bluegreen algal abundance increased the abundance of other groups declined ($r^2 = -0.54$, sign. at 5%) thus decreasing algal diversity, and 2) diatom populations increased as a function of nitrate concentration ($r^2 = 0.44$, sign. at 10%).The straw sampler for collection of algae yeilded an average epilimnetic (top 5 m) abundance. An abundance greater than 300 cells ml^{-1} was used to identify epilimnetic bloom conditions which occurred three times during the study (Fig. 6).

RTRM30 varied between 4 and 5 m, which corresponds to the depth of maximum change in temperature as a function of depth (3.5–4.5 m). The depth of the anoxic interface was also variable, reaching a minimum depth of about 4.2 m. TP and, to a lesser degree TSP, exhibits a peak at about 4 m (maximum concentration = 186 mg TP m^{-3}) (Fig. 2). RTRM and TP concentration were significantly correlated ($r^2 = 0.88$, sign. at 5%). These data suggest that as the density difference between adjacent layers increases TP increases, which is probably a result of sedimenting materials and cells suspended by the density barrier (Fig. 2). The lake stratum between 3 and 5 m is a very active region, subject to changes in thermal partitioning, mixing rates, and associated effects.

The depth of light penetration (1%) and anaerobic–aerobic interface varied seasonally and exhibit-

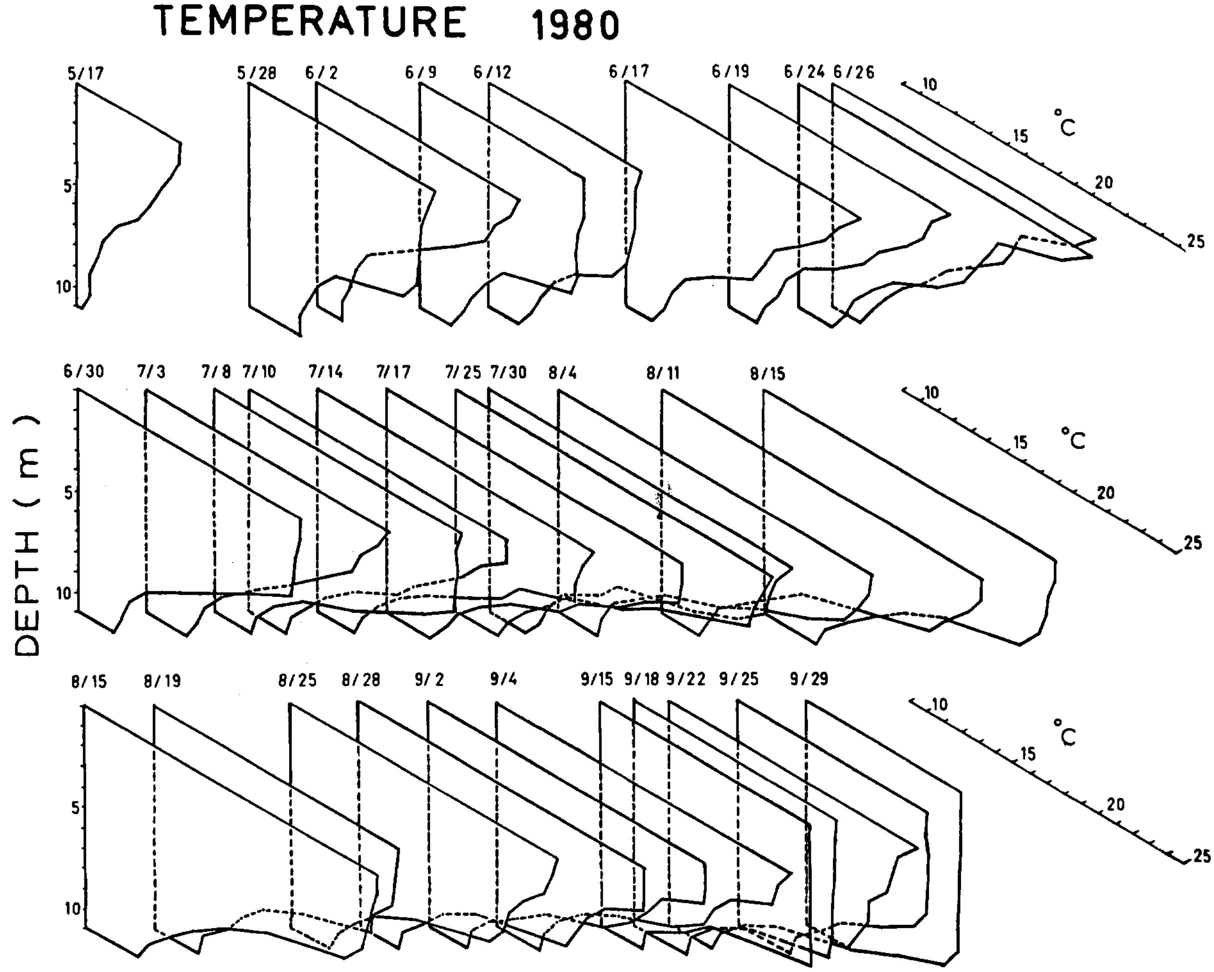

Fig. 5. Seasonal distribution of temperature at the deep station in Lake Waramaug.

ed short term fluctuations, with mean values of about 3.3 and 8.0 m, respectively (Figs. 2 and 3). The McEwen eddy diffusion coefficient estimates for the 1977 and 1980 heating seasons were high, relative to other lakes (Fig. 4). The 1980 estimate was greater than 1977, which may have been due to greater transfer of heat by seiches (Powell & Jassby 1974) or interflow (Wetzel 1975) of large inputs of water from Sucker Brook. A gradual increase in temperature gradient, with intermittent disruption of the upper layers, was observed (Fig. 5). Conversion of temperature to density and comparison between adjacent layers (i.e. RTRM) identified periods when surface heating resulted in very steep density gradients (Fig. 6). These data suggest that for short calm periods the epilimnion is not totally mixed, but is further partitioned by density barriers. These calm intervals were ended by input of wind energy sufficient to mix the entire epilimnion. Such events occurred in late June and July (Fig. 6). Periods of epilimnion expansion occurred in early June, August, and September. Fluctuation of D_e (as estimated by RTRM30) and its proximity to the anoxic interface is shown, relative to thermocline depth, in Fig. 7. An algal abundance greater than 300 cells ml^{-1} occurred following each mixing event in which RTRM30 came within 1 m of the thermocline and 1 ppm dissolved oxygen (approximate lower limit of the electrometric detection). The mixing events in July were sufficient for disruption of epilimnetic density partitioning, but did not result in significant metalimnetic erosion (Figs. 6 and 7). The comparison of D_e with anoxic depth, relative to thermocline location (Fig. 7), illustrates the dy-

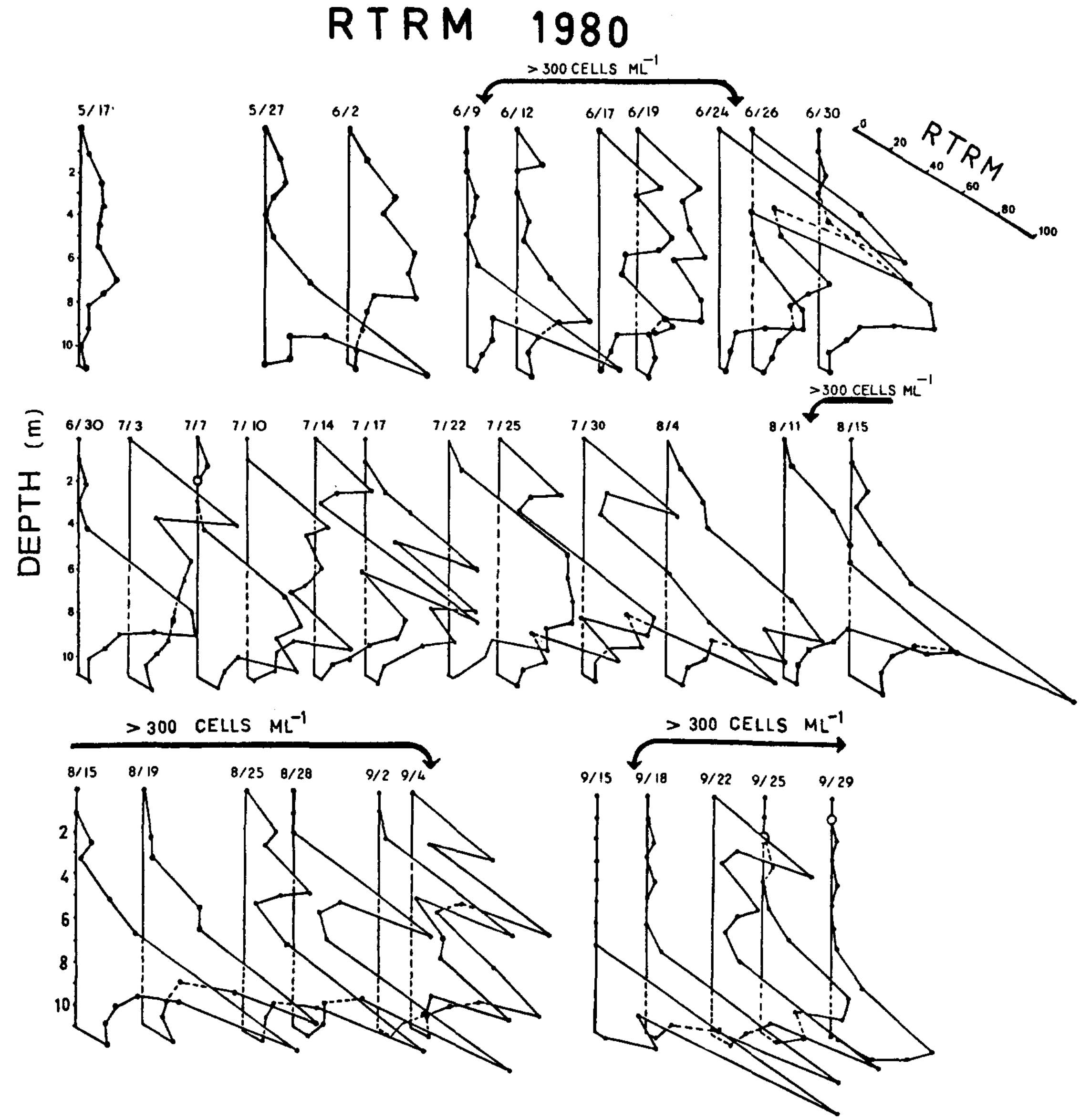

Fig. 6. Seasonal distribution of relative thermal resistance to mixing (RTRM) at the deep station in Lake Waramaug. Arrows indicate periods when average epilimnetic algal abundance exceeded 300 cells ml^{-1}.

namics of short term mixing more clearly than a comparison of anaerobic–aerobic interface depth and compensation depth (Fig. 3), which tend to vary in the same direction.

Boundary statistics for the top and bottom of the metalimnion (obtained graphically, after Stauffer & Lee 1974) and short-term vertical transport estimates for each period of downward migration of RTRM30 are given in Fig. 8 and Table 1. Each mixing event resulting in epilimnetic expansion eroded the top of the metalimnion (i.e. D_e migration was greater than thermocline migration) (Fig. 8). The epilimnion was treated as a compartment with TP inputs from the watershed, hypolimnion, shallow sediments, and macrophyte release (Table 1). Total mass increase of TP in the water column indicates net benthic and watershed contribution during the experimental period. Direct capture (based on D_e migration) and short-term mixing resulting from meteorologic events (based on

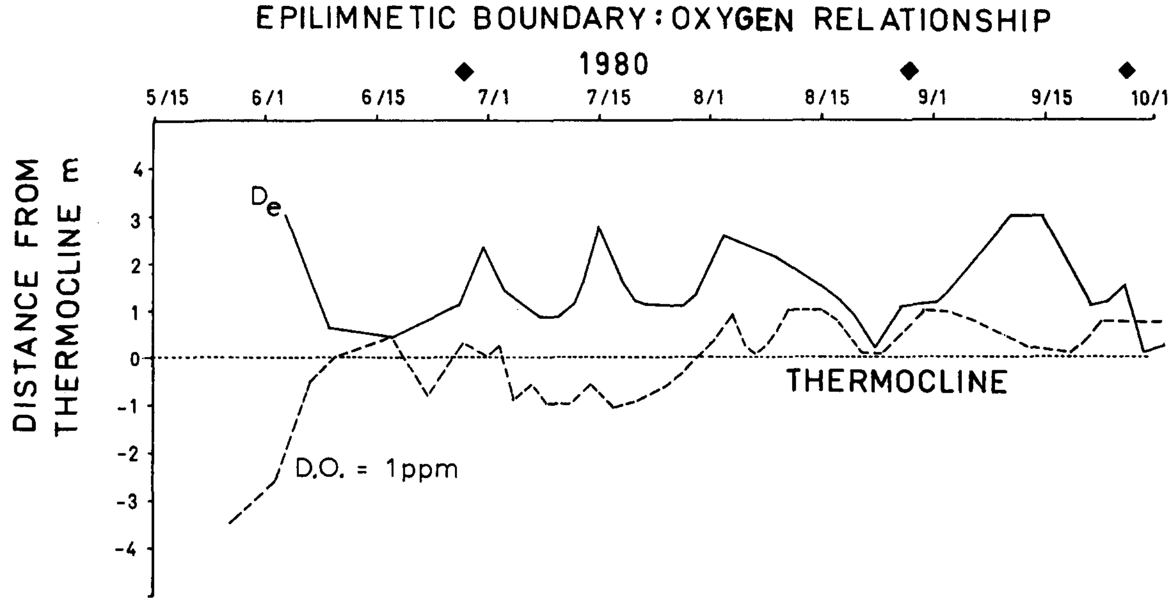

Fig. 7. Fluctuations of the upper metalimnetic boundary and its proximity to the anaerobic–aerobic interface, relative to thermocline depth. Diamonds indicate times when average epilimnetic algal abundance increased above 300 cells ml^{-1}.

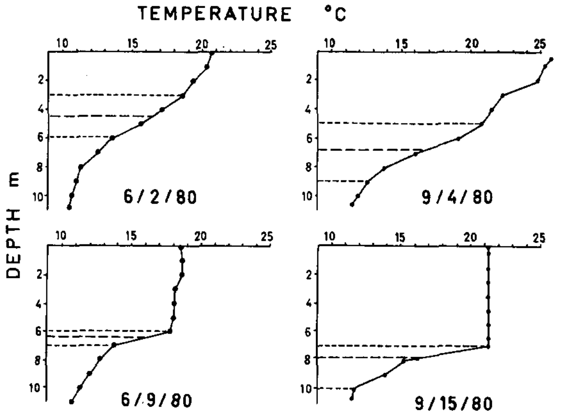

Fig. 8. Meteorologic event related mixing and its effect on density layer boundaries. Upper and lower dashed lines indicate the top and bottom of the metalimnion. Thermocline depth was taken to be the depth at which temperature is midway between these metalimnetic boundaries (heavy dashed lines).

mixing ratios) obtained using the vertical transport model accounted for significant contributions of TP to the productive epilimnion in early June and in September (Table 1). The meteorologic mixing event in September accounted for an epilimnetic input equal to about 25% of an estimated annual lake TP load. Watershed contribution of TP to the epilimnion was obtained as the difference between epilimnetic mass balance increase and vertical transport (Table 1). The epilimnetic TP load in June was primarily from external sources. Because the watershed loads were derived by difference these inputs include watershed input, and such shallow sediment phenomena as resuspension and macrophyte pumping. In late summer the relative contribution from vertical transport was greater than from external sources due to decreased hydrologic flow and increased metalimnetic nutrient concentration.

Conclusions

We found the use of RTRM, to describe the stability of thermal stratification, preferable to temperature profiles because it accounts for the nonlinearity of density–temperature relationships and identified periods of density partitioning within the epilimnion. RTRM and RTRM30 are very useful to lake managers because they are comparatively easy to calculate and provide a more accurate description of stratification structure and mixing behavior in a lake than the use of temperature data alone. The vertical transport model of Stauffer & Lee (1974) is very useful in describing non-steady-

Table 1. Meteorologic event related phosphorus budget for the epilimnion, hypolimnion, and entire lake (kg TP). Epilimnetic loading is partitioned into estimates of direct capture, turbulent mixing, and watershed loading for the experimental period and on a daily basis.

	Month–day, time periods 6/1–6/9	7/1–7/9	7/15–7/20	8/5–8/19	9/4–9/15
Change in epilimnetic content (kg)	+304	+65	+49	−1280	+408
Change in hypolimnetic content (kg)	−35	+50	+187	−211	−79
Total lake content change (kg)	+269	+115	+236	−1496	+329
Epilimnetic Loading Sources					
Direct capture (kg)	+71	0	0	0	+202
Event related mixing (kg)	+10	0	0	0	+267
Watershed and shallow sediments (kg)	+223	+65	+49	–	–
Watershed rate (kg day^{-1})	+32	+8	+10	–	–
D_e Migration* (m)	−3.0	+0.1	+0.2	+0.6	−1.0
Thermocline* migration (m)	−1.8	+0.2	+0.2	+0.5	−0.8

* + denotes upward migration, – denotes downward migration

state nutrient transport. McEwen's technique is based on seasonal steady-state heating and does not account for heat transfer by seiches. Vertical transport is clearly not a steady-state phenomenon in Lake Waramaug and eddy diffusion estimates by McEwen's method are probably inaccurate in this lake. The use of the boundary statistics and vertical transport model provides reasonable estimates of short-term internal and external epilimnetic loading when incorporated into a mass balance model. Because the epilimnion is totally mixed during downward migration of D_e, nutrient loads from deeper layers are probably taken up rapidly by algae. High values of eddy diffusion coefficient estimates, changes in RTRM profiles, and algal abundance, indicate that benthic nutrient flux and subsequent migration into the productive epilimnion significantly contributes to algal bloom conditions. Vertical TP transport was greatest in late summer (1980) when hypolimnetic concentrations were high, and contributed about 25% of an annual lake TP load in 10 days.

Acknowledgements

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