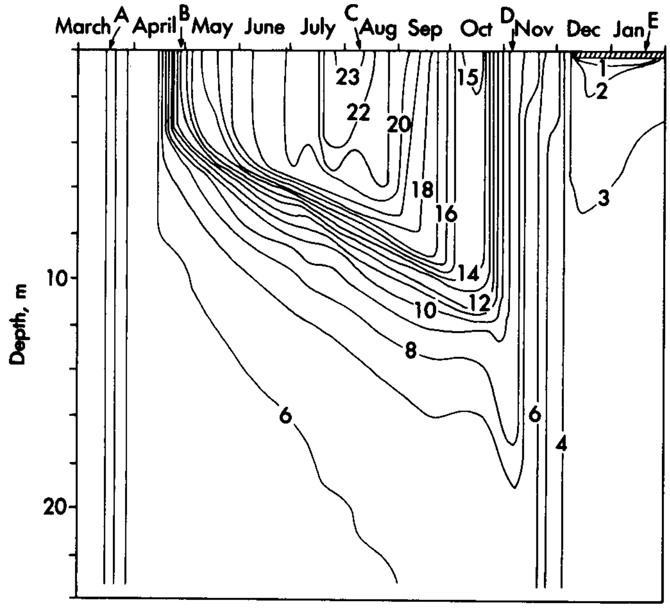
Limnology 2009

Temperature stratification and related topics.

A. Temperate lake "prototype".

If the temperature in the water column is measured with sufficient frequency, a complete picture of the annual pattern of thermal stratification will be available. A compact graph which summarizes temperature vs. depth over an annual cycle is a depth-time diagram of isotherms.

1. A "typical" deep lake located in an area of continental climate at middle latitude can be used to illustrate the commonly used vocabulary of temperature stratification.



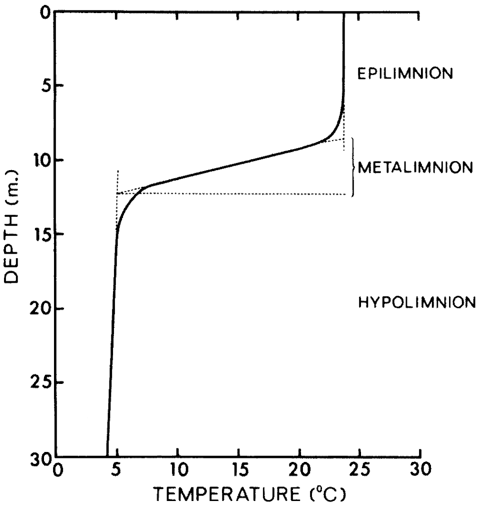


Figure 10-6
Isotherms from spring overturn (*A*) to inverse stratification beneath winter ice cover (*E*). Dimixis in Mountain Lake, Virginia, during 1962-63. *B*, Early summer stratification; *C*, the height of summer stratification; *D*, the approach of the autumn overturn as direct stratification is being destroyed. (Modified from Roth and Neff, 1964.)

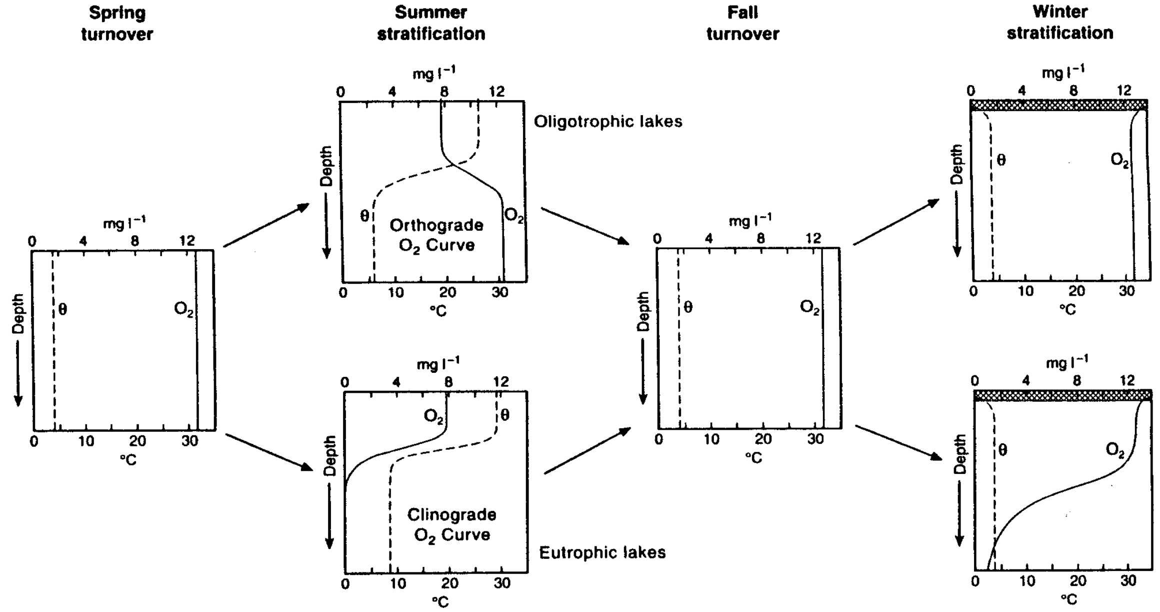


FIGURE 9-2 Idealized vertical distribution of oxygen concentrations and temperature (Θ) during the four main seasonal phases of an oligotrophic and a eutrophic dimictic lake.

2. Some commonly used vocabulary

Layers:

Epilimnion: The surface layer of a lake during the period of summer stratification.

Thermocline: A horizontal layer of water in a lake with a particularly steep temperature gradient. During the summer stratification period it is the intervening layer between the epilimnion and the hypolimnion but during winter, with ice cover, it may be near the surface. (A more general term for a stratified layer is *pycnocline*, for density stratification, whether caused by temperature or salinity. Other terms in use are: *Sprungschicht* and *discontinuity layer*.)

Metalimnion: The thermal transition layer below the epilimnion. Commonly used interchangeably with thermocline. Some authors have defined the thermocline as the depth at which the temperature changes most rapidly and the metalimnion as the entire zone over which the temperature is changing rapidly.

Hypolimnion: The deep water region in a lake below the thermocline or metalimnion.

The stratification and mixing regimes of lakes can be described as follows:

Amictic: Perennially ice covered

Holomictic lake: A lake which circulates right down to the bottom at least once per year.

Cold monomictic: Water temperatures never exceed 4 C, with only one period of circulation in summer at or below 4 C

Dimictic: Circulate twice each year, in spring and fall and are directly stratified in summer (warmest water on top) and inversely stratified (warmest water on bottom at 4 C) in winter under ice

Warm monomictic: Circulate once a year in the winter at or near 4 C and are thermally stratified the remainder of the year; not ice covered

Oligomictic: Thermally stratified much of the year but cooling sufficiently for rare circulation periods at irregular intervals; not ice covered

Meromictic: Highly saline water results in permanent stratification. The deep laye that does not participate in vertical mixing because it is too dense (dissolved salts) is called a **monimolimnion.** The surface layer is called the **mixolimnion**, and seasonally may become stratified due to a temperature gradient in addition to the chemical stratification lower in the water column**.** The layer between the mixolimnion and the monimolimnion, in which the concentration of salt changes rapidly with depth, is called the **chemocline**. Stratification due to salinity may be very persistent, and last for hundreds or thousands of years! Meromixis may be caused by: (1) input of salt from an outside source, such as an intrusion of seawater ("ectogenic meromixis"), (2) submerged saline springs ("crenogenic meromixis"), or (3) by decomposition of organic material leading to an elevated salt concentration in deeper water ("biogenic meromixis").

In very deep lakes (e.g. Crater Lake) pressure can also influence water density. Water is only slightly compressible; nevertheless with great depth such effects are evident. In the case of Crater Lake, vertical stratification can be metastable (Crawford and Collier, L&O, 1997, 42:299-306 "Observations of a deep-mixing event in Crater Lake, Oregon".)

Lakes which mix infrequently and at irregular intervals (many deep tropical lakes) are called **oligomictic** lakes. Shallow lakes which mix frequently are called **polymictic** lakes.

The approximate geographic distribution of dimictic, polymictic, etc. lake types is illustrated in the figure below.

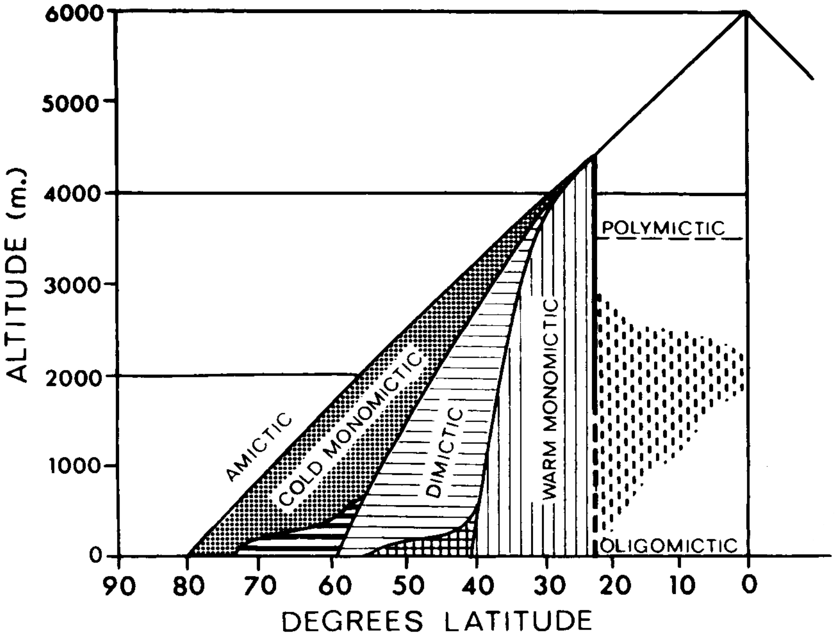


FIGURE 6-7 Schematic arrangement of thermal lake types with latitude and altitude. *Black dots:* cold monomictic; *black-and-white horizontal* bars: transitional regions; *horizontal lines:* dimictic; *crossed lines*: transitional regions; *vertical lines:* warm monomictic. The two equatorial types occupy the unshaded areas labeled oligomictic and polymictic, separated by a region of mixed types, mainly variants of the warm monomictic type (*broken vertical lines*). (Modified from Hutchinson and Löffler, 1956.)

Effect of wind on the thermocline

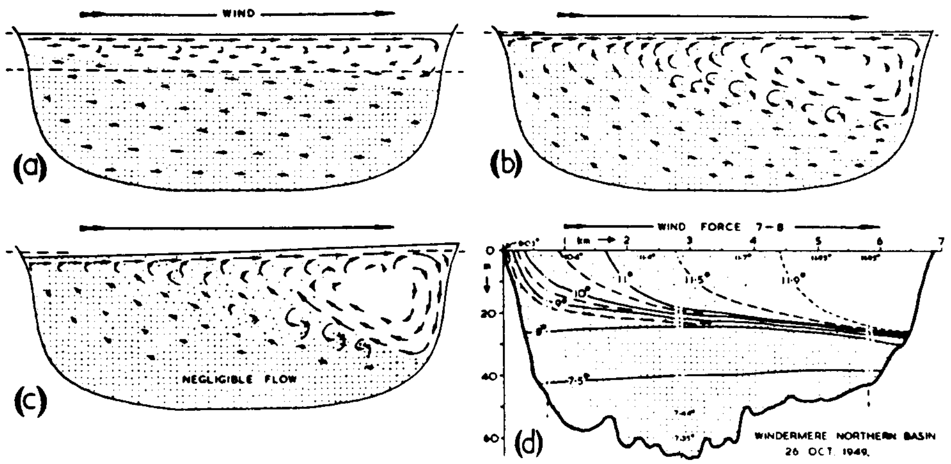


FIGURE 7-14 Stages of wind drift and circulation that led, after about 12 hours of strong wind, to the thermal situation depicted in (d), Lake Windermere, England, in late fall. Broken lines show equilibrium levels of water surface in (a), (b), and (c), and of the thermocline in (a). The initial layer below the thermocline is stippled; speed and direction of flow are roughly indicated by arrows. (From Mortimer, C. H.: *Verhandlungen Int. Ver. Limnol. 14:*81, 1961.)

B. Some quantitative aspects of stratification.

The dynamics of heat flux and temperature stratification are intricate and the subject extended treatment by Imberger and others. (See reference above)

Nevertheless, some aspects of temperature stratification may be given quantitative treatment at a rudimentary level.

1. Stability of a parcel of water.

The stability of a parcel of water in a water column may be described by the Richardson number:

$$Ri = \frac{g(d\rho/dz)}{\rho(du/dz)^2}$$

Where: g = acceleration of gravity
ρ = density
u = horizontal velocity
z = depth

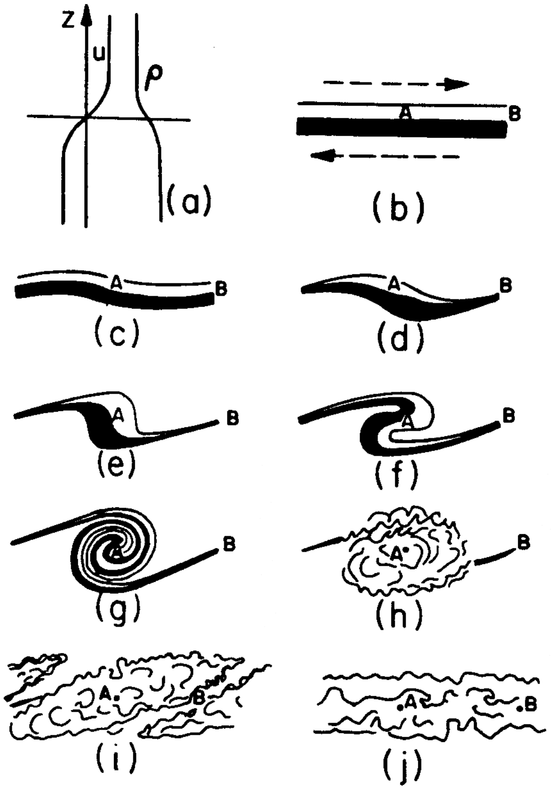


FIGURE 7-2 Growth of shear instability leading to turbulent mixing in a stratified fluid with the velocity and density (ρ) distribution shown in *a*. A and B are fixed points, the arrows indicate direction of flow, and the lines represent surfaces of equal density. (From Mortimer, C. H.: *Mitteilungen Int. Ver. Limnol. 20:*134, 1974, after Thorpe.)

When the Richardson number is less than 0.25, internal waves spontaneously appear, and break. Mixing ensues until gradients are reduced and the system again stabilizes.

2. Sample stratification and stability pattern.

A sample of the intensity of stratification in a water column in a stratified lake appears in figure to the right. It can be seen that the thermocline is stable. The stratification of thermocline is a very effective barrier to vertical transport of heat and dissolved ions and gases. ("RTR", or *relative thermal resistance* is defined here by Vallentyne as: the ratio of the density difference between the top and bottom of a 0.5 meter segment divided by the density difference between water of temperature 5 degrees and water of temperature of 4 degrees. That is, the density difference between water of 5 degrees and water of 4 degrees is one unit of RTR. In the figure, density differences over the span of 1/2 meter are as much as 60 times greater.)

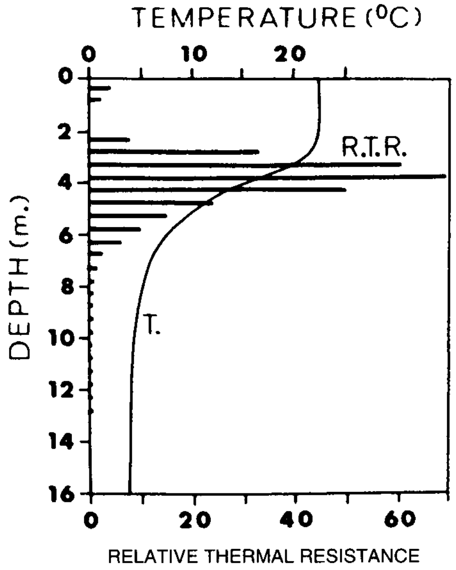


FIGURE 6-2 A summer temperature profile (*single line*) and relative thermal resistance to mixing (bars) for Little Round Lake, Ontario. The relative thermal resistance (R.T.R.) to mixing is given for columns of water 0.5 m deep. One unit of R.T.R. = 8×10^{-6}, that is the density difference between water at 5 and at 4°C. The R.T.R. of the lake water columns is expressed as the ratio of the density difference between water at the top and bottom of each column to the density difference between water at 5 and 4°C. (Modified from Vallentyne, 1957.)

3. Stability of a lake.

The stability of a lake is the amount of work that would be required to mix the heat in the lake uniformly over depth. The calculation of the stability of a lake is based on a comparison between the vertical location of the center of mass of the stratified lake compared to the vertical location of the center of mass of the same lake after complete mixing (and with the same total heat content). [See discussion of Schmidt stability index, p164ff.]

The concept of stability was introduced by Schmidt in 1915. Few authors have calculated S since, however, the term has become engrained in limnological theory and vocabulary. It is defined as the amount of work needed to mix the entire body of water to uniform temperature without addition or subtraction of heat, or the inertial resistance to complete mixing caused by vertical density differences.

$$S\ (\mathrm{g\ cm/cm^2}) = 1/A_0 \int_0^{Zm} (z - z_g)\, A_z\, (\rho_z - \rho_m)\, dz \qquad \text{[integral from 0 to Zm]}$$

Where: A_0 = surface area of the lake

Z = the height above the bottom

Z_g = the center of volume in [cm] above the bottom

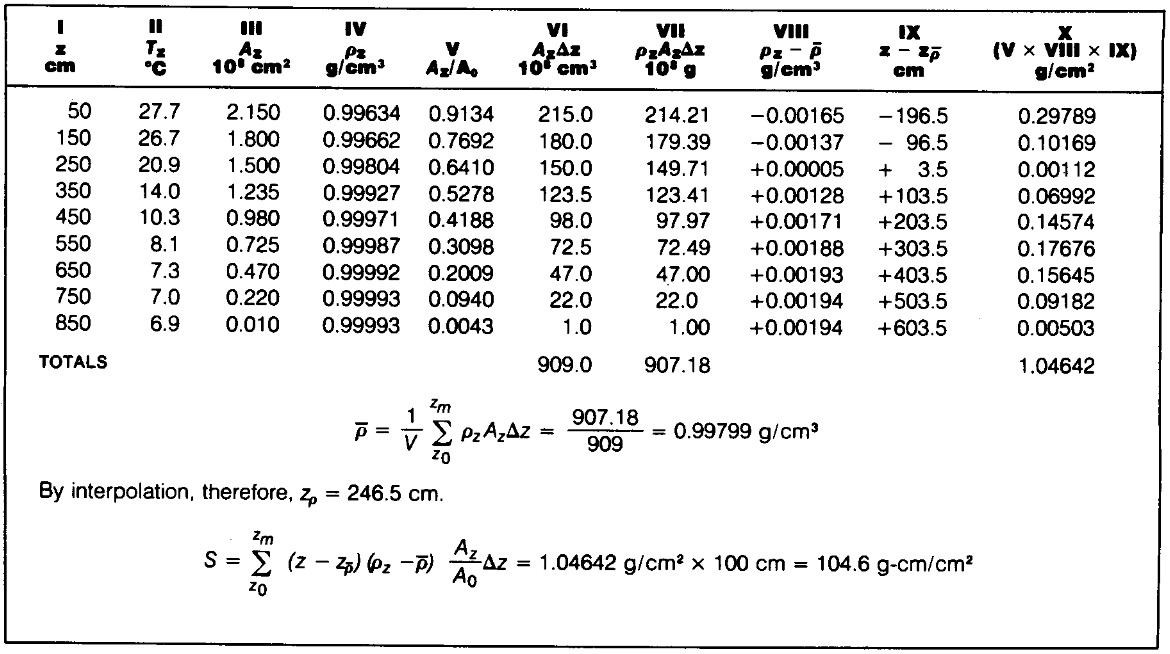
A_z = the area of the lake at depth z

ρ_z = density of water at depth z

ρ_m = density at complete mixing

If density is uniform from top to botton, stability is zero; no work must be performed to promote heterogeneity. As surface waters warm the so-called center of gravity of the lake moves deeper into the water column as a result of vertical differences in density.

Table 10-2
Data and calculations of the stability of stratification in Tom Wallace Lake, Kentucky, 26 June 1954



I z cm	II T_z °C	III A_z 10^6 cm²	IV ρ_z g/cm³	V A_z/A_0	VI $A_z\Delta z$ 10^6 cm³	VII $\rho_z A_z \Delta z$ 10^6 g	VIII $\rho_z - \bar{\rho}$ g/cm³	IX $z - z_{\bar{\rho}}$ cm	X (V × VIII × IX) g/cm²
50	27.7	2.150	0.99634	0.9134	215.0	214.21	−0.00165	−196.5	0.29789
150	26.7	1.800	0.99662	0.7692	180.0	179.39	−0.00137	− 96.5	0.10169
250	20.9	1.500	0.99804	0.6410	150.0	149.71	+0.00005	+ 3.5	0.00112
350	14.0	1.235	0.99927	0.5278	123.5	123.41	+0.00128	+103.5	0.06992
450	10.3	0.980	0.99971	0.4188	98.0	97.97	+0.00171	+203.5	0.14574
550	8.1	0.725	0.99987	0.3098	72.5	72.49	+0.00188	+303.5	0.17676
650	7.3	0.470	0.99992	0.2009	47.0	47.00	+0.00193	+403.5	0.15645
750	7.0	0.220	0.99993	0.0940	22.0	22.0	+0.00194	+503.5	0.09182
850	6.9	0.010	0.99993	0.0043	1.0	1.00	+0.00194	+603.5	0.00503
TOTALS					909.0	907.18			1.04642

$$\bar{\rho} = \frac{1}{V} \sum_{z_0}^{z_m} \rho_z A_z \Delta z = \frac{907.18}{909} = 0.99799\ \mathrm{g/cm^3}$$

By interpolation, therefore, $z_{\bar{\rho}} = 246.5$ cm.

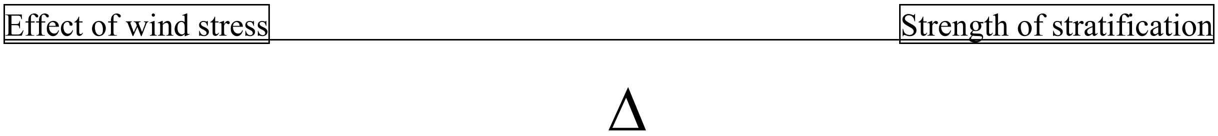
$$S = \sum_{z_0}^{z_m} (z - z_{\bar{\rho}})(\rho_z - \bar{\rho}) \frac{A_z}{A_0} \Delta z = 1.04642\ \mathrm{g/cm^2} \times 100\ \mathrm{cm} = 104.6\ \mathrm{g\text{-}cm/cm^2}$$

4. Lake Number

Reference: Robertson, D.M. & J. Imberger, 1994. "Lake Number, A Quantitative Indicator of Mixing used to Estimate Changes in Dissolved Oxygen." Int. Rev. ges. Hydrobiol. **79**:159-176

The basic concept of Robertson and Imberger is:

- *Is* **strength of stratification** *stronger than the effect of wind stress*? [If so, no mixing.]
- *Or, is the effect of* **wind stress** *stronger than the strength of stratification*? [If so, mixing top to bottom of the lake.]



Lake number, LN, is the ratio of the *strength of stratification* to the *effect of the wind stress.*

L_N = (Strength of Stratification/Effect of Wind Stress)

$L_N << 1$ means stratification is weak with respect to wind stress, and the lake will mix.

$L_N >> 1$ means stratification is strong and dominates the forces introduced by surface wind energy.

$L_N = 1$ means the wind is just strong enough to deflect the thermocline to the surface at the upwind end of the lake.

Strength of stratification:

The Schmidt stability is:

$$S_t = 1/A_m \int_0^{Zm} (z-Z_g) \times A_z \times (1-\rho_z)\, dz$$

Where:

S_t = Schmidt stability

Am = Surface area of the lake (cm^2)

z = height above the bottom (cm)

Z_m = maximum depth of the lake (cm)

Zg = center of volume in (cm) above bottom

A_Z = area of the lake at height Z (cm^2)

ρ_Z = density of water at depth z ($g\ cm^{-3}$)

S_t is multiplied by g (acceleration of gravity) and the height of the thermocline (Z_t/Z_m)

above the bottom to express the *strength of stratification*:

Strength of stratification = $g \times S_t \times (1-Z_t/Z_m)$

Effect of wind stress:

The *water friction velocity* is represented by an empirical formula:

$$u_*^2 = \rho_a/\rho_m \times C_D \times U_{10}^2$$

Where:

ρ_a/ρ_m is the ratio of the density of air to water (= 1.2×10^{-3})

C_D is the drag coefficient (= 1.3×10^{-3})

U_{10} is the wind velocity at 10 meters above the surface (cm/sec).

(*note that the only variable is wind velocity*)

The *effect of the wind stress* is calculated as:

Effect of wind stress = $\rho_m \times u_*^2 \times /A_m^{1.5} \times (1-Z_g/Z_m)$

Where:

ρ_m is the water density at the surface (g cm^{-3})

Z_t = thermocline height above the bottom (cm)

Effect of wind stress = $\rho_m \times u_*^2 \times A_m^{1.5} \times (1-Z_g/Z_m)$

Robertson and Imberger describe the derivation of ***Lake Number*** and its application to several lakes and reservoirs in North America and Australia. Lake Number serves as a quantitative parameter that predicts lake mixing by considering both temperature stratification and wind mixing in a single index. The index has the advantages of (1) being relatively simple and (2) serving as a predictor of stability or mixing. *[I have followed Robertson and Imberger's notation, which is slightly different. E.g. A_m instead of A_0. Also, they do not include g in their definition of S_t.]*

"Lake number is a quantitative index of the **dynamic** stability of the water column; it is defined as the ratio of the moments about the water body's center of volume, of the stabilizing force of gravity (resulting from density stratification) to the destabilizing forces from wind, cooling, inflow, outflow, and artificial destratification devices." ..."

"A $L_N = 1$ indicates that the wind is just sufficient to force the seasonal thermocline to be deflected to the surface at the windward end of the lake. For $L_N >> 1$, stratification is strong and dominates the forces introduced by surface wind energy. Under these circumstances, the

isopycnals (surface of constant density) are expected to be primarily horizontal. Little seiching of the seasonal thermocline and little turbulent mixing in the hypolimnion are expected. Above the value of 1.0, increases in L_N represent very little difference in terms of mixing below the seasonal thermocline. For L_N <<1, stratification is weak with respect to wind stress. Under these circumstances, the seasonal thermocline is expected to experience strong seiching and the hypolimnion is expected to experience turbulent mixing due to internal shear ..." (p 161)

"The period over which the wind should be averaged depends on the length of time required to tilt the thermocline to the surface, which is dependent on the strength of stratification." [Usually 2 or 3 days for lakes in their study when the lakes were weakly stratified, i.e. $L_N \sim 1$.] (p 163)

"Deep mixing events can often be detected by a rapid increase in deep DO concentrations... However, even during this weakly stratified period [winter], L_N values are often greater than 1.0 which suggests there are discrete episodes of deep mixing. During this period, which usually has been referred to as holomixis, WAR [one of their study reservoirs] is actually acting as a polymictic system....." (p164)

Conclusion: "L_N values are superior to S_t values as an indicator of the extent of deep mixing. S_t values represent the strength of stratification and not the extent of mixing; whereas L_N values less than approximately 1.0 directly indicate deep mixing..." (p166)

Comment: In effect, L_N provides a dynamic indicator of mixing under existing wind and stratification conditions, rather than the static concept provided by S_t alone.

Note: Authors apply L_N to a number of well studied North American and Australian lakes and reservoirs. Their results demonstrate the effectiveness of using L_N as an indicator of deep mixing. Their time/depth diagrams of oxygen vs. L_N are revealing. They go on to develop models of oxygen concentration in their lakes based on the prediction of mixing from application of L_N.

Wedderburn Number (W)

W is based on a similar concept as LN. W is based upon the Richardson number and the mixed layer depth (H) to basin length at the thermoncline (L) (see Kalff page 183 for complete explanation).

W is the ratio of the depth-based buouyancy/length-based wind mixing.

C. Some consequences of stratification.

The vertical distribution of dissolved gases, especially oxygen, can be strongly influenced by temperature stratification. If only physical processes are important, the vertical distribution of dissolved oxygen can be predicted strictly from the temperature. The resulting oxygen-depth curve is called an **orthograde oxygen curve.** The shape of the curve results from the influence of temperature on the solubility of oxygen in water. Oxygen is less soluble at higher temperatures than at lower temperatures, and therefor the epilimnion of a stratified lake will contain less oxygen than the hypolimnion (if only temperature is influencing oxygen concentration). Other oxygen curves are possible if oxygen-reduction processes are quantitatively important (discussed later with oxygen and redox chemistry).

The availability of light decreases exponentially with depth because of light scatter and absorption. As a consequence, light energy is more available in the epilimnion than in the lower strata. The upper layer of a lake which receives sufficient light for net photosynthesis to occur is called the **photic zone**, or **trophogenic zone**, and may coincide with the epilimnion. Note however that water transparency may dictate that the photic zone is less than the depth of the epilimnion, or extend into the metalimnion.

Reynold's model of phytoplankton succession invokes the pattern of mixing as one important ingredient. His treatment is the current paradigm for explaining the broad patterns of phytoplankton succession.

D. Heat budgets. Two types of heat budgets have been developed.

1. Annual heat budget

The annual heat budget of a lake is the record of heat content of the lake, normalized for surface area. The annual heat budget is usually reported in units of calories/cm^2. The amount of heat required to warm a dimictic lake from winter stratification to isothermal mixing in the spring is called **winter heat income**, and the amount of heat required to further heat the lake to its maximum summer heat content is called **summer heat income.** Some sample annual heat budgets are presented in the following table.

Heat storage is a simple calculation based upon mass, temperature, and specific heat. In general, we assume that a gram of water = 1 cc or 1 ml and that its heat content is milliliters x degrees C. Thus, 1 ml of water at 8 C contains 8 calories of heat. This makes calculating heat content of a lake relatively straightforward.

Annual heat budget of some selected lakes

Lake	Annual heat budget (cal/cm^2)	Summer heat income	Winter heat income
Baikal	57000	34500	22500
Michigan	52000	41000	11000
Tahoe	35000	35000	(warm monomictic)
Crater	**30100**	**30100**	**(warm monomictic)**
Washington	21069	21069	(warm monomictic)
Mendota	23000	18000	5000

TABLE 6-3 Variations in the Annual Heat Budgets of Several Lakes[a]

Lake	*Number of annual observations*	*Mean depth* *($\bar{z}$)*	*Mean θ_a* *(cal cm^{-2} yr^{-1})*	*Range* *(cal cm^{-2} yr^{-1})*
Green, Wisconsin	5	33.1	34,200	32,300–36,400
Geneva, Switzerland	4	154.4	32,325	22,000–40,200
Mendota, Wisconsin	5	12.4	24,073	22,308–25,953
Orta, Italy	8	71.1	22,670	18,809–26,667
Whatcom, Washington	8	45.0	23,000	20,000–26,100
Washington, Washington	13	33.0	21,069	12,000–28,200
Menona, Wisconsin	3	7.7	17,559	17,256–18,041
Waubesa, Wisconsin	3	4.6	11,362	10,948–11,739
Murchison, Tasmania	2	20.6	10,498	10,095–10,900
Valencia, Venezuela	2	19.0	5309	4755–5862
Mize, Florida	3	4.0	4720	3767–6003

[a] From data of Birge (1915), Nordlie (1972), Stewart (1973), Lewis (1983b), Bowling (1990), and Ambrosetti and Barbanti (1993).

The effect of sediment heating can be an important in the heat budget of some lakes. This effect is often overlooked, but as is shown in the table below, sediment heating can account for nearly 38% of the heat accumulation in a lake.

Lake Mendota sediment temperature at:

8 m and 23.5 m

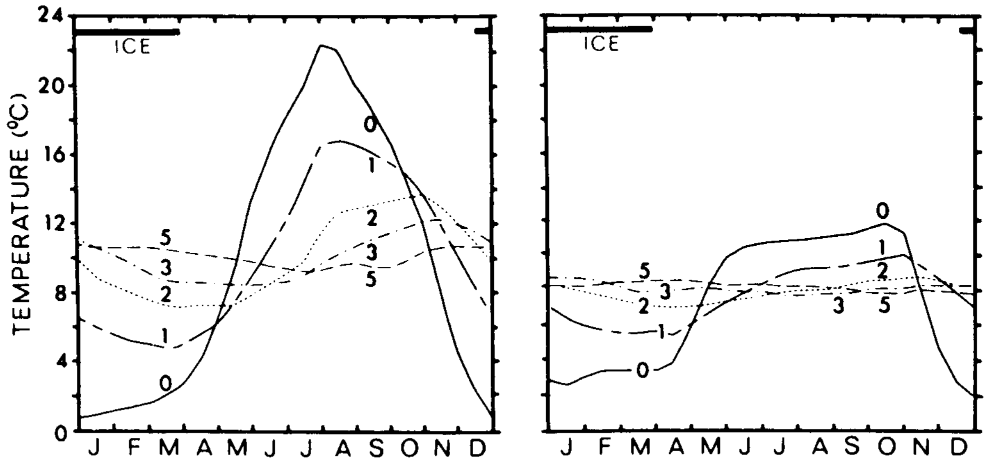


FIGURE 6-11 Annual temperature curves at 0, 1, 2, 3, and 5 m within the sediments of Lake Mendota, Wisconsin (means for 1918, 1919, and 1920). *Left:* Sediments at a water depth of 8 m. *Right:* Sediments at 23.5 m. (Modified from data of Birge, Juday, and March, 1927.)

TABLE 6-4 Heat Budgets of Lakes in Which the Heat Budget of the Sediments Is Compared to That of the Water[a]

Lake	*Mean depth (m)*	*Heat budget of water θ_a (cal cm^{-2} yr^{-1})*	*Heat budget of sediments θ_m (cal cm^{-2} yr^{-1})*	*Heat budget of lake (cal cm^{-2} yr^{-1})*	*% Sediments of total heat budget*
Mendota, Wisconsin	12.1	23,500	2000	25,500	7.8
Stewart's Dark, Wisconsin	4.3	7000	730	7730	9.4
Beloie, Russia	4.15	8000	2500	10,500	23.8
Tub, Wisconsin	3.6	8000	970	8970	10.8
El Porcal, Spain	3.0	6068	2962	9030	32.8
Hula, Israel	1.7	2290	1400	3690	37.9

[a] Data from Hutchinson (1957), Likens and Johnson (1969), and Cobelas (1992).

2. Analytical heat budget

An **analytical heat budget** is a budget based on a complete identification of all of the sources and sinks for heat to or from a lake. The analytical heat budget also illustrates the general characteristics of analytical budgets for lakes. For example, detailed budgets for water (hydrological budget) and nutrients (nutrient budget) are sometimes necessary for management of human impacted lakes.

The **rate of heat storage** in a lake is defined by:

$$Q_\Theta = [Q_S + Q_H - Q_R - Q_U] + [Q_A + Q_M - Q_W] + Q_S + Q_i - Q_E - Q_e$$

where:

Q_S = radiation from the sun,

Q_H = radiation from the sky,

Q_R = reflected radiation (from the surface of the lake),

Q_U = back scattered radiation (upwelling radiation),

Q_A = longwave radiation from the atmosphere,

Q_M = longwave radiation from surrounding mountains,

Q_W = longwave radiation from the water to the sky,

Q_S = net sensible heat transfer (transfer by conduction from air to water, minus transfer from water to air),

Q_i = net advective heat transfer (heat in influent minus heat in effluent),

Q_E = heat loss due to evaporation, and

Q_e = transfer of heat in evaporated water.

Some of these terms can be measured directly (net advective heat transfer, radiation from the sun, etc.) and some can be satisfactorily calculated from physical principals (longwave radiation terms, if temperatures of water and air are known), or safely ignored (longwave radiation from mountains). Some terms are important, but difficult to measure (evaporation especially).

In summary, an analytical heat budget focuses on the *processes* responsible for the addition or subtraction of heat to a lake.

Data for three analytical heat budgets (from Hutchinson)

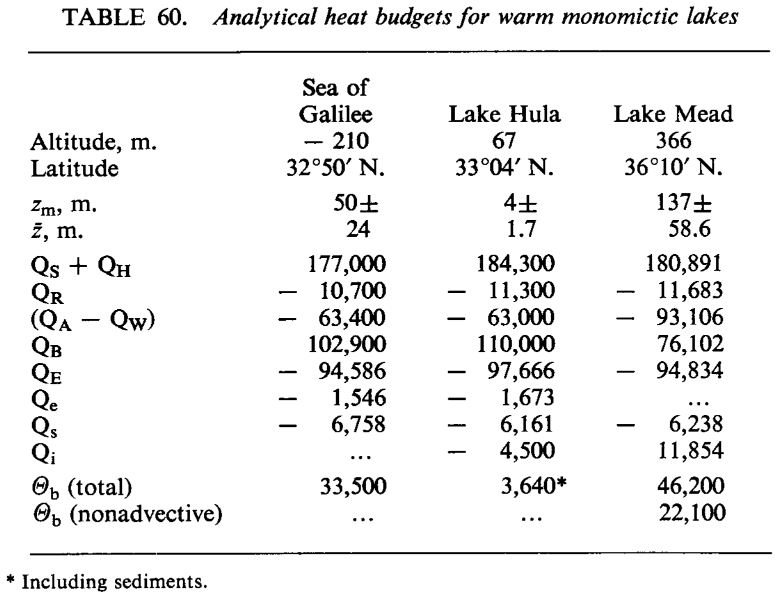


TABLE 60. *Analytical heat budgets for warm monomictic lakes*

	Sea of Galilee	Lake Hula	Lake Mead
Altitude, m.	– 210	67	366
Latitude	32°50′ N.	33°04′ N.	36°10′ N.
z_m, m.	50±	4±	137±
$\bar{z}$, m.	24	1.7	58.6
$Q_S + Q_H$	177,000	184,300	180,891
Q_R	– 10,700	– 11,300	– 11,683
$(Q_A - Q_W)$	– 63,400	– 63,000	– 93,106
Q_B	102,900	110,000	76,102
Q_E	– 94,586	– 97,666	– 94,834
Q_e	– 1,546	– 1,673	...
Q_s	– 6,758	– 6,161	– 6,238
Q_i	...	– 4,500	11,854
Θ_b (total)	33,500	3,640*	46,200
Θ_b (nonadvective)	...	...	22,100

* Including sediments.

An aside on transfer of heat. There are *3 distinct modes of heat transfer.*

conduction: A process of heat transfer within a material medium in which thermal energy is passed from molecule to neighboring molecule in the course of purely thermal activity. No mass motion of the medium is involved. A temperature gradient is required for conduction to occur.

convection: A process of heat transfer resulting from the movement of a heated material from one place to another, carrying heat.

radiation: The transfer of heat by electromagnetic waves. No material medium plays an essential role.

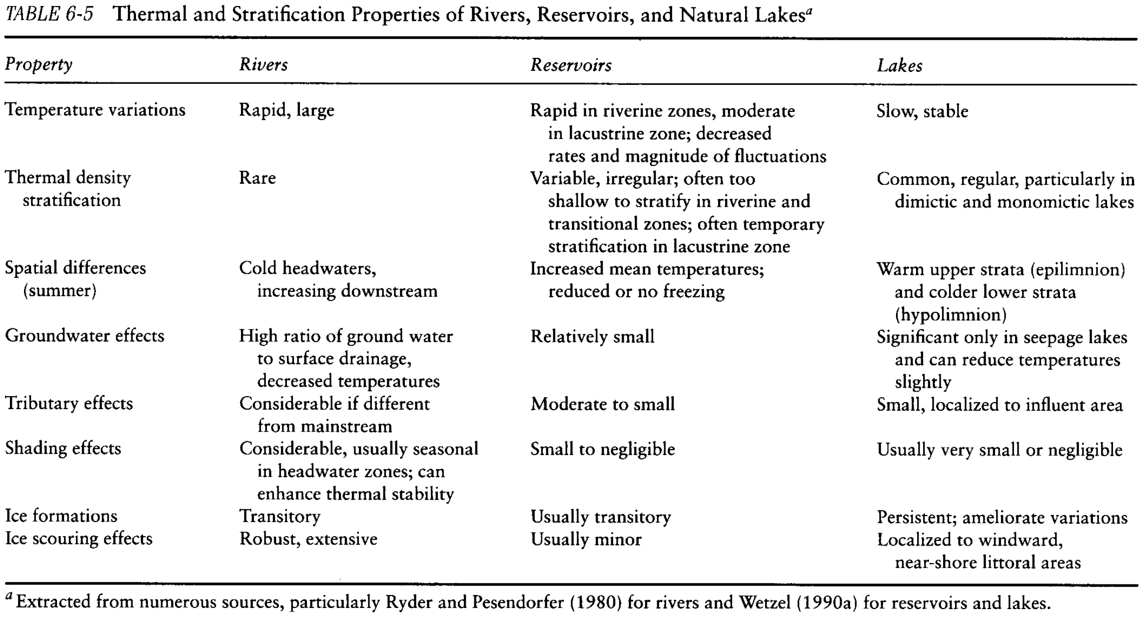


TABLE 6-5 Thermal and Stratification Properties of Rivers, Reservoirs, and Natural Lakes[a]

Property	*Rivers*	*Reservoirs*	*Lakes*
Temperature variations	Rapid, large	Rapid in riverine zones, moderate in lacustrine zone; decreased rates and magnitude of fluctuations	Slow, stable
Thermal density stratification	Rare	Variable, irregular; often too shallow to stratify in riverine and transitional zones; often temporary stratification in lacustrine zone	Common, regular, particularly in dimictic and monomictic lakes
Spatial differences (summer)	Cold headwaters, increasing downstream	Increased mean temperatures; reduced or no freezing	Warm upper strata (epilimnion) and colder lower strata (hypolimnion)
Groundwater effects	High ratio of ground water to surface drainage, decreased temperatures	Relatively small	Significant only in seepage lakes and can reduce temperatures slightly
Tributary effects	Considerable if different from mainstream	Moderate to small	Small, localized to influent area
Shading effects	Considerable, usually seasonal in headwater zones; can enhance thermal stability	Small to negligible	Usually very small or negligible
Ice formations	Transitory	Usually transitory	Persistent; ameliorate variations
Ice scouring effects	Robust, extensive	Usually minor	Localized to windward, near-shore littoral areas

[a] Extracted from numerous sources, particularly Ryder and Pesendorfer (1980) for rivers and Wetzel (1990a) for reservoirs and lakes.

E. Applications

1. Reference: Seasonal Mixing and Catastrophic Degassing in Tropical Lakes, Cameroon, West Africa. by George W. Kling, Science: 237:1022-1024. 1987.

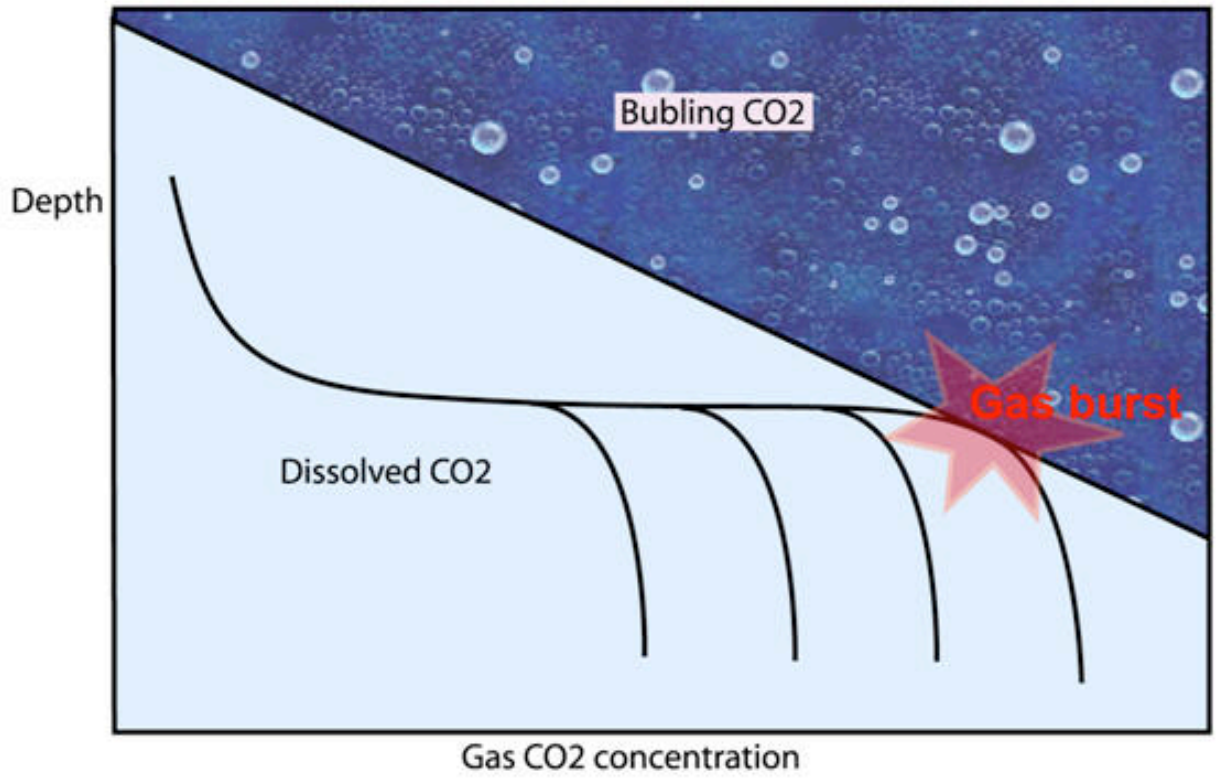
"On 21 August 1986 a massive release of CO_2 from Lake Nyos claimed 1700 lives in northwest Cameroon."

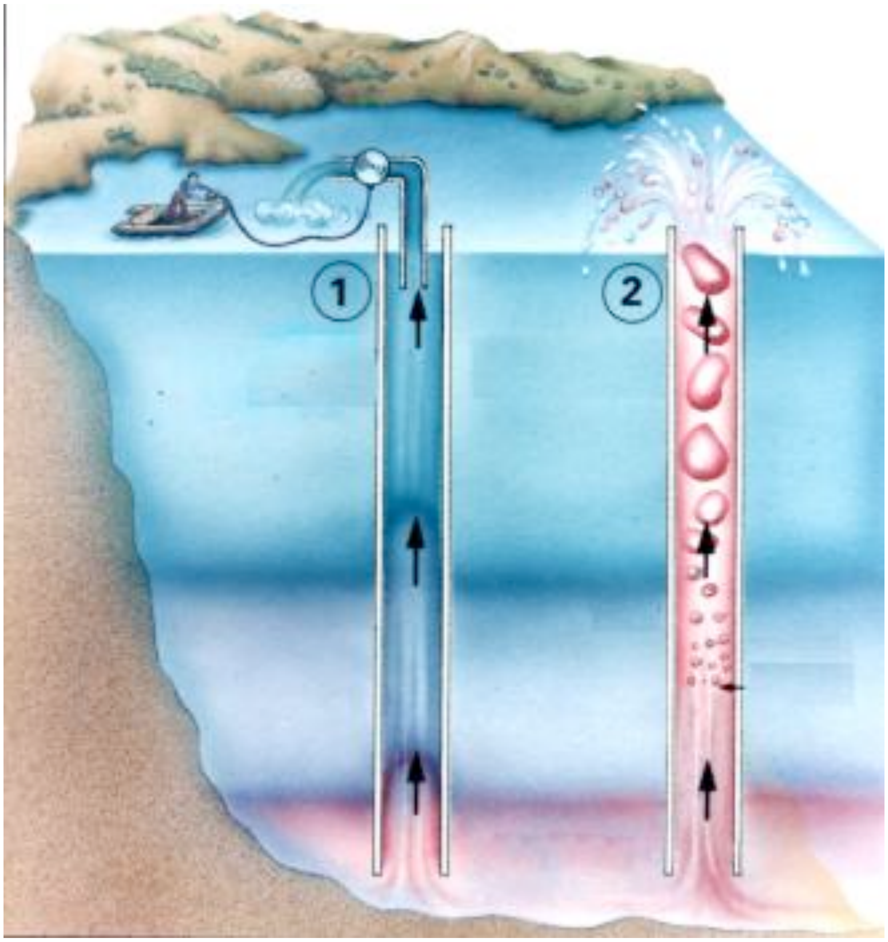
Kling comments on various hypotheses put forward to explain this event (and other similar catastrophic lake degassing events in Cameroon crater lakes). Kling's analysis indicates that the sudden degassing was probably the result of turnover in an oligomictic lake. Evidently, CO_2 and other gases can accumulate over many years in the hypolimnion. Turnover occurs irregularly every few years or decades when unusually cool weather persists for enough time to cool the epilimnion and produce turnover. (Other factors are also influential, such as advection of cool water from the watershed to the hypolimnion, cooling the hypolimnion.) Kling's analysis would predict that such catastrophic degassing could be expected during August or September in this region when unusually cool weather occurs. The timing would likely be different in other tropical areas, but similar degassing events could be expected in other oligomictic lakes with sufficient productivity to produce a significant accumulation of hypolimnetic gasses, kept in solution by hydrostatic pressure. Vertical circulation will bring "supersaturated" gases to the surface. Indeed the bubbles could accelerate the circulation.

McCord and Schadow, 1998, "Numerical simulations of degassing scenarios for CO2 -rich Lake Nyos, Cameroon" Journal of Geophysical Research 103:12,355-12,364 and an interesting web site: `http://www.biology.lsa.umich.edu/~gwk/research/nyos.html`

2. Reference: Collier et al re Crater Lake mixing. 1997 L&O **42**:299

Some unusual consequences of stratification





Self-sustained “soda fountain” in Lake Nyos

ENOUGH IS ENOUGH; So just who is now degassing Nyos and Monoun:
a French-Cameroonian or an American-Japanese-Cameroonian team?.

Overview - Experimental venture - Webcam - Degassing Monoun Nyos - Dam problems - Site Map
Visit our site about the extraction and the utilisation of methane gas in Lake Kivu

Go to "http://perso.orange.fr/mhalb/kivu/index.htm"