Limnology 2009

# Water in Motion: Waves, Seiches, Currents

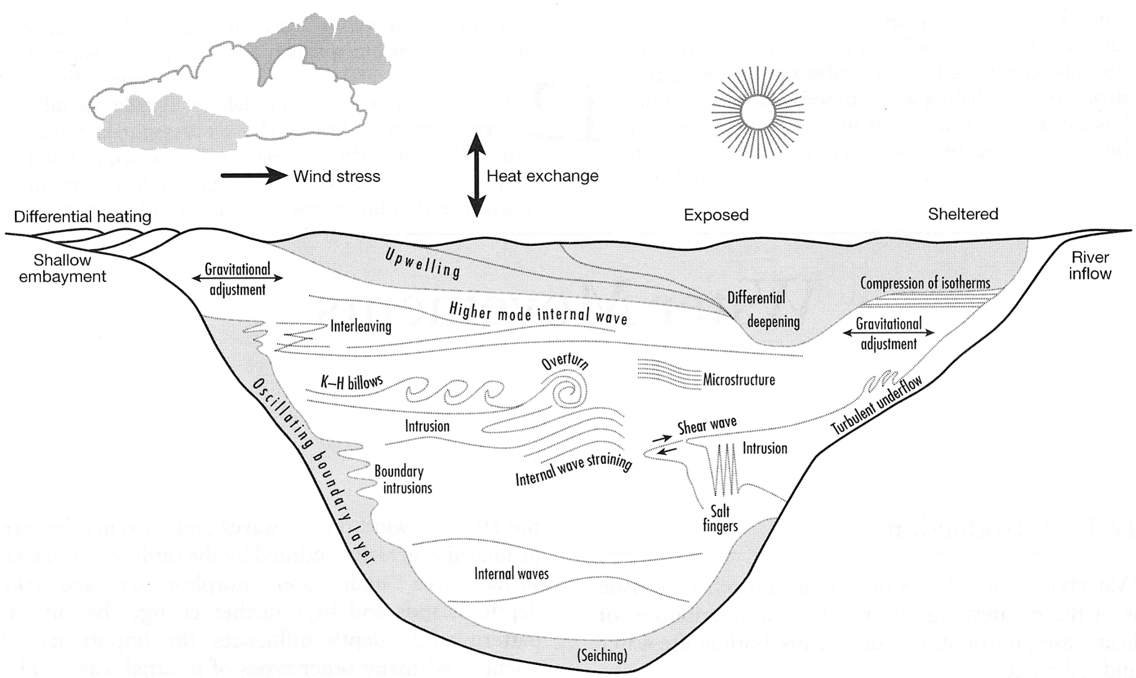



*Figure 12–1* Diagrammatic illustration of some possible mixing mechanisms, not all discussed in the text, operating in a stratified lake subject to sudden wind stress. *(After Spigel and Imberger 1987.)*

## A. Surface Waves (Figure 12.3, Kalff)

When the wind blows, there are surface waves. The size of the waves depends on the strength and duration of the wind and the fetch (length of exposed surface) of the lake. Kalff (p181) gives an empirical formula to describe wave height as a function of fetch:

$$\text{maximum height (m) (crest to trough)} = 0.332\ \sqrt{F} \text{ in m}$$

or

$$\text{maximum height (cm) (crest to trough)} = 0.105\ \sqrt{F} \text{ in cm}$$

where: F is the fetch, in kilometers, and Hmax is wave height, in meters.

Wetzel gives an example from Lake Superior where Hmax = 6.9 m with a fetch of 482 km, which agrees well with the Hmax predicted from the equation (7.3 m)

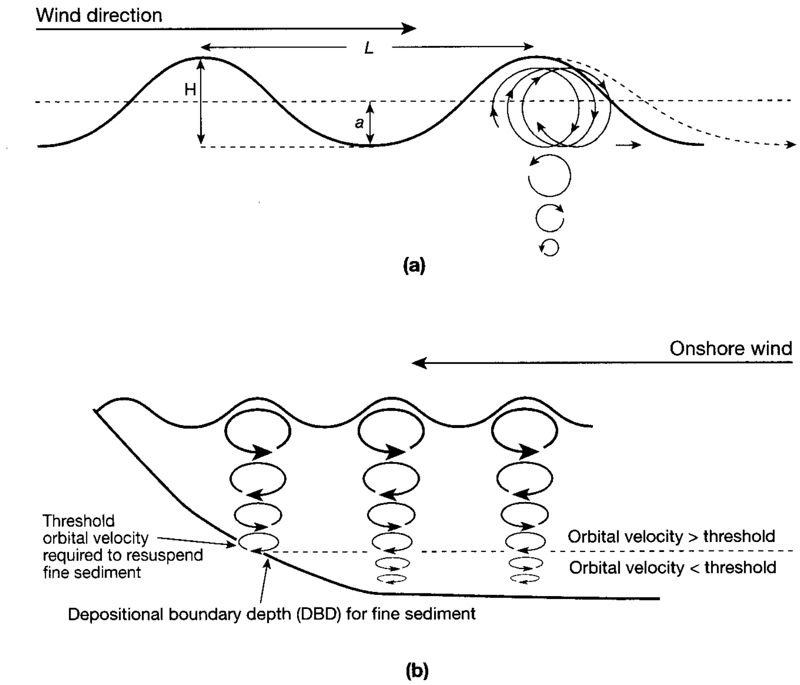



*Figure 12–3* (a) Diagram of the motion of water parcels and the various linear definitions of a rhythmic wave. The water parcels oscillate elliptically, but exhibit only minor forward motion. The more important vertical movement decreases exponentially with depth. $L$ = wavelength, $H$ = wave height, $a$ = wave amplitude ($\frac{1}{2}$h). Motion of the water parcels is not to scale. (b) Diagram of the orbital velocity of the elliptical water parcels and their ability to resuspend and transport fine sediments along shallow slopes. Coarse sediments are found above the orbital velocity threshold where slopes are steep and transport to less turbulent water possible. *(Part (b) after Rasmussen and Rowan 1997.)*

log DBD (m) = -0.107 + 0.742 log F (km) + 0.0653 slope (%)
in Lake Memphramogog (Quebec/Vermont)

Amazingly, 88 % of the variability in benthic biomass was explained by a regression that included whether the area was depositional (below the DBD) or epilimnetic (above the thermocline)

log biomass (g/m2) = 0.47 + 0.49 DBD (0,1) + 0.43 thermocline (0,1)

where DBD= 0 for nondepositional and 1 for depositional sites and thermocline = 0 for hypolimnetic and 1 for epilimentic sites (Rasmussen and Rowan, 1997)

Wavelength = ~20 wave height

Gravity waves: Short surface waves with wavelength >6.28 cm

When in deepwater are called "short" waves, that is the wavelength is much less than the water depth.

**Deep water waves travel at a speed proportional to the √wavelength.**
Specifically,

wave speed = √(g*wavelength/6.28)
= 12.5 √ (wavelength) cm/sec.
(see Hutchinson for full discussion and derivation)

When water depth is < wavelength/2 the bottom of the wave interacts with the lake bottom and a wave becomes a "shallow water" or "long" wave". In shallow water waves the water motion is transformed into a to-and-fro sloshing, which extends to the bottom of the water column.

In shallow water, speed is determined by the square root of the water depth, not the wavelength (wave speed = $\sqrt{(gz)}$; where g = accel due to gravity and z = depth)

Therefore, deep water waves slow down when they enter shallow water and there is a simultaneous reduction in wavelength. Momentum is conserved and wave height increase dramatically and the crest of the wave collapses over the front of the wave forming breakers.

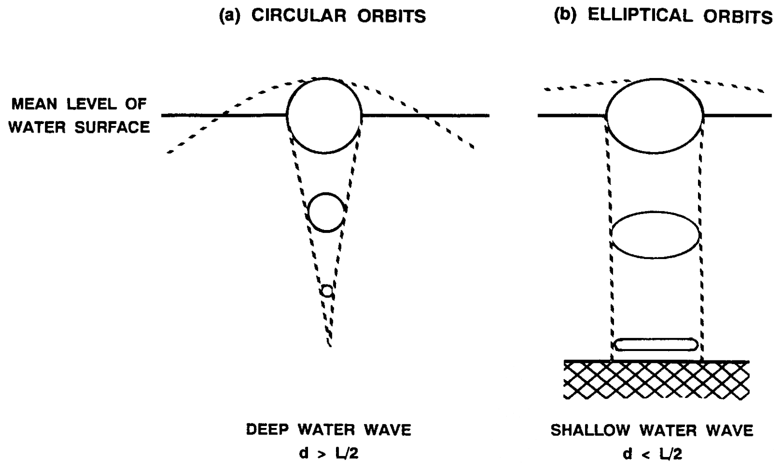



*FIGURE 7-10* Orbital motions of water beneath waves. (a) Deepwater waves where water depth ($d$) is greater than the wavelength $\lambda/2$. (b) Shallow water waves where $d < \lambda/2$. (Modified from Denny, 1988.)

**Spilling breakers** occur on beaches with a flat or gentle gradient (1:15-1:30). They break slowly as they approach the shore and wave energy is released over time and the beach.

**Plunging breakers** are associated with beaches with steep gradients. Wave energy is released suddenly as the crest curls and descends violently. Best for surfing!

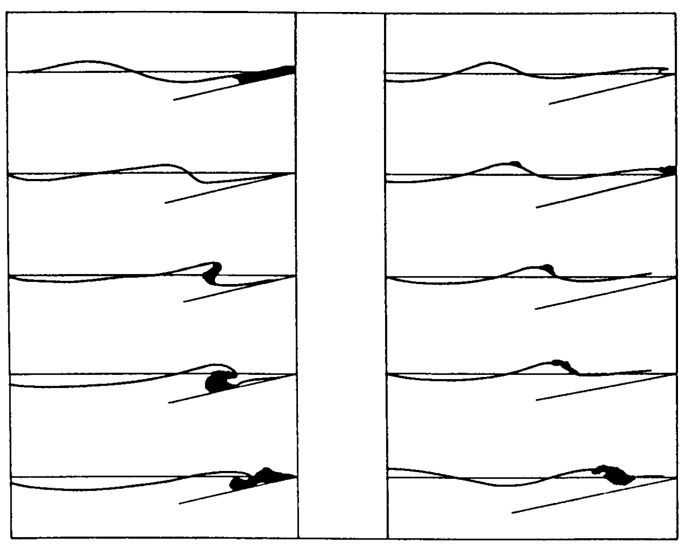


*FIGURE 7-11* The breaking of waves on beaches. *Left:* Plunging breaker. *Right:* Spilling breaker. (From Hutchinson, G. E.: *A Treatise on Limnology*. Vol. 1, New York, John Wiley & Sons, Inc., 1957; after Iversen, 1952, and Mason, 1952.)

Ripples or capillary waves: Wavelength < 6.26 cm where surface tension effects become important

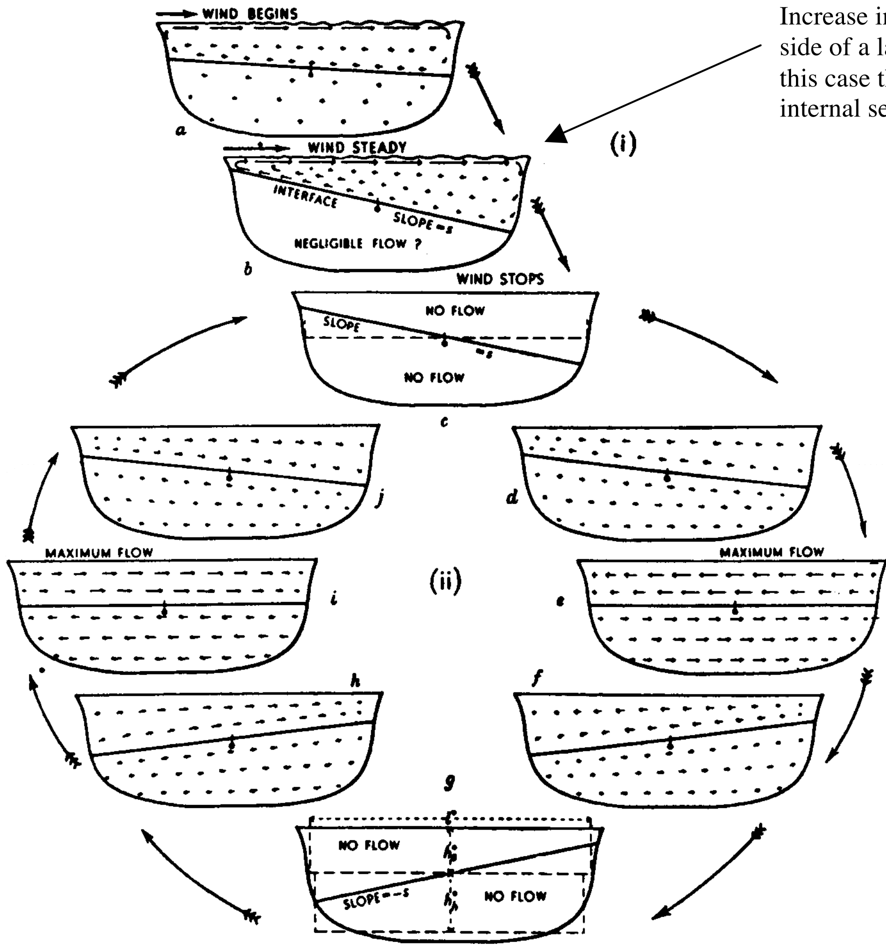
Whitecaps form at a height:wavelength ~1:10. The occurrence and density of whitecaps increases abruptly at wind velocities between 7 and 8 m/sec

Wind shear stress on the water surface is influenced by surrounding topography. In the lee of trees, hills, and rocks the surface wind shear stress will remain zero over a length of 6x the height of the sheltering feature. Fully developed wind shear stress and associated turbulence occurs at 7x the height of the feature.

Waves with very long wavelengths (e.g. Tsunamis) behave as "shallow water" waves as they traverse the ocean (wave speed = $\sqrt{(gz)}$. It follows that it is possible to predict the arrival time anywhere around a basin given the time at which such a wave is generated (by an earthquake). In water of depth 4 km, you can verify that the tsunami speed is about 200 m/s or 400 mph. Such a warning system is in place, giving the predicted time of arrival of a tsunami at various locations around the Pacific.

B. Seiche (Standing Waves) (Reference: Hutchinson, vol 1) See Kalff, p194ff

A body of water in an enclosed basin (i.e. a lake) can be set in motion back and forth over the entire basin in a periodic oscillation. (Think about inducing such an oscillation in a bathtub, which has a periodicity of a few seconds.) The expected periodicity of such a standing wave oscillation, called a **seiche**, is a function of basin dimensions. A seiche may be set in motion by a steady strong wind followed by a cessation of wind (or by an earthquake).




Increase in depth on leeward side of a lake is call "setup" in this case the "setup" is for an internal seiche

*FIGURE 7-16* Movement caused by (*i*) wind stress and (*ii*) a subsequent internal seiche in a hypothetical two-layered lake, neglecting friction. Direction and velocity of flow are approximately indicated by arrows. o = nodal section. (From Mortimer, C. H.: *Proc. Royal Soc. London, Series B 236*:355, 1952.)

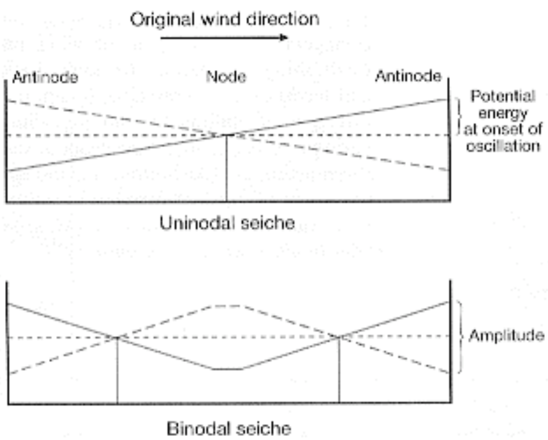



*Figure 12–15* Diagram of uninodal and binodal seiches in a rectangular lake. The movement of a uninodal seiche is akin to that of a seesaw, and the binodal seiche resembles a trampoline. The potential energy relative to the still water is converted to kinetic energy when the stress (wind) is removed. *(In part after Smith 1979.)*

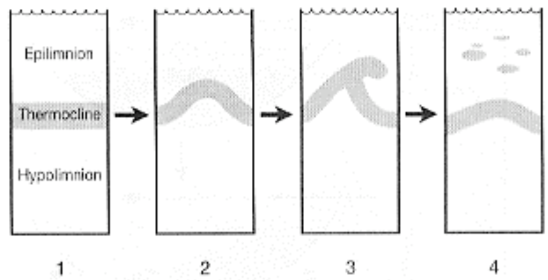



*Figure 12–16* Schematic representation of internal wave formation and breakage of internal (thermocline) waves resulting from shear instability. (1) Condition prior to wave formation (2) An internal wave forms, (3) breaks and incorporates different water layers at the crest, and finally (4) produces water of intermediate density in the epilimnion. *(After Thorpe 1971.)*

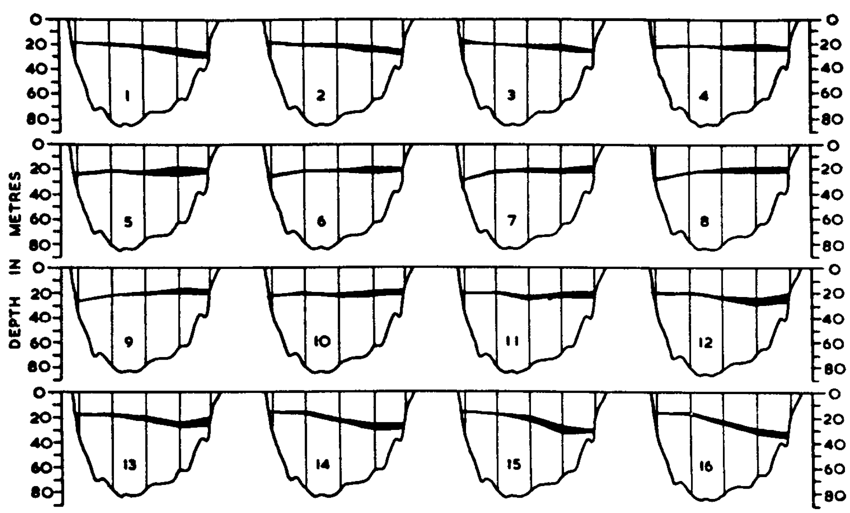



*FIGURE 7-17* Successive hourly positions (0100 to 1600 hours, 9 August 1911) of the metalimnion bounded by the 9 and 11°C isotherms on a longitudinal section of Loch Earn, Scotland. (From Mortimer, C. H.: *Schweiz. Zeitschrift f. Hydrologie* 15:94, 1953, after Wedderburn.)

The period (length of time for one complete oscillation) for a seiche is given by:

$T_n = 1/n\ [2L/\sqrt{(g z_{mean})}]$,

where $n = 1, 2, 3, \ldots$ (an integer, for the number of nodes)

$L$ = length of the lake

$g$ = gravity

$z_{mean}$ = lake depth

$T$ = period of oscillation (a measure of time).

For the primary seiche (just one node, in the middle of the lake), n = 1. For more complicated seiches, n = 2, 3, etc. It can be seen that basin dimensions determine the period of a seiche. The period of a seiche increases with lake length, and decrease as depth increases.

An interesting example is Lake Erie, with a length of approximately 400 kilometers and a mean depth of about 21 meters. The primary seiche for the lake is about 13 hours. Because the lake is oriented from SW to NE, and the period of the seiche resonates with the diurnal weather pattern, very large seiches are sometimes generated. Surface deviations as great as 4 or 5 meters have been observed. Such a deviation is enough to delay shipping across the shallow western basin of the lake (mean depth about 12 meters).

Generally, however, the amplitude of surface seiches are small in comparison to internal seiches.

An aside: Tidal movement in lakes analogous to tides in oceans have been poorly investigated in lakes, but it is certain that true tidal amplitudes, even in large lakes, is small. Maximum tide in Lake Superior is 20 mm. All measured lake tides are half or less than half of the theoretical value. The elastic yielding of the Earth to the tide-generating forces presumably accounts for the difference.

Period for internal seiches

Internal seiches, along the thermocline, also occur and are generally more important to the economy of a lake than are surface seiches. Because the density of the water in the hypolimnion is only slightly greater than the density of the water in the epilimnion (in contrast to the difference between water and air for the surface seiche), the density and dimensions of the epilimnion and hypolimnion must be taken into account. The predicted periodicity of the primary internal seiche is given by:

$$Ti = (2L)/\sqrt{[(g(\rho_h - \rho_e)/(\rho_h/Z_h + \rho_e/Z_e)]}$$

where: L = length of the lake
g = gravity
$\rho_h$ = density of the hypolimnion
$\rho_e$ = density of the epilimnion
$Z_h$ = depth (thickness) of the hypolimnion
$Z_e$ = thickness of the epilimnion.

Because of the slight difference in density between the two layers, the period of an internal seiche is much slower than the surface seiche. The amplitude of an internal seiche can also be much greater. As a consequence, internal seiches in some large lakes can roll back and forth for an extended time, giving seemingly anomalous temperature vs. depth data. Reportedly, such internal seiches sometimes reach the surface in Lake Baikal, much to the consternation of summertime swimmers.

The effect of internal seiches on the surface sediment can be important. Kalff describes the creation of a "**nephaloid layer**" of resuspended sediment stirred up by passing internal waves (p199).

C. Currents

1. Set-up

Wind blowing over an enclosed basin (i.e. a lake) produces a displacement of the surface elevation. The increased elevation at the leeward end of a lake is given (approximately) by:

$$S_h = [(3.2 \times 10^{-6})/(g\ z_m)][W^2\ l]$$

where: $S_h$ = set-up (surface level increase)
$l$ = length of the lake
$z_m$ = mean depth
$g$ = gravity
$W$ = wind velocity

Notice that the setup is proportional to the square of the wind velocity (in a sailboat it is very apparent that the force of the wind is proportional to the square of the wind velocity!). Not surprisingly, the setup is also proportional to fetch.

In a two layered system (e.g. stratified lake) a setup of the surface of the lake will produce a depression in the epi:hypo interface. In both unstratified and stratified systems, the wind also induces a surface current with a return flow at depth (near bottom if unstratified, but along the top of the thermocline if the lake is stratified).

2. Langmuir circulation (p192-193)

Above a wind velocity of 2 or 3 meters/sec, surface streaks parallel to the wind direction appear. These streaks appear in the areas of convergence of convectional helices that are generated by the wind. These helices, which alternate between parallel clockwise and counterclockwise helices proceed in the direction of the wind in the upper few meters of the lake. These helical cells are known as “Langmuir circulation”.

The vertical velocities in these circulations can reach at least 1 or 2 cm/sec, sufficient to affect the distribution of swimming planktonic animals. Vertical velocities in Langmuir circulations are approximately 5 or 10% of the horizontal current velocity induced by the wind. The mechanism responsible for langmuir circulation are poorly understood, however, theoretical considerations suggest that they form as a result of complicated interaction between wind and waves.

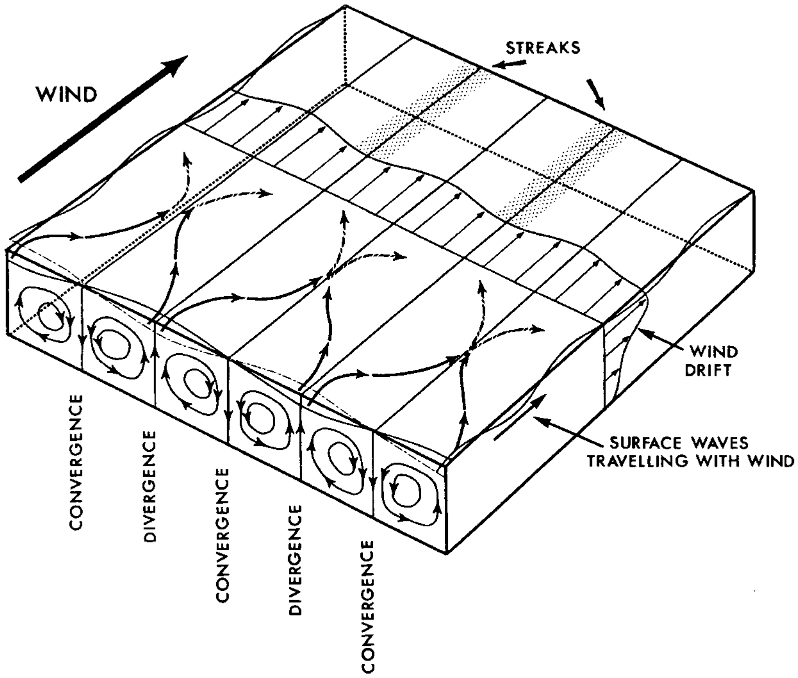



*FIGURE 7-13* Diagrammatic representation of the helical flow of Langmuir circulations in surface waters with streaks of aggregated organic matter occurring at lines of divergence. (Based on the experimental work of Faller, 1978, and others.)

This link provides an animation of langmuir circulation:
http://faculty.gvsu.edu/videticp/langmuir.htm

2. Wind currents and density currents (Kalff, p188ff)

Wind drives surface currents. Because of the Coriolis force (more below under "Geostrophic considerations") currents are not parallel to the wind, but deviate somewhat to the right in the Northern Hemisphere (to the left in the southern). Examples are presented in figures 12-10 and 12-12 in Kalff. A consequence of the combined effect of wind and the Coriolis Effect is that the long term surface pattern in large northern hemisphere lakes is a counter-clockwise circulation pattern.

A second physical phenomenon that gives rise to currents is density differences. Surface cooling over night, especially in bays creates denser water that may dive down into the main lake as an intrusion current. Conversely, shallow bays warm more quickly during the day and create warm surface currents that flow out into the main lake. Movement of shallow water can impact some lake management activities. For example, a herbicide applied to aquatic plants in shallow water could move offshore if water cools sufficiently to generate density currents. See Horsch and Stefan(1988) L&O 33:1068-1083 for theoretical discussion and James and Barko (1991) L&O 36: 949-960 for practical application and demonstration.

Inflowing rivers and streams can also create density underflows. When water flows into a lake or reservoir the incoming water will flow into a density layer in the lake that is most similar to its own density, which is determined by temperature, dissolved material, and suspensoids. Depending upon the density differences inflowing water can iner the lake as **overflow**, **underlow**, or **interflow**.

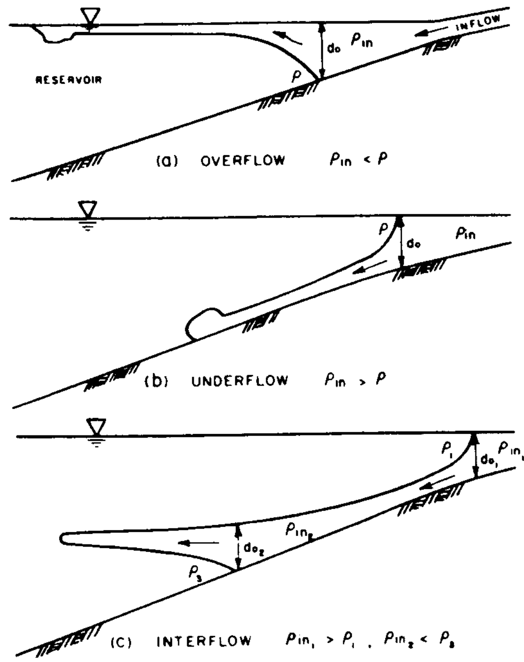



*FIGURE 7-25* Types of inflow into lakes and reservoirs. (From Wunderlich, W. O.: The Dynamics of Density-Stratified Reservoirs. *In* Hall, G. E. (ed.), *Reservoir Fisheries and Limnology*, Washington, D.C., American Fisheries Society, 1971.)

3. Kelvin and Poincare wave-generated currents

"Coastal jets"are generated by Kelvin waves and hypolimnetic currents can be generated by Poincare wavea.

Kelvin waves are influenced by interaction with the lakebed and are formed by basin-scale internal gravity waves. Kelvin wave amplitude decreases exponentially away from shore. Poincare waves occur in open water of large lakes and travel without interference of shore basin boundaries. Poincare waves generate Kelvin waves when they encounter shorelines.

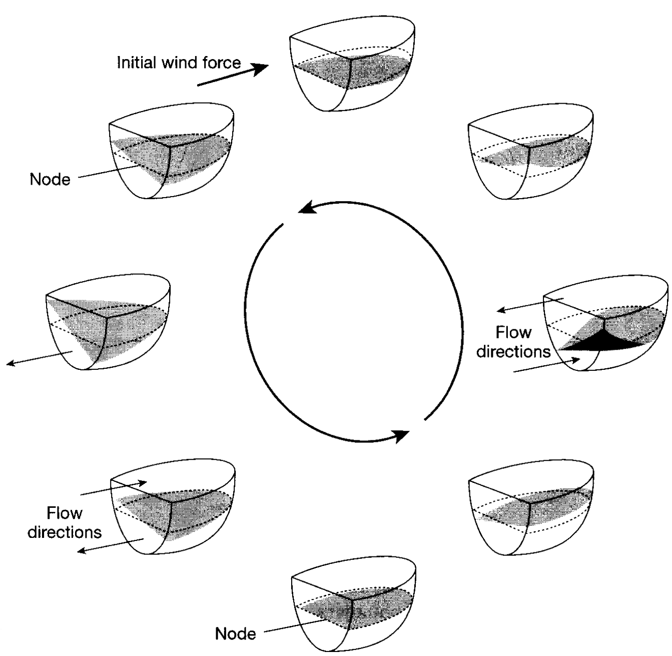



*Figure 12–19* One cycle (exaggerated) of a Kelvin wave as reflected in the nearshore tilting of the thermocline, resulting in large nearshore currents. The shaded area represents the oscillating lake surface, and the equilibrium position is indicated by a dashed line. *(Modified after Mortimer 1974.)*

4. Geostrophic considerations

In large lakes, and especially in the ocean, geostrophic forces are of significance. As a consequence of the inertial influence of the earth's rotation (the Coriolis force), there are characteristic patterns of motion, distribution of mass and deviations of surface elevation of a large mass of water in motion. The effect of the Coriolis force is important in the pattern of circulation in the world's oceans and such processes as wind driven coastal upwelling. Because of the deviation of the Coriolis force, the surface current deviates to the right (Northern Hemisphere). As the surface current drags lower layers along, they in turn deviate further to the right, until at the "depth of frictional resistance", the wind driven current is actually flowing opposite the wind that is driving it. The entire vertical structure is known as the **Ekman spiral** (see Kalff, p 188 and figure 12-10, p190). As a consequence, wind driven transport is at right angles to the wind (e.g. the surface upwelling along the Oregon coast is driven by the strong northwesterly winds of summer).

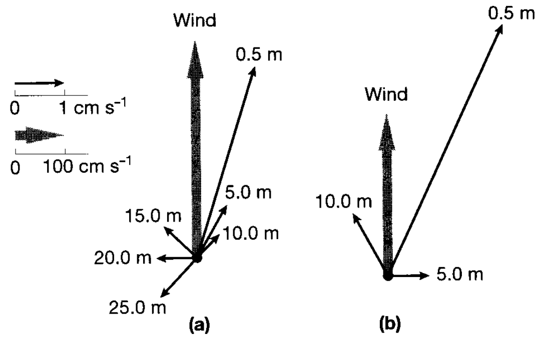



*Figure 12–10* Vertical distribution of currents for monomictic Lake Windermere (GB) (south basin, LA = 6.7 km$^2$, $\bar{z}$ = 18 m) on (a) January 29, 1974 (unstratified) and (b) July 27, 1973 (thermocline at 13 m). *(After George 1981.)*

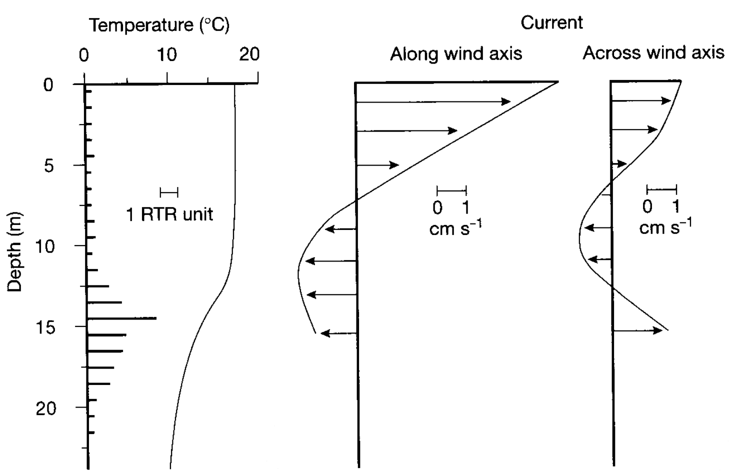



*Figure 12–11* Deduced current profile in Lake Windermere, GB (south basin) during a period of steady wind and stable stratification on August 23, 1994. The temperature profile present is also presented as the relative thermal resistance (RTR) to mixing (see also Fig. 11–8). *(After George 1981).*

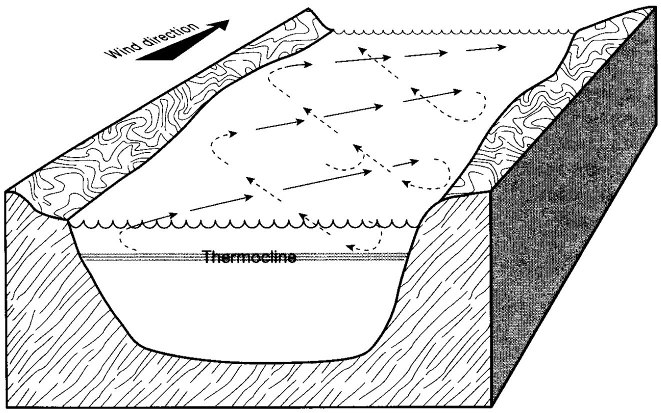



*Figure 12–12* A conceptual representation of the circulation in stratified Lake Windermere, GB (south basin). The estimated pattern is one resembling a distorted conveyor belt with surface currents deflected to the right of the wind due to the Coriolis effect and countercurrents just above the thermocline moving at about 90° to the left of the wind direction. *(After George 1981.)*

[Note that the water exiting a sink drain is ***not*** significantly influenced by the Coriolis force, which is of significance only for very large masses of water. The water exiting a drain is described as cyclostrophic flow. The whirlpools seen exiting a drain result from a balance between surface elevation, centrifugal force, and the shape and surface of the container.]

5. Velocities, time scales, and biotic responses.

Kalff (p199) points out that biota must adjust to the various physical forces, including currents and mixing.

*Table 12–2* **Expected range of current speeds associated with different types of motions in moderate sized lakes such as Lake Windermere, GB. Higher speeds are encountered during exceptional storms and in larger lakes.**

| Type of Motion | Source of Estimate | Current Speeds (cm $s^{-1}$) |
|---|---|---|
| Surface seiche movements | Calculated from water level records. | 0.1–2.0 |
| Internal seiche movements | Estimated from published observations, but up to 30 cm $s^{-1}$ in great lakes. | 0.5–3.0 |
| Inshore–offshore density currents | Calculated from hydrographic temperature distribution data and dye release. | 1.0–15.0 |
| Direct wind stress on water surface | Estimated from measured current speed and wind speed. | 2.0–15.0 |

*Source:* George 1981, and Nepf and Oldham 1997.

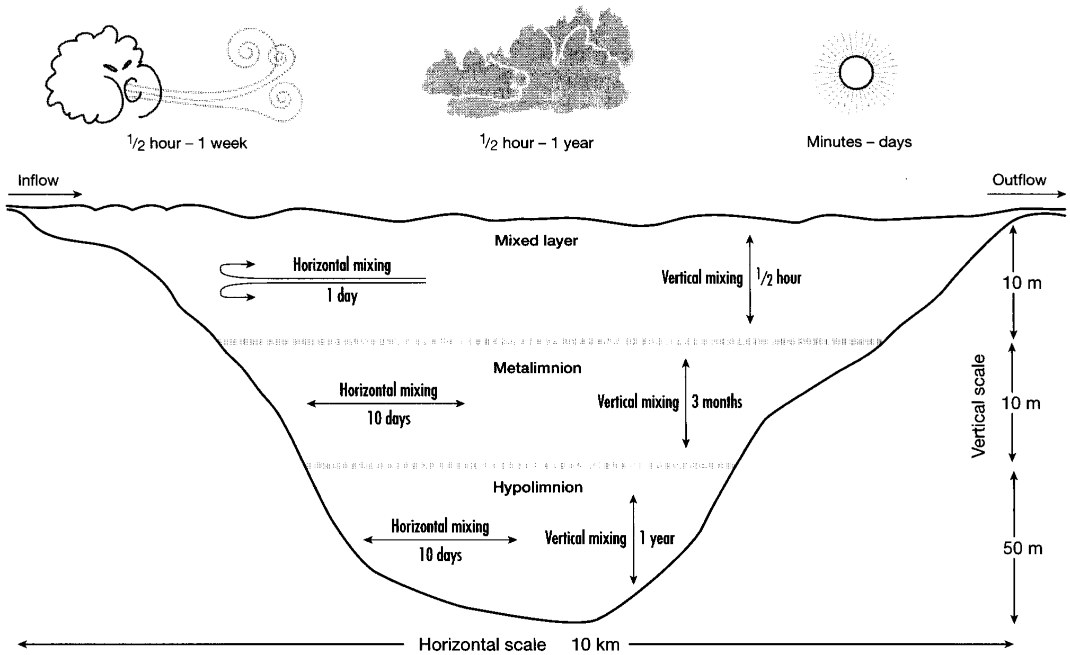



*Figure 12–20* Estimates of mixing times in a medium-sized holomictic lake with a thick hypolimnion. *(Modified after Imberger 1985.)*