

STRATIFICATION AND MIXING IN LAKES AND RESERVOIRS

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1 Introduction

Primary concern with regards to lakes and reservoirs, from the point of view of environmental engineering, has to do with water quality. Water quality in such water bodies depends on the presence of dissolved and suspended species and associated reactions, governed by water chemistry and biological processes. Such species can be nutrients, dissolved oxygen, phytoplankton, suspended solids and toxic substances, to name just a few. Physics plays an important role in this context, determining the availability of the compounds for the chemical and biological reactions, as well as the water temperature distribution within the water body, which modulates the biological processes in particular. Physics drives mass and heat transport, through advection and diffusion, as well as mass and heat transfer processes at the free surface and at the bottom sediment-water interface. The thermo-hydrodynamics of lakes and reservoirs can thus modulate, to a great extent, their water quality, which results to be in constant change in response to physical forcings, such as heat exchange with the atmosphere, wind, inflow and outflow discharges.

The mean *residence time* in a water body is defined as the ratio between the water volume and the mean inflow discharge. In large lakes, the mean residence time can be equivalent to several years, while in small reservoirs its value drops to the order of weeks. If the residence time is small, water quality depends mainly on that of the inflows; at large residence times, it is determined by internal process occurring within the lake, that is, by chemical and biological reactions modulated by the thermo-hydrodynamics of the water body.

Even in the case of rather small residence times, the physical behavior of lakes and reservoirs is completely different to that in rivers and streams. In these surface flows, gravity is the main driving force while friction with the bed is the main resistance mechanism. This results in large velocity gradients, turbulence, and high mixing capacity. In lakes and reservoirs, on the contrary, water motion is very slow. Driving forces are given by heat exchange with the atmosphere, wind stresses on the free surface, momentum exchange with inflows, currents induced by outflows, buoyancy and Coriolis effects.

The thermo-hydrodynamics of lakes and reservoirs is usually determined by very small density differences associated to temperature gradients within the water body, to concentration gradients of dissolved and suspended species (e.g., salinity, suspended sediment), or both. Phenomena that are not observed or that can be neglected in rivers are dominant in the case of lakes and reservoirs: stable temperature stratification induced by solar radiation which precludes vertical mixing; natural convection caused by an unstable density stratification; circulation, seiches, internal waves and

mixing induced by wind; circulation and internal waves induced by the earth rotation in sufficiently large water bodies; density and turbidity currents generated by inflows; circulation, currents and mixing induced by selective withdrawal.

Differences in residence time can also explain different behavior between reservoirs and lakes, being surface elevation variations, caused by changes in the outflow discharges in response to reservoir management decisions, one important factor affecting the hydrodynamics and water quality in reservoirs.

The interactions between the water column and the sediment-bed are also very different between rivers and water bodies such as lakes and reservoirs. While advection and turbulence dominate mass transfer processes between the bed and the water column in the former case, they have a much less important effect in the latter, due to the much reduced flow velocity fields. Instead, slow geo-chemical processes leading to the liberation of chemical compounds from the bed and their transformation in the water column, dominate the exchange. These processes, nonetheless, are also largely modulated by physical processes, such as the slow deposition of fine organic and inorganic materials on the bed and the dynamics of the benthic boundary layer. Bioturbation by invertebrates and fish, and sediment resuspension induced by wind, currents and internal-wave breaking, are other mechanisms affecting mass exchange in the sediment-water interface and water quality in lakes and reservoirs.

The term *thermo-hydrodynamics* used in previous paragraphs, loosely refers to the physical processes associated with heat, energy, mass and momentum transport in a water body. It concerns three main aspects (see Fig. 1): temperature distribution, turbulence, and currents. These three aspects are interrelated and interdependent. Any one of them is affected and modulated by the other two. While the temperature structure in a water body is mainly driven by solar radiation (or heat exchange with the atmosphere), turbulence and currents are mainly driven by wind, inflows and outflows, buoyancy, and, eventually, Coriolis force. Solar energy input at the free surface tends to build up a potential energy gradient, as warmer and lighter surface waters typically lay on top of colder and heavier ones, defining a stable stratification of the water column. This mechanic stability tends to arrest motion in the water body, precluding any vertical exchange between surface and deep waters. Kinetic energy inputs from the wind, inflows and outflows, tend to disturb this stability by generating currents, turbulence and large scale basin seiches. The latter, in particular, degenerate into smaller scale internal waves which, through instability mechanisms, ultimately also produce turbulence. Ambient turbulence eventually produces mixing, which can be understood as a net upwards buoyancy flux, raising the overall center of gravity of the water body and thus modifying its potential energy (and temperature) structure. Thermo-hydrodynamics, in this context, can be interpreted as the interplay between the potential energy set up by solar radiation and the turbulent kinetic energy input from the wind, inflows and outflows.

Based on the arguments above, it seems obvious that environmental assessment of lakes and reservoirs requires not only the traditional limnology approach, based on water chemistry, microbiology and ecology, but a physical-limnology approach as well, as the thermo-hydrodynamics of water bodies is one important agent that modulates chemical and biological processes in them. An integrated approach requires crossing discipline barriers, such as those posed by specific terminology and basic knowledge of the different processes involved. Nonetheless, the pay-off, in terms of gaining more thorough analysis capabilities, makes the effort worthwhile.

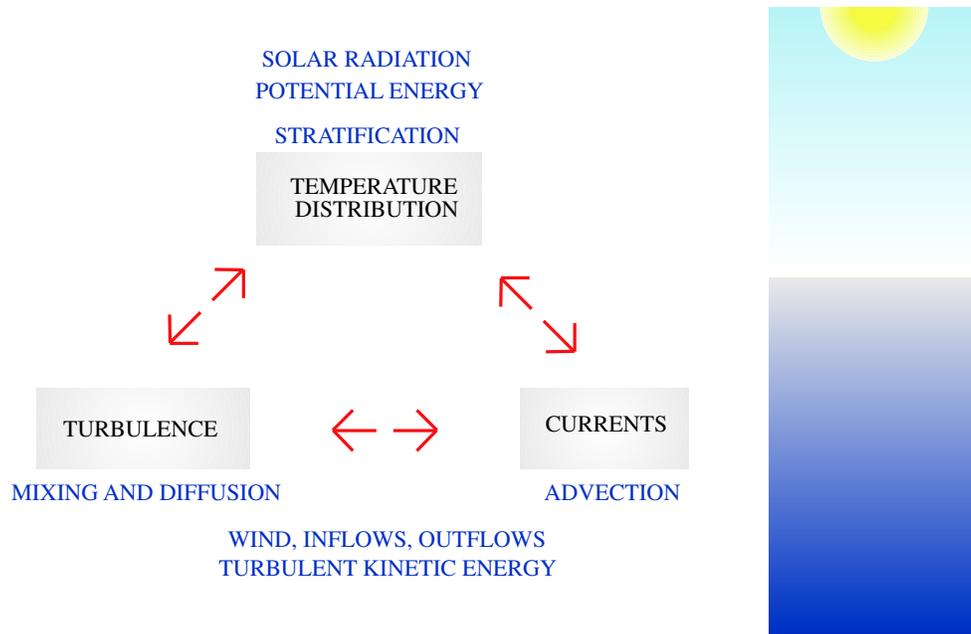


Figura 1: Thermo-hydrodynamics of lakes and reservoirs.

2 Stratification changes in lakes and reservoirs

Solar radiation acting on the free surface of lakes and reservoirs warms up the surface waters, inducing a positive vertical gradient of temperature due to heat diffusion towards deeper waters. The temperature gradient in the water column has a density gradient associated to it, according to the thermodynamic relationship between temperature and density in water (see Fig. 2). Distilled Water at 1 atmosphere has a maximum possible density of 1 gr/cm^3 occurring at a temperature of 4° C , and this property decreases slightly (but significantly in terms of buoyancy effects) at higher and lower temperatures. For temperatures higher than 4° C , the positive temperature gradient corresponds to a negative density gradient in the water column, with lighter water located over heavier water. This kind of stratification is called *stable* as it does not induce baroclinic motion (or natural convection) within the water body.

Density gradients are able to reduce the turbulent diffusivity (or mixing coefficient) of the ambient waters, and this effect is enhanced as the density gradients increase. In terms of energy balance considerations, this phenomenon can be simply interpreted as follows. As density gradients increase, also does the turbulent kinetic energy required to mix fluid against those gradients, since the potential energy gain associated to such mixing increases; for constant available turbulent kinetic energy, the mixing capacity of the flow is thus reduced. This effect induces a positive feedback mechanism, as the heat that accumulates in the surface waters increases their temperature and the associated density gradients, reducing the local diffusivity even more. Wind stirring of the surface waters tends to amplify the effect, increasing mixing and heat transport within this region and also the density gradients at its base. The result is the formation of a sharp density and

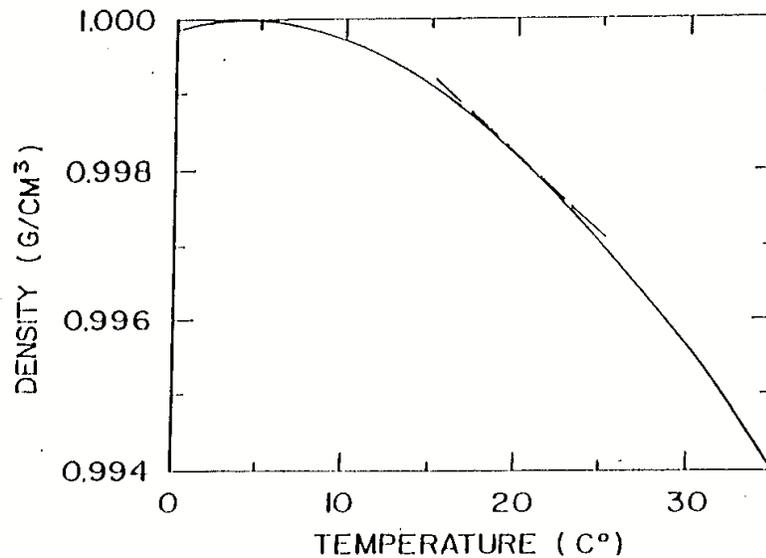


Fig. II-3. Water temperature/density relation (from Table 93 of Dorsey [1940]).

Figura 2: Density as a function of temperature for distilled water at 1 atmosphere.

temperature interface that tends to isolate the surface warmer and lighter layer from the colder and heavier bottom region of the water column. The temperature and density interface, where the gradients of these variables are maximum (in absolute value) is called *thermocline*. The surface layer is called *epilimnion* and the bottom layer *hypolimnion*.

The epilimnion is usually well mixed due to wind induced turbulence. On the contrary, the hypolimnion remains rather quiescent, as the thermocline inhibits momentum exchange between surface and bottom layers. Strong wind events, sustained in time, increase the turbulent kinetic energy level of the epilimnion and the mixing capacity across the thermocline. Eventually, high intensity levels of local turbulence can erode and deepen the thermocline, causing mixing of bottom and surface waters. This process decreases (increases) the temperature (density) of the surface waters and increases of the overall potential energy of the water body. This occurs at the expense of the turbulent kinetic energy transferred from the wind.

At a seasonal level, changes in the stratification of lakes and reservoirs are driven by seasonal changes in atmospheric conditions and meteorological variables. Seasonal changes in solar radiation and air temperature alone can completely change the heat exchange balance between the water body and the atmosphere. For example, a lake that remains stratified during the summer can lose the stratification during the fall due to the reduction of the temperature in the epilimnion, as heat is released from the surface waters to the atmosphere. A phenomenon known as *turnover* of the lake can occur, if the epilimnion reduces its temperature with respect to that in the hypolimnion, in response to rapid cooling of the air temperature, generating an unstable stratification, natural convection and rapid mixing of the water column.

Another turnover event can occur in spring, if during winter water temperatures remain below about 4° C. In this case, a stable winter stratification can occur, with a layer of colder and lighter water on top of warmer and heavier waters. The melting of the ice cover and warming up of the surface layer can trigger the inversion of the density stratification and the subsequent strong mixing of the water column.

3 Classification of lakes in terms of seasonal stratification regime

Obviously, the seasonal stratification cycles depend on the local climatic conditions and thus are related to parameters such as latitude and elevation of the lake. Because of this, not all lakes get stratified and not all of them present two turnover events in a year period. Lakes are called *dimictic* when they have two turnover events a year and *monomictic* when they have just one turnover event a year. Among the latter are *cold monomictic* lakes, with temperatures that never go far over 4° C, and *warm monomictic* lakes, with temperatures that remain always above 4° C. Fig. 3 shows a classification chart for lakes in terms of their latitude and elevation.

A brief definition of the different kinds of lakes recognized in the classification of Fig. 3 is given below.

- Amictic lakes: Never mix or undergo a turnover because they have a permanent ice cover.
- Dimictic lakes: Have two turnover events a year, in spring and fall, and maintain a stable stratification in summer and winter.
- Cold monomictic lakes: Water temperatures never exceed 4 ° C, and have only one turnover event in late spring at or below 4° C.
- Warm monomictic lakes: Have only one turnover event in late fall at or above 4° C. Never form an ice cover.
- Oligomictic lakes: Are thermally stratified much of the year with rare and irregular events of circulation.
- Polymictic lakes: Present frequent or continuous periods of mixing per year as a result of high wind and little seasonal change in air temperature.
- Meromictic lakes: Remain perennially stratified due to steep salinity gradients.

4 Diurnal behavior of the stratification

Even though the concepts epilimnion, hypolimnion and thermocline are useful for description, they should be considered more carefully if the detailed physical behavior of these regions is to be understood. For instance, the surface layer, or epilimnion, usually is not as well mixed as it is generally considered, nor it is in a state of uniform and constant turbulence, as this layer responds to diurnal changes in surface fluxes of heat and momentum. The thermocline, on the other hand, is not a plane but a region of finite depth that contains the major temperature changes between

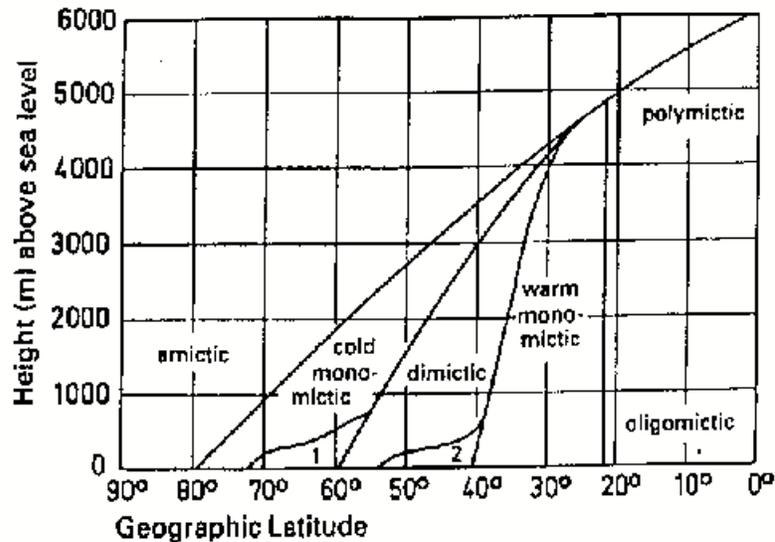


Figura 3: Lake classification as a function of latitude and altitude (from Wetzel, 2001).

surface and bottom waters. A better term for this region is *metalimnion*. It is usually made up of several temperature steps. Because of this, it is unrealistic to define the thermocline at the depth at which the temperature gradient is maximum. Furthermore, temperature gradients associated with measured temperature profiles in lakes and reservoirs, strongly depend on the resolution of the instrument used to make the measurements. High resolution temperature measurements have shown the existence of microstructures within the surface layer, with values of the associated gradients that are as high as those observed in the metalimnion.

Imberger and Patterson (1989) propose a more realistic temperature structure model, composed of a *diurnal surface layer*, a *parent thermocline*, a metalimnion and a hypolimnion. The parent thermocline is the temperature step caused by the most severe mixing or deepening event in the immediate past. The metalimnion is the region between the parent thermocline and a depth where the temperature profile reaches a certain percentage of the coldest temperature in the hypolimnion.

Usually, in the early morning the surface layer appear well mixed, mainly because of penetrative convection associated to heat losses from the surface waters during the night. A parent thermocline is defined at the base of this well mixed layer (see Fig. 4). As the air temperature rises during the morning, so does the water temperature near the free surface. A diurnal shallow thermocline may appear, only a few meters deep or less, due to diffusion of heat within the surface layer. If wind blows over the free surface during the day, the turbulent kinetic energy transferred to the surface layer will enhance the transport of heat, decreasing the temperature near the free surface and deepening the diurnal thermocline. If the new thermocline reaches deeper waters than the parent thermocline, then it becomes the new parent thermocline.

Generally, during spring lakes stratify and the location of the parent thermocline becomes shallower in time. During the fall, as the lakes get cooler, the parent thermocline becomes progressively

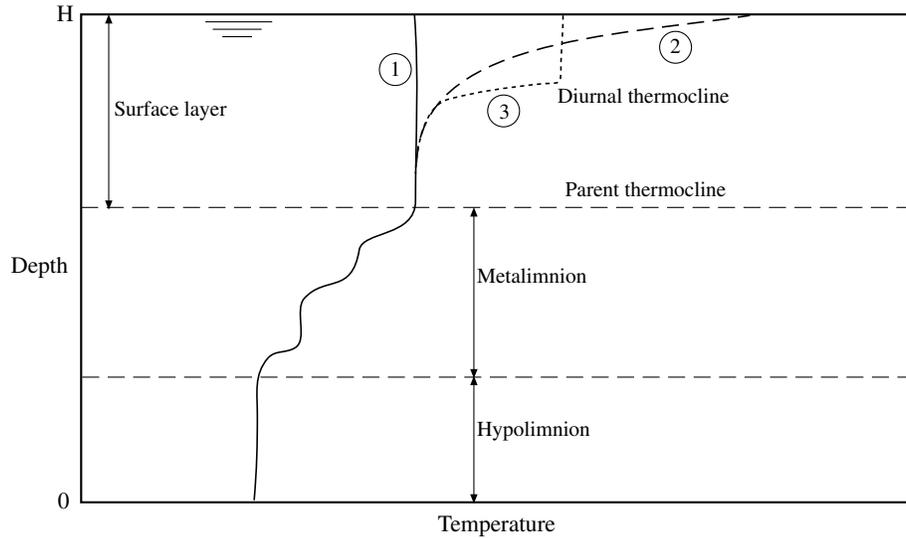


Figura 4: Example of diurnal behavior of the stratification in a water body. Line (1) represents the temperature profile in the early morning. Nocturnal mixing due to penetrative convection has created a parent thermocline. Line (2) represents the temperature profile about midday. Heat coming from solar radiation is diffused within the surface layer in absence of wind, creating a diurnal thermocline that deepens in time. Line (3) represents the response of the surface layer to momentum transfer from the wind, when it starts blowing. Heat transport has increased due to turbulence and the diurnal thermocline has become sharper. The rate of deepening of the latter has also increased. (Adapted from Imberger and Patterson, 1989).

deeper and the temperature difference between surface and bottom layers decreases.

5 References

- Imberger and Patterson (1989) Physical Limnology.
- Wetzel, R. G. (2001) Limnology. Lake and River Ecosystems. Academic Press.