CHAPTER 6

LAKES

1. INTRODUCTION

1.1 How do you define a lake? Perhaps the best way of defining a ***lake*** is that it's *a body of water surrounded by land with no connection to the oceans*. Here are some comments on this definition:

- It excludes all the oceans.
- There's a conventional size restriction that excludes little puddles and small ponds.
- Some bodies of water that are called seas are thus lakes; examples are the Caspian Sea and the Dead Sea.
- The salinity of the lake water is not part of the definition. But in this chapter I'll deal only with fresh-water lakes.

2. THE ORIGIN OF LAKES

2.1.1 Although the origin of lakes is not really a part of this course, here are some comments that might be of interest to you. Lakes originate in a variety of ways:

- subsidence of land below the groundwater table (Figure 6-1A).
- isolation of a part of the ocean, either by local constructive processes of sediment deposition or by crustal uplift (Figure 6-1B).
- glacial erosion and deposition on the continents (Figure 6-1C).
- miscellaneous ways: volcanoes, damming by landslides, or meteorite impacts.

2.2 Here are some comments on the foregoing list:

- The first two items involve earth movements, and they're very slow.
- Some large lakes caused by isolation of an arm of the ocean are called "seas", although they really are lakes. If you could somehow close the Mediterranean Sea at the Strait of Gibraltar, it would be a lake—and in recent geologic times it's widely believed that it once *was* closed to form a gigantic lake, which at one point might actually have evaporated to dryness!

- Lakes of glacial origin are very important in the northern part of the North American continent nowadays, because of the extensive glaciation in recent geological times.

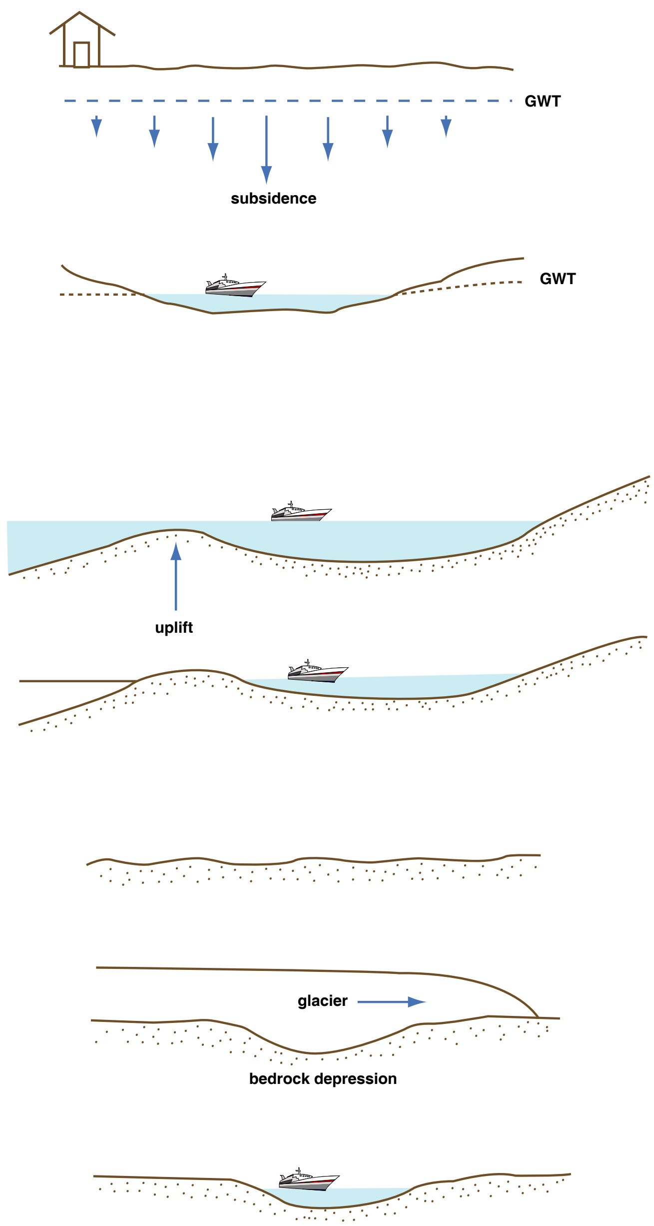

Figure by MIT OCW.
Figure 6-1. Ways lakes are formed.

2.3 The study of lakes is called ***limnology***. Limnology has several important aspects:

- water balance
- temperature structure
- water circulation
- chemistry
- biology
- bottom sediments

2.4 Study of the water circulation, especially of large lakes, is based on the same principles as in the oceans, and tends to be practiced by the same set of specialists as in oceanography. The bottom sediments are studied by much the same techniques as the bottom sediment of the oceans. In this chapter I'll consider only the first two items on the above list.

3. THE GEOMETRY OF LAKES

3.1 You can measure various geometrical things about lakes:

- area of water surface
- water volume
- maximum depth
- shoreline length
- lake length: this is equal to shortest distance through the water surface between the most distant points along the shore (Figure 7-2). This gets tricky when lakes have complicated surface geometry.
- lake breadth: this is equal to the length of a line perpendicular to the length defined above, at any point; the mean breath is equal to the area divided by the length (Figure 6-2).

3.2 In plan view, lakes range from equidimensional or irregular to very elongated. In certain special situations lakes are approximately circular—for example, kettle lakes (see Chapter 7).

3.3 In cross section, lakes are usually much wider than they are deep, especially large lakes. Small lakes are often deeper relative to their width than large lakes.

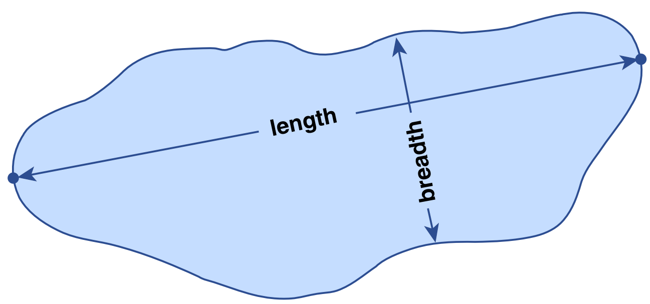

Figure by MIT OCW.

Figure 6-2. Length and breadth of a lake.

3.4 Table 6-1 gives some data about several well known large lakes around the world.

	A (km^2)	Z_{max} (m)	Z_{ave} (m)	V (km^3)	D_n (km)	D_n/z
Superior	83,300	307	145	12,000	326	2250
Caspian	436,400	946	182	79,300	745	4090
Baikal	31,500	1741	730	23,000	199	270
Crater	55	608	364	20	8	23
Balkhash	17,600	26	6	112	150	25,000

A	area of water surface
Z_{max}	maximum depth
Z_{ave}	average depth
V	volume
D_n	nominal diameter, 4 A/p$^{1/2}$ p = perimeter

Figure by MIT OCW.

Table 6-1. Data on large lakes of the world.

4. RESIDENCE TIME

4.1 The concept of the residence time of water in a lake is a natural one, because typically the water stays in a lake a long time, and velocity is much smaller than the source of inflow and outflow. The concept is not particularly interesting for rivers, though, because the velocity is about the same everywhere.

The ***residence time*** of a lake is defined as *the volume of the water in the lake divided by the discharge into or out of the lake*.

4.2 Letting the volume of water in the lake be V and the discharge to and from the lake be Q, The residence time T_r is

$$T_r = \frac{V}{Q} \qquad (1)$$

(A comment on the discharge here: this is easy to deal with only for stream discharge, not for groundwater discharge.) You can easily check that Equation 1 provides the right physical dimensions for T_r, namely time. In terms of the dimensions mass **M**, length **L**, and time **T**, the dimensions of T_r are by Equation 1

$$\frac{\mathbf{L}^3}{\mathbf{L}^3/\mathbf{T}}$$

or, canceling out the **L** dimensions, just **T**, which is what we should have expected.

4.3 The residence time is important because it tells you something about how long it might take to clear pollutant from a lake. The trouble with it is that it *deals only with the average properties of the lak*e. A given drop of water or molecule of pollutant may actually reside in the lake for a very short time or a very long time.

4.4 Here's an example of residence time in a lake. Look at a lake that's one kilometer by one kilometer in surface area and ten meters deep, with a stream feeding the lake with an average discharge of 20 cubic meters per second. This is a rather small river, but it's larger than just a stream. You could have this kind of discharge in a river with a mean velocity of about half a meter per second, a width of 20 meters and a depth of 2 meters. By Equation 1 the residence time then is

$$T_r = \frac{V}{Q} = \frac{(1000 \text{ m})(1000 \text{ m})(10 \text{ m})}{20 \text{ m}^3/\text{s}} = 5 \times 10^5 \text{ s} \qquad (2)$$

or a little less than one day.

4.5 On the other hand, very large lakes like Lake Superior or Lake Baikal can have residence times of many hundreds of years! Two important implications are that *it takes a lot longer to pollute large lakes but also a lot longer to clean them up*.

5. THE WATER BALANCE OF LAKES

5.1 Lakes have many sources of both inflow and outflow. The main sources of inflow are:

- streams
- precipitation onto the lake surface
- ground water

The main sources of out flow from a lake are:

- streams
- evaporation from the lake surface
- groundwater

5.2 Various configurations of streams are possible:

- *Stream or streams flow in, stream flows out* (Figure 6-3A). Usually only one stream flows out. In this kind of configuration the stream can be viewed as simply a fat place along a river. This is the most common kind of lake.
- *Stream or streams flow in, no stream flows out* (Figure 6-3B). The loss is made up by groundwater outflow and/or net evaporation. This is common in arid and semiarid regions; the streams are usually ephemeral. Lakes like this tend to be playa lakes. The Great Salt Lake is a good (and large) example.
- *Stream flows out, no stream flows in* (Figure 6-3C). The lake is fed by groundwater, usually not just by precipitation.
- *No stream flows in, no stream flows out* (Figure 6-3D). The lake is both fed and drained by groundwater movement. Lakes like this are common in glaciated areas underlain by a thick mantle of highly permeable glacial sediment, as on Cape Cod.

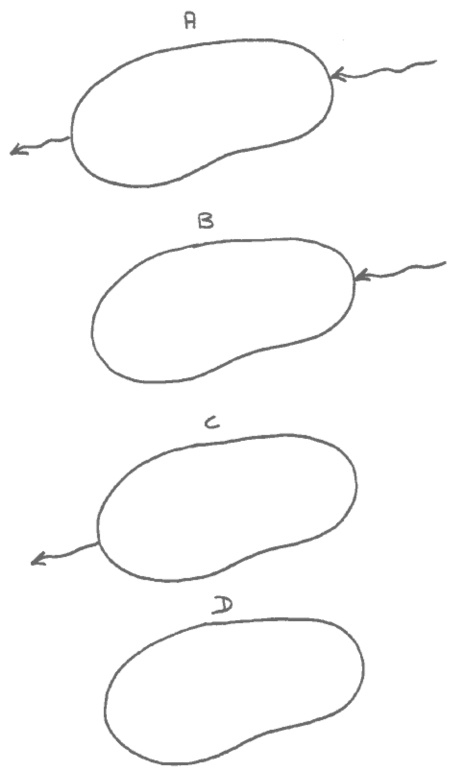

Figure 6-3. Configurations of streams flowing into and out of lakes.

6. THE VERTICAL TEMPERATURE STRUCTURE OF BATH WATER

6.1 The vertical temperature structure of lakes is a surprisingly intricate matter, and one that's more important than would seem at first thought. Remember that the density of water varies significantly with temperature, so if there's exchange of heat between the lake and its environment, giving rise to temperature differences, buoyancy forces will cause motions of the lake water until a gravitationally stable arrangement is reached, with less dense water overlying more dense water. What makes these processes interestingly complex is the strange density maximum at 4°C, noted back in Chapter 1.

6.2 In one sense, the water in your bathtub is a good model of a small lake. Think about the temperature and density structure of your bath. First of all, here are the two obvious scenarios for how you draw your bath:

- First you run water that's too cold, and then, to make it warmer, you run water that's too hot (or vice versa). Then you swash it all around for a few seconds to wind up with a nice homogeneous well mixed bath at the desired temperature.
- You run it in all at the same temperature and then simply turn the tap off.

In both of these scenarios, if you measured the temperature with a little thermometer you'd find very close to the same temperature at all points. If you stuck in your little cream whipper coated with slowly soluble dye and beat the water, you'd generate a lot of turbulence and also set up a complicated circulation pattern through the entire bath, and the dye would rapidly become mixed uniformly throughout the bath.

6.3 You might think that the uniformly mixed situation described above is the normal situation in lakes, but it isn't. To illustrate, here's another bathtub scenario. First you put in hot water and then cold water, or vice versa, and then the phone rings and you don't get a chance to mix them. When you come back to the bathtub you measure the vertical temperature profile. You'd find that the temperature is somewhat lower near the bottom than near the water surface (Figure 6-4). This temperature difference from bottom to top depends partly on the original temperature difference between the cold water and the hot water you used, but just as importantly on how fast you filled the tub. The stronger the water jet hitting the water surface, the greater the mixing between cold water and hot water.

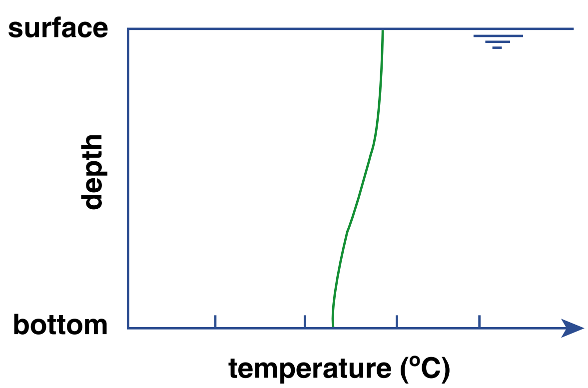

Figure by MIT OCW.

Figure 6-4. Temperature profile in your bathtub.

6.4 Why the temperature difference from bottom to top? Because *cold water is denser than the hot water* (provided that its temperature is above 4°C), so it tends to stay at the bottom (if you ran the cold water first) or find its way to the bottom (if you ran the hot water first). The only reason you don't end up with a perfectly stratified situation, with all the original cold water as a lower layer and all the original hot water as an upper layer, is the mixing occasioned by the jet from the faucet as the jet impinges on the water surface during filling.

6.5 With a little extra effort you can indeed set up an almost perfectly two-layer temperature-stratified bath. You get the best results by filling first with cold water and then with hot water, and by letting the water jet fall on a spreading plate that floats on the surface (Figure 6-5). The purpose of the spreading plate is to break the momentum of the downward jet, so that the warm water flows slowly off the plate horizontally and has no chance to mix with the cold layer below. That leads to two nearly homogeneous layers, cold below and hot above, separated by *a thin zone of very sharp temperature change* (effectively a temperature discontinuity), called a ***thermocline*** (Figure 6-6). In real lakes, the thermocline is also called the ***metalimnion***; the zone above is called the ***epilimnion***, and the zone below is called the ***hypolimnion***.

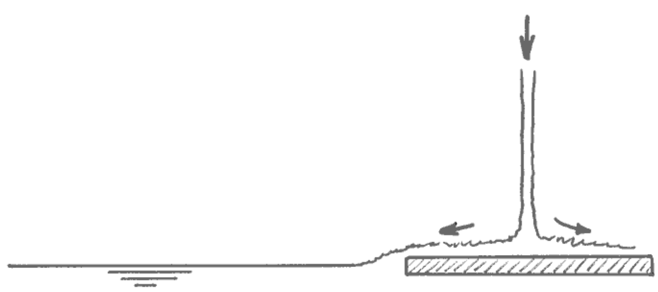

Figure 6-5. Drawing a two-layer bath.

6.6 Now if you put in your little dye-coated beater, what would you see? If you put the beater in either the upper (hot) or the lower (cold) layer, you'd produce a lot of turbulence in that layer, but the other layer would be little affected: each layer acts largely independently of the other (Figure 6-7). If, however, you put the beater at the interface, you'd mix some of the hot and cold together to produce water with intermediate density and temperature, and that intermediate water would drift out laterally to form a new and easily recognizable intermediate layer (Figure 6-8).

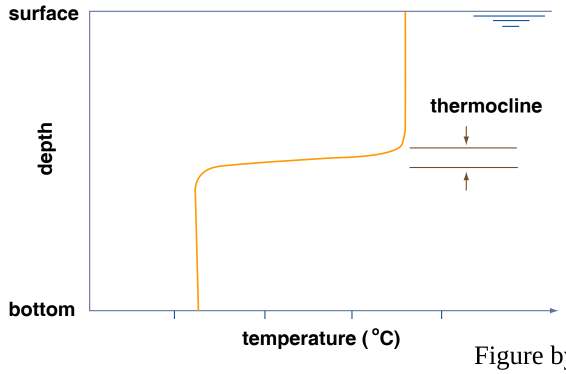

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Figure 6-6. Your two-layer bath.

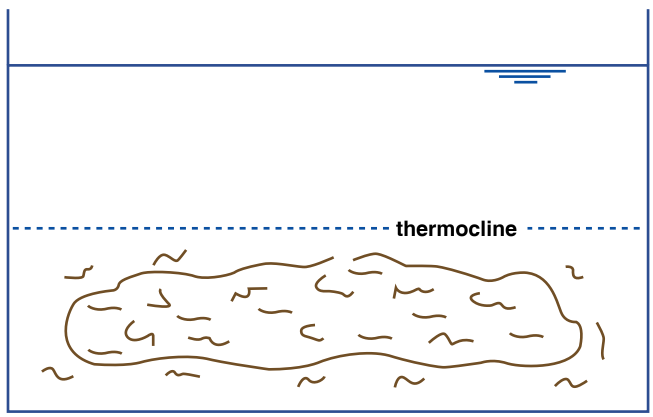

Figure by MIT OCW.

Figure 6-7. Near-independence of flow in the two layers.

6.7 What's going on here is that in arranging a cold layer below and a hot layer above you've produced a gravitationally stable stratification, and it takes *work* (literally, in the sense of physics—force times distance) to mix the waters of the two layers. The motions produced when the beater was in just one layer weren't enough to disrupt the stratification. You'd need a more powerful mixer to break down the stable density stratification.

6.8 Here are a few other instructive things you could do in your bathtub to gain some insights into the thermal regime of lakes:

• Line your bathtub the best you can with a coating of thermal insulation, including a floating insulating lid. In this way you eliminate all possibility of changing the temperature and therefore the density of the bath water by exchange of heat with the environment. Start with a thermally stratified bath, as above, and then come back hours later and re-measure the vertical temperature profile. You'd find that *the thermocline has thickened* (Figure 6-9). Why? By conduction of heat from the hot layer to the cold layer by molecular motions. This effect, called thermal diffusion, is slow but inexorable. In this situation of total isolation, *the water in the bath would come to have a uniform temperatur*e.

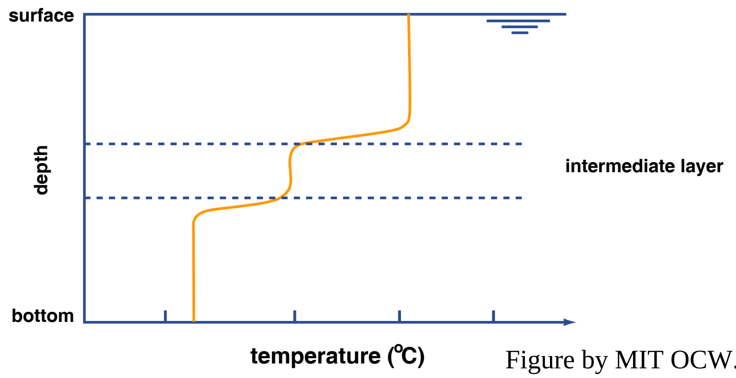

Figure by MIT OCW.

Figure 6-8. Beating the interfacial zone to make an intermediate layer.

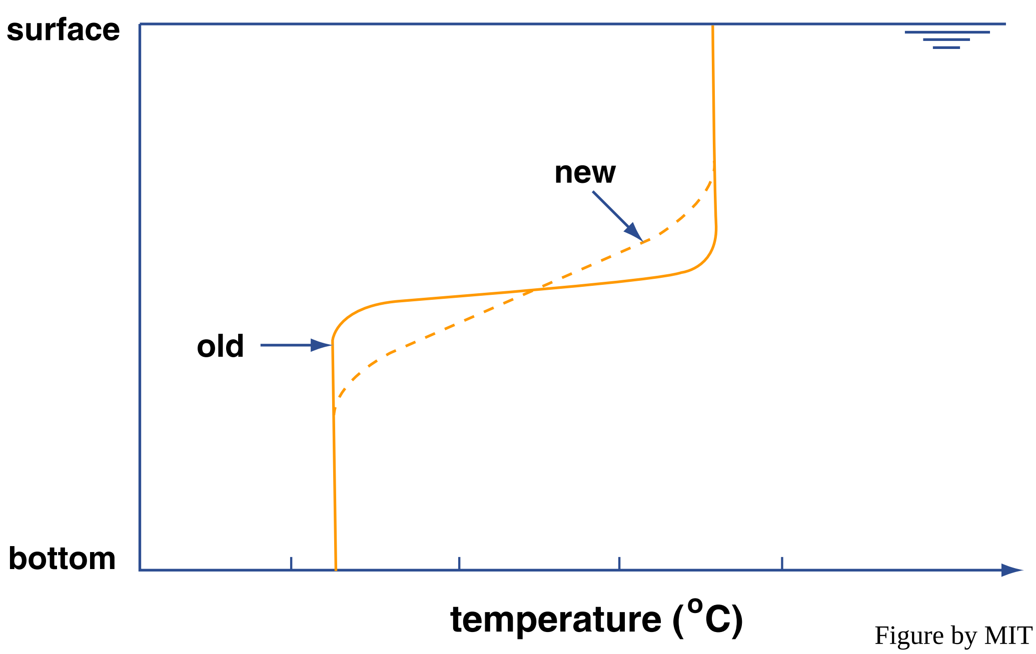

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Figure 6-9. Thickening of the thermocline by molecular diffusion.

BACKGROUND: DIFFUSION

1. Diffusion is an important process in a great many natural environments. ***Diffusion*** is *a flow of a material or property in some medium as a consequence of the existence of a spatial gradient in the concentration of that material or property in the presence of random motions of the material of which the medium is composed.*

2. That's a rather long and abstract definition. Here are some examples of diffusion:

- The warming of the handle of a metal frying pan when it's set on the burner.
- The spread of a cooking odor throughout the house, even though there's no organized air circulation in the house.
- the widening of a plume of black smoke as it rises from the top of the chimney.

3. Here's a thought experiment (one you couldn't actually do) to make the concept of diffusion more concrete. Suppose that you could place a vertical airtight partition down the middle of a sealed room, to make a "left" side and a "right" side, and then color all of the air molecules on the right side of the partition green and all of the air molecules on the left side of the partition red. Keep in mind that the air molecules are zipping continuously this way and that, colliding now and then with the walls of the room and with each other, because of their thermal energy.

4. Now magically remove the partition, instantaneously, and think about what happens. There's a balanced exchange of molecules across the vertical plane where the partition was located: at any given time, just about equal numbers of molecules are passing across the plane in the two opposite directions. But at the beginning, all of the molecules passing from right to left are red molecules, and all of the molecules passing from left to right are green molecules. We say that there is a net flow of red molecules from left to right and a net flow of green molecules from right to left. That's the essence of diffusive transport. Eventually, of course, the concentrations of both red molecules and green molecules become evened out everywhere throughout the room. After that, even though molecules are still zipping around, there's no net transport, because there's no longer any spatial gradient in concentrations of red or green molecules.

5. The random motions of the medium can involve the individual atoms or molecules, or random motions of turbulent eddies in a fluid. The example of the pan on the stovetop involves the vibrations of the atoms of the metal handle. The temperature of the pan is higher than that of the handle, meaning that the speed of vibration of the atoms is greater. The flow of heat down the handle is just a manifestation of the tendency for the speed of vibration of the molecules to even out, by the interaction of adjacent atoms. The other two examples, however, involve the motions of turbulent eddies in a fluid—although in the case of the cooking odor the spread could be entirely by molecular diffusion, as in the case of the red and green molecules in your partitioned room, if the air in the house is very still. In a fluid medium, turbulent diffusion is much more effective than molecular diffusion, if the medium is turbulent.

6. In the example of heat transport by diffusion, what's being diffused is a property, the temperature of the metal. In the case of diffusive transport of the cooking odor, it's the concentration of the gas or colloid that we sense as the odor. In the case of the smoke coming out of the smokestack, it's the concentration of smoke particles.

7. The rate of diffusive flow of the property or material, called the ***diffusive flux***, is proportional to the spatial gradient of the concentration of that property or material. The proportionality constant is called the ***diffusivity***, or the ***diffusion coefficient***. In some cases it can be derived from theory; in many other situations, however, especially when fluid turbulence is involved, it just has to be a measured empirical value.

• Leave the insulation around the walls of the tub in place leave the top lid off. Draw a hot bath, and then keep track of the vertical temperature profile as a function of time. You'd find that the water temperature stays vertically uniform as it cools, and that the water cools more and more slowly as the temperature approaches the ambient temperature (Figure 6-10).

• Draw a cold bath, and do the same. The result would be spectacularly different! As the surface water is warmed, a cold layer is maintained below, and this stratification persists until all of the bath is at the same temperature (Figure 6-11). You'd also find that the time it takes to develop a uniform bath is longer than in the previous case.

7. THE THERMAL STRUCTURE OF REAL LAKES

7.1 Now you can apply your knowledge of the thermal structure of bathtubs to real lakes. Think about a lake in a temperate region, with good contrast between summer warmth and winter cold, as in New England. Also, assume that the lake isn't ridiculously shallow. Start with a hypothetical all-warm lake (but see the end of this section, after on full annual cycle).

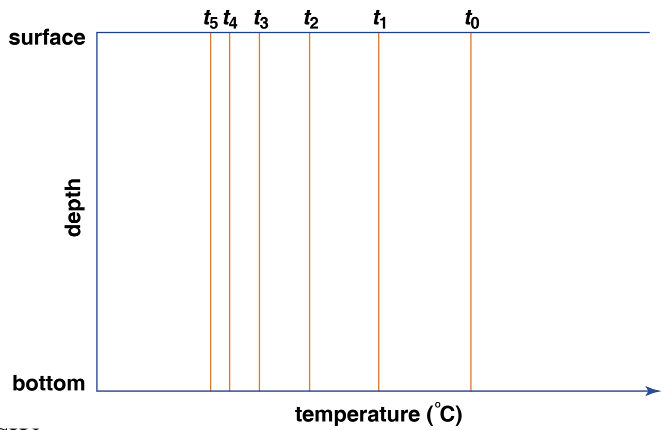


Figure by MIT OCW.

Figure 6-10. Time series of temperature profiles during cooling of your hot bath from the surface.

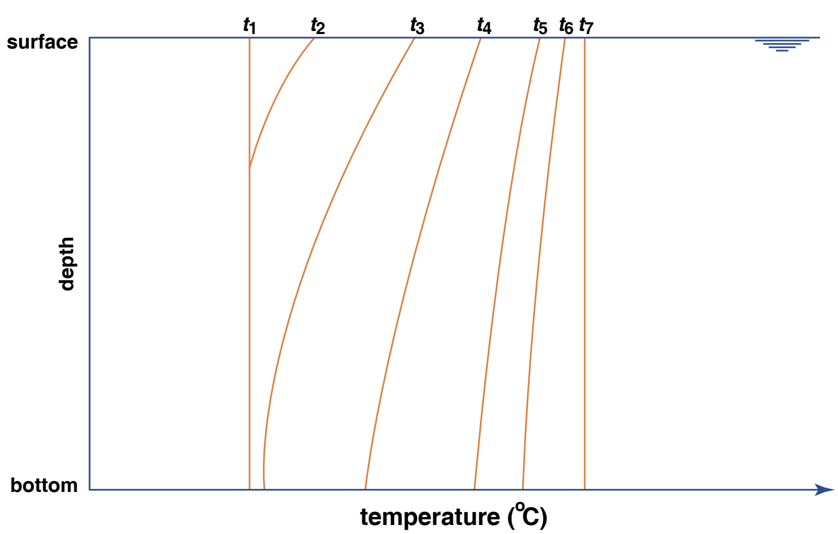


Figure by MIT OCW.

Figure 6-11. Time series of temperature profiles during warming of your cold bath from the surface.

Late fall: The surface waters are cool, with a uniform temperature profile and free vertical mixing (Figure 6-12A).

Early winter: The picture above holds until the surface water is about 4°C. Cooling past that point produces less dense water. Now stable stratification develops, because colder water remains at the surface. Vertical convection turns off (Figure 6-12B).

Middle winter: The lake reaches 0°C at the surface and becomes covered with ice. There's gradual cooling downward by conduction. There's no mixing, because of the stable stratification. The bottom water stays at nearly 4°C, unless the lake is shallow and/or the winter is very cold (Figure 6-12C).

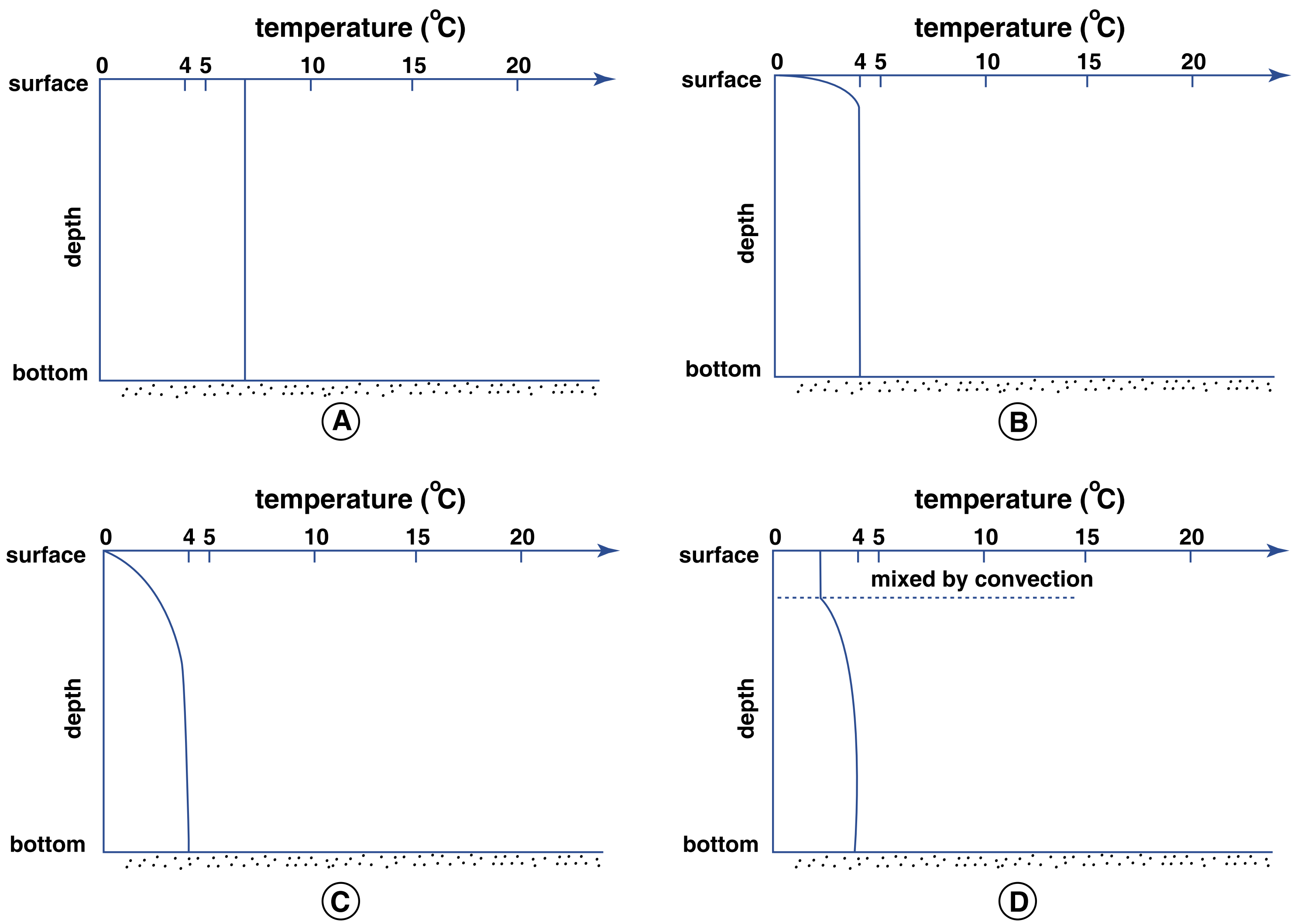
Early Spring: The ice melts, the surface warms, and convective instability develops, because below 4°C the warmer water is more dense than the colder water (Figure 12D).

Middle Spring: The surface water reaches 4°C, and the whole lake mixes, because 4°C water at the surface is denser than the water at any level and convection operates through the entire depth. This is called the ***spring overturning*** (Figure 6-12E).

Late Spring to Early Summer: The surface warm mixed layer lies above the thermocline. The cold water below the thermocline is gradually warmed by conduction (Figure 6-12F).

Early Fall: There's cooling at the surface, and mixing downward to the level at which the temperature equals the surface temperature (Figure 6-12G).

Late Fall: The surface develops the same temperature as the bottom, now greater than 4°C by conduction. Mixing is complete. This is called the ***fall overturning*** (Figure 6-12H).


temperature (°C)
0
4 5
10
15
20
surface
depth
bottom
A
temperature (°C)
0
4 5
10
15
20
surface
depth
bottom
B
temperature (°C)
0
4 5
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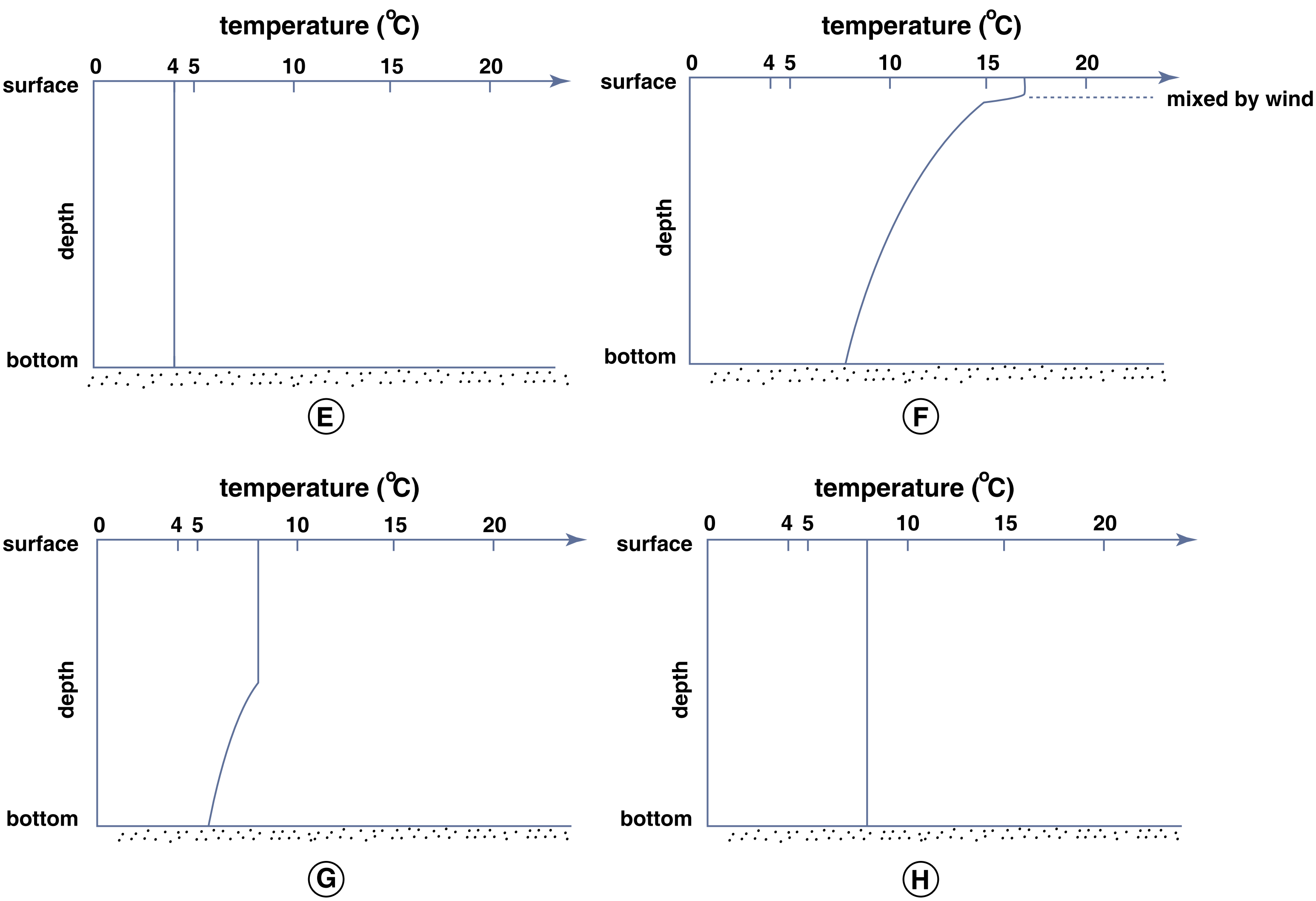

Figure by MIT OCW.

Figure 6-12. Temperature profiles in a temperate-region lake.

8. CLASSIFICATION OF LAKES BY THERMAL REGIME

8.1 Lakes can be classified on the basis of their thermal behavior in the course of a year. The hypothetical lake considered in the last section is just one possibility for the annual changes in thermal regime.

8.2 First we need to distinguish between holomictic lakes and meromictic lakes.

Holomictic lakes are of the same salinity (essentially zero) throughout, so that if the temperature becomes the same everywhere in the lake, the density also has to be the same everywhere in the lake, and the water of the lake can circulate freely. In such holomictic lakes, only the temperature, not the salinity, controls the density.

Meromictic lakes, on the other hand, can't circulate freely even if the temperature becomes the same everywhere, because of greater salinity in the bottom waters. Any higher-salinity water produced within the lake or introduced from outside the lake will find its density level and then spread out horizontally to form a distinctive layer, and the resulting density stratification prevents or at least inhibits vertical circulation.

8.3 Holomictic lakes can be further subdivided into dimictic lakes, warm monomictic lakes, and cold monomictic lakes, depending on the history of surface-water temperature in the course of the year, which in turn is a function of the climate.

Dimictic lakes are those in temperate regions where the annual fluctuations in air temperature are such that the surface water temperature of the lake is above 4°C for a part of the year and below 4°C for part of the year. Dimictic lakes *circulate freely by overturning twice a year*. The lake described in Section 7 is a dimictic lake.

Warm monomictic lakes are those in tropical regions where the air temperature never gets very low during the year. The surface water temperature of the lake stays above 4°C, so *there's free vertical circulation only at the time of coldest surface water temperature*.

Cold monomictic lakes are those in polar regions where the air temperature never gets very high during the year. The surface water temperature of the lake stays below 4°C, so *there's free circulation only at the time of warmest surface water temperature*.

8.4 The basic reason why lakes show such diverse circulation behavior is that maximum in water density at 4°C.

9. THE LIFETIME OF LAKES

9.1 How long do lakes last? There's an inevitable tendency for lakes to disappear, by sedimentation to the point where the lake basin is occupied by sediment rather than water, so the water surface is replaced by land surface, perhaps with a stream or river flowing across that land surface.

9.2 One cause for the disappearance of lakes is the mechanical deposition of inorganic mineral sediment (gravel, sand, and mud) carried in mainly by *streams* and rivers feeding the lake, or to a much lesser extent by wind or by mass movements of soil down slopes to the edge of the lake. The sediment load of a stream feeding the lake tends to become segregated into coarse material deposited near the mouth of the stream to form a delta, and fine material deposited from suspension widely over the lake bottom (Figure 6-13).

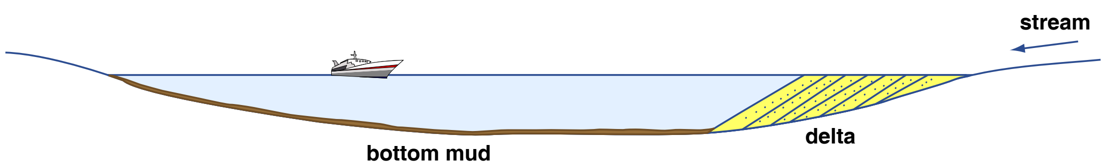

Figure by MIT OCW.
Figure 6-13. Sediment deposition in lakes.

9.3 The other important cause for the disappearance of lakes is biogenic sedimentation of non-decomposed organic matter, mainly plant material, on the lake bottom. This process is called ***eutrophication***. The important factor here is *availability of oxygen in the bottom waters*.

• If the biogenic productivity of the lake (mainly at the surface) is relatively low and the vertical mixing of water in the lake is relatively high, then the bottom water is well oxygenated, and most or all of the organic matter that settles to the bottom is decomposed before it has a chance to build up an organic bottom-sediment deposit.

• On the other hand, if the biogenic productivity is relatively high and the vertical mixing of water in the lake is relatively low, then the bottom water is deficient in dissolved oxygen, and a deposit of organic sediment builds up on the lake bottom.

Because the vertical circulation is controlled almost entirely by physical effects, as discussed in earlier sections, the critical factor in eutrophication is biogenic productivity, which in turn is a function of supply of dissolved nutrients in the water entering the lake. In most lakes, phosphorus is the limiting nutrient. One of man's strongest effects on lakes (in urban areas, suburban areas, and rural agricultural areas) is the introduction of much greater concentrations of nutrients, especially phosphorus, leading to greatly accelerated eutrophication.