Thermal Ecology of Lakes

In this section, we begin to consider the flow of energy. We will look at lakes and the role that energy flow plays in lake ecology. Ultimately, we will be interested in questions about the distribution of nutrients (or pollutants) in lakes. Lakes are common places for human activities and, as such, a focus of environmental concern. Because they usually contain less water than rivers or oceans, they are more sensitive to chemical inputs.

To understand the heat balance of lakes, we need to recognize that changes in heat will be equal to the sources of heat energy – losses of heat energy.

In lakes, there are a number of different sources of heat. Solar radiation (both direct and indirect) adds heat to lakes. Thermal radiation, often known as “latent heat exchange” contributes to the heat in a lake. There is transfer of heat from overlying air and net advection from streams, springs, and rain. There can be heat transfer from the sediments and the condensation of water vapor can add heat.

The losses of heat include: conduction to the air; conduction to sediments; blackbody radiation; evaporation.

Dominant heat flows are through the surface waters and are strongly seasonal.
What happens to the energy from the sun? Direct solar radiation is sunlight that hits the water directly. Indirect solar radiation is scattered by the atmosphere. In general, 2-3% of short wave radiation is reflected and scattered on a summer day, the rest will be absorbed.¹

In thinking about thermal radiation, we often invoke the notion of a “black body”, which will emit energy proportional to the fourth power of its temperature in degrees C

\[ Q = 8.26 \times 10^{-9} \text{cal} \cdot \text{cm}^{-2} \cdot \text{min}^{-1} \cdot \text{deg} K^{-1} (T \text{deg} K)^4 \]

Water emits about 95% of ideal blackbody radiation. Radiation from the sky is also not perfectly a black body. The approximate net thermal radiation is \(-11 \times (T_{\text{water}} - T_{\text{air}})\) in units of \(\frac{\text{cal}}{\text{cm}^2 \text{day}}\)

¹ Source in Hutchinson 1957, p 371 citing previous work.
The most important sources of radiation are direct and indirect solar as well as long wave thermal radiation. At night, most terms are negligible and net radiation is just thermal radiation.

How does light penetrate into water? In the laboratory, the intensity of light follows an exponential decay function.

\[ I = I_0 e^{-\eta z} \]

The extinction coefficient, given by \( \eta \) in the equation above varies with the wavelength of light being considered and the type of water (particularly the composition of dissolved material within it). In pure water, the extinction coefficients for infrared (thermal) radiation are about 2.2.5 to 2.5, for red visible light about 0.31 to 0.45 and for blue visible light (higher energy than red light) about 0.009 to 0.008. Phytoplankton, where highly abundant, are green and thus absorb least in the green range of the spectrum. Many dissolved organic materials are brownish and thus absorb least in the yellow to read portions of the spectrum.
Water appears blue because longer wavelengths have been absorbed preferentially along the path followed by back-scattered light, enriching the scattered light with blue.

Model Light Extinction

Crystal lake has extinction coeff. = 0.129
Little Star Lake has coeff. = 3.90

From this we gather than Little Star Lake has more dissolved organic matter in it than Crystal Lake.
Another important feature in understanding the distribution of energy and matter in lakes is the way in which the density of water varies with temperature. Most of us learn that the density of fresh water is \( \frac{1 \text{ g}}{\text{cm}^3} \) but to understand lakes, we’ll need to be more precise (quick question – do you remember – is salt water more or less dense than fresh water?).

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In addition, you should know the following facts about water. It has a specific heat of 1 cal/gram or 4.19 joules/g. This is the amount of energy that it takes to raise 1 g of water by 1 degree. The specific heat is slightly higher at lower temperatures and slightly lower at higher temperatures but varies by less than 1% over the range of temperatures we will be interested in.

It conducts $\frac{5.92 \text{ mW}}{\text{cm} \cdot \text{deg}}$ and this number varies about 10% over the range of temperatures of interest.

It has a latent heat of evaporation of 539.55 cal/g. This is how much energy it takes to evaporate 1 gram of water (or alternatively, how much energy is released when 1 gram of water vapor condenses).
The latent heat of fusion of water is 79.67 cal/g. This is how much energy it takes to melt 1 g of ice (or the amount of energy released by freezing 1 g of water).

All of this together – the seasonal distribution of thermal energy as well as the extent to which light penetrates water and the density of water as a function of temperature – leads to vertical stratification in temperate lakes.

Below, we will qualitatively describe the seasonal patterns and then explain why they are significant in affecting the distribution of nutrients in a temperate lake.

In the spring, as ice melts, the surface waters warm to match deep water temperatures. Small density differences that exist are reduced or eliminated. Ice-off permits wind induced mixing and allows for convection too. The water in the lake becomes thermally uniform from top to bottom.

In the summer, the solar radiation increases. The surface water absorbs thermal radiation and warms the water. The near exponential decline in light penetration implies a near exponential drop in warming with depth. The surface waters warm above 4 degrees and become less dense than the water underneath them. The less dense surface water continues to “float” on top of the more dense water.

Because of evaporative cooling and radiative cooling at night, the maximum temperature is a few cm below the surface. Wind induced mixing mixes the surface waters and that leads to a narrow homogeneous band of water with the same temperature near the surface. Because of this homogeneous temperature band, it takes less energy to move a parcel of warm water downward. The mixing processes can then reach a greater depth and the band of warm water at the top of the lake increases in depth. The thermocline (depth of maximum temperature change) increases throughout the summer.
In the fall, solar radiation declines and thermal radiation from the atmosphere declines. Initially, thermal radiation from the lake does not decline much. Radiative heat loss increases, which cools the surface of the lake. Convection cells develop at night and mix downward. The surface waters cool. Wind eventually disrupts the thermocline, which leads to vertical mixing of the lake.

In the winter, evaporative and radiative energy losses from the surface continue. The temperature of the surface water continues to drop. As the surface water drops below 4 degrees, water gets less dense (see data and figure above). This creates a delicate thermal stratification, which can be upset by wind. In the absence of winds, continued radiative cooling tends to supercool surface waters, eventually leading to crystalization of water into ice. As in summer, in winter lakes are fairly stable and don’t undergo much mixing. As they freeze over there is less exchange of energy with the atmosphere.

Back of the envelope calculation

_How many chocolate bars would you have to eat to provide the fuel to warm up a bath from room temperature (about 20C) to body temperature (about 40C)? You can ignore maintenance metabolism in your calculation._

Chocolate bars are about 150 to 200 Calories, with a Capital C.
That's 150,000 calories

Volume of water in your tub

\[2 \text{ m} \times 0.5 \text{ m} \times 25 \text{ cm} = 0.25 \text{ m}^3 = 2.5 \times 10^5 \text{ cm}^3\]

So, Total Energy needed is

\[250000 \text{ cm}^3 \times 1 \text{ g/cm}^3 \times 1 \text{ cal/g/degree} \times 40 \text{ degrees C}\]

= 10,000,000 calories
= 10,000 Calories
10,000/200 = 50 chocolate bars.