Limnology: the study of lakes and rivers.

Limnology encompasses everything from the geologic origins of lakes to the development of a lake in prehistoric times (Paleolimnology) to the structure of food webs. As do oceanographers, limnologists generally specialize in physical, chemical or biological limnology. Modeling is a tool that can reach across the boundaries of these specialty areas. There are three major limnological topics that are covered here: (1) temperature structure of lakes, (2) light, and (3) chemistry (nutrients, oxygen, pH, alkalinity, DOC). Following this background material is a section on field sampling methods. The handout concludes with the exercises to be performed on the field trip.

1. Temperature Structure in Lakes

   The fact that water is most dense at 4°C (rather than at the freezing point as for most other liquids) has enormous importance for lakes. You will recall that this behavior results from the formation of hydrogen bonds between water molecules that spaces the molecules further apart at cold temperatures; because the hydrogen bonds are weak, they are broken by the movement of water molecules at temperatures above 4°C. In winter, this behavior results in the coldest water being at the top of the lake (Fig. 1) and forming a protective barrier that itself cools as a result of contact with cold air and keeps the whole lake from becoming even colder. This situation is called inverse stratification. Also as a result, ice floats on top of lakes rather than forming from the bottom up. Ice not only acts as a thermal barrier, it also prevents the wind from mixing the lake waters (and thereby slows further cooling) as well as preventing oxygen from contacting and dissolving into the lake water. In shallow or highly productive lakes, all of the oxygen can be used up during winter by bacteria decomposing the organic matter in the sediments; the result can be an under-ice fish-kill in such lakes.

   ![Figure 1. Temperature profile in winter.](image)

   In summer, just the opposite occurs. The cold, dense water is at the bottom of the lake, and the warmer water sits on top. Again, this allows the warm layer to get warmer and shields the cold layer from the warmth of the atmosphere. The cool, deep water provides a refuge for many fish species. This temperature profile is stably stratified because the least dense water is on top. Often, wind energy is sufficient to mix the upper waters and create an upper layer of nearly uniform
temperature. The upper, warm layer is termed the **epilimnion**, the cold deep layer is called the **hypolimnion**, and the zone of transition is called the **metalimnion**. The depth at which the maximum temperature change occurs is called the **thermocline**.

**Figure 2.** Summer temperature profile.

There are numerous effects of summer **stratification** upon a lake. Any pollutants brought into a lake in summer are diluted into a much smaller volume while the lake is stratified. Stratification makes it possible to swim in summer even in northern latitudes. Any nutrients lost from the epilimnion during summer (e.g., via settling of dead algal cells) will not be available for algal growth again until the lake mixes in fall. Because the hypolimnion does not have contact with the atmosphere, it must rely on diffusion across the metalimnion (a slow process) to resupply any oxygen that is consumed within the bottom waters. In productive lakes, oxygen consumption can be faster than oxygen transfer across the metalimnion, and the bottom of the lake can go **anoxic**. This anoxia kills most organisms except bacteria in the bottom waters and sediments. In the absence of oxygen, the bacteria must use other electron acceptors, and, as a result, substances such as dissolved iron, hydrogen sulfide (the molecule that gives rotten eggs their odor), and methane may build up in the hypolimnion. Anoxia has a huge effect on phosphorus, generally the most important nutrient in lakes. When oxygen is present, phosphorus in the sediments adsorbs on the surface of iron oxides. Under anoxic conditions, the iron oxides dissolve and the phosphorus is released to the water and becomes available to support further algal growth. This phosphorus release from anoxic sediments is a type of positive feedback that promotes **eutrophication** (see below) in lakes.

**Fig. 3.** Seasonal temperature development in Lake Superior. The y-axis is depth (m) and the x-axis is time in Julian days (Jan. 1 = 1, Dec. 31 = 365). The color scale gives temperature in °C.

Spring and fall are periods of transition between the two temperature profiles shown above. At some point, the whole lake will reach 4°C, and at this point there is the least resistance (from buoyancy) to complete mixing of the lake. The period of complete mixing is termed **overturn** or **holomixis**. In spring and fall, the epilimnion gradually thickens as the thermocline
is driven deeper by wind energy. Around Houghton, spring holomixis generally occurs between mid-April and mid-May, and fall holomixis occurs between late September and mid-November (Fig. 3).

The timing and pattern of lake mixing and stratification depend on climate (Fig. 4). The pattern of mixing twice (dimictic) per year as described above occurs in temperate latitudes. Further north, lakes may never stratify in summer, and further south many lakes never stratify in winter; these patterns are called cold monomictic and warm monomictic. Very shallow lakes may stratify and be mixed by the wind numerous times in a year and are called polymictic. By the equator or at high latitudes, lakes tend to be permanently stratified and mix only rarely (oligomictic) if at all (amictic) either because of continuous ice cover or continuous warm weather.

Figure 4.
Geographic distribution of lake mixing patterns. (Figure from [Wetzel, 1975 #1321])

One other category of lake mixing deserves mention. Meromictic lakes are permanently stratified; wind energy is inadequate to mix these lakes completely either because of their great depth (many graben lakes are meromictic) or because of high concentrations of salts in the lowest layer, the monimolimnion. The high salt concentrations may be derived from geological sources (geothermal inflows, ancient brines, highly soluble rock layers) or biological sources (decomposition of the organic matter that falls into the deeper waters). High concentrations of reduced substances (Fe$^{2+}$, sulfide, methane, ammonium) typically accumulate in the monimolimnion and provide a source of energy for large populations of chemosynthetic or photosynthetic autotrophs including the colorless, purple and green sulfur bacteria.

2. Light in lakes

Photosynthesis can only occur in the portion of a lake that has adequate light, the photic zone. Sunlight that impinges on the lake surface may be reflected from the surface, scattered by particles in the water, absorbed by water or particles or dissolved substances, or transmitted to greater depth. Light absorption by water itself varies systematically with wavelength; light absorption is least for blue light (~460 nm) and increases as wavelength increases and decreases
away from this portion of the spectrum. Light absorption in lakes is characterized by the extinction coefficient, $\lambda$:

$$I = I_0 e^{-\lambda z}$$

where $I$ is the light intensity at depth $z$, and $I_0$ is the intensity at the surface. The extinction coefficient is wave-length specific although an “average” value for photosynthetically-active radiation (400-700 nm), PAR, is often given. The **photic zone** is defined as the region between the surface and the depth at which light decreases to 1% of the surface irradiance. In lakes, the photic zone may range from less than one meter to 40 meters in deep, oligotrophic lakes such as Lake Superior.

![Average Secchi Depth in North America](image)

**Figure 5.** Results of volunteer surveys of secchi depths in lakes. (Figure from Dip-In web site [http://dipin.kent.edu/](http://dipin.kent.edu/))

The simplest method to measure the depth of light penetration in lakes is with a secchi disk. This white, circular (diameter 20 cm) plate is lowered into the water until it disappears from view and, upon raising, reappears at the **secchi depth**. Although seemingly crude, this method is reproducible to within $\pm$ 5% and permits rapid, large-scale surveys of lake clarity (e.g., Fig. 4). Although inorganic particles and dissolved substances may also contribute to light absorption, algal pigments are often the dominant absorber of light. Hence, the secchi depth is a measure of the abundance of algae within a lake. In general, secchi depths of less than 2 m are indicative of eutrophic conditions, and secchi depths greater than 4 m indicate oligotrophic
Dissolved organic matter (DOM), composed of substances secreted by algae and macrophytes as well as complex macromolecules released during the decomposition of organic matter by bacteria and fungi, is also a major determinant of the light environment in aquatic systems. **Dystrophic** lakes are brown-colored lakes that receive large inputs of DOM usually from wetlands in the catchment. The DOM not only absorbs light that might otherwise have been used for photosynthesis (i.e., photosynthetically active radiation or PAR), but it also absorbs very strongly in the ultra-violet (UV) region of the spectrum. Apart from water molecules that also absorb UV light, DOM in lakes provides the primary protection for organisms against harm from UV radiation.

### 3. Chemistry

Environmental engineers and limnologists generally are most concerned about chemicals in the environment that might adversely affect aquatic ecosystems. These chemicals include nutrients, toxins (trace metals, synthetic organic compounds), and acids (primarily from acid rain). Nutrients might include both inorganic nutrients such as nitrogen and phosphorus and organic matter that may stimulate the activity of bacteria. These classes of chemicals will be considered in turn.

Phosphorus and nitrogen are the two nutrients that most often limit algal productivity in lakes because they are in short supply relative to demand (i.e., **limiting nutrients**). About 85% of North American lakes are estimated to be phosphorus-limited, and the remainder are nitrogen-limited. The primary sources of both pollutants are sewage, animal wastes, fertilizers and (P only) detergents containing phosphate binders. While point sources (sewage outfalls, industrial discharges) of these pollutants are relatively easy to control, non-point sources remain difficult to manage. Reduction of nonpoint sources may require changes in agricultural practices (e.g., limiting timing or magnitude of fertilizer applications, requiring buffer zones between agricultural fields and waterways), separation of combined sewage collection systems into separate storm-water and domestic/industrial systems, treatment of storm water runoff, and improvements in septic systems.

**Eutrophication**, the enhanced productivity in lakes resulting from increased nutrient inputs, is one of the most widespread water quality problems throughout the world. As shown by the distribution of eutrophic lakes (Fig. 5), eutrophication is exacerbated by urbanization, agriculture, and low water flow rates. Although a number of in-lake treatments have been devised to combat eutrophication, in general these treatments only combat one of the symptoms of eutrophication rather than the cause. The cause of eutrophication is excessive nutrient inputs relative to a lake’s assimilation capacity; the only solution that addresses the source of the

\[
J (gP/m^2yr) = 3.01 \times 10^{-2} k_{flushing} (m/yr)
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J (gP/m^2yr) = 3.01 \times 10^{-2} H^*k_{flushing} (m/yr)
\]
problem is to reduce nutrient inputs. The symptoms and in-lake treatment options for eutrophication are discussed extensively in lectures.

Figure 6. Vollenweider plot of lake trophic status. The position of a lake on this plot can be used to indicate its trophic state as well as to predict the reduction in nutrient loading required to improve its condition.

A simple model for prediction and control of eutrophication in lakes was developed over 30 years ago [Vollenweider, 1975 #1294]. This model predicts that as the phosphorus loading to a lake increases, eutrophication is likely unless the lake is either very deep or rapidly flushed (Fig. 6). The lines that are typically drawn in the Vollenweider plot to separate eutrophic, mesotrophic and oligotrophic lakes (lines at C = 10 and 20 μg P L⁻¹) are based on empirical observations. However, it has long been recognized that many lakes do not fit in the appropriate region of the graph because they have coefficients for P removal that differ from that of other lakes (typical value of 10 m/yr). Recently, the U.S. EPA has proposed surface water quality guidelines for N and P in lakes that recognize that systematic geographic variations exist in lakes’ ability to assimilate nutrients.

One step in developing water quality criteria for nutrients is defining the trophic state of a lake based on measurable characteristics. One widely used approach for determining the trophic state is Carlson’s Trophic State Index. An index value is calculated separately using three parameters (secchi depth, total phosphorus concentration, and chlorophyll concentration). In general, a value of Carlson’s Index of < 40 indicates oligotrophic conditions, values between 40 and 55 indicate mesotrophic conditions, and values greater than 55 indicate eutrophic conditions. This is comparable to saying that secchi depths > 4 m, total phosphorus concentrations < 5 mg/m³, and chlorophyll concentrations < 2.5 mg/m³ indicate oligotrophic conditions while secchi depths < 2 m, TP concentrations > 20 mg/m³ and chlorophyll concentrations > 10 mg/m³ indicate eutrophic conditions.

The presence of toxic substances in surface waters can result in risks to human health as well as risks to other organisms. The presence of toxins in surface waters is a very widespread problem. Approximately 98% of Michigan’s lakes fail to meet surface water quality criteria because of the presence of mercury and/or PCBs; atmospheric deposition is the major source of these two toxic substances to lakes. Point sources contribute toxic substances to other lakes, notably those on the National Priority Listing (Superfund sites), and agricultural runoff is also a significant source of pesticides.

Acid deposition continues to be a problem affecting water quality in regions whose lakes are poorly buffered. These regions include Scandinavia, the U.K., some parts of Germany and the Czech Republic, eastern Canada, and the Appalachian and northern Midwest areas of the United States. The problem also likely exists in areas of China, but it has been poorly
documented in the international literature. The major natural buffer in lakes is bicarbonate derived from dissolution of calcite. Natural organic matter also provides some buffering, but at pH values below those generally considered desirable in lakes. In-lake processes such as nitrate assimilation, denitrification, and sulfate reduction also can contribute alkalinity particularly in lakes with longer water residence times. In general, lakes with alkalinity below 200 μeq/L are considered susceptible to acidification.

4. Field sampling techniques

For monitoring of chemical constituents in water there are three approaches available. The most common approach is to take “grab” samples of water and return them to the laboratory for analysis. A common way of collecting grab samples is with a Niskin bottle or similar device; all of these devices are tripped to close and collect water from a single depth. Large ships often use an array of niskin bottles in a rosette sampler such as shown in Fig. 7. An alternative to a grab sample is an integrated sample that collects water from the entire depth of interest. Water may also be pumped from any given depth to a sampling vessel or filter onboard.

Figure 7. Rosette sampler containing 8 niskin or Go-Flo samplers. Each sampling bottle may be tripped at a different depth.

Figure 8. A CTD being deployed from a research ship in the Great Lakes (right).

An alternative to grab samples and individual analyses are sensors that record continuously while in the water. There are a great variety of probes or sondes available. Typically, depth is recorded with a pressure sensor, and a variety of other sensors may be attached to the sample sonde. Sensors available include ones for temperature, chlorophyll (fluorescence), conductivity, turbidity, pH, dissolved oxygen, oxidation-reduction potential, some specific ions (e.g., chloride). In oceanographic work, a sonde with probes for conductivity, temperature and depth is often
employed; this sonde is called a CTD (Fig. 8).

5. Laboratory techniques
   In the laboratory, grab samples may be analyzed for a vast number of analytes. The variety of such analyses is too great to begin to describe here. For all such analyses, a quality assurance protocols must be followed to insure that samples are not contaminated, that the analyte concentration is above the detection limits, and that the results are reproducible.

6. CE4505 Class activities
   Learning Objectives:
   1. To observe and perform common limnological sampling techniques;
   2. To measure the range of pH in a few local lakes;
   3. To assess the contributing causes of light attenuation in lakes;
   4. To contrast suspended solids concentrations in a few local lakes;

   On the boat we will do the following activities:
   1. Measure and record depth profile of temperature and D.O.;
   2. Measure and record secchi depth for contrast with previous week;
   3. Collect Niskin samples at 3 depths (surface, 1 m above bottom, thermocline) for the following:
      a. store sample for alkalinity and DIC;
      b. measure pH;
      c. measure absorption spectrum (see SOP);
      d. filter 1 L for suspended solids determination;

   In your report, you should compare the measured suspended solids concentration with that estimated from secchi depth, and similarly you should compare the extinction coefficients measured with the spectrophotometer with that estimated from secchi depth. To calculate the wavelength-specific extinction coefficients from your measured absorbance values, you must use the two relationships:

   (1) \[ \text{Absorbance} = \log(I_o/I) \]

   (2) \[ I = I_o e^{-kz} \]

   The depth, \( z \), in this case will be the width of the cuvet.
Last updated: 12/7/2009

**Field Data**

Date: ____________________  Location _________________________

Water depth (m) __________

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Secchi Depth (m) __________________________
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TSS Measurement:

Weight of filter ________________________

Weight filter + solids ____________________

Volume filtered _________________________
To be done before class:
   1. Calibrate pH meter;
   2. Calibrate DO probe;
   3. Weigh & label filters for TSS;
   4. Try out spec. with 1- and 5-cm cuvet; (use water blank with 2 cells)

To be done after class by instructor/TA:
   1. Dry TSS filters in oven then desiccator and weigh;
Topics:
Stratification, mixing, wind, fetch
Optics: light attenuation vs. wavelength, turbidity, absorbance
Chemistry: DO (incl. AHOD), pH & alkalinity, DOC, nutrients

Conductivity as indicator of hardness and ANC

Equipment:
Secchi disk
Hydrolab
Hach probes (pH, conductivity, LDO)
Niskin bottles
Spectrophotometer with cuvets
Vacuum pump
GFF filters, pre-weighed in petri dishes
Forceps
1-L graduated cylinder
Labeling tape
Sharpies
White board with markers, eraser
Stir plate with magnetic bars (for pH)
Bottle(s) or beakers for pH, conductivity measurement