Limnology – The Basics

Frank M. Wilhelm

Our *LakeLine* editor invited me to write a readily accessible introduction to "limnology" for this issue of *LakeLine* that includes "everything" – basically to distill volumes of textbooks into an article – a formidable task. Reflecting on how to tackle this "small" task, I have chosen to focus on what I would consider most important to know as background if I were a member of the public attending a seminar or technical presentation regarding some aspect concerning my local lake. I will start with some basic definitions, then move from the formation of lakes to physical, chemical, and biological processes. Hopefully, you'll make it to the end, and emerge with an appreciation for the beauty and complexity that is the aquatic realm – something that has captivated me since chasing salamanders and tadpoles in creeks and quarry ponds during my childhood. I consider myself fortunate to have lakes and reservoirs as my "office" and to be able to work on them regularly. However, it comes with the burdensome insight that we are rapidly approaching a reckoning: an expanding human population that needs access to clean water and a finite quantity of such water available on earth. Thus, it is imperative that each of us becomes informed and takes appropriate actions to protect this life-giving resource. Thanks for joining me, let's get started.

Limnology – is the study of inland water; it includes some waters more saline than the ocean, ponds, streams, rivers, to lakes and reservoirs – large and small. Basically, if the aquatic system is inland or drains to the ocean, it is encompassed in limnology. So, what do limnologists study? There is a myriad of physical, chemical, and biological processes that occur in our lakes (I'll primarily focus on lakes here) that make them function. Considered as a whole, lakes are living ecosystems.

Nutrients – includes a wide variety of elements necessary to fuel life. In the case of freshwater, nitrogen (N) and phosphorus (P) are typically the nutrients in shortest supply – this is termed a limiting nutrient – and hence our overwhelming focus on them because adding just a little can have large effects (Schindler 1971). Realize that N and P are only two of a plethora of nutrients. For example, silica may limit the growth of diatoms (small algae) in some lakes seasonally.

Eutrophication – is the presence of excess nutrients that stimulate high plant biomass; it comes in two flavors – natural and cultural. The former is the typical process for all waterbodies as they evolve to solid land over geologic time periods. As soon as a lake is created, it's on a death march to solid land – stick around for 10,000-plus years and you'll see your favorite lake change. Cultural eutrophication is the acceleration of this process shortening it to tens of years so that ecosystem changes become noticeable during a human lifetime. It is the result of human activities that increase the rate of sediment and nutrient transport to our aquatic ecosystems.

Trophic state – is a classification system devised by limnologists based on the productivity (amount of plant growth) in a lake. While trophic state is a continuum (Figure 1), you will encounter the following terms – Oligotrophic (low nutrients, low algal biomass, high transparency); Eutrophic (high nutrients, high algal biomass, low transparency); and Mesotrophic (intermediate conditions). Trophic state can be assigned based on the concentration of nutrients in the water column, the amount of plant biomass, or the depth to which light penetrates (Carlson 1977; Carlson and Simpson 1996).

Secchi disk – is a 0.2-m diameter weighted disk with opposing white and

Trophic state boundaries

	Oligo-	Meso-	Eutrophic
Total Phosphorus	<6 µg/L	12-24	24-48
Chlorophyll a	<0.95 µg/L	2.6-7.3	7.3-20
Secchi Depth	>8 m	4-2	2-1

Figure 1. Trophic state boundaries from oligotrophy to eutrophy for total phosphorus, chlorophyll a, and Secchi depth based on Carlson 1977, and Carlson and Simpson 1996.

black quadrants that limnologists use to measure the depth to which light that plants use to photosynthesize penetrates into a lake. Because light needs to reflect off the disk for you to be able to see it, the actual depth to which useable light penetrates is approximately two times the Secchi depth. NALMS is the coordinator of the Secchi Dip-in program which encourages citizens to measure the Secchi depth on their lake during the month of July each year and enter the data into an online database. You can find more information here: https://www.nalms.org/secchidipin/ and I encourage you to participate.

Algae – are small plants that are suspended in the water column and for which one usually requires a microscope to see them properly. When light is present, they photosynthesize turning light energy into chemical energy in the form of sugar. They form the basis of the food chain, similar to grass on land.

Macrophytes – are large plants that are easily seen with the naked eye, like lily pads and cattails. Similar to algae, they also photosynthesize, and are usually found around the margin of lakes which is called the "littoral zone." The littoral zone is defined by the depth to which macrophytes grow along the bottom of water bodies.

Zooplankton – are small animals that typically graze algae and other small bits and pieces in the water column. They in turn are food for larger organisms such as fish. It's interesting to note that even the most voracious fish predators such as pike or bass feed on small zooplankton when they first start life. Zooplankton density changes seasonally, with high densities in early to mid-summer, and low densities over winter.

Microinvertebrates – are easily seen denizens such as dragon-, May-, or Damselflies, or amphipods (scuds) or shrimp. Beware, some such as giant water bugs can deliver a memorable bite and regularly capture and consume small fish!

Catchment – is the land area from which water drains into a particular water body. It is identified from elevation maps or rectified photographs. Catchment size changes with scale of interest. For example, the catchment of Lake Ontario is composed of many small catchments of individual lakes, whereas most of us on smaller lakes look to the high points around our own lake and use those to draw in the boundary of the land that drains to the lake. Lakes represent the drain of the landscape where water accumulates. It serves us well to remember this, as the health of a lake will be reflective of what is happening in its catchment. It's easy to add something to a lake but much harder, if not impossible to remove it again.

Lake formation

Lakes can be classified by their basin type and the way in which they were created. Many lakes result from catastrophic geologic events, be it shifts in faults, volcanism, or the wandering of glaciers (think Great Lakes of North America, African Rift Valley lakes, or the lakes in the Sierra Nevada Mountains) that create divots in the landscape which fill with water. For example, consider one of my favorite types – kettle lakes – aptly named for their near vertical-sided basin shapes that are like a kettle. Each is formed upon burial of a sizeable chunk of ice that broke off from a retreating glacier. When the ice melts, it leaves behind a kettle-shaped depression. Interestingly, quaking bogs often occur atop kettle lakes after vegetation from the sides has gown inward in a floating mat to entirely cover the top of the kettle lake. Other examples of lake types include reservoirs created by dams – debris, landslides, beavers, and humans, and oxbow lakes formed from the pinching off of part of a meander river during a flood event. How was your favorite lake formed?

Water chemistry

Just as interesting as how a lake's basin is formed, is the geologic setting in which it occurs as this predominantly controls the water chemistry in the lake. A mnemonic I give to my students is that "Hard Rock equals Soft Water, and Soft Rock equals Hard Water." Soap or shampoo in the shower at the lake cabin will quickly reveal your geologic setting. A good lather indicates soft water, while a poor lather indicates hard water.

A geology of "soft" rocks such as sedimentary or limestone is readily weathered and materials are easily transported to a receiving water body; calcium and magnesium are chief among dissolved elements. In contrast, "hard" rocks such as granites and feldspar resist weathering and result in little transport of materials to lakes.

An accurate determination of the constituents in the water requires a laboratory analysis. A rough generalization is that hard water lakes tend to be more productive than soft water lakes. Another generalization is that certain organisms such as those requiring calcium for incorporation into body parts like shells will not occur in soft water lakes because of inadequate underlying base chemistry. Hence some lakes are thought to be less susceptible to hosting populations of the highly invasive zebra and quagga mussels (e.g., Karatayev et al. 2015; Mellina and Rasmussen 1994).

Base chemistry is also important in determining a lake's resistance to change under assaults of human inputs such as acid precipitation – soft water lakes such as those in the Adirondack Mountains. are highly susceptible (Driscoll and Newton 1985) compared to hardwater lakes elsewhere. It should also be noted that depending on the aquatic life present and their density, they can seasonally influence chemistry as well (e.g., Lehman 1980). While not readily apparent to us, water chemistry varies widely in different lakes across the landscape which has consequences for what we find in them.

Temperature and lake stratification

Perhaps one of the most striking features in moderately deep to deep lakes is the occurrence of temperature stratification, where a layer of warm, low-density water (termed the epilimnion) is atop a layer of cold, high-density water (termed the hypolimnion) throughout the summer (Figure 2; 3A). This is called "direct stratification" and is the result of differential heating of the water column. It has important consequences for the biotic communities in lakes. Because the epilimnion is in constant contact with the atmosphere gas exchange is good; it also contains the algae that produce oxygen via photosynthesis, which means that the dissolved oxygen saturation in this layer is typically near or above 100 percent. This is not necessarily the case in the hypolimnion.

In oligotrophic lakes, biotic biomass (aquatic life) is low and therefore oxygen consumption via respiration is low in the hypolimnion (bacteria consuming decomposing aquatic life in the bottom of the lake), which is cut off from gas exchange with the atmosphere during the stratified period when the top and bottom layer do not mix. Consequently, many oligotrophic lakes retain good concentrations of dissolved oxygen during stratification, allowing communities of cold-water fish to exist.

In contrast, in eutrophic lakes, there tends to be more aquatic life, and thus more organic material accumulates at the bottom of the lake. Its decomposition plus the respiration of biota in the deep water can consume all of the dissolved oxygen resulting in anoxia (lacking oxygen; Figure 3b). This absence of oxygen in the hypolimnion explains why eutrophic lakes typically only have fish species tolerant of warm water; fish requiring cold water are unable to survive in the hypolimnion due to the lack of dissolved oxygen. This is an excellent example of the interconnectedness among chemical (heat and oxygen), physical (temperature/density), and biological (type of fish) phenomena in our lakes.

The occurrence of low oxygen in the bottom waters has further chemical consequences that can affect nutrients, especially dissolved phosphorus, the biotic community (algae), and subsequently our ability to use a lake. Low or no oxygen in the hypolimnion can lead to chemistry changes in the lake sediment, that result in changing phosphorus from an immobile phase in the lake sediments to a phase that dissolves into the water column, a process known as internal loading of phosphorus.

When internal loading occurs, it is not uncommon for very high concentrations of dissolved phosphorus to build up in the hypolimnion (Figure 3C), some of which can be transferred to the epilimnion by wind and wave action, diffusion and/or the movement of organisms from deep in the lake to the upper water layer. Should this occur, algae in the epilimnion receive a phenomenal boost of nutrients that stimulates a spurt of growth termed a bloom. Because of the overabundance of phosphorus, nitrogen now becomes the limiting nutrient which provides a competitive advantage to cyanobacteria, a group of algae capable of fixing their own nitrogen from the atmosphere, *and* also capable of producing some of the most potent toxins known to humans (Chorus and Bartram 1999). In such cases the bloom is termed a "harmful algal bloom" (HAB), especially if toxins are present that results in the issuing of no-contact advisories for the duration of the bloom. Obviously, such an occurrence detracts greatly from the value of our aquatic resources at multiple levels.

This temperature-chemistry relationship again demonstrates the interconnectedness of the physical, chemical, and biological relationships that occur in aquatic ecosystems. As you can imagine with such interconnectedness, managing lakes is not a trivial task. It also demonstrates that we must consider lakes holistically before undertaking any actions to avoid any unintended consequences.

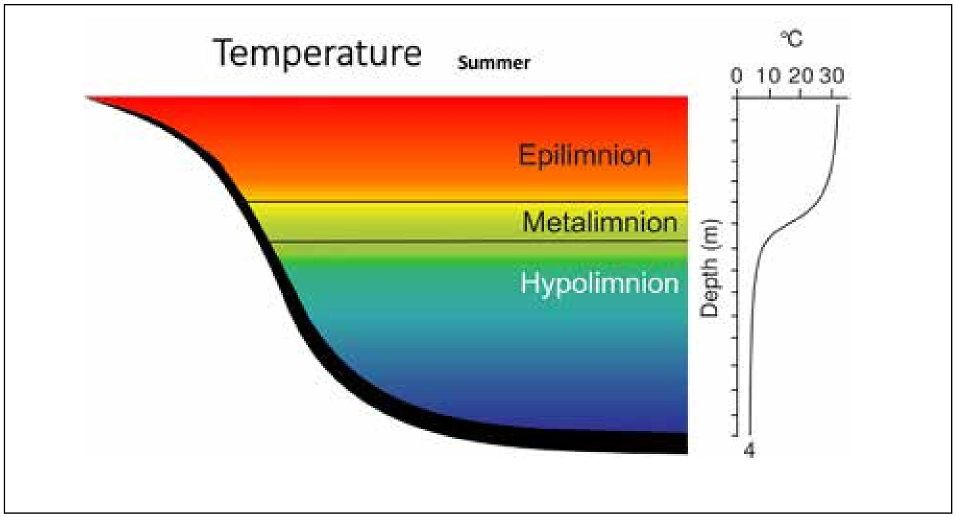

Figure 2. Temperature zonation for a directly stratified deep lake showing warm less dense water in the epilimnion atop the hypolimnion with cold and high-density water at the bottom.

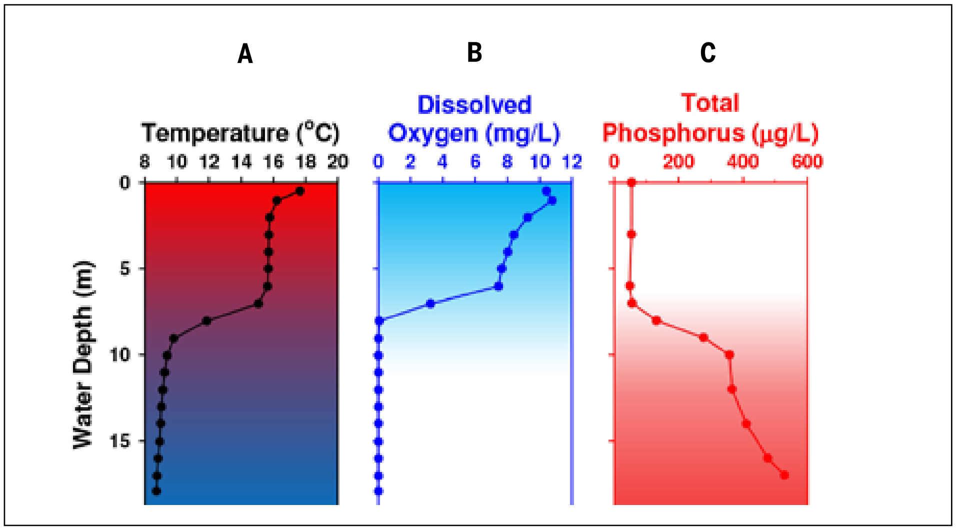

Figure 3. Profiles of Temperature (A), Dissolved oxygen (B), and Total phosphorus (C) as a function of depth in Willow Creek Reservoir, OR, on September 24, 2018, showing anoxia below the thermocline and high internal loading of phosphorus (data from Figure 3C courtesy of S. Burnet).

Further Reading

While I've only touched on some common relationships and connections that occur in lakes, they should serve to illustrate the complexity of what happens under the water surface. It's a fascinating world, and I encourage you to dive in deeper to learn more. A plethora of resources exist for your further exploration of our aquatic ecosystems.

NALMS has a series of easily accessible guides, starting with *Your Lake and You* (https://www.nalms.org/product/your-lake-you-2nd-edition/), and *The Lake Pocketbook* (https://www.nalms.org/nalms-publications/). More technical reference texts include *Limnology: Lake and River Ecosystems* (R.G. Wetzel, 3rd ed. Elsevier), *Freshwater Ecology* (W. Dodds and M. Whiles, Elsevier), *Textbook of Limnology* (Cole and Weihe, Waveland Press), *Limnology* (Horne and Goldman 2nd ed) and *Lake and Reservoir Restoration* (Cooke et al. Elsevier).

Great resources are also available on the web such as Water on the Web (https://www.waterontheweb.org/), and the U.S. Geologic Survey (https://www.usgs.gov/special-topic/water-science-school/science/lakes-and-reservoirs?qt-science_center_objects=0#qt-science_center_objects).

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Frank M. Wilhelm is a professor in the Department of Fish and Wildlife Sciences in the College of Natural Resources at the University of Idaho, where he teaches under- and graduate courses in limnology. His research is focused on whole-lake nutrient budgets, the occurrence of harmful algal blooms and their mitigation, and the effects of wakes on resuspension of sediment and nutrients in the nearshore area of lakes. He is also is a past president of NALMS.