2.0 General Concepts in Lake Water Quality

There are a number of concepts and terminology that are necessary to describe and evaluate a lake's water quality. This section is a brief discussion of those concepts, divided into the following topics:

- Eutrophication
- Trophic states
- Limiting nutrients
- Stratification
- Nutrient recycling and internal loading

To learn more about these five topics, one can refer to any text on limnology (the science of lakes and streams).

2.1 Eutrophication

Eutrophication, or lake degradation, is the accumulation of sediments and nutrients in lakes. As a lake naturally becomes more fertile, algae and weed growth increases. The increasing biological production and sediment inflow from the lake's watershed eventually fill the lake's basin. Over a period of many years the lake successively becomes a pond, a marsh and, ultimately, a terrestrial site. This process of eutrophication is natural and results from the normal environmental forces that influence a lake. Cultural eutrophication, however, is an acceleration of the natural process caused by human activities. Nutrient and sediment inputs (i.e., loadings) from wastewater treatment plants, septic tanks, and stormwater runoff can far exceed the natural inputs to the lake. The accelerated rate of water quality degradation caused by these pollutants results in unpleasant consequences. These include profuse and unsightly growths of algae (algal blooms) and/or the proliferation of rooted aquatic weeds (macrophytes).

2.2 Trophic States

Not all lakes are at the same stage of eutrophication; therefore, criteria have been established to evaluate the nutrient status of lakes. Trophic state indices (TSIs) are calculated for lakes on the basis of total phosphorus, chlorophyll *a* concentrations, and Secchi disc transparencies. TSI values range upward from 0, describing the condition of the lake in terms of its trophic status (i.e., its degree of fertility). All three of the parameters can be used to determine a TSI. However, water transparency is typically used to develop the TSI_{SD} (trophic state index based on Secchi disc transparency) because people's perceptions of water clarity are often directly related to recreational-use impairment. The TSI rating system results in the placement of a lake with medium fertility in the mesotrophic trophic status category. Water quality trophic status categories include oligotrophic (i.e., excellent water quality), mesotrophic (i.e., good water quality), eutrophic (i.e., poor water quality), and hypereutrophic (i.e., very poor water quality). Water quality characteristics of lakes in the various trophic status categories are listed below with their respective TSI ranges:

1. **Oligotrophic** – [$20 \leq TSI_{SD} \leq 38$] clear, low productive lakes, with total phosphorus concentrations less than or equal to 10 μg/L, chlorophyll *a* concentrations of less than or equal to 2 μg/L, and Secchi disc transparencies greater than or equal to 4.6 meters (15 feet).
2. **Mesotrophic** – [$38 \leq TSI_{SD} \leq 50$] intermediately productive lakes, with total phosphorus concentrations between 10 and 25 μg/L, chlorophyll *a* concentrations between 2 and 8 μg/L, and Secchi disc transparencies between 2 and 4.6 meters (6 to 15 feet).
3. **Eutrophic** – [$50 \leq TSI_{SD} \leq 62$] high productive lakes relative to a neutral level, with 25 to 57 μg/L total phosphorus, chlorophyll *a* concentrations between 8 and 26 μg/L, and Secchi disc measurements between 0.85 and 2 meters (2.7 to 6 feet).
4. **Hypereutrophic** – [$62 \leq TSI_{SD} \leq 80$] extremely productive lakes which are highly eutrophic and unstable (i.e., their water quality can fluctuate on daily and seasonal basis, experience periodic anoxia and fish kills, possibly produce toxic substances, etc.) with total phosphorus concentrations greater than 57 μg/L, chlorophyll *a* concentrations of greater than 26 μg/L, and Secchi disc transparencies less than 0.85 meters (2.7 feet).

Determining the trophic status of a lake is an important step in diagnosing water quality problems. Trophic status indicates the severity of a lake's algal growth problems and the degree of change needed to meet its recreational goals. Additional information, however, is needed to determine the cause of algal growth and a means of reducing it.

2.3 Limiting Nutrients

The quantity or biomass of algae in a lake is usually limited by the water's concentration of an essential element or nutrient "the limiting nutrient". (For rooted aquatic plants, the nutrients are derived from the sediments.) The limiting nutrient concept is a widely applied principle in ecology and in the study of eutrophication. It is based on the idea that plants require many nutrients to grow, but the nutrient with the lowest availability, relative to the amount needed by the plant, will limit plant growth. It follows then, that identifying the limiting nutrient will point the way to controlling algal growth .

Nitrogen (N) and phosphorus (P) are generally the two growth-limiting nutrients for algae in most natural waters. Analysis of the nutrient content of lake water and algae provides ratios of N:P. By comparing the ratio in water to the ratio in the algae, one can estimate whether a particular nutrient may be limiting. Algal growth is generally phosphorus-limited in waters with N:P ratios greater than 12. Laboratory experiments (bioassays) can demonstrate which nutrient is limiting by growing the algae in lake water with various concentrations of nutrients added. Bioassays, as well as fertilization of in-situ enclosures and whole-lake experiments, have repeatedly demonstrated that phosphorus is usually the nutrient that limits algal growth in freshwaters. Reducing phosphorus in a lake, therefore, is required to reduce algal abundance and improve water transparency. Failure to reduce phosphorus concentrations will allow the process of eutrophication to continue at an accelerated rate.

2.4 Stratification

The process of internal loading is dependent on the amount of organic material in the sediments and the depth-temperature pattern, or "thermal stratification," of a lake. Thermal stratification profoundly influences a lake's chemistry and biology. When the ice melts and air temperature warms in spring, lakes generally progress from being completely mixed to stratified with only an upper warm well-mixed layer of water (epilimnion), and cold temperatures in a bottom layer (hypolimnion). Because of the density differences between the lighter warm water and the heavier cold water, stratification in a lake can become very resistant to mixing. When this occurs, generally in mid-summer, oxygen from the air cannot reach the bottom lake water and, if the lake sediments have sufficient organic matter, biological activity can deplete the remaining oxygen in the hypolimnion. The epilimnion can remain well-oxygenated, while the water above the sediments in the hypolimnion becomes completely devoid of dissolved oxygen (anoxic). Complete loss of oxygen changes the chemical conditions in the water and allows phosphorus that had remained bound to the sediments to reenter the lake water.

As the summer progresses, phosphorus concentrations in the hypolimnion can continue to rise until oxygen is again introduced (recycled). Dissolved oxygen concentration will increase if the lake sufficiently mixes to disrupt the thermal stratification. Phosphorus in the hypolimnion is generally not available for plant uptake because there is not sufficient light penetration to the hypolimnion to allow for growth of algae. The phosphorus, therefore, remains trapped and unavailable to the plants until the lake is completely mixed. In shallow lakes this can occur throughout the summer, with sufficient wind energy (polymixis). In deeper lakes, however, only extremely high wind energy is sufficient to destratify a lake during the summer and complete mixing only occurs in the spring and fall (dimixis). Cooling air temperature in the fall reduces the epilimnion water temperature, and consequently increases the density of water in the epilimnion. As the epilimnion water density approaches the density of the hypolimnion water very little energy is needed to cause complete mixing of the lake. When this fall mixing occurs, phosphorus that has built up in the hypolimnion is mixed with the epilimnion water and becomes available for plant and algal growth.

2.5 Nutrient Recycling and Internal Loading

The significance of thermal stratification in lakes is that the density change in the metalimnion (middle transitional water temperature stratum) provides a physical barrier to mixing between the epilimnion and the hypolimnion. While water above the metalimnion may circulate as a result of wind action, hypolimnetic waters at the bottom generally remain isolated. Consequently, very little transfer of oxygen occurs from the atmosphere to the hypolimnion during the summer.

Shallow water bodies may circulate many times during the summer as a result of wind mixing. Lakes possessing these wind mixing characteristics are referred to as **polymictic** lakes. In contrast, deeper lakes generally become well-mixed only twice each year. This usually occurs in the spring and fall. Lakes possessing these mixing characteristics are referred to as **dimictic** lakes. During these periods, the lack of strong temperature/density differences allow wind-driven circulation to mix the water column throughout. During these mixing events, oxygen may be transported to the deeper portions of the lake, while dissolved phosphorus is brought up to the surface.

Phosphorus enters a lake from either watershed runoff or direct atmospheric deposition. It would, therefore, seem reasonable that phosphorus in a lake can decrease by reducing these external loads of phosphorus to the lake. All lakes, however, accumulate phosphorus (and other nutrients) in the sediments from the settling of particles and dead organisms. In some lakes this reservoir of phosphorus can be reintroduced in the lake water and become available again for plant uptake. This resuspension or dissolution of nutrients from the sediments to the lake water is known as “internal loading”. As long as the lake’s sediment surface remains sufficiently oxidized (i.e., dissolved oxygen remains present in the water above the sediment), its phosphorus will remain bound to sediment particles as ferric hydroxy phosphate. When dissolved oxygen levels become extremely low at the water-sediment interface (as a result of microbial activity using the oxygen), the chemical reduction of ferric iron to its ferrous form causes the release of dissolved phosphorus, which is readily available for algal growth, into the water column. The amount of phosphorus released from internal loading can be estimated from depth profiles (measurements from surface to bottom) of dissolved oxygen and phosphorus concentrations. Even if the water samples indicate the water column is well oxidized, the oxygen consumption by the sediment during decomposition can restrict the thickness of the oxic sediment layer to only a few millimeters. Therefore, the sediment cannot retain the phosphorus released from decomposition or deeper sediments, which results in an internal phosphorus release to the water column. Low-oxygen conditions at the sediments, with resulting phosphorus release, are to be expected in eutrophic lakes where relatively large quantities of organic material (decaying algae and macrophytes) are deposited on the lake bottom.

If the low-lying phosphorus-rich waters near the sediments remain isolated from the upper portions of the lake, algal growth at the lake's surface will not be stimulated. Shallow lakes and ponds can be expected to periodically stratify during calm summer periods, so that the upper warmer portion of the water body is effectively isolated from the cooler, deeper (and potentially phosphorus-rich) portions. Deep lakes typically retain their stratification until cooler fall air temperatures allow the water layers to become isothermal and mix again. However, relatively shallow lakes (such as Keller Lake) are less thermally stable and may mix frequently during the summer periods. Shallow lakes are, therefore, frequently polymictic, experiencing alternating periods of stratification and destratification. It is the destratification, brought about by wind-induced mixing of the water column, that re-introduces phosphorus to the upper (epilimnetic) portion of the lake.

The pH of the water column can also play a vital role in affecting the phosphorus release rated under oxic conditions. Photosynthesis by macrophytes and algae during the day tend to raise the pH in the water column, which can enhance the phosphorus release rate from the oxic sediment. Enhancement of the phosphorus release at elevated pH (pH > 7.5) is thought to occur through replacement of the phosphate ion (PO_4^{-3}) with the excess hydroxyl ion (OH^-) on the oxidized iron compound (James, et al., 2001).

Another potential source of internal phosphorus loading is the die-off of curlyleaf pondweed, an exotic (i.e., non-native) lake weed present in all three lakes. Curlyleaf pondweed grows vigorously during early-spring, crowding out native species. It releases a small reproductive pod that resembles a small pinecone during late-June. After curlyleaf pondweed dies out in early-July, it may sink to the lake bottom and decay, causing oxygen depletion and exacerbating internal sediment release of phosphorus. This potential increase in phosphorus concentration during early-July likely could result in an algal bloom during the peak of the recreational-use season (the fourth of July).