# Chapter 4 – Overview
## Limnological Characteristics, Productivity and Eutrophication of Portage Lakes

Lakes are affected by – and affect - complex interactions of biological, chemical, and meteorological conditions, landscape, and physical lake characteristics, at scales ranging from microscopic to lake- and watershed-wide. This chapter presents background on lake processes and discusses the limnological characteristics of the Portage Lakes.

The Portage Lakes are predominantly in the shallow littoral zone, where rooted plants grow, an ecologically important area, where people interact with the lakes. The lakes are eutrophic: Excessive phosphorus drives dense plant growth and could fuel Harmful Algal Blooms. Reducing the phosphorus loading from the watershed and within the lakes is crucial to protecting the health of the lakes. Plant management is key to reducing internal phosphorus loading.

### Chapter Organization

# 4. Limnological Characteristics, Productivity and Eutrophication of Portage Lakes

Limnology is the study of inland freshwater ecosystems:

- Physical, chemical, biological, geological, meteorological factors affecting the ecosystems
- Dynamics and interaction between them
- Productivity, the amount of plant or animal material (biomass) a lake can support

The volume and location of plants is what lake residents and visitors experience from homes, boats, beaches, fishing access points, and businesses. The abundance of aquatic plants in the Portage Lakes is a measure of their productivity.  The productivity of the lakes is *affected by* lake characteristics, and in turn, *affects* certain aspects of the lakes.

- Plants and algae are at the base of the food web of the lakes, producing oxygen and providing food and habitat for fish and other animals.
- Productivity ⟵ *reflects* lake environments, inputs, conditions, health, and disturbances.
- Productivity *affects* ⟶ lake conditions - water clarity, oxygen, nutrients, water quality.

The uses and value of the lakes depend on good lake health and water quality, which depend in large part on the lake ecosystem and productivity. This chapter looks at some of the components of the lakes ecology. Chapter 5 focuses on aquatic plants.

## Life in Lake Systems – Producers, Consumers, Decomposers, and Building Blocks[1]

In order to address Portage Lakes aquatic plants and productivity, it is necessary to understand the factors affecting how the lakes work and the plants and animals living there. Lakes are complex systems, affected by combinations of many characteristics - physical, geological, biological, and chemical - operating at vastly different scales. Examples include:

- Factors operating at a lake or watershed-wide scale include wind, sunlight, basin shape and depth, lakewide nutrient availability, and watershed inputs.
- Factors operating at a minute scale include invertebrates foraging and burrowing among aquatic plants, algae generating oxygen, or nutrients being released from pore water in the sediment.

The Portage Lakes – and their health - are the result of interactions of these systems.

### Photosynthesizers (Primary Producers), Consumers, Decomposers

Plants, algae, diatoms, and cyanobacteria are *primary producers*. They can be rooted or floating, microscopic (phytoplankton) or macroscopic (macrophytes). Photosynthesizers convert light energy and chemicals- nutrients- into organic material – fats, starches, sugars, proteins - which is the base of the food web and makes up living things. At excessive levels of nutrients, plant, algae, or cyanobacteria ("blue-green algae") growth can become a nuisance.

*Consumers* are those that feed on the primary producers or animals higher up the food web. *Decomposers* feed on decaying organic material, breaking it down again into available nutrients.

### Building Blocks of Life – Energy and Chemicals

*Light and temperature (heat)*– Plants and algae need light for photosynthesis. The depth that light penetrates determines how deep photosynthesizers can grow (down to one percent of light at the surface) and also affects water temperature. Cloudy (turbid) water reduces light penetration but increases the temperature in the surface, as the particles absorb and release heat. Water temperature affects density and stratification, dissolved oxygen, and animal metabolism.

*Tall plants can live in deeper water, as they can reach up toward the light. Light penetrates deeper in clear water, so plants can grow deeper. Left, short lily pads; center, tall Eurasian watermilfoil; right, eel grass. Portage Lakes examples.*

*Nutrients* (*phosphorus*)- The primary nutrients that plants need are carbon, nitrogen, and phosphorus.

- In freshwater systems, carbon and nitrogen are plentiful.
- Phosphorus is the *limiting nutrient* – adding phosphorus increases plant and algae growth. Algae blooms occur after an input of dissolved phosphorus, from bottom waters or stormwater runoff.
- Most phosphorus comes from decomposed organic matter –animal waste or dead plants, algae, animals (or pieces cast off from them)- and added chemicals. Some comes from soil or rock.
- Phosphorus enters the lakes *externally*, through streams, discharge, or runoff, or is released *internally*, within the lakes, during decomposition of organic material or from phosphorus stored in sediment. Particulate phosphorus is not readily available for growth, but in low oxygen (anoxic) conditions, it is released as dissolved phosphorus, which photosynthesizers can use.
- Phosphorus is recycled many times and builds up in the sediment over time. One pound of phosphorus input can yield hundreds of pounds of biomass.
- Phosphorus is recycled from sediment in deep oxygen-poor water or by disturbance, zebra mussels, and plant growth in shallow water.

Note: recent research shows that nitrogen availability affects growth and toxicity of Harmful Algal Blooms.[2] This will be further studied in later lakes work.

*Photosynthesis at work – oxygen bubbles under mats of filamentous green algae.*

*Oxygen* –is essential for living things, which take in oxygen and give off carbon dioxide when they respire. Certain bacteria live in anoxic conditions.

- Plants generate oxygen during photosynthesis (daylight) but use oxygen in respiration all the time.
- Decay of organic material, a biological process, uses oxygen.
- Concentrations of dissolved oxygen (DO) in water are very low compared to air. Well-saturated water has 10 parts per *million* (ppm or milligrams per liter, mg/l). Air has 21 percent (parts per *hundred*) of oxygen.
- Cold water holds more dissolved oxygen than warm water.
- Coldwater species of fish, salmonids, require the highest amounts of dissolved oxygen to survive and are very sensitive to changes in temperature or dissolved oxygen levels.
- Most game fish need from 5 to 8 ppm of oxygen. Few fish can survive less than that, and when the levels reach 1 or 2 ppm, no fish can survive.

## Physical Setting: Lake Morphometry (Study of Form), Depth, Location, Watershed

Morphometry is the measurement of lakes' external form. The size, shape, watershed, and connection to other water bodies affects what inputs – characteristics and amount of water, energy, and materials - that enter and move through the lakes.

Lake size and depth affect:

- The amount of water and substrate with enough light to support plant and algae growth
- Temperature differences throughout the water column, which influences water mixing, availability of oxygen and nutrients, plant and algae growth and the biological communities.

The shape of the lakes and location in the watershed also affect how lakes work:

- The shape affects how much of the lakes is margin, the productive area where shallow plant communities can live, and the area most susceptible to influence from the landscape.
- Kettle lakes are isolated and often small, and lakes in the headwaters have small watersheds. There is little input from the surrounding landscape, greater influence by groundwater, and little opportunity to flush the system. They are very susceptible to changes in the landscape.
- Reservoirs and lakes along rivers are affected by the flow of water and materials from a larger watershed. The inputs are greater, but with small lakes like the Portage Lakes, there is more opportunity for flushing. There may be more shallow areas than kettle lakes. The water levels may fluctuate greatly during flood season, which affects plant growth and nearshore habitats.
- Lakes with complex shapes and longer shorelines are more affected by influences from the land.
- How much of the shoreline or watershed are natural or altered affects inputs to the lakes and shoreline habitat. (Chapter 5 - shoreline habitat; Chapter 6 - watershed characteristics.)

## Depth, Light, and Substrate - Zones of Lakes

Lake zones influence the kind of communities supported in each area, depending on available light and substrate. The numbers refer to Figure 4.1.

*1 - Littoral Zone,* the nearshore, is the where rooted plants live. In this productive area of the lake, rooted plants provide habitat, substrate, food, shelter, spawning area, flowers that attract insects. It is also where people's activities directly contact a fragile, important lake habitat.

*2 - Limnetic Zone*– open water - light does not reach the bottom of the lake.

*3 - Euphotic/photic zone,* penetrating light supports photosynthesis –both littoral and limnetic zones. Primary producers in the open-water photic zone are phytoplankton (microscopic floating photosynthesizers).

*4 – Aphotic/profundal zone*, the deepest areas where not enough light penetrates for photosynthesis. Some fish here have barbels to feel for food.

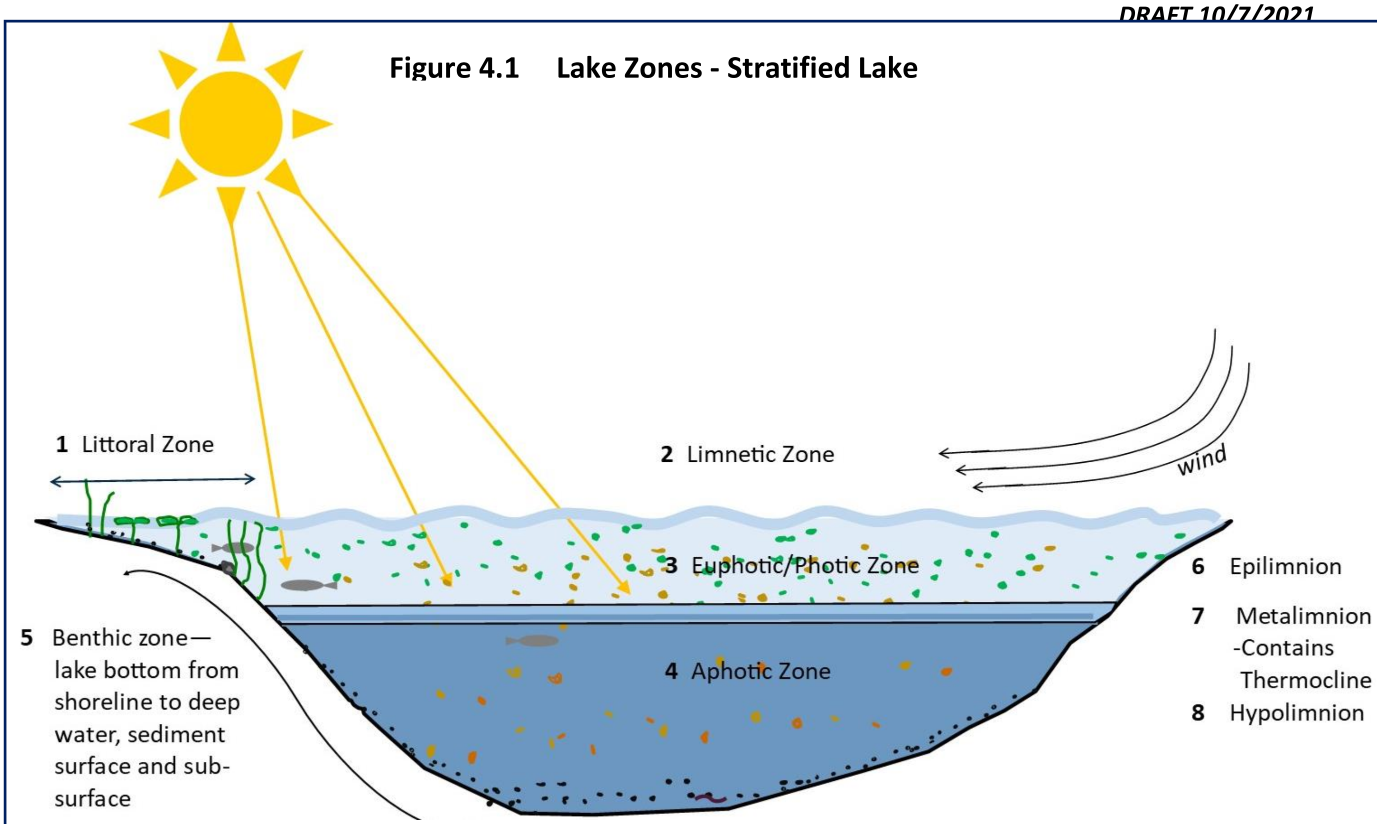
*5 - Benthic Zone* – the bottom of the lake and substrate, from shoreline to the deepest water. In the shallow water, the benthic zone provides habitat for many species of benthos (bottom-dwellers), spawning ground, and, because of the plants, a complex substrate supporting various invertebrates. In the deep waters, the benthos are mostly burrowers, feeding on material falling from the euphotic zone. The benthic zone is where decomposers consume dead organisms, releasing nutrients to be re-used.

*Top- Littoral zone with floating-leaved and submerged plants. Middle - Limnetic, photic zone (photosynthesis by algae here). Bottom, shallow, sandy benthic. habitat. Many benthic areas are covered with decaying plants. Examples from Portage Lakes*

## Vertical Zones - Stratification and Turnover– Interaction of Depth, Light, Temperature, Density

Lake stratification is the layering of the lake by density. It affects what nutrients are available. The density of water changes with temperature. Water of less density floats on top of water of higher density, and there is little mixing between the layers. The density of lake water is affected by sunlight, air temperature, and mixing by wind and waves. Figure 4.1 shows layers in a stratified lake.

**Figure 4.1 Lake Zones - Stratified Lake**




*6. - Epilimnion* - During the summer, the upper layers of the lake, are warmed by the sun and mixed by wind and waves and may be around 75 degrees F or more. As the sun warms the layer, it becomes less dense. This layer often coincides with the depth that enough light penetrates to support plants. Rooted plants grow in the littoral zone, but floating algae lives in the epilimnion throughout the lake.

*7. - Metalimnion* - In between the upper and lower waters is a zone of temperature change. It contains the thermocline, the zone of greatest temperature change. Many swimmers have experienced the thermocline, the sudden coldness at depth.

*8. - Hypolimnion* - The lowest, coldest water, perhaps around 45 degrees F, is densest. Decomposition of dead organisms in the hypolimnion releases nutrients that remain there until conditions change.

During the summer, the temperature and density differences between the upper and lower layers become so great that there is almost no mixing through the thermocline.

## Low Oxygen and Phosphorus Release

Decomposition of dead organisms at the bottom uses oxygen and releases phosphorus. Dissolved phosphorus released to the water is immediately available for use. Particulate phosphorus is stored in the sediment, but in anoxic conditions, particulate phosphorus is dissolved and can fuel growth.

- Stratified lakes may develop an anoxic hypolimnion, because oxygen-rich surface waters do not mix with the deeper water where decomposition uses oxygen. In these anoxic zones, the particulate phosphorus is dissolved and enters the water, reaching the surface waters if mixed. .
- Water between sediment particles (pore water) is also often anoxic, even in shallow lakes. Sediment disturbance and mixing often brings dissolved phosphorus from the sediment into the water column, where it can fuel growth. Weakly stratified lakes are more likely to mix.

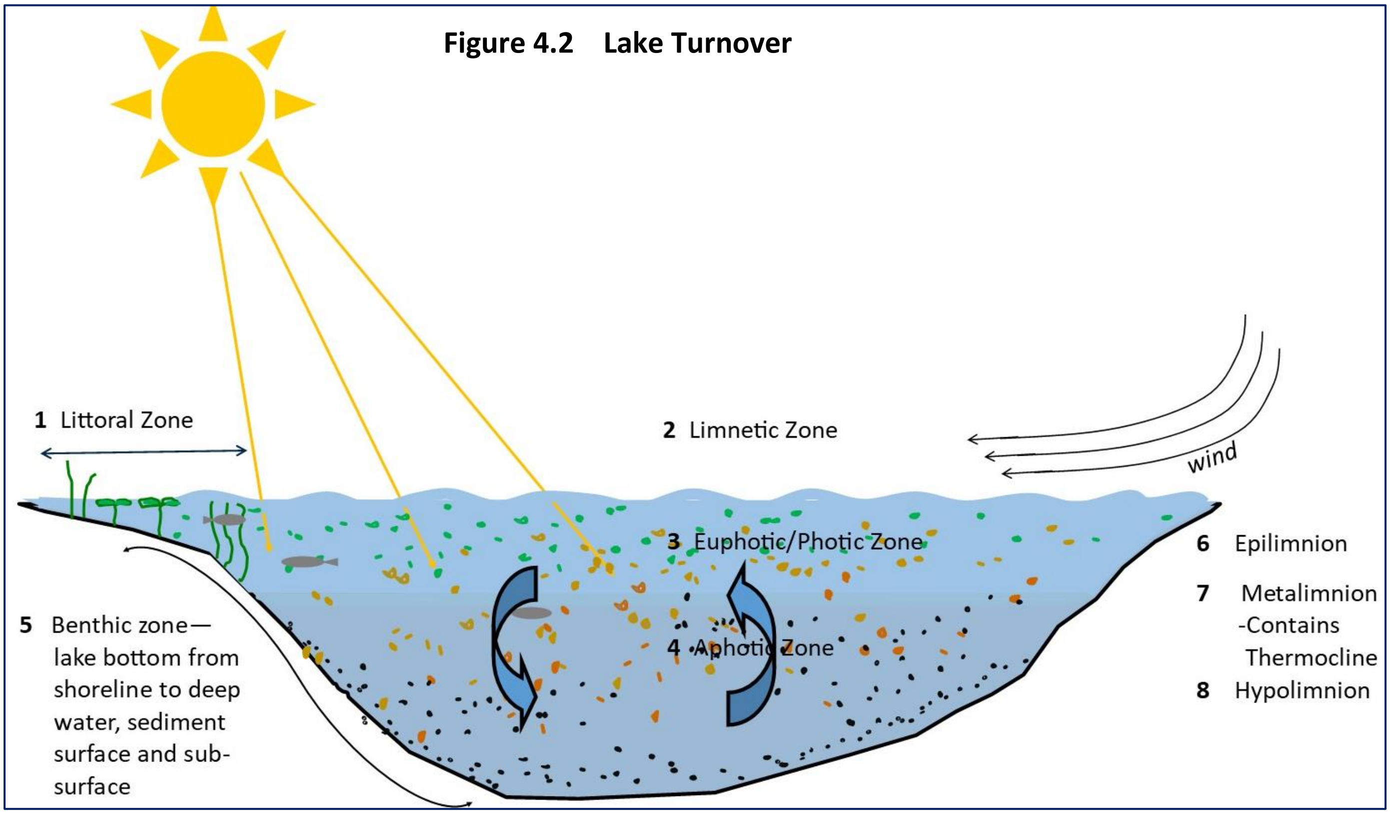
Anoxic zones are typical of deep basins in many lakes. Fish that tolerate warmer surface waters migrate to where the oxygen is. However, if the surface is too warm, or too much of the lake volume becomes anoxic, fisheries may be affected, as in the "Dead Zones" of Lake Erie or the Gulf of Mexico.

## Other Seasons and Turnover

During the winter, the lake is essentially stratified if it is covered with ice. Water is densest at 39° F (4°C); water at or near the freezing point floats. The dense water near the bottom is close to 40 degrees Fahrenheit, and the less dense ice and melt water is at the surface.

In spring and fall, changes in the air temperature and amount of sunlight warm or cool the water from the surface down. With less difference in temperature and density between the surface and bottom waters, the wind, waves, and changing density gradually mix the water deeper. (Figure 4.2) This mixing allows the nutrient-rich bottom waters to rise to the surface, and the oxygen-rich upper water to be mixed in at depth, known as turnover. The influx of nutrients supports new growth of plants and algae.

**Figure 4.2 Lake Turnover**

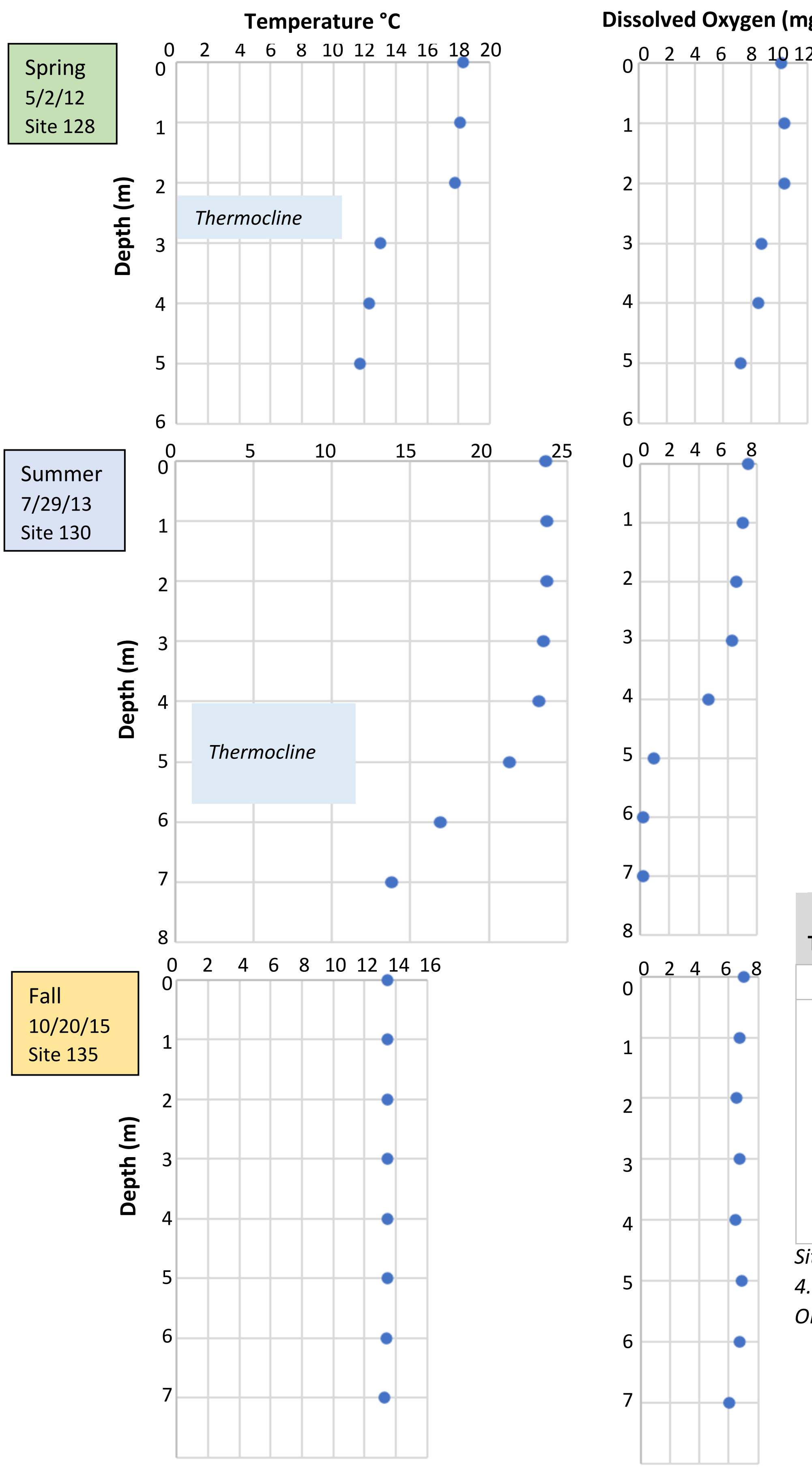



## Limnological Profiles – Measuring and Depicting Conditions through the Lake Depths

Lake stratification, turnover, and oxygen levels are determined by measuring lake characteristics by depth during different seasons. The example limnological profiles in Figure 4.3, from locations in Turkeyfoot Lake, show typical seasonal conditions of temperature, oxygen, and thermocline:[3]

- Spring – Warming water, thermocline developing, oxygen decreases at depth but still high
- Summer – Surface much warmer than bottom, oxygen depletion below thermocline
- Fall – Thoroughly mixed

**Figure 4.3 Example Limnological Profiles Showing Stratification and Mixing, Turkeyfoot Lake**




| Conversions | | | |
|---|---|---|---|
| Temperature | | Length | |
| °C | °F | m | ft |
| 0 | 32 | 1 | 3.3 |
| 5 | 41 | 2 | 6.6 |
| 10 | 50 | 3 | 9.8. |
| 15 | 59 | 4 | 13.1 |
| 20 | 68 | 5 | 16.4 |
| 25 | 77 | 6 | 19.7 |
| 30 | 86 | 7 | 23.0 |

*Site numbers refer to Map 4.3. Data source: C. Wagner, ODNR Div. of Wildlife, 2020*

## Portage Lakes Morphometry (Form) Related to Depth, Lake Zones, and Watershed

This section discusses the morphometry of the Portage Lakes and how it relates to various aspects of the lakes. Table 4.1 and Map 4.1 present the characteristics for each lake.[4] Figures 4.4 and 4.5 summarize the characteristics of the Portage Lakes system.

### Depth

Depth influences littoral and photic zones, stratification, and influence by waves.

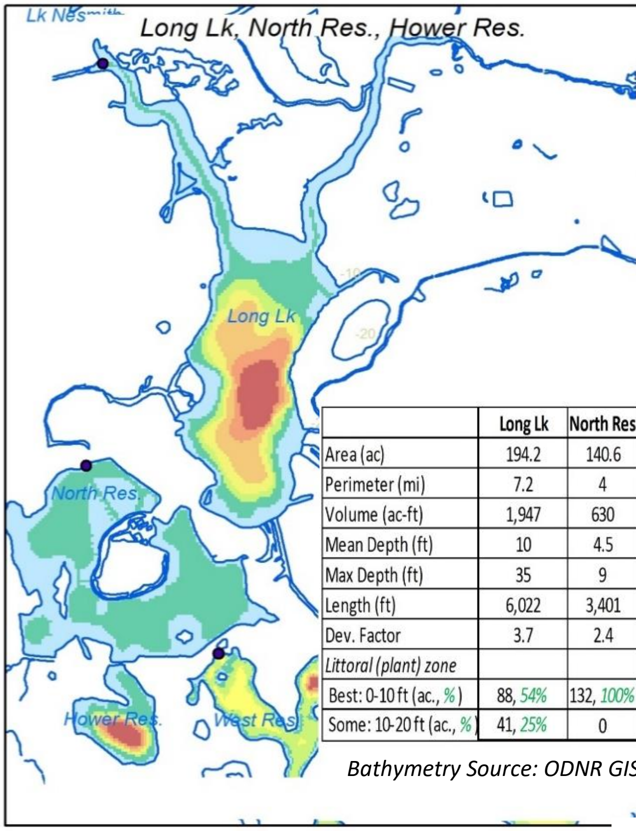
- The Portage Lakes are relatively shallow, with an overall mean depth of 11.2 feet, and mean depths ranging from 4.5 feet in North Reservoir, to 14.6 feet in Turkeyfoot Lake.
- From 70 to 100 percent of each lake is in the shallow littoral zone, where aquatic plants grow.
- Several lakes have extensive shallow areas that will be more affected by waves and mixing.
- The deepest areas are in Turkeyfoot, Long, Hower, and Mud Lakes, and West Reservoir. In these basins, water at depth may not circulate and mix with water from other areas in the lakes. They may become anoxic at depth: The large epilimnion generates a great deal of algae, which uses up oxygen at depth during decomposition, and the small basins have limited oxygen stored.

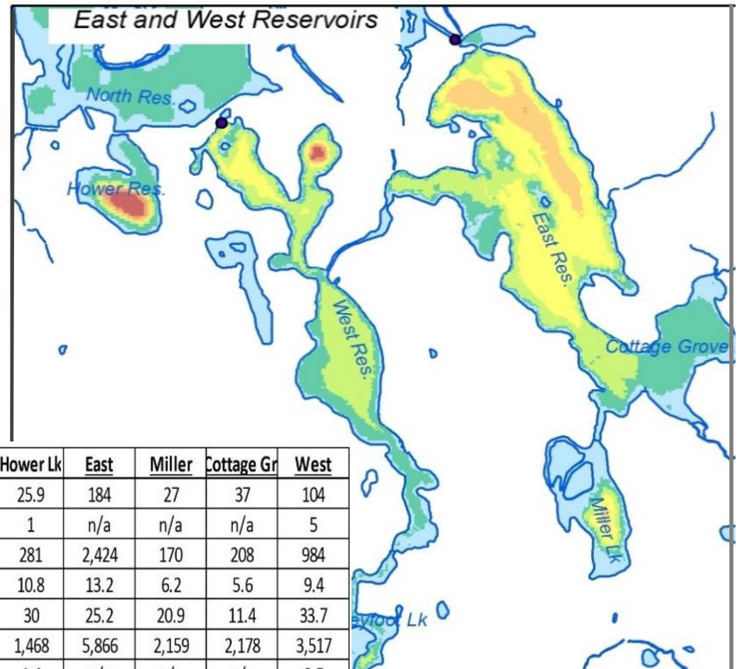
**Table 4.1 Lake Morphology Characteristics**

| | Long Lk | North Res | Hower Lk | East | Miller | Cottage Gr. | West |
|---|---|---|---|---|---|---|---|
| Area (ac) | 194.2 | 140.6 | 25.9 | 184 | 27 | 37 | 104 |
| Perimeter (mi) | 7.2 | 4 | 1 | n/a | n/a | n/a | 5 |
| Volume (ac-ft) | 1,947 | 630 | 281 | 2,424 | 170 | 208 | 984 |
| Mean Depth (ft) | 10 | 4.5 | 10.8 | 13.2 | 6.2 | 5.6 | 9.4 |
| Max Depth (ft) | 35 | 9 | 30 | 25.2 | 20.9 | 11.4 | 33.7 |
| Length (ft) | 6,022 | 3,401 | 1,468 | 5,866 | 2,159 | 2,178 | 3,517 |
| Dev. Factor | 3.7 | 2.4 | 1.4 | n/a | n/a | n/a | 3.5 |
| *Littoral (plant) zone* | | | | | | | |
| Best: 0-10 ft (ac., *%*) | 88, *54%* | 132, *100%* | 15, *62%* | 50, *27%* | 20, *73%* | 37, *100%* | 53, *50%* |
| Some: 10-20 ft (ac., *%*) | 41, *25%* | 0 | 3, *13%* | 113, *62%* | 7, *24%* | 0 | 50, *48%* |

| | Turkeyfoot-Rex-Mud | Turkeyfoot | Rex | Mud | Nimisila |
|---|---|---|---|---|---|
| Area (ac) | 504 | 366 | 53 | 85 | 769 |
| Perimeter (mi) | 16.1 | n/a | n/a | n/a | 15.5 |
| Volume (ac-ft) | 7,027 | 5,322 | 566 | 1,139 | 8,607 |
| Mean Depth (ft) | 14 | 14.6 | 10.7 | 13.4 | 11.2 |
| Max Depth (ft) | 61.2 | 61.2 | 42 | 25.8 | 31.8 |
| Length (ft) | 8,079 | 4,698 | 2,773 | 3,684 | 9,827 |
| Dev. Factor | 5.1 | n/a | n/a | n/a | 4.0 |
| *Littoral (plant) zone* | | | | | |
| Best: 0-10 ft (ac., *%*) | 273, *54%* | 199, *54%* | 28, *52%* | 46, *54%* | 349, *48%* |
| Some: 10-20 ft (ac., *%*) | 121, *24%* | *84, 23%* | 22, *41%* | 15, *18%* | 267, *37%* |

## Map 4.1 Lake Characteristics - Portage Lakes




| | Long Lk | North Res | Hower Lk | East | Miller | Cottage Gr | West |
|---|---|---|---|---|---|---|---|
| Area (ac) | 194.2 | 140.6 | 25.9 | 184 | 27 | 37 | 104 |
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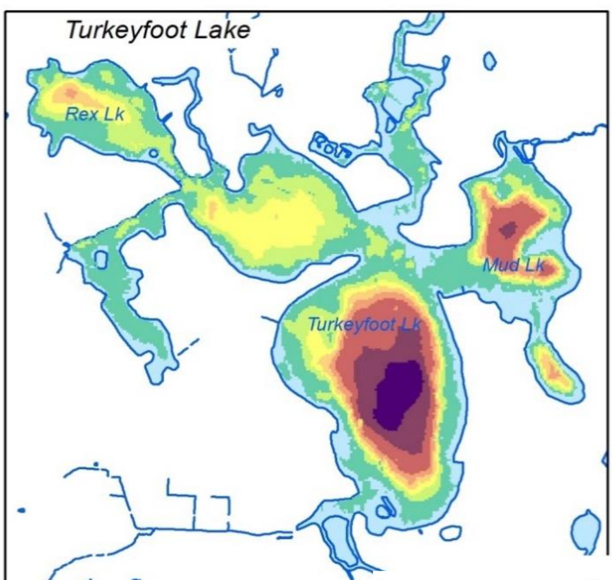
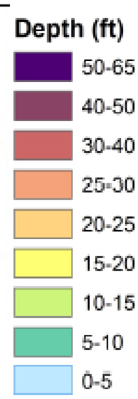
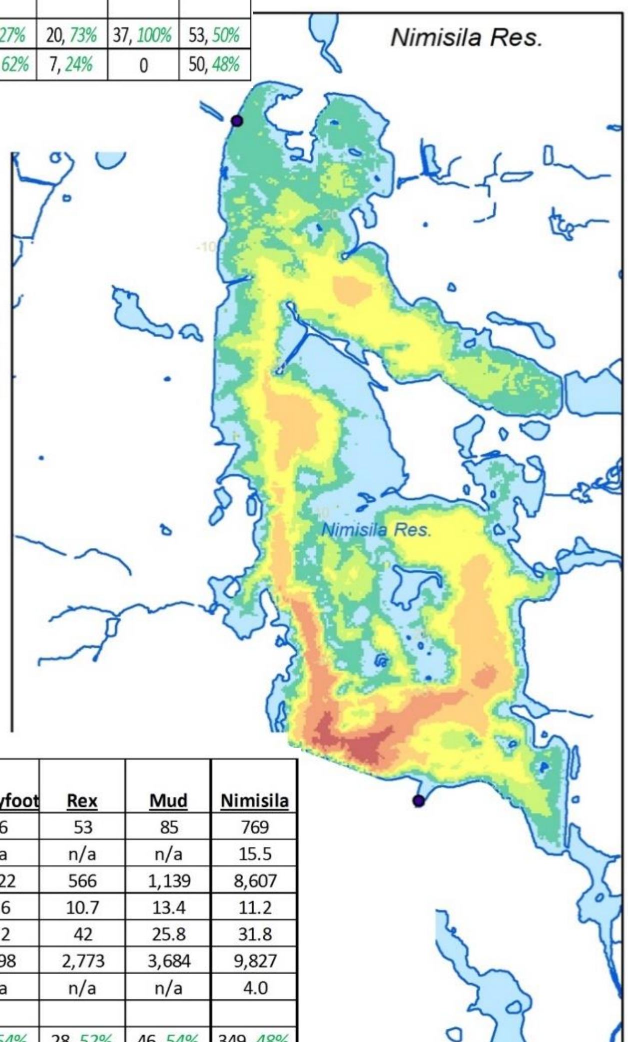
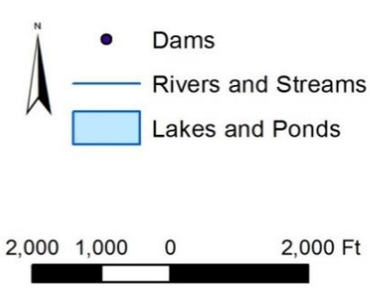
*Bathymetry Source: ODNR GIS*



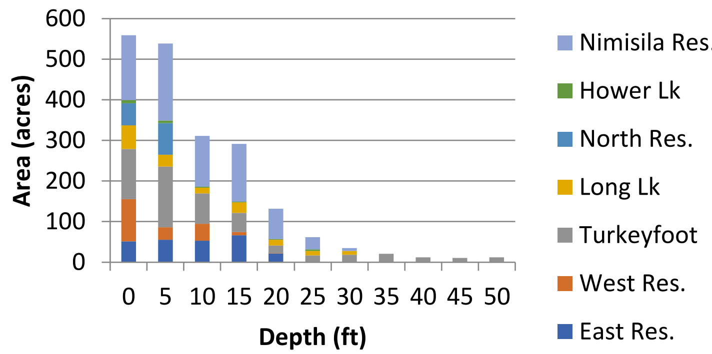




| | Turkeyfoot-Rex-Mud | Turkeyfoot | Rex | Mud | Nimisila |
|---|---|---|---|---|---|
| Area (ac) | 504 | 366 | 53 | 85 | 769 |
| Perimeter (mi) | 16.1 | n/a | n/a | n/a | 15.5 |
| Volume (ac-ft) | 7,027 | 5,322 | 566 | 1,139 | 8,607 |
| Mean Depth (ft) | 14 | 14.6 | 10.7 | 13.4 | 11.2 |
| Max Depth (ft) | 61.2 | 61.2 | 42 | 25.8 | 31.8 |
| Length (ft) | 8,079 | 4,698 | 2,773 | 3,684 | 9,827 |
| Dev. Factor | 5.1 | n/a | n/a | n/a | 4.0 |
| *Littoral (plant) zone* | | | | | |
| Best: 0-10 ft (ac., %) | 273, 54% | 199, 54% | 28, 52% | 46, 54% | 349, 48% |
| Some: 10-20 ft (ac., %) | 121, 24% | 84, 23% | 22, 41% | 15, 18% | 267, 37% |

**Figure 4.4 Area by Depth Portage Lakes**

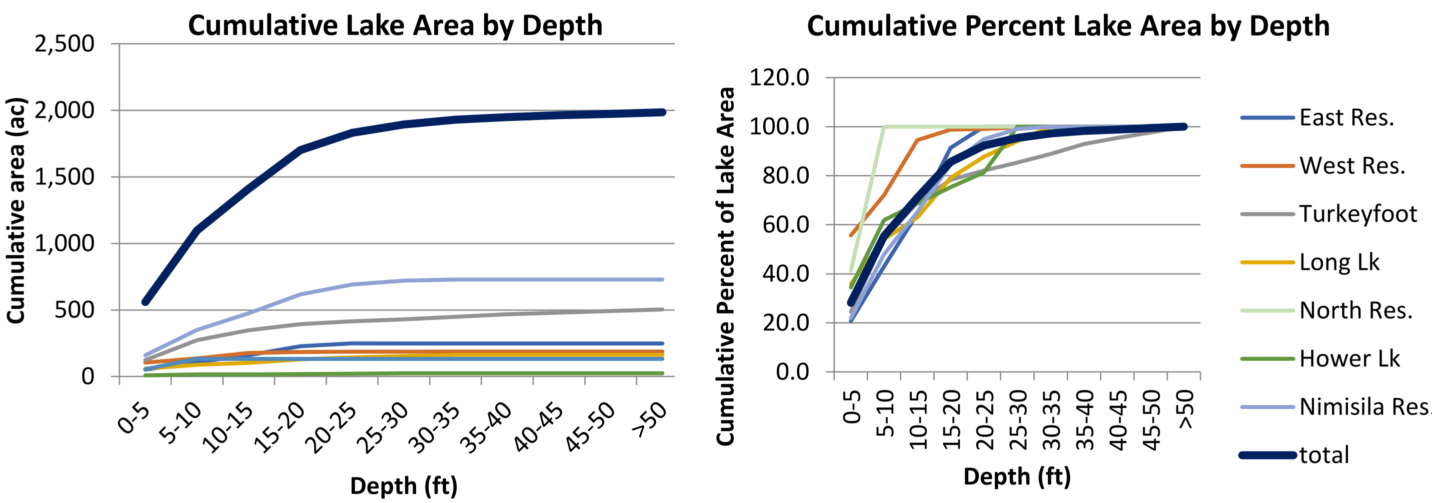



Comparing Figure 4.4 with Map 4.1 shows:

- Extensive shallows in Nimisila Reservoir, Turkeyfoot Lake, and West Reservoir
- North Reservoir is entirely less than 10 feet
- The shallows in Long Lake and East Reservoir are concentrated at one end of each lake.
- The deeper areas in Long Lake, Nimisila Reservoir, West Reservoir, and Turkeyfoot Lake are visible on the graph.

Figure 4.5 shows that 1,700 acres, 86 percent of the lakes area, is in the littoral zone. This shallow nearshore area is where the aquatic plants grow, where most people live, swim, boat, and interact with the lakes, affecting the lakes and encountering aquatic plants. Because it is at the edge of the lake, it is affected by and affects human activity – and expectations - to the greatest degree. (See Figure 4.6)

**Figure 4.5 Cumulative Lake Area and Percent by Depth**




## Residence Time

The residence (or replenishment) time is how long water that come stays in a water body. Residence time can vary from days for a very small pond or lake to hundreds of years (e.g., Great Lakes). Residence time also represents how long nutrients entering the lakes may remain available if not used.

**Table 4.2 Estimated Residence Time**

| Lake(s) | Volume (ac-feet) | Flow In/Out (ac-feet/yr) | Residence Time (yr) |
|---|---|---|---|
| Main Chain | 10,227 | 11,730 | .96 |
| North/Hower | 910 | 1,014 | .87 |
| Long Lake | 1,947 | 48,255 | 0.04 |

Residence time for the lakes was estimated by dividing lake volume in acre-feet (one acre area, one foot deep) by flow in or out (acre-feet per year), estimated with StreamStats.[5] This does not include flow management. Table 4.2 shows the residence time for the Main Chain and North Reservoir/Hower Lake is close to a year much less for Long Lake, which receives water from the other lakes and the Tuscarawas River. Additional input from Nimisila Reservoir during 18 inches of drawdown in the Main Chain affects residence time by a couple of days.

**Figure 4.6 Life at the Edge: Portage Lakes Littoral Zone**

The littoral zone is:

- Where the rooted plants grow – converting nutrients, gases, and light, into oxygen and organic material (biomass); providing habitat, food, spawning areas, hunting areas for various creatures.
- The zone closest to the shoreline, where houses, roads, runoff, septic systems, land animals, boat activity, and chemical applications (or spills) affect the water.
- Where people just want to enjoy the water, where most use the water, and where they encounter the aquatic plants.
- Where nutrients enter from land by numerous pathways, adding what is already in the lakes.
- Where the natural lake environment is altered or preserved.
- Shallow, thus easily disturbed by waves, motors, and activity.

## Lake Length and Wave Base

Wave base is how deep wave-generated turbulence extends, often much deeper than the wave height.  It affects depth of mixing the depth that turbulence may re-suspend sediment.

Wave base is half the wave length (trough to crest), and it is a factor of wind speed and fetch (distance the wind blows across open water). Table 4.3 shows wave base depth estimated for fetch distances similar to the longest dimensions of the Portage Lakes.[6] The wind velocities typify an average summer breeze, a windy day in fall or spring, and a storm.[7]

**Table 4.3  Estimated Wave Base Depth (ft) by Wind Velocity, Fetch**

| | Wind Velocity (mph) | | |
|---|---|---|---|
| **Fetch (ft)** | 6 | 14 | 24 |
| 2,000 | 1.7 | 4.2 | 7.3 |
| 4,000 | 2.3 | 5.7 | 10.1 |
| 6,000 | 2.7 | 6.9 | 12.2 |
| 8,000 | 3.0 | 7.9 | 14.0 |
| 10,000 | 3.3 | 8.7 | 15.5 |

*Modified from: Florida Lakewatch, 2001.*

These estimates convey a *general* idea how turbulence may affect the lakes, but do not account for:

- Direction of prevailing wind, which is southwest for much of the year; or
- Aquatic plants, or other obstructions, which dampen wave energy and stabilize sediments.

During a gentle summer breeze, turbulence may only extend a few inches to a couple of feet down, affecting only the margins of the lakes. During breezy days of autumn or spring, approximately half of the lakes area may be affected, depending on the fetch of each lake. During stormy weather, approximately two-thirds of the lakes area would be affected.


In the hundreds of pictures taken and reviewed for this study, at different dates, seasons, and locations, the surface of the water typically appears mirror-smooth or ruffled by small waves.

One of the reasons that the Portage Lakes are such a good location for boating is their relatively small size, many protected coves, and limited fetch.  Being inland, they do not experience the stronger winds of Lake Erie.

The average wind speed for summer 2020 was 7 miles per hour.  (Weather Underground, 2020)

Waves at the State Park beach after with 5-8 mph northeast wind blowing directly on-shore.
Fetch -  2,000 feet; wave height - approximately 3 to 4 inches; wavelength, measured crest to crest – approximately 1 to 2 feet; wave base, one-half of wavelength - approximately 6 inches to 1 foot.

## Portage Lakes Wave Base and Sediment Disturbance

In a Masters degree study of the Portage Lakes, Mitchell (2015) estimated the wave base of Rex, Mud, and Turkeyfoot Lakes as 2 m (~ 6 feet).  Sediment samples from the lake bottom reflect the disturbed shallow lake bottom versus the accumulating, quiet, deep bottom below the wave base Figure 4.7 graphs the sediment characteristics by depth and the calculated wave base:[8]

- Shallow-water sediment dominated by sand and gravel with low organics, high density
- Deep-water sediment was dominated by mud and organic material, lower density
- Sediment samples were not collected in shallow water with plants.

**Figure 4.7 Wave Base and Sediment in Rex, Mud, and Turkeyfoot Lakes**

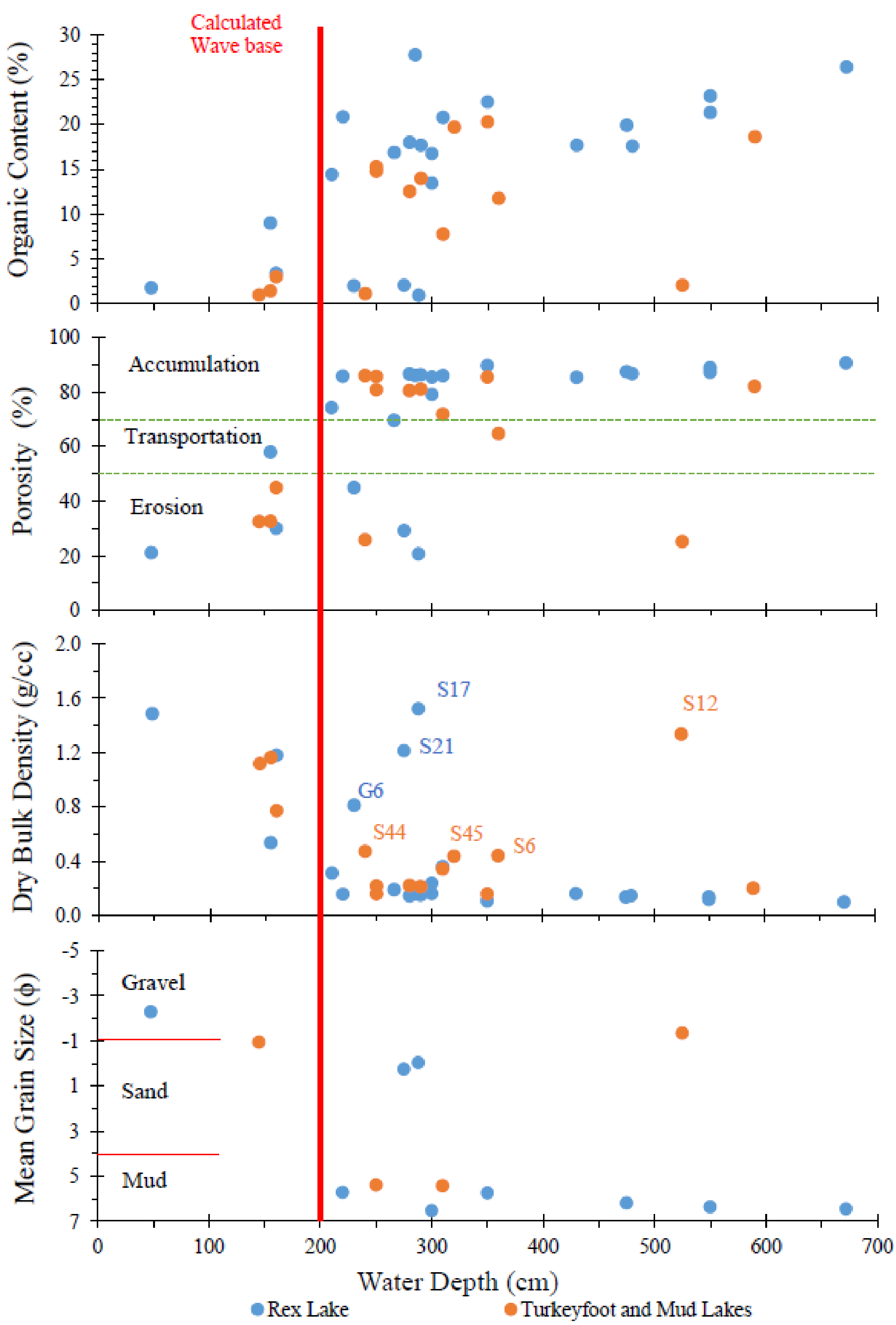



Figure 60. Surface sediment property variation versus water depth. The fields of erosion, transportation, and accumulation are inferred from sediment porosity values after Hakanson (1982). The red vertical line marks the calculated wave base, see text for explanation. *(Source: S. Mitchell, 2015.)*

## Shoreline Development Factor

The shoreline development factor reflects how much the shoreline influences the lake. It compares the lake area to a perfect circle (development factor of 1). Higher numbers indicate more complex shapes, greater perimeter, and more shoreline influence. Hower Lake is closest to a circle, and Turkeyfoot Lake and East Reservoir have more complex shapes and are more susceptible to shoreline influence.

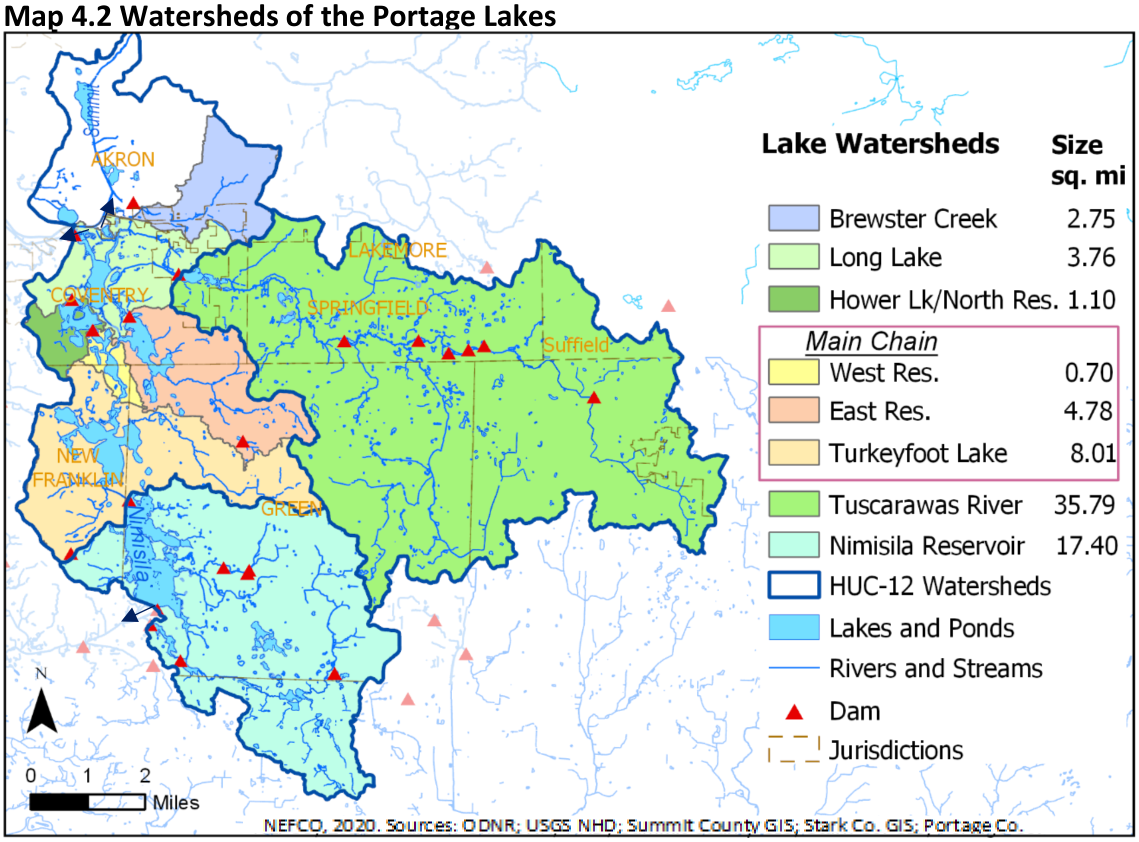
### Individual Lake Watersheds

Watershed size reflects the influence on the watershed on lakes. The watersheds feeding each area of the Portage Lakes are shown in Map 4.2.[9] The Nimisila Reservoir drains south to the Tuscarawas River; the other Portage Lakes drain north to the canal or Tuscarawas River. Subwatersheds feeding each of the lakes in the Portage Lakes HUC 12 watershed were modeled using elevation data in ArcGIS Map.

- The three interconnected Main Chain lakes have a combined watershed of 13.5 square miles, and Turkeyfoot Lake, the most upstream lake, has a watershed of 8 square miles.
- Hower Lake and North Reservoir have very small watersheds. Hower Lake is likely an original kettle lake, small, deep isolated, with a small watershed, and is likely fed by groundwater. These two lakes are interconnected and receive some water from the upstream Main Chain.
- As noted previously, Long Lake receives water from the upstream lakes as well as the Tuscarawas River and Brewster Creek, totaling 42.3 square miles.
- Nimisila Reservoir, with a 17.4-mile watershed, is occasionally used to refill the other lakes.

Most of the lakes are interconnected and are influenced by watersheds upstream. If water quality concerns are identified, assessing watershed characteristics may help identify contributing factors.

**Map 4.2 Watersheds of the Portage Lakes**



## Portage Lakes Limnological Data – Temperature, Oxygen, and Depth

ODNR Division of Wildlife periodically samples fish populations in the Portage Lakes and collects limnological data at the same time. Table 4.4 shows temperature and dissolved oxygen for example sites (shown on Map. 4.3)[10] The highlighted cells indicate data of interest:

- Blue shows the depth where the temperature changes by 0.5°C or more – this change was often associated with a sudden decrease in oxygen.
- Yellow indicates low oxygen values, from 2-5 ppm.
- Orange indicates oxygen-depletion, under 2 ppm.

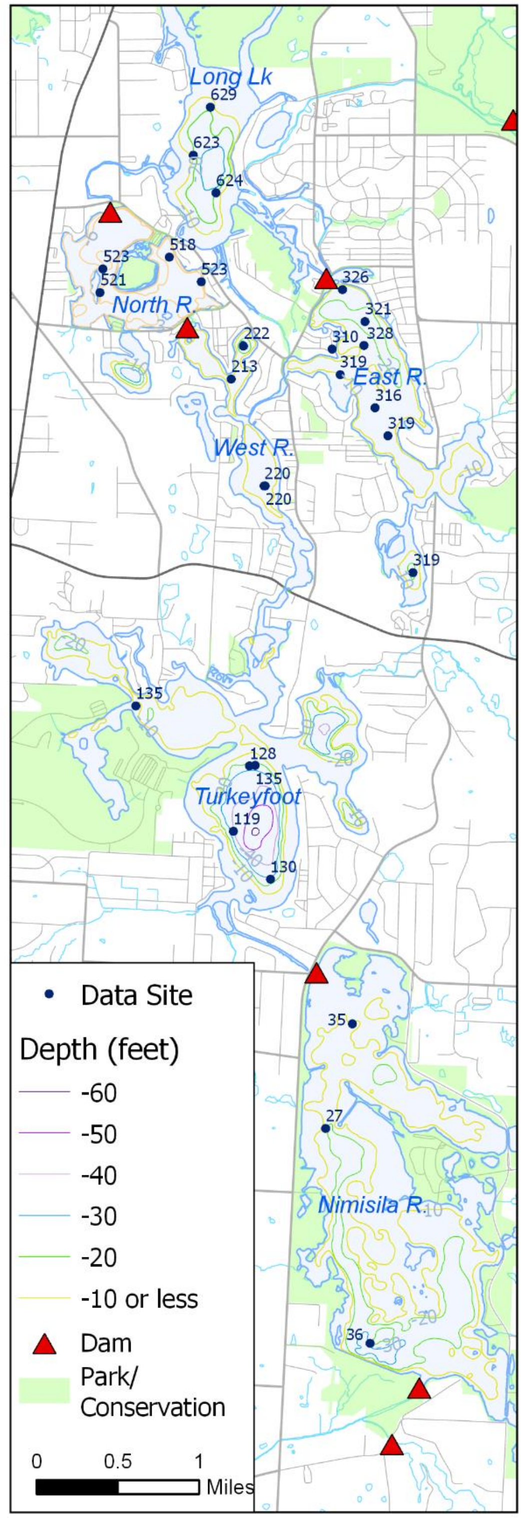
The example graphs shown previously in Figure 4.3 depict typical limnological profile changes over seasons.

The average temperature and depth values for several hundred sites over 18 years of ODNR data were compiled by lake and season (Appendix E) and are summarized in Table 4.5. Even though the data has been averaged, the total record shows similar characteristics to the example limnological profiles.

As shown on Table 4.4 and summarized in Table 4.5:

- In spring, the water column warms from the surface and often is well oxygenated through much of the depth.
- The summer warming extends through the top several meters of the lakes. There is a temperature and oxygen change from 3 to 6 meters overall.
- The thermocline is a barrier to mixing. The lower depths become depleted in oxygen, especially in summer and in the basins. Phosphorus is released in anoxic water.
- During the fall, the water column is mixed to much greater depths. The temperature and oxygen levels become much more uniform in the individual examples.
- In some cases, fall average temperatures increase toward the bottom, possibly reflecting cooling from the surface down to the warmer bottom water.
- Anoxic water occupies the lower levels of the lakes. The deep basins may remain stratified and low in oxygen much of the year, with the thermocline dropping lower in cooler weather. Fish may be able to migrate to higher depths, where oxygen is present.

**Map 4.3**
**Example Limnological Data Locations**




NEFCO, 2020. Sources: ODNR GIS; USGS NHD; Summit County GIS; Stark Co. GIS; Portage Co.

**Table 4.4 Examples of Portage Lakes Limnological Profile Data**

| Spring | | | Summer | | | Fall | | |
|---|---|---|---|---|---|---|---|---|
| ***Long Lake*** | | | ***Long Lake*** | | | ***Long Lake*** | | |
| 5/13/2013 | Sample ID 623 | | 7/29/2013 | Sample ID 624 | | 10/18/2016 | Sample ID 629 | |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 15.9 | 8.25 | 0 | 22.8 | 7.64 | 0 | 17.7 | 8.58 |
| 1 | 15.8 | 7.9 | 1 | 22.6 | 7.58 | 1 | 17.7 | 8.45 |
| 2 | 15.6 | 7.61 | 2 | 22.5 | 7.18 | 2 | 17.7 | 8.41 |
| 3 | 15.4 | 7.61 | 3 | 21.7 | 3.51 | 3 | 17.7 | 8.22 |
| 4 | 15.2 | 6.57 | 4 | 21.1 | 0.54 | 4 | 17.6 | 8.18 |
| 5 | 12.7 | 1.1 | 5 | 20 | 0.79 | 5 | 17.6 | 7.97 |
| | | | | | | 6 | 17.5 | 7.54 |
| | | | | | | 7 | 15.3 | 0.11 |
| | | | | | | 8 | 12.9 | 0.08 |
| | | | | | | 9 | 12.4 | 0.06 |
| ***North Reservoir*** | | | ***North Reservoir*** | | | ***North Reservoir*** | | |
| 5/3/2016 | Sample ID 521 | | 7/17/2012 | Sample ID 518 | | 10/19/2017 | Sample ID 523 | |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 16.6 | 7.94 | 0 | 27.6 | 9.43 | 0 | 16.8 | 8.58 |
| 1 | 16.6 | 7.85 | 1 | 27.6 | 9.06 | 1 | 16.8 | 8.48 |
| 2 | 15.7 | 7.73 | 2 | 26.6 | 2.18 | 2 | 16.8 | 8.11 |
| 3 | 15 | 7.04 | Note: several areas have low DO within 1 m of surface | | | 3 | 16.4 | 7.35 |
| ***West Reservoir*** | | | ***West Reservoir*** | | | ***West Reservoir*** | | |
| 5/13/2014 | Sample ID 220 | | 7/26/2010 | Sample ID 213 | | 10/18/2017 | Sample ID 222 | |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 21.7 | 11.03 | 0 | 29.1 | 4.87 | 0 | 18.7 | 5.88 |
| 1 | 21.3 | 10.78 | 1 | 28.5 | 5.56 | 1 | 18.7 | 5.68 |
| 2 | 20.1 | 10.76 | 2 | 28.1 | 4.5 | 2 | 18.7 | 5.44 |
| 3 | 17.3 | 6.3 | 3 | 28 | 4.74 | 3 | 18.7 | 5.43 |
| 4 | 14.7 | 2.12 | 4 | 27.7 | 2.05 | 4 | 18.7 | 5.33 |
| | | | 5 | 24.6 | 0.18 | 5 | 18.6 | 5.55 |
| | | | | | | 6 | 18.6 | 4.97 |
| | | | | | | 7 | 18.4 | 5.55 |
| | | | | | | 8 | 17.9 | 3.92 |
| | | | | | | 9 | 13.4 | 0.13 |
| | | | | | | 10 | 11.1 | 0.04 |

*Data Source: C. Wagner, ODNR, 2020.*

Legend:
- Temp. drop 0.5°C or greater (blue shading)
- DO from 2-5 mg/l (yellow shading)
- DO < = 2mg/l (orange shading)

Note: Each sample location is different, even within same lake

**Table 4.4 Examples of Portage Lakes Limnological Profile Data - (cont'd)**

| Spring | | | Summer | | | Fall | | |
|---|---|---|---|---|---|---|---|---|
| ***East Reservoir*** | | | ***East Reservoir*** | | | ***East Reservoir*** | | |
| 5/29/2013 | Sample ID | 319 | 7/29/2013 | Sample ID | 321 | 11/8/2018 | Sample ID 328 | |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 18.9 | 7.88 | 0 | 24.6 | 5.88 | 0 | 10.6 | 7.41 |
| 1 | 18.9 | 7.66 | 1 | 24.5 | 5.75 | 1 | 10.6 | 7.4 |
| 2 | 18.7 | 7.69 | 2 | 24.4 | 5.84 | 2 | 10.6 | 7.38 |
| 3 | 18.6 | 7.34 | 3 | 24.4 | 5.51 | 3 | 10.6 | 7.38 |
| 4 | 18.4 | 7.14 | 4 | 24.4 | 5.47 | 4 | 10.5 | 7.35 |
| 5 | 18 | 6.06 | 5 | 24.3 | 5.14 | | | |
| | | | 6 | 22.3 | 0.13 | | | |
| | | | 7 | 18.5 | 0.05 | | | |
| ***Turkeyfoot Lake*** | | | ***Turkeyfoot Lake*** | | | ***Turkeyfoot Lake*** | | |
| 5/2/2012 | Sample ID | 128 | 7/29/2013 | Sample ID | 130 | 10/20/2015 | sample ID | 135 |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 18.3 | 10.12 | 0 | 23.6 | 7.42 | 0 | 13.5 | 7.06 |
| 1 | 18.1 | 10.38 | 1 | 23.7 | 6.99 | 1 | 13.5 | 6.74 |
| 2 | 17.8 | 10.35 | 2 | 23.7 | 6.56 | 2 | 13.5 | 6.57 |
| 3 | 13 | 8.74 | 3 | 23.5 | 6.29 | 3 | 13.5 | 6.76 |
| 4 | 12.3 | 8.53 | 4 | 23.2 | 4.68 | 4 | 13.5 | 6.45 |
| 5 | 11.7 | 7.27 | 5 | 21.3 | 0.93 | 5 | 13.5 | 6.86 |
| | | | 6 | 16.9 | 0.23 | 6 | 13.4 | 6.78 |
| | | | 7 | 13.8 | 0.2 | 7 | 13.3 | 6.06 |
| ***Nimisila Reservoir*** | | | ***Nimisila Reservoir*** | | | ***Nimisila Reservoir*** | | |
| 5/28/2013 | Sample ID | 31 | 7/22/2014 | sample ID | 35 | 9/26/2012 | sample ID | 27 |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 18.3 | 9.29 | 0 | 26.9 | 9.89 | 0 | 17.7 | 8.2 |
| 1 | 18.2 | 9.17 | 1 | 26.3 | 9.46 | 1 | 17.7 | 8.14 |
| 2 | 17.5 | 8.86 | 2 | 25.4 | 8.88 | 2 | 17.7 | 7.75 |
| 3 | 17.4 | 8.53 | 3 | 24.5 | 5.62 | 3 | 17.6 | 7.31 |
| 4 | 17.3 | 8.44 | 4 | 24.2 | 3.72 | | | |
| 5 | 17.1 | 7.53 | | | | | | |

Temp. drop 0.5°C or greater

DO from 2-5 mg/l

DO < = 2mg/l

*Data Source: C. Wagner, ODNR, 2020.*

Note: Each sample location is different, even within same lake

Table 4.4 Examples of Portage Lakes Limnological Profilie Data (cont'd)

| Spring | | | Summer | | | Fall | | |
|---|---|---|---|---|---|---|---|---|
| Other sites of interest | | | | | | | | |
| *Turkeyfoot Lake Basin* | | | *Nimisila Near Dam* | | | *Cottage Grove Lake* | | |
| 5/20/2008 | Sample ID 119 | | 7/22/2014 | Sample ID 36 | | 10/21/2015 | Sample ID 325 | |
| **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** | **Depth (m)** | **Temp °C** | **DO mg/l** |
| 0 | 15.4 | 7.83 | 0 | 26.9 | 8.72 | 0 | 13 | 7.92 |
| 1 | 15.5 | 7.41 | 1 | 25.6 | 9.36 | 1 | 12.9 | 7.88 |
| 2 | 15.5 | 7.93 | 2 | 24.9 | 8.55 | 2 | 12.7 | 7.82 |
| 3 | 15.5 | 7.71 | 3 | 24.4 | 8.24 | | | |
| 4 | 15.4 | 7.06 | 4 | 24 | 5.12 | | | |
| 5 | 15.2 | 6.26 | 5 | 23.8 | 3.39 | | | |
| 6 | 13.5 | 1.51 | 6 | 23.5 | 0.5 | | | |
| 7 | 9.1 | 0.32 | 7 | 20.5 | 0.27 | | | |
| 8 | 7.6 | 1.21 | 8 | 16.3 | 0.25 | | | |
| 9 | 6.8 | 1.43 | | | | | | |
| 10 | 6.5 | 1.31 | | | | | | |
| 11 | 6.4 | 0.4 | | | | | | |
| 12 | 6.3 | 0.04 | | | | | | |
| 13 | 6.3 | 0.02 | | | | | | |
| *Miller Lake* | | | | | | | | |
| 5/7/2009 | Sample ID 316 | | | | | | | |
| **Depth (m)** | **Temp °C** | **DO mg/l** | | | | | | |
| 0 | 17.7 | 7.79 | | | | | | |
| 1 | 17.7 | 7.93 | | | | | | |
| 2 | 17.6 | 7.79 | | | | | | |
| 3 | 16.9 | 7.33 | | | | | | |
| 4 | 16.7 | 7.67 | | | | | | |
| 5 | 15.7 | 7.36 | | | | | | |

Temp. drop 0.5°C or greater

DO from 2-5 mg/l

DO < = 2mg/l

Note: Each sample location is different, even within same lake

*Data Source: C. Wagner, ODNR, 2020.*

**Table 4.5 Summary of Portage Lakes Temperature and DO Data**

| Characteristic | Spring | Summer | Fall |
|---|---|---|---|
| Temperature | 5.20 to 18.65°C, declines with depth | 13.8 to 29.1°C, declines with depth | 10.6 to 18.6 °C<br>Examples and averages vary, some uniform, some increase at depth as lake cools from the surface. |
| Oxygen | 0 to 10.86 mg/l | 0.18 to 9.36 mg/l | 0.04 to 8.78 mg/l |
| Thermocline (temperature-oxygen change) | Average depth 3-4 m most lakes; 6 m Nimisila Res. Examples vary more | Average depth 2-4 m | No obvious change in individual examples. Averages show great variability in temperature change through water column. |
| Depth where Low/Depleted Oxygen Begins | 4 to 8 meters<br><br>Oxygen depletion apparent only in Long Lake, West Res., and Turkeyfoot Lake - Average depth 5 to 8 m; individual examples 4- 8 m | 3 to 4 meters, shallower in some individual examples.<br><br>Oxygen depletion in all lakes, starting at 4 to 6 m in averages and examples. | 5-7 meters<br><br>Oxygen depletion only in basins of Long Lake, West Reservoir, and Nimisila Reservoir, starting at 7 - 10 m |

## Discussion – Lake Form and Productivity

The Portage Lakes are all stratified during the summer. Many of the examples are low or depleted in oxygen during the summer and in the basins. Oxygen depletion is important in the release of phosphorus from the sediments, which spurs growth of aquatic plants, algae, and cyanobacteria ("blue-green algae"). This is part of the "internal loading" of phosphorus, discussed later in the chapter.

This study summarizes several years of data from many points. In understanding the contribution of phosphorus to lake productivity, it will be important to map out the individual limnological profiles of temperature and oxygen by depth, as well as develop a consistent sampling and monitoring program:

- Mixing of cold deep water with surface water may be limited, trapping phosphorus.
- In shallow lakes, phosphorus released in the bottom waters may be more readily mixed with surface waters, fueling growth, especially when the thermocline is not well developed. It will be instructive to compare oxygen profiles with temperature and depth in each lake, to better understand phosphorus release and mixing.
- The seasonal timing of oxygen depletion affects nutrient release and thus productivity (growth).
- Small, shallow, connected "urban" lakes (managed waters, large developed watershed) are susceptible to eutrophication. Both watershed and in-lake management are essential.[11]

The form and size of the lakes and their watersheds contribute to the "external loading" of phosphorus– the effect of the landscape and watershed on the lakes. As the watershed size and amount of shoreline increases, the influence of watershed and shoreline increase. The "downstream" lakes receive water from the others, as well as the entire watershed. Long Lake, the furthest downstream, is affected by all the lakes as well as the entire upper Tuscarawas watershed. The residence time indicates that phosphorus entering the lakes remains in the Main Chain and North Reservoir for approximately one year, but would be flushed out of Long Lake within weeks, assuming even mixing and flushing.

## About Lakes - Lake Productivity and Trophic State

Lake productivity is the amount of biomass, or living matter, that a lake can support. It depends on photosynthesis and is often measured by the amounts of substances related to photosynthesis:

- Phosphorus – the primary, *critical* nutrient in freshwater systems for photosynthesizers (e.g., rooted plants and algae, photosynthesizing plankton like algae, diatoms, bacteria). Increased phosphorus is directly linked to an increase in photosynthesizers.
- Turbidity – cloudiness of the water, often growth of phytoplankton like floating algae. Turbidity is often measured by using a Secchi disk to measure water transparency. High transparency means low turbidity and vice-versa. High levels of turbidity can shade out aquatic plants.
- Chlorophyll –necessary for photosynthesis.

**Secchi Disk: Measuring Water Clarity/Turbidity and Productivity**

The depth that light penetrates, heating up the water and driving plant growth, is affected by water clarity or turbidity (cloudiness). Turbid water has a lot of suspended particles – fine sediment and micro-organisms (algae, plankton), reducing light penetration. Algal productivity increases turbidity. Turbidity can also increase where fine sediment enters from streams or is stirred up by waves or activity.

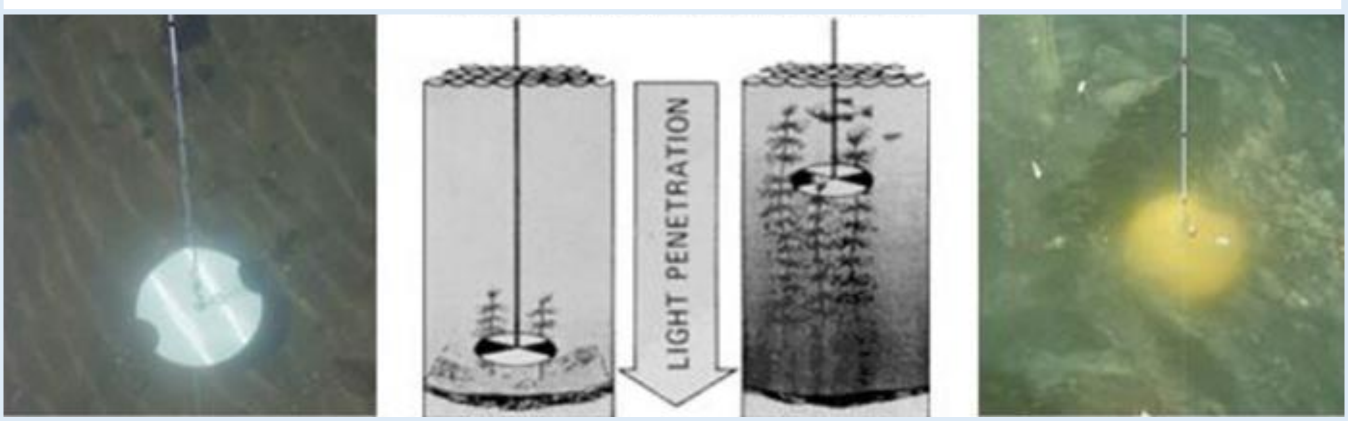
Lake monitors use Secchi discs to determine light penetration/turbidity and monitor seasonal and long-term changes at different locations, recording depth where the highly visible Secchi disc is no longer seen.

The depth that the disc is visible is related to how far light can penetrate – it is assumed that twice the Secchi transparency depth is the approximate depth that 1 percent of light can penetrate, the limit of plant growth.

The white areas allow volunteers to determine color, and thus the likely reason for turbidity (algae, sediment, or natural organic dyes like tannins).

Equations relate visibility of Secchi discs to trophic state indices, which are used with other factors to characterize lake productivity.

**Measuring Turbidity with a Secchi Disc**




*Secchi disk in clear lake versus turbid lake. Modified from: Minnesota Water Pollution Control Agency (2016).*

## Trophic State - Oligotrophic? Mesotrophic? Eutrophic?

Productivity is affected by factors in the lake and watershed and affects characteristics of the lake. Lakes are classified by *trophic state* based on their productivity. The classifications are descriptive, but they can point to trends, potential risks, and management measures. Trophic status can change over time as conditions change.

Productivity reflects availability of nutrients. Table 4.6 highlights characteristics of trophic states identified by the Carlson Trophic State Index, one of many indices of productivity/trophic state.[12]

- *Oligotrophic* – the clearest lakes and ocean areas have lower levels of nutrients and little biomass. These are often deep and cold, limiting the amount of nutrients available from the deep water. There are many species of algae. Fish tend to be few but large, requiring cold, highly oxygenated water. Lake Superior and recent lakes in granite or sand are examples.

*The clear water of oligotrophic Yellowstone Lake (left) contrasts with turbid water of highly productive Lake Erie (right), known for its walleye fisheries.*

- *Mesotrophic* – intermediate level of productivity – more plant life supports more fish, often very productive sport fisheries like walleye. These lakes or areas are often shallower, with a higher proportion of the lake volume supporting plants and algae, and warming during the summer. Some of the shores of Lake Michigan are considered mesotrophic. Lake Erie has been identified as either mesotrophic or eutrophic at different times.
- *Eutrophic* – high level of nutrients and productivity. Like mesotrophic lakes, these tend to be warmer and shallower. They are characterized by higher turbidity and dense plant growth. Some support highly productive fisheries with warm-water sport fish like northern pike or bass. Because of the high level of algal productivity, warmer waters, and smaller proportion below the thermocline, there is increased chance of oxygen depletion in the deep water in summer.
- *Hypereutrophic* – water body extremely enriched in nutrients. In extreme cases, nuisance plant growth gives way to algae and harmful cyanobacteria, which out-compete plants for nutrients and light. The water is very cloudy (turbid) and may have extensive algal blooms and algae scums. The few fish species are tolerant of warm water and lower oxygen. There may be fish kills in summer. The bottom-dwelling “rough” fish and anoxic water release more nutrients from the sediment.

Trophic state reflects environmental conditions and possibly stage of development of a lake. The deep, cold, clear lakes differ in form, setting, and inputs from shallower, warmer, more productive lakes. Turbidity, nutrients, plants, algae, algal blooms, productivity are often an important part of how lakes work. However, a hypereutrophic lake is often unhealthy for plants and humans, and other animals:

- Excessive or nuisance algal blooms shade out rooted aquatic plants
- Oxygen depletion at depth during the summer, releasing phosphorus that spurs more growth
- The risk of toxic cyanobacteria, especially as nutrient input continues
- Fish kills during the summer due to low oxygen

**Table 4.6 A list of possible changes that might be expected in a north temperate lake as the amount of algae changes along the trophic state gradient**

| TSI | Chl (µg/l) | SD (m) | TP (µg/l) | Attributes | Fisheries |
|---|---|---|---|---|---|
| <30 | <0.95 | >8 | <6 | **Oligotrophy:** Clear water, oxygen throughout the year in the hypolimnion | Salmonid fisheries dominate |
| 30-40 | 0.95-2.6 | 8-4 | 6-12 | Hypolimnia of shallow lakes may become anoxic | Salmonid fisheries in deep lakes only |
| 40-50 | 2.6-7.3 | 4-2 | 12-24 | **Mesotrophy:** Water moderately clear, increasing probability of hypolimnetic anoxia during summer | Hypolimnetic anoxia results in loss of salmonids. Walleye may predominate. |
| 50-60 | 7.3-20 | 2-1 | 24-48 | **Eutrophy:** Anoxic hypolimnia, macrophyte problems possible | Warm-water fishes only. Bass may dominate. |
| 60-70 | 20-56 | 0.5-1 | 48-96 | Blue-green algae dominate. Algal scums and macrophyte problems. | Nuisance macrophytes. Algal scums and low transparency may discourage swimming and boating. |
| 70-80 | 56-155 | 0.25-0.5 | 96-192 | **Hypereutrophy:** (light-limited productivity) Dense algae and macrophytes | |
| >80 | >155 | <0.25 | 192-384 | Algal scums, few macrophytes | Rough fish dominate; summer fish kills possible. |

*TSI – Carlson Trophic State Index – one index of trophic state that focuses on algae production*
*Chl – Chlorophyll, usually measured as chlorophyll A*
*SD – Secchi Disk transparency*
*TP – Total Phosphorus*
*Source: Modified after North American Lake Management Society 2020.*

## Eutrophication

Eutrophication is the process of increasing the level of nutrients and productivity (biomass) in water bodies. Sediment and nutrients continuously wash in from the watershed and build up in a lake over time, spurring growth.

- Nutrients that wash in from the watershed outside the lakes are considered *external loading*.
- As areas of the lakes become shallower and enriched in nutrients, they support more plant matter and greater volumes of fish.
- Decay of dead plants and animals releases nutrients, which are stored in sediment, building up the level of nutrients in the system. Nutrients are recycled over and over as *internal loading*.
- Over time, the lakes continue to become shallower and support denser growth of plants, which decompose and continue to build up nutrients.
- Eventually some lakes may fill in so much that they become wetlands – marshes and swamps.

Eutrophication may occur naturally over centuries to millennia.

Eutrophication is greatly accelerated by human activities and alteration, which increase external loading from the watershed, as well as the internal loading that comes from recycling the increased amount of nutrients in the water. This cultural eutrophication takes *years to decades*:

- Clearing, farming, and converting natural landscapes to development introduces more sediment and nutrients into lakes, filling them in and spurring productivity.
- Pavement and turf increase how much rain runs off the landscape, which carries more sediment and nutrients into the lakes.
- Wastewater treatment plants, poorly-functioning septic systems, and phosphorus in fertilizers and other chemicals contribute additional nutrients into surface waters. ‘
- Urban lakes are more susceptible to eutrophication than pristine lakes.

## Aquatic Plants, Green Algae, and Harmful Algal Blooms

*Left - Filamentous green algae (dark green) attaches to aquatic plants (leafy, lighter green) and solid objects. Right - With excessive growth, mats may detach and float to the surface. (Portage Lakes Examples)*

Lakes are full of photosynthesizers, which all require nutrients and light. Warm, nutrient-rich water may encourage excessive, nuisance growth of some types, is often an indicator of eutrophic conditions.

*Plants* – multi-cell organisms with specialized parts, can be floating, like the rooted duckweed or coontail, or sessile – rooted to the bottom.

*Algae* – single-cell, floating (plankton) or multi-cell unspecialized organisms. They generate oxygen, and are important to the food chain. Like plants, excessive growth can become a nuisance. An example is *Cladophora*, branching strands of green algae that attach to objects. In eutrophic waters, it can form mats that disconnect and then float to the surface. When it collects and decays, it releases nutrients. Decaying mats smell foul and may harbor bacteria.

*Cyanobacteria*, also known as blue-green algae or “Harmful algae” – Not true algae, they are related to bacteria and photosynthesize. Some use nitrogen directly from the air (“fix” nitrogen). Some are harmful to people and animals, releasing toxins that affect skin, digestive system, nerves, or liver. Cyanobacteria are present at all levels of nutrients, but at high levels of phosphorus, they may become predominant.[13]

*Blooms* of algae and cyanobacteria occur when nutrients are released in the water and conditions support growth. Hot weather, stormwater runoff, and phosphorus release from sediment in anoxic water all contribute to blooms. See Figure 4.8 for examples of plants, algae, and Harmful Algae Blooms.

- Algae blooms are *not* toxic. They make the water turbid.
- Cyanobacteria grow well in calm, slow-moving, warm, nutrient-rich water. “Harmful Algae Blooms” (HABs) often appear as strangely colored scum or blebs in the water. They can be on the surface, concentrated at lower levels, mixed through the water column, or they may migrate vertically. These may be toxic to people and animals and should be reported and avoided.

- The State of Ohio has developed response procedures among Department of Health, Ohio EPA, and ODNR.
- Ohio EPA posts weekly lists during warm months of larger lakes with cyanobacteria visible on satellite imagery.
- In the Portage Lakes, ODNR is responsible for monitoring, sampling, and posting notices about HABs.
- More frequent, intense storms associated with climate change increase algal blooms.
- Levels of response can range from warnings not to ingest the water and to clean after going in the water to the extreme measures of closing the lake to recreational use.

  Two good reference websites:
  - Ohio EPA https://epa.ohio.gov/hab-algae#147744472-basics
  - Ohio Dept. of Health https://odh.ohio.gov/wps/portal/gov/odh/know-our-programs/harmful-algal-blooms/Harmful-Algal-Blooms-in-Ohio/


**Figure 4.8 Are they Harmful? Examples of Algae, Plants, Duckweed, and Harmful Algal Blooms.[14]**

Plants and algae may be mistaken for HABs. These are *not* harmful, but excessive growth may become a nuisance, and it indicates high levels of nutrients, possibly eutrophic conditions.


*a and b Filamentous green algae mats with plants (water lilies, spatterdock), Portage Lakes.*

*c Filamentous green Algae (Cladophora)*

*e ,f Duckweed –floating rooted plant. Duckweed is tiny rooted plants.. Example e from Portage Lakes.*

Harmful algal blooms appear many ways. **When in doubt, Stay Out, and report your sighting.**

*g - Huron River, 2009*

*h – Grand Lakes St. Marys, 2010*

*I – Microcystin blebs, mixed in the water column, Ohio River, 2008*

*Source:* *https://odh.ohio.gov/wps/portal/gov/odh/know-our-programs/harmful-algal-blooms/media/habs-photos c, d, f, g, h, I*


## Flipping the Switch from Plants to Algae/HABs

Limnologists and lake managers have found that highly eutrophic lakes can switch from a plant-dominated ("clear") state to an algae-dominated ("turbid") state, which has increased turbidity, HABs, and a loss of rooted plants. Perturbations in lake systems, e.g., removal of plants, may trigger the shift. The new algae- dominant equilibrium is very stable, difficult to reverse, and reinforced by feedback loops.[15]

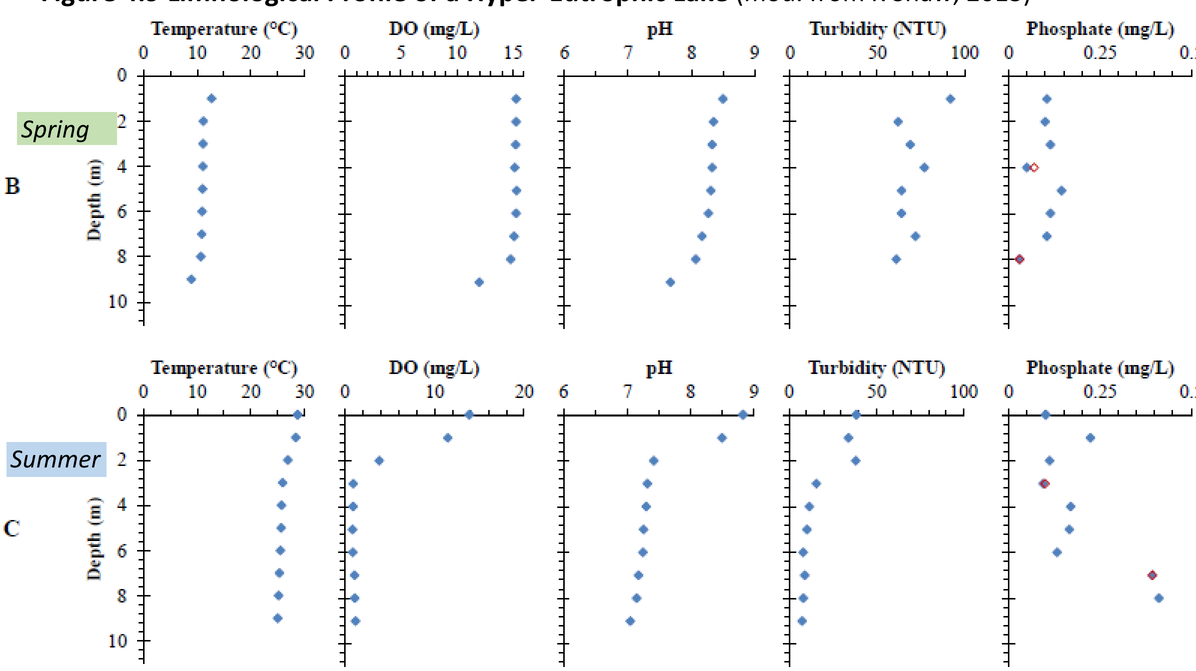
- Rooted plants and phytoplankton (algae) compete for nutrients and light. At certain high levels of nutrients, the algal growth shades out the rooted plants and out-competes them for nutrients. With no plants, sediment is stirred up, increasing turbidity.
- Particles in turbid water absorb and give off heat, raising water temperature and favoring algae.
- Decomposition of the algae results in anoxia at depth, fish kills, and more phosphorus release.
- At excessive levels of nutrients, the cyanobacteria that cause HABs become predominant. Some lakes become closed to recreational use, and are toxic to people, pets, and wildlife.

There are on-going efforts in lakes and rivers in Ohio to remediate lakes with HABs due to excessive nutrients, using various techniques to destratify lakes and remove phosphorus. While there has been some success, fixing nature when it is broken is very expensive, does not always work as planned, and may have unintended consequences if not carried out in the precise manner needed.

**Case Example: Characteristics of a Hyper-Eutrophic Lake**

Figure 4.9 shows data from a hypereutrophic lake in Summit County after the lake equilibrium had shifted to turbid, algae-dominated conditions. The spring data shows the water warming, phosphate and high levels of DO throughout the water column, and high turbidity, possibly due to spring algal blooms. Summer conditions show excessively warm water, DO absent below two meters, and high levels of phosphate being released in the anoxic deep waters. The lake has since been remediated, and the return of rooted plants is seen as a great success.[16]

**Figure 4.9 Limnological Profile of a Hyper-Eutrophic Lake** (mod. from K Shaw, 2013)



## Portage Lakes Secchi Disk Data and Turbidity

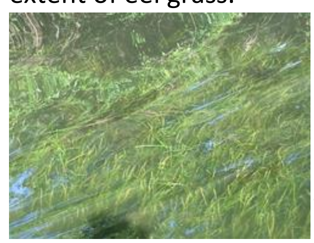
Secchi disk transparency data is one of the components used to measure and track productivity and trophic state. Volunteers and ODNR Wildlife staff have developed substantial records, which provide an important starting point for assessing lake productivity:

- Secchi disk transparency is a simple field measurement that does not require sampling or lab analysis. Lake managers and volunteers can develop long-term, seasonal records.
- It measures one of the key indicators of lake conditions, including productivity.
- It reflects a very visible aspect of lake condition – the clarity or turbidity of the water.

Figure 4.10 shows seasonal and long-term Secchi disk data (in inches) for three lakes, along with the Carlson Trophic State Index (TSI) for turbidity.[17] Map 4.4 shows the ODNR Secchi disk data, contrasting summer with other seasons, throughout the lakes. Lower transparency means higher turbidity.

- Turbidity is high (transparency low) in the summer, typical of lakes with summer algae growth.
- In some of the summer data, the Carlson TSI values correlate with moderate to higher eutrophy.
- North Reservoir and Long Lake generally are more turbid. Long Lake receives water (and nutrients) from the other Portage Lakes and the Tuscarawas River watershed.
- Nimisila has lower turbidity. The landscape around Nimisila is less developed, and there are extensive aquatic plant beds. The nutrients available and suspended algae may be less.
- Figure 4.10 shows that transparency has generally increased over time, indicating less turbidity. Lakers have noticed the increased clarity and greater extent of eel grass.





*Left: Clear water of Nimisila Reservoir. Center: Turbid North Reservoir. Right – eel grass beds.*

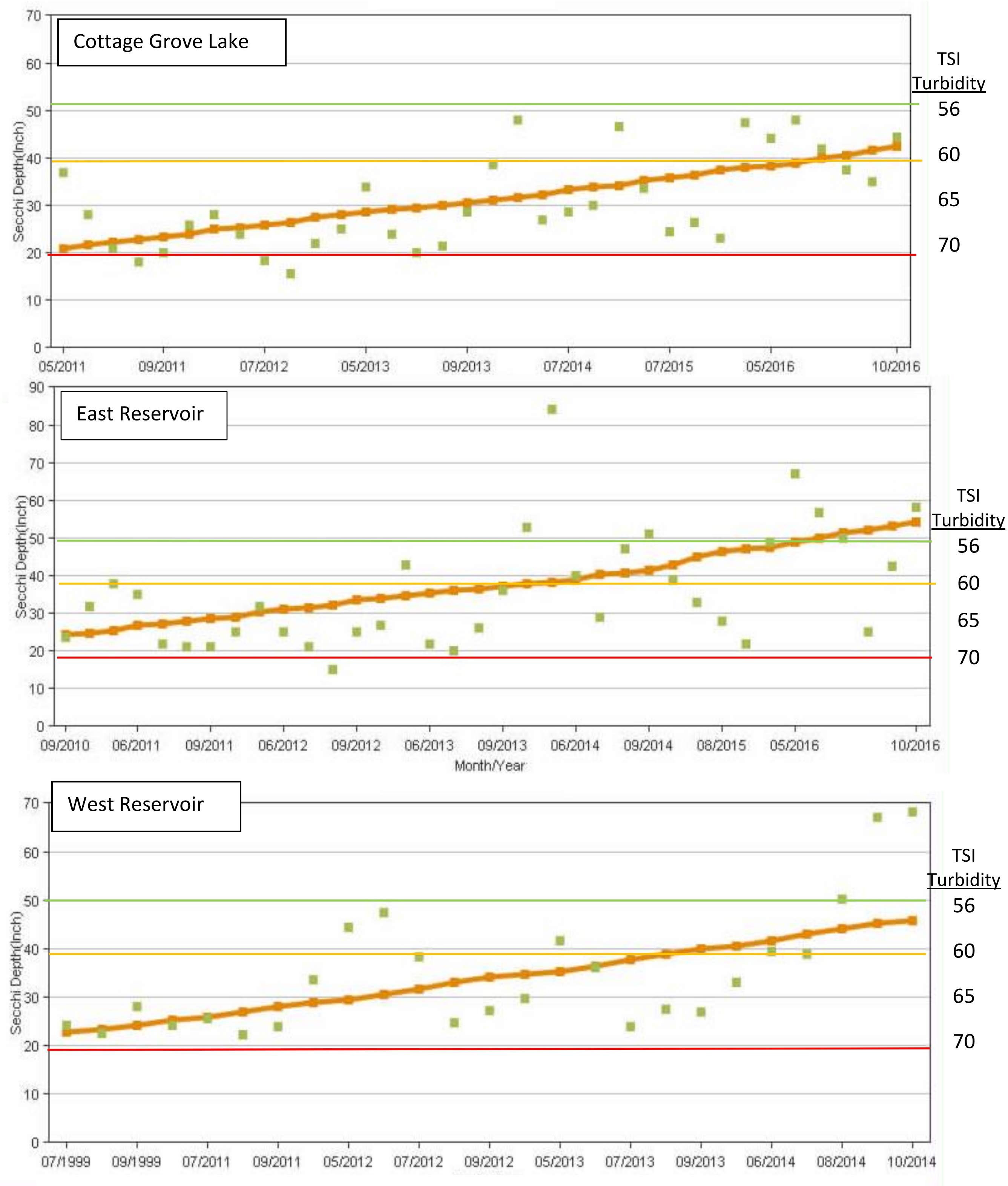
Additional factors can affect turbidity, including plant tannins, propeller disturbance, sediment entering from stream, silty versus sandy bottom, and the presence or absence of aquatic plants.

➢ *Note:* Secchi disk data is a valuable measurement. Seasonal monitoring should continue and expand to other areas, but it is only one of several factors used to measure lake productivity.

### Water Clarity, Phosphorus, and Invasive Mussels

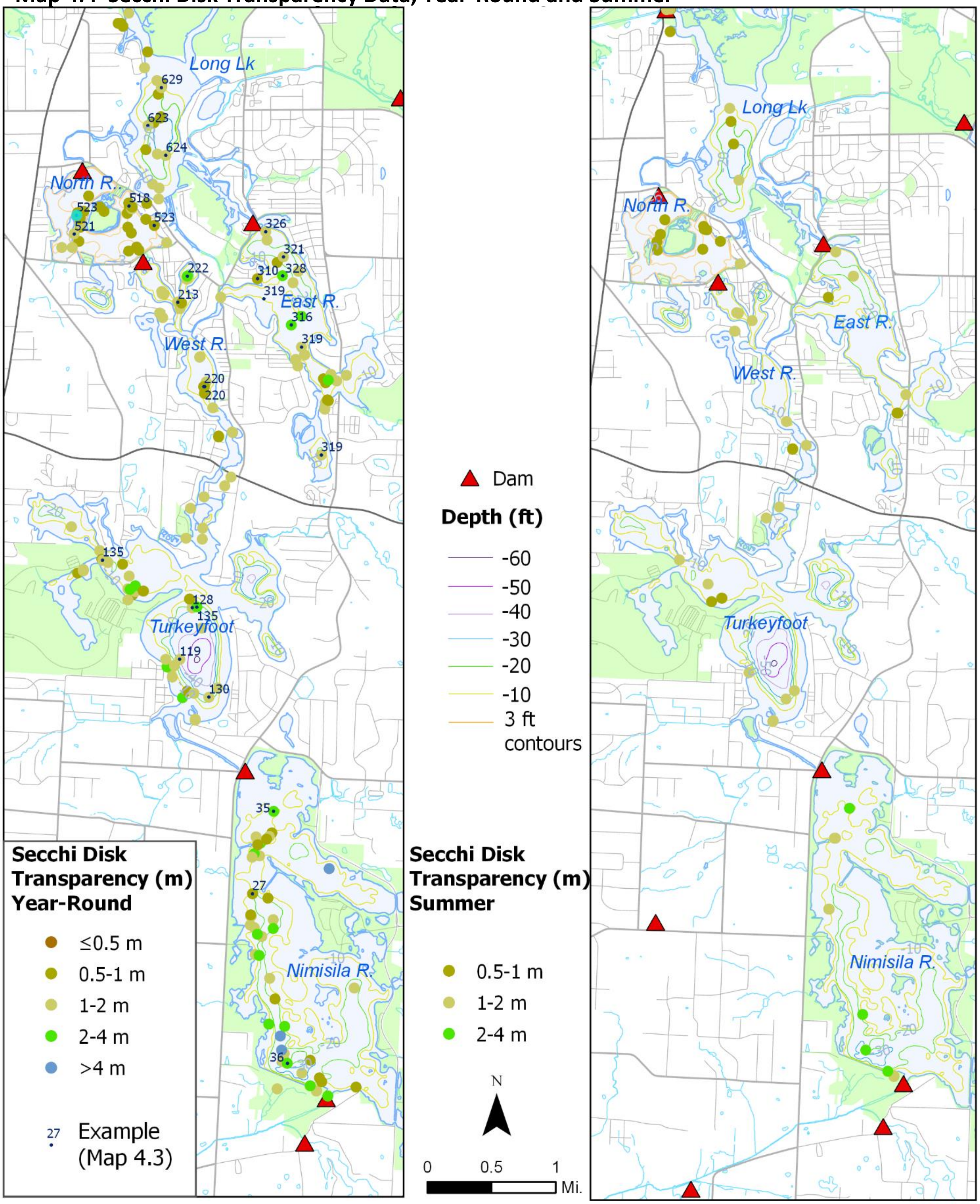
Invasive Zebra (and/or Quagga) mussels have been found in the Portage Lakes for over a decade. These animals filter vast quantities of water, removing algae and plankton, which is the base of the food chain. The water clarity increases, favoring plants versus algae. Boaters and anglers report increased stands of aquatic plants in deeper water. Increased water clarity does not necessarily mean an improvement in water quality, as the food chain is disrupted, and phosphorus is shifted from open water toward the littoral zone as the mussels filter great volumes of water and excrete the waste. The shift in nutrients may encourage more plant or algae growth in the shallow zones, and increased clarity may encourage plant growth in deeper water. The interactions are still being studied by researchers. The best tool is consistent monitoring of many characteristics, to better understand how the whole system works.

**Figure 4.10 Secchi Disk Transparency - Cottage Grove Lake, East and West Reservoirs**




*Orange is the mean value. Low transparency = high turbidity. Carlson TSI for Turbidity added. Higher TSI indicates more turbidity. Data Source: Citizens Lake Awareness and Monitoring data from Ohio Lake Management Society webpage [http://www.eyesonthewater.org/olms/](http://www.eyesonthewater.org/olms/) (2018)*

**Map 4.4 Secchi Disk Transparency Data, Year-Round and Summer**




NEFCO, 2020. Sources: ODNR Div. of Wildlife; ODNR GIS; USGS NHD; Summit County GIS; WRLC, AMATS

## Portage Lakes Trophic State Indicators and Productivity

Periodically the ODNR staff take samples for chemical and physical limnological analyses, including phosphorus and chlorophyll A, which are used together to measure productivity. These samples are not taken yearly but provide important data related to the lakes' trophic state. Figure 4.11 and Table 4.9 show the Carlson trophic state indices (TSI) and data for Secchi disk transparency/turbidity, phosphorus, and chlorophyll. (Productivity increases toward the top of the graph.) The turbidity data reflect only the Secchi Disk measurements taken at the same time as the full sampling suite. (Other Secchi disk data, obtained with depth and DO measurements and shown in Map 4.4, have not been compared to the state criteria.) Table 4.7 also shows how the parameters compare to the Ohio inland lakes criteria.

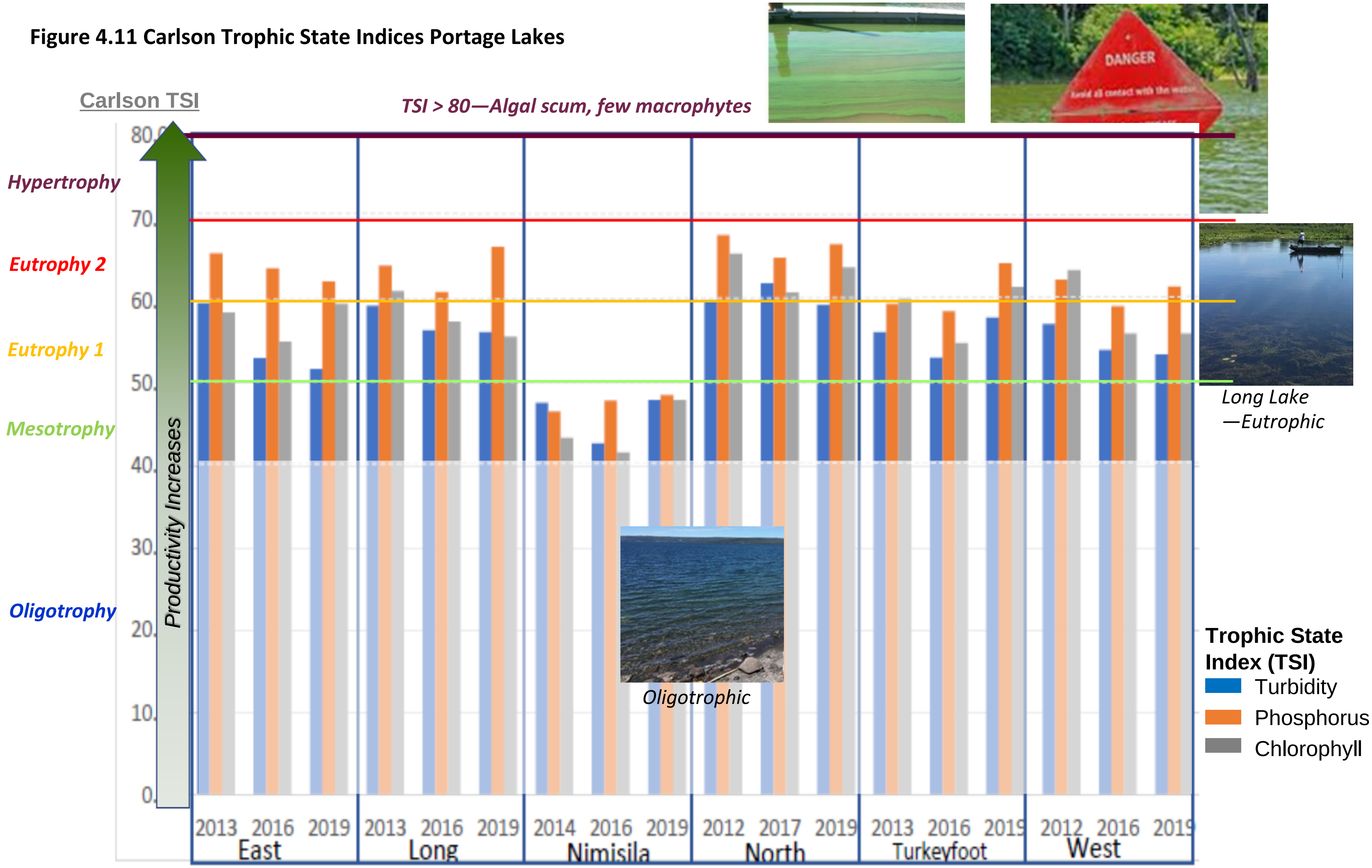
Figure 4.11 and Table 4.7 show that, except for Nimisila Reservoir, which is mesotrophic:[18]

- All the lakes except are in the eutrophic ranges, for all parameters.
- The phosphorus index is generally high. The phosphorus levels generally exceed Ohio criteria.
- The chlorophyll index is high, with chlorophyll often exceeding Ohio lakes criteria.
- North Reservoir appears to be the most eutrophic, and all indicators exceed state criteria.

The trophic state determined for the lakes is consistent with observations.

- Substantial amount of aquatic vegetation and algae, which use phosphorus for growth
- Bass fisheries
- Several of the aquatic plant species that are abundant in the lake are typically found in eutrophic waters, e.g., Eurasian watermilfoil, coontail, and curly-leafed pondweed.
- Urban lakes, like the Portage Lakes, are especially vulnerable to nutrient enrichment and eutrophication.

**Figure 4.11 Carlson Trophic State Indices Portage Lakes**




*Hypertrophy* — *Dense algae, plants*
*Eutrophy 2* — *Nuisance plants, algae*
*Eutrophy 1* — *Possible plant/algae problems, bass*
*Mesotrophy* — *Possible summer anoxia, walleye*
*Oligotrophy* — *Low nutrients, low productivity, cold water fish*

*Sources: NEFCO, 2020; ODNR Div. of Wildlife, 2020; NALMS, 2020 (mod.); image Ohio Dept. of Health, 2013.*

**Table 4.7 Carlson Trophic State Indices (TSI) and Soluble Reactive Phosphorus (SRP) - Portage Lakes**

| Lake | Year | Date | Secchi Disk Transparency* | | | Total Phosphorus (TP)** | | | Chlorophyll A (ChlA)** | | | SRP** ug/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Secchi Depth (m) | Lake Criterion (m) | TSI Secchi | TP ug/L | Lake Criterion µg/L | TSI TP | ChlA ug/L | Lake Criterion µg/L | TSI Chl A | |
| East | 2013 | 07/29/2013 | 1.02 | 1.19 | 59.71 | 71.9 | 34.0 | 65.8 | 17.4 | 14.0 | 58.6 | 3.5 |
| | 2016 | 07/19/2016 | 1.62 | 1.19 | 53.05 | 63.4 | 34.0 | 64.0 | 12.1 | 14.0 | 55.1 | 1.8 |
| | 2019 | 07/18/2019 | 1.77 | 1.19 | 51.77 | 56.7 | 34.0 | 62.4 | 19.5 | 14.0 | 59.7 | 2.5 |
| Long | 2013 | 07/29/2013 | 1.04 | 1.19 | 59.43 | 64.8 | 34.0 | 64.3 | 22.8 | 14.0 | 61.2 | 1.8 |
| | 2016 | 07/21/2016 | 1.28 | 1.19 | 56.44 | 52 | 34.0 | 61.1 | 15.6 | 14.0 | 57.5 | 3.4 |
| | 2019 | 07/18/2019 | 1.30 | 1.19 | 56.22 | 75.9 | 34.0 | 66.6 | 12.9 | 14.0 | 55.7 | 4.0 |
| Nimisila | 2014 | 07/22/2014 | 2.36 | 1.19 | 47.63 | 19.0 | 34.0 | 46.6 | 3.7 | 14.0 | 43.4 | 4.0 |
| | 2016 | 07/19/2016 | 3.32 | 1.19 | 42.71 | 20.8 | 34.0 | 47.9 | 3.1 | 14.0 | 41.6 | 2.0 |
| | 2019 | 07/18/2019 | 2.30 | 1.19 | 48.00 | 21.8 | 34.0 | 48.6 | 5.9 | 14.0 | 48.0 | 3.0 |
| North | 2012 | 07/17/2012 | 1.00 | 1.19 | 60.00 | 83.9 | 34.0 | 68.0 | 36.1 | 14.0 | 65.8 | 1.0 |
| | 2017 | 07/19/2016 | 0.86 | 1.19 | 62.17 | 69.2 | 34.0 | 65.2 | 22.4 | 14.0 | 61.1 | 4.0 |
| | 2019 | 07/18/2019 | 1.03 | 1.19 | 59.57 | 77.6 | 34.0 | 66.9 | 30.6 | 14.0 | 64.1 | 2.0 |
| Turkeyfoot | 2013 | 07/29/2013 | 1.30 | 1.19 | 56.22 | 47.0 | 34.0 | 59.7 | 20.7 | 14.0 | 60.3 | 4.4 |
| | 2016 | 07/19/2016 | 1.61 | 1.19 | 53.14 | 44.2 | 34.0 | 58.8 | 11.9 | 14.0 | 54.9 | 2.2 |
| | 2019 | 07/18/2019 | 1.15 | 1.19 | 57.99 | 66.2 | 34.0 | 64.6 | 24.0 | 14.0 | 61.7 | 2.0 |
| West | 2012 | 07/17/2012 | 1.21 | 1.19 | 57.25 | 57.6 | 34.0 | 62.6 | 29.5 | 14.0 | 63.8 | 10.2 |
| | 2016 | 07/19/2016 | 1.51 | 1.19 | 54.06 | 46.1 | 34.0 | 59.4 | 13.5 | 14.0 | 56.1 | 5.3 |
| | 2019 | 07/18/2019 | 1.57 | 1.19 | 53.50 | 54.5 | 34.0 | 61.8 | 13.4 | 14.0 | 56.1 | 4.2 |

*Secchi disk transparency is high when turbidity/productivity is low. Measurements *equal to or higher* than the criterion meet the Ohio lakes criterion.
** High values of phosphorus and chlorophyll A indicate high productivity. Measurements *equal to or lower* than the criterion meet the Ohio lakes criterion.

Values in green meet or are better than the Ohio inland lakes criterion. Values in red do not meet the Ohio inland lakes criterion.

*Data Sources: C. Wagner 2020; Ohio EPA, 2010.*

It is difficult to discern trends on Figure 4.11 and Table 4.7, as the data were not collected yearly. Table 4.8 compares data for turbidity, phosphorus, and chlorophyll from the 1990s with the recent data.[19] Ohio criteria for inland lakes are also shown for comparison. Except for Nimisila Reservoir, Secchi transparency/turbidity and chlorophyll levels have generally improved, but phosphorus shows more mixed results. Many of the parameters meet state criteria partially or not at all.

**Table 4.8 Trophic Indicators Over Time - 1990s and Post-2010**

| Lake | Secchi Depth (m) | | | Total Phosphorus µg/l | | | Chlorophyll A (µg/l)* | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1990s | 2010-2018 | Lake Criterion | 1990s | 2010-2018 | Lake Criterion | 1990s | 2010-2018 | Lake Criterion |
| Long | 0.69-0.92 | 1.04-1.30 | 1.19 | 42-117 | 52-76 | 34 | 31.5-58.2 | 12.9-22.8 | 14.0 |
| North | 0.38-0.81 | 0.86-1.03 | 1.19 | 41-70 | 69-83 | 34 | 22.7 | 22.4-36.1 | 14.0 |
| West | 0.65-1.01 | 1.21-1.57 | 1.19 | 37-130** | 46-54 | 34 | 72.5-73.2 | 13.4-29.5 | 14.0 |
| East | 0.84-7.90 | 1.02-1.77 | 1.19 | 20-190 | 57-72 | 34 | 54.8-63.6 | 12.1-19.5 | 14.0 |
| Turkeyfoot | 0.92-1.02 | 1.15-1.61 | 1.19 | 60-70 | 44-66 | 34 | 23.2-35.3 | 11.9-24.0 | 14.0 |
| Mud | 1.07-1.08 | | | 42-60 | | 34 | 17.3-19.2 | | |
| Rex | 0.98-1.12 | | | 50-90 | | 34 | 21.7-35.0 | | |
| Nimisila | 0.71-1.15 | 2.30-3.30 | 1.19 | 31-140 | 19-22 | 34 | 14.6-18.2 | 5.9 | 14.0 |

*Data Sources: Ohio EPA 2010; ODNR Div. of Wildlife, 2020.*

*Note*: *High* Secchi Disc readings indicate greater transparency; *low* readings mean more turbidity. Secchi disk data should *equal or exceed* the lake criterion. Other categories should be *less than or equal* to the criteria.

*1990s – August-Sep; 2010-2018 – July **Two values 100 µg/l or greater

| | | | |
|---|---|---|---|
| (green) | Recent data improved | XX | Recent data meets criterion |
| (yellow) | Some recent data improved | XX | Some recent data meets criterion |
| (orange) | Recent data worse | XX | Recent data does not meet criterion |

As shown on Table 4.10:

- Conditions have improved in Nimisila Reservoir, and the recent readings meet state criteria.
- Secchi Disc transparency/turbidity has improved since the 1990s in the other lakes, but only meets the Ohio criterion in some of the readings.
- Phosphorus has improved somewhat, with reduction of the highest readings but increase of lower readings. Except for Nimisila Reservoir, none of the readings meet the Ohio criterion.
- Chlorophyll has improved considerably in most lakes but does not meet the Ohio lakes criterion.
- Phosphorus and chlorophyll have not improved in North Reservoir as they have in other lakes. Secchi depth measurements in North Reservoir do not meet the lake criterion.

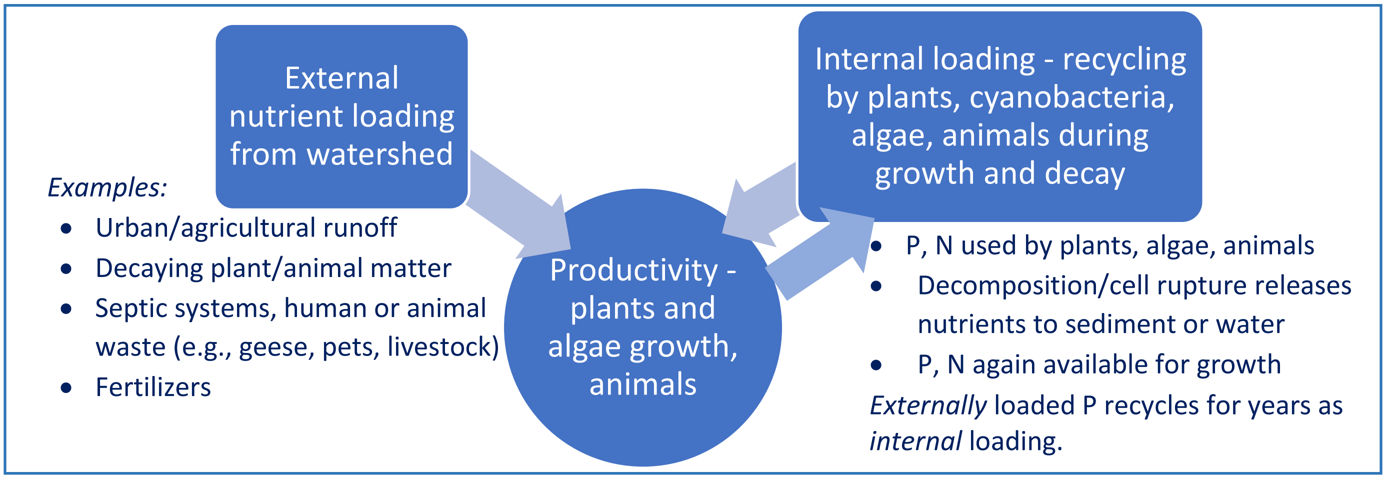
As an urban, eutrophic chain of lakes, the Portage lakes are especially susceptible to eutrophication. In 2020, two to three dozen Ohio lakes were listed on the state weekly cyanobacteria monitoring reports, including several reservoirs and state and local parks.[20] Some of the lakes are listed repeatedly, for many weeks, year after year. Turkeyfoot and Long Lake are occasionally on the list, usually with limited occurrence. Changing climate conditions, including more frequent and intense storms and hotter summers, will increase the likelihood of HABs. It is important to reduce the characteristics in the Portage Lakes that could trigger a shift to the "turbid" algae dominated state.

## Portage Lakes Productivity and Nutrient Loads

Nutrients drive productivity in the Portage Lakes, which are all eutrophic except for Nimisila Reservoir. (Recent studies suggest that ***both*** phosphorus (P) and nitrogen (N) affect cyanobacteria blooms and toxicity.[21]) Both ***external*** and ***interna***l loading affect nutrient levels in the lakes: (See Figure. 4.12):[22]

- ***External loading*****,** nutrients entering from the watershed. Development, fertilizer, small lots with septic systems, and geese have contributed large loads of  for many years, and still do.
- ***Internal loading***, recycling of nutrients many times.  Nutrients in lakes do not just go away, in fact the opposite happens. They enter the lakes as *external* loading from the watershed or shoreline and are used in living matter. Decomposition (or rupture of cyanobacteria cells) releases nutrients to the sediment or water, which are then available for more growth over and over again. *External* loading from the watershed thus lasts for years as recycled *internal* loading from within the lakes.

**Figure 4.12 External and Internal Phosphorus Loading**




**How are nutrients internally recycled?** Like many living systems, it is complex, with many interacting parts.

- Phosphorus occurs in dissolved/soluble or particulate forms.
- Photosynthesizers use dissolved phosphorus for growth.
- Decomposition of organisms (photosynthesizers, animals) or waste releases dissolved phosphorus to the water, which is immediately available for short-term bursts of growth (a few days).
- Particulate phosphorus may be bound to sediment but can be released in anoxic conditions over time.

Many factors affect when and how much phosphorus is available within lakes for growth including:

- How photosynthesizers obtain phosphorus (roots and/or directly from water)
- What kind of photosynthesizers are dominant –large plants/algae or phytoplankton
- Plant characteristics – when is the growth period, how much phosphorus is stored, and when is it released during senescence or fragmentation of aquatic plants and algae?
- Grazing on phytoplankton by zooplankton, which are then consumed by larger animals
- Filter-feeding by zebra mussels relocates phosphorus to near-shore sediment
- Water chemistry at the sediment surface and within it, including pH, oxygen, iron, aluminum, calcium. Pore water of sediment can be anoxic. Disturbance of sediment can release phosphorus.
- Lake mixing – shallow lakes are more easily mixed than deep basins.
- Recent research suggests cyanobacteria recycle nitrogen rapidly as individual cells rupture.

Figure 4.13 shows examples of where external and internal loading may be occurring in the lakes. The large volume of plants reflects the high levels of nutrients available in the lakes.

**Figure 4.13 External and Internal Phosphorus Loading in the Portage Lakes**


***External*** *loading - nutrients enter the lakes from many sources on land. The abundant aquatic plants and algae in the eutrophic lakes use and recycle nutrients from the water and sediment. Decomposition of organic matter like dead plants, plant fragments, leaves, animals, or animal waste releases nutrients back into the water or sediment, resulting in* ***internal*** *loading that can continue for years after the external loading stops.*

## Rooted Plants or Harmful Algal Blooms

Aquatic plants are part of the internal loading cycle, storing nutrients in life, releasing them during decay.

- It is important to note that internal loading is not due to plants but supports them. ***Without aquatic plants, the nutrients in the lakes would still be used – potentially by organisms that cause HABs.***

In hypereutrophic lakes, *excessive turbidity* and *loss of rooted plants* have marked the shift from plant-dominated to an algae-dominated system, with its much higher risk of HABs. The North American Lake Management Society notes that generally, lakes *either* have excessive rooted aquatic plants *or* HABs, because the plants and algae compete for light.

Fortunately, even though most of the Portage Lakes are eutrophic, the littoral zone is still dominated by rooted plants…for now. In spite of occasional HABs, the lake ecosystem is not dominated by algae/cyanobacteria, as in severely hypereutrophic lakes.

Aquatic plants in the lakes may, in fact, help defend against HABs-dominated lakes: Nutrients incorporated in plants are unavailable for HAB growth while plants are growing.

## Safeguarding the Lakes: Reduce External and Internal Nutrient Loading

The eutrophic conditions, the dense aquatic plant growth in the Portage Lakes, are the product of decades of external nutrient loading from the surrounding land and internal loading, the recycling that extends the life of the external loading for years. With high nutrient levels from recycling and continued inputs, the lakes are at risk of shifting from plant- to algae-dominated turbid conditions.

The Portage Lakes community can – and needs to – take steps to minimize or reduce further eutrophication, and protect the lakes:

- ***Reduce external nutrient loading***
- ***Reduce internal loading***
- ***Seasonal monitoring of limnological conditions and biological communities to understand the role of nutrients in the lakes.***

**Reducing External Nutrient Loading -** involves watershed and property management practices:

- Stormwater management to reduce or treat runoff or increase infiltration, such as rain gardens, stormwater treatment, reducing impervious surfaces, and using cover crops;
- Reduce septic system inputs, e.g., by extending sewers or septic system maintenance, siting, or replacement with non-discharging technology;
- Reducing animal waste, especially from geese along the shoreline; and
- Protecting/restoring important habitats (stream channels, deep-rooted vegetation, floodplains, wetlands, vegetated buffers) by the lakes and in the watershed.

**Lessons from Grand Lakes St. Marys**

These findings were highlighted in studies of HAB-dominated lakes in Ohio.

- Shutting down a lake due to long-term HAB problems is devastating to the local economy and property values.
- Fixing a lake after it shifts is *very* expensive and may not turn out as planned.
- Park managers may not have the technical background to manage lake ecosystems.
- Loss of aquatic plants was the warning sign that managers missed in Grand Lakes St. Marys.
- The first plants to become re-established may have a short growing season, allowing summer algal blooms. Stable, long-term recovery requires a diverse aquatic plant community, ensuring plant growth all season.
- It is necessary to "turn off the tap" of external nutrient loading, ***as well as*** address internal loading. Focusing on just one is not enough.
- It is very important to get to know the lakes and the watershed. Watch for changes.
- Climate change increases the risk of HABs.

*S. Fletcher, n.d.; H. Paerl et al., 2021; S. Newell et al. 2021.*

*Watershed measures often used to reduce phosphorus loading range from use of deep-rooted native plants, trees, and shrubs to engineered measures like bioretention or restoration of stream channels and floodplains.*

Watershed management is a large task, because of the number and variety of impacts in a developed watershed. However, there is a well-established knowledge base, programs, funding, and groups to carry it out. Many organizations in the Portage Lakes area are engaged in watershed management.

*Studies of HABs-dominated and restored lakes have shown that*

***To address HABs and eutrophication,***
***both internal and external nutrient loading must be reduced.***
***Efforts that target just one source are not successful over time.***

**Reducing Internal Loading.** Because there are so many factors affecting internal loading, there is not a single, universal solution. Depending on the lake characteristics, restoration efforts in lakes have included, among other things:

- Changing the chemistry of the water at the bottom or in the sediment, e.g., with alum;
- De-stratifying (aerating) the lake to change its structure;
- Harvesting and disposing of aquatic vegetation, which removes phosphorus from the lake but also leaves less vegetation to use up phosphorus;
- Dredging or capping sediment; or
- Changing the structure of the grazing, predatory, and bottom-feeding animal communities.

*Harvesting (for navigation) can reduce internal P loading if the cuttings are removed right afterward.*

It is essential to quantify internal versus external nutrient loading, including the contribution of phosphorus from sediment. The measures noted above are significant efforts that can be costly, may disrupt the lake ecosystem, and may not work as planned.[23] Choosing an approach requires full understanding of lake conditions and consideration of costs, requirements, resources, limitations, effectiveness, and impacts to the lake ecosystem of the different methods. The analyses are beyond the scope of this document and require more information about lake chemistry, processes, and plant community characteristics than is currently available.

- Managing internal loading requires focus, coordination, monitoring, and resources, which are not available now, in contrast with watershed management, which has an organizational framework, broad participation, coordination, technical background, and various sources of funding. Currently, there is no organized focus on reducing internal loading; any efforts are occurring as part of other efforts.
- The PLAC coordinates with other agencies as possible but is a volunteer organization.
- The ODNR Parks and Watercraft staff actively involved in lake management is responsible for flood and flow management, dams, and managing the park and lake facilities. These offices do not have adequate staffing, use of equipment, data, the mandate, or management options to monitor trophic conditions, coordinate efforts, and reduce internal phosphorus loading. There

is a limnologist on staff, and some expertise is available from ODNR in Columbus, but the focus is on concerns other than the health of the lake itself.

- The focus of the Wingfoot and Portage Lakes parks is on maintenance and improvements to support the visitor experience, recreation and nature education, and managing the buoys, docks, and access points in the lakes.
- The three ODNR Canal Lands staff responsible for maintaining the lake elevations, flood control, and flow into the Lake Erie basin are tasked with clearing vegetation for navigation on the Portage Lakes and elsewhere as their time is demanded. Disposing or composting harvested plant material on land is not feasible with the current level of staffing, resources, and disposal options.
- Note: ODNR will be dredging in the lakes for several years and may also be issuing contracts to reduce aquatic plants. Coordination is important to protect habitat, provide for navigation, and reduce nutrients. Dredge disposal sites could be evaluated as sites for disposing of harvested plants.

- The necessary data about limnological conditions and plant communities is minimal. Monitoring and inventories are needed to characterize the conditions, plant communities, and changes.

**Aquatic plant management** is part of managing internal loading and allowing for uses, regardless of other approaches used.

- Aquatic plants should be managed in a way that addresses needs of lake residents and visitors while protecting the lake ecosystem.
- Aquatic plants play an important role in the uptake and release of nutrients, which varies by species.
- It is important to use professional expertise and data to guide decisions about the most appropriate approach that balances the need for access with habitat and reducing nutrients.

Understanding what plant communities are present provides the basis for management decisions. For instance, curly-leafed pondweed, an early-season invasive plant common in eutrophic waters, takes up substantial amounts of phosphorus but then dies off early, creating anoxic areas on the bottom and releasing phosphorus that spurs new growth.[24] An approach may include insuring a more diverse plant population to spread growth and phosphorus uptake through the growing season.

Because of the potential for phosphorus uptake during the growing season, managing aquatic plants can play a part in reducing internal loading, if data about plant communities, staffing, equipment, and on-land disposal/ composting sites are available. Currently they are not. Such "phytoremediation" needs to proceed with caution, so as not to throw the lakes system out of balance into a turbid state.

**Seasonal monitoring of limnological conditions and water chemistry through the water column; inventory and monitoring of aquatic plants and animals -** is essential for:

- Understanding the chemical and physical lake conditions, plant and animal communities, and phosphorus loading mechanisms,

- Detecting changes, and
- Developing, implementing, and monitoring in-lake measures to address eutrophication.
- Monitoring flow between lakes would provide insight on residence time.

Ohio EPA has begun an Inland Lakes monitoring program. The Portage Lakes are not on the list, but Ohio EPA can provide some technical support and equipment for a monitoring effort.
ODNR Division of Wildlife staff periodically collects limnological data related to lake productivity, and there has been some volunteer monitoring. The limnological data available currently provides a basic understanding of certain characteristics, but additional data is needed during each growing season for each lake, for parameters related to productivity and nutrient loading, including:

- Temperature
- Dissolved oxygen (DO)
- Turbidity/clarity
- Chlorophyll A
- Phosphorus
- Nitrogen compounds
- pH
- Conductivity

  - Note: Phosphorus loading likely occurs from sediment throughout shallow urban lakes like the Portage Lakes, and it easily mixes. The sediments may have gradients of phosphorus or oxygen because of the dams and streams. It is important to take chemistry profiles at several locations within the lakes, including shallow areas, and in different settings (e.g., near developed shorelines, near streams, or near dams) not just in the deepest parts.

- An aquatic plant survey and monitoring are necessary to determine the extent, type, seasonality, and other characteristics of the aquatic plants, and to identify trends and changes.

## Public Forum Questions

At the 2019 public forum, the following questions were asked about turbidity and water quality.

- Why does Hower Lake have such low turbidity when North Reservoir has much higher, even though they are so close? *-There is no Secchi data for Hower Lake; however, it is a deeper kettle lake with a small watershed and probably more limited inflow from the Main Chain. Sediment is less likely to get disturbed. Hower Lake may also have lower nutrient input and less algae.*

- Does the water get dirtier as you go from Turkeyfoot to the reservoirs?
  *-There is limited water quality data for the lakes. Certain indicators from Turkeyfoot are comparable to some of the other lakes. North Reservoir is more eutrophic than the other lakes, and Nimisila Reservoir is less so. Some of the factors include watershed size and characteristics, and lake depth/volume. Long Lake receives water from other lakes and the Tuscarawas; North Reservoir is shallow in a developed watershed; Hower Lake is somewhat isolated and deep; Turkeyfoot Lake has a less developed watershed and is upstream of the others.*

## Key Considerations

### Summary of the Portage Lakes Limnological Conditions

- 86 percent of the lakes area is in the littoral zone – the shallow, productive area with rooted plants and intense human activity, where human activities are affected by aquatic plants, and habitat areas are subject to disturbance from land- and water-based activities.
- The Portage Lakes include shallow reservoirs, and other, deeper lakes. The lakes are all stratified in the summer, limiting mixing of oxygen-rich surface waters and deeper nutrient-rich, oxygen poor waters. The lakes mix in fall and spring, but the deepest waters may not mix.
- The lakes are considered shallow urban lakes, managed, with the large development factor (perimeter) and watersheds, increasing potential for land-based impact and eutrophication.
- Turbidity, which often reflects algae growth, increases in the summer months.
- The lakes are highly productive. They are classified as eutrophic using the Carlson Trophic State Index, based on turbidity, phosphorus, chlorophyll, except for Nimisila Reservoir, which is mesotrophic. This classification is consistent with the volume of plants and nuisance algae.
- North Reservoir is the most eutrophic and has shown less improvement since the 1990s than other lakes. None of parameters measured in North Reservoir meet the state inland lakes criteria. In 2020, North Reservoir had extensive, nuisance growth (likely Eurasian watermilfoil).
- In the other lakes, some of the turbidity and chlorophyll measurements meet the state criteria, but phosphorus does not and generally has the highest trophic state index.
- Comparing recent data with records from the 1990s, turbidity has improved in all lakes, chlorophyll has improved in all lakes except North Reservoir. Some phosphorus levels have improved, some are higher.
- Phosphorus is the critical nutrient for photosynthesis, driving plant and algae growth. Recent studies indicate that both phosphorus (P) and nitrogen (N) affect HAB growth and toxicity. P and N enter as ***external*** loading from the watershed. They are recycled with growth and decay. P recycles for years as ***internal*** loading within the lakes from decay of organic matter – including aquatic plants. P is also released from sediment in anoxic water. Internal P loading occurs in the deep anoxic water and may occur throughout the lakes at the sediment-water boundary. The volume of plants indicates a great store of nutrients in the lakes and sediment, typical of urban, eutrophic lakes.
- In shallow lakes, phosphorus release in anoxic water at or within the sediment may mix throughout the lakes and continue to generate plant or algae growth during the growing season.
- Die-off of early season aquatic plants like the abundant, invasive, curly-leafed pondweed releases phosphorus and spurs new growth. Chemical application may have similar effects.

### Lake Management Considerations

- Nutrient-rich lakes may switch from a plant-dominated (“clear”) to algae-dominated (“turbid”) state, with frequent HABS. Perturbations to lakes ecosystems (e.g., removing large amounts of plants) may trigger such shifts. The presence of rooted plants in the Portage Lakes is a positive sign that the lakes ecosystem is still healthy. However, eutrophic lakes with continued high phosphorus levels, as in the Portage Lakes, could become algae-dominated. This undesirable, harmful condition is difficult and expensive to reverse. Climate change impacts favor HABs.

- ***Protecting the future of the lakes requires reducing the external nutrient loading from the watershed and the internal loading within the lakes, involving land-based and in-lake actions.***
- Watershed management, which reduces *external* loading, is a well-developed discipline, with resources available to carry it out, and watershed partners already involved in the task. There is still a substantial need for documentation, external funding for projects, establishing priorities, project management and coordination by partners and, ideally, a coordinator.
- ***Protecting the lakes from further eutrophication will require a greater investment in time, staffing, equipment, monitoring, funding, and coordination than currently exists.*** Reducing internal loading is a complex, developing discipline, that involves water and sediment chemistry, aquatic plants, other biological components, as well as lake users. There is inadequate staffing or resources to carry it out, coordinate efforts, provide technical expertise and guidance, or even obtain data to characterize the lakes**.** Currently a small staff, along with a few volunteers, conduct some monitoring, manage the park, manage the water, clear vegetation for navigation, plan for projects, coordinate, work with residents, businesses, and visitors, and conduct outreach and events. Lake management is not their primary focus - in many cases, the staff and volunteers do what they can to address lake management concerns around their other responsibilities, with limited funding and resources.
- ***Protecting the Portage Lakes requires developing and implementing monitoring program(s)*** for limnology data, entering streams, and aquatic plants. ODNR Division of Wildlife staff and volunteers have collected limnological data occasionally, which provides a snapshot of lake conditions. Consistent, seasonal limnological data for each lake is needed, at different locations throughout the lakes to determine phosphorus loading, patterns, and changes. Monitoring streams will help determine input (e.g., phosphorus or bacteria), and an aquatic plant inventory with occasional monitoring is essential for characterizing the aquatic plant community, manage the aquatic plants and internal loading, and detect changes.
- The ODNR Wingfoot and Portage Lakes have the benefit of a boat, a naturalist, and at least for 2021, a naturalist intern, who could *assist* with monitoring. However, monitoring needs to be consistently done, with dedicated staff, time, and equipment from a partner agency/agencies.
- ODNR is beginning dredging and may contract for control of aquatic vegetation in limited areas with heavy traffic and intense use. This may help in certain areas and should be done in coordination with lake advisers.
- ***Managing plants and internal loading is likely to require a multi-pronged approach.*** Managing aquatic plants may be one tool that can achieve two goals – improving conditions for lake users and residents, as well as reducing internal loading. Any solution should be carefully considered, as manipulating ecosystems may have unintended consequences.

    - Control of nuisance vegetation and dredging should be done in such a way as to reduce nutrient loading and harmful effects to the ecosystem as much as possible. Use of chemicals and mowing without harvesting generates decaying vegetation, which releases phosphorus and fuels growth, dredging stirs up fine sediment, which carries nutrients and increases turbidity, even excessive harvesting may alter the plant-phosphorus balance.
    - Harvesting and on-land disposing/composting of plants would remove phosphorus from the lakes but should be evaluated in terms of resources needed and impacts to the plant-phosphorus balance, as well as other impacts (e.g., removing animals living within

the stands of vegetation). This is a substantial effort, requiring adequate staffing, funding, disposal/composting sites, background information on phosphorus uptake and impacts, and transportation. It should not be done exclusively, as excessive harvesting could disrupt the ecology and phosphorus-plant balance.

- A more diverse, native plant community would allow plant growth to better span the growing season and could reduce nuisance tangles of certain invasive species.
- Other techniques, such as alum or manipulating biological communities may be appropriate in places but should be carefully evaluated. Aeration can be useful in small isolated deep lakes but is unlikely to be beneficial in the linked shallow lake system of the Portage Lakes.

## Recommendations:

**Goal: Reduce external (watershed) and internal (in-lake) nutrient loading to decrease the risk of further eutrophication.** This requires an in-depth understanding of lake conditions and the biological communities in the lakes, feasible approaches, benefits, impacts, and the resources to implement them.

Safeguarding the lakes, protecting them from further eutrophication, while addressing residents' concerns, requires increased emphasis, a stronger framework for lake management, including:

- ➢ Lakes management partnership and a decision-making process to provide for consistent direction, technical expertise, community engagement, a forum for discussion and outreach, coordination of efforts, and sharing resources.
- ➢ Coordinator(s) who work with the partners to identify and implement priorities, integrate efforts, provide technical background, seek funding, share resources, build partnership opportunities. Managing the lakes involves both a ***land-based approach*** to watershed/shoreline management and reducing external loading, as well as ***a water-based approach*** to coordinate monitoring, data management, aquatic plant/phosphorus loading management, and other in-lake activities. Ideally a single coordinator could address both areas.
- ➢ A structure that provides for funding source(s), coordination of responsibilities, a shared understanding and expectations among the Portage Lakes communities of what areas will be managed regularly, opportunities for community input and involvement in lake management, how decisions will be made. Lake management programs in other states operate this way.
- ➢ Consistent, seasonal monitoring of lake and stream conditions, an aquatic plant inventory and monitoring, and phosphorus budget to characterize the lakes, identify changes, and determine appropriate measures. Lake management staff need to keep abreast of current research, share information, and use the information to direct lake management efforts.
- ➢ Adequate staff, resources to carry out specific lake management measures in partnership with other agencies, partners, and volunteers.
- ➢ Increased awareness in the lakes community about the lakes system, needs, responsibilities, and opportunities.

Some of these efforts are underway already. Others that can be started soon include:

- ➢ Public outreach programs/workshops/tours/displays/website focusing on topics like lake ecology, plants, minimizing impacs, property management, lakescaping, geese. Potential audiences can include property owners, residents, boaters, fishermen, community officials, and other visitors. Various partners can contribute. PLAC and SWCD already do similar work.

- Build a partnership that meets periodically to choose priorities, coordinate, review technical materials, and address concerns of the lakes community.
- Hire a coordinator for the watershed and/or lakes
- Bolster, build on existing monitoring efforts, develop preliminary guidelines, and identify resources and partners for monitoring lake and stream conditions
- Research lake management programs, funding, and in-lake phosphorus management options
- Along with wastewater management agencies, identify remedies for discharging septic systems.
- Continue to develop a coordinated aquatic plant management for docks and navigation areas, to manage plants to protect the habitat, water quality, and functions they provide, reduce internal loading of phosphorus, and accommodate the uses of the lakes, addressed further in Chapter 5.
- Continue discussions among Department of Health, wastewater treatment Management Agencies concerning the best wastewater treatment practices and feasibility for the area.

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[1] General limnological background from various sources, e.g.:
Kimball's Biology Pages, Freshwater Ecosystems. https://www.biology-pages.info/F/Freshwater.html;
Robert M. Thorson, 2009. Beyond Walden: The Hidden History of America's Kettle Lakes and Ponds. Walker and Co., New York, NY. Pp. 149-168.
J. Voshell, 2007. A Guide to Common Freshwater Invertebrates of North America. McDonald and Woodward Publishing, Blacksburg, VA. Pp. 17-37.
Walker, J.L., T. Younos, and C.E. Zipper, 2007. Nutrients in Lakes and Reservoirs – A Literature Review for Use in Nutrient Criteria Development. Virginia Tech Water Resources Center. VWRRC Special Report SR34-2007. Blacksburg, VA. https://vtechworks.lib.vt.edu/bitstream/handle/10919/49481/VWRRC_sr200734.pdf?sequence= Retrieved June, 2020.
Water on the Web, 2004. Understanding Lake Ecology. This is a closed site, but it has good background information. https://www.waterontheweb.org/under/lakeecology/index.html. Accessed May, 2020.

[2] Hans Paerl, et al., 2021. Where Do We Go from Here? Mitigating Harmful Cyanobacterial Blooms in a World Facing Human Nutrient Over-enrichment and Climate Change. Sylvia Newell et al., 2021. Nitrogen as a Driver of HABs and Toxins: The Missing Modeling Link? Both talks presented at Understanding Algal Blooms, State of the Science Virtual Conference, Sept. 8, 2021. Ohio Sea Grant/Ohio State University. Archived at: https://ohioseagrant.osu.edu/news/calendar/2021/09/08/rz151/state-of-the-science?utm_source=Ohio+Sea+Grant+and+Stone+Lab&utm_campaign=f238ceca56-EMAIL_CAMPAIGN_2019_05_22_01_28_COPY_01&utm_medium=email&utm_term=0_84c2c6f5d9-f238ceca56-424285100; May be viewed at: https://www.youtube.com/watch?v=Exc9zfVYjRY

[3] Data Source: C. Wagner, 2020. ODNR Division of Wildlife, District 3.

[4] Map Sources: ODNR. Bathymetry data and depth points for Portage Lakes and Nimisila Reservoir. https://ohiodnr.gov/wps/portal/gov/odnr/business-and-industry/services-to-business-industry/data-records/metadata-downloads Retrieved Feb., 2017. Bathymetry data currently available at: https://ohiodnr.gov/wps/portal/gov/odnr/business-and-industry/services-to-business-industry/gis-mapping-services/gis-mapping-services

[5] USGS StreamStats https://streamstats.usgs.gov/ss/ . Accessed March, 2021.

[6] Modified from Florida Lakewatch, 2001. A Beginner's Guide to Lake Management: Lake Morphometry, 2nd ed. Information Circular 104. University of Florida Dept. of Fisheries and Aquatic Sciences. Gainesville, FL. Accessed 6/22/2020 from https://edis.ifas.ufl.edu/pdffiles/FA/FA08100.pdf.

[7] Table Modified from Florida Lakewatch, 2001. Ibid. Akron wind information from Weather Underground, 2020. Akron, OH Weather Conditions. https://www.wunderground.com/weather/us/oh/akron, accessed Feb., 2021; Weather Spark, 2020. Average Weather in Akron, OH. https://weatherspark.com/y/18132/Average-Weather-in-Akron-Ohio-United-States-Year-Round accessed Aug., 2020.

[8] Stephanie Mitchell, 2015. Sediment Dispersal Processes and Anthropogenic Impacts at Rex Lake, Summit County, Ohio. Masters Thesis. University of Akron, Akron, OH.

[9] Map source: NHD, 2016; ArcGIS watershed mapping using USGS 2018 data; ODNR dams; Summit, Stark, Portage Co. GIS

[10] Data Source: C. Wagner, 2020. Op. Cit. Map sources: Summit Co. GIS ODNR Dams and Bathymetry data; NHD.

[11] Various writers have noted the susceptibility of shallow, connected, “urban” lakes to eutrophication, including:

Naselli-Flores, 2008. Urban Lakes Ecosystems at Risk, Worthy of the Best Care. In Sengupta, M. and Dalwani, R. (Editors). 2008. Proceedings of TAAL2007, the 12th World Lake Conference.1333-1337. https://www.researchgate.net/publication/228465620_Urban_Lakes_Ecosystems_at_Risk_Worthy_of_the_Best_Care Accessed Feb. 2021.

Dale Robertson and Matthew Diebel, 2020. Importance of Accurately Quantifying Internal Loading in Developing Phosphorus Reduction Strategies for a Chain of Shallow Lakes. Lake and Reservoir Management. 3(4):391-411. Taylor and Francis Online. Published online July 2020. DOI: 10.1080/10402381.2020.1783727 https://www.tandfonline.com/doi/full/10.1080/10402381.2020.1783727 Retrieved Feb., 2021.

Tom Schueler and Jon Simpson, 2001. Why Urban Lakes are Different. Wat. Prot. Techniques 3(4): 747-750. https://owl.cwp.org/mdocs-posts/schuelert-_why_urban_lakes_are_different/ Retrieved June, 2020.

[12] Table modified from North American Lake Management Society (NALMS) 2020. Trophic State Equations. . https://www.nalms.org/secchidipin/monitoring-methods/trophic-state-equations/ (excerpted from Carlson, R.E. and J. Simpson. 1996.A Coordinator’s Guide to Volunteer Lake Monitoring Methods (North American Lake Management Society. 96 pp.)

[13] S. B. Watson, E. MacCauley, and J. Downing, 1997. Patterns in Phytoplankton Taxonomic Composition Across Temperate Lakes of Differing Nutrient Status. Limnol. Oceanogr. 42(3):487-495. American Limnological Society. https://aslopubs.onlinelibrary.wiley.com/doi/10.4319/lo.1997.42.3.0487 retrieved April, 2020.

[14]Ohio Dept. of Health, 2018. Know Our Programs, Harmful Algal Blooms. HABS photos. *https://odh.ohio.gov/wps/portal/gov/odh/know-our-programs/harmful-algal-blooms/media/habs-photos*

[15] Many writers describe the shift in ecological equilibrium between clear and turbid states. For example:

EcoShape, 2021. Clear and Turbid Lakes. https://www.ecoshape.org/en/knowledge-articles/sediment-and-ecology-in-delta-lakes/1-clear-and-turbid-lakes/ retrieved Feb., 2021.

Marten Scheffer and Egbert H. Van Nes, 2007. Shallow Lakes Theory Revisited: Various Alternative Regimes Driven by Climate, Nutrients, Depth, and Lake Size. Hydrobiologia 584:455-466. Springer Link: https://link.springer.com/article/10.1007/s10750-007-0616-7 Retrieved Feb., 2021.

Istvan Tatrai et al., 2008. Abrupt Shift from Clear to Turbid State in a Shallow, Eutrophic, Biomanipulated Lake. Hydrobiologia 620(1): 149-161. https://www.researchgate.net/publication/226817493_Abrupt_shift_from_clear_to_turbid_state_in_a_shallow_eutrophic_biomanipulated_lake Retrieved Feb., 2021.

[16] Kelly Shaw, 2013.Assessing Two Centuries of Anthropogenic Impacts, Silver Lake, Summit County, Ohio. Masters Thesis, University of Akron. Akron, OH; M. Hilovsky 2017. Presentation to NEFCO’s ERTAC.

[17] Secchi disk data 3 lakes Data Source: Citizens Lake Awareness and Monitoring data from Ohio Lake Management Society webpage http://www.eyesonthewater.org/olms/ (2018)

[18] NALMS 2020, Op. Cit. Data sources: C. Wagner, 2020, Op. cit. Ohio Dept. of Health 2013 images; Ohio EPA 2010; Ohio EPA, 2010. https://epa.ohio.gov/Portals/35/rules/nutrient_criteria_document_2010.pdf

[19] Ohio EPA 2010, ibid.

[20] During the growing season, Ohio EPA obtains monitors satellite data for cyanobacteria in many lakes and sends out weekly reports. (The pixel size of the images is 30m x 30m, so lakes must be large enough to show pixels without interference from the shore.)

Webinars address several examples of hypereutrophic, “turbid state” lakes in Ohio, for example: Fletcher, S. n.d. Short and Long Term Strategies to Reduce Harmful Algal Blooms in Ohio Lakes.Webinar on Ohio Watershed Network, Ohio State University Extension. https://ohiowatersheds.osu.edu/resources/best-practices/short-and-long-term-strategies-address-harmful-algal-blooms-ohio-lakes Accessed April, 2020.

Articles in the Cleveland Plain Dealer also noted that inland lakes were experiencing algal blooms. For example: Brian Albrecht, 2020. Several Inland Lakes Battling Same Algal Blooms as Lake Erie. Cleveland Plain Dealer. https://www.cleveland.com/news/2020/04/several-inland-lakes-in-ohio-battling-same-algal-blooms-as-in-lake-erie.html; Brian Albrecht, 2020b. Toxic Algae Also Threatens Ohio’s Inland Lakes and Waterways. Cleveland Plain Dealer. https://www.cleveland.com/news/2020/04/several-inland-lakes-in-ohio-battling-same-algal-blooms-as-in-lake-erie.html.

[21] H. Paerl et al., 2021 and S. Newell, et al. 2021, op. cit.

[22] There are a number of articles on the importance of internal phosphorus loading in lakes and the role of sediment, including:

Stephen Carpenter, 2005. Eutrophication of Aquatic Systems: Bistability and Soil Phosphorus. PNAS 102(29):10002-10005. https://www.pnas.org/content/102/29/10002 Retrieved Feb., 2021.

S. Fletcher, n.d. Op. cit.

Sabine Hilt et al., 2017. Response of Submerged Macrophyte Communities to External and Internal Restoration Measures in North Temperate Shallow Lakes. Front. Plant Sci., 19 February 2018 https://doi.org/10.3389/fpls.2018.00194 Retrieved Feb., 2021.

M.C. Randall, et al. (2019) Sediment potentially controls in-lake phosphorus cycling and harmful cyanobacteria in shallow, eutrophic Utah Lake. PLoS ONE 14(2):e0212238.https://doi.org/ 10.1371/journal.pone.0212238

Robertson, D.M. and Diebel, M.W. 2020. Op. cit.

M. Sondergaard, J.P. Jensen, J.P., and E. Jeppesen, 2001. Retention and internal loading of phosphorus in shallow, eutrophic lakes. TheScientificWorld 1, 427–442. https://www.researchgate.net/publication/10708991_Retention_and_Internal_Loading_of_Phosphorus_in_Shallow_Eutrophic_Lakes retrieved June, 2020.

Sondergaad, M., Jensen, J.P., and Jeppesen, E. 2003. Role of Sediment and Internal Loading of Phosphorus in Shallow Lakes. Hydrobiologia 506–509: 135–14. http://www.colby.edu/chemistry/EastPond/BioManipPDF/Sondergaard%202003.pdf retrieved June, 2020.

Gabrielle Thiebaut, 2008 . Phosphorus and Aquatic Plants. In P.J. White and J.P. Hammond (eds). The Ecoy-Physiology of Plant-Phosphorus Interactions, ch. 3. Springer Science and Business Media. https://link.springer.com/chapter/10.1007/978-1-4020-8435-5_3 retrieved Feb., 2021

Walker, J.L., T. Younos, and C.Zipper, 2007. Op cit.p. 28.

[23] For example:

S. Fletcher, n.d., Op. cit.;

Jan J. Kuiper, et al. 2017. Mowing Submerged Macrophytes in Shallow Lakes with Alternative Stable States: Battling the Good Guys? Environmental Management (2017) 59:619–634 DOI 10.1007/s00267-016-0811-2 https://link.springer.com/article/10.1007/s00267-016-0811-2. Retrieved Feb., 2021.

M. Sondergaard, et al., 2007. Lake Restoration: Successes, Failures, and Long-Term Effects. Journal of Applied Ecology. 2007 44: 1095-1105. https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/j.1365-2664.2007.01363.x Retrieved Feb., 2021.

[24] Steven Heiskary and Ray D. Valley. 2012. Curly-Leaf Pondweed Trends and Interrelationships with Water Quality. Minnesota Department of Natural Resources Investigational Report 558. https://www.researchgate.net/publication/230846292_Curly-leaf_pondweed_trends_and_interrelationships_with_water_quality