Trophic State Index for Lakes and the Effects of Eutrophication

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Lakes are dynamic ecosystems whose physical, chemical, and biological conditions change in response to natural processes and human activities. One of the most important measures used to describe these conditions is the trophic state of a lake. Trophic state refers to the amount of biological productivity within a water body, particularly the production of algae and aquatic plants. A lake with low productivity is generally clear and nutrient-poor, whereas a highly productive lake contains larger quantities of nutrients, algae, and plant material.

The Trophic State Index, commonly known as the TSI, provides a numerical method for evaluating lake productivity. Robert Carlson developed the most widely used version of the index in 1977. Carlson's method evaluates trophic conditions through three closely related indicators, including Secchi depth, chlorophyll *a*, and total phosphorus. The index is valuable because it translates different water-quality measurements into a common numerical scale that can be used to compare lakes and monitor changes over time.

Although eutrophication is a natural component of lake development, human activities can accelerate it dramatically. Agricultural runoff, wastewater discharges, urban development, soil erosion, and poorly managed animal waste may introduce excessive amounts of nitrogen and phosphorus into lakes. These nutrients stimulate algae and aquatic plant growth, reduce water transparency, alter oxygen conditions, and may eventually harm fish, wildlife, drinking-water supplies, and recreational activities.

Understanding Eutrophication in Lakes

Eutrophication is the process through which a water body becomes increasingly enriched with nutrients and biologically productive. Nitrogen and phosphorus are essential nutrients that support the growth of algae, phytoplankton, and aquatic plants. Under natural conditions, these nutrients enter lakes gradually through weathering, decomposition, groundwater movement, and runoff from surrounding land.

Problems occur when nutrients enter a lake faster than the ecosystem can absorb or recycle them. Excessive enrichment stimulates rapid biological growth, particularly among algae and cyanobacteria. The resulting algal blooms may form green, blue-green, brown, or reddish layers across the surface of the water. Not every algal bloom is toxic, and algae are natural components of healthy aquatic food webs. However, unusually dense blooms may interfere with ecosystem functions and create unsafe conditions for humans and animals.

Large blooms reduce the amount of sunlight penetrating the water column. Submerged aquatic plants consequently receive less light for photosynthesis and may begin to die. When algae and plants die, bacteria and other decomposers break down the organic material. This decomposition consumes dissolved oxygen, especially in deeper water where atmospheric oxygen cannot be replaced quickly.

The process may lead to hypoxia, which refers to low dissolved-oxygen conditions, or anoxia, which refers to the near-complete absence of oxygen. Fish and mobile organisms may attempt to escape affected areas, while less mobile organisms may suffocate. The United States Environmental Protection Agency explains that nutrient enrichment can simultaneously block sunlight, increase biological oxygen demand, and make sections of a water body unsuitable for aquatic life.

Natural and Cultural Eutrophication

Natural eutrophication occurs gradually as a lake ages. Soil particles, organic matter, plant remains, and nutrients accumulate within the lake over centuries or thousands of years. The lake may slowly become shallower and more productive until it eventually develops into a wetland or terrestrial ecosystem. This process is influenced by geology, climate, lake depth, watershed size, and the natural nutrient content of the surrounding landscape.

Cultural eutrophication is the accelerated enrichment of a lake caused by human activity. The term does not mean that eutrophication is created entirely by humans. Instead, it indicates that development and land use have increased the rate at which nutrients enter the aquatic environment.

Major causes of cultural eutrophication include the following:

- Excessive application of agricultural fertilizers
- Runoff carrying animal manure
- Discharge from wastewater treatment facilities
- Leaking septic systems
- Urban stormwater runoff
- Soil erosion from construction and deforestation
- Phosphorus-containing lawn fertilizers
- Industrial effluents
- Atmospheric deposition of nitrogen compounds

Agriculture and urban development are particularly important nonpoint sources of phosphorus and nitrogen. Nonpoint pollution does not originate from a single identifiable discharge pipe. It is transported across broad areas of land through rainfall, snowmelt, groundwater, and surface runoff. Carpenter et al. (1998) concluded that agricultural and urban activities are major contributors of nitrogen and phosphorus to aquatic environments and that reducing excess nutrient flows is essential for reversing eutrophication.

Cultural eutrophication can occur in almost any region where nutrient inputs exceed the capacity of the receiving ecosystem. Remote lakes may receive less direct pollution from cities and farms, but distance from human settlements does not guarantee protection. Atmospheric nitrogen deposition, climate change, wildfires, tourism, and changing patterns of precipitation can influence nutrient cycling even in relatively isolated ecosystems. Warmer and more stable water conditions may also favor longer or more intense cyanobacterial blooms.

The Carlson Trophic State Index

Carlson developed the Trophic State Index to provide a continuous numerical representation of algal biomass in lakes. Instead of placing every lake into a rigid category, the index recognizes that biological productivity exists along a gradient.

Carlson (1977) explained that “each major division represents a doubling in algal biomass.” The index commonly extends from approximately 0 to 100, although it does not have absolute mathematical limits. Higher values generally indicate greater algal biomass, higher nutrient concentrations, and lower water transparency.

The index uses three principal measurements:

1. Secchi disk transparency
2. Chlorophyll *a* concentration
3. Total phosphorus concentration

Each measurement represents a different aspect of lake productivity. Secchi depth measures water clarity, chlorophyll *a* estimates the amount of phytoplankton, and total phosphorus indicates the quantity of a nutrient that frequently controls algal growth in freshwater lakes.

Carlson designed the equations so that the three measurements would produce similar index values under expected lake conditions. However, the values do not always agree because water colour, sediment, zooplankton grazing, nitrogen limitation, aquatic plants, and other factors can alter the relationships among nutrients, algae, and transparency.

How Secchi Depth Measures Water Transparency

A Secchi disk is a circular disk divided into alternating black and white sections. During measurement, the disk is lowered into the water until it can no longer be seen. The depth at which it disappears is recorded, often after taking a second measurement as the disk is raised.

A deep Secchi reading generally indicates clear water, while a shallow reading indicates low transparency. In algae-dominated lakes, reduced transparency may reflect greater phytoplankton abundance. However, a low Secchi depth does not always prove that algae are responsible. Suspended clay, disturbed sediment, dissolved organic matter, tannins, or storm runoff may also reduce visibility.

The equation for Secchi depth is:

TSI SD = 60 − 14.41 ln SD

In this equation, SD represents Secchi depth in metres, while ln represents the natural logarithm.

A Secchi depth of 1 metre produces a TSI value of approximately 60, whereas a depth of 2 metres produces a value of approximately 50. As transparency doubles, the Secchi-based index decreases by about 10 points. The North American Lake Management Society emphasizes that Secchi depth is especially useful in volunteer monitoring because it can be measured inexpensively, although chlorophyll *a* is generally a more direct indicator of algal biomass.

How Chlorophyll Measures Algal Biomass

Chlorophyll *a* is the primary photosynthetic pigment found in algae and cyanobacteria. Its concentration is commonly measured in micrograms per litre and used as an estimate of phytoplankton biomass.

The chlorophyll equation is:

TSI CHL = 9.81 ln CHL + 30.6

In this equation, CHL represents chlorophyll *a* concentration in micrograms per litre.

Chlorophyll *a* is often considered the most useful of the three Carlson variables because it directly reflects the biological response of the lake. Phosphorus represents a potential cause of algal production, while chlorophyll describes the algae that have actually developed.

Nevertheless, chlorophyll levels can vary greatly over time. Weather, water temperature, mixing, grazing by zooplankton, nutrient availability, and bloom-forming species all influence measured concentrations. A single sample may therefore fail to represent conditions throughout an entire season. Reliable assessment usually requires repeated measurements at consistent locations and depths.

How Total Phosphorus Indicates Nutrient

Availability

Total phosphorus includes dissolved phosphorus and phosphorus attached to suspended particles or organic material. In many freshwater lakes, phosphorus is the nutrient most likely to limit algal growth. When additional phosphorus enters such a lake, algal production may increase rapidly.

The total phosphorus equation is:

$TSI\ TP = 14.42 \ln TP + 4.15$

In this equation, TP represents total phosphorus concentration in micrograms per litre.

Long-term whole-lake experiments have demonstrated the importance of controlling phosphorus to reduce freshwater eutrophication. Schindler et al. (2008) studied nutrient enrichment over 37 years and found that reducing nitrogen alone did not prevent eutrophication when phosphorus inputs continued. This evidence established phosphorus reduction as a central strategy in lake restoration.

However, nitrogen should not be ignored. An analysis of 1,382 lakes found that both nitrogen and phosphorus were related to chlorophyll conditions. Phosphorus showed a stronger relationship in lakes with low to moderately high productivity, while both nutrients became important under hypereutrophic conditions (Liang et al., 2020).

Interpreting Trophic State Index Values

Carlson TSI values are commonly interpreted using broad trophic categories. These categories describe biological productivity rather than providing an absolute judgment of whether a lake is good or bad.

TSI range	General trophic state	Typical lake characteristics
Below 30	Oligotrophic	Very clear water, low algal biomass, low phosphorus, and oxygen commonly present in deeper water
30 to 40	Oligotrophic to early mesotrophic	Clear water with modest biological productivity
40 to 50	Mesotrophic	Moderate clarity, increasing algal biomass, and possible oxygen loss in deeper water

TSI range	General trophic state	Typical lake characteristics
50 to 60	Eutrophic	Reduced clarity, elevated nutrients, greater algal growth, and possible aquatic plant problems
60 to 70	Highly eutrophic	Frequent cyanobacterial dominance, algal scums, taste and odour problems, and low transparency
70 to 80	Hypereutrophic	Dense algae, very poor transparency, severe oxygen problems, and impaired recreational use
Above 80	Extremely hypereutrophic	Persistent scums, very high algal biomass, and increased risk of summer fish kills

These ranges are most applicable to north temperate lakes and should be interpreted alongside regional conditions, lake depth, climate, seasonal patterns, and management objectives. A TSI between 40 and 50 generally indicates mesotrophic conditions. A lake should not be classified as mesotrophic, however, unless actual Secchi, chlorophyll, or phosphorus measurements are available. The appearance of cloudy water alone is insufficient evidence.

The North American Lake Management Society also cautions that trophic state and water quality are related but not identical. A productive lake may support a valuable warm-water fishery while being unsuitable for drinking-water supply or swimming. Conversely, a clear oligotrophic lake may provide excellent recreational water but support relatively low fish production.

Example of a Trophic State Calculation

Consider a hypothetical lake with the following measurements:

- Secchi depth of 3 metres
- Chlorophyll *a* concentration of 5 micrograms per litre
- Total phosphorus concentration of 18 micrograms per litre

Using Carlson’s equations produces the following results:

TSI SD

60 − 14.41 ln 3 = approximately 44.2

TSI CHL

9.81 ln 5 + 30.6 = approximately 46.4

TSI TP

14.42 ln 18 + 4.15 = approximately 45.8

All three values fall within the mesotrophic range. Because they are relatively close, the measurements suggest that algal biomass, transparency, and phosphorus are behaving in a broadly expected manner.

Researchers should not automatically average the three values into a single score without considering their ecological meaning. Carlson later argued that chlorophyll *a* should normally receive priority because it measures algal biomass more directly. Differences among the values may reveal useful information rather than simply representing error.

For example, a high Secchi-based TSI combined with a lower chlorophyll TSI may indicate that sediment or coloured dissolved material is reducing transparency. A high phosphorus TSI with lower chlorophyll and Secchi values may suggest that nitrogen limitation, grazing, or another environmental factor is preventing algae from using all the available phosphorus.

Physical and Chemical Effects of Sediment Pollution

Sediment pollution affects lakes through both physical and chemical pathways. Its physical effects occur when eroded soil enters streams and lakes. Sheet erosion, rill erosion, construction activity, unstable streambanks, and poorly protected agricultural land may transport large quantities of fine soil into receiving waters.

Suspended sediment increases turbidity and reduces the amount of light available to submerged plants. It may clog fish gills, bury fish eggs, fill spaces used by bottom-dwelling organisms, and alter spawning habitat. When sediment settles, it can make lakes shallower and cover gravel, vegetation, and other important habitats.

The chemical effects arise because soil particles transport attached nutrients and contaminants. Phosphorus frequently binds to clay and fine sediment particles. When these particles are eroded, the attached phosphorus may be carried into a lake. Nitrate behaves differently because it is highly soluble and can move through soil, groundwater, drainage systems, and streams.

Sediment may also carry pesticides, metals, organic contaminants, and disease-causing microorganisms. The original description of sediment pollution should therefore distinguish nutrients from pesticides. Nitrogen and phosphorus are normally associated with fertilizers, manure, wastewater, and decomposing organic matter. Pesticides may contaminate runoff, but they are not the principal source of nitrogen and phosphorus in most agricultural watersheds.

Once nutrient-rich sediment enters a lake, some phosphorus may accumulate on the bottom. Under low-oxygen conditions, phosphorus can be released from sediment back into the water column. This process, known as internal phosphorus loading, can sustain algal blooms even after external pollution has been reduced.

The Relationship Between Eutrophication and Dead Zones

A dead zone is an area in which dissolved oxygen becomes too low to support most aquatic organisms. Dead zones can develop in lakes, reservoirs, estuaries, and coastal waters. They often occur when nutrient enrichment increases algal production and decomposition consumes oxygen faster than it can be replenished.

Water-column stratification makes the problem more severe. During warm weather, lakes may separate into a warm upper layer and a cooler, denser lower layer. Because the layers mix slowly, oxygen from the atmosphere may not reach deeper water. Decomposition continues in the lower layer, gradually consuming its available oxygen.

The northern Gulf of Mexico provides a major coastal example of nutrient-related hypoxia. Nutrients carried through the Mississippi River watershed stimulate biological production, while water stratification restricts oxygen replacement near the seafloor. NOAA measured a hypoxic zone covering approximately 4,402 square miles in 2025.

The Gulf example illustrates the downstream consequences of watershed nutrient pollution, but it should not be described as a lake classified by Carlson’s Trophic State Index. Carlson’s index was developed primarily for lakes and evaluates algal biomass through transparency, chlorophyll, and phosphorus. Coastal hypoxic zones are usually assessed through dissolved-oxygen measurements, nutrient loads, hydrology, and oceanographic conditions.

Harmful Algal Blooms and Public Health

Some eutrophic lakes experience harmful algal blooms dominated by cyanobacteria, often called blue-green algae. Certain cyanobacterial species can produce toxins that affect the liver, nervous system, skin, and gastrointestinal system.

People may be exposed through drinking contaminated water, swimming, accidental ingestion, or eating affected aquatic organisms. Pets and livestock are particularly vulnerable because they may drink bloom-contaminated water or consume concentrated surface scum.

Even nontoxic blooms can create serious problems. They may produce unpleasant tastes and odours, interfere with drinking-water treatment, reduce property values, discourage tourism, and restrict boating or swimming. The presence of a bloom does not prove that toxins are present, but visible scum or discoloured water should be treated cautiously until appropriate testing has been completed.

Reducing Nitrogen and Phosphorus Pollution

The most effective eutrophication strategy is to prevent excessive nutrients from entering the lake. In-lake treatments may provide temporary relief, but long-term recovery generally depends on managing the entire watershed.

Improving Fertilizer Management

Farmers, gardeners, golf courses, and property managers should apply nutrients according to soil tests and plant requirements. Fertilizer should be used at the correct rate, time, placement, and method. Applying more fertilizer than crops can absorb increases the likelihood of runoff and groundwater contamination.

Fertilizer application should be avoided immediately before heavy rainfall or on frozen, saturated, or highly erodible soil. Where soil already contains sufficient phosphorus, a phosphorus-free fertilizer may be appropriate.

Developing Manure Management Plans

Animal manure contains valuable nutrients, but improper storage and application may pollute surface water. A manure management plan should address collection, storage, transportation, application timing, nutrient content, field conditions, and crop uptake.

Application rates should account for nutrients already present in the soil and manure. Storage structures should be inspected for leaks, and manure should not be applied close to streams, lakes, wells, or drainage channels when runoff is likely.

Restricting Livestock Access

Unrestricted livestock access damages streambanks, increases erosion, disturbs sediment, and allows manure and urine to enter the water directly. Fencing sensitive shorelines and providing alternative drinking sources can reduce nutrient loading while protecting riparian vegetation.

The EPA recommends keeping animals and their waste out of waterways because this reduces nitrogen and phosphorus pollution and protects streambank stability.

Maintaining Vegetated Buffers

Vegetated buffer zones consist of grasses, shrubs, or trees maintained between developed land and a water body. Buffers slow surface runoff, trap sediment, promote infiltration, and absorb a portion of the nutrients moving from the land.

Buffers work best when combined with broader soil and nutrient management. Concentrated runoff may pass through a narrow buffer without adequate treatment, so drainage pathways and steep slopes also require attention.

Reducing Soil Erosion

Cover crops, contour farming, conservation tillage, terracing, stabilized drainage channels, and erosion-control measures at construction sites can reduce sediment transport. Preventing erosion is particularly important for phosphorus management because phosphorus is commonly attached to fine soil particles.

However, no single conservation practice works equally well in every watershed. Soil type, slope, climate, drainage systems, crop selection, and nutrient form influence effectiveness. Watershed programmes should therefore monitor outcomes and adapt management practices when expected improvements do not occur.

Improving Wastewater Treatment

Municipal treatment facilities can reduce nutrient discharges by using biological and chemical processes that remove phosphorus and nitrogen. Septic systems should be inspected and maintained regularly because failing systems can release nutrients and pathogens into groundwater and nearby lakes.

Urban communities can also reduce nutrient pollution by controlling stormwater, maintaining green infrastructure, repairing leaking sewer systems, and limiting phosphorus-containing products where suitable alternatives exist.

Monitoring and Managing Lake Recovery

Reducing nutrient inputs does not always produce immediate improvement. Nutrients stored in lake sediment may continue to circulate for years, and ecological communities may respond slowly. Recovery time depends on water residence time, lake depth, sediment chemistry, watershed conditions, climate, and the scale of historical enrichment.

Effective monitoring should include repeated measurements of:

- Secchi depth
- Chlorophyll *a*
- Total phosphorus
- Total nitrogen
- Dissolved oxygen
- Water temperature
- Turbidity
- Cyanobacterial abundance
- Aquatic plant coverage
- Nutrient loads entering through tributaries

Measurements should be collected during comparable seasons and at consistent locations. A single TSI measurement provides only a snapshot, while long-term monitoring reveals whether lake conditions are improving, deteriorating, or fluctuating naturally.

Community participation can strengthen monitoring. Trained volunteers can collect Secchi readings, photograph blooms, report pollution sources, and help communicate lake conditions. Laboratory measurements and professional sampling remain necessary when management decisions involve drinking-water safety, toxic blooms, regulatory compliance, or expensive restoration measures.

Conclusion

The Trophic State Index is a practical method for describing the biological productivity of lakes. Carlson's index uses Secchi depth, chlorophyll *a*, and total phosphorus to place a lake along a numerical trophic gradient. Values between 40 and 50 generally indicate mesotrophic conditions, while values above 50 indicate increasingly eutrophic conditions. Nevertheless, a valid classification requires measured data, and the index should be interpreted in relation to the lake's climate, depth, sediment, biology, and intended uses.

Eutrophication becomes environmentally damaging when excessive nitrogen and phosphorus stimulate dense algal growth, reduce light penetration, increase decomposition, and contribute to oxygen depletion. Sediment intensifies the problem by increasing turbidity and transporting phosphorus and other contaminants into the lake.

Cultural eutrophication can be reduced through responsible fertilizer use, manure management, livestock exclusion, vegetated buffers, erosion control, wastewater treatment, and coordinated watershed planning. Because lakes respond slowly and internal nutrient loading may continue after external sources are controlled, restoration requires long-term monitoring and sustained management.

The Trophic State Index should therefore be viewed as more than a label. When used carefully, it helps scientists, communities, and policymakers understand ecological change, identify likely causes, evaluate restoration programmes, and protect lakes for future generations.

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