A Beginner's Guide to Water Management – Lake Trophic State and Eutrophication

Mark V. Hoyer and Daniel E. Canfield Jr.

LAKEWATCH staff demonstrating how to measure chlorophyll concentrations that are used to estimate trophic state of lakes (Credits: Mark Hoyer).

Preface

This circular was initiated by many questions directed toward Florida LAKEWATCH regarding the definition and use of the terms "lake trophic state" and "eutrophication." We hope this Information Circular will address these questions in clear, understandable detail. For those not interested in reading the entire document, please read the following paragraph that should help you understand, in a quick and simple format, the definitions and use of these two terms:

It is important to clarify distinctions between the terms lake trophic status and eutrophication, which are often used interchangeably by both professionals and lay persons. Lake trophic state is a classification system based on the amount of biologically productivity in that lake determined by the concentration of nutrients (primarily nitrogen and phosphorus) in the system. The scale works on a continuum from low nutrient/production (oligotrophic) to high nutrient/production (eutrophic). Eutrophication is the process by which a water body, such as a lake, becomes entriched in nutrients causing higher biologic productivity. There is a natural long-term eutrophication process due to continued accumulation of particulate organic matter over decades/centuries (Wetzel 1975) and an human induced (anthropogenic) accelerated eutrophication due to increased additions of nutrients to aquatic systems (Carpenter et al. 1998b, Smith et al. 1999). Additionally, oligotrophication is the reduction of nutrient loading to systems causing a decrease in trophic state, which can also be natural or cultural (Anderson et al. 2005).

Introduction

Most limnologists consider François-Alphonse Forel (Figure 1, February 2, 1841 – August 7, 1912), a Swiss physician and scientist who pioneered the study of lakes, to be the founder and father of limnology. Simply stated, limnology is the study of inland freshwaters. Not so simply, limnology in the 21st century incorporates many scientific, sociological, and political disciplines that impact inland waters including, but not limited to, geology, hydrology, chemistry, biology, physics, human dimensions, and others. As technology advances, the disciplines used in limnology continue to expand. For example, geomatic sciences are now used by limnologists incorporating satellite/drone imagery to monitor and understand water clarity and algal blooms in lake systems.

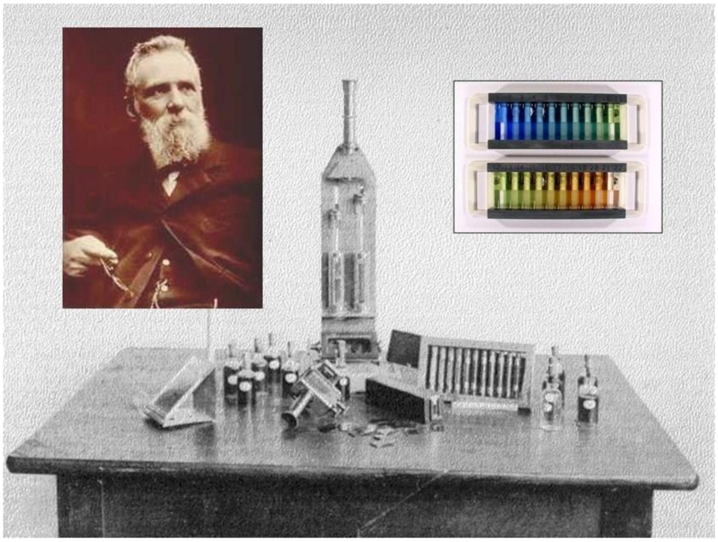

Figure 1. Portrait: François-Alphonse Forel, the initiator of the colour comparator scale. On his laboratory table are all the ingredients needed to use his new Forel scale (ca. 1905). Marcel R. Wernand (https://www.researchgate.net/figure/Portrait-Francois-Alphonse-Forel-the-initiator-of-the-colour-comparator-scale-On-his_fig1_254886155) .

Trophic State Concept

While limnology continues to evolve, lake trophic status and eutrophication are core concepts that underlie or are related to most limnological investigations and aquatic system management. Einar Naumann (Figure 2), a Swedish limnologist, first developed what is now thought of as the trophic state concept (Naumann 1919, Naumann 1929), a lake classification system based on a lakes productivity, which is primarily limited by nutrients that are delivered to the lakes from the lake's watershed. Naumann's concept of trophic state can be summarized by the following four statements (Carlson and Simpson 1996):

- The amount of algae (production) in a lake is determined by several factors, primarily by the concentration of phosphorus and nitrogen.

- Regional variations in algal production correlate with the geological structure of the watershed with lakes in agricultural, calcareous regions being greener than lakes in forested, granitic watersheds.
- The amount of production in a lake affects lake biology as a whole.
- There are certain evolutionary (ontological) connections between lakes of the various types; lakes become more productive as they age.

Figure 2. Photograph of Einar Naumann (https://en.wikipedia.org/wiki/Einar_Naumann).

Understanding the significance of these four propositions is fundamental to understanding how the trophic state concept is or should be applied in the 21st century. So, let's delve into each proposition:

Proposition 1 - The amount of algae (production) in a lake is determined by several factors, but primarily by the concentration of nitrogen and phosphorus.

Naumann emphasized that the trophic classification of a water body was based on the production of phytoplankton (defined as algal biomass). In contemporary times, chlorophyll has been used as a surrogate for algal biomass and algal production because it is highly correlated with algal biomass (Dillion and Rigler 1974, Smith 1979). Naumann also developed the common trophic state terminology based on quantitative production of phytoplankton that is still used today. Oligotrophic lakes are those with low nutrients and algal production and eutrophic lakes have high nutrients and high algal production. Carlson and Simpson (1996) describe how others have since added additional classification terms commonly used today; mesotrophic (production between oligotrophic and eutrophic) and hypereutrophic (production above eutrophic). While Naumann's primary classification system was based on algal/plant production he understood factors other than nutrients (temperature, light, and chemical factors such as calcium, humic content, iron, pH, oxygen, and carbon dioxide) could also impact algal production, thus he added additional classification terminology (lake types) to account for these factors. These extra classifications have since fallen into disuse, but limnologists still understand that environmental factors other than nutrients can limit algal production.

Proposition 2 - Regional variations in algal production correlate with the geological structure of the watershed; lakes in agricultural, calcareous regions were greener than lakes in forested, granitic watersheds.

Naumann recognized that agriculture existed in areas where there were abundant nutrients available in the soil and that forested areas remained in rockey regions where nurients were not very available in the thin soils. Recognition of the importance of a region's geological structure in determining algal production stimulated many studies in the United States during the rest of the 20th century. These works ultimately lead to the establishment of Ecoregions that the U.S. Environmental Protection Agency (USEPA) used to establish regional water chemistry expectations (Omernik 1987).

Here in Florida, the first statewide study to specifically assess the chemical and trophic state characteristics of Florida lakes in relation to regional geology was conducted in 1979 and 1981 (Canfield 1981). This study confirmed that there were regional patterns due to geological structure, but Florida's geology was so complex that multiple regions would be needed for establishing in-lake nutrient concentrations for lake protection and management (Canfield and Hoyer 1988).

USEPA and many Florida scientists agreed that USEPA's level III Ecoregions for the United States (Omernik 1987) were too broad to encompass the diversity of Florida lakes and that subregions were needed for water quality management purposes. Consequently, a collaborative project between the USEPA, the Florida Department of Environmental Protection (FDEP), and the University of Florida's LAKEWATCH program was initiated in the 1990s, resulting in the establishment of 47 Florida Lake Regions (Figure 3, Griffith et al. 1997).

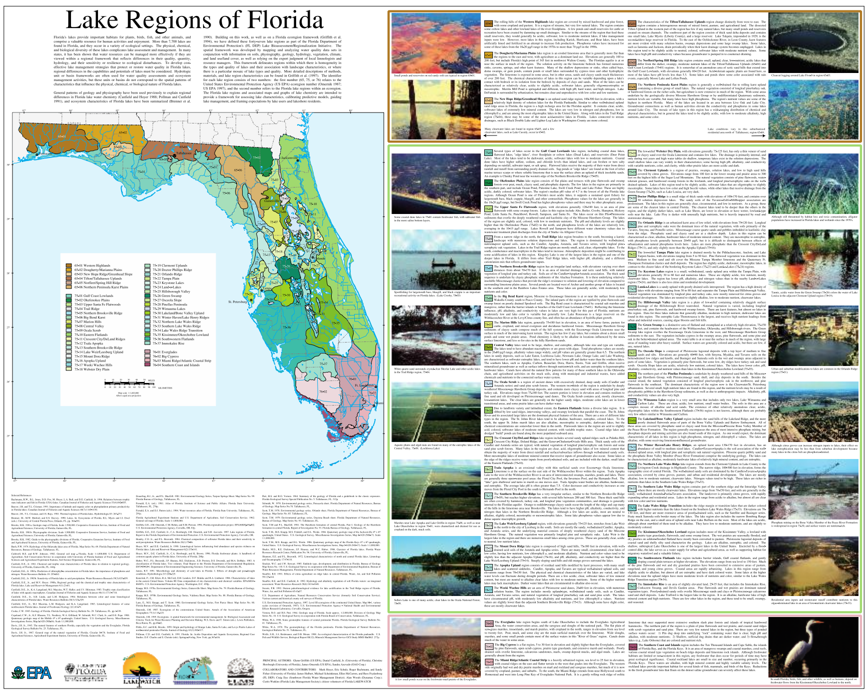

Figure 3. Lake Regions of Florida (https://floridadep.gov/sites/default/files/fl_lkreg_front.pdf).

Lakes within a specific region were grouped together because there were similarities in the types and quality of lakes and their associations with landscape characteristics. The boundaries between the regions also generally followed those on soil maps. Thus, the different regions represented a manifestation of the differences in geology, soils, and hydrology from one part of the state to another, resulting in a patchwork appearance when the lake regions were represented on a map.

In the 21st century USEPA was establishing Numeric Nutrient Criteria (NNC) for Florida lakes. They defined NNC as a tool for protecting and restoring a waterbody's designated uses related to nitrogen and phosphorus pollution. USEPA decided not to use the Florida Lake Regions directly in their approach because of the high number of regions and the limited data for some regions. This led to a study of the factors determining the distributions of total phosphorus, total nitrogen, and chlorophyll a in Florida lakes (Bachmann et al. 2012a). Knowing the lake region where a lake was located still was the best predictor of its trophic state, but statistically different nutrient zones for the primary nutrients of concern (six phosphorus zones and five nitrogen zones) were established to reduce the number of regions that had to be considered as regulations were developed (Figure 4). This added to the development of Florida’s NNC for lakes (Bachmann et al. 2012b).

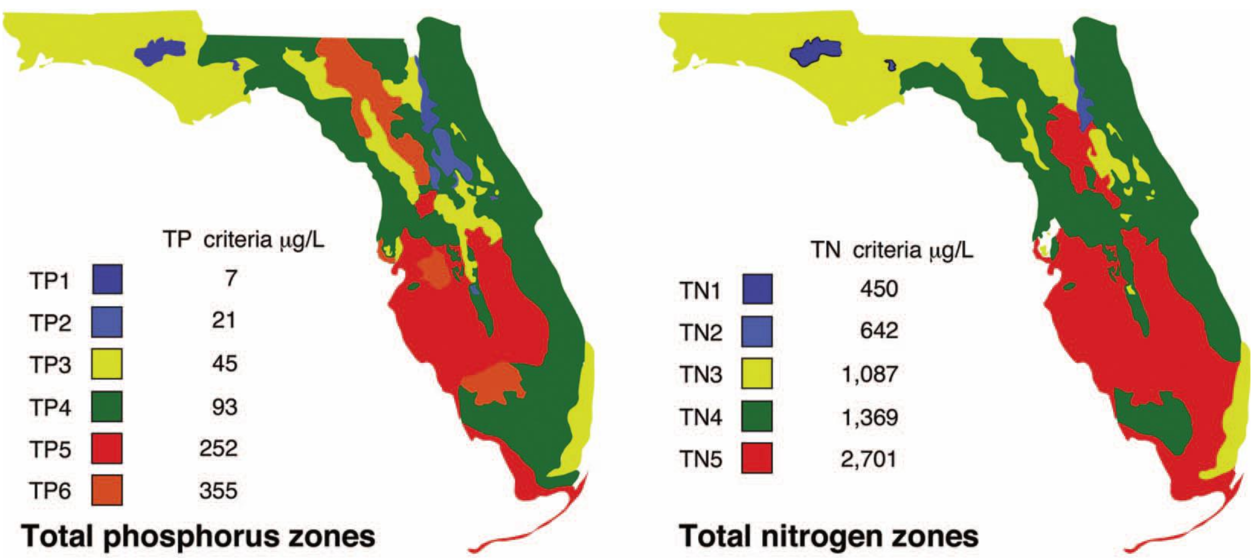

Figure 4.Maps showing the phosphorus and nitrogen zones and the proposed numeric criteria for TP and TN (Bachmann et al. 2012b).

Figure 4 shows the 6 nutrient zones for TP and the 5 nutrient zones for TN. Each color zone represents areas where lakes have similar nutrient concentrations and the listed concentrations represent the value where 95% of the lakes in the region have lower nutrient concentrations. While mean values for each nutrient zone are statistically different from each other, the range of values demonstrate the diversity of nutrient concentrations in Florida lakes, even within individual nutrient zones.

These nutrient zones are now incorporated in Chaper:62-302 (Surface Water Quality Standards) of the Florida Administrative Code & Florida Administrative Register Rule. Reference to the nutrient zones is specifically found in 62-302.200(19) where they are used to define what natural background conditions, which is the condition of waters in the absence of man-induced alterations.

Proposition 3 - The amount of production in a lake affects the lake biology as a whole.

One of the most noticeable impacts of the amount of algal production on lakes was the influence on the quantity of aquatic organisms. Soon after Naumann’s work, limnological surveys clearly showed numerous lakes with additions of domestic drainage over and above the normal geologic influences showed marked biological changes (Hasler 1947). Lakes with additions of nutrients by humans (cultural eutrophication) led to increases in the biomass of fish. In Florida, research has also shown similar positive relations between the amount of chlorophyll (estimate of algal abundance) and zooplankton abundance (Canfield and Watkins 1984), fish abundance (Canfield and Hoyer 1992), aquatic bird abundance (Hoyer and Canfield 1994) and even the abundance of top predators like alligators (Evert 1999). Thus, as the bottom of the food chain increases (plant biomass), food becomes more available for all levels of aquatic organisms and abundances increase.

While the total abundance of organisms increases with trophic state, species composition also changes. In the northern regions, when nutrient inputs became too great in thermally stratified waterbodies, their bottom water (hypolimnion) lost oxygen and there was the elimination of “desirable” cold-water fish (e.g., trout and salmon). There was also a decline in the percentage of “desirable” cold-water fish” within a water body due to an increase in “rough” or “course” fish (carp and shad) numbers and biomass (Larkin and Northcote 1969).

Florida waters, however, do not show the same changes in fish populations often described for northern lakes (Bachmann et al. 1996). Florida waters do not have cold hypolimnia (bottom waters), and do not support cold-water fish species. Species richness of fish (total number of fish species in a lake) in Florida is also directly related to the waterbody's surface area and not trophic state. Additionally, the absolute biomass of Florida's premier sportfish the largemouth bass (*Micropterus salmoides*) shows increases with trophic state, but their percentage of the total biomass becomes less abundant at higher trophic states. On average the percentages of largemouth bass by weight in oligotrophic, mesotrophic, eutrophic, and hypereutrophic lakes were 20, 17, 16, and 4%, respectively, of the total biomass. Smaller centrarchids (i.e., bluegill *Lepomis macrochirus* and redear sunfish *Lepomis auritus*), likewise showed higher total biomass in lakes with higher trophic state but the centrarchids represented a lower percentage of total fish biomass in lakes of higher trophic states. With these changes come increases in bottom and filter feeding fish like gizzard shad (*Dorasoma cepedianum*) and threadfin shad (*D. petenense*). Bachmann et al. (1996) found that total fish and sportfish biomass did not declined with increasing trophic state even in the study lake with the highest chlorophyll concentration of 240 µg/L.

Another transition that can happen to shallow waterbodies as the water becomes more productive is a change from a clear-water macrophyte (aquatic plants) dominated water to an algal dominated system (Brönmark and Weisner 1992). Naumann's original idea was to classify the trophic status of lakes based on plant production (biomass). He focused on phytoplankton production for the practical reason that his study lakes were large, deep, and only had a fringe of aquatic macrophytes that were confined to small littoral areas (nearshore areas that have enough sunlight penetrating to the sediment to support aquatic plant growth). As regional limnological studies examined shallower lakes, the presence of large amount of macrophytes made limnologist realize these plants play an important role in providing fish habitat and overall lake-wide production. Visual observations clearly indicated that the presence of aquatic macrophytes were indicative of great levels of production, but measures of nutrients, chlorophyll and Secchi disk transparency suggested the macrophyte-dominated water bodies were not productive.

There are forward switches that move water bodies from macrophyte to algal states, which generally occur during eutrophic conditions with phosphorus concentrations around 100 µg/L (Moss et al. 1996). This type of switch can happen in many of the world's shallow productive waters, including those in Florida. Additionally, lakes can switch back to macrophyte dominated systems after a major event like a massive drought exposing the lake bottom to air and light allowing large expansion of wetland plants. The switch between a clear macrophyte state and a turbid algal state and back is now known as an Alternative Stable States (Scheffer 1998, Bachmann et al. 1999). This can be either a short-term event after aquatic plant management activities or a long-term change.

This causes additional difficulties when classifying the trophic state of lakes with abundant aquatic macrophytes, especially when using open water measures of water chemistry (Carlson and Simpson 1996). Open water measures of chemistry in lakes with abundant aquatic plants miss the plant production associated with aquatic macrophytes and attached periphytic algae (Canfield et al. 1983). Errors in trophic state assessment would be small where macrophytes were confined to small littoral areas, but large errors would result in macrophyte-dominated lakes. This problem was emphasized when aquatic weed control efforts removed large amounts of plants as described previously. When abundant aquatic plants in lakes are killed by management activities or by natural events, nutrients are released and plant production shifts from aquatic plants and associated periphyton (algae attached to plants) to open-water algae. Xiong and Hoyer (2019) suggested that there are three mechanisms that can contribute to increases in nutrient concentrations and thus chlorophyll concentrations of a lake when abundant aquatic plants (> 30% area covered with aquatic macrophytes; Canfield et al. 1983) decrease in a lake either naturally or through management. First, nutrients within the plant and attached algae (periphyton) are released, making it available to open-water algae. Secondly, when macrophytes are removed wave action increases, potentially increasing resuspension of sediment-associated nutrients to the water column. Finally, particles like phytoplankton containing nutrients are not allowed to settle without calm water, keeping them in the surface water where there is sufficient light for growth (photic zone). It was not until the 1980s that approaches were developed for classify the trophic status and predicting chlorophyll concentrations in macrophyte-dominated lakes (Canfield et al. 1983).

Lake Weohyakapapka also known as Lake Walk-in-Water is a good Florida example of a long-term shift in chlorophyll values based on a large change in aquatic macrophyte abundance. Walk-in-Water is a large shallow lake in Polk County, Florida with a surface area of 3050 ha and a mean depth of 1.25 m. From 1990 to 2004, Walk-in-Water was dominated by the non-native submersed aquatic plant hydrilla (*Hydrilla verticillata*). During that time, hydrilla coverage averaged 640 ha with a range from 24 ha to 2600 ha (FWC 2017, Invasive Plant Management (IPM) Annual Aquatic Plant Survey). In 2004 hurricanes Charlie, Francis and Jeanne traveled almost directly over Lake Walk-in-Water. After the storms ripped up all submersed aquatic vegetation, releasing nutrients, and allowing continued wind resuspension, algae populations dominated plant production from 2005 to 2019. Chlorophyll levels during the pre- and post-hurricane years averaged 10 µg/L and 23 µg/L, respectively (Figure 5).

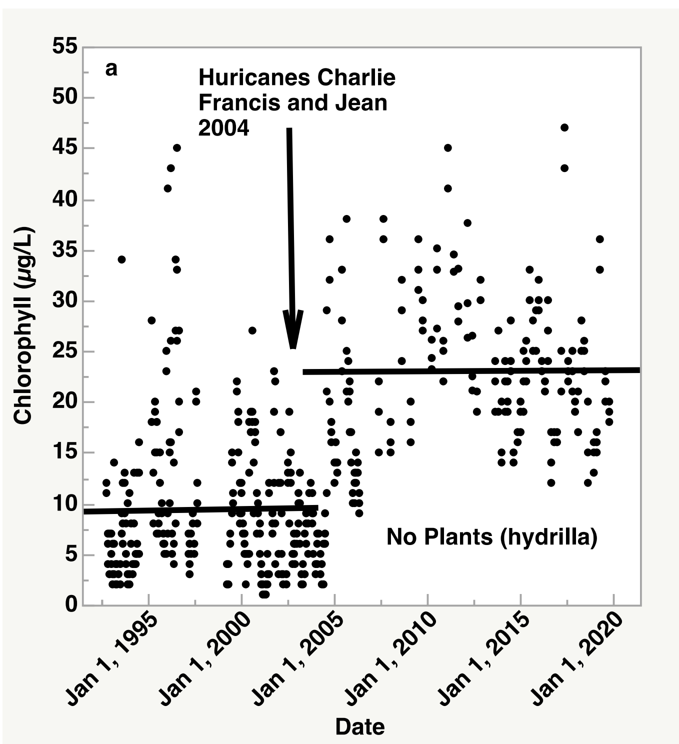

Figure 5. Plot of chlorophyll concentrations versus date from Lake Walk-in-Water. Horizontal lines indicate average chlorophyll concentrations before and after hurricanes Charlie, Francis and Jeanne crossed central Florida in 2004.

Proposition 4 - There are certain evolutionary connections between lakes of the various types; lakes become more productive as they age.

Naumann's trophic state concept began with the watershed. Nutrients and other chemicals from the watershed, together with factors such as temperature and light, were seen as factors influencing the abundance of algae in a lake. It was also recognized that the watershed delivered sediments and other biological material produced within the watershed to the lake. These materials, over geological time, would shallow a lake providing less dilution capacity for incoming nutrients. The reduction in dilution capacity would then lead to increased nutrient concentrations and increased in-lake biological production; hence lakes would become more productive as they aged.

It is to Naumann's credit that he also insisted that in-lake production would affect the system's biological structure, and thus the ontogeny of the lake itself. However, many limnologists began to consider the evolution of lakes as a unidirectional process. They also accepted the notion that the addition of nutrients by human activities (cultural eutrophication), which enhances in-lake algal production, contributed directly to the aging of lakes by delivering organic sediments to deeper waters.

Understanding the ontogeny of lakes, however, becomes more complicated once exotic aquatic macrophytes began to dominate a shallow water's biological production, especially in Florida's shallow lakes. Increases in aquatic vegetation results in a rapid accumulation of organic matter on the bottom of water bodies in a relatively short period of time, especially for exotic aquatic plants like water hyacinth (*Echhornia crassipes*) or torpedo grass (*Panicum repens*). Expansive monocultures of native emergent vegetation, such as pickerelweed (*Pontederia cordata*) and cattails (*Typha spp.*) also produce tremendous amounts of leaf litter that allows for the expansion of the littoral zone, often within an individual's lifetime (Hoyer and Canfield 1997).

Figure 6. Muck removal and in-lake disposal creating islands of muck at Lake Tohopekaliga in 2003 (Credits: Mark Hoyer).

The extensive accumulation of organic matter on the bottom of water bodies can lead to expensive muck removal programs (Figure 6, Hoyer et al. 2008). In Florida, the stabilization of water levels with dikes and other water control structures have also eliminated the natural self-cleaning processes that minimized muck accumulation prior to settlement (Hoyer et al. 2008, Canfield et al. 2021). High water levels and wind activity would permit resuspended fine-grain organic particles to be swept out of the basin and deposited downstream. Organic matter trapped in stem and root structures of emergent and floating-leaved plants such as spatterdock (*Nuphar luteum*) provided another mechanism for organic matter removal by creating tussocks (floating plant islands with an organic base).

Tussocks, occur globally in many wetland and aquatic ecosystems, and are also formed when anaerobic gasses accumulate on the bottom, causing mats to break loose and float to the surface (Clark 2000). Formation of tussocks results in hydropattern changes that can significantly alter the structure and function of pre-existing biological communities and influence ontological development. Prior to the building of water control structures in Florida, high water and wind could deposit the floating islands outside the normal water bodies basin (Hoyer et al. 2008), Floating island and sediment deposition onto normally dry floodplain when water levels receeded also resulted in organic sediments drying and oxidizing. This mechanism would efficiently remove large amounts of muck, leaving behind sandy shorelines in many Florida lakes, thus reversing the ontological process.

Another feature of Florida lakes that can reset the ontological clock is extreme low water during drought conditions. Organic sediments are again exposed to drying and oxidation (process where organic matter is broken down by oxygen using/stealing electrons that form those organic compounds) only this time on the lake bottom. When thoroughly dry, wind can remove the dry oxidized sediments from the basin. Additionally, in some lakes sediments can catch on fire from lighting strikes among other causes, creating large muck fires. All of these mechanisms functioned to reduce the accumulation of organic matter and create a diverse, dynamic, aquatic plant community in the littoral zone (Hoyer et al. 2008. Clark 2000).

Chain of trophic state models

Since Naumann's time, extensive research has confirmed that phosphorus is the primary limiting nutrient for algal production in many if not most lakes (Vollenweider 1968, Schindler 1975, 1977, Schindler et al. 2016). The limiting nutrient is generally defined as a nutrient that limits the amount of the product that can be formed or its rate of formation, because it is present in the smallest quantities of nutrients needed. Multiple models (mechanistic and empirical) were therefore developed to estimate phosphorus concentrations in lakes from annual phosphorus loads adjusted for ranges in lake morphology and hydrology (Vollenweider 1976, Canfield and Bachmann 1981). Empirical models were also developed to predict chlorophyll concentrations from total phosphorus concentrations (Dillon and Rigler 1974, Canfield 1983), water clarity from chlorophyll concentrations (Carlson 1977, Canfield and Hodgson 1983) and the maximum depth of aquatic macrophyte colonization from water clarity as measured by using a Secchi disk (Chambers and Kalff 1985, Caffrey et al. 2007). This chain of empirical models (Figure 7), based on the assumption of phosphorus-limitation, provided managers with a basis for estimating how increases or decreases in phosphorus loading would potentially change the chemical and biological properties of targeted aquatic system (Hoyer et al. 2015, Takoukam et al. 2021). Thus, managers of aquatic systems who were trying to control algal blooms and other symptoms of eutrophication focused efforts on reducing inputs of a single nutrient, phosphorus (Schindler et al. 2016).

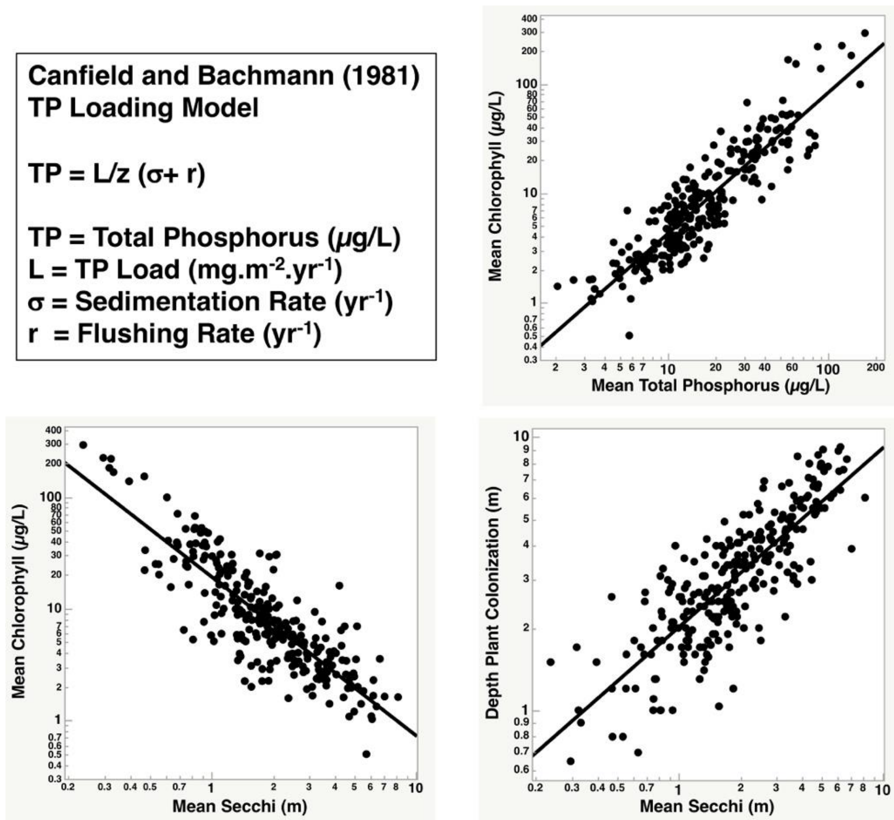

Figure 7. Chain of trophic state models: Canfield and Bachmann's (1981) phosphorus loading model (upper left), and total phosphorus versus chlorophyll (upper right), chlorophyll versus Secchi depth (lower left) and Secchi depth versus maximum depth of plant colonization (lower right) using data from 279 Florida lakes (Caffrey et al 2007).

Focusing on solely controlling phosphorus inputs to alleviate eutrophication symptoms can be problematic, however, because Naumann and other limnologists demonstrated that environmental factors other than phosphorus can limit algal production. For example, when total nitrogen to total phosphorus ratios (by mass) are under 10, nitrogen generally becomes limiting to chlorophyll concentrations (Sakamoto 1966, Forsberg and Ryding 1980). The importance of nitrogen limitation also becomes more important when lakes are phosphorus rich (100 µg/L Canfield 1983, Filstrup and Downing 2017). Lakes with greater color (humic substances) and/or non-algal suspended solids also tend to have less chlorophyll per unit of phosphorus than phosphorus-limited lakes (Canfield and Hodgson 1983, Hoyer and Jones 1982, Brezonik et al. 2019). Lakes with high flushing rates (water exchange) and high zooplankton grazing can also have less chlorophyll per unit of phosphorus than phosphorus-limited lakes (Swanson and Bachmann 1976; Hoyer and Jones 1982, Soballe and Kimmel 1987). Occasionally, even trace metals can also be an environmental limiting factor (Downs et al. 2008). Managers of aquatic systems, therefore, need a tool to determine when such factors need to be considered so that implemented phosphorus-control programs do not fail to achieve management objectives (Canfield et al. 2021).

Hoyer and Canfield (2022) developed such a tool called the "Limnological Yardstick". The Limnological Yardstick was developed using long-term (15 to 35 years) lake chemistry data collected by volunteers of the Florida LAKEWATCH program. The Yardstick can assist managers or users of aquatic systems with identifying where there is a great probability that phosphorus is not only the limiting nutrient, but the limiting environmental factor. The Yardstick is simply the 95% confidence interval determind by regressing daily phosphorus concentrations with paired chlorophyll concentrations using data from known phosphorus limited lakes. When a lake's phosphorus-chlorophyll data lie below the Yardstick's lower 95% confidence interval, phosphorus may be the limiting nutrient but not the limiting environmental factor, indicating where phosphorus control strategies will most likely fail. The Limnological Yardstick cannot directly identify the limiting environmental factor(s) as this requires a thorough limnological study of the lake because each lake has unique properties. However, Figure 8 shows how the Limnological Yardstick can identify lakes with the most common limiting environmental factors: nitrogen, true color (Pt-Co units), non-algal suspended solids, flushing rate.

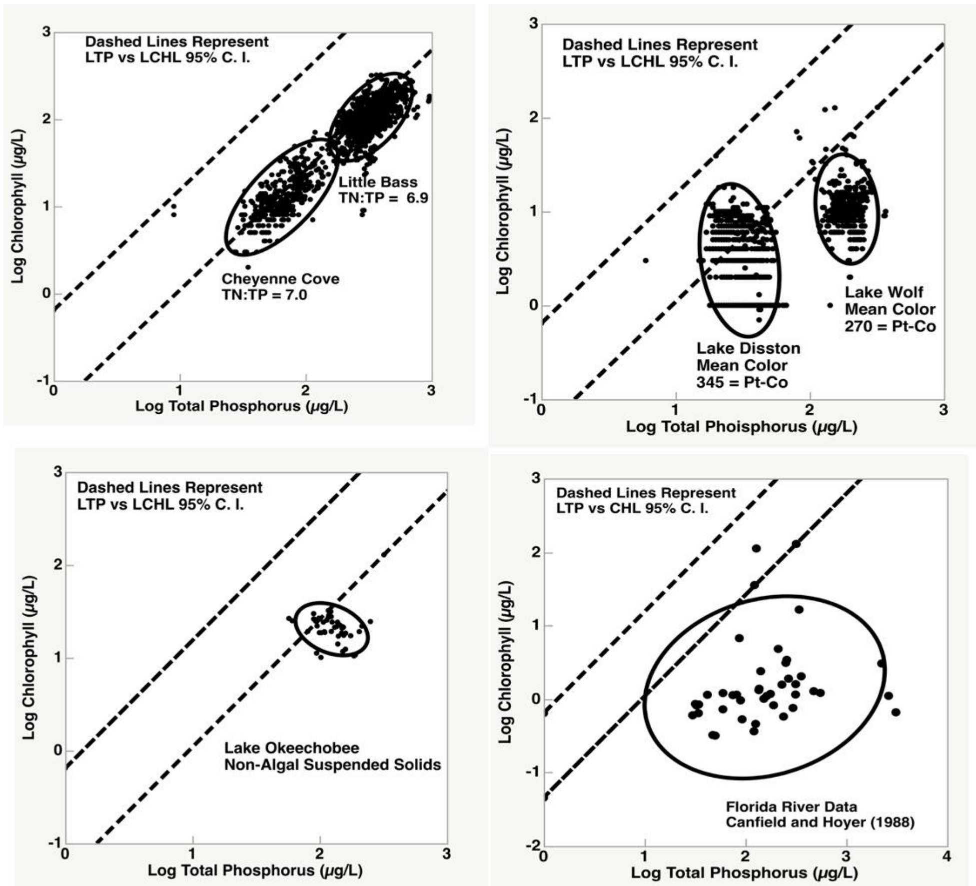

Figure 8. Plots of phosphorus versus chlorophyll with the dashed lines representing the Limnological Yardstick (Hoyer and Canfield 2022) showing lakes that are nitrogen limited (upper left), light limited by color (upper right), limited by nonalgal suspended solids (lower left) and rivers/streams limited by flushing rate (lower right).

Trophic state classification systems

It is important to clarify distinctions between the terms trophic status and eutrophication, which are often used interchangeably by both professionals and lay persons. Defining a lake's trophic state is a static exercise, placing a lake somewhere along Naumann's gradient of lake production from low production (oligotrophic) to high production (eutrophic). Eutrophication on the other hand, is the movement from a lower trophic state to a higher trophic state (Carlson and Simpson 1996, Le Moal et al. 2019). There is a natural long-term eutrophication process due to continued accumulation of particulate organic matter (Wetzel 1975) and an anthropogenic accelerated eutrophication due to increased additions of nutrients to aquatic systems (Carpenter et al. 1998b, Smith et al. 1999). Additionally, oligotrophication is the reduction of nutrient loading to systems causing a decrease in trophic state, which can also be natural or cultural (Anderson et al. 2005). This paragraph has been said above

There are many different published lake trophic state classifications systems (Carlson and Simpson 1996 and scientists continue to rethink these indices (Farnez et al. 2019). Being true to Naumann's original intent would mean basing indexes solely on some measures of plant abundance (production). However, scientists have developed multiple trophic state indices including those based on the above chain of empirical models (Figure 7), which assume phosphorus limitation, to give discrete values for predicted chlorophyll concentrations using other variables like total phosphorus, and water clarity that are correlated with chlorophyll (Carlson 1977, Forsberg and Ryding 1980, OECD 1982). If a water body falls within the 95% confidence limits of Limnological Yardstick, these classification systems work very well. However, Figures 8 give examples of systems where trophic state classification based on variables related to chlorophyll concentrations would be inappropriate and it would be best to classify these lakes based only on some measure of algal abundance.

Staying with Naumann's intent and using only chlorophyll concentration, Florida LAKEWATCH follows the trophic state classification system published by Forsberg and Ryding (1982). Others can use any of the published trophic state indexes because they all divide the trophic state continuum (oligotrophic, low plant productivity to eutrophic, high plant productivity) into different discrete units. However, we recommend using only the chlorophyll aspects of any index and cite specifically which index you are using so everyone can compare apples with apples. We also advise that the abundance of aquatic macrophytes be considered when classifying the trophic status of aquatic systems.

Conclusions

From the beginning Naumann (Naumann 1919, Naumann 1929) and others understood that most lakes follow patterns that could be used for classification of trophic status and/or management of eutrophication. However, then as now limnologists understand that many lakes are individuals having characteristics that make them unique, to some extent. Certainly, algal populations are nutrient limited in many of the world's lakes and control of phosphorus inputs can be a successful strategy for curbing lake eutrophication. Unfortunately for managers of aquatic systems, phosphorus while being the major limiting nutrient is not always the limiting environmental factor. Unless phosphorus can be made both the limiting nutrient and the limiting environmental factor expensive lake management programs can be implemented without great success.

Literature Cited

Anderson NJ, Jeppesen E, Sondergaard M. 2005. Ecological effects of reduced nutrient loading (oligotrophication) on lakes: an introduction. Freshwat Bio. 50:1589–1593.

Bachmann RW, Jones BL, Fox DD, Hoyer M, Bull LA, Canfield DE Jr. 1996. Relations between trophic state indicators and fish in Florida (U.S.A.) lakes. Can. J. Fish. Aquat. Sci.53: 842–855.

Bachmann RW, Hoyer MV, Canfield DE Jr. 1999.The restoration of Lake Apopka in relation to alternative stable states. Hydrobiologia 394:219–232.

Bachmann RW, Bigham DL, Hoyer MV, Canfield DE Jr. 2012a. Factors determining the distributions of total phosphorus, total nitrogen, and chlorophyll a in Florida lakes. Lake Reserv. Manage. 28:10–26.

Bachmann RW, Bigham DL, Hoyer MV, Canfield DE Jr. 2012b. A strategy for establishing numeric nutrient criteria for Florida lakes. Lake Reserv. Manage. 28:84–91.

Brezonik P L, Bouchard RW Jr., Finlay JC, Griffin CG, Olmanson LG, Anderson JP, Arnold WA, Hozalski R. 2019. Color, chlorophyll a, and suspended solids effects on Secchi depth in lakes: implications for trophic state assessment. Ecol Appl. 29(3):e01871. 10.1002/eap.1871

Brönmark C, Weisner SEB. 1992. Indirect effects of fish community structure on submerged vegetation in shallow, eutrophic lakes: an alternative mechanism. Hydrobiologia 243/244:293-301.

Caffrey AJ, Hoyer MV, Canfield DE Jr. 2007. Factors affecting the maximum depth of colonization by submersed macrophytes in Florida lakes. Lake Reserv Manage. 23:287–297.

Canfield DE Jr., Bachmann RW. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depth in natural and artificial lakes. Can J Fish Aquat Sci. 38:414–423.

Canfield DE Jr. 1983. Predictions of chlorophyll a concentrations in Florida lakes: importance of phosphorus and nitrogen. Water Resour Bull. 19:255–262.

Canfield DE Jr., Hodgson LM. 1983. Predictions of Secchi disc depths in Florida lakes: Impacts of algal biomass and color. Hydrobiol. 99:51–60.

Canfield DE Jr., Watkins CE, II. 1984. Relationships between zooplankton abundance and chlorophyll a concentrations in Florida lakes. J Freshwater Ecology. 2:335-344.

Canfield DE Jr., Shireman JV, Colle DE, Haller WT, Watkins CE. II, Maceina MJ. Predictions of chlorophyll a in Florida lakes: importance of aquatic macrophytes. 1983. Can J Fish Aquat Sci. 41:497–501.

Canfield DE Jr, Hoyer MV. 1988. Regional geology and the chemical and trophic state characteristics of Florida lakes. Lake Reserv. Manage. 4:21–31.

Canfield DE Jr, Hoyer MV. 1992. Aquatic macrophytes and their relation to the limnology of Florida lakes. Final Report. Bureau of Aquatic Plant Management. Florida Department of Natural Resources. Tallahassee, FL.

Canfield DE Jr., Bachmann RW, Hoyer MV. 2021. Restoration of Lake Okeechobee, Florida: mission impossible? Lake and Reservoir Management 37:95–111.

Carpenter SR, Cole JJ, Kitchell JF, Pace ML. 1998a. Impact of dissolved organic carbon, phosphorus, and grazing on phytoplankton biomass and production in experimental lakes. Limnol Oceanogr. 43:73–80.

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH. 1998b. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl. 8:559–568.

Carlson RE. 1977. A trophic state index for lakes. Limnol Oceanogr. 22:361–369.

Carlson RE, Simpson J. 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society. 96 pp.

Carlson RE, Havens KE. 2005. Simple graphical methods for the interpretation of relationships between trophic state variables. Lake Reserv Manage. 21:107–118.

Chambers PA, Kalff J. 1985. Depth distribution and biomass of submersed aquatic macrophyte communities in relation to Secchi depth. Can J Fish Aquat Sci. 42:701–709.

Clark MW. 2000. Biophysical characterization of floating wetlands (flotant) and vegetative succession of a warm-temperate aquatic ecosystem. Dissertation. University of Florida. Gainesville, FL.

Dillon PJ, Rigler FH. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol Oceanogr. 19:767–773.

Dillon PJ. 1975. The phosphorus budget of Cameron Lake, Ontario: the importance of flushing rate to the degree of eutrophy of lakes. Limnol Oceanogr. 20:28–39

Downs TM, Schallenberg M, Burns CW. 2008. Response of lake phytoplankton to micronutrient en richment: a study in two New Zealand lakes and an analysis of published data. Aquat. Sci. 70:347-360.

Evert, J. D. 1999. Relationships of alligator (Alligator mississippiensis) population density to environmental factors in Florida lakes. Master's Thesis. University of Florida. Gainesville, Florida.

Farnaz NA, Kreakie BJ, Hollister JW, Qian SS. 2019. Rethinking the lake trophic state index. PeerJ. 7:e7936.doi: 10.7717/peerj.7936.

Filstrup CT, Downing JA. 2017. Relationship of chlorophyll to phosphorus and nitrogen in nutrient-rich lakes. Inland Waters. 7:385–400.

Forbes SA. [1887] 1925. The lake as a microcosm. Bulletin of the Illinois Natural History Survey 15: 537–550.

Forsberg C, Ryding SR. 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste receiving lakes. Arch Hydrobiol. 89:189–207.

Griffith GE, Canfield DE Jr, Horsburgh CA, Omernik JM. 1997. Lake Regions of Florida. Corvallis (OR): Environmental Protection Agency; National Health and Environmental Effects Research Laboratory; EPA/R-97/127. U.S; [cited 5 Jul 2010]. Available from http://www.epa.gov/wed/pages/ ecoregions/fl eco.htm.

Hasler AD, 1947. Eutrophication of lakes by domestic drainage. Ecology 28:383–395.

Hoyer, M. V., and D. E. Canfield Jr. 1994. Bird abundance and species richness on Florida lakes: Influence of lake trophic status, morphology, and aquatic macrophytes. Hydrobiologia 297/280: 107-119.

Hoyer MV, Jones JR. 1982. Factors affecting the relation between phosphorus and chlorophyll a in midwestern reservoirs. Can J Fish Aquat Sci. 40: 192–199.

Hoyer MV, Canfield DE Jr. [eds.]. 1997. Aquatic plant management in lakes and reservoirs. Prepared by the North American Lake Management Society (PO Box 5443, Madison, WI 53705) and the Aquatic Plant Management Society (PO Box 1477, Lehigh, FL 33970) for U.S. Environmental Protection Agency, Washington, D.C.

Hoyer MV, Bachmann RW, Canfield DE Jr. 2008. Lake management (muck removal) and hurricane impacts to the trophic state of Lake Tohopekaliga, Florida. Lake Reserv. Manage. 24:57–68.

Hoyer MV, Terrell JB, Canfield DE Jr. 2015. Chain of Eutrophication Models for Assessing the Potential Impact of Nutrient Enrichment on Choctawhatchee Bay, FL, USA. FL Sci. 78:20–35.

Hoyer, M. V., and D. E. Canfield Jr. 2022. A Limnological Yardstick based on phosphorus limitation. Lake Reserv. Manage. https://www.tandfonline.com/loi/ulrm20

Larkin PA, Northcote TG.1969. Fish as indices of eutrophication. In Eutrophication, causes, consequences, correctives. Proceeding of a symposium, June 11-15, Madison,Wis. National Academy of Sciences, Washington, DC.

Lee GF, Jones R A. 1991. Effects of eutrophication on Fisheries. Reviews in Aquatic Sciences (CRC Press, Boca Raton, FL) 5:287-305. (1991)

Le Moal M, Gascuel-Odoux C, Ménesguen A, Souchond Y, Étrillarde C, Levain A, Moatar F, Pannard A, Souchu P, Lefebvre A, Pina G. 2019. Eutrophication: A new wine in an old bottle? Sci Total Environ. 652:1–11.

Moss B, Madgwick J, Phillips G. 1996. A guide to the restoration of nutrient-enriched shallow lakes. Broads Authority, Norwich, UK.

Naumann, E. 1919. Nagra synpunkter angaende limnoplanktons okologi med sarskild hansyn till fytoplankton Sv Bot Tidskr. 13:129–163.

Naumann E. 1929. The scope and chief problems of regional limnology. Int Revue ges Hydrobiol. 21:423.

OECD (Organization for Economic Cooperation and Development). 1982. Eutrophication of Waters. Monitoring assessment and control. Final Report. OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Environment Directorate, OECD, Paris, 154 p

Omernik JM. 1987. Ecoregions of the conterminous United States. Lake Reservoir Management. 77:118-125.

Osgood, R. 1983. Using differences among Carlson's trophic state index values in regional water quality assessment. Water Res Bull. 18:67–74.

Sakamoto M. 1966. Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Arch Hydrobiol. 62:1–28.

Scheffer, M., 1998. Ecology of shallow lakes. Chapman & Hall. London, UK.

Schindler DW. 1975. Whole-lake eutrophication experiments with phosphorus, nitrogen and carbon. Verh Int Ver Theor Angew Limnol. 19:3221–3231.

Schindler DW. 1977. Evaluation of phosphorus limitation in lakes. Science. 195:260–262.

Schindler DW, Carpenter SR, Chapra SC, Hecky RE, Orihe DM. 2016. Reducing phosphorus to curb lake eutrophication is a success. Environ Sci Technol. 50,17:8923–8929.

Smith VH, Tilman GD, Nekola JC. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environ Pollut. 100:179–196.

Smith VH. 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: an empirical and theoretical analysis. Limnol Oceanogr. 27:1101–1112.

Soballe DM, Kimmel BL. 1987. A large-scale comparison of factors influencing phytoplankton abundance in rivers, lakes and impoundments. Ecology. 68:1943–1954.

Swanson CD, Bachmann RW. 1976. A model of algal exports in some Iowa Streams. Ecology. 57:1076–1080.

Takoukam A, Gomes D, Hoyer M, Keith-Diagne L; Bonde R, Francis-Floyd R. 2021. African manatee (Trichechus senegalensis) habitat suitability at Lake Ossa, Cameroon using trophic state models and predictions of submerged aquatic vegetation. Ecol Evol. In press.

Vollenweider RA. 1968. The scientific basis of lake and stream eutrophication, with particular reference to phosphorus and nitrogen as eutrophication factors. Technical Report OAS/DSI/68.27. Organization for Economic Cooperation and Development. Paris, Fr.

Wetzel RG, 1975. Limnology. Saunders WB. Company. Philadelphia, PA.

Xiong C, Hoyer MV. 2019. Influence of land use and rainfall variability on nutrient concentrations in Florida lakes. Lake Reserv Manage. 35:25–37.