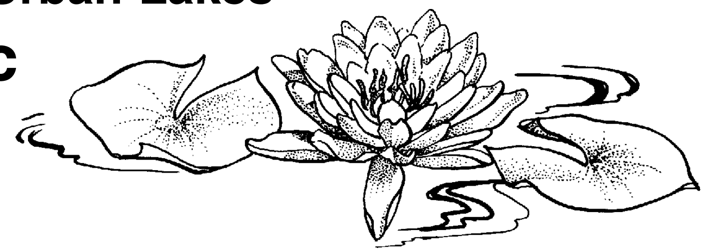
Managing Phosphorus Inputs to Urban Lakes

I. Determining the Trophic State of Your Lake



by Ted Brown and Jon Simpson

Trophic State Classification

Lakes are commonly classified according to their *trophic state,* a term that describes how "green" the lake is as measured by the amount of algae biomass in the water. Three trophic state categories are used to describe lakes as they grow progressively greener: *oligotrophic*, *mesotrophic*, and *eutrophic*. Watershed managers typically do not determine trophic state by directly measuring algae biomass, however. Instead, they indirectly assess it by doing the following:

(1) Measuring the levels of nutrients and chlorophyll *a* in the lake (the primary photosynthetic pigment found in plant cells)
(2) Measuring lake water clarity using a Secchi disk

Using these measurements, lake managers can classify the lake based on typical ranges for phosphorus, nitrogen, chlorophyll *a* and Secchi depth values reported in the lifecycle (Table 1).

Eutrophication is a term used to describe a directional movement over time towards the eutrophic trophic state from a lower trophic state (US EPA, 2000) (see Table 2 for more lake terminology). Note that a lake does not have to reach the eutrophic state to undergo eutrophication; rather, use of the term indicates a trend toward a more eutrophic state (e.g., higher phosphorus, nitrogen, and chlorophyll concentrations and lower Secchi depth readings over time). For example, a lake is undergoing eutrophication if trophic state indicators show that it was once oligotrophic but is now mesotrophic. In general, the primary concern of most lake managers is slowing down, halting, or even reversing eutrophication.

Determining the Trophic State of Your Lake

In general, trophic state measurements serve as benchmarks for measuring the success of a lake management program. Initial determinations about the trophic state of a lake can be made by simply observing the lake's basic characteristics (Table 3). However, more sophisticated approaches to assessing trophic state require analysis of key variables such as phosphorus, nitrogen, chlorophyll, and Secchi depth. Lake managers can learn about setting up a sampling program to measure these variables from several sources, including US EPA (1990; 1991), Carlson and Simpson (1996), and US EPA (2000).

Table 1. Ranges of Variable Values Associated with Trophic Levels in Lakes (adapted from Vollenweider and Kerekes, 1980)

Water Quality Variable	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus			
Mean	8	27	84
Range	3-18	11-96	16-390
Total Nitrogen			
Mean	660	750	1,900
Range	310-11600	360-1400	390-6100
Chlorophyll *a*			
Mean	1.7	4.7	14
Range	0.3-4.5	3-11	2.7-78
Peak Chlorophyll *a*			
Mean	4.2	16	43
Range	1.3-11	5-50	10-280
Secchi Depth (m)			
Mean	9.9	4.2	2.4
Range	5.4-28	1.5-8.1	0.8-7.0

Note: Units are Ug/l (or mg/m^3), except Secchi depth; means are geometric annual means (log 10), except peak chlorophyll a.

Table 2. A Primer on Lake Terminology

Areal phosphorus load: Total watershed phosphorus load delivered to the lake divided by the lake surface area.

Chlorophyll *a:* A type of photosynthetic element present in all types of algae which is used to indicate the biomass of algae in a lake.

Epilimnion: Uppermost, warmest, well-mixed layer of a lake during summertime thermal stratification. The epilimnion extends from the surface to the thermocline.

Eutrophication: The process of physical, chemical, and biological changes associated with nutrient enrichment of a lake or reservoir.

Flushing rate: The rate at which water enters and leaves a lake relative to lake volume, usually expressed as time needed to replace the lake volume with inflowing water.

Hypolimnion: Lower, cooler layer of a lake during summertime thermal stratification.

In-lake phosphorus concentration: Phosphorus concentration measured in the water column of a lake that is representative of well-mixed lake conditions. Frequently used as a trophic state indicator.

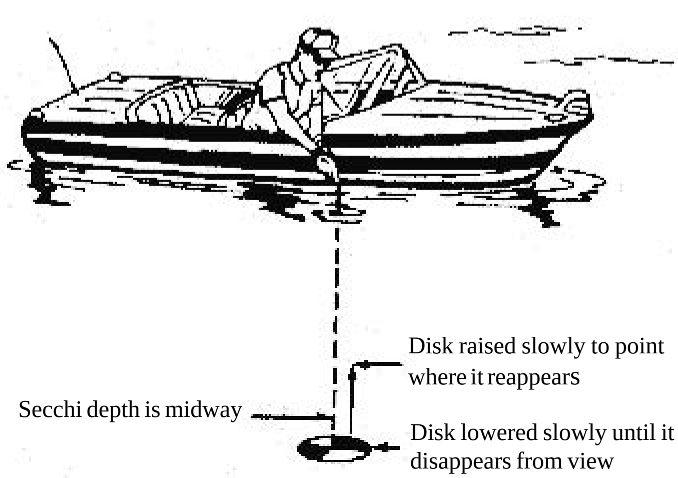
Phosphorus budget: Quantitative assessment of phosphorus moving into, being retained in, and moving out of a lake.

Production: The mass of new organic material formed over a period of time, plus any losses during that period. A lake's productivity is then the rate of production divided by a period of time.

Secchi depth: (See graphic below.) A measure of transparency of water obtained by lowering a black and white, or all white, disk (Secchi disk, 8 inches in diameter) into water until it is no longer visible. Measured in units of meters or feet.

Trophic state: The degree of eutrophication of a lake, based on an index of water clarity, chlorophyll *a* levels, and nutrient levels.

The Secchi Disk



(graphic courtesy Sebago Lake Association)

A Secchi disk is a weighted 8-inch diameter disk with alternating black and white quadrants. Named after Pietro Angelo Secchi, a papal scientific advisor and head of the Roman Observatory in the 1800's, it is the oldest tool in a lake manager's toolbox. The disk is lowered into the water by a measured cord or rope until it cannot be seen. The depth (i.e., the length of the rope from the disk to the water surface) is recorded. Then the disk is raised until it can be seen again. The average between the depth of disappearance and the depth of appearance is called the Secchi depth (US EPA, 2000). The relationship between this measurement and algae biomass in the water column is strongly correlated in lakes where clarity is not affected by sediments, silts, or other materials that stain or make the water cloudy or muddy.

Table 3. Trophic State Classification Based on Simple Lake Characteristics (adapted from Rast and Lee, 1987)

	General Characteristics	
Variable	**Oligotrophic**	**Eutrophic**
Total aquatic plant production	Low	High
Number of algal species	Many	Few
Characteristic algal groups	Greens, diatoms	Blue-greens
Rooted aquatic plants	Sparse	Abundant
Oxygen in hypolimnion	Present	Absent
Characteristic fish	Deep-dwelling cold water fish such as trout, salmon, and cisco	Surface-dwelling, warm water fish such as pike, perch, and bass; also bottom-dwellers such as catfish and carp
Secchi depth	25 feet or none	6 feet or less

Lake managers should have an understanding of the many forms of phosphorus that can be found in a lake. The two most important forms to consider are soluble reactive phosphorus (SRP) and particulate phosphorus (PP) (Rigler, 1974). Soluble and particulate phosphorus are differentiated by whether or not they pass through a 0.45-micron membrane filter. The sum of these two components is known as total phosphorus (TP). TP is the parameter generally used in trophic assessments and in a wide variety of empirical lake and watershed models.

In some instances managers may also want to measure the soluble concentration of phosphorus. This fraction consists largely of inorganic orthophosphate, which can be taken up by algae. Consequently, if the concentrations in a lake are low (e.g., <5 µg/l), phosphorus is likely to be the limiting element for algae growth.

Carlson Trophic State Index

A popular method for examining algal biomass as it relates to trophic state is through the use of the Trophic State Index (TSI) developed by Carlson (1977). A watershed manager can use measurements of three variables - chlorophyll *a*, TP, and Secchi depth - to calculate a TSI value within a numerical trophic continuum. The continuum is divided into units based on a base-2 logarithmic transformation of Secchi depth, each 10-unit division of the index representing a halving or doubling of Secchi depth. The TSI index ranges from zero to 100 and can be used to assign a trophic state "grade" to a lake.

When classifying lakes, priority is often given to the TSI value associated with chlorophyll, since it is the most accurate of the three parameters for predicting algal biomass. Any of the three variables, however, can theoretically be used to classify a lake (an especially useful attribute if only one variable was measured in historical monitoring). The formulas for calculating the TSI values for Secchi disk, TP, and chlorophyll *a* are as follows:

Secchi disk: $TSI(SD) = 60 - 14.41 \ln(SD)$

Chlorophyll *a*: $TSI(CHL) = 9.81 \ln(CHL) + 30.6$

Total phosphorus: $TSI(TP) = 14.42 \ln(TP) + 4.15$

Where ln = natural log

Table 4 lists TSI values and corresponding measurements of the three lake parameters. Ranges of TSI values can by grouped into the traditional trophic state categories. Lakes with TSI values less than 40 are usually classified as oligotrophic. TSI values greater than 50 are generally defined as eutrophic lakes. Mesotrophic lakes have TSI values between 40 and 50.

The TSI formulas are interrelated by linear regression models and should produce the same TSI value for a given combination of variable values. In cases where they do not agree, managers can possibly gain some greater insight about their lakes. Table 5 presents some possible interpretations associated with various combinations of TSI results.

Cautions

Lake managers need to keep in mind that the TSI classification scheme is a simple tool to provide benchmark information about the trophic state of a lake. Just like there are no absolutes when categorizing people by age (e.g. young, middle-aged, or elderly), there are also no absolutes when classifying lakes into oligotrophic, mesotrophic, or eutrophic states. When trophic state is

Table 4. TSI Values Associated With Variable Measurements			
TSI	**Secchi Disk (meters)**	**Surface total Phosphorus (ug/L)**	**Surface Chlorophyll *a* (ug/L)**
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1,183

used to classify a lake, lake managers are implying that algal biomass is the key parameter defining lake quality.

For many urban lakes, the assumption that algal biomass is the primary management concern is entirely appropriate, given the host of problems that algal blooms can create (see Table 6). However, some shallow urban lakes may not fit this mold. These shallow urban lakes suffer from an overgrowth of emergent and/or submergent aquatic weeds, not algae. In these lakes, control of algal biomass might not be the primary concern. Lake managers must therefore understand the dynamic nature of their lake and prepare management strategies based on current and anticipated conditions.

Tracking Trophic State and Phosphorus

Understanding phosphorus is often the key to slowing down, stopping, or even reversing eutrophication. Lake managers need to answer many questions about phosphorus: Where are sources of phosphorus in my watershed? How it is transported to the lake and in what amounts? Do loading amounts vary seasonally? What forms does phosphorus take once it gets there? How is it transported out of the lake?

It is important to keep in mind that not all lakes start out with the same lake phosphorus concentration. Indeed, even lakes with identical watershed geometry can have dramatically different phosphorus concentrations depending on their geologic regions, land use and climatic settings. Lake managers should understand how these differences can influence the trophic status of their lakes. For example, Table 7 compares the reported in-lake total phosphorus concentrations for lakes and reservoirs over a broad range of ecoregions in North America. As can be seen, in-lake phosphorus concentrations range from 6.4 to 170 µg/l, spanning the full range of trophic conditions. Trophic state can be extremely variable even within an ecoregion: Figure 1 illustrates how in-lake phosphorus concentrations vary across the state of Ohio (Fulmer and Cooke, 1990).

These regional variations often constrain the trophic state target for an individual lake. For example, it may not be possible to attain an oligotrophic or mesotrophic state in certain regions of the country, such as Florida, or the corn-belt, or, in some cases, reservoirs. A knowledge of the expected in-lake phosphorus concentration helps to set attainable goals for lake management and establish what is an acceptable level of eutrophication, given existing uses. In fact, Fulmer and Cooke (1990) and Heiskary (1989) have proposed an ecoregion-based approach to establish

Table 5. Interpretations of Deviations From Typical Conditions Associated With TSI Values	
TSI Relationship	**Possible Interpretation**
TSI (CHL) = TSI (SD)	Algae dominate light attenuation
TSI (CHL) > TSI (SD)	Large particulates, such as Aphanizomenon flakes, dominate
TSI (TP) = TSI (SD) > TSI (CHL)	Non-algal particulate or dissolved color dominate light attenuation
TSI (SD) = TSI (CHL) >= TSI (TP)	Phosphorus limits algal biomass (TN/TP ratio greater than 33:1)
TSI (TP) > TSI (CHL) = TSI (SD)	Zooplankton grazing, nitrogen, or some factor other than phosphorus limits algal biomass

lake management goals and standards in Ohio and Minnesota, respectively, that reflect attainable lake trophic status and user expectations. The approach proposed by Heiskary was ultimately adopted in Minnesota (NALMS, 1992).

1. How can in-lake total phosphorus concentration be measured or estimated?

In-lake total phosphorus concentration is probably the most common and useful indicator of trophic state, since it can be directly measured or empirically derived. It can be directly measured by collecting water quality samples in the lake over time. When appropriate sampling protocols are followed, lake monitoring provides an accurate measure of trophic conditions in a lake (US EPA, 1988). However, the effort and cost to properly mobilize, collect and analyze samples can be significant. For example, due to thermal stratification that can occur in lakes, samples may need to be collected at several depths. US EPA guidance (1990) recommends that three points be sampled for deep lakes (i.e., lakes that stratify). One sample should be collected from the epilimnion at the center of the lake one foot below the surface. The other two samples should be collected from the hypolimnion: one near the top of the hypolimnion and the other just above the lake sediments. For shallow lakes (i.e., lakes with fairly uniform oxygen concentrations in the surface-to-bottom profile that do not stratify), a single sample from the center of the lake at a depth of one foot below the surface is adequate.

In-lake phosphorus concentrations can also be estimated using empirical lake response models. These models have the advantage of being fairly easy and quick to apply; however, their accuracy depends on the quality of the input data. Well-established empirical models by Vollenweider (1968 and 1975) and Walker (1977) can be used to quickly estimate lake trophic status, assuming some basic input parameters are known, such as areal phosphorus load, hydraulic residence time, and lake depth. Chapra and Tarapchuk (1976) and Rast and Lee (1987) advanced Vollenweider's original work to include additional data and mechanisms that allow for refined estimates of phosphorus concentrations as well as chlorophyll *a*. While this article focuses on Vollenweider's model, other models can just as easily be used. It should be noted that most of the simple lake response models (such as Vollenweider's) do not take into account the potentially significant effect of internal phosphorus loading from lake sediments.

Mathematically, the Vollenweider model can be expressed in the following form:

Eq. (1) $$P = 0.368 \times \frac{L}{Zp} \times \frac{1}{1 + 1/\sqrt{p}}$$

where:

0.368 = conversion factor
P = in-lake total phosphorus concentration (mg/l)
L = areal phosphorus load (lbs/ac/yr)
Z = mean depth of lake (feet), and
p = the flushing rate in times (per year)

A common graphical representation of the Vollenweider model is shown in Figure 2, which shows the analytical solution to Equation 1 for in-lake total phosphorus concentrations of 10, 20, and 50 µg/l, respectively. The product of mean lake depth and flushing rate is shown on the x-axis, while the areal phosphorus load is shown on the y-axis. The Vollenweider relationship is most sensitive to changes in areal phosphorus load, which is implicitly a function of the drainage area to surface area ratio. As watershed development occurs, the areal phosphorus load increases, as shown in Figure 3. The effect of urbanization can potentially increase lake areal loading by a full order of magnitude. It should be noted that Figure 3 is based on extremely conservative assumptions, since it only considers the increase in primary phosphorus loads due to impervious cover, and does not consider secondary or internal sources, which can boost the areal load significantly during watershed development.

It is important to keep in mind that not all lakes start out with the same lake phosphorus concentration.

Table 6. Why it Matters: Impacts of Eutrophication on Lake and Reservoir Quality

- Nuisance algal blooms in the summer
- Reduced dissolved oxygen in the bottom of the lake
- Fish kills due to low dissolved oxygen
- Taste and odor problems with drinking water
- Formation of THMs and other disinfection byproducts in water supplies
- Increased cost to treat drinking water
- Reduced water clarity
- Decline in fish community (more rough fish, fewer game fish)
- Blockage of intake screens by algal mats
- Reduced quality of boating, fishing and swimming experience
- Decline in lakefront property values
- Floating algal mats and/or decaying algal clumps
- Increased density of aquatic weeds in shallow areas

The Vollenweider model is less sensitive to changes in lake depth and flushing rate, since for a constant drainage area to surface area ratio, flushing rate generally decreases as depth increases, effectively canceling each other out. However, deep lakes tend to be less eutrophic than shallow lakes, given the same areal phosphorus load and flushing rate.

To establish the existing trophic condition of a lake, one needs to solve the Vollenweider equation for in-lake total phosphorus concentration. This requires the lake manager to know what the areal loading, mean depth, and lake flushing rate are. Given some basic data on lake geometry (e.g., surface area and mean depth) and watershed area, these unknowns can be quickly estimated.

Areal phosphorus loading, L, can be computed by dividing the total watershed phosphorus budget by the surface area of the lake. Mean depth, Z, can be determined from bathymetric maps, direct sampling, or as-built drawings (for reservoirs).

Table 7. Regional Differences in In-Lake Total Phosphorus Concentrations for Lakes and Reservoirs (ug/l)

State	Region	TP [ug/L]	Notes	Reference
Alaska	Southeastern and South-central Coastal Region	6.4	52 clear lakes	Edmundson and Carlson, 1998
	Southeastern and South-central Coastal Region	8.4	21 organically stained lakes	
	Southeastern and South-central Coastal Region	22.3	14 glacial turbid lakes	
Connecticut	Eastern Uplands	27	26 lakes	Canavan and Siver, 1994
	Coastal Slope	19	7 lakes	
	Central Valley	52	8 lakes	
	Western Uplands	33	14 lakes	
	Marble Valley	31	5 lakes	
Florida	Entire State	32	209 lakes	Brown *et al*., 1998
Iowa	Entire State	91	12 lakes and reservoirs	Knowlton and Jones, 1993
Kansas	Entire State	62	4 reservoirs	Knowlton and Jones, 1993
Missouri	Ozark Highlands	28	25 reservoirs	Jones and Knowlton, 1993
	Ozark Border	40	14 reservoirs	
	Great Plains	48	32 reservoirs	
	Osage Plains	65	22 reservoirs	
Minnesota	Northern Lakes and Forests	20	Reference Lake	Heiskary, 1989
	North Central Hardwood Forests	30	Reference Lake	
	Western Corn Belt Plains	105	Reference Lake	
	Northern Glaciated Plains	170	Reference Lake	
Ohio	Huron/Erie Lake Plain	142	1 reservoir	Fulmer and Cooke, 1990
	Eastern Corn Belt Plain and Erie/Ontario Lake Plain	54.8	10 reservoirs	
	Western Allegheny Plateau	17.2	8 reservoirs	
Oklahoma		73	12 reservoirs	Knowlton and Jones, 1993
Texas	West	50	15 reservoirs	Ground and Groeger, 1994
	Central	44	44 reservoirs	
	East	64	21 reservoirs	
Washington	Mountain Region	15	6 mountain lakes	Larson *et al*., 1998
Southwest US	CO, TX, UT, NM,.and OK	36	56 reservoirs	Thornton and Rast, 1989

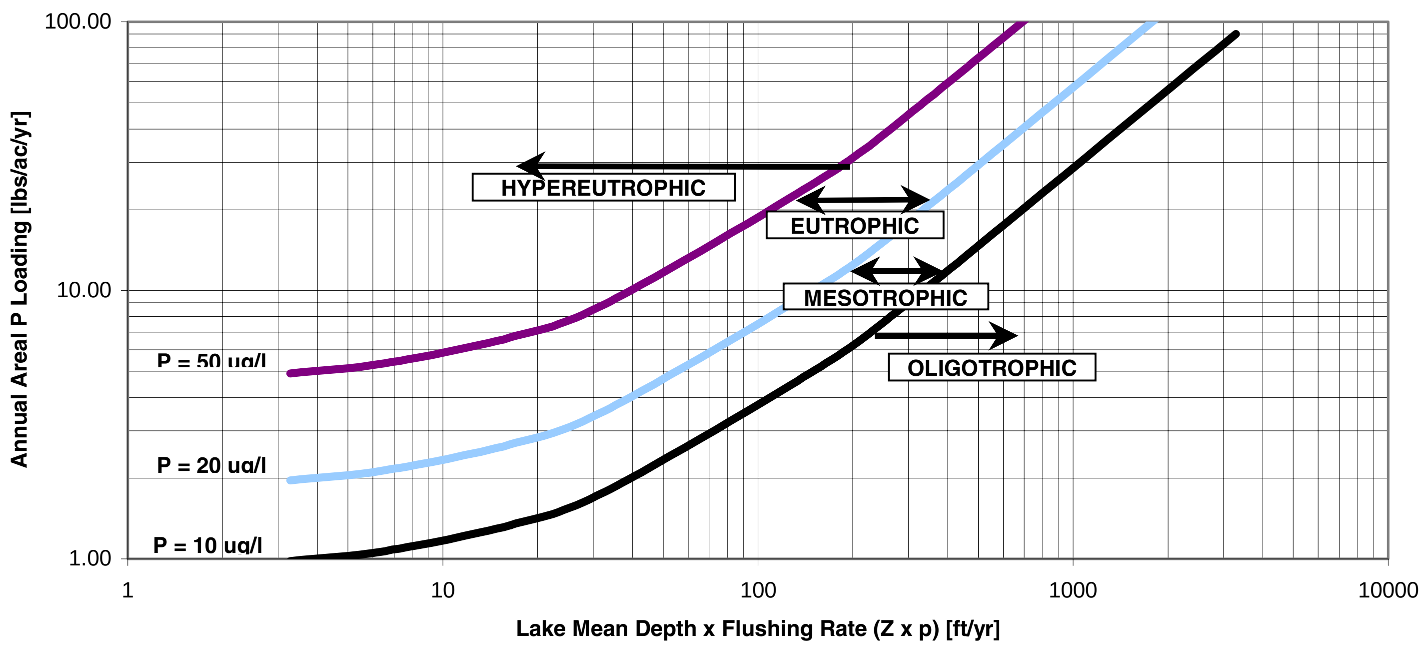


Figure 2. Phosphorus Loading vs. Lake Trophic Condition (Vollenweider, 1975)

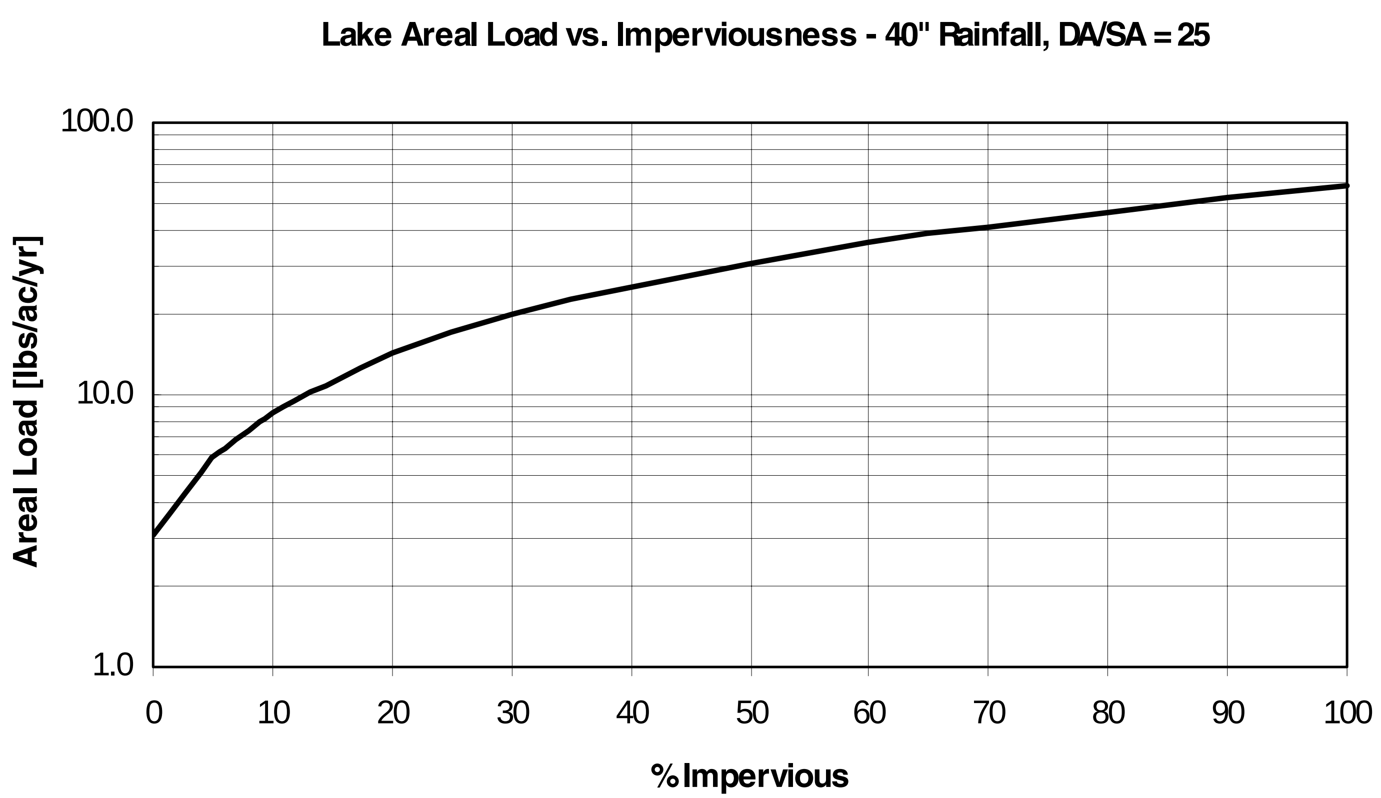


Figure 3. Areal Phosphorus Loads as a Function of Watershed Imperviousness
(loads calculated using the Simple Method, assuming a total phosphorus concentration of 0.3 mg/l for the full range of impervious cover and without considering secondary sources such as wastewater discharges)

Flushing rate, p, is the lake outflow rate divided by the lake volume, and is computed as follows:

$$P = \frac{(R)(A)}{[(SA)(Z)]}$$

where:

p	=	Flushing rate (times per year)
R	=	Watershed unit runoff (feet/year)
A	=	Watershed area (acres)
SA	=	Lake surface area (acres), and
Z	=	Lake mean depth (feet)

Even relatively minor changes in land use can have a profound effect on the trophic state of a lake.

Annual runoff, R, is best derived from hydrologic models for the lake, but can be estimated from regional runoff maps, such as the one depicted in Figure 4. It is important to note that the runoff includes both storm event surface runoff volume and the annual baseflow volume.

Armed with estimates of the areal loading, depth, and flushing rate, it is possible to solve the Vollenweider model directly for in-lake total phosphorus concentration (Equation 1). An example scenario is provided in Box 1.

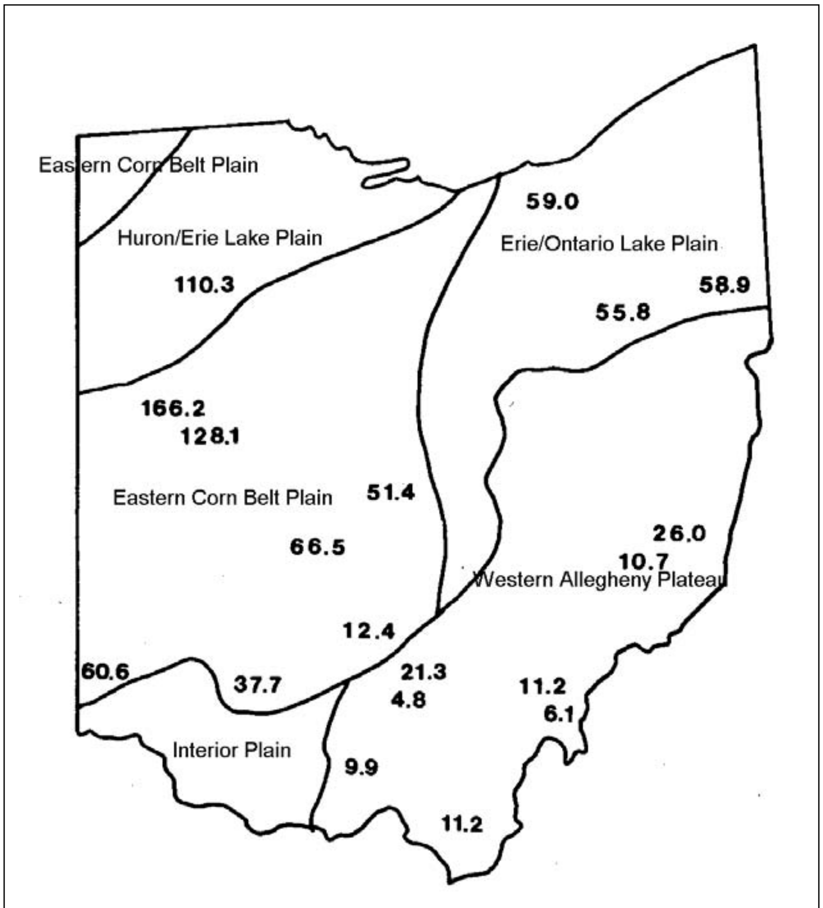


Figure 1. Total Phosphorus Concentrations (ug/l) in 19 Ohio Lakes by Ecoregion (Fulmer and Cooke, 1990)

2. Will the lake trophic state shift because of future growth, and if so, by how much?

Once the current trophic state has been established, the next step is to determine how much additional phosphorus load could occur, while still maintaining the same trophic state. This sensitivity analysis helps to ultimately shape the phosphorus loading targets for the lake watershed management. Lake areal loading changes that can be expected as a result of future watershed development can be estimated by deriving current and future phosphorus budgets. An example calculation of the impact of future growth in a lake watershed is presented in Box 1, which illustrates how even relatively minor changes in land use can have a profound effect on the trophic state of a lake.

3. How much areal load reduction is necessary to maintain current trophic status?

If an urban lake is expected to shift to a higher trophic state, a lake manager must evaluate whether watershed treatment strategies can reduce enough phosphorus load to maintain desired lake uses. There are two approaches lake managers can take to make this evaluation. First, it is possible to calculate the areal phosphorus load reduction necessary to maintain the current trophic state. This is accomplished by subtracting the predicted future areal load by the maximum allowable areal load associated with the current trophic state. Using our Lake Mesotroph example, a quick inspection of Figure 2 indicates that the necessary phosphorus reduction is approximately 2.5 lbs/ac/yr (i.e., 6 lbs/ac/yr minus 3.5 lbs/ac/yr). A second approach is to set forth a management goal of no net increase in areal phosphorus load, which simply translates to reducing the increase in phosphorus load quantified from the projected watershed growth. Either approach will require a fairly high level of treatment for both existing and new development.

Lake Sensitivity: Implications for the Lake Manager

Most urban lakes are very sensitive to increases in phosphorus load caused by watershed development. Exceptions to this general rule can occur where lakes are unusually deep and/or have very small drainage area to surface area ratios. In general, uncontrolled watershed development will likely shift a lake's trophic status upward, even under relatively low density development scenarios.

Consequently, aggressive phosphorus reduction programs will be needed for most lakes that are forecasted to experience watershed growth. The next articles

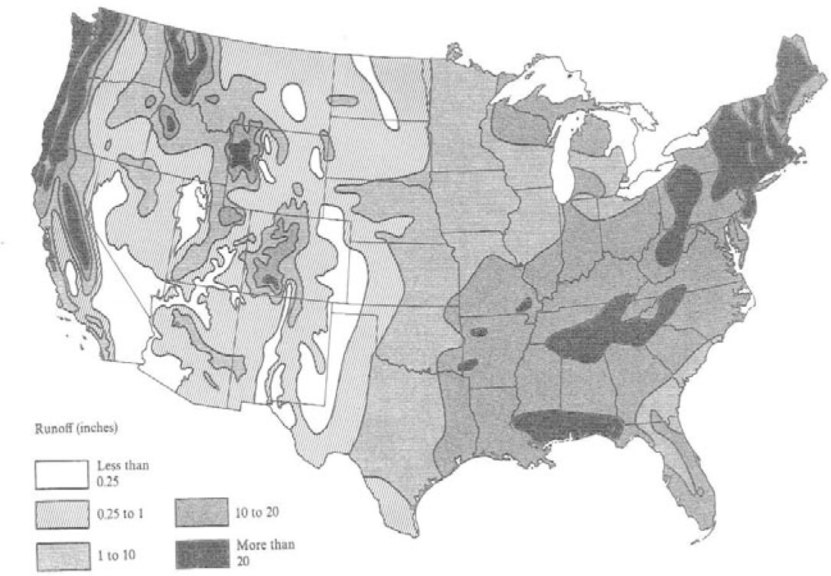


Figure 4. Average Annual Runoff in the United States (Leopold *et al.*, 1964)

Box 1. Example Scenario: Determining Existing Trophic State

Lake Mesotroph is a pristine Mid-Atlantic Piedmont lake. The lake surface area is 10 square miles, and has an average depth of 20 feet. Its 250 square mile watershed is entirely forested. The county government and the state jointly own much of the land in this watershed. In order to stimulate the local economy, these governments are considering a sale of the property, to be developed as two-acre lots over approximately 90 square miles of the watershed (watershed imperviousness of about 5%). These homes would be seasonal, primarily operating during half of the year, and served by septic systems. A study is being conducted to estimate the impacts of this potential development, and in particular whether the change would shift the lake trophic status.

Existing Conditions

Monitoring in the area suggests that the forested land use exports only 0.1 lbs/acre of phosphorus per year, and that total streamflow represents approximately 15 watershed inches of runoff per year. The flushing rate, p, of the lake is determined as:

$$p = (15 \text{ in/year})(250 \text{ mi}^2)/[(12 \text{ in/ft})(10 \text{ mi}^2)(20 \text{ ft})] = 1.55/\text{yr}$$

and the flushing rate times lake mean depth, pZ, is determined as:

$$pZ = 1.55/\text{yr} \times 20 \text{ ft} = 31 \text{ft/yr}$$

With the current land use, and including atmospheric deposition, the total annual load to the lake is 19,200 lbs/year. With the lake area of 10 square miles (6,400 acres), the current lake areal load is 3 lbs/acre/year. Using Vollenweider's model as illustrated in Figure 2, we can see that the lake is mesotrophic.

Projected Future Conditions

The future land use plan will convert 90 square miles of the 250 square mile Lake Mesotroph watershed to two-acre lots (i.e., 11% imperviousness for the land use, 5% imperviousness for the watershed), and assuming seasonal septic operation, it is calculated that the external load to the lake will increase to 38,400 lbs/year (up from 19,200 lbs/year), or an areal loading rate of 6 lbs/acre/year.

To determine the resulting trophic state from the projected growth, the same approach that is used in the example above is followed. However, the total annual runoff volume also increases from 15 inches/year to 17 inches/year as a result of the increased impervious cover and loss of evapotranspiration. So the flushing rate multiplied by lake mean depth, pZ, is determined as:

$$pZ = (17 \text{ in/year})(250 \text{ mi}^2)/[(12 \text{ in/ft})(10 \text{ mi}^2)(20 \text{ ft})] \times 20 \text{ ft} = 35 \text{ ft/yr}$$

Again, using Vollenweider's model as illustrated in Figure 2, we can see that the change in land use would result in a trophic shift from mesotrophic to eutrophic.

will provide guidance on developing phosphorus budgets, and evaluate the degree to which watershed treatment practices can reduce phosphorus inputs.

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