Ecologically Based Small Pond Management

Volume 2: The Limnology of Small Ponds

Ecologically Based Small Pond Management

Volume 2: The Limnology of Small Ponds

This is the second "volume" of a report on the ecology and management of small ponds in Chester County, Pennsylvania, summarizing the results of a study funded by the Growing Greener program, Commonwealth of Pennsylvania. The research was conducted by Dr. G. Winfield Fairchild and staff at West Chester University of Pennsylvania, and by Dr. David J. Velinsky and staff at the Academy of Natural Sciences of Philadelphia, with assistance from the Chester County Water Resources Authority.

The two volumes of the report are available on-line as separate documents at http://darwin.wcupa.edu:16080/ponds/. A limited number of paper copies of the report, including both volumes, are available from the Chester County Water Resources Authority, Government Services Center, Suite 260, 601 Westtown Road, P.O. Box 2747, West Chester, PA 19380-0990.

We gratefully acknowledge the assistance of Jamie Anderson, Quill Bickley, Jamie Carr, Jason Cruz, Jen DeAlteris, Lara Jarusewic, Paul Kiry, Lisa Nowicki, Jeff Overstreet, Lynnette Saunders, Roger Thomas and David Yezuita in fieldwork and laboratory analyses. The Chester County Department of Computing and Information Services and the Chester County Water Resources Authority are also acknowledged for providing digital data, mapping and geographic information. We thank Harry Campbell (Gannett Fleming Engineers), Barb Lathrop (PA Department of Environmental Protection), Chotty Sprenkle (Chester County Conservation District) and Alfred Wright (Chester County Water Resources Authority) for their reviews of earlier drafts of this manuscript.

The project that produced this document was sponsored in part by Growing Greener Grant ME# 351439 provided by the Pennsylvania Department of Environmental Protection. The views expressed herein are those of the author(s) and do not necessarily reflect the views of the Department of Environmental Protection.

January, 2004

Cover: The pond at Georgia Farm, in East Bradford Township

Volume 2: The Limnology of Small Ponds

Table of Contents

A. Introduction

Whereas Volume 1 considered the ecological implications of pond management methods, Volume 2 is particularly focused upon the limnology of small pond ecosystems. Limnology is the study of freshwater systems, emphasizing the interactions among aquatic organisms and their abiotic (non-living) environment. The intended readers of Volume 1 are working professionals in the environmental sciences, but the presentation is at a level that should be accessible with careful reading to pond owners. In contrast to Volume 1, references cited here are largely from the scientific literature.

Volume 2 contains the following five general elements:

1) the locations and general attributes of ponds in Chester County
2) the major biological components of typical food webs of ponds in this region
3) physical and chemical characteristics of small ponds, using data collected from 13 ponds in the county
4) a nutrient budget model predicting phosphorus loading to the 13 study ponds based on land use practices in their watersheds
5) the influence of nutrients (especially phosphorus) on the abundances of algae and other pond characteristics.

B. Methods

Locations and general features of ponds in Chester County were determined from aerial photographs taken during spring 2000, and referenced to preexisting geologic, surface water and land use GIS coverages obtained from the Chester County GIS Department. We tabulated the information in Microsoft Access and incorporated it into a new GIS coverage compatible with existing data for the county.

We first mapped all 13 target ponds using a Trimble Global Positioning Unit and depth line to assess depths. The data were used to compute pond volumes and prepare bathymetric maps using ArcView GIS. Watersheds for each pond were delineated from topographic information, and land uses within each watershed were determined by digitizing aerial photos.

Field measurements were taken at each pond during early March, late May and early July 2002 by staff at the Academy of Natural Sciences of Philadelphia (ANSP) and West Chester University (WCU). Most subsequent water chemistry determinations were conducted at ANSP using standard methods, while light measurements and most biological analyses were conducted at WCU.

C. Ponds in Chester County

A total of 3183 ponds were identified in the county. As indicated in Figure 1, most were less than a half acre. Of the total, 255 (8% - not shown in the Figure) were larger ponds, lakes or reservoirs that ranged widely in size from 1.5 – 137 acres. The number of ponds <0.1 acre is underestimated, as many could not be detected from the aerial photographs.

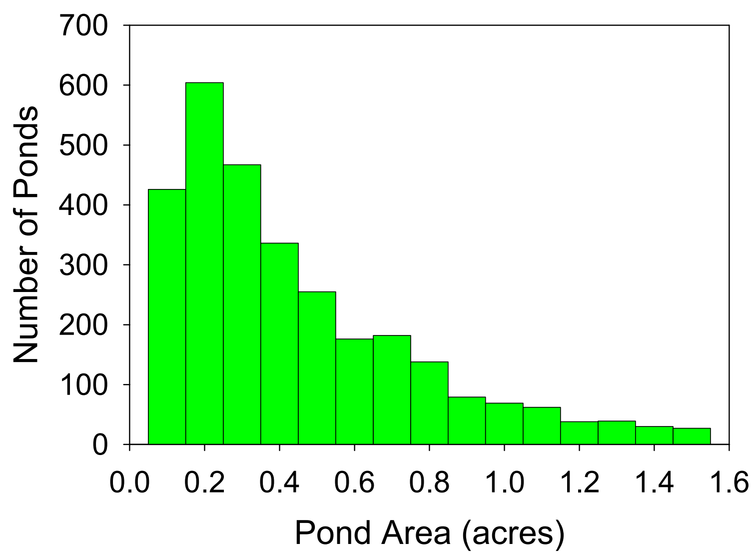


Fig. 1. Areas of ponds in Chester County. Bar heights indicate the number of ponds in the 0.1 acre interval whose upper bound is shown below the bar. Water bodies exceeding 1.5 acres are not shown in the figure.

Most were "headwater ponds", fed by springs or by streams too small to be identified on USGS topographic maps (Fig. 2). Ponds receiving water from first order streams (streams without tributaries) constituted 15.4% of the total, while downstream impoundments of larger streams (second order or higher) were less common (5.0%). In effect, most ponds in the county likely have their greatest and most direct influence on very small streams. Downstream impacts of pond nutrients are considered in Section M.

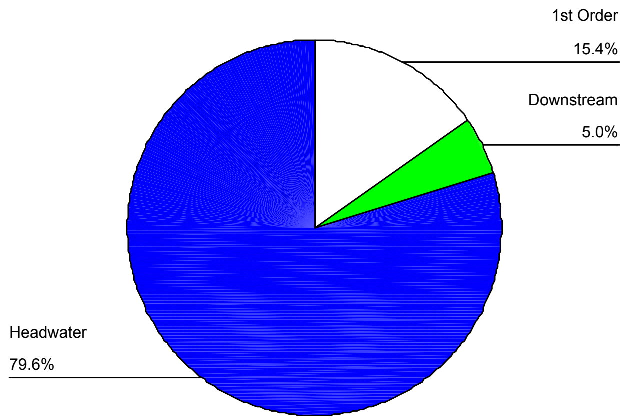


Fig. 2. Proportion of a) "headwater" ponds not receiving stream inflows but typically contributing water to headwater streams, b) ponds created by impounding "first order" streams, and c) "downstream" impoundments of larger streams.

Pond densities ranged from <1 to 2.5 ponds/km^2 among the 21 major stream watersheds in the county, with highest densities in the Crum and Ridley Creek watersheds (Fig. 3).

Land use characteristics within the watersheds of individual ponds are known to strongly influence pond water quality. For example, wooded areas are generally thought to maximally protect pond water quality, as tree canopies and deep root systems retain nutrients that might otherwise enter the pond (leaf fall from trees directly overhanging the water, however, can be a substantial seasonal nutrient source). Infrequently cut, unfertilized meadows, because they are usually effective in reducing runoff, likewise are considered to protect ponds relative to most other land uses.

By contrast, agricultural land consisting of row crops (e.g., corn, soybeans) may contribute large quantities of sediments and nutrients to a pond, particularly if close to the pond and/or on moderate to steep slopes. Runoff from erosion-prone land surfaces can carry phosphorus-laden sediments to a pond. Nitrogen is more likely to enter the pond in dissolved form, either in surface runoff or in groundwater inflows.

Residential housing, like intensively cultivated agricultural land, exports large quantities of both sediments and nutrients. Nutrients originate primarily from septic systems, if present, and fertilized lawns. Generally, nutrient loading to a pond from residential land is considered to be proportional to the density of housing. A high proportion of impervious surface in residential land contributes to overland runoff, impacting ponds by increased sediment inflow and by rapid changes in water level and discharge (volume of water) at the outfall. Typical impervious surface include roads, sidewalks, roofs and driveways, which increase with increasing housing density. Effects of land use on nutrient export to ponds are considered more formally in Section 2-L.

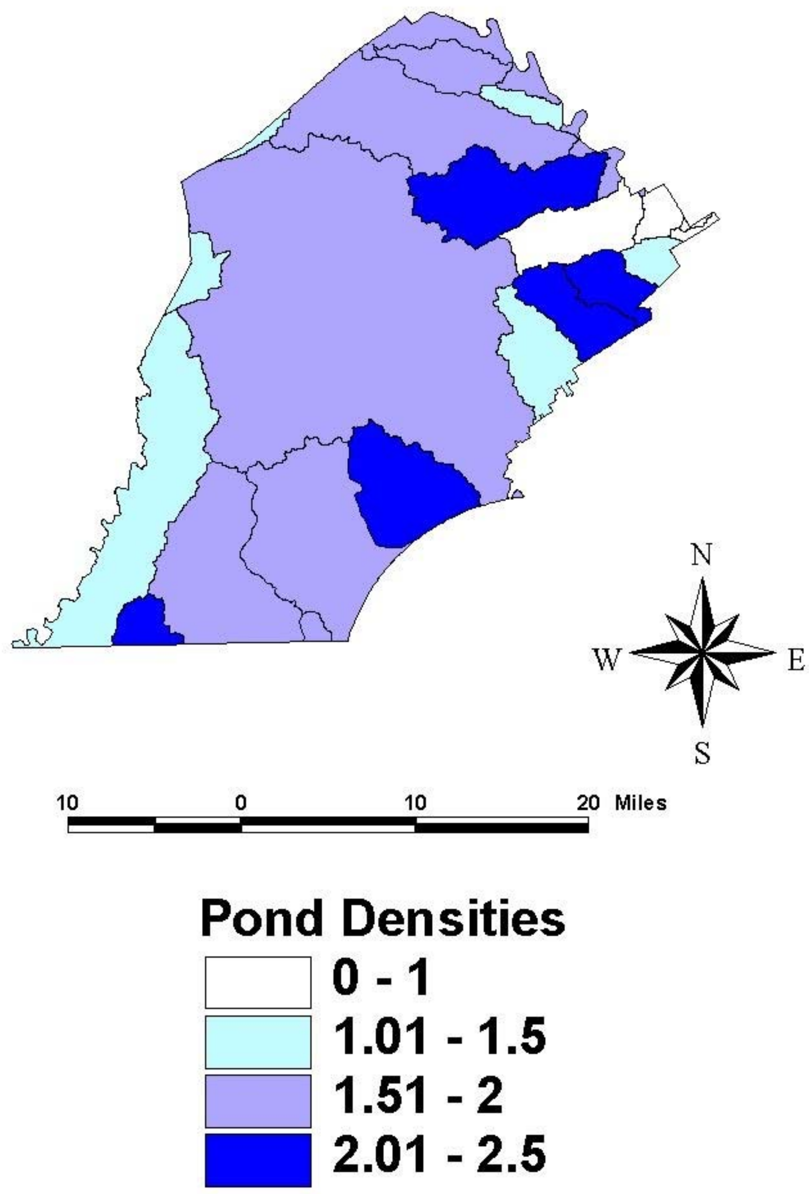


Fig. 3. Map of 21 major stream catchments in Chester County, PA, indicating densities of ponds (number/km^2) within the catchment boundaries.

General uses of ponds in the county, crudely estimated based on land surrounding the ponds in the aerial photos, are shown in Figure 4. Nearly all ponds were manmade; the few ponds identified as "natural" were predominantly ox-bows produced by the isolation of former stream meanders and found in the floodplains of larger streams. Farm ponds, identified on the basis of surrounding agriculture or pastureland, constituted nearly half of the total, and were more common in the western part of the county. Approximately 37% of ponds were considered residential, typically serving as centerpieces of developments, retention basins with permanent water, or belonging to individual landowners in residential areas. "Commercial" ponds were associated with nurseries requiring irrigation, golf courses, company headquarters, etc. A small number of ponds were presumed to have resulted from former quarry operations.

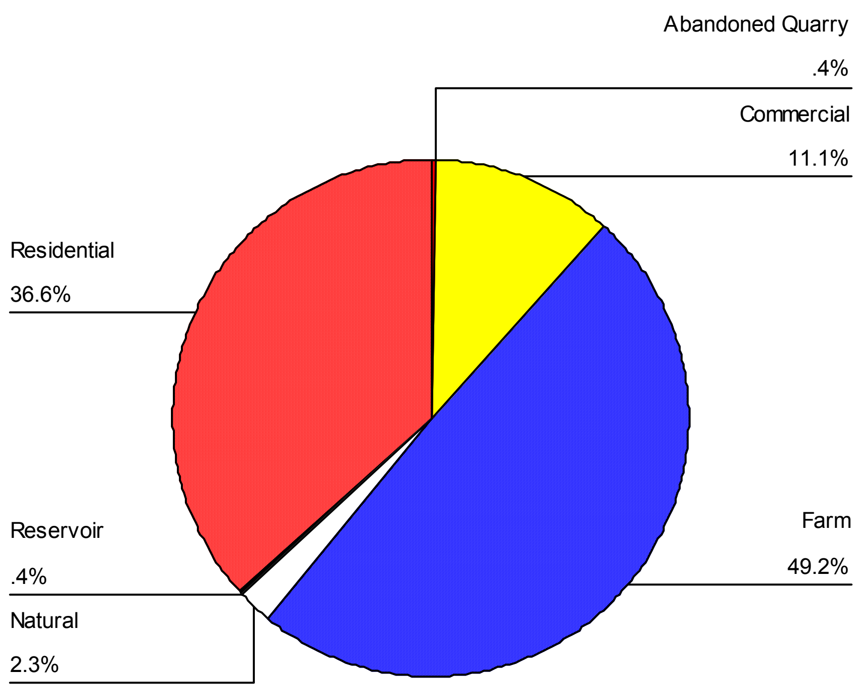


Fig. 4. Estimates of general uses of ponds in Chester County based on aerial photos of surrounding land.

The underlying bedrock within the watershed also influences pond water quality. Bedrocks of differing weathering properties also contribute to the formation of hills and valleys, and greater elevation change within the watershed may indicate greater supplies of nutrients and other materials to the pond.

Much of the northern part of Chester County is underlain by gneisses and quartzites - hard, metamorphic rocks that weather slowly and contribute sparingly to overlying soils and surface waters (Fig. 5).

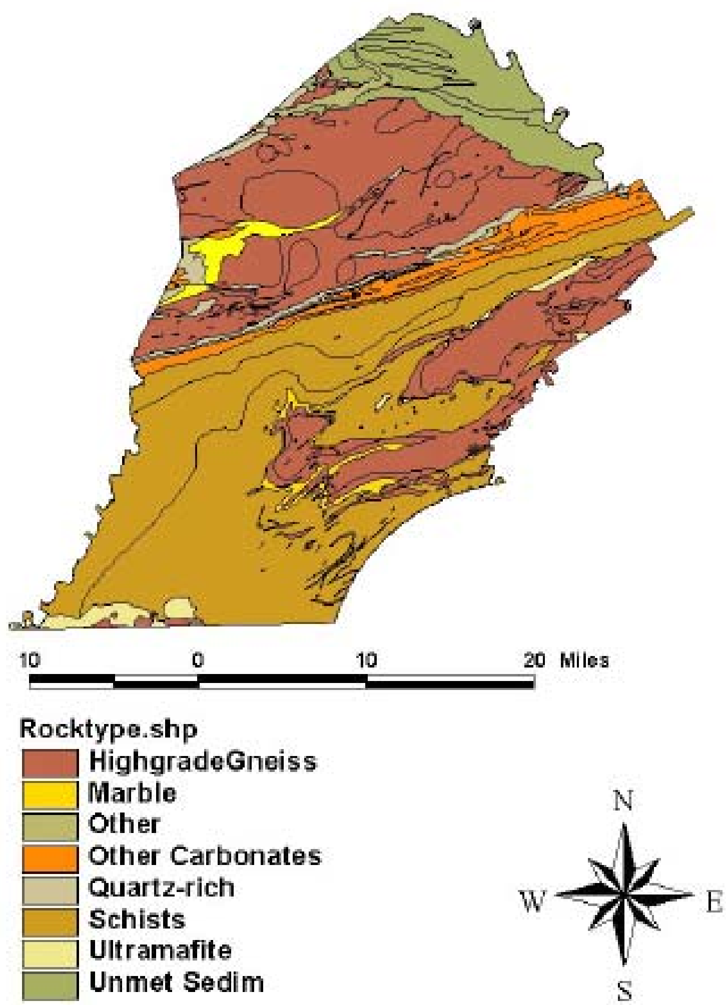


Fig. 5. Major rock types in Chester County, PA.

Schists, also metamorphic and slowly weathered, comprise much of the bedrock in the southern part of the county. Between these two regions a band of more easily weathered carbonate-rich rock (seen in orange) transects the county along a NE-SW axis, forming the Chester Valley. As a result of this weathering, which causes many rock constituents to become dissolved in water, surface waters in the Chester Valley typically have larger quantities of ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and bicarbonate (HCO_3^-), and often more abundant nutrients (e.g., nitrogen and phosphorus) than in other parts of the county.

The riparian vegetation immediately surrounding the pond helps to intercept nutrients and sediment runoff. Another important function of the riparian vegetation is stabilization of the shoreline, preventing bank erosion and thus reducing sediment load (see Volume 1 Section D). Riparian vegetation surrounding the 3183 ponds identified in Chester County was visually classified as "mowed", "meadow" or "woods" based on aerial photos (Fig. 6). Most of the shoreline consisted of mowed lawns (56%), with smaller amounts woody vegetation (26%) and infrequently cut meadow (18%).

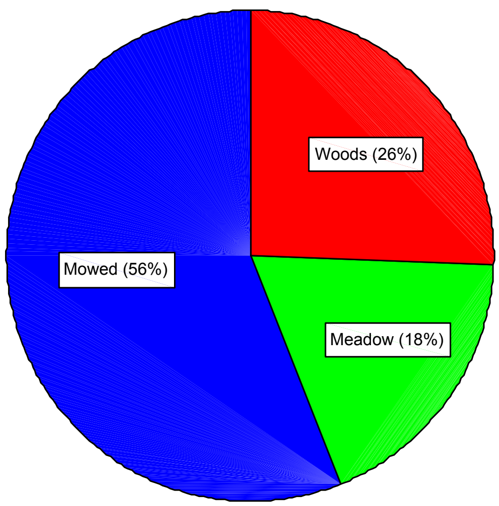


Fig. 6. Proportions of forested land, meadows and mowed grass forming the riparian vegetation immediately adjacent to ponds in Chester County, based on aerial photos taken in 2000.

Locations of the 13 ponds selected for study are shown in Figure 7. Seven ponds were residential and six were farm ponds. They are identified by two-letter codes in the figure and throughout the text to protect the privacy of the land owners.

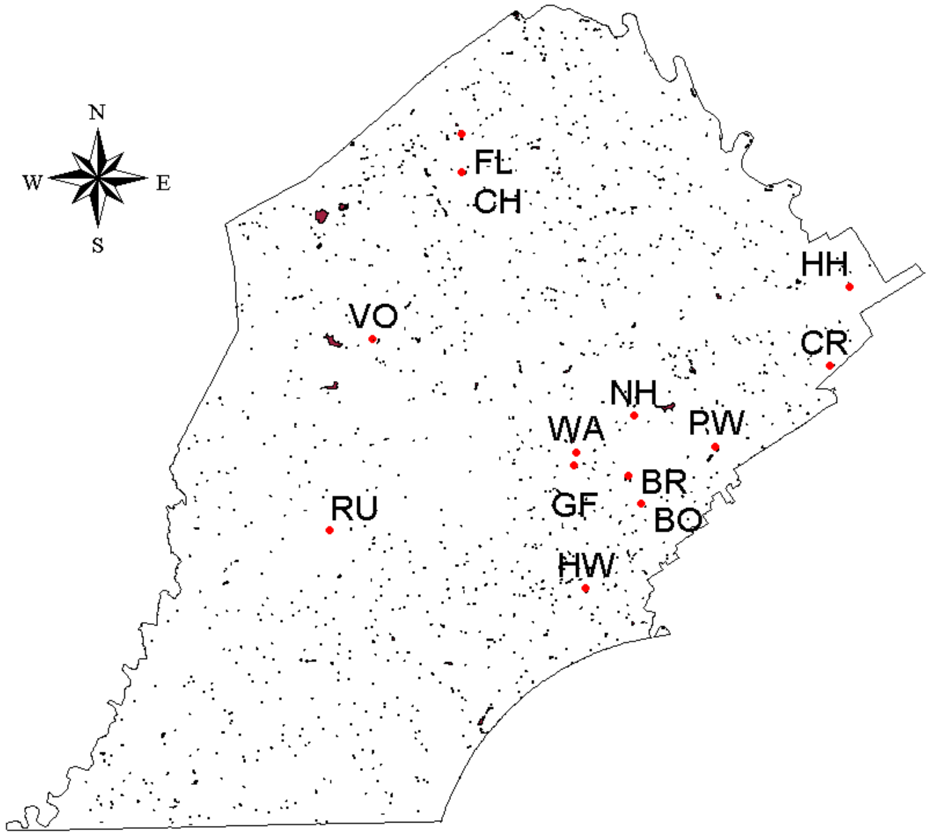


Fig. 7. Locations of ponds in Chester County are shown as small dots. The 13 target ponds are identified by two-letter codes to provide a measure of privacy to the owners.

D. Pond Food Webs

A generalized diagram linking the major groups of organisms found in a small pond is shown in Figure 8. Each group is described more fully in sections that follow. The arrows connecting the biological compartments indicate the direction of energy flow. Zooplankton, for example, depend on the energy contained in the phytoplankton they eat. Management measures intended to control a particular compartment (for example, excess phytoplankton) thus inevitably indirectly affect all those foodweb components (e.g, zooplankton and fish) that depend on it.

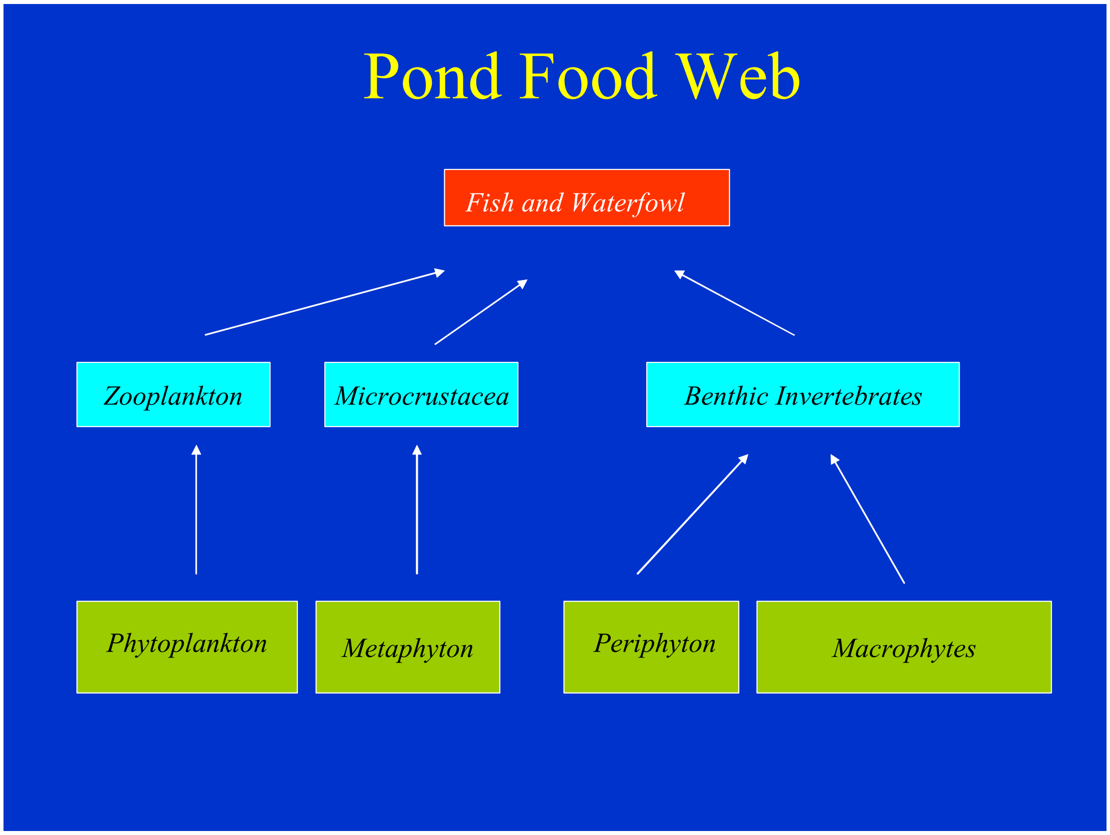


Fig. 8. Generalized food web showing major groups of primary producers (in green), invertebrate consumers (in light blue) and vertebrate predators (in red). Arrows indicate the direction of flow of both energy and materials (e.g., nutrients).

Ponds provide habitat for an array of primary producers (photosynthetic organisms), all of which are influenced by water chemistry and also interact with each other. They form the base of a food web for consumers, including a variety of invertebrates, fish and waterfowl. The following groups are especially important:

Primary producers are classified here into four general groups, distinguished by their form, location and ecological roles within the pond.

1. The phytoplankton consists of microscope, free-floating algae composed of individual cells or small colonies.
2. The periphyton refers to substrate-associated algae, normally forming a thin layer that covers rocks, the sediments and other surfaces in well-lit portions of the pond.

3. The metaphyton is a scum of filamentous algae, clearly visible at the surface or suspended in the water column of hypereutrophic ponds. Metaphyton "clouds" typically appear only in ponds with high nutrients. Scums of metaphyton usually originate as periphyton that lifts off the bottom, buoyed upward by oxygen bubbles produced in photosynthesis. The metaphyton decomposes at the surface, releasing its stored nutrients to the water column.
4. Aquatic vascular plants, and a few large algae resembling aquatic plants, are collectively termed macrophytes. Rooted plants typically obtain most of their nutrients from the sediments. When they die and decompose, most of the nutrients taken up into the stems and leaves of the plants are released to the water column, often stimulating algal growth. Some plants are not rooted in the sediments (e.g., duckweed), and thus compete with phytoplankton and metaphyton for nutrients in the water column.

Each group of primary producers has a unique assemblage of invertebrate consumers associated with it. Within all four invertebrate assemblages are species that consume primary producers directly, as well as predators that consume other invertebrates. These are generally found with the algae or plants on which they depend:

1. Zooplankton, consisting primarily of microcrustacea (cladocerans and copepods) and rotifers, is actually a community of both grazers on phytoplankton and invertebrate predators that eat other zooplankton. When larger grazers dominate the zooplankton, they can effectively control phytoplankton biomass in some ponds.
2. Consumers found in the clouds of metaphyton include ostracods and other microcrustacea, as well as some larger invertebrates, tadpoles, etc. Many of these animals feed on the bacteria and smaller algae associated with the large filaments that make up the metaphyton, and are unlikely to control overall metaphyton abundance.
3. Associated with the periphyton on rock surfaces or on the sediments is a diverse group of benthic invertebrates, including a wide variety of aquatic insects (larval dragonflies, beetles, midges) and crustacea (e.g., isopods, scuds, crayfish). Benthic invertebrates also colonize the surfaces of aquatic

plants. Some of these invertebrates actually consume plant tissues, but most glean attached periphyton and bacteria from the plant surfaces.

Fish and waterfowl are important predators on invertebrates, and some species also consume primary producers directly. The suitability of a pond for the growth of fish or sustaining waterfowl thus depends in large part on these other components of the food web.

E. The "chain of relationships" based on nutrients

Just as food webs were organized by "who eats whom" in Section D above, a pond ecosystem can also be described as a set of interacting processes, including both biotic and abiotic compartments. Figure 9 describes a "chain of relationships" (Portielje and van der Molen, 1999) among measurable attributes of shallow ponds that are directly or indirectly affected by nutrient supply.

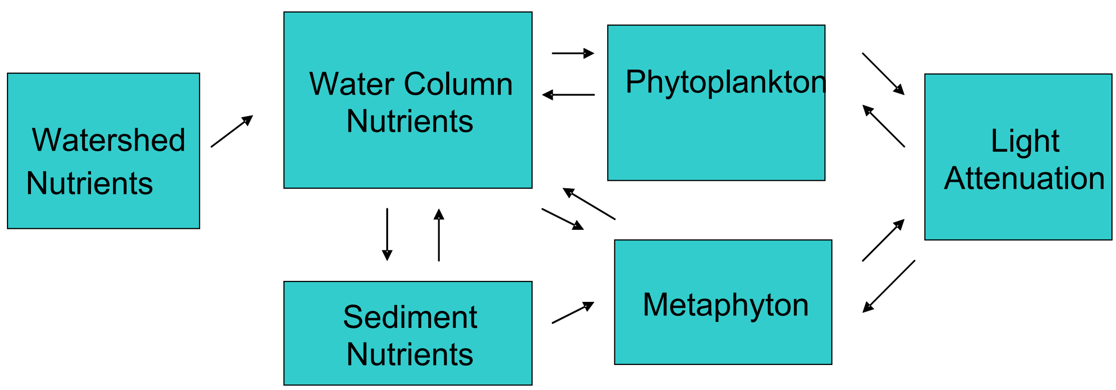


Fig. 9. Effects of nutrients on other components of a pond ecosystem.

As indicated by the arrows connecting compartments, increased loading of growth-promoting nutrients can lead to elevated nutrient concentrations in the water column, which in turn stimulate the growth of phytoplankton and metaphyton. A portion of the incoming nutrients is precipitated to the sediments, which form a second major reservoir capable of resupplying nutrients to the water column. Increased abundance of phytoplankton and metaphyton in turn increases the rate of light depletion within the water column, leading to inhibitory feedbacks on algae deeper in the pond, and to impacts on other pond organisms (not shown). In effect, many important elements of the pond ecosystem are driven directly or indirectly by nutrient supply. We consider two nutrients, phosphorus and nitrogen, in Section K, and focus particularly on system responses to phosphorus.

The strengths of the relationships between compartments in Figure 9 (and many other relationships in the report) are estimated by regression analysis in many of the sections that follow. Two variables are considered, X and Y, in an equation of the form $Y = a + b(X)$. This equation may be represented visually by a line of best fit accompanying a scatterplot of individual values of X and Y. Associated with the regression equation is a correlation coefficient (r) indicating the strength of the relationship. Possible values for the correlation coefficient range from -1 (indicating a strong negative relationship) through 0 (indicating no relationship) to +1 (indicating a strong positive relationship). For example, total phosphorus in the water column and phytoplankton biomass (Fig. 28) show a relatively strong, positive relationship with an r value of +0.84 (phytoplankton biomass is consistently greater in ponds with higher total phosphorus). The relationship between phosphorus in the sediments and phosphorus in the water column (Fig. 29) is also positive but less strong ($r = +0.27$). Statistical "significance" of the relationships is indicated by "p" values, with smaller values being more significant and values exceeding 0.05 considered "not significant". For example, the relationship in Figure 28 is highly significant ($p = 0.000$), while that in Figure 29 is not significant ($p = 0.40$). In effect, the chain of relationships in Figure 9 has some links which are apparently stronger than others.

Nutrient supply is considered the primary determinant of pond trophic state, a concept that recurs frequently in this report. Trophic state refers to the abundance and productivity of photosynthetic algae and plants, the primary producers of the pond ecosystem. Deep lakes in pristine watersheds with little nutrient inflow, low primary producer abundances and excellent light penetration are termed "oligotrophic" (poorly nourished). Most ponds in this region are shallow (typically 1-3 m average depth), have watersheds that supply abundant nutrients, and are periodically fertilized as well by wind-driven mixing of nutrient-rich bottom sediments into the water column. Ponds with these characteristics are termed "eutrophic" (well nourished), and typically have an abundance of primary producers. Ponds with excessive nutrient-generated growth are often termed “hypereutrophic”, and may be considered “overfed” (Fig. 10). Hypereutrophic ponds are common in Chester County, and their symptoms constitute the principal causes for management efforts by landowners. We will describe a quantitative method for classifying the trophic state of ponds in Section P.

Fig. 10. A hypereutrophic pond in Chester County. The scums visible at the water surface are termed “metaphyton”.

F. Pond Morphology

Morphological features of a pond include its area, depth and volume, the length of its shoreline, and hydraulic residence time. These features can have a large influence on pond trophic state.

Pond area (the planar area of the pond surface, A_s) can be determined directly from a topographic map or spatially indexed aerial photograph. Because it is so easily obtained, area is often used as a convenient index of pond size. Areas of the 13 study ponds ranged from 0.1 to 1.7 ha (mean 0.79 ha, or 1.95 acres).

Determining pond volume (V) requires a depth profile. A bathymetric map of a pond looks much like a topographic map. Contour lines within the pond indicate points with the same depth, allowing quick interpretation of deep and shallow areas, and computer-assisted computation of pond volume. For example, the bathymetric map of FL (Fig. 11) indicates shallower areas on the west side of the pond, sloping uniformly toward a deeper hole (approximately 3.5 m, or 11.6 ft) near the east end. Volumes of the 13 ponds based on measurements taken in March ranged from 1.7×10^3 m^3 to 27.4×10^3 m^3.

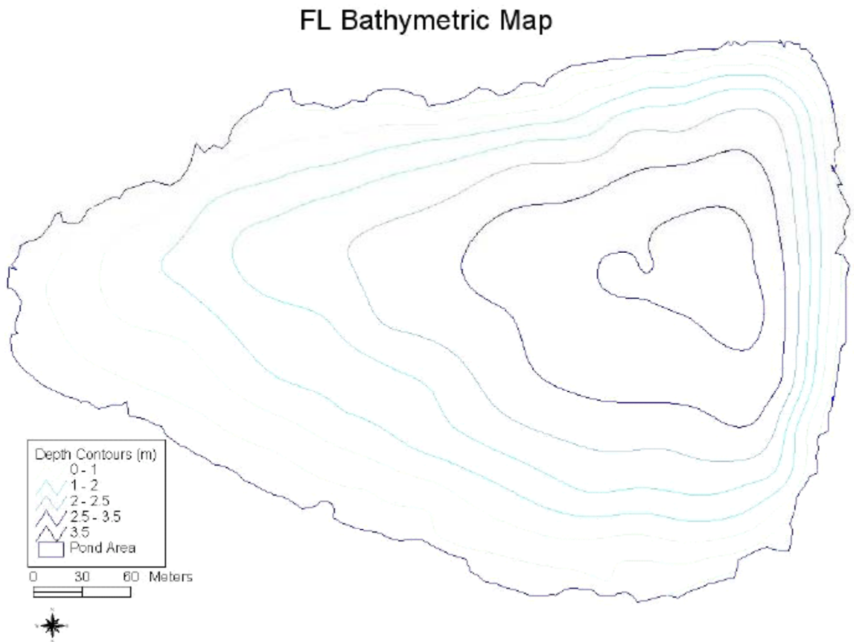


Fig. 11. Bathymetric map of pond FL. Contour lines describing deeper portions of the pond are darker.

The quotient of a pond's volume/area (V/A_s) is termed its "mean depth". Mean depth is especially important to primary producers in ponds. Deeper ponds have less light penetrating to the bottom (see Section H). Because light levels are too low to support adequate photosynthesis at the pond bottom, deeper ponds (and deeper areas of shallow ponds) often have fewer submersed aquatic plants. Pond areas, volumes and mean depths of the 13 study ponds are summarized in Figure 12.

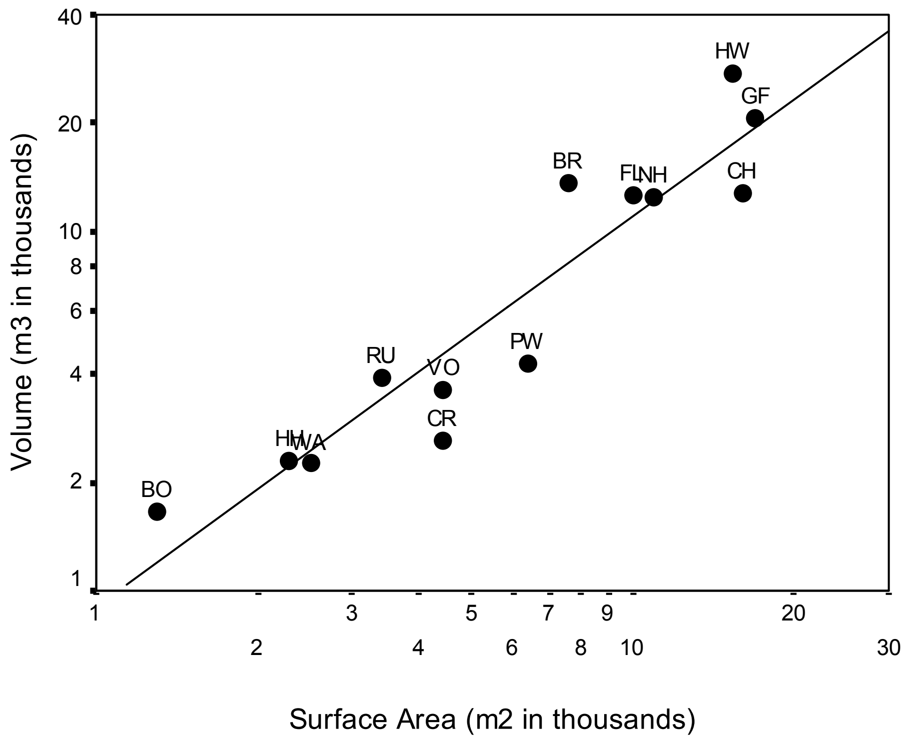


Fig. 12. Pond volume in relation to surface area based on measurements in March. Ponds above and to the left of the regression line had deeper mean depths while those at the lower right were shallower. Regression line is log(Volume, in m^3) = -0.30 + 1.08[log(Area, in m^2); r = +0.94 (p=0.000).

The discharge, or the rate of water volume leaving the pond at the outfall (standpipe or dam), is normally proportional to the combined inputs via stream inflows, surface runoff during rain events and groundwater inputs (Fig. 13)**.** Discharge declined in the 13 study ponds later in the very dry summer of 2002, however, and the outfalls of most ponds dried up by July; further water losses were largely the result of "evapotranspiration" (evaporation of water from the pond surface, combined with losses of water vapor from plants growing in the pond).

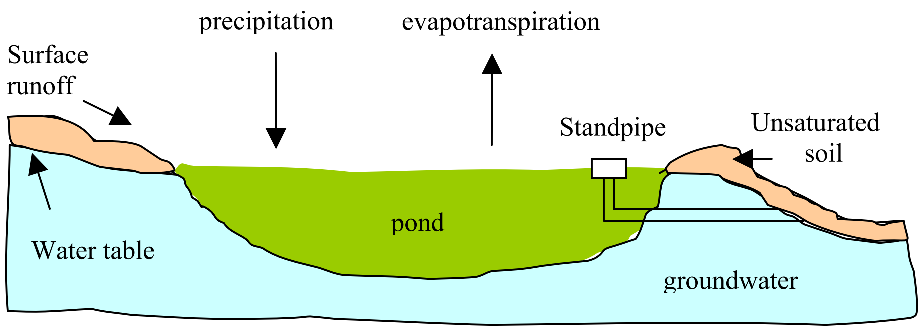


Fig. 13. Sources and losses of pondwater.

The calculation of "hydraulic residence time" of water in a pond, computed as [Pond Volume, in m^3] divided by [surface water discharge at the outfall, in m^3/day], helps to determine the likely impact of nutrients on phytoplankton growth. Ponds with very low residence times (high flushing rates) have large proportions of their water passing through each day. Ponds that are impoundments of stream systems, for example, alter stream water chemistry and particle content much more if they have long residence times.

Residence times of the 13 study ponds ranged from less than 1 week (pond BO) to more than 2 years (HW) based on measurements in March (Fig. 14). Owing to drought conditions during summer 2002, water levels fell below the standpipes or dams in most ponds, and subsequent losses of water were largely due to evapotranspiration.

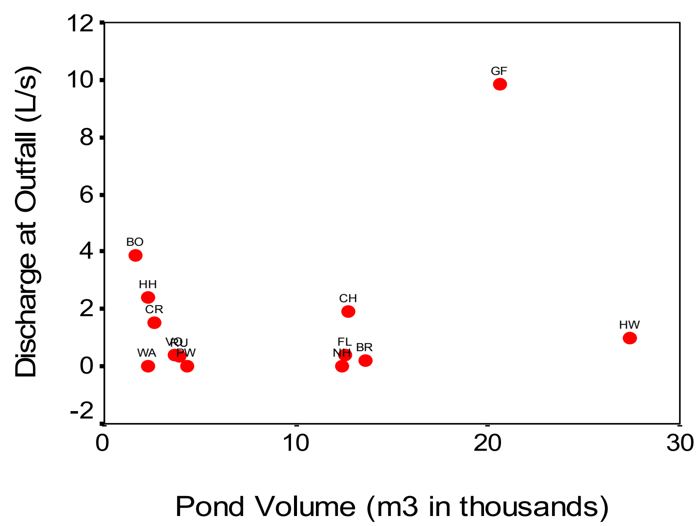


Fig. 14. Discharge and Volume estimates based on measurements in March. Large ponds with low discharges (lower right) had high residence times, while small ponds with high discharges had low residence times.

G. Pond Watersheds

The watershed (= catchment, or drainage basin) of a pond consists of land which conveys surface runoff and groundwater in the direction of the pond. The boundary of the watershed is usually determined from a topographic map as the set of ridges or other high ground surrounding the pond. Pond WA, shown in the Figure 15, has moderately steep slopes surrounding the pond. The steepness and vegetation type on land directly surrounding the pond is particularly important in determining probable effects of surface runoff during precipitation events.

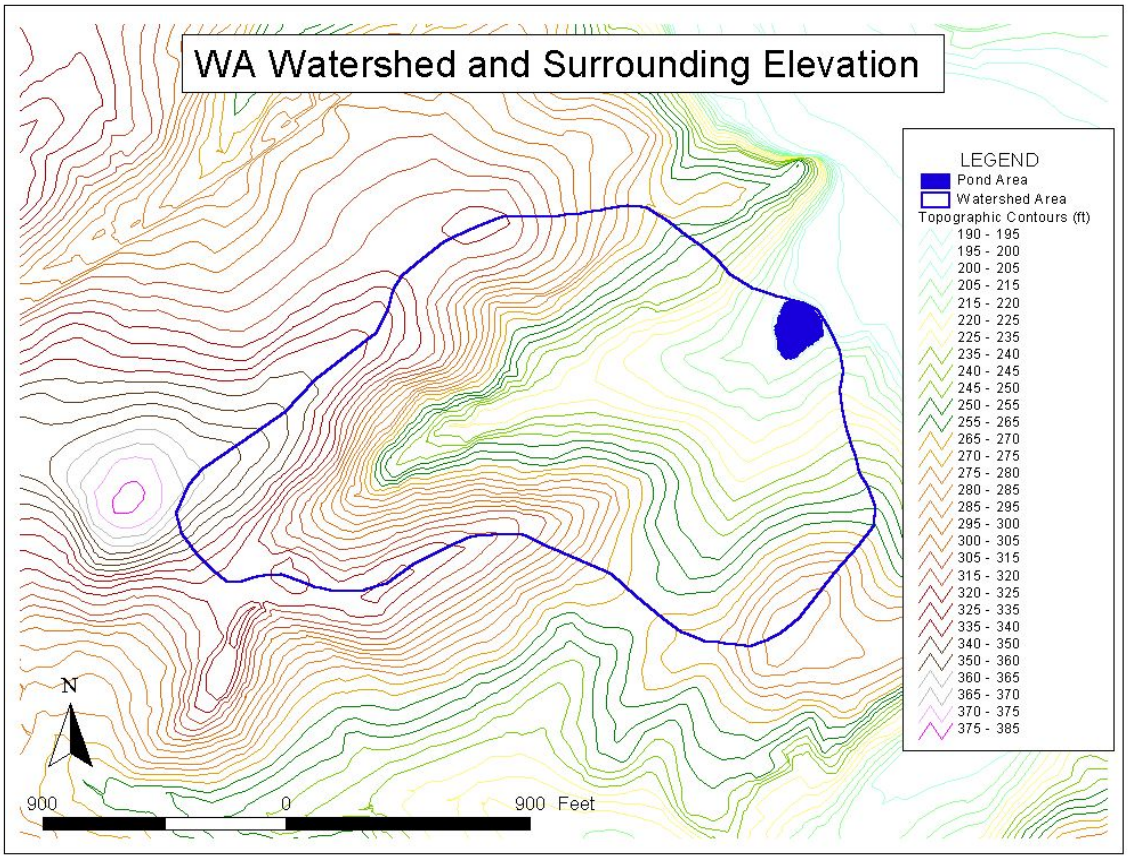


Fig. 15. Watershed boundary for one of the target ponds (WA), superimposed on contours indicating elevational change within the watershed.

The size of the watershed relative to the size of the pond itself can be a useful index of land use impacts; ponds with higher ratios of watershed areas (A_d) to pond area (A_s) may be especially prone to inputs of nutrients and other materials and are often hypereutrophic as a consequence. The relationship of watershed area to pond area for the

13 ponds is shown in Figure 16. Some ponds had very large watersheds relative to their size, falling below and to the right of the regression line in the figure (e.g., HH), while others had very small watersheds relative to their size, and fall above and to the left of the regression line (e.g., NH).

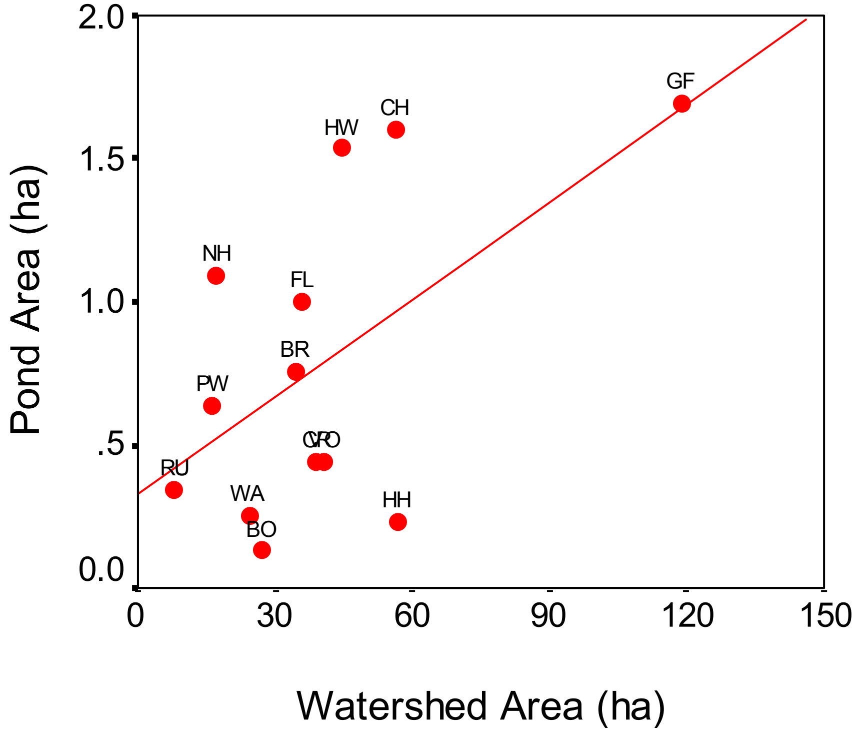


Fig. 16. Pond surface area (A_s) vs. watershed area (A_d) for 13 ponds in Chester County. Ponds more likely to be negatively impacted by excessive nutrient loading from their watersheds are located below and to the right of the line of best fit (e.g., HH), while better protected ponds are located at the upper left (e.g., NH). Regression line is $As = 0.33 + 0.011(A_d)$; $r = +0.57$ ($p = 0.041$).

H. Light

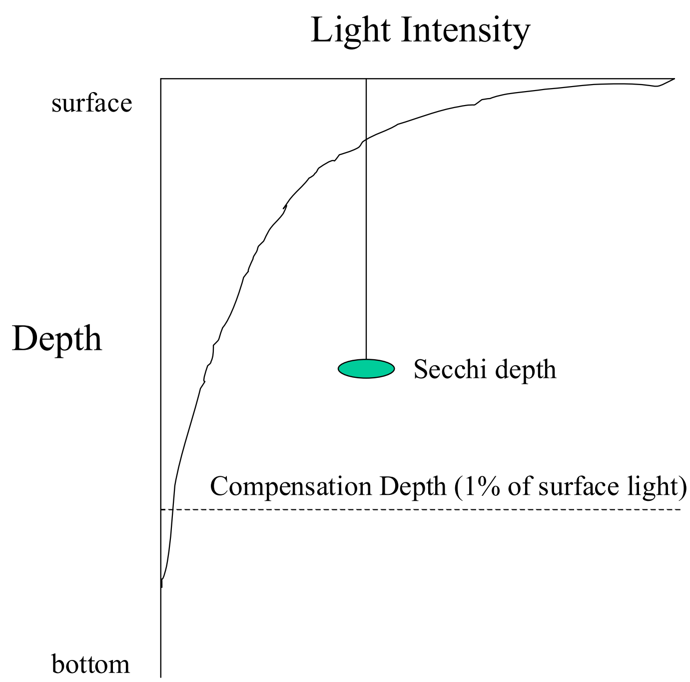
Light penetration in a pond is a) an indicator of pond trophic state, b) the principal origin of heat acquisition and c) a critical resource determining the growth potential of primary producers. As indicated earlier in Fig. 9, light is also closely linked to algal biomass, and thus responds indirectly to nutrient supply.

A portion of the light entering the water column is backscattered and leaves the pond as light. Most of the light, however, is absorbed by water molecules, particles and dissolved materials and converted to heat. The color of a pond is determined by which wavelengths of light are scattered most and absorbed least.

Light decreases exponentially with depth as shown in Figure 17. Light penetration is greatly reduced in ponds with abundant algae, suspended sediments or high amounts of dissolved organic substances.

The depth to which 1% of light entering the pond penetrates is termed the "compensation depth". The (shallower) portion of the pond above this depth is considered to have sufficient light to support phytoplankton and aquatic plants. Light levels below the compensation depth are inadequate for most photosynthetic organisms, although tolerance of low light varies with species.

Fig. 17. Diagram of light penetration with depth. High light intensities at the surface (upper right) decline exponentially with increasing depth (shown as an inverted vertical axis).



Light penetration in this study was measured in two ways. We used a quantum meter with an underwater sensor to record light intensity at successive 0.5 m (1.6 ft) intervals, and calculated average percent light attenuation per meter based on the quantum data. We also used a secchi disk to measure changes in visibility with depth (Fig. 18).

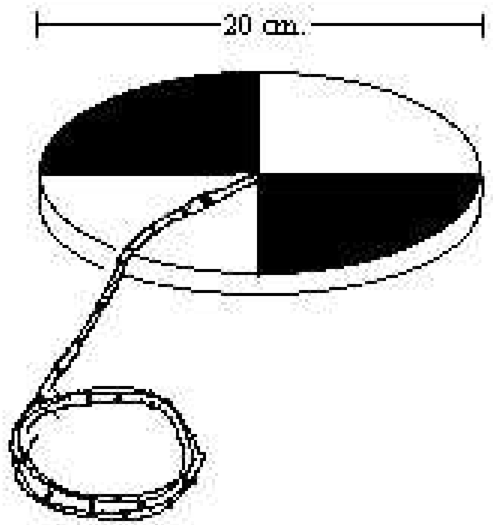


Fig. 18. Diagram of a standard secchi disk, with calibrated line, for measuring light penetration in ponds.

Secchi depth, the depth at which the disk is just visible from the surface, is normally the depth receiving approximately 15% of incident light (the compensation depth is sometimes assumed to be roughly twice the secchi depth). A secchi disk provides less information about light penetration than does a quantum meter, and cannot be used in ponds where secchi depth exceeds the maximum depth, but is a convenient, inexpensive, and widely used means of monitoring changes in water quality by landowners.

Percent light depletion is negatively related to secchi depth (high rates of depletion are associated with shallow secchi depths). As shown in Figure 19, although light penetration varied widely among the 13 ponds studied during March and May, the ponds consistently experienced more rapid light depletion during July, with secchi depths often < 1 m. The more rapid depletion of light later in the growing season is related to increased phytoplankton abundance (see Section O).

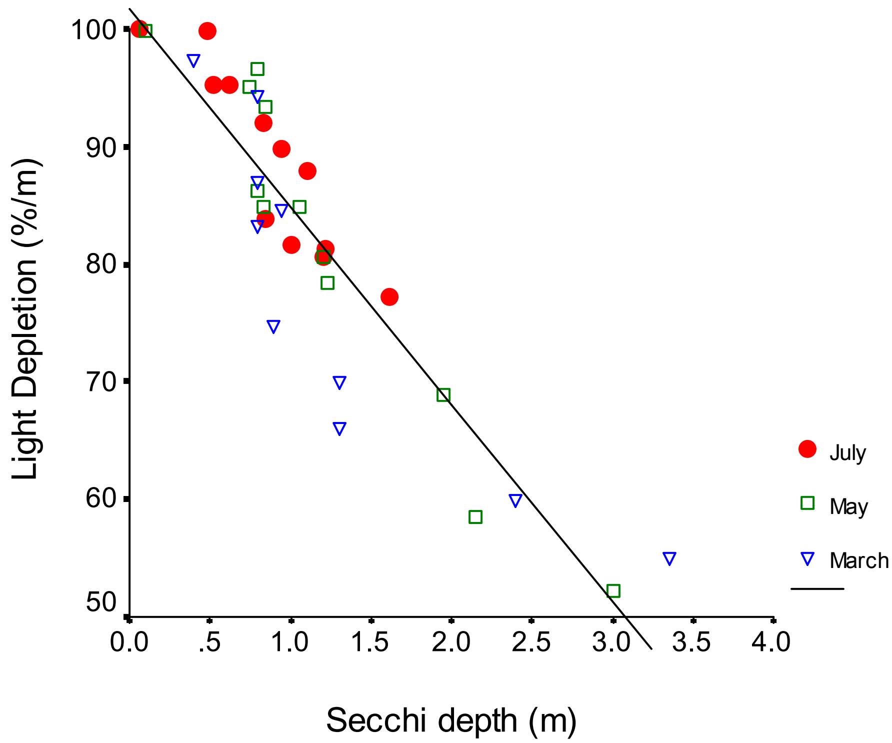


Fig. 19. Relationship of light depletion (LD, as % decline in light per meter) to secchi depth. Most ponds fell close to the line of best fit, indicating that secchi depth could be used fairly effectively to estimate light availability in the water column. Regression line is LD = 98.13 – 14.51(Secchi Depth, in m); r = -0.79 (p = 0.000).

I. Temperature and Oxygen

Changes in water temperature with depth are largely determined by season, light penetration and pond morphology. Water in very shallow ponds often circulates from top to bottom throughout the year. In deeper ponds, especially if light penetration is low or if the pond is protected from wind-driven mixing, the water column may be "stratified" in summer. Light heats up water at a particular depth in proportion to its intensity; thus, surface waters warm up faster than deeper water. The resulting temperature differences produce differences in water density. Water at 4^{o}C is most dense, and warmer water is progressively less dense; thus, warmer water will sit stably above cooler water, resulting in stratification. Wind activity in stratified ponds is sufficient only to mix the upper portion of the water column, termed the "epilimnion", while the lower layer below, the “hypolimnion”, remains cool, dense and relatively unmixed. Separating the two layers is a zone of rapid temperature transition, termed the “thermocline”. More precisely, in a series of temperature measurements with increasing depth, the thermocline occurs where the rate of change in temperature exceeds 1^{o} C (1.8^{o}F) per meter (Fig. 20).

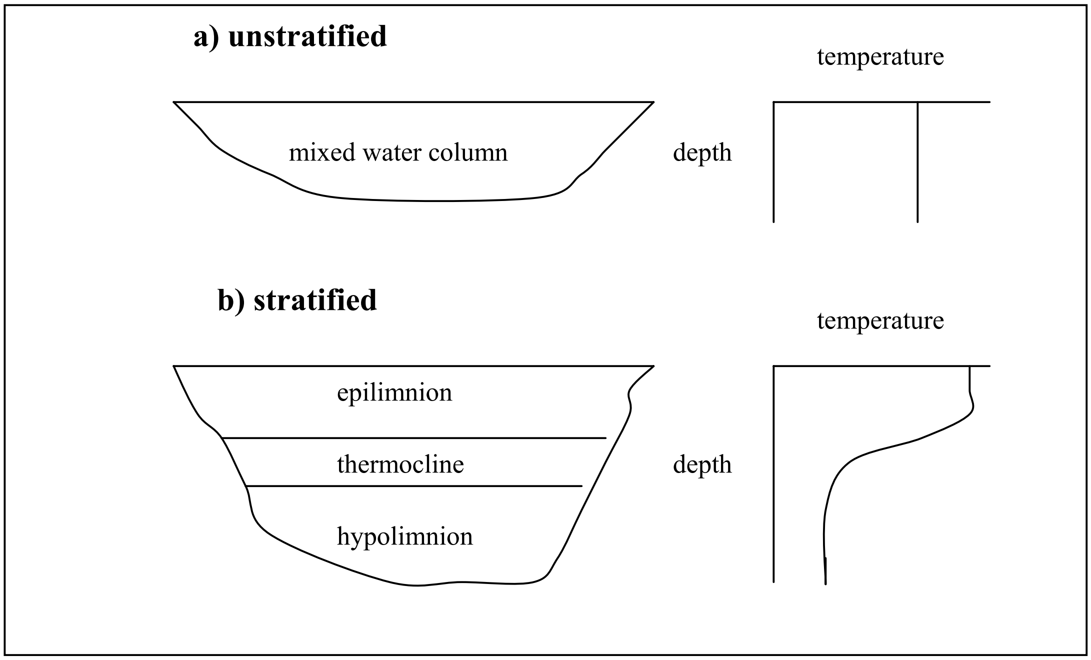


Fig. 20. Temperature profiles in shallow vs. deep ponds in summer. In shallow ponds (a), wind-driven mixing circulates water from top to bottom. In deeper ponds (b), wind activity is insufficient to mix the water column completely, and stable density layers develop during the growing season. In the graphs at right, temperature is seen to be relatively uniform from top to bottom; in stratified ponds the epilimnion typically shows little temperature change, but a rapid decline in temperature occurs in the thermocline.

The epilimnion of a stratified pond typically has adequate light, but becomes progressively depleted of nutrients as phytoplankton and other particles take them up, then sink to the bottom. In contrast, the hypolimnion has a relative abundance of nutrients, but little light. Because photosynthetic organisms require both nutrients and light for rapid growth, ponds that stratify in summer gain a measure of protection from overgrowth by these organisms during the growing season.

The depth of the epilimnion in the 13 ponds studied was closely related to light penetration (Fig. 21); ponds with rapid light depletion had shallow epilimnia and occur at the lower right of the figure, while ponds with less light depletion and correspondingly deeper epilimnia are shown at the upper left. Differences in wind-driven mixing (reduced by trees surrounding some ponds, and increased with increasing pond surface area) likely accounted for some of the remaining variation (scatter about the trend line) in the figure. Slight differences in time of day of sampling (stratification may in some instances break down due to loss of heat from the surface waters at night and reform the following day) and the occurrence of recent storm events may also have influenced the depth of the epilimnion.

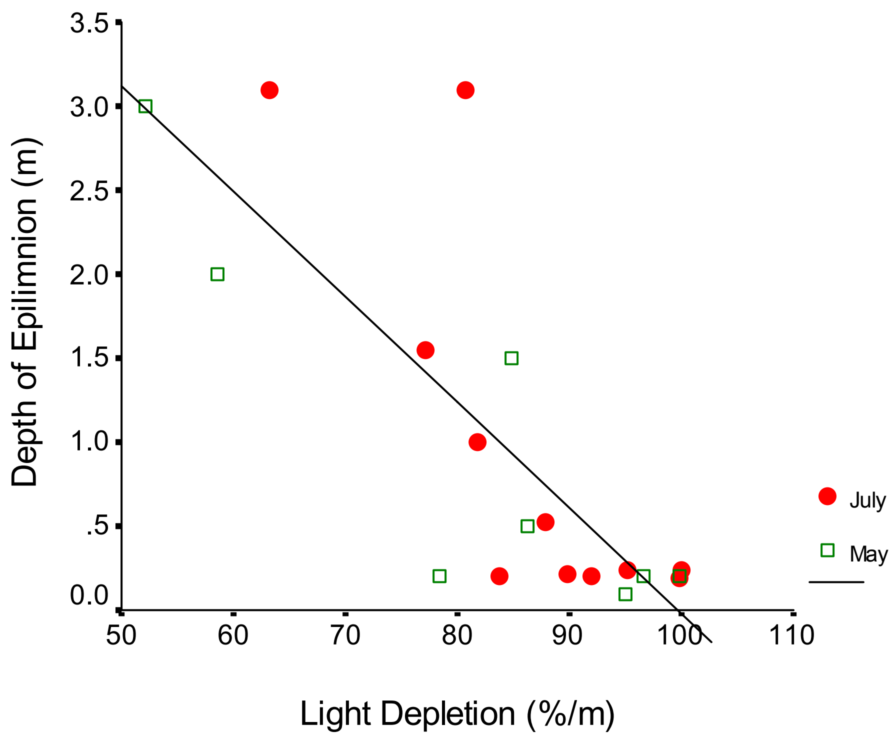


Fig. 21. The relationship between depth of the epilimnion (EPI) to percent light depletion per meter in the water column (LD). None of the ponds had stratified in March, but 19 instances of stratification occurred among the 26 sampling visits during May and July. Regression line is EPI = 6.27 – 0.063(LD); r = -0.80 (p = 0.000).

Dissolved oxygen concentrations strongly influence the distributions and growth of most pond organisms. Oxygen is exchanged between the water column and atmosphere, such that a well mixed water column, if it contained no living organisms, would be expected to be 100% saturated (in equilibrium with the atmosphere). Oxygen concentrations under such circumstances are determined solely by temperature (cold water holds more oxygen) and thus vary predictably with season, declining as temperatures increase during the spring and summer.

Living organisms are a part of the pond, however, and their photosynthesis and respiration greatly modify oxygen concentrations (Equation 1).

$$\xrightarrow{\text{Photosynthesis}}$$
$$6CO_2 + 6H_2O \leftrightarrow 6O_2 + C_6H_{12}O_6 \qquad (1)$$
$$\xleftarrow{\text{Respiration}}$$

In equation 1 photosynthesis by plants and algae uses the energy in sunlight to take up carbon dioxide (CO_2) and water (H_2O) on the left side of the double-headed arrow, and produces glucose ($C_6H_{12}O_6$) needed for growth, releasing oxygen (O_2) as a by-product to the water column (on the right side of the double-headed arrow). Algae and aquatic plants thus elevate oxygen levels near the pond surface during daylight hours. Respiration may be thought of as the reverse process, using up glucose and oxygen, and producing carbon dioxide and water. All organisms respire, and oxygen levels thus drop at night, particularly in highly productive ponds with high densities of organisms. Bacterial decomposition of dead organic material in particular is a major cause of high respiration rates. Because light is rapidly depleted with depth in some ponds, photosynthesis is less important than respiration in deeper water, causing a decline in oxygen near the bottom (Fig. 22). Organisms living on or in the bottom sediments are thus exposed to very low oxygen levels. Many species may find deeper areas of the pond uninhabitable under these conditions.

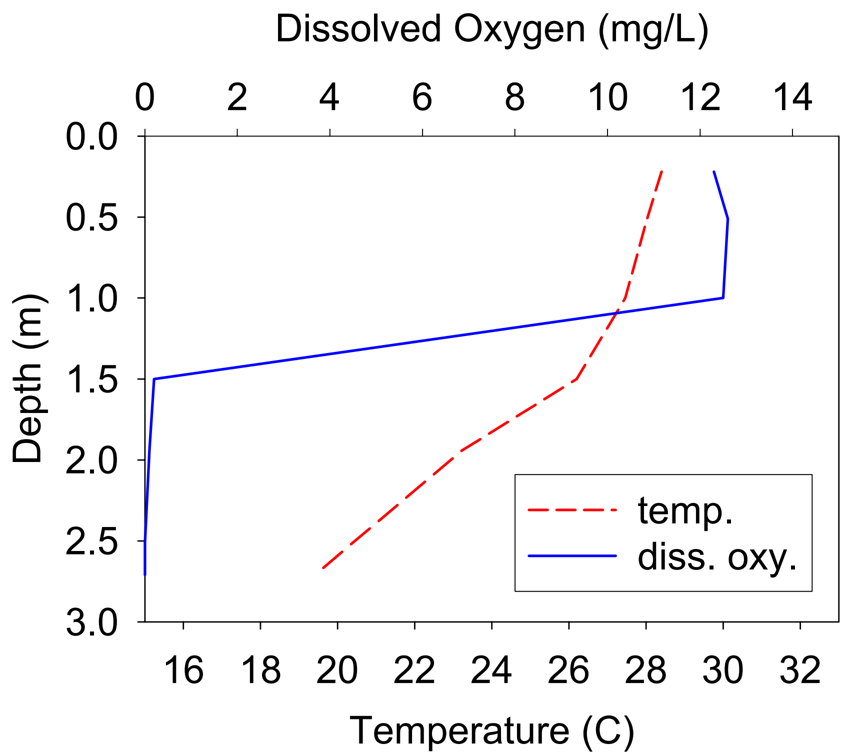


Fig. 22. Changes in dissolved oxygen with depth in a stratified pond (HW) in July. Dissolved oxygen near the surface was most influenced by high rates of photosynthesis and exchange with the atmosphere. High respiration relative to photosynthesis caused the sharp drop in dissolved oxygen below 1.0 m.

Staying in the well-lit upper waters of a pond can be a tactical challenge to members of the phytoplankton. Phytoplankton cells are slightly heavier than water, and depend on wind-driven mixing to remain suspended in the water column. Those cells that settle below the epilimnion are typically in the slow process of sinking to the bottom of the pond. If they sink below the compensation depth, their respiration exceeds their ability to photosynthesize and they are likely to die, decompose and thus contribute to the net consumption of oxygen in the bottom waters (e.g., Brönmark and Hansson, 1998).

Mean oxygen levels (averaged for the entire water column) in the 13 ponds are shown in Figure 23. As mentioned above, cold water holds more oxygen at 100% saturation (the amounts of oxygen predicted solely by equilibrium with oxygen in the atmosphere above the pond) than warm water (the “pluses” in the figure decline as water temperature increases toward the right); in effect, a pond in early spring with water just above freezing is expected to hold about 14 mg/L dissolved oxygen, while the same pond in mid-summer might be expected to hold just half that amount (about 7 mg/L).

However, photosynthesis elevates, and respiration reduces, the amounts of oxygen predicted in the water column solely on the basis of water temperature. In this study photosynthesis elevated dissolved oxygen levels above 100% saturation in most ponds during March, and respiration associated with the decomposition of organic material caused declines in oxygen below 100% saturation in most ponds during May and July. In effect, even though the ponds appeared greenest during July, this was actually a time when many primary producers were already dying and decomposing.

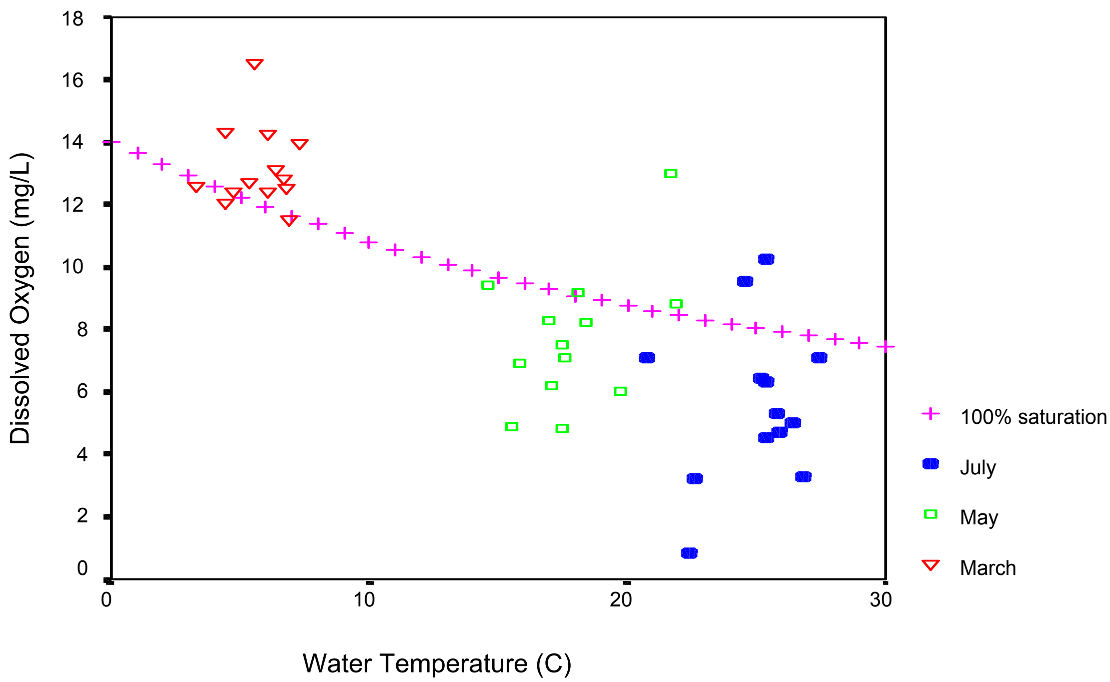


Fig. 23. Mean dissolved oxygen concentrations in the water column relative to mean water temperature during March, May and July. Expected oxygen concentrations at 100% saturation were calculated assuming an atmospheric pressure at sea level of 760 mm Hg and an average elevation of the ponds equal to 100 m. Effects of respiration in reducing oxygen below saturation levels predicted by temperature were most pronounced in July.

J. Major Ions dissolved in Water

Water chemistry reflects in part the influence of watershed characteristics (e.g., bedrock, soils and land use). In this section we consider ions in largest supply in freshwaters (nutrients are in much smaller concentrations and are discussed separately in Section J). Ions are actually the charged constituents of salts that dissolve in water; for example, table salt is sodium chloride (NaCl), with one positively charged ion (Na^+) and one negatively charged ion (Cl^-) that dissociate in solution. The major positively charged ions of ponds in southeast Pennsylvania are calcium (Ca^{2+}) and magnesium (Mg^{2+}), with lesser amounts of sodium Na^+ and potassium (K^+). The major negatively charged ions are bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulfate (SO_4^{2-}) and chloride (Cl^-).

Specific conductance is a measure of the total dissolved ion content of water, and is based on how well the water conducts an electrical current (the more the ions, the greater the specific conductance). Specific conductance can be an excellent indicator of pond trophic state; ponds with higher specific conductance values are usually more productive because they contain not only higher concentrations of the major ions above, but also higher concentrations of nutrients.

Calcium and magnesium ions in ponds largely originate from limestones ($CaCO_3$) and dolomites (($CaMg(CO_3)_2$) in the watershed. The concentrations of calcium and magnesium ions are measured together as “hardness”. Water with hardness values of 0-60 mg/L as calcium carbonate is considered “soft”, values of 61-120 mg/L indicate “moderately hard” water, values of 121-180 mg/L indicate “hard” water, and water with hardness > 180 mg/L is considered “very hard”. All 13 study ponds had soft or moderately hard water (< 120 mg/L). Because calcium and magnesium contributed strongly to total ion content, a tight positive relationship between hardness and specific conductance was observed in the 13 study ponds (Fig. 24).

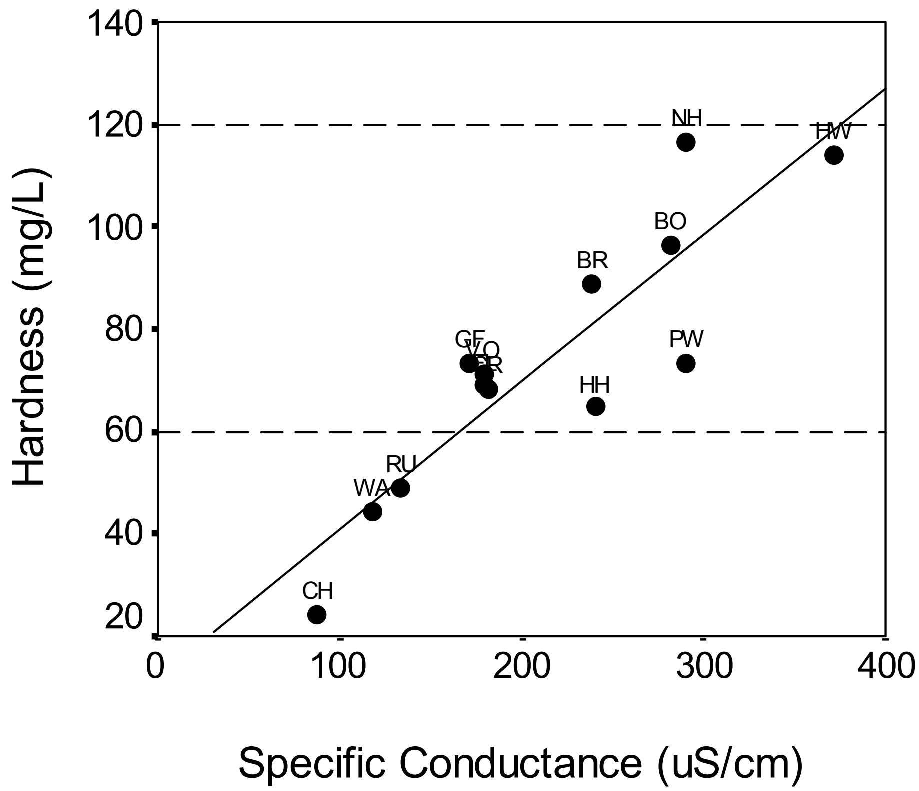


Fig. 24. Relationship of hardness to specific conductance in 13 ponds (mean values based on visits during July, 2003 (values in March and May were similar). Dashed lines separate soft, moderately hard, and hard water. As indicated by the relatively little scatter around the regression line, hardness and specific conductance were closely related . Hardness = 14.6 + 0.27(Spec.Cond.); r = +0.92 (p=0.000).

The relative concentrations of positively and negatively charged ions help to determine the pH of pond water. Ponds with pH values < 7 are considered more acidic, while those with pH > 7 are more basic. "Alkalinity" measures the concentrations of negatively charged ions that collectively raise the pH above 7. The most common negatively charged ion is bicarbonate (HCO_3^-). Ponds with watersheds containing limestone may be expected to have higher alkalinity (and consequently higher pH) than other ponds of the county.

Knowing the pH and alkalinity of a pond is important for two reasons. First, although most organisms characteristic of shallow ponds are able to tolerate a fairly wide range in pH, many algae have preferred pH "optima" and most cannot tolerate severely acid conditions (e.g., pH < 5) resulting, for example, from acid rain or acid mine drainage. Ponds in Chester County are typically sufficiently buffered that pH levels are above 7, so this first concern is likely minimal. Secondly, intense photosynthesis by algae and aquatic plants elevates the pH relative to the alkalinity present, while respiration involved in the breakdown of organic materials causes pH declines. In effect, pH and alkalinity together can provide a strong indication of pond trophic state.

The 13 study ponds ranged in pH from approximately 6 to nearly 10, and in alkalinity from 10 to 70 mg/L. Increased photosynthesis by algae and aquatic plants in July slightly elevated the values of both variables in most ponds (Fig. 25). An exception was BR, which had large amounts of filamentous algae already growing at the bottom of the pond in March.

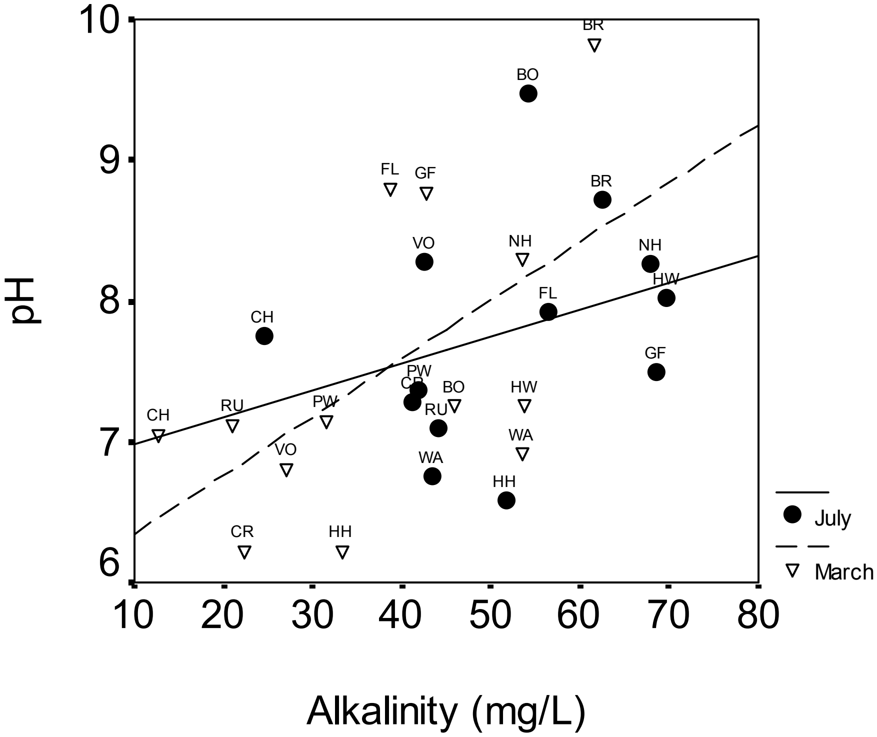


Fig. 25. Relationship of pH to alkalinity (Alk) in 13 ponds visited during March and July, 2003. Regression for March was pH = 5.9 + 0.04(Alk); r = 0.58 (p = 0.038). Regression for July was pH = 6.8 + 0.02(Alk); r = +0.32 (p = 0.283).

K. Water Column Nutrients

Two nutrients often needed by primary producers in larger amounts than are available in ponds for sustained growth are <u>nitrogen</u> (used to make proteins) and phosphorus (used in phospholipids, adenosine triphosphate and other biomolecules). In addition, concentrations of carbon (taken up via photosynthesis by algae and macrophytes, and present in all organic molecules) and silica (needed in large amounts by one group of algae, the diatoms, for cell wall construction) may occasionally limit the growth of particular species, but are unlikely to control overall primary producer biomass. This report focuses on seasonal changes in nitrogen and phosphorus. The forms of both nutrients are described in Table 1.

Table 1. Major forms of nitrogen and phosphorus present in ponds.

Form of N or P	Notation	Major function or use in ponds
Total N	TN	Includes all forms of nitrogen; often used to determine nutrient limitation
Nitrate	NO_3^--N	Oxygen-rich, inorganic form of N used directly by primary producers
Nitrite	NO_2^--N	Found in small quantities and often lumped with nitrate as $NO_{2+,3}$-N
Ammonium	NH_4^+-N	Oxygen-poor, inorganic form of N used directly by primary producers
Diss. Organic N	DON	Organically-bound N present as dissolved molecules
Particulate N	PN	N contained in particles (e.g., phytoplankton, sediments)
Total P	TP	Includes all forms of phosphorus; often used to determine nutrient limitation
Orthophosphate	PO_4^{3-}-P	Dissolved, inorganic P used directly by primary producers
Diss. Organic P	DOP	Organically-bound P present as dissolved molecules
Particulate P	PP	P contained in particles (e.g., phytoplankton, sediments)

Nitrogen (N) may be taken up by primary producers either as ammonium (NH_4^+) or nitrate (NO_3^-). Both are available for uptake by phytoplankton and metaphyton in the water column, but sometimes occur in low enough concentrations to limit growth. Total nitrogen (TN) in the water column includes ammonium, nitrate, dissolved organic nitrogen (DON) and particulate nitrogen (PN: nitrogen incorporated into phytoplankton and other particles suspended in the water column), and is frequently used to assess the potential for nitrogen limitation of algal growth. Whereas phytoplankton, metaphyton and free-floating aquatic plants obtain nitrogen from the water column, total sediment nitrogen is a better indicator of potential limitation of the growth of rooted aquatic plants, which obtain the bulk of their nutrients from the sediments.

Phosphorus (P) is frequently in short supply relative to the needs of primary producers and thus potentially capable of controlling their growth in many ponds.

Phosphorus is taken up by primary producers as orthophosphate (PO_4^{3-}) and incorporated internally into phosphorus-containing organic molecules. Total phosphorus (TP), including orthophosphate, dissolved organic phosphorus (DOP) and particulate phosphorus (PP), is usually used to evaluate the potential for P-limitation.

Both nitrogen and phosphorus are essential for growth, and the growth of primary producers is limited by whichever nutrient is in least supply relative to need. If, for example, phosphorus is the "limiting" nutrient for the phytoplankton community then the growth of phytoplankton is determined solely by the availability of phosphorus, regardless of the concentrations of nitrogen. Although the <u>needs</u> of primary producers are known to vary according to species, an approximate ratio of need for the two nutrients is thought to be between [7.2 mg N:1 mg P] (Redfield, 1958) and [14 mg N:1 mg P] (Downing and McCauley, 1992).

The ratio of relative <u>availability</u> of nitrogen and phosphorus is normally expressed as TN:TP (Dodds, 2003), although recognizing that some forms of both nitrogen and phosphorus are not directly usable by primary producers. This means that if the (weight:weight) ratio of TN:TP in the water column greatly exceeds 14:1, then nitrogen is in excess and phosphorus is considered the limiting nutrient. If the TN:TP ratio is much less than 7.2:1 then nitrogen is considered limiting. The interval between 7.2:1 and 14:1 may be taken as a zone of "joint limitation" by nitrogen and phosphorus (the growth of primary producers cannot increase unless both nitrogen and phosphorus levels increase). Identifying whether the limiting nutrient is nitrogen or phosphorus is often considered a critical first step in developing a management plan for controlling excessive growth by primary producers. For example, if phosphorus either limits or jointly limits growth, then reducing the supply of phosphorus can be used to reduce primary producer biomass.

Total nitrogen levels declined between March and July in 8 of the 13 ponds, whereas total phosphorus increased in 9 of the 13 ponds (Fig. 26). Both phenomena have been observed elsewhere in shallow, highly productive ponds (Sondergaard et al., 1999; Sondergaard et al., 2003). Briefly, nitrate undergoes bacterially-mediated "denitrification" under low oxygen conditions, and is converted to nitrogen gas which is lost from the pond; phosphorus in contrast is released from binding to iron in the sediments under low oxygen and enters the water column. Both processes are facilitated later in the growing season by a combination of warmer temperatures, lowered oxygen near the bottom, and increased bacterial activity at the sediment surface. We have not measured either process directly, but both are reasonable explanations for the opposing seasonal trends of nitrogen and phosphorus in the 13 study ponds.

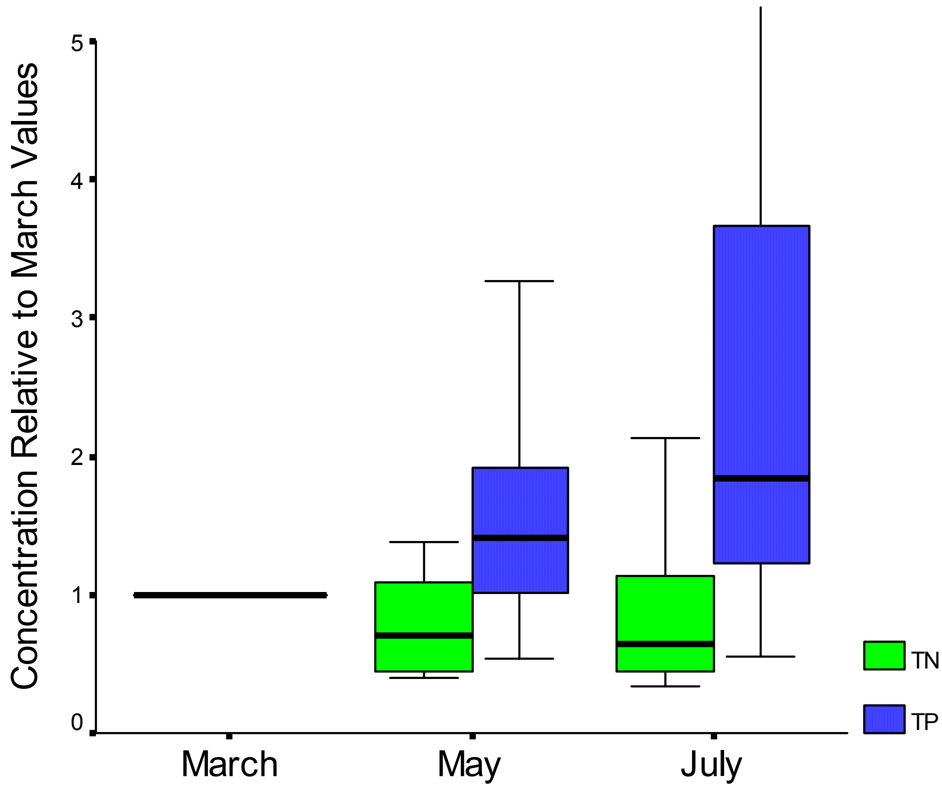


Fig. 26. Concentrations of total nitrogen and total phosphorus relative to values in March in the water column of 13 study ponds. Lines through the boxes are median values. Upper and lower limits of the boxes indicate quartiles, and whiskers indicate ranges.

As a consequence of declines in TN but increases in TP in most ponds, ratios of TN:TP typically declined between March (when most ponds were P-limited) and July (when many ponds were jointly limited by nitrogen and phosphorus) (Fig. 27). Because P either limited or jointly limited growth, however, this report has focused on the sources and management of phosphorus as a means of controlling algal growth.

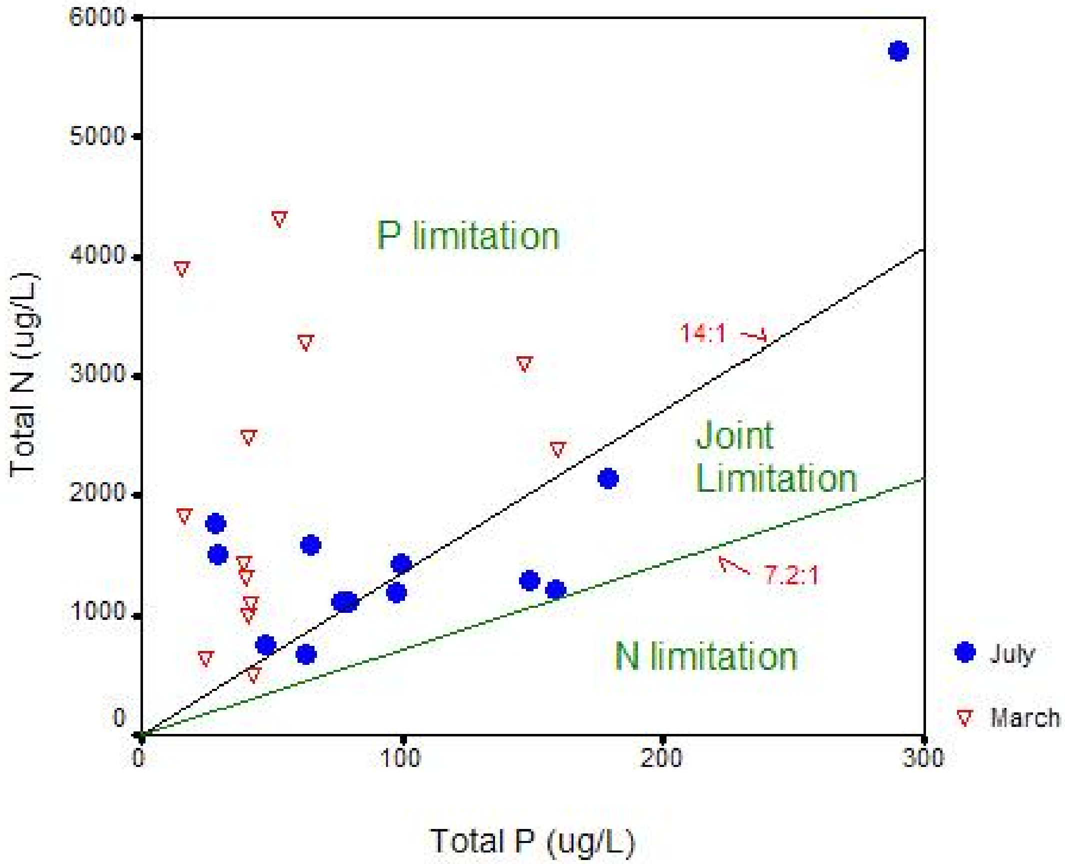


Fig. 27. Ratios of TN:TP for 13 ponds in Chester County, PA. "Optimal" ratios of 7.2N:1P and 14N:1P are shown as diagonal lines and demarcate approximate zones of N limitation, P limitation and joint limitation.

As one indication of the importance of TP to primary producers, phytoplankton biomass was strongly related to TP in the water column; ponds with greater total phosphorus supported greater phytoplankton growth (Fig. 28).

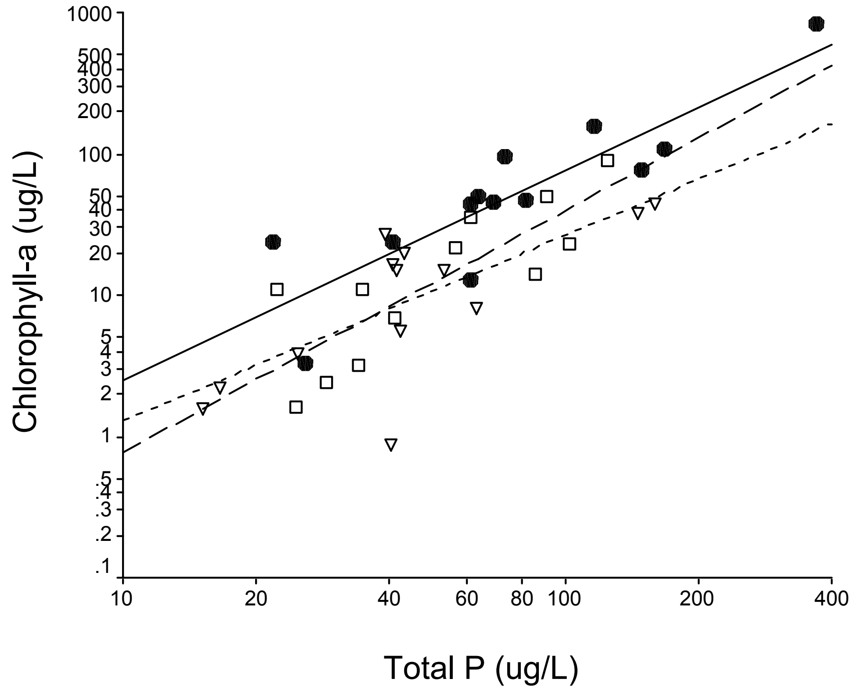


Fig. 28. Relationship of phytoplankton biomass as chlorophyll-a (CHL, as µg/L) to total P (TP, as µg/L) in surface samples taken in March (∇) May (ᵈ) and July (ᶲ). Regressions are (March, dotted line): log_{10}(CHL) = -1.21 + 1.32[log_{10}(TP)]; r = 0.73 (p = 0.005); (May, dashed line): log_{10}(CHL) = -1.82 + 1.71[log_{10}(TP)]; r = 0.82 (p = 0.001); (July, solid line): log_{10}(CHL) = -1.09 + 1.49[log_{10}(TP)]; r = 0.87 (p = 0.000).

L. Sediment Nutrients

The sediments contain inorganic particles, organic "detritus" (the remains of algae, zooplankton, etc.), live benthic algae, a host of bacteria, very small invertebrates termed the meiobenthos, and larger macroinvertebrates. The sediments also contain much higher quantities of nutrients than are found in the water column; some of these are bound in solid phase organic molecules, while a portion is present in inorganic form in the interstitial water.

In marked contrast to larger lakes, reducing external phosphorus inputs from the watersheds of P-limited shallow ponds frequently has little immediate impact on pond water quality (Perrow et al., 1994; Moss et al., 1996; Nixdorf and Deneke, 1997). This occurs because of the large reserves of phosphorus remaining in the sediments. Phosphorus in the sediments can be resupplied to the water column both by upward diffusion of dissolved PO_4^{3-} under anoxic conditions and by resuspension of particulate phosphorus by storms or human activity. Increases in total P in the water column during July in most of the study ponds (see Section F) likely occurred because of increased PO_4^{3-} release from the sediments as the bottom waters became more anoxic. Even if external sources of P are reduced, recycling of P from the sediments may thus maintain high levels of phosphorus in the water column for many years until sediment concentrations are depleted.

Cores of the top 0.5 cm of the sediments in the 13 ponds were obtained during visits in July. The relationship between particulate phosphorus in the surface sediments to total phosphorus in the water column is shown in Figure 29.

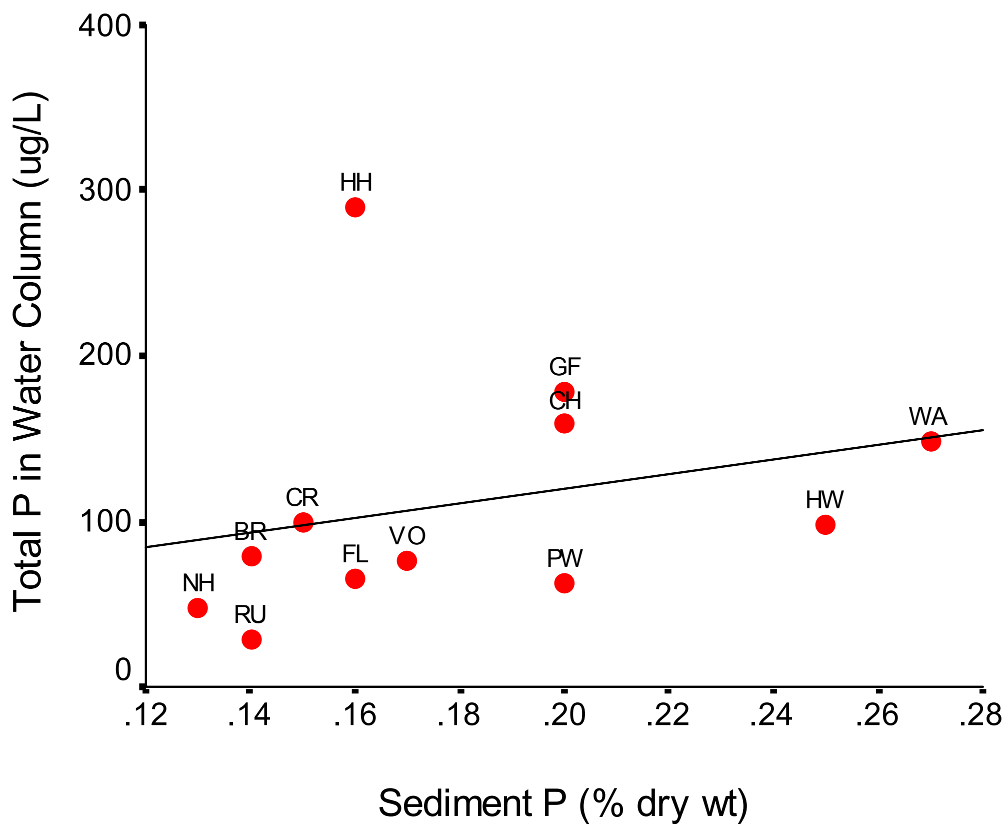


Fig. 29. Sediment P content vs. total phosphorus in the water column (TP) in 12 of the 13 ponds during July. Regression line is TP = 31.53 + 439.9(Sediment P); r = 0.27 (p = 0.40).

Sediment P was typically slightly greater in ponds with higher concentrations of P in the water column. A positive correlation between sediment P and water column P is expected because not only does sediment-associated phosphorus reenter the water column (directly via resuspension and indirectly via remineralization and diffusion), but particulate phosphorus within the water column (e.g., as phytoplankton) sinks to the sediments. The correlation is not strong, however. In particular, total phosphorus in the water column of HH was much higher than could be predicted from sediment P.

Estimates of particulate phosphorus deeper in the sediments (not shown) were generally slightly lower than at the sediment surface owing to decomposition of organic materials (see also Rooney et al., 2003), but are presumed to have less effect than surface sediments on water column nutrients.

M. Phosphorus Budgets

Because nutrient concentrations have such a large influence on pond trophic state, much attention has been devoted to means of assessing the sources and fates of nutrients. These include a) point source inputs from specific, identifiable inflows, b) nutrients contained in direct precipitation, and c) nutrients originating as runoff from non-point sources such as agriculture, septic fields or fertilized lawns within the watershed. The latter category is typically the most important, and unfortunately also the most difficult to quantify or control.

A variety of nutrient budget models have been formulated to estimate the relative contributions of various nutrient inputs. These differ in part according to their complexity and data requirements. Very simple models, such as the one described here, are easily compiled and understandable, but are not sensitive to year-to-year or shorter term variation in weather, whereas the use of more complex models often requires daily rainfall and much more detailed land use information.

Phosphorus budgets for the 13 ponds were prepared following Reckhow and Chapra (1983):

$$[P] = L / [v_s + q_s] \tag{2}$$

where [P] = the predicted mean phosphorus concentration in the pond, L = the estimated annual phosphorus loading to the pond, v_s = net P settling velocity and q_s = the estimated annual water loading to the pond.

A nutrient budget for one of the 13 ponds (GF) is shown in Table 2. Total loading for each land use is the product of its area multiplied by a loading coefficient that estimates P export per unit area for that land use. Export coefficients were derived from available literature (e.g., Reckhow et al. 1980). Nutrients also reach the pond through direct precipitation. These inputs are summed to obtain predictions of total annual nutrient influx from the watershed (W). Water loading (q_s) is calculated from precipitation data for the region. Finally, predicted concentrations of P are compared with actual values to determine the likely effects of other watershed or pond features.

As seen in Table 2, the watershed of pond GF is dominated by cropland (37%) and forest (35%), with smaller amounts of residential housing and pasture. Cropland typically yields more phosphorus per unit area than does forest, and is estimated to provide more than half (11.11 kg/yr / 25.14 kg/yr, or 52%) of total phosphorus loading to GF. Watershed management efforts to reduce phosphorus loading to the pond might thus reasonably focus on agricultural practices.

Table 2. Nutrient Budget for GF. Export (loading) coefficients estimated from previous studies were multiplied by areas of each land use (determined from aerial photographs taken in 2000). Direct precipitation inputs were based on pond surface area.

Land Use	**Area (ha)**	**Loading Coefficient (P) (kg/ha/yr)**	**Total Loading (P) (kg/yr)**	**Model Calculations**	
Residential	11.11	0.50	5.55	**L(g/m^2/yr)**	1.54
Cropland	44.43	0.25	11.11	**v_s (m/yr)**	14.96
Pastures	19.88	0.20	3.98	**q_s (m/yr)**	14.43
Forest	41.93	0.10	4.19	**P (ug/L)**	**52.48**
Precipitation		0.19	0.31		
			Total = 25.14		
Pond Surface Area	1.63				
Total Watershed Area	118.98				

Predicted values of total phosphorus concentration in the water column deviated widely from actual mean values in the 13 study ponds. BO was notable in having much less phosphorus than predicted, while several ponds (especially CH, WA) had higher concentrations than predicted. The lack of fit suggests that other environmental variables may influence actual phosphorus concentrations.   A more complete description of the nutrient budget model used and the degree of concordance between observed and predicted phosphorus concentrations is presented in Anderson (2003).

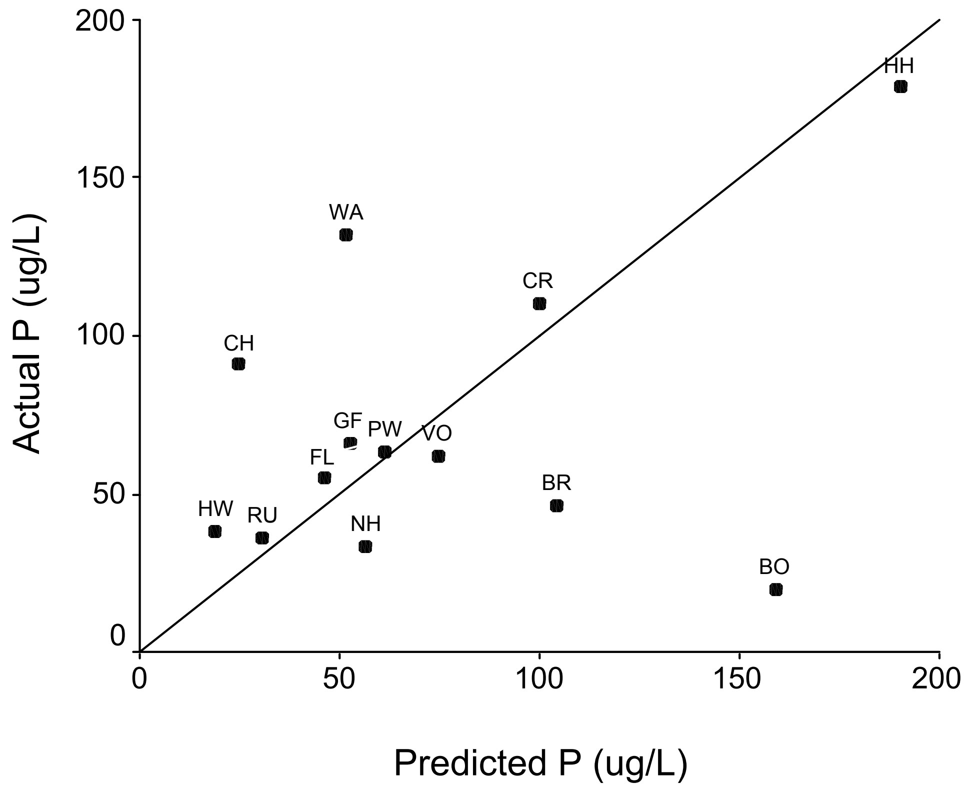


Fig. 30. Fit of TP predicted by Reckhow and Chapra model to actual TP based on three visits to each of 13 ponds. Line represents a 1:1 fit.

N. Effects of Ponds on Stream Nutrients

Most ponds in Chester County are connected to stream networks, usually providing the source for headwater streams or occurring as impoundments of headwater streams. The impoundment of small streams may strongly impact their water chemistry. Water flow is slowed, and a much larger portion of the water surface becomes exposed to direct solar radiation. These changes have the effect of warming the impounded water, and stimulating photosynthesis by algae and vascular plants. The growth of these primary producers in turn increases nutrient uptake.

All but one of the target ponds had both inflows and outflows, although drought conditions prevented measurement of water chemistry during some visits. By comparing nutrient concentrations and particulate matter entering vs. leaving the ponds, it was possible to estimate the probable impact of the ponds on the streams with which they were associated. Changes in nitrogen, phosphorus and silica and suspended particles between the inflowing waters and outfalls of the 13 ponds are shown in Table 3.

Table 3. Mean concentrations (averaged across all ponds) of PO_4^{3-}-P), dissolved organic P (DOP), particulate P (PP), NH_4^+-N, NO_{2+3}, dissolved organic N (DON), particulate N (PN), silica (SiO_2), TN and TP, all expressed in μg/L, and particle concentrations (TSS = total suspended solids, in mg/L) in the inflow vs. outflow from the 13 study ponds during March, May and July 2002.

	March		**May**		**July**	
	In	**Out**	**In**	**Out**	**In**	**Out**
PO_4^{3-}-P	14.7	20.8	8.4	3.2	10.9	2.6
DOP	5.8	13.9	3.3	12.45	11.5	16.2
PP	70.7	77.8	12.8	59.7	45.3	60.6
TP	28.4	55.5	24.5	75.4	67.8	79.4
NH_4^+-N	152.5	288.4	22.8	95.6	35.2	44.3
***NO_{2+3}*-N**	2833.	924.6	1907.	339.0	2200.	275.8
DON	198.9	456.6	150.6	414.3	330.5	509.6
PN	144.9	270.7	39.1	191.5	273.0	430.5
TN	3421	1940	2120	1040	2772	1260
SiO_2	17198	5097	20074	5839.	18153	6153.
TSS	3.11	7.71	21.54	26.32	8.66	10.23

As expected, the ponds sequestered much of the incoming nutrients. Retention of orthophosphate (PO_4^{3-}-P) increased later in the season, presumably because of uptake by primary producers. Similar patterns of net uptake were observed for the inorganic nutrients nitrate (NO_{2+3}-N) and silica (SiO_2). By contrast, ammonium (NH_4^+-N), which results primarily from the decomposition of organically bound N, consistently showed net export downstream.

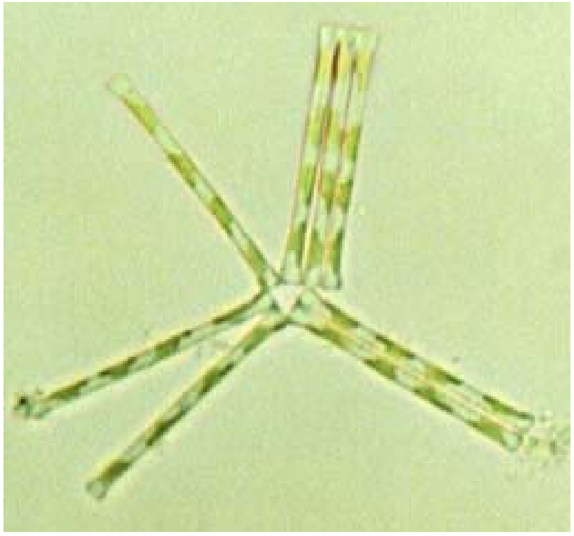
Ponds produced by impounding streams have the well-deserved reputation of trapping particles suspended in the inflow during rain events. At other times (when streams are at normal flow), however, ponds are likely to be net exporters of particles. Basically, the ponds may be viewed as reaction chambers, converting dissolved nutrients into phytoplankton tissue, bacteria and other organic particles, exporting a portion of these particles downstream (the remaining fraction may settle to the sediments or be returned to dissolved inorganic forms by decomposition). Particulate forms of nitrogen (PN) and phosphorus (PP) both showed net export from the ponds. A further indication of the net export of particles is indicated by the slightly higher concentrations of total suspended solids in the outflows than in the inflows of the ponds.

O. Phytoplankton

Phytoplankton abundance provides a major indication of pond trophic state. More eutrophic ponds typically support higher phytoplankton biomass, usually measured by the concentration of the photopigment chlorophyll-*a* in the water column. The phytoplankton consists of an array of species that vary in their seasonal dominance, light and nutrient requirements, and susceptibility to consumption by zooplankton. Three major groups of species typically dominate the phytoplankton. They are described briefly below, and examples of each group are shown in Fig. 30.

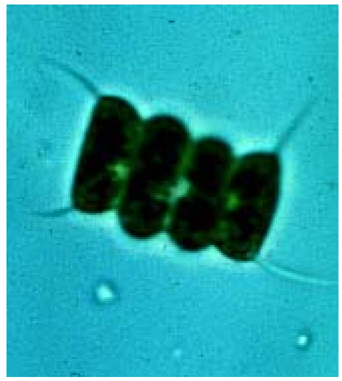
Diatoms are often particularly abundant during early spring. Unlike most other algae, diatoms require silica (SiO_2) in large amounts for cell wall construction and ponds dominated by diatoms often experience sharp declines in silica concentrations during the growing season because of uptake by diatoms. Uptake by diatoms also likely caused the pronounced retention of silica within the ponds noted in Table 3. Diatoms may be present either as individual cells or as colonies of many cells, such as the star-shaped colony of *Asterionella* shown in the figure.

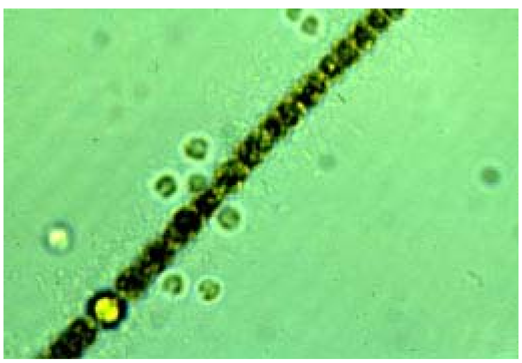
Green algae include many species which have small, fast-growing cells, such as the *Scenedesmus* shown in Figure 30, that are highly palatable to zooplankton. Other species may have cells encased in gelatinous mucilage, rendering them larger and less edible. Under conditions of high nutrient loading in eutrophic ponds it is often the green algae that become particularly abundant.



← Diatoms often dominate the phytoplankton in early spring, but may be outcompeted by green and blue-green algae later in the season. Smaller species in particular are an important food for zooplankton. Under conditions of inadequate nutrients, they typically sink to the sediments. The diatom shown here, Asterionella, is a common member of the phytoplankton in southeast Pennsylvania.

Green algae may be single-celled, form large gelatinous colonies or form filaments. Smaller single-celled species and small colonies, such as the genus Scenedesmus shown here, are considered excellent food for zooplankton. →





← Blue-green algae, such as Anabaena, are typically very small-celled, but may form large gelatinous colonies or filaments comprised of many cells. Tolerant of high temperatures and light, they often proliferate in nutrient-rich ponds, forming blooms that may be toxic to livestock.

Fig. 30. Three groups of algae most commonly found in the phytoplankton of ponds in Chester County.

Blue-green algae have much smaller cells than do members of the other two groups. Many species are very tolerant of warmer water, and are less preferred by zooplankton, so often dominate ponds during summer. Their presence is often indicative of ponds with excess P and limiting N concentrations. In hypereutrophic ponds some species may form algal "blooms" which can be unsightly and toxic to livestock.

Phytoplankton biomass is commonly estimated as chlorophyll-*a*, a photopigment used for photosynthesis and present in all groups of algae. Chlorophyll-*a* in the 13 target ponds varied from 1 to 552 μg/L, with highest values in July (Fig. 31). As is evident from the figure, light depletion in the ponds largely results from the interception of light by phytoplankton.

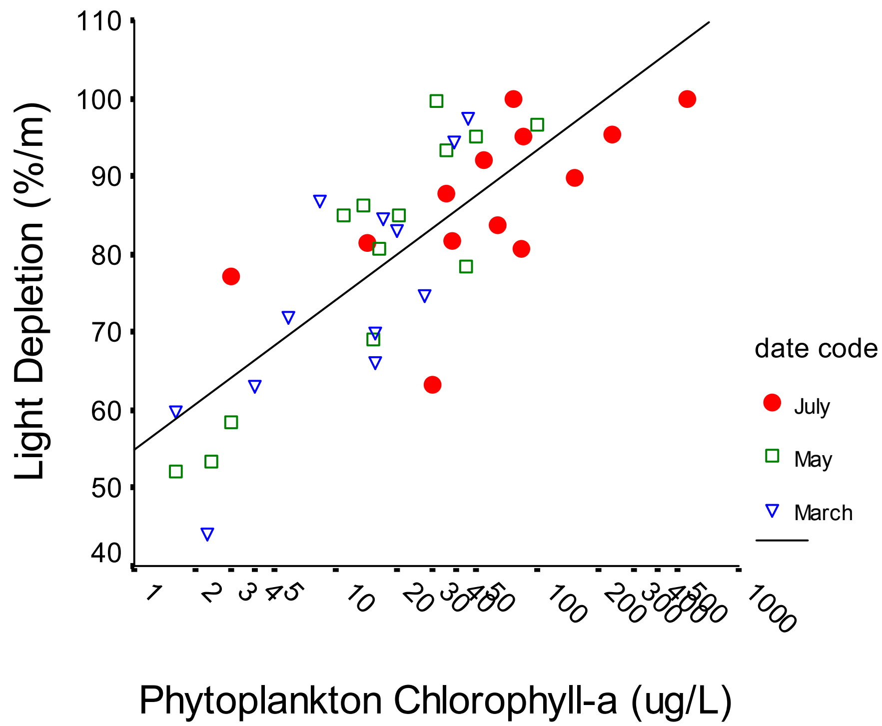


Fig. 31. Relationship of light depletion (LD) to phytoplankton chlorophyll-a (CHL). Regression line is LD = 54.81 + 19.31[log(CHL)]; r = +0.81 (p = 0.000).

P. Pond Trophic State

The trophic state of a pond, described qualitatively in Section E, may be quantified using Carlson's (1977) Trophic State Index (TSI) for comparing lakes. The TSI is based on three separate calculations: 1) phytoplankton chlorophyll-*a*, 2) Secchi depth, and 3) total P in the water column during summer. Of these, $TSI_{chl\text{-}a}$ is usually deemed the most accurate. Oligotrophic water bodies are defined as having TSI < 40. Ponds with TSI values between 40 and 50 are classified as mesotrophic, ponds with TSI between 50 and 70 are termed eutrophic and ponds with TSI > 70 are termed hypereutrophic (Carlson and Simpson 1996). Because Carlson's focus was on deeper lakes dominated by phytoplankton, TSI estimates are not sensitive to influences of metaphyton (see Section Q) or aquatic plants (see Section S). Calculations of TSI are nonetheless useful as a first step in summarizing the susceptibility of ponds to nutrient-related management problems.

TSI estimates for the 13 ponds based on phytoplankton chlorophyll-*a*, secchi depth, and total P recorded during July are shown in Figure 32. The 13 ponds were ranked in ascending order of $TSI_{chl\text{-}a}$. Secchi depths were greater than expected given the phytoplankton biomass estimates (TSI_{secchi} estimates were typically less than $TSI_{chl\text{-}a}$), and likely were influenced by additional light reflected from the shallow bottoms of the ponds.

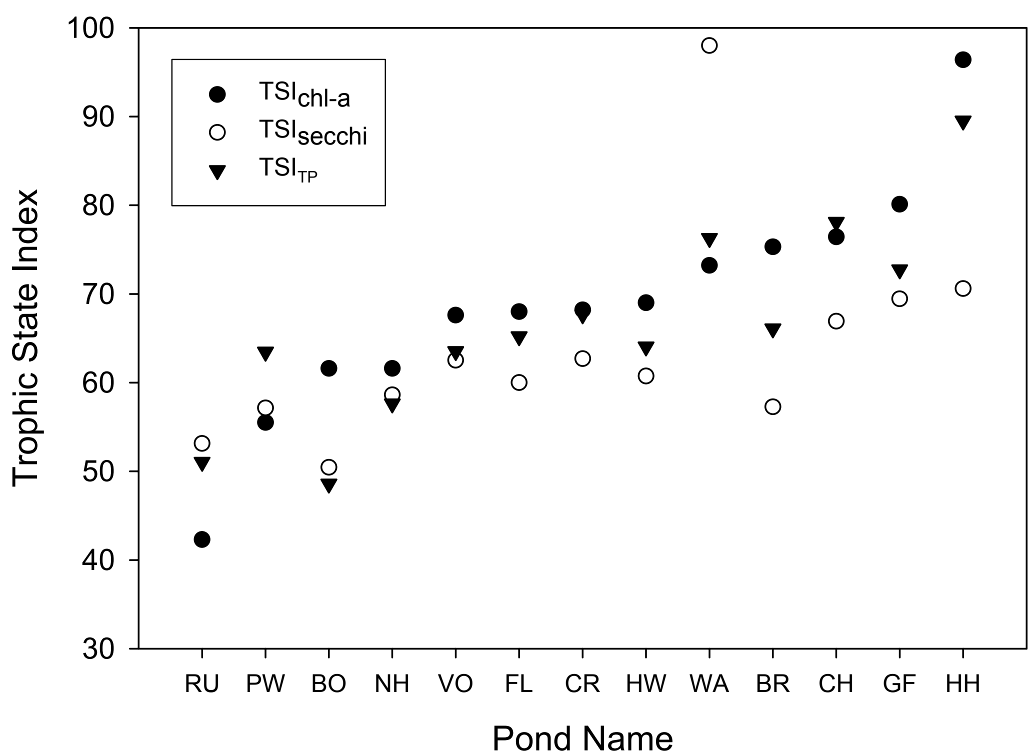


Fig. 32. Carlson's TSI for 13 ponds. Ponds were ranked on the X axis in order of ascending values of TSI for phytoplankton chlorophyll-a. Individual calculations for chlorophyll-a, secchi depth, and total P are shown separately.

As shown in the figure, RU (with a rank of 1) is an especially clear-water pond with low available phosphorus and little phytoplankton growth, whereas WA and HH (ranked 12 and 13) have comparatively high P, abundant phytoplankton and relatively turbid water.

Q. Metaphyton

In hypereutrophic ponds with abundant nutrients scums of filamentous green algae often become obvious near the water surface. These floating clouds of metaphyton originate on sediment, rock or macrophyte surfaces, from which they become disengaged and rise to the surface (Fig. 33). Because of the high density of algal cells within the clouds of metaphyton, access to light and nutrients for many individuals may be poor, and the scums probably start to decompose soon after they appear. Constant replenishment from below, however, may result in the continued presence of metaphyton during much of the summer (Lembi, 1988).

Fig. 33. Metaphyton at the surface of a pond, showing columns to filamentous algae buoyed upward by oxygen bubbles.

The relative amounts of phytoplankton and metaphyton in a pond may provide a useful indication of its trophic state. Abundances of metaphyton are compared to phytoplankton abundances in the 13 target ponds based on samples taken in July in Figure 34. Of the 5 ponds with especially high overall algal biomass, two (BR, WA) had large quantities of metaphyton while three (GF, HH, HW) had high phytoplankton densities but little metaphyton. The overall effect of total P on metaphyton biomass was not as strong as for the phytoplankton (Fig. 35).

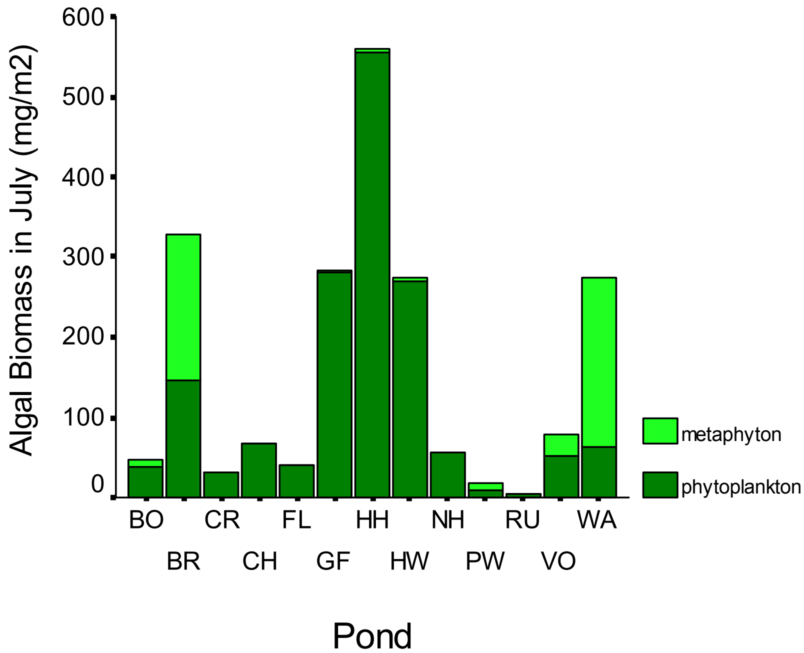
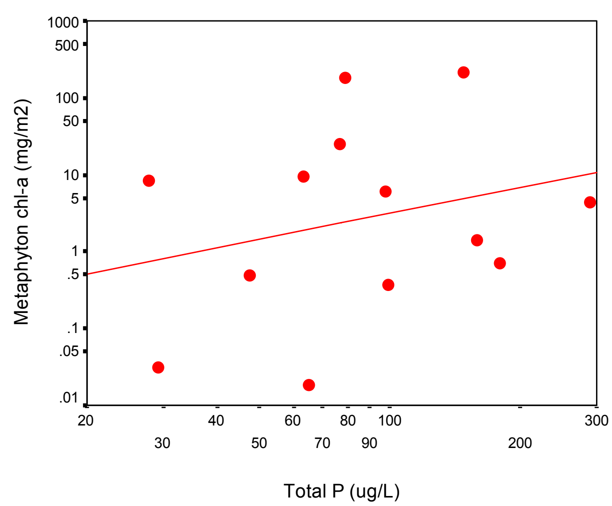
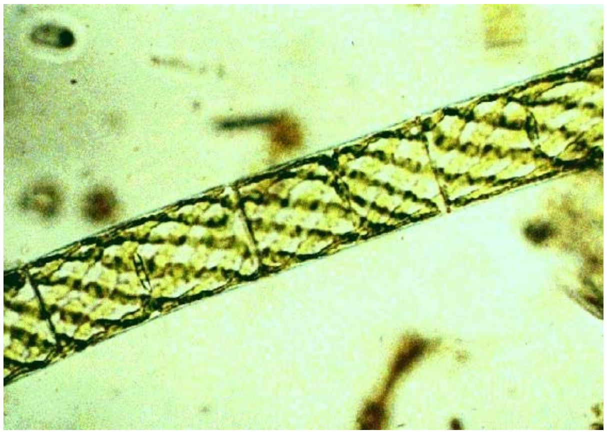


Fig. 34. Biomass of phytoplankton vs. metaphyton in 13 ponds in July.

Fig. 35. Relationship between total phosphorus (TP) and metaphyton biomass (MB) in July. Regression line is logMB) = 0.05 + 0.40[log(TP)]; r = +0.15 (p= 0.63).

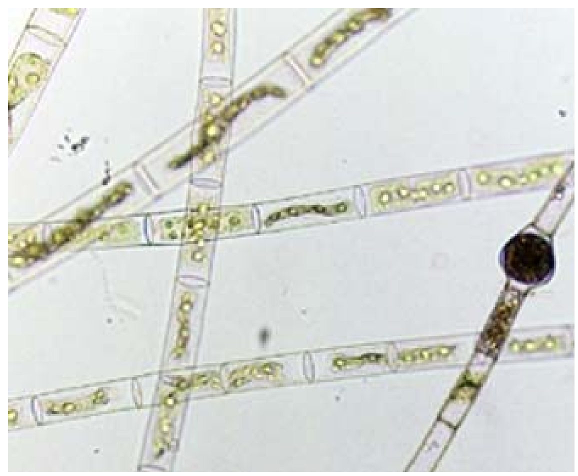


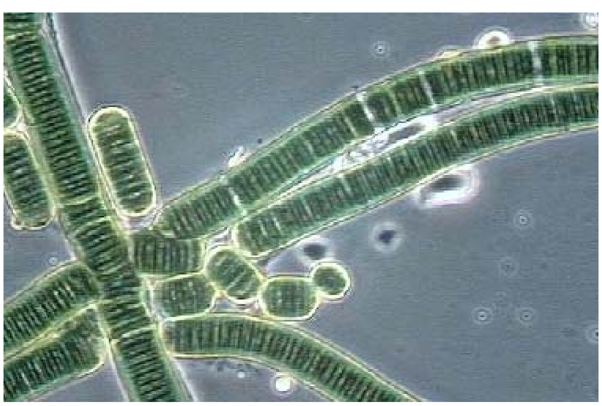
Some examples of filamentous green algae and filamentous blue-green algae responsible for scum formation in southeast Pennsylvania are shown in Fig. 36a-b.



← Spirogyra is a common mat-forming green alga early in the growing season. Spirogyra is unbranched, and may provide high-quality food for some grazers. Spirogyra is often less tolerant of higher temperatures and light, and is often replaced by other species later in the summer.

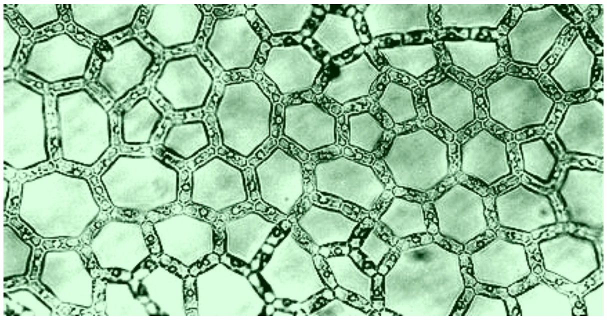
Oedogonium is one of the most common members of the metaphyton encountered later in the growing season. It often starts to grow attached to firm substrates such as rocks or plants, but may become detached as its biomass increases. Oedogonium has thick, cellulosic walls that normally support other algae such as diatoms that attach to the bigger filaments.→





← Lyngbya is an unusually large-celled blue-green alga. Extensive mats of intertwined filaments are common. Direct feeding of invertebrates on Lyngbya is probably uncommon, but Lyngbya does act as a substrate for attached diatoms that provide food for invertebrate grazers. Note the presence of cells inside a well-developed sheath.

Fig. 36a. Major kinds of unbranched metaphyton-forming algae



←Note the net-like arrangement of cells of the genus Hydrodictyon, a green alga that often becomes dominant in the metaphyton during summer. The net-like arrangement may trap oxygen bubbles that help lift the alga off the sediments into the water column.

The genus Cladophora, a member of the green algae, is considered one of the most common and widespread indicators of nutrient enrichment in ponds. Filaments are branched, and often heavily colonized by epiphytes. Although usually attached to rocks and other structures, filaments may detach to form floating scums of metaphyton.→

Fig. 36b. Major kinds of branched or reticulate (net-like) metaphyton-forming algae.

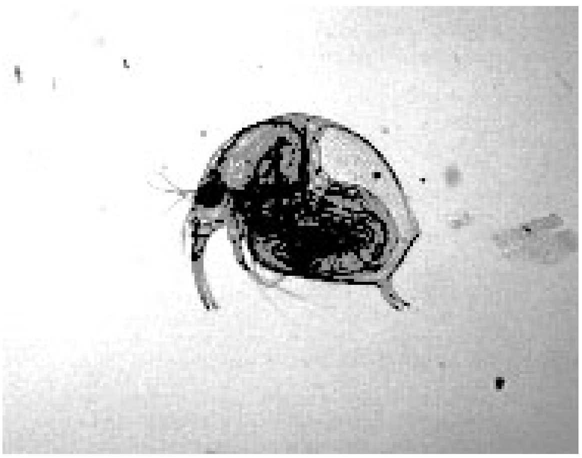
Many other species of algae may be attached or intertwined with the green algal filaments, and may constitute the principal food for metaphyton-associated invertebrates. Both the algae and invertebrates associated with scums of metaphyton differ from those present in the plankton and in/on the sediments. In effect, metaphyton clouds are unique communities within the larger pond ecosystem.

R. Zooplankton

The zooplankton in ponds are important a) as grazers reducing the abundance of phytoplankton, b) as recyclers of nutrients needed by algae, and c) as a critical food for many species of fish, particularly in early stages of development. Three major groups dominate the zooplankton – the cladocerans, copepods and rotifers. Zooplankton typical of shallow ponds in the region are shown in Figure 37a-c.

Cladocerans are often called water fleas, so-called for their hopping behavior as they move slowly through the water column. Many species are excellent filter feeders, consuming large quantities of phytoplankton. Eggs are borne in a brood chamber under the carapace of the parent until sufficiently developed for release.

Many copepods are also effective consumers of phytoplankton, though they often display more selectivity for particular types of algae than do the cladocerans. Copepods are tubular in body shape, and are hydrodynamically streamlined for efficient swimming.



← The cladoceran Bosmina is an important filter feeding member of the plankton in shallow ponds. Because of its smaller size (approximately 0.4 mm) it often escapes the attention of fish. Note the large egg in the brood chamber at the upper right.

Daphnia are very effective and rapidly growing filter feeders, capable of controlling algal growth when they become very abundant. Daphnia, however, are very prone to fish predation owing to their larger size (adults of many species exceed 1 mm) and visibility, and as a consequence are often at a disadvantage in small ponds with good visibility to the bottom. The individual seen at right is carrying a single egg which is in fact an identical genetic copy (clone) of herself.→

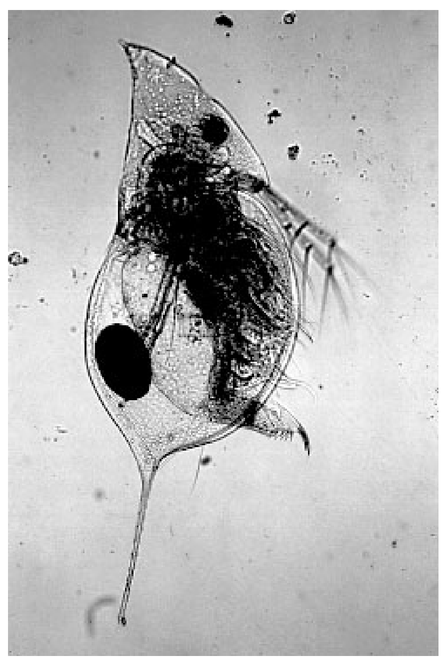
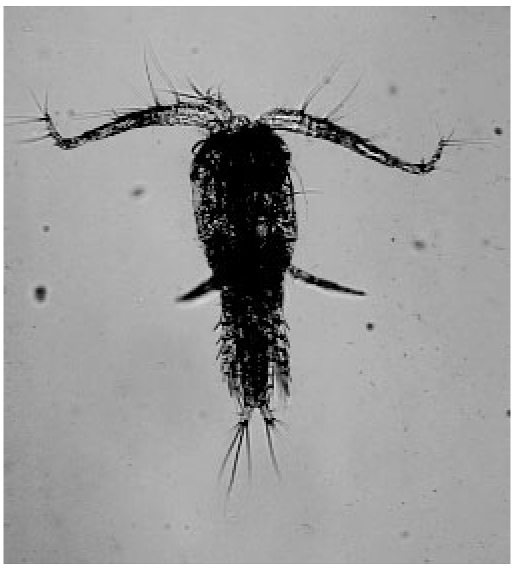


Fig. 37a. Cladocerans common to ponds in southeast Pennsylvania.

Rotifers form a diverse group of multicellular organisms that are only distantly related to the crustacean cladocerans and copepods. Many rotifer species ingest algal and bacterial cells, and are capable of rapid population growth (population size may double within 1-2 days). The rotifers thus are often the first of the three zooplankton groups to respond to increases in phytoplankton food. Because of their small size (often 0.1 to 0.2 mm), rotifers often are less subject to fish predation than cladocerans and copepods, but are often consumed by predaceous zooplankton species.

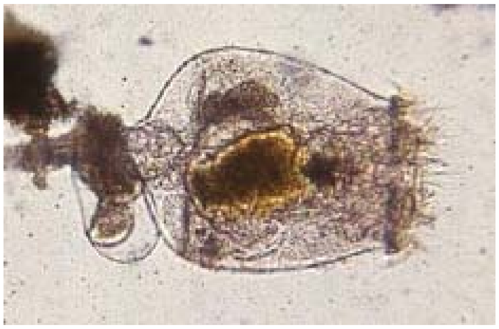


← The copepod Cyclops is an example of a raptorial feeder, seizing individual algal cells or small animals. Cyclopoid copepods have relatively short antennae. The individual shown is an immature.

The copepod genus Diaptomus is a filter feeder, but is thought to be slower growing and a more selective feeder than Daphnia. Diaptomus is recognized by its long swimming antennae. The female shown at right is carrying a single sac of eggs. →

Fig. 37b. Common copepods of ponds in southeast Pennsylvania..

Note the armor surrounding this individual of <u>Keratella</u>, which provides protection against invertebrate predators. The individual shown is a female, and is carrying a single egg that is an identical genetic copy of herself.→



← <u>Brachionus</u> is particularly common in nutrient-rich ponds with abundant algae. The two spines at the back end can be spread out when threatened to make the animal effectively too large to be consumed by many invertebrate predators.

Fig. 37c. Rotifers common in the zooplankton of ponds in Chester County.

Rotifer densities were highest in March and July, while abundances of the slower growing Cladocera and Copepoda generally increased during the season (Fig. 38).

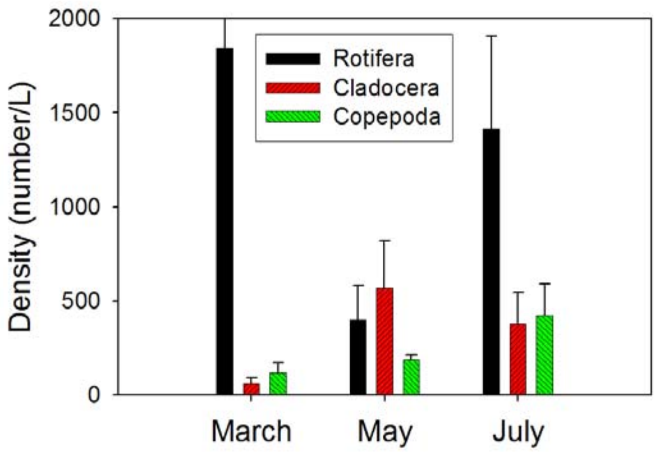


Fig. 38. Mean zooplankton densities in 13 study ponds.

S. Aquatic Plants

Aquatic plants, or macrophytes, are often classified according to their growth form. "Emergent" species such as cattails and sweetflag (*Acorus calamus*) are common in near-shore areas in southeast Pennsylvania, and provide shading, surfaces for aquatic insect emergence and protection against bank erosion. Oxygen generated in photosynthesis by leaves and stems above the water is often translocated to the roots, which must exist in (usually) anoxic sediments via specialized passageways termed "aerenchyma". Most are pollinated by either wind or insects.

"Floating-leaved plants" (e.g., waterlilies) are usually found in quiet water over soft, flocculent sediments. Leaves are often waxy to shed water and are designed to resist damage due to currents and wave action.

"Submersed" species often extend from the sediments into the upper portion of the water column (e.g., water milfoil, *Elodea*), where light levels sustain more rapid growth. Leaves are usually thin and filiform or highly dissected for more rapid gas exchange with the surrounding water.

In contrast to most aquatic plants, which obtain the bulk of their nutrients from the sediments, "free-floating" plants have no attachment to the sediments and obtain their nutrients from the water column. Duckweed (*Lemna*, *Spirodela*) and watermeal (*Wolffia*) may become abundant in smaller, hypereutrophic ponds that are protected from wind action. Examples of these growth forms are shown in Figure 39a-c.

Aquatic plants collectively provide surfaces for periphyton, help to control blooms of excess phytoplankton and metaphyton, provide shelter and feeding sites for invertebrates, and are used as cover and feeding sites by fish. As such, a diverse plant community is important to the overall productivity of a pond. Rooted plants are often light-limited in deeper ponds, relegated to near-shore areas and shaded out by the phytoplankton and metaphyton above them in deeper water. Extensive feeding by ducks or swans may also reduce aquatic plants to very low levels. Loss of plant cover may have a devastating impact on fish populations, and ponds without aquatic plants often experience obnoxious phytoplankton blooms.

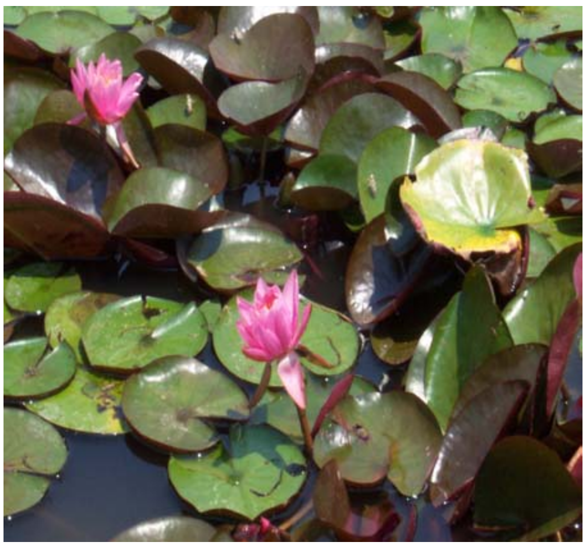
← Purple Loosestrife (<u>Lythrum salicaria</u>), seen at the front left, is an attractive ornamental sold by some plant nurseries in the region. Purple Loosestrife is, however, a highly invasive species originally from Eurasia. It often outcompetes native species and has taken over many wetlands in Chester County.

Soft-stemmed Bulrush (<u>Scirpus</u> <u>validus</u>) is a common inhabitant of sandy sediments both on-shore and in shallow water. Like most emergent plants, Bulrushes have relatively high quantities of lignin and cellulose, needed for physical support out of water. Specialized air passageways, termed aerenchyma, allow passage of gases between the roots and leaves.→

← Cattails (<u>Typha</u>), although they are often stabilize shorelines, may form mono-specific stands that crowd out other species. In the photograph shown of a newly constructed wetland, cattails are just one of a diverse aquatic plant community. A year later, the wetland was entirely dominated by cattails. Cattails may be eradicated by cutting the stems back to below the waterline, which prevents the flow of oxygen to the root systems.

Fig. 39a. Emergent plants typical of ponds in southeast Pennsylvania.

The yellow water lily, or spatterdock (Nuphar), often forms dense stands in quiet areas with soft sediments. Most photosynthesis takes place at the water surface, and light penetration below the floating leaves is minimal. →



← The white water lily (Nymphaea odorata) is typical of quiet, shallow water and fine, organic sediments. Like many aquatic plants, it restricts water movement and thus reduces the resuspension of sediments. Ornamental varieties, such as the one shown here, are available from nurseries that specialize in water gardens.

Floating, non-rooted plants include duckweeds (Lemna, the larger-leaved plants in the photo, and watermeal (Wolffia), with smaller leaves). These species extract nutrients from the water column, and may completely cover small, protected, hypereutrophic ponds, thereby preventing light from penetrating into the pond and eliminating other primary producers.→

Fig. 39b. Rooted, floating-leaved plants, and free-Floating plants common to ponds in Chester County.

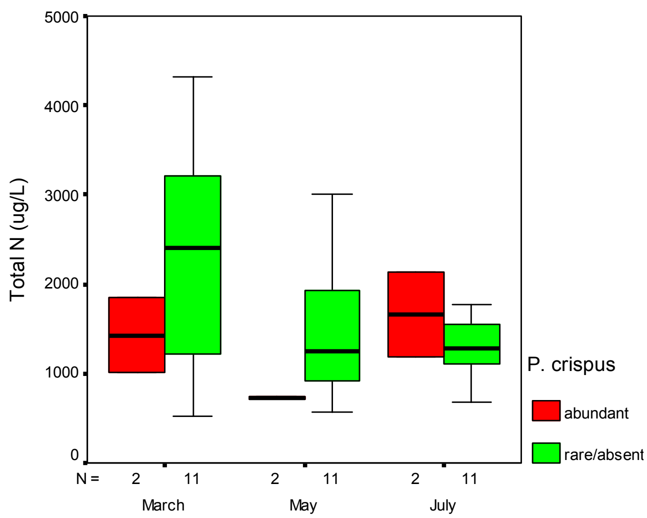
← Curly-leaf Pondweed (Potamogeton crispus) is a non-native species that has become well established in Chester County. Unlike most aquatic plants, it germinates in Fall, and grows rapidly during early Spring, reproducing and decomposing by late June. Its decomposition releases nutrients that may stimulate the growth of algae during summer.

Many native pondweeds (Potamogeton spp.) are also found in ponds of the region. Submersed leaves are typically thin and ribbon-like, while floating leaves may be thicker, waxier and wider. →

← Elodea (Elodea canadensis) is a native plant common to ponds and slow-moving streams in the county. It produces tiny white flowers at the water surface in summer. Elodea can be distinguished from the invasive species Hydrilla verticillata in having 3 leaves per whorl (Hydrilla has 4-8 visibly toothed leaves per whorl).

Fig. 39c. Common submersed plants in ponds of southeast Pennsylvania.

Two ponds in the study were strongly influenced by the presence of the invasive pondweed *Potamogeton crispus* (see Fig. 39c). Unlike most other aquatic plants in southeast Pennsylvania, which grow all summer and die off in the fall, *P. crispus* dies and decomposes in late June (Nichols and Shaw, 1986), presumably releasing its stored nutrients to the water column where they may stimulate phytoplankton growth. As shown in Figure 40, the two ponds with *P. crispus* actually had lower concentrations of both total nitrogen and total phosphorus during March and May when the plants were actively growing. Concentrations of both nutrients increased in the ponds with *P. crispus* relative to other ponds during July, however, likely resulting from its decomposition.



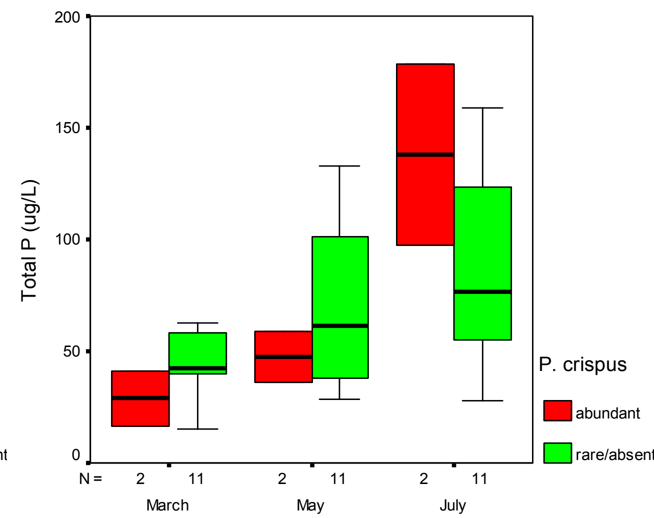


Fig. 40. Comparison of seasonal trends in total nitrogen (left) and total phosphorus (right) in 2 ponds with abundant <u>Potamogeton</u> <u>crispus</u>, compared to values for 11 other ponds in the study. The line through each box is the median; upper and lower bounds of the boxes indicate quartile, and the range of observations are shown as "whiskers".

T. Alternative Stable States

Because they compete for light and nutrients, aquatic plants and phytoplankton tend to exclude one another, and ponds can usually be identified as either having a) turbid water with abundant phytoplankton or b) having clear water with abundant plant growth. These two conditions have often been referred to as “alternative stable states” (Scheffer et al., 1993; Moss et al., 1997; Scheffer, 1998). In general, high nutrient levels favor dominance by phytoplankton over rooted aquatic plants, and aquatic plants tend to predominate in ponds with lower nutrients. As the word “stable” implies, however, ponds with abundant phytoplankton and few plants tend to remain that way even if nutrients are reduced (following the dotted line in Figure 41) Likewise, aquatic plants resist replacement by phytoplankton even with moderate increases in nutrients (solid line in Figure 41).

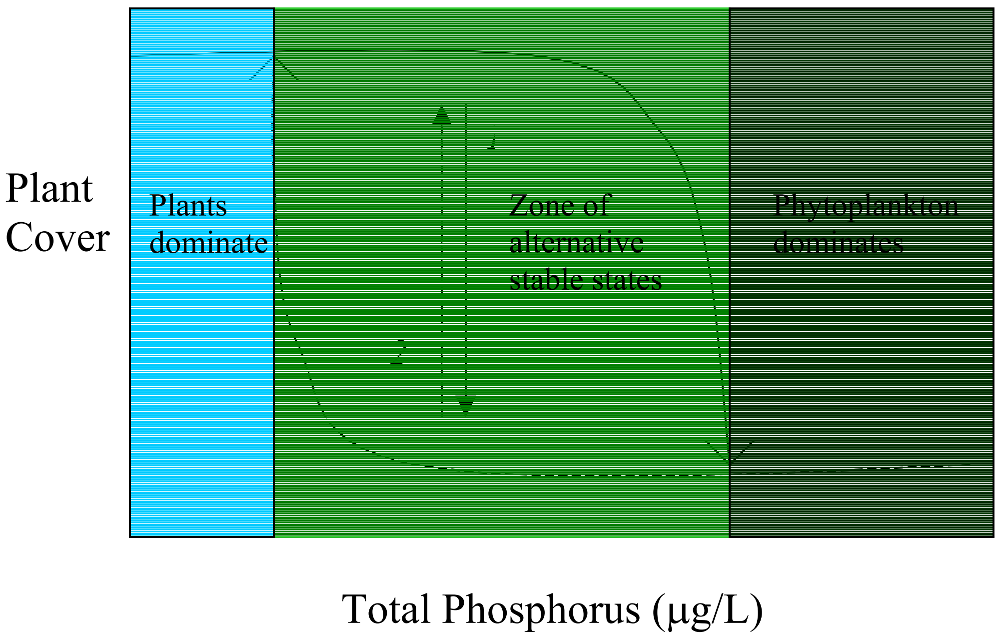


Fig. 41. Trajectories of change in plant abundance with increasing nutrients (solid line) or decreasing nutrients (dashed line).

Dramatic shifts from a plant-dominated state to one dominated by phytoplankton, or vice versa, within the intermediate zone of alternative stable states are nonetheless possible. For example, treatment with herbicides, or introduction of grass carp (see Volume 1 Section K), or even a high-water year providing less light at the pond bottom may suppress plant growth and promote dominance by phytoplankton (vertical line 1). By contrast, a die-off of fish during a severe winter can, by releasing predation pressure on zooplankton, increase grazer control of phytoplankton and thereby increase light penetration enough to promote dominance by aquatic plants (vertical line 2).

In our study 7 ponds supported healthy plant populations, while 4 ponds were dominated by phytoplankton and had few aquatic plants. The two ponds with curly-leaf pondweed showed intermediate characteristics in being dominated by plants in early spring but by phytoplankton later in summer.

U. Conclusions

Volume 2 of this report described the limnology and nutrient ecology of ponds in Chester County, drawing on our study of 13 ponds during spring and summer 2002. We believe the study ponds to be representative in size, watershed influences and trophic state of the large population of ponds from which they were selected. The following major conclusions are drawn from our study:

1) All 13 ponds were classified as either eutrophic or hypereutrophic based on Carlson's (1977) Trophic State Index, indicating that most ponds in the county not only experience high levels of primary productivity but also potential management problems related to the excessive growth of primary producers.

2) Concentrations of total N declined in 8 of the 13 ponds between March and July, while total P increased in 9 ponds. The pattern was not completely consistent, but suggested probable increases in denitrification and release of PO_4^{3-} at the sediment surface later in the growing season.

3) Based on ratios of [total N/total P], phosphorus concentrations in the water column likely limited algal growth in early spring, and was likely limiting or co-limiting (with N) later in the growing season. Reducing the entry of phosphorus from the watershed and reducing phosphorus regeneration from the sediments are thus reasonable management approaches for controlling excessive plant or algal growth.

4) Based on a simple nutrient budget model, predicted phosphorus concentrations underestimated actual phosphorus concentrations in 8 ponds and overestimated phosphorus concentrations in 5 ponds. The degree of fit provided by the nutrient budget model was highly variable among ponds, but likely reflected differences in pond

morphology and internal nutrient cycling (e.g., influences of metaphyton and aquatic plants, periodic additional internal P regeneration from the shallow sediments).

5) Phytoplankton abundance was closely and positively related to total P concentration, as is typical of larger lakes, and phytoplankton abundance in turn strongly influenced light penetration (increased phytoplankton biomass was associated with decreased light penetration).

6) Metaphyton abundance was less predictably related to ambient concentrations of P in the water column, and may reflect growing conditions at the sediment surface where the clouds of metaphyton algae are presumed to originate.

7) Some ponds were clearly dominated by phytoplankton, while others were dominated by rooted aquatic plants, in general agreement with the concept of alternative stable states. The influence of metaphyton algae, which are initially associated with the sediments but later become planktonic, on the alternative-stable-states model remains poorly understood . The invasive aquatic plant *Potamogeton crispus* (curly-leaf pondweed), by translocating nutrients from the sediments and releasing them to the water column in late June-early July, may also seasonally shift some ponds from dominance by rooted aquatic plants to dominance by phytoplankton.

Units of Measure

Metric-to-English Conversions

Flow (Discharge)
1 Liter (L) /second equals 0.0353 cubic feet/second
1 Liter/second equals 2.12 cubic feet/minute
1 Liter/second equals 0.264 gallons/second
1 Liter/second equals 15.85 gallons/minute

Volume (V)
1 cubic meter (m^3) equals 35.3147 cubic feet

surface area (A_s)
1 hectare (ha) equals 2.47104 acres
1 hectare equals 107,639 square feet

Length
1 meter (m) equals 3.28084 feet
1 kilometer equals 0.621 miles

Literature Cited

Anderson, J.N., 2004. Watershed effects on nutrients in shallow ponds. Masters Thesis, West Chester University.

Bronmark, C., and L.-A. Hansson. 1998. The Biology of Lakes and Ponds. Oxford University Press, New York, NY. 216p.

Carlson, R.E. 1977. A trophic state index for lakes. Limnology and Oceanography 22:361-369.

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

Dodds, W.K. 2003. Misuse if inorganic N and soluble reactive P concentrations to indicate nutrient status of surface waters. Journal of the North American Benthological Society 22:171-181.

Downing, J.A., and E. McCauley. 1992. The nitrogen:phosphorus relationship in lakes. Limnology and Oceanography 37:936-945.

Lembi, C.A. 1988. Algae as Weeds: Economic Impact, Ecology and Management Alternatives. Pp. 455-481 in C.A. Lembi and J.R. Waaland (eds.). Algae and Human Affairs. Cambridge University Press. New York. 590p.

Moss, B., J. Stansfield, K. Irvine, M. Perrow, and G. Phillips. 1996. Progressive restoration of a shallow lake: a 12-year experiment in isolation, sediment removal and biomanipulation. Journal of Applied Ecology 33:71-86.

Moss, B., Madgwick, J., and G. Phillips. 1997. A guide to the restoration of nutrient-enriched shallow lakes. Broads Authority, Norwich, Norfolk, GB. 179p.

Nichols, S.A. and B.H. Shaw. 1986. Ecological life histories of the three aquatic nuisance plants, *Myriophyllum spicatum*, *Potamogeton crispus* and *Elodea canadensis*. Hydrobiologia 131:3-21.

Nixdorf, B., and R. Deneke. 1997. Why 'very shallow' lakes are more successful opposing reduced nutrient loads. Hydrobiologia 342/343: 269-284.

Perrow, M.R., Moss, B., and J. Stansfield. 1994. Trophic interactions in a shallow lake following a reduction in nutrient loading: a long-term study. Hydrobiologia 275/276:43-52.

Portielje, R., and D.T. Van der Molen. 1999. Relationships between eutrophication variables: from nutrient loading to transparency. Hydrobiologia 408/409: 375-387.

Reckhow, K.H., Beaulac, M.N., and J.T. Simpson. 1980. Modeling phosphorus loading and lake response under uncertainty: a manual and compilation or export coefficients. EPA440/5-80-011.

Reckhow, K.H., and S.C. Chapra. 1983. Engineering approaches for lake management. Vol. 1: Data analysis and empirical modeling. Butterworth Publishers, Boston, 340p.

Redfield, A.C. 1958. The biological control of chemical factors in the environment. American Scientist 46:205-221.

Rooney, N., J. Kalff, and C. Habel. 2003. The role of submerged macrophyte beds in phosphorus and sediment accumulation in Lake Memphremagog, Quebec, Canada. Limnology and Oceanography 48:1927-1937.

Scheffer, M. 1998. Ecology of Shallow Lakes. Kluwer Academic Publishers. 357p.

Scheffer, M, Hosper, S.H., Meijer, M.-L., Moss, B., and E. Jeppesen. 1993. Alternative equilibria in shallow lakes. Trends in Ecology and Evolution 8:275-279.

Sondergaard, M., Jensen, J.P., and E. Jeppesen. 1999. Internal phosphorus loading in shallow Danish lakes. Hydrobiologia 408/409: 145-152.

Sondergaard, M., E. Jeppesen, and J.P. Jensen. 2003. Internal phosphorous loading and the resilience of Danish lakes. Lakeline 23:17-20.