The Wilderness Conservancy at Mountain Lake
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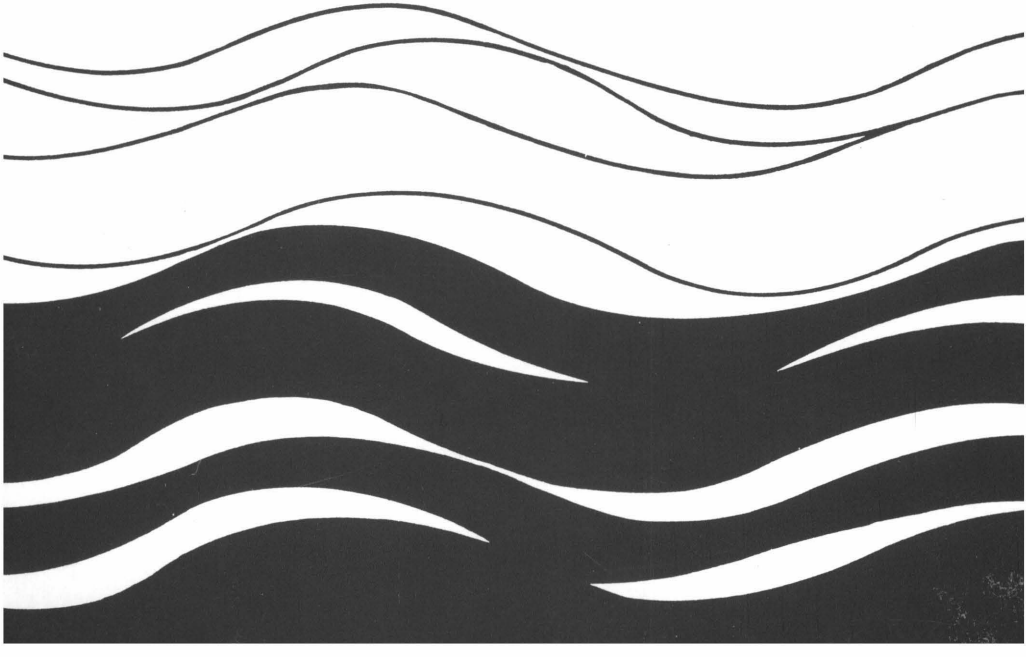

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## The Wilderness Conservancy at Mountain Lake

The Wilderness Conservancy at Mountain Lake is a non-profit organization established by Mary Moody Northen, Inc., a private foundation, to manage the Mountain Lake property and run environmental education programs. The property covers 2600 acres of forested land surrounding Mountain Lake, one of only two natural lakes in the state of Virginia. The mission of the Wilderness Conservancy at Mountain Lake is three-fold: (1) to conserve the natural beauty and ecological integrity of the Mountain Lake property and its natural resources; (2) to promote an understanding of natural and human ecology through educational programs; and (3) to encourage visits to, and use of, the property for recreation, experiences with nature, and personal and professional development. Activities connected to the mission emphasize collaborative efforts between the Conservancy and other organizations.

One of many approaches to achieving the educational goal of the Wilderness Conservancy at Mountain Lake is the publication of Occasional Papers. Occasional Paper No. 1 is a scientific acccount of research on Mountain Lake itself. Mary Moody Northen, Inc. is pleased to share the cost of production of this bulletin with the Virginia Water Resources Research Center.

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## Abstract

Mountain Lake, Giles County, is one of only two natural lakes in Virginia and is the only natural lake in the unglaciated southern Appalachians. Since its discovery by Gist in 1751, the lake has been considered relatively clean and unspoiled. Recent data on nitrate-nitrogen, orthophosphate-phosphorus, hypolimnetic oxygen deficit, and the phytoplankton community suggest that the lake may be shifting toward a more eutrophic state. This paper reviews the existing data for Mountain Lake, then examines various trophic state indices in an attempt to establish whether the Mountain Lake ecosystem may be undergoing eutrophication.

Keywords: Eutrophication, Mountain Lake, nitrogen, phosphorus, oxygen deficits, primary productivity.

# 1 Introduction

## 1.1 Eutrophication

The terms oligo-, meso-, and eu-trophy were incorporated into limnology by Naumann in the early 1900s (Hutchinson, 1969). Nutrient composition within the water column provides the theoretical basis for these terms, however, in practice, trophic state has been recognized by the poorness or richness of the phytoplankton community (Hutchinson, 1969). Since biological productivity is the key factor in trophic typology (Sullivan and Carpenter, 1982), eutrophication may be defined simply as the increase in productivity of an aquatic ecosystem. Many factors may lead to eutrophication, both natural and anthropogenic (Figure 1). In addition, eutrophication is not considered to be an entirely reversible process (Cairns et al., 1972) (Figure 2). Such incomplete reversibility, in part, led to a growing concern over inland water eutrophication in the late 1960s. Consequently, a cooperative program to monitor inland waters for eutrophication control by the Organization for Economic Cooperation and Development (OECD) was established in the early 1970s (Maloney, 1979).

Two goals of this program were to understand 1) the extent of eutrophication and 2) the processes involved. To accomplish these goals, more precise definitions of trophic state were needed. Selected indices and the authorities who proposed them are listed in Table 1. From this information, two schools of thought emerged on the concept of what defines trophic state: 1) the nutrient concentrations entering as well as within the aquatic ecosystem or 2) the biological structure, including standing crop and productivity within the aquatic ecosystem. These contrasting ideas reflect both the theoretical and practical determinations of trophic state first elaborated by Naumann (1927).

In this paper, indices from both schools of thought are utilized in an effort to describe as completely as possible the current conditions and changes which have taken place in Mountain Lake. Availability of continuous year-round data collected from 1985 to 1990 provides a beginning for

assessing whether Mountain Lake may be shifting toward a more eutrophic state. Such a eutrophication process is of great interest, because although it is generally recognized as a common successional feature of surface waters, relatively few lakes have been traced through this process, and none of these few have had features even remotely similar to Mountain Lake. Therefore, any evaluation of Mountain Lake should prove useful in designing future research on this and other aquatic ecosystems.

## 1.2 Morphometry and Physiography

Mountain Lake (elevation 1180m) is an alpine, oligotrophic lake located near the top of Salt Pond Mountain in the Allegheny range of the southern Appalachians, southwest Virginia (37° 21' 56" N, 80° 31' 39" W)(Figure 3). The lake is ovoid in shape, with its long axis directed southwest-to-northeast and having the following approximate dimensions: maximum length 900 m, width 250 m, and depth 31 m (mean depth 9.7 m), surface area 189,000 $m^2$, and volume 1,850,000 $m^3$ (Roth and Neff, 1964) (Figure 4). The lake was formed through the damming of a small mountain stream by talus (slide rock) and has a tripartite basin consisting of Ordovician Martinsburg shale, Ordovician Juniata sandstone, and Silurian Tuscarora sandstone (Parker et al., 1975). The rocks of these formations are low in nutrients required by aquatic life, e.g., nitrogen and phosphorus, and thus have influenced the historically oligotrophic condition of the lake.

## 1.3 Lake History

In addition to its geology, this ~2000 year old aquatic ecosystem (Marland, 1967) has remained relatively pristine as a result of few human perturbations, well preserved natural vegetation within the small drainage basin (~1 $km^2$), short hydraulic retention time (~1 year), and restricted recreational use of the lake and surrounding land (Parson and Parker, 1989a). For several decades the restricted use of the surrounding land has been regulated by the policies of Mountain Lake Hotel and more recently by Mary Moody Northen, Inc., a private foundation. The foundation owns and operates the 66 room hotel and 19 cottages. The forested

area (maple, beech, oak, birch, and hemlock) on the property around the lake was designated a wildlife sanctuary in 1983 (Figure 5). As of January 1992 these lands have been classified as a wilderness conservancy, thus further protecting the grounds from possible future anthropogenic perturbations. Some of the previous perturbations in the lake's drainage basin have been reported by Parson and Parker (1989a) and include:

1) 19th and early 20th century grazing of sheep and cattle;
2) construction of Rt. 613, the current hotel, and its associated cottages in the 1930s;
3) routine salting of Rt. 613 in the winter months since 1940;
4) loss of the American chestnut, *Castanea dentata*, trees due to blight in the 1920s and 30s;
5) leakage of cottage septic tanks in the summer months prior to the installation of a new sewage treatment system;
6) occasional stocking of fish in the lake and the addition of tons of sand at the south end;
7) input of phosphate from a coin-operated laundromat in 1984; and
8) lowering of the lake to construct pilings for the boathouse in the mid 1980s.

However, none of these activities have been cited as causing permanent trophic changes within the lake. Since Parson and Parker's report in 1989, some additional human impacts within the lake basin have been noted:

9) changing from a May-to-October to a year-round hotel operation from 1986-1992, then from 1992, only open on weekends and for conferences in the winter months;
10) activities from the filming of the movie "Dirty Dancing" in September 1986;
11) partial draining of the lake to repair the plumbing of the lake-shore cottage at the north end in 1989;
12) excavation, removal, and filling of old septic tanks in June 1989;
13) aerial spraying of ammonia- and phosphate-rich substances throughout the lake basin as part of the joint USDA/US Forest Service gypsy moth experiment in summer 1989; and

14) razing an old cottage and erecting a new cottage at the southern end in summer 1993.

## 2 Materials and Methods

For this investigation previously published physical, chemical, and biological data relating to Mountain Lake were assembled (Table 2). Additional data unpublished and available from Parker (1988-1990) and data from our current investigations since November 1992 were included. Methods used for the current investigation were described earlier by Parson and Parker (1989a) with the exception of inductively coupled plasma emission analyses for trace metals in the water column which began in November 1992. An updated list of these methods occurs in Table 3. Figures 6-8 elaborate important sampling methods, field instruments, and experimental techiques refered to in Table 3. Techniques and formulae to evaluate trophic states and eutrophication also were assembled. After compiling these data, various trophic state indices were applied in an attempt to assess the changes in Mountain Lake which date back to the earlier, more limited investigations listed in Table 2.

## 3 Results and Discussion

### 3.1 pH, Alkalinity, and Hardness

The pH, alkalinity, and hardness of Mountain Lake has remained unchanged on average, albeit variable since the earliest investigations. The pH has ranged from ~6.5 to ~8.0, the alkalinity has remained consistently at 7-10 mg/l $CaCO_3$ equivalents, and the hardness generally has been 20-40 mg/l $CaCO_3$ equivalents with occasional values as high as 80 mg/l in the winter months. Higher values in the winter months probably are a result of the natural decay and release of calcium from leaves of deciduous trees and shrubs in the watershed (Parker, unpublished). The pH fluctuation around neutrality, low alkalinity, and low hardness all reveal the naturally poor buffering capacity of the water.

## 3.2 Temperature

The thermal characteristics of the water column in Mountain Lake also have not changed significantly over the years. The lake is normally dimictic, mixing completely once in the fall and again in the spring, with summer thermal stratification usually developing from late April to November. Surface temperatures approach a maximum of 25°C in August, and a thermocline region between 6 and 10 m develops from May through October. The hypolimnion depth can be estimated by thermal data and begins at approximately 14 m, according to Roth and Neff (1964). This depth is consistently reported throughout the literature (Obeng-Asamoa, 1971; VanBrunt, 1984; Parson, 1988; and Parker et al., 1991) and was considered to be the metalimnion-hypolimnion boundary for the purposes of this paper.

## 3.3 Major Nutrients

Tables 4-6 summarize data on nitrate-nitrogen, ammonia-nitrogen, and orthophosphate-phosphorus, respectively, and Figures 9-11 present the annual means for these nutrients. Figure 9 shows that the nitrate-nitrogen concentration has increased dramatically since 1987. This increase may be important, because nitrate-nitrogen is a key limiting nutrient in some aquatic environments (Wetzel, 1983). Although not all organisms utilize nitrate as a nitrogen source (Cairns et al., 1972; Parson and Parker, 1993), its increase may contribute to eutrophication in this lake. Moreover, nitrate-nitrogen has become the most abundant form of inorganic nitrogen in the lake since 1988, which may eventually induce further changes in the phytoplankton community (Parson and Parker, 1993). Potential sources of this nutrient for Mountain Lake are precipitation, runoff, and springs, all of which can have nitrates derived from natural or anthropogenic sources. Nitrogen fixation as a significant nitrogen source in this aquatic ecosystem was ruled out by Parson and Parker (1993). Precipitation data available from 1978-1991 (Boris Chevone, National Atmospheric Deposition Study, Virginia Tech) does not indicate any recent increase in nitrate; thus, the likely sources of increased nitrate are from runoff and

springs, although the actual cause of the nitrate increase remains uncertain (Parson and Parker, 1993).

Ammonia-nitrogen (Figure 10) has fluctuated somewhat over the years according to the available data. Since 1985 values have remained relatively constant, near 0.03 mg/l. An exception occurred in 1990 when an annual mean of 0.14 mg/l was observed. This high value was in part due to an extremely high concentration measured in July (0.80 mg/l), for which no error in the analytical procedure could be found. The relatively non-fluctuating mean annual ammonia-nitrogen levels since 1985 are encouraging since ammonia-nitrogen is the preferred source of nitrogen for many phytoplankton (Wetzel, 1983; Parson and Parker, 1993). Although the annual mean concentrations of this compound are similar, the concentrations of ammonia-nitrogen in the hypolimnion during summer thermal stratification show an increase since 1987 (Parson, 1988; Parker, unpublished). This increase in ammonia-nitrogen may come from increased bacterial decomposition of organic matter, which is one indicator of increased lake productivity (Wetzel, 1983). Small increases in this form of nitrogen might cause more rapid eutrophication to take place than for similar changes in nitrate-nitrogen, because ammonia-nitrogen requires less metabolic energy for utilization, and where there is limited energy, more growth has been shown to occur with ammonia as the nitrogen source (Cairns et al., 1972). Therefore, ammonia-nitrogen deserves regular monitoring in future investigations.

Variations in the annual mean orthophosphate-phosphorus concentration are shown in Figure 11. The high values of 1970-1971 have been discounted because the analytical technique used by Obeng-Asamoa (1971) was different and probably in error. As with nitrate-nitrogen, ortho-phosphate-phosphorus showed an increase since 1985 with large increases in 1989 and 1990. The increased concentration of phosphorus in June 1989 more or less coincided in time with the excavation and filling of the old septic systems associated with the hotel's lakefront cottages. Appreciable visible foam on the lake occurred from June through September 1989. Also, the USDA/US Forest Service began a field trial spray to control the gypsy moth which

included airplanes spraying throughout the watershed and over the lake during this time. The spray material used for chemical adhesion to the trees was analyzed and found to be extremely high in orthophosphorus and ammonium (Parker, unpublished). Not only were these unusual activities taking place at and around the lake, but 1989 was an unusually wet year, resulting in increased runoff and groundwater (spring) input, which may have washed additional materials into the lake. As will be seen in subsequent tables, the increase in orthophosphate-phosphorus in 1989 was accompanied by increases in phytoplankton primary productivity and chlorophyll *a*, with reduced transparency in July and August based on both Secchi disc and submersible quantum light sensors. However, the increased levels of ortho-phosphate-phosphorus did extend into 1990, but were not accompanied by an increase in productivity, high chlorophyll *a*, or low transparency despite the concurrently high inorganic nitrogen. Some other factor, such as a micronutrient, e.g., iron may have become limiting. Unfortunately, micronutrient data have not been obtained for Mountain Lake prior to 1992. It is also possible that the pesticide used for the gypsy moth control was organophosphorus based, which is known to kill aquatic herbivores at low concentrations (Shapiro, 1980). No data on zooplankton were collected. However, if reduction in the planktonic herbivores did take place, this might have explained the increase in phytoplankton density (Shapiro, 1980). In the most recent data collected from November 1992 to May 1993, the orthophosphate-phosphorus levels apparently have returned to approximately the levels reported from 1985 to 1988. Regular monitoring of this nutrient should be continued in future years due to its potential for stimulating an increase in the trophic state of the lake.

Dissolved silica ($SiO_2$) also has been measured routinely in Mountain Lake by investigators, with concentrations ranging from 0.13 to 3.59 mg/l. Levels of this required nutrient for diatoms often appear limiting (Parker, unpublished), which may explain the paucity of diatoms in the plankton community during winter and spring when a dominance of this group normally would be expected (Wetzel, 1983).

We are not certain that inorganic nitrogen, orthophosphorus, and dissolved silica represent the only nutrients potentially limiting growth of the algae and other organisms in Mountain Lake. Inadequate data on iron and other trace elements have been collected in the past, and iron is known to be a limiting nutrient in a number of freshwater and marine ecosystems (Hooper, 1956; Silker, 1964; Cole, 1983; Chavez et al., 1991; Duce and Tindale, 1991; Martin et al., 1991; and Price et al. 1991).

### 3.4 Phytoplankton Primary Productivity

Table 7 shows primary productivity of the phytoplankton of Mountain Lake, expressed as mean monthly observations from five depths (0.1, 1, 6, 10, and 17 m) and also as annual means in mg $C/m^2/day$. Data for phytoplankton primary productivity are very sparse prior to 1985. However, comparisons among annual means since 1985 show no great increase in productivity with the exception of 1989 which will be discussed below. As noted by Wetzel (1983), use of the annual mean productivity provides a better assessment of total lake productivity. Lakes with short growing seasons can have high productivities of short duration, while remaining unproductive over the rest of the year. These types of lakes are truly oligotrophic, although temporarily exhibiting eutrophic phytoplankton productivities. The limited primary productivity data for Mountain Lake prior to 1985 show no overall increase in phytoplankton productivity until possibly 1973. Values in 1973 reported by Parker (1976) included extracellular products which accounted for an increase of $\leq 30\%$. After correction for this extra amount not determined by other studies, the 1973 values are still higher. Since 1985, the productivity increase in 1989 is apparent and can be seen in the July and August data, as mentioned above. This increase in productivity may have been induced by increases of phosphorus and nitrogen leaching from the excavated septic systems.

Figure 12 illustrates fecal coliform data reported for 1989 and supports the septic tank leachate theory. The old septic systems would be the only practical source for high fecal coliforms in Mountain Lake. An increase in fecal coliforms was observed in July, coinciding well with the excavation

and filling of the old septic systems. The return to more normal conditions in 1992-1993 for ammonia-nitrogen and orthophosphate-phosphorus is an expected outcome of leachate reduction in the old septic fields. These systems are no longer used. Since 1989, a secondary wastewater treatment plant has processed the hotel and cottage waste. The effluent from this plant is piped into the adjacent watershed west of Mountain Lake where it is sprayed on the forest understory, located on deep virgin soils (Anderson and Associates, unpublished).

### 3.5 Phytoplankton Chlorophyll *a*

Table 8 shows chlorophyll *a* concentrations for Mountain Lake. Annual mean values for five select depths (0.1, 1, 6, 10, and 17 m), for 1-m depth, and mean values at 1 m depth from May-October are presented. Carlson (1977) suggests using the growing season surface chlorophyll *a* concentration in assessing his trophic state index (Table 1). However under this scheme, lakes such as Mountain Lake, which have relatively short growing seasons, may be misrepresented. During a short growing season, accelerated production can occur relative to the annual production, thus leading to a misrepresention of the true nature of the system (Wetzel, 1983). Therefore, for the purposes of this paper, the annual mean concentrations from 1-m depth have been used to assess the trophic state in all subsequent calculations. Chlorophyll *a* concentrations vary widely from year-to-year in Mountain Lake, ranging from 1.43 to 4.71 $mg/m^3$ (Table 8). Furthermore, the chlorophyll *a* values do not correlate well with the primary productivity data for 1985. In 1985 an annual mean chlorophyll *a* concentration of 4.36 $mg/m^3$ was reported, the second highest value and only 0.25 $mg/m^3$ less than reported in 1989. However, the primary productivity value for 1985 was the fourth highest value reported, approximately 590 mg $C/m^2/day$ lower than reported in 1989. This wide variation in the data for chlorophyll *a* and primary productivity only occurred in 1985. The lowest mean annual chlorophyll *a* concentration was observed in 1990, when both orthophosphate-phosphorus and inorganic nitrogen concentrations were elevated. No investigations of trace metals were conducted

during this period, and it is possible that in the preceeding highly productive, wet year, 1989, an essential trace metal, e.g., iron or molybdenum, may have been exhausted to the point of not being restored in 1990. This phenomenon could have occurred either through uptake and sedimentation of phytoplankton cells or coprecipitation and adsorption on particulate matter washed into the lake (Goldman, 1972; Wetzel, 1983).

### 3.6 Water Transparency

Secchi disk transparency values are shown in Table 9. Only slight variations occur in the mean annual Secchi disk transparency, which seem to correspond to the variations in chlorophyll *a* discussed above. A low annual mean of 4.76 m in 1989 corresponds to the increased mean productivity. Secchi disk transparencies from the summers of 1932 (Hutchinson and Pickford) and 1937 (Coker and Hayes) and those of 1985-1988 do not indicate sufficient change to suggest increases in plankton biomass, i.e., eutrophication, over the 60-year period. However, Roth and Neff (1964) caution that Secchi depth values were not correlated to other lake characteristics.

### 3.7 Dissolved Oxygen

Depletion of the oxygen concentration in the hypolimnion during summer thermal stratification can be another indication of lake productivity (Hutchinson, 1957). Representative oxygen profiles for Mountain Lake are shown in Figure 13. Since 1971, an increase in hypolimnetic oxygen depletion has occurred. In fact, the areal hypolimnetic oxygen deficit has increased about threefold since 1962 and doubled since 1970 (Table 10). The depletion of hypolimnetic oxygen causes great concern. As oxygen concentrations approach 0 mg/l near the sediment water interface, this lowering of the redox potential facilitates reduction of iron and other metals, increasing their solubility, as well as enhancing the release of phosphates and ammonia (Wetzel, 1983). When these dissolved substances reach the photic zone, e.g., during mixing, the increased nutrient concentration can stimulate phyto-plankton growth which would, in turn, create greater

oxygen deficits through greater productivity and subsequent bacterial degradation. This cycle is self-perpetuating and can lead to a rapid increase in the rate of eutrophication of a lake.

Whereas the epilimnion and metalimnion of Mountain Lake remain fully saturated or even somewhat supersaturated with oxygen (Parker et al., 1991), the decrease in the hypolimnetic oxygen concentration may be the single most detrimental change observed in Mountain Lake. Hutchinson and Pickford (1932) showed only a 30% reduction in oxygen saturation at 20 m. Furthermore, they report, "The bottom fauna of the lake is apparently very meagre, no chironomids or other forms could be found in a can full of mud from 20 m., but four ostracods occurred in the bottom plankton sample. It is clear that this poverty is not due to oxygen deficiency." However, Roth and Neff (1964) observed large numbers of chironomids in the profundal zone of Mountain Lake, although the hypolimnetic oxygen deficit was well within the oligotrophic range. Additionally, typical oligotrophic fauna were reported to be either restricted to the littoral and sublittoral zones or to move to these zones in midsummer. These observations disagree with Thienemann's 1913 classification of lakes based on benthic fauna (Hutchinson, 1969). It is possible that Hutchinson and Pickford (1932) through inadequate sampling techniques overlooked chironomid larvae which were present. However, this also may be a significant early indicator of the shifting of Mountain Lake's trophic status. Based on the limited data, advancement in the hypolimnetic oxygen deficit occurred between 1971 and 1985, a period when few studies were conducted at the lake. Since 1985, the oxygen deficit has developed annually in late summer, with the muds at 20-22 m becoming almost anoxic. Recent surveys demonstrate that chironomid larvae still occupy these muds when the late summer oxygen deficit approaches the anoxic danger point (Parker, unpublished). This depth of 20-22 m in Mountain Lake (Figure 4) comprises a sizeable area and volume (9.5% and 4.9% of the total, respectively) which, if impacted by anaerobiosis, could produce major changes.

During the period of summer thermal stratification, dissolved oxygen often exceeds saturation levels in Mountain Lake's metalimnion. This phenomenon was first examined by Roth and Neff (1964). Subsequently Dubay and Simmons (1979) observed the greater biomass of the attached alga, *Nitella*, located within the high oxygen layer of the metalimnion and suggested that *Nitella*'s photosynthesis might be responsible. However, Parker et al. (1991) conducted extensive photosynthesis measurements on phytoplankton and *N. megacarpa*'s young, largely unepiphytized thalli. Their data and calculations indicated that phytoplankton photosynthesis was about 20X that of *Nitella*, and that phytoplankton in the metalimnion were more likely responsible for the oxygen supersaturation.

### 3.8 Phytoplankton Taxa and Numbers

Various methods of phytoplankton collection have been reported from Mountain Lake prior to 1985 (Parson and Parker, 1989a). Due to the diversity of collection methods, direct comparisons of the phytoplankton community before 1985 is of doubtful worth. However, since 1985 Utermohl settling chambers have been used for enumeration and identification of the phytoplankton community, yielding excellent comparative data. Our current investigations have revealed that even differences in mesh size (50 *u*m vs. 100 *u*m) of a plankton net can drastically alter the observed cell density as well as the dominant species in this lake. Even so, comparison of pre- and post-1985 data does reveal a significant change in the composition of the phytoplankton community (Parson and Parker, 1989b). The community is dominated by green algae, according to all investigators. However, 60% of the 163 phytoplankton identified from 1985-1987 were new reports for Mountain Lake (Parson and Parker, 1989a). Even with the dissimiliar methods of collection, a remarkable difference in the phytoplankton community [taking place between 1971 and 1985] is apparent, and corresponds well with the timing of the increase in the hypolimnetic oxygen deficit. Whether the hypolimnetic oxygen deficit and the community shift are related, i.e., cause and effect, we can only speculate.

Since 1985 the phytoplankton community has remained relatively stable. Winter and spring flora were dominated by *Cryptomonas* in 1992-1993, which is similar to the community assessments from 1985-1990 (Parson and Parker, 1989a; Parker, unpublished). *Dinobryon* has been an important late summer species reported since 1985. Summer flora have been dominated by green algae including *Oocystis, Botryococcus, Gloeocystis,* and *Sphaerocystis,* all of which indicate soft waters and low productivity (Hutchinson, 1967). However, the increase in the number of cyanophycean algae in the late summer and fall since 1985 suggests deterioration (Parson and Parker, 1989a). Some phytoplankton algae and zooplankton common during spring are illustrated in Figures 14-17.

Cell densities from 1985 through 1990 are shown in Figure 18. Since 1985, cell densities have been calculated from settling chamber techniques described by Parson and Parker (1989b). It is clear that cell densities increased dramatically in 1988-1989. However, the increases in phytoplankton density of 1988 were not represented by Secchi disk transparencies, chlorophyll *a*, or primary productivity values, while those of 1989 were. No error is suspected in the cell density analyses reported from 1988-1990; however, caution must be taken when well accepted correlations such as cell density and chlorophyll *a* concentration are not obvious. In 1990 the cell densities were comparable to those observed in 1985-1987 and correlate well with other data. The increase in cell density over those reported in 1970-1971 by Obeng-Asamoa (1971), as well as the shift in the phytoplankton community stated previously, correspond well with the increasing hypolimnetic oxygen deficit. However, Obeng-Asamoa's plankton tow method may have contributed to the cell density differences observed; from a maximum of 62 cells/ml in 1970-1971 to an average of ~400 cells/ml in 1985-1987 (Parson 1988). Dubay and Simmons (1979) report summer cell densities of 41 to 15,338 cells/ml from 1973-1976 using a similar collection method as Parson (1988).

## 3.9 Attached Macrophyte Community

Trophic state indices largely have used physical, chemical, and phytoplankton parameters to assess lakes. However, it has been recognized that the biomass of attached vegetation can be important in competing with phytoplankton (Dubay and Simmons, 1979; Wetzel, 1983). The rooted vegetation can acquire nutrients bound in the sediments under aerobic conditions and do not rely totally on the limited nutrient sources in the water column as do the phytoplankton. Dubay and Simmons (1979) reported that the metalimnetic oxygen maximum observed in Mountain Lake between 6 and 10 m was most closely related to the macrophyte community of which >90% was one species of *Nitella*. According to Dubay and Simmons (1979), a reduction in the *Nitella* beds would cause a trophic state shift of Mountain Lake toward eutrophy and dominance by the phytoplankton community. Parker et al. (1991) have reported an apparent significant reduction in biomass of the dominant macrophyte, *Nitella macrocarpa*, in Mountain Lake since the first, earlier studies of Dubay and Simmons (1979). They reported a reduction of approximately 10 fold in ash free dry weight ($g/m^2$) from 1973 to 1990. These ash free dry weight values by Dubay and Simmons (1979) and Parker et al. (1991) include *Nitella* and the epiphytes (mostly diatoms) which colonize the older thalli surfaces. We are not certain whether this reduced *Nitella* biomass reported by Parker et al. (1991) is permanent or indicates a trend toward some change in Mountain Lake. However, it appears that the oxygen profile and overall lake productivity is currently under phytoplankton control.

## 3.10 Acid Rain

Whereas acid rain is not directly involved in eutrophication, it is a variable that can influence nutrients, primary productivity, aquatic community composition, and the trophic state of lakes. The relatively low alkalinity and hardness values for Mountain Lake make the potential impact of acid rain a major concern. Two ways to assess acid rain impacts are 1) to look for changes in sulfate anion levels over time and 2) to examine Schindler's (1988) acid rain index over time.

Under the first assessment method, increases in sulfate anion concentrations would be expected with increased impacts of acid rain. Sulfate data for Mountain Lake are shown in Table 11. It is not apparent from these data that acid rain has had any significant impact on this aquatic ecosystem. Although sulfate levels did increase between 1971 and 1985 they have decreased substantially since 1985. However, the sulfate anion levels reported are quite variable year-to-year and even month-to-month, making any firm conclusions difficult.

Under the second assessment method, Schindler's acid rain index, where alkalinity is divided by the $Ca^{++}$ and $Mg^{++}$ cation concentration, index values are expected to decrease with increased impacts from acid rain. According to Shindler, index values < 0.2 indicate sensitive freshwater ecosystems impacted heavily by acid rain and index values between 0.6 and 1.1 are generally indicative of pristine freshwater ecosystems. Table 12 shows the calculated index values for Mountain Lake. These data reveal higher values for the acid rain index since 1985, thus suggesting that Mountain Lake if impacted between 1971 and 1985 as indicated by the sulfate anion concentrations is recovering albeit, only slightly. Both the decrease in the sulfate anion concentration and the increase in the acid rain index values are encouraging even though the average pH of the precipitation less than 3 kilometers from the lake has remained relatively constant for the past 10 years at about 4.5 (Boris Chevone, National Atmospheric Deposition Study, Virginia Polytechnic Institute and State University). Thus, although some acid precipitation currently falls on Mountain Lake, apparently the quantities do not reach levels that override its natural buffering capacity.

### 3.11 Trophic State Indices

Several trophic state indices have been developed since the early 1970s to better quantify and compare aquatic ecosystems. Some indices are based on nutrient composition, others use biota, and still others use a combination of the two. Tables 1, 13, 14, and 15 list several proposed trophic state evaluations, including all the indices used for trophic state evaluation in this paper. Practically speaking, no

single index accurately assesses all systems (Maloney, 1979). However, evaluations using several indices on the same aquatic ecosystem over time should indicate any shifting of trophic status within that system. Evaluations of trophic state are not always calculated in absolute terms, but instead compare observed ranges of a particular parameter and its associated trophic state. Examples of these are given in Tables 13-15.

Table 16 is a compilation of available trophic state indices and values calculated for the data available on Mountain Lake. Unfortunately, many of the trophic state indices could not be utilized, because the necessary parameters were not measured in Mountain Lake (see Tables 1 and 2). For example, the Shannon and Brezonik (1972) trophic state index requires values for total phosphorus, total organic nitrogen, conductivity, and Pearsall's cation ratio; none of which were available on Mountain Lake. Current investigations at Mountain Lake include measurements of these variables, so assessments of trophic status using these additional indices may be applied in the future.

Phosphorus and nitrogen are included in many trophic state indices, because these elements represent the two most commonly reported limiting nutrients in aquatic ecosystems. Total phosphorus is used generally, because 70% or more of the phosphate in freshwater lakes is complexed and not in the form of soluble reactive phosphate [orthophosphate] (Wetzel, 1983). Although orthophosphate is not used in direct calculations of any trophic state index, some general assessment of trophic state can be inferred by its abundance. Orthophosphate and total phosphate have similar vertical distribution patterns dependent on trophic state (Wetzel, 1983). Oligotrophic systems are characterized by uniform phosphate concentrations throughout the water column, while eutrophic systems are characterized by increased phosphate concentrations in the hypolimnion (Wetzel, 1983). Mountain Lake fits the former type with concentrations of orthophosphate remaining similar throughout the epi-, meta-, and hypolimnion, thus indicating an oligotrophic system.

As with total phosphorus, total organic nitrogen is used in many trophic indices, because it often represents over 50% of the total soluble nitrogen in freshwater ecosystems (Wetzel, 1983). Unfortunately, accurate measurement of total organic nitrogen requires tedious analysis and specialized equipment. Therefore, these values have not been reported for the previous investigations at Mountain Lake. However, as with orthophosphate, trophic state trends are associated with the vertical distribution of inorganic nitrogen components (nitrate-nitrogen and ammonia-nitrogen). Oligotrophic lakes are generally characterized by uniform concentrations of ammonia-nitrogen throughout the water column, but tend to show slightly increased concentrations of nitrate-nitrogen in the hypolimnion. Eutrophic lakes, on the other hand, tend to have increased ammonia-nitrogen concentrations in the hypolimnion and decreased nitrate-nitrogen concentrations in the hypolimnion (Wetzel, 1983). Mountain Lake displays a combination of these two features, showing an increase in ammonia-nitrogen concentrations in the hypolimnion (since 1987), but showing similar nitrate-nitrogen concentrations throughout the water column (although total concentrations have increased since 1987). The increase in the ammonia-nitrogen in the hypolimnion may be due to the lowering of the redox potential as these waters approach anoxia (Wetzel, 1983; Forsberg, 1989).

To this point, we have discussed largely nutrient composition and trophic state assessment as they have applied to Mountain Lake. As mentioned previously, biological parameters also can be utilized for trophic state assessment. Application of phytoplankton community structure to trophic state has been attempted in several indices (Sullivan and Carpenter, 1982). However, while some generalizations are possible, to date, community structure remains an unreliable predictor. For example, Nygaard's compound index (Table 1) classifies Mountain Lake as eutrophic, with values of 1.8 in 1971 (Obeng-Asamoa, 1971) and 1.59 from the species list of 1985-1987 (Parson, 1988). Additionally, since Mountain Lake is quite unique geologically, physically, and chemically, it may be unwise to extrapolate from species compositions based on other lakes. Table 16 shows trophic state evaluations of Mountain Lake

based on other biologically associated parameters (Secchi disk, chlorophyll *a*, primary productivity, and hypolimnetic oxygen deficit). From the available data, Mountain Lake is gradually approaching a higher trophic state. All indices presented show a definite trend toward mesotrophy. However, the lake appears to be near the boundary of oligotrophy and mesotrophy. The major concern is that once this boundary is crossed, a more rapid increase through mesotrophy-to-eutrophy may occur (Figures 1 and 2). For this reason the decreased hypolimnetic oxygen concentration is of special interest. Gliwicz and Kowalczewski (1981) have suggested that even though biological parameters in the epilimnion may not indicate eutrophication, hypolimnetic symptoms can be important. They suggest that the thickness of the epilimnion and the temperature gradient of the thermocline play a major role in the location of the eutrophication symptoms. A shallow epilimnion and steep thermocline temperature gradient will be associated with eutrophication symptoms first developing in the epilimnion; in contrast, a deep epilimnion with a shallow thermocline temperature gradient will be associated with eutrophication symptoms first appearing in the hypolimnion. Mountain Lake has a relatively deep epilimnion; thus, symptoms of eutrophication may be expected to appear first in the hypolimnion. Only minor fluctuations in nutrient availability may cause a relatively permanent change in the trophic state of this delicate aquatic ecosystem.

Some changes which have occurred are temporary increases in the total number of phytoplankton organisms/ml (Figure 18), a shift in phytoplankton species composition (Parson and Parker, 1989b), and a reduction in littoral *Nitella* biomass (Parker et al., 1991). Table 17 lists the differences in dominant phytoplankton species reported by Obeng-Asamoa (1971) and Parson and Parker (1989a). Parker et al. (1991) reported that *Nitella* is still the dominant macrophyte in Mountain Lake; however, as stated previously, an apparent reduction in biomass has taken place since 1973-1974. Although the *Nitella* biomass in the metalimnion was 11 times as great as the phytoplankton biomass, the phytoplankton rate of carbon assimilation (photosynthesis) was 25 times greater than for *Nitella*

(Parker et al., 1991). This contribution to lake productivity by the phytoplankton community is characteristic of oligotrophic ecosystems (Wetzel, 1983).

## 4 Conclusions

Mountain Lake, Virginia, the only natural lake in the southern Appalachians, has displayed changes which may foretell the onset of eutrophication. Factors which may cause or indicate a shift toward higher trophic levels in Mountain Lake include:

1) increase in nitrate-nitrogen concentrations;
2) increase in orthophosphate-phosphorus concentrations;
3) increase in hypolimnetic oxygen deficiency; and
4) change in the phytoplankton community.

Factors which indicate stability of the trophic level of Mountain Lake include:

1) variable, but relatively stable, chlorophyll *a* concentrations;
2) similar Secchi disk transparency values;
3) similar primary productivity values; and
4) similar, albeit low, acid rain index values.

Mountain Lake has exhibited temporary and significant changes from anthropogenic influences. However, at this time, the data are insufficient, in terms of duration, to assess the rate of eutrophication. Just how much additional impact would be needed to drastically disturb Mountain Lake and accelerate eutrophication remains conjectural. Despite our inability at this time to make a reasonably firm conclusion regarding the rate of eutrophication, we have made a first attempt, and have pulled together the data needed and identified the needs for future studies. Subsequent investigations at Mountain Lake should address:

1) any unexplained changes in nutrient concentrations such as increased nitrate-nitrogen throughout the water column;
2) possible micronutrient limitations (e.g., iron) as suggested by the 1990 data;
3) changes in benthic fauna as oxygen deficits in the hypolimnion increase;

4) parameters such as total phosphate, conductivity, and cation ratios so additional trophic state indices can be applied;
5) the herbivorous plankton community in an effort to assess changes which may be occurring as the phytoplankton community undergoes change; and
6) studies of the biological and chemical composition of sediments below the photic zone (i.e., $\geq$ 20 m).

## References

American Public Health Association (APHA), American Water Works Association(AWWA) and Water Pollution Control Federation (WPCF). 1989. Standard Methods for the Examination of Water and Wastewater (17th ed.) APHA, Washington, DC.

Carlson, R. E. 1977. A trophic state index for lakes. Limnol. and Oceanogr. 22 (2): 358-369.

Cairns, J. Jr., G. R. Lanza, and B. C. Parker. 1972. Pollution related structural and functional changes in aquatic communities with emphasis on freshwater algae and protozoa. Preceedings of the Academy of Natural Sciences of Philadelphia 124 (5): 79-127

Chavez, F. P., K. R. Buck, K. H. Coale, J. H. Martin, G. R. DiJullio, N. A. Wellschmeyer, and A. C. Barber. 1991. Growth rate, grazing, sinking, and iron limitation of equatorial Pacific phytoplankton. Limnol. Oceanogr. 36: 1816-1833.

Coker, R. E. and W. J. Hayes, Jr. 1940. Biological investigations in Mountain Lake, Virginia. Ecology. 21 (2): 192-198.

Cole, G. A. 1983. Textbook of Limnology (3rd ed). C. V. Mosby Co. St. Louis. 401 pp.

Dubay, C. I. 1976. The standing crop and distribution of macrophytes in Mountain Lake, Virginia, with particular emphasis on the contribution of *Nitella flexilis* (L.) to the metalimnetic oxygen maximum. M. S. Thesis. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Dubay, C. I. and G. Simmons. 1979. Contribution of macrophytes to the metalimnetic oxygen maximum in a montane, oligotrophic lake. Amer. Midl. Nat. 101: 108-117.

Duce, R. A. and N. W. Tindale 1991. Atmospheric transport of iron and its deposition in the oceans. Limnol. Oceanogr. 36: 1715-1726.

Environmental Protection Agency. 1974. "An Approach to a Relative Trophic State Index for Classifying Lakes and Reservoirs." Working Paper No. 24, Corvallis, Oregon.

Forsberg, C. 1989. Importance of sediments in understanding nutrient cyclings in lakes. Dev. in Hydrobiol. 176/177: 263-277.

Gliwicz, Z. M. and A. Kowalczewski. 1981. Epilimnetic and hypolimnetic symptoms of eutrophication in Great Mazurian Lakes, Poland. Freshwater Biology 11: 425 -433.

Goldman, C. R. 1972. The role of minor nutrients in limiting the productivity of aquatic ecosystems. *In* Nutrients and Eutrophication: The Limiting Nurtient Controversy. (G. E. Likens, ed.) Special Symposium Amer. Soc. Limnol. Oceanogr. 1:21-38.

Grover, W. W. and R. E. Coker. 1940. A study of the depth distribution of certain net plankters in Mountain Lake, Virginia. Ecology 21 (2): 199-205.

Hooper, F. F. 1956. Some chemical and morphometric characteristics of southern Michigan lakes. Papers Michigan Acad. Sci. 41: 109-130.

Hutchinson, G. E. 1938. On the relation between the oxygen deficit and the productivity and typology of lakes. Int. Rev. Gasamt. Hydrobiol. 36: 336 - 355.

Hutchinson, G. E. 1969. Eutrophication past and present. *In* Eutrophication: Causes, Consequences, Correctives. Proceedings National Academy of Sciences, Washington, D. C. pp. 17 - 28.

Hutchinson, G. E. and G. E. Pickford. 1932. Limnological observations on Mountain Lake, Virginia. Intern. Rev. ges. Hydrobiol. u. Hydrogr. 27: 252 -264.

Likens, G. E. 1975. Primary productivity of inland aquatic ecosystems. *In* Primary Productivity of the Biosphere. H. Lieth and R. H. Whittaker (eds.) Spinger - Verlag. pp. 185 - 202.

Lind, O. T. 1979. Handbook of Common Methods in Limnology. C. V. Mosby Co., St. Louis. 199 pp.

Maloney, T. E. (ed.) 1979. Lake and Reservoir Classification Systems. USEPA-600/3-79-074. 241 pp.

Marland, F. C. 1967. The history of Mountain Lake, Giles County, Virginia: an interpretation based on paleolimnology. Ph.D. Dissertation. Virginia Polytechnic Institute and State University, Blacksburg, Virginia. 127 pp.

Martin, H. H., R. M. Gordon, and S. E. Fitzwater. 1991. The case for iron. Limnol. Oceanogr. 36: 1793-1802.

Mortimer, C. H. 1941. The exchange of dissolved substances between mud and water I and II. J. Ecol. 29: 280-329.

Murphy, J. S. and J. P. Riley. 1962. A single-solution method for the determination of phosphate in natural waters. Analyt. Chim. Acta. 27: 31-36.

Naumann, E. 1927. Ziel und Hauptprobleme der regionale Limnologie. Bot. Notiser 1927: 81-103

Nygaard, B. 1949. Hydrobiological studies of some Danish ponds and lakes, II. Biol. Sci. 7: 293

Obeng-Asamoa, E. K. 1971. Limnological investigations of Mountain Lake, Giles County, Virginia. Ph. D. dissertation, Virginia Polytechnic Inst. and State Univ., Blacksburg, Virginia. 113 pp.

Parker, B. C. 1976. An estimate of the trophic state of Mountain Lake, Giles County, Virginia. *In* The Distributional History of the Biota of the Southern Appalachians: Part IV Algae and Fungi. Parker, B. C. and Roane, M. K. (eds.) Univ. Press of Virginia, Charlottesville pp. 102-109.

Parker, B. C. and M. J. Parson. 1987. A modified $^{14}C$ primary productivity method. Virginia J. Sci. 38 (3): 214-219.

Parker, B. C., L. J. Wenkert, and M. J. Parson. 1991. Cause of the metalimnetic oxygen maximum in Mountain Lake, Virginia. J. Freshwater Ecol. 6 (3): 293-303.

Parker, B. C., H. E. Wolfe, and R. V. Howard. 1975. On the origin and history of Mountain Lake, Virginia. Southeastern Geology 16 (4): 213-226.

Parson, M. J. 1988. Ammonia uptake by phytoplankton and limnological studies of Mountain Lake, Virginia. Ph. D. dissertation, Virginia Polytechnic Inst. and State Univ., Blacksburg, Virginia. 281 pp.

Parson, M. J. and B. C. Parker. 1989a. Mountain Lake, Virginia: an oligotrophic lake under increasing stress. Current Pract. in Environ. Sci. and Engng. 4: 1-24.

Parson, M. J. and B. C. Parker. 1989b. Algal flora in Mountain Lake, Virginia: past and present. Castanea 54 (2): 79-86.

Parson, M. J. and B. C. Parker. 1993. Seasonal pattern of ammonium (methylamine) uptake by phytoplankton in an oligotrophic lake. Hydrobiologia 250: 105-117.

Price, N. M., L. F. Andersen, and F. M. M. Morel. 1991. Iron and nitrogen nutrition of equatorial Pacific plankton. Deep-Sea Res. 38: 1361-1378.

Rhode, W. 1969. Crystallization of eutrophication concepts in northern Europe. *In* Eutrophication: Causes, Consequences, Correctives. Proceedings National Academy of Sciences. Washington, D. C. pp. 50 - 64.

Roth, J. C. and S. E. Neff. 1964. Studies of physical limnology and profundal bottom fauna Mountain Lake, Virginia. Technical Bulletin 169. Virginia Agricultural Experiment Station, Blacksburg, Virginia. 43 pp.

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

Shannon, E. E. and P. L. Brezonik. 1972. Relationships between lake trophic state and nitrogen and phosphorus loading rates. Envir. Sci. Tech. 6: 719-725.

Shapiro, J. 1980. The importance of trophic-level interactions to the abundance and species composition of algae in lakes. Dev. in Hydrobiol. 2: 105-116.

Silker, W. B. 1964. Variations in elemental concentrations in the Columbia River. Limnol. Oceanogr. 9: 540-545.

Simmons, G. M., Jr. and S. E. Neff. 1973. Observations on limnetic carbon assimilation rates in Mountain Lake, Virginia, during its thermal stratification periods. Virginia J. Sci. 24: 206-211.

Sullivan, P. F. and S. R. Carpenter. 1982. Evaluation of fourteen trophic state indices for phytoplankton of Indiana lakes and reservoirs. Env. Pollution (Series A) 27: 143-153.

Van Brunt, M. R. 1984. Seasonal patterns of colonization by protozoa in an oligotrophic lake. M. S. thesis, Virginia Polytechnic Inst. and State Univ., Blacksburg, Virginia. 94 pp.

Vollenweider, R. A. 1969. A Manual on Methods for Measuring Primary Production in Aquatic Ecosystems. Blackwell Scientific Pub., Oxford. 213 pp.

Walker, W. W. 1979. Use of hypolimnetic oxygen depletion rate as a trophic state index for lakes. Wat: Res. Research 15 (6): 1463-1479.

Wetzel, R. G. 1975. Limnology (1st ed.). Saunders College Pub., Philadelphia. 743 pp.

Wetzel, R. G. 1983. Limnology (2nd ed.). Saunders College Pub., Philadelphia. 767 pp.

# Tables

**Table 1. 10 trophic state indices proposed.**

| Author | Index Calculation |
|---|---|
| Nygaard's (1949) Compound Index where # <1 are considered oligotrophic and >1 eutrophic | $\frac{\text{Myxophyceae + Chlorococcales + Centrales + Euglenineae}}{\text{Desmidiaceae}}$ |
| Shannon and Brezonik (1972) Trophic State Index where # <3 are considered oligotrophic, >3 and <7 mesotrophic, and >7 eutrophic | TSI = 0.94(Primary Productivity (mg $C/m^3/hr$)) + 0.92(1/Secchi Disk (m)) + 0.90(Total Organic Nitrogen (mg/l)) + 0.86(Chl *a* ($mg/m^3$)) + 0.80(Conductivity ($\mu$mhos/cm)) + 0.74(Total Phosphorus (mg/l)) + 0.63(1/Cation ratio (Na + K(mg/l)/ Mg + Ca (mg/l)) |
| USEPA (1974) Trophic State Index where # >499 are considered oligotrophic, >420 and <499 mesotrophic, and <420 eutrophic | Table value for: Median total phosphorus (mg/l) + median inorganic nitrogen (mg/l) + [500 - mean Secchi disk (inches)] + mean Chl *a* ($mg/m^3$) + [15 - minimum hypolimnion DO (mg/l)] + median dissolved phosphorus (mg/l) |
| Carlson's (1977) Trophic State Indices where # <40 are considered oligotrophic, >40 and <50 mesotrophic, and >50 eutrophic | Secchi Disk = $10\left[6 - \frac{\ln SD\ (m)}{\ln 2}\right]$ |
| | Chlorophyll *a* = $10\left[6 - \frac{(2.04 - 0.68 \ln Chl\ a\ (mg/m^3))}{\ln 2}\right]$ |
| | Total Phosphorus = 14.42 ln TP($mg/m^3$) + 4.15 |
| Walker's (1979) Trophic State Index where # <25-30 are considered oligotrophic, >30 and <45-50 mesotrophic, and >45-50 eutrophic | $\frac{(Chl\ a\ (mg/m^3) + TP(mg/m^3) + SD\ (m))}{3}$ |
| | where: Chl *a* = 20 + 33.2 $\log_{10}$ Chl *a* |
| | TP = -15.6 + 46.1 $\log_{10}$ Total Phosphorus |
| | SD = 75.3 + 44.8 $\log_{10}$ (1/SD-$\propto$) $\propto$ = 0.08/meter SD |

**Table 2. Authority, parameters and duration of investigations relevant to this paper.**

| | Parameters | | | |
|---|---|---|---|---|
| Authors | Biological | Chemical | Physical | Duration |
| Hutchinson and Pickford 1932 | Organic Matter, Net plankton, Benthic fauna, Littoral veg. | Dissolved $O_2$, Alk., pH, Fe $PO_4$, $SiO_2$, $SO_4$, Mg, Ca | Temp., Color, Transparency Inorganic residue | July - Aug 1931 |
| Coker and Hayes 1940 | Net plankton, Rooted veg. | | Transparency Temp. | Summer 1937 |
| Grover and Coker 1940 | Net plankton distribution | Dissolved $O_2$ | | July & Aug. 1937 |
| Roth and Neff 1964 | Bottom Fauna, Littoral veg. | Dissolved $O_2$, Alk., pH, Cond. Hardness | Temperature, Transparency Inorg. residue | October 1961 - Jan 1963 |
| Obeng-Asamoa 1971 | Primary Prod., Chl *a*, Phyto-plankton | Dissolved $O_2$, Alk., pH, Hard., $NO_3$, $NH_4$, $PO_4$, $SiO_2$, $SO_4$ | Temperature | Feb 1970- Apr 1971 |
| Simmons and Neff 1973 | Primary Prod. | | | Sept 1965 May 1968 |
| Dubay 1976 | Primary Prod. | | | June 1976 |
| Parker 1976 | Primary Prod. | | | July and Aug. 1973 |
| Van Brunt 1984 | | Alk., pH, Hard. | Temperature | Oct. 1982- Sept. 1983 |
| Parson 1988/ Parson and Parker 1989a | Primary Prod., Chl *a*, Phyto-plankton | Dissolved $O_2$, Alk., pH, Hard $NO_3$, $NH_4$, $PO_4$, $SiO_2$, $SO_4$ | Temperature, Transparency | Mar. 1985- Nov. 1987 |
| Parker et. al. 1991 | Primary Prod., Chl *a*, DOC, Dry weight | Dissolved $O_2$ | Temperature | Summers 1985-90 |
| Parker unpub. | Primary Prod., Chl *a*, phyto-plankton | Dissolved $O_2$ Alk., pH, Hard. $NO_3$, $NH_4$, $PO_4$, $SiO_2$, $SO_4$ | Temperature, Transparency | Mar. 1988 -Nov. 1990 |

**Table 3. List of variables, methods, and instruments used at Mountain Lake, Virginia since 1985.**

| | |
|---|---|
| Water Samples | Kemmerer Bottle (Wildco Wildlife Supply Company, Saginaw, MI) |
| °C | Yellow Springs Instrument S-C-T Meter, Model 33 (Yellow Springs Instrument Company, Yellow Springs, OH) |
| Photosynthetically Available Radiation | Li-Cor, Inc., Quantum Radiometer/Photometer (Licor, Inc., Lincoln, NE) |
| Transparency | Secchi Disk |
| pH | Corning pH Meter, Model 610A (Corning Medical, Corning Glass Works, Medford, MA) |
| Hardness | Titrimetric, EDTA (APHA-AWWA-WPCF, 1989) |
| Alkalinity | Titimetric, Methyl Purple (APHA-AWWA-WPCF, 1989) |
| Oxygen, Dissolved | Modified Winkler (APHA-AWWA-WPCF, 1989) |
| Inorganic Nitrogen | $NH_4$-N, Phenate Method (Lind, 1979); $NO_3$-N, Cadmium Reduction (APHA-AWWA-WPCF, 1989) |
| Phosphate | Ascorbic Acid Method, Isobutanol Extraction(Murphy and Riley, 1962) |
| Silica, Dissolved | Molybdate Method (APHA-AWWA-WPCF, 1989) |
| Sulfate | Barium Sulfate Turbidimetric Method (APHA-AWWA-WPCF, 1989) |
| Metals (Select: Fe, Cu, etc.) | Inductively Coupled Plasma Spectrometry (Jarrell-Ash ICAP 9000) |
| Primary Productivity | Uptake of $^{14}C$, $NaH^{14}CO_3$ (Parker and Parson, 1987) |
| Extractable Chlorophyll *a* | Spectrophotometric (APHA-AWWA-WPCF, 1989) Perkin Elmer Spectrophotometer, model 552 (Perkin-Elmer, Norwalk, CT) |
| Phytoplankton | Utermohl settling (Vollenweider, 1969) |

**Table 4. Mean nitrate-nitrogen concentrations in mg/l from five select depths (0.1, 1, 6, 10, and 17m) in Mountain Lake: 1970-71 from Obeng-Asamoa (1971), 1985-87 from Parson (1988), 1988-90 from Parker (unpubl.), and 1992*-1993 from Beaty and Parker (unpubl.).**

| | 1970-71 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|---|---|---|
| Jan | 0.020 | | 0.011 | | | | | |
| Feb | 0.024 | | 0.016 | 0.028 | | | | |
| Mar | 0.018 | 0.018 | 0.012 | 0.016 | 0.062 | 0.160 | 0.118 | |
| Apr | | 0.012 | 0.024 | 0.020 | 0.058 | 0.065 | 0.099 | 0.193 |
| May | 0.033 | 0.010 | 0.011 | 0.006 | 0.067 | 0.062 | 0.037 | 0.153 |
| Jun | 0.026 | 0.097 | 0.010 | 0.011 | 0.050 | 0.061 | 0.062 | 0.098 |
| Jul | 0.028 | 0.006 | 0.018 | 0.012 | 0.053 | 0.028 | 0.110 | 0.085 |
| Aug | | 0.011 | 0.018 | 0.003 | 0.023 | 0.024 | 0.300 | 0.042 |
| Sep | 0.000 | 0.005 | 0.023 | 0.018 | 0.031 | 0.037 | | 0.027 |
| Oct | 0.015 | 0.001 | 0.019 | 0.015 | 0.087 | 0.038 | 0.069 | 0.032 |
| Nov | 0.026 | 0.016 | 0.018 | 0.019 | 0.057 | 0.034 | | 0.030 |
| Dec | 0.006 | 0.021 | 0.018 | | | | | 0.066 |
| Mean | 0.020 | 0.020 | 0.016 | 0.015 | 0.054 | 0.057 | 0.114 | 0.081 |

* Nov 1992 = 0.027
Dec 1992 = 0.049

**Table 5. Mean ammonia-nitrogen concentrations in mg/l from five select depths (0.1, 1, 6, 10, and 17m) in Mountain Lake: 1970-71 from Obeng-Asamoa (1971), 1985-87 from Parson (1988), 1988-90 from Parker (unpubl.), and 1992*-1993 from Beaty and Parker (unpubl.).**

| | 1970-71 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|---|---|---|
| Jan | 0.100 | | 0.016 | | | | | |
| Feb | 0.088 | | 0.017 | 0.007 | | | | |
| Mar | 0.000 | 0.007 | 0.026 | 0.006 | 0.002 | 0.023 | 0.010 | |
| Apr | | 0.005 | 0.019 | 0.008 | 0.003 | 0.021 | 0.008 | 0.013 |
| May | 0.000 | 0.012 | 0.030 | 0.019 | 0.013 | 0.044 | 0.030 | 0.005 |
| Jun | 0.000 | 0.012 | 0.019 | 0.077 | 0.011 | 0.026 | 0.004 | 0.021 |
| Jul | 0.000 | 0.010 | 0.018 | 0.069 | 0.046 | 0.022 | 0.802 | 0.028 |
| Aug | | 0.007 | 0.015 | 0.055 | 0.076 | 0.040 | 0.050 | 0.035 |
| Sep | 0.000 | 0.016 | 0.024 | 0.047 | 0.053 | 0.024 | | 0.071 |
| Oct | 0.000 | 0.015 | 0.016 | 0.041 | 0.016 | 0.024 | 0.066 | 0.030 |
| Nov | 0.035 | 0.013 | 0.006 | 0.037 | 0.021 | 0.014 | | 0.026 |
| Dec | 0.133 | 0.0163 | 0.0062 | | | | | 0.045 |
| Mean | 0.036 | 0.011 | 0.018 | 0.037 | 0.027 | 0.026 | 0.139 | 0.030 |

* Nov 1992 = 0.034
Dec 1992 = 0.038

**Table 6. Mean orthophosphate-phosphorus concentrations in mg/l from five select depths (0.1, 1, 6, 10, and 17m) in Mountain Lake: 1970-71 from Obeng-Asamoa (1971), 1985-87 from Parson (1988), 1988-90 from Parker (unpubl.), and 1992*-1993 from Beaty and Parker (unpubl.).**

| | 1970-71 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|---|---|---|
| Jan | 0.023 | | 0.001 | | | | | |
| Feb | 0.023 | | 0.001 | 0.001 | | | | |
| Mar | 0.020 | 0.002 | 0.001 | 0.001 | 0.017 | 0.015 | 0.034 | |
| Apr | | 0.002 | 0.001 | 0.002 | 0.003 | 0.009 | 0.046 | 0.003 |
| May | 0.027 | 0.002 | 0.001 | 0.002 | 0.002 | 0.013 | 0.018 | 0.006 |
| Jun | 0.020 | 0.002 | 0.001 | 0.002 | 0.004 | 0.003 | 0.009 | 0.005 |
| Jul | 0.038 | 0.002 | 0.001 | 0.001 | 0.009 | 0.169 | 0.004 | 0.003 |
| Aug | | 0.001 | 0.001 | 0.003 | 0.000 | 0.010 | 0.067 | 0.005 |
| Sep | 0.050 | 0.002 | 0.001 | 0.003 | 0.011 | 0.016 | | 0.008 |
| Oct | 0.042 | 0.001 | 0.004 | 0.008 | 0.013 | 0.015 | 0.012 | 0.008 |
| Nov | 0.058 | 0.004 | 0.002 | 0.003 | 0.012 | 0.012 | | 0.019 |
| Dec | 0.070 | 0.002 | 0.002 | | | | | 0.018 |
| Mean | 0.036 | 0.002 | 0.001 | 0.002 | 0.008 | 0.029 | 0.027 | 0.008 |

* Nov 1992 = 0.006
Dec 1992 = 0.004

**Table 7. Mean phytoplankton primary productivity ($mgC/m^2/day$) from a minimum of five depths (0.1, 1, 6, 10, and 17m) in Mountain Lake: 1965-68 from Simmons and Neff (1973), 1973 from Parker (1976), 1974 from Dubay (1976), 1985-87 from Parson (1988), 1988-90 from Parker (unpubl.), and 1992*-1993 data from Beaty and Parker (unpubl.).**

| | 1965 | 1966 | 1967 | 1968 | 1973 | 1974 |
|---|---|---|---|---|---|---|
| Feb | | 0.90 | | 170.00 | | |
| Apr | | | | | | |
| May | | 233.00 | | 482.20 | | |
| Jun | | | | | | 348.44 |
| Jul | | 296.70 | | | 886.00 | |
| Aug | | | 218.7 | | 752.00 & 437.00 | |
| Sep | 267.50 | | | | | |

| | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|---|---|
| Jan | | 49.00 | | | | | |
| Feb | | 10.03 | | | | | |
| Mar | | 48.31 | | 92.70 | 49.80 | 18.59 | |
| Apr | 171.50 | | | 355.30 | 497.19 | 34.64 | 1.45 |
| May | | | | 903.13 | 555.63 | 91.67 | 67.33 |
| Jun | 84.48 | | 32.92 | 228.13 | 580.00 | 81.25 | 237.66 |
| Jul | 372.30 | 656.45 | 260.19 | 95.63 | 2500.00 | 900.00 | 302.50 |
| Aug | 708.90 | 1281.88 | 234.56 | 140.00 | 3018.00 | 46.00 | 247.60 |
| Sep | 339.10 | | 472.29 | 109.90 | 131.61 | | 162.08 |
| Oct | 141.16 | 197.00 | 63.25 | 296.56 | 110.99 | 186.04 | 111.00 |
| Nov | 67.50 | | 366.25 | 184.69 | 45.00 | | 23.46 |
| Dec | 59.10 | | | | | | 15.42 |
| Mean | 243.01 | 373.78 | 238.24 | 265.11 | 832.11 | 194.03 | 129.83 |

* Nov 1992 = 9.887
Dec 1992 = 3.394

**Table 8. Chlorophyll *a* concentrations in mg/m$^3$ from Mountain Lake: 1970-71 from Obeng-Asamoa (1971), 1985-87 from Parson (1988), 1988-90 from Parker (unpubl.), and 1993 from Beaty and Parker (unpubl.).**

| | 1970-71 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|---|---|---|
| Annual Mean for five depths | 5.39 | 4.35 | 1.88 | 2.62 | 2.09 | 4.76 | 1.54 | 1.18 |
| Annual Mean for 1m depth | 4.58 | 4.36 | 2.26 | 2.24 | 3.26 | 4.71 | 1.43 | 1.35 |
| Mean for 1m depth from May-October | | 4.45 | 2.30 | 1.40 | 3.88 | 6.03 | 1.10 | 1.68 |

**Table 9. Secchi disk transparency data in meters for Mountain Lake: 1962 from Roth and Neff (1964), 1985-87 from Parson (1988), 1988-89 from Parker (unpubl.), and 1992-93 from Beaty and Parker (unpubl.).**

| Month | 1962 | 1985 | 1986 | 1987 | 1988 | 1989 | 1992 | 1993 |
|---|---|---|---|---|---|---|---|---|
| Mar. | 7.0 | 3.5 | 6.0 | 5.6 | | 6.5 | | |
| Apr. | 5.5 | 3.5 | 3.7 | 3.7 | 6.0 | | | 6.5 |
| May | 6.0 | 6.1 | 8.1 | 6.1 | 4.0 | 5.5 | | 7.7 |
| June | 6.5 | 8.1 | 5.8 | 7.2 | 9.0 | 5.0 | | 4.5 |
| July | 5.5 | 5.5 | 8.8 | 6.0 | 4.0 | 4.0 | | 3.7 |
| Aug. | 6.4 | 4.9 | 8.8 | 7.8 | 5.5 | 3.7 | | 5.0 |
| Sept. | 5.5 | 6.1 | 7.0 | 6.1 | 9.0 | 4.0 | | 5.3 |
| Oct. | 7.9 | 9.2 | 7.2 | 8.0 | 7.5 | 4.9 | | 5.0 |
| Nov. | 5.5 | 5.6 | 6.1 | 7.5 | 6.5 | 4.5 | 4.3 | 5.5 |
| Dec. | 5.5 | 5.6 | 4.3 | | | | 6.2 | 6.9 |
| Mean | 6.13 | 5.51 | 6.58 | 6.44 | 6.43 | 4.76 | 5.2 | 5.7 |

* Aug 1932 = 7.0
Aug 1937 = 5.5

**Table 10. Hypolimnetic oxygen deficits calculated for Mountain Lake from April to October: 1962 from Roth and Neff (1964), 1970 from Obeng-Asamoa (1971), 1985-87 from Parson (1988), 1988-89 from Parker (unpubl.), and 1993 from Beaty and Parker (unpubl.).**

| Year | Difference in $O_2$ conc. | No. of Days Past | Hypolimnetic Oxygen Deficit ($mgO_2/cm^2/day$) |
|---|---|---|---|
| 1962 | 0.520 | 187 | 0.0028 |
| 1970 | 0.710 | 176 | 0.0040 |
| 1985 | 1.392 | 164 | 0.0085 |
| 1986 | 1.344 | 162 | 0.0083 |
| 1987 | 1.431 | 173 | 0.0083 |
| 1988 | 1.497 | 174 | 0.0086 |
| 1989 | 1.460 | 185 | 0.0079 |
| 1993 | 1.994 | 193 | 0.0103 |

**Table 11. Mean sulfate concentrations in mg/l from five select depths (0.1, 1, 6, 10, and 17m) in Mountain Lake: 1970-71 from Obeng-Asamoa (1971), 1985-86 from Parson (1988), 1988-90 from Parker (unpubl.), and 1993 from Beaty and Parker (unpubl.).**

| | 1970-71 | 1985-86 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|---|
| Jan | 2.00 | 4.38 | | | | 0.573 |
| Feb | 3.50 | 5.05 | | | | |
| Mar | 2.00 | 6.15 | 4.57 | 1.19 | 3.19 | |
| Apr | 1.00 | 5.80 | 2.35 | 0.00 | 3.55 | 0.51 |
| May | 4.0 | 8.96 | 3.62 | 0.00 | 4.21 | 0.47 |
| Jun | 2.00 | 5.81 | 4.50 | 0.00 | 3.76 | 0.00 |
| Jul | 1.00 | 6.67 | 0.82 | 3.31 | 1.96 | |
| Aug | 2.00 | 6.65 | 4.49 | 0.74 | 3.99 | 0.19 |
| Sep | 4.00 | 3.25 | 1.60 | 1.19 | | 0.00 |
| Oct | 5.00 | 2.27 | 0.98 | 3.16 | | |
| Nov | 4.00 | 3.26 | 1.01 | 3.64 | | 0.26 |
| Dec | 0.00 | 3.92 | | | | |
| Mean | 2.54 | 5.18 | 2.66 | 1.47 | 3.44 | 0.29 |

**Table 12. Schindler's (1988) acid rain index calculated for Mountain Lake: 1985-86 from Parson (1988), 1988-90 from Parker (unpubl.), and 1993 from Beaty and Parker (unpubl.).**

| | 1985-86 | 1988 | 1989 | 1990 | 1993 |
|---|---|---|---|---|---|
| Jan | 0.287 | | | | 0.370 |
| Feb | 0.314 | | | | |
| Mar | 0.261 | 0.250 | 0.081 | 0.632 | |
| Apr | 0.214 | 0.202 | 0.045 | 0.822 | 0.261 |
| May | 0.250 | 0.196 | 0.423 | 0.893 | 0.269 |
| Jun | 0.087 | 0.198 | 0.512 | .0966 | 0.285 |
| Jul | 0.173 | 0.259 | 0.541 | 1.008 | 0.286 |
| Aug | 0.171 | 0.328 | 0.405 | 0.600 | 0.350 |
| Sep | 0.176 | 0.262 | 0.449 | | 0.323 |
| Oct | 0.167 | 0.104 | 0.466 | | 0.372 |
| Nov | 0.171 | 0.103 | 0.423 | | 0.329 |
| Dec | 0.171 | | | | 0.333 |
| Mean | 0.204 | 0.211 | 0.372 | 0.820 | 0.318 |

**Table 13. Several proposed trophic state ranges of surface waters based on areal primary productivity.**

| Trophic State | Productivity ($mgC/m^2/day$) | | |
|---|---|---|---|
| | Rhode, 1969 | Likens, 1975 | Wetzel, 1975 |
| Ultraoligotrophic | 0 - 30 | < 50 | < 50 |
| Oligotrophic | 30 - 100 | 50 - 300 | 50 -300 |
| Mesotrophic | 100 - 300 | 250 - 1000 | 250 -1000 |
| Eutrophic | 300 - 1000 | 600 - 8000 | > 1000 |
| Hypereutrophic | 1500 - 3000 | | |

**Table 14. Two trophic state classifications based on chlorophyll *a* concentrations ($mg/m^3$).**

| Trophic State | Sakamoto, 1966 | Wetzel, 1975 |
|---|---|---|
| Oligotrophic | 0.3 - 2.5 | 0.3 - 3.0 |
| Mesotrophic | 1.0 - 15 | 2.0 - 15 |
| Eutrophic | 5.0 - 30 | 10 - 500 |

**Table 15. Two trophic state classifications based on hypolimnetic oxygen depletion ($mg/cm^2/day$)**

| Trophic State | Hutchinson, 1938 | Mortimer, 1941 |
|---|---|---|
| Oligotrophic | 0.004 - 0.033 | Below 0.025 |
| Eutrophic | 0.05 - 0.14 | Above 0.055 |

**Table 16. Trophic state assessments based on calculated index values for Mountain Lake data: 1931 from Hutchinson and Pickford (1932), 1962 from Roth and Neff (1964), 1985-87 from Parson (1988), 1988-89 from Parker (unpubl.).**

| Author/Parameter | | YEAR 1931 | 1962 | | 1985 | 1986 | 1987 | 1988 | 1989 |
|---|---|---|---|---|---|---|---|---|---|
| Carlson | Secchi disk | 31.9 (0) | 33.8 (O) | | 35.3 (O) | 32.8 (O) | 33.12 (O) | 33.1 (O) | 35.7 (O) |
| | Chl *a* | | | | 42.3 (M) | 38.5 (O) | 38.5 (O) | 42.2 (M) | 45.8 (M) |
| Walker | Secchi disk | 37.5 (M) | 40.2 (M) | | 42.4 (M) | 38.9 (M) | 39.3 (M) | 39.3 (M) | 42.8 (M) |
| | Chl *a* | | | | 41.2 (M) | 31.8 (M) | 31.8 (M) | 37.0 (M) | 42.3 (M) |
| Sakamoto | Chl *a* | | | | 4.36 (M) | 2.26 (O/M) | 2.24 (O/M) | 3.26 (M) | 4.71 (M) |
| Wetzel | Chl *a* | | | | 4.36 (M) | 2.26 (O/M) | 2.24 (O/M) | 3.26 (M) | 4.71 (M) |
| | Primary Prod. ($mgC/m^2/d$) | | | | 243.01 (O) | 373.78 (M) | 238.24 (O) | 265.11 (O/M) | 832.11 (M) |
| Likens | Primary Prod. ($mgC/m^2/d$) | | | | 243.01 (O) | 373.78 (M) | 238.24 (O) | 265.11 (O/M) | 832.11 (M/E) |
| Rhode | Primary Prod. ($mgC/m^2/d$) | | | | 243.01 (M) | 373.78 (E) | 238.24 (M) | 265.11 (M) | 832.11 (E) |
| Hutchinson | Oxygen ($mgO_2/cm^2/d$) | | .003 (O) | '71 .004 (O) | | | | 0.009 (O) | 0.007 (O) |
| Mortimer | Oxygen ($mgO_2/cm^2/d$) | | .003 (O) | .004 (O) | | | | 0.009 (O) | 0.007 (O) |

(O) = OLIGOTROPHIC
(M) = MESOTROPHIC
(E) = EUTROPHIC
'71 = 1971

Chl *a* = CHLOROPHYLL *a*
Prod. = PRODUCTIVITY
d = DAY

**Table 17. Phytoplankton ranks for July 1970 (Obeng-Asamoa, 1971) and July 1985 (Parson and Parker, 1989a) for Mountain Lake.**

| 1970 | 1985 |
|---|---|
| 1. *Bambusina brebissonii* | *Scenedesmus bijuga* |
| 2. *Staurastrum ophiura* | *Asterionella formosa* |
| 3. *Radiofilum confunctivum* | *Gymnodinium sp.* |
| 4. *Quadrigula chodatii* | *Cyclotella meneghiniana* |
| 5. *Sphaerocystis schoeteri* | *Chilomonas paramecium* |
| 6. *Mougeotia sp.* | *Peridinium wisconsinense* |
| 7. *Micrasterias radiosa* | *Chroococcus minutus* |
| 8. *Quadrigula lacustris* | *Spondylosium planum* |
| 9. *Micrasterias radiata* | *Chromulina ovalis* |
| 10. *Staurastrum arctiscon* | *Tabellaria fenestrata* |

# Figures

**Figure 1.** Simplified illustration of natural eutrophication and the effect of fertilizers on the biological productivity per unit area of lake surface (modified from Cairns et al., 1972).

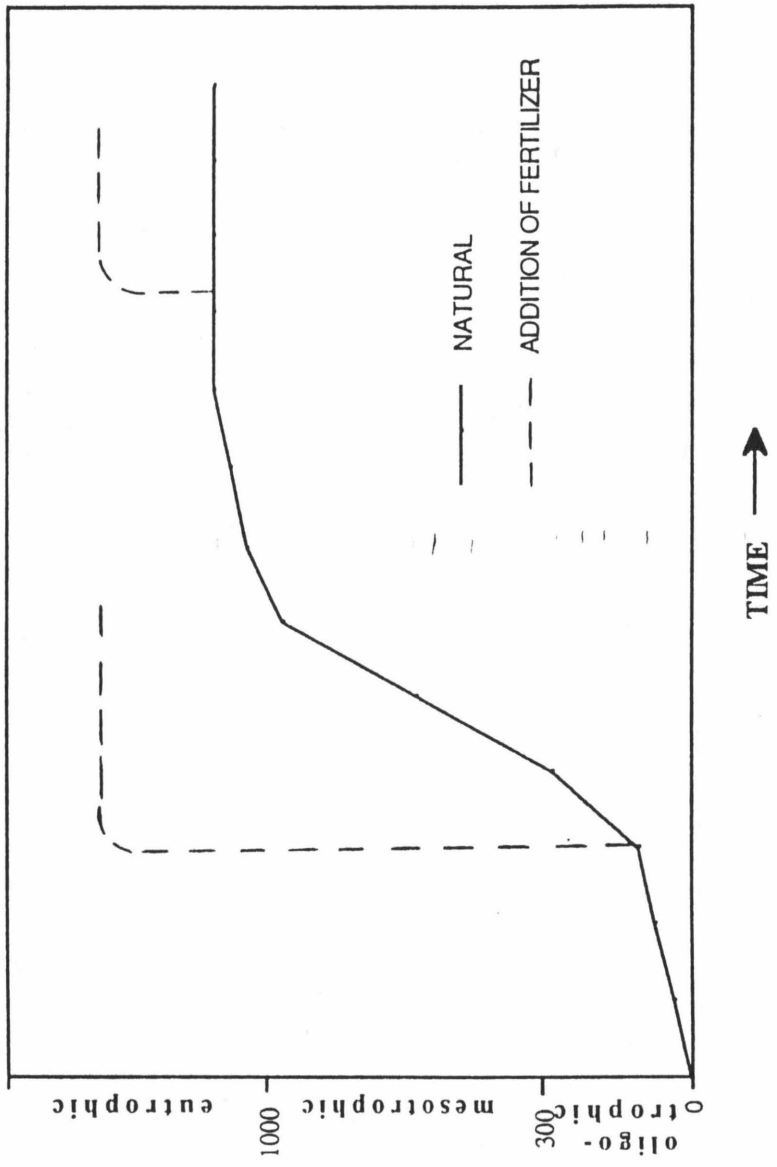


**Figure 2. Hypothetical eutrophication of lakes. Arrows up indicate maximum inducible eutrophic levels; arrows down indicate maximal return to natural trophic level (modified from Cairns et al., 1972).**

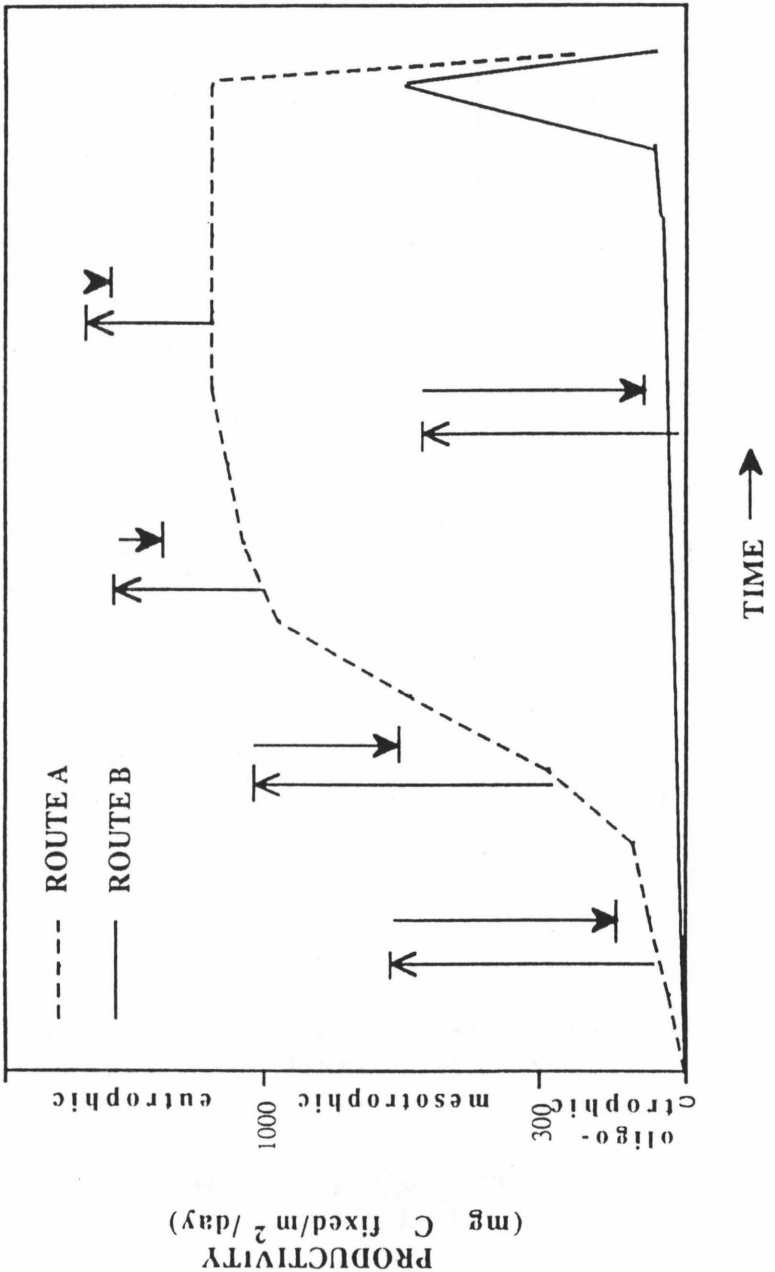


**Figure 3.** Aerial photographs showing the virgin Canadian hemlock-Rhododendron forest around Mountain Lake's perimeter: (A) Looking eastward, 1973; (B) Looking southward where the hotel and cottages are located, 1987.

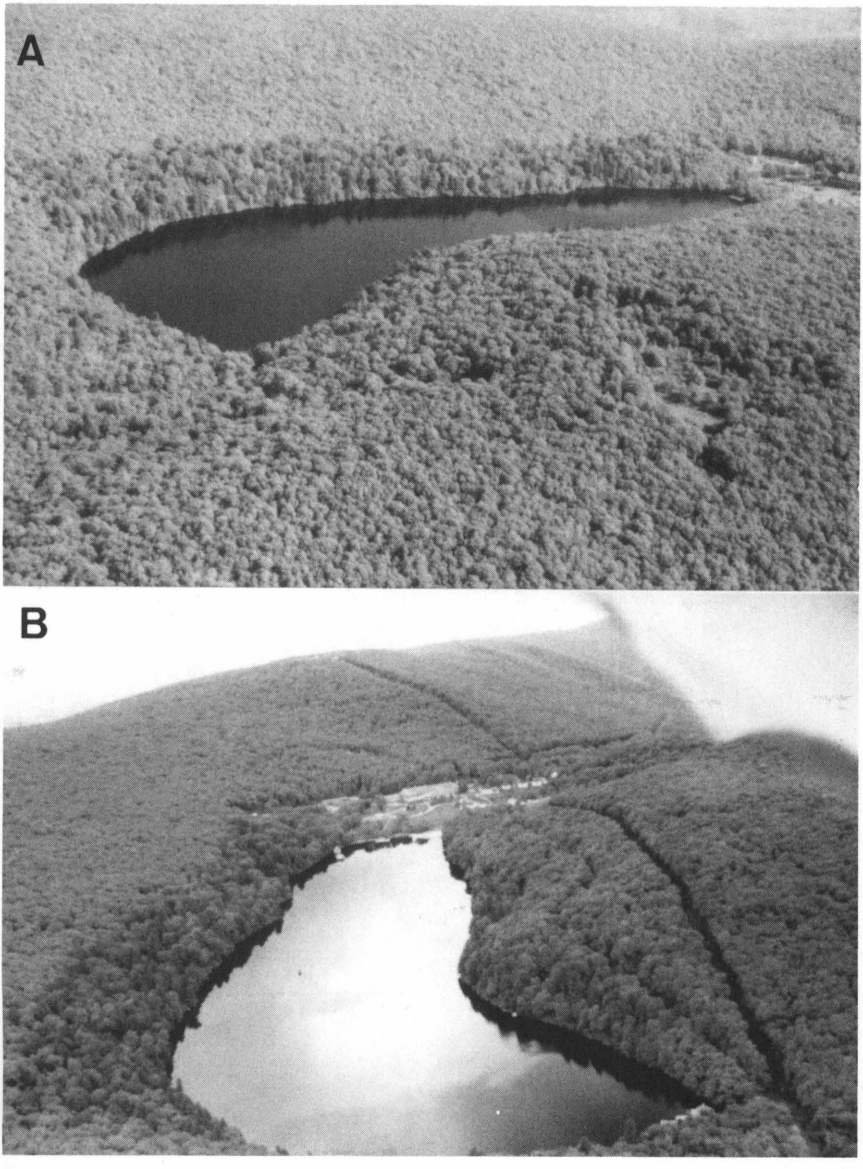


**Figure 4. Morphometric map of Mountain Lake, Virginia (modified from Parker et al., 1975). Numbers represent depth in meters.**

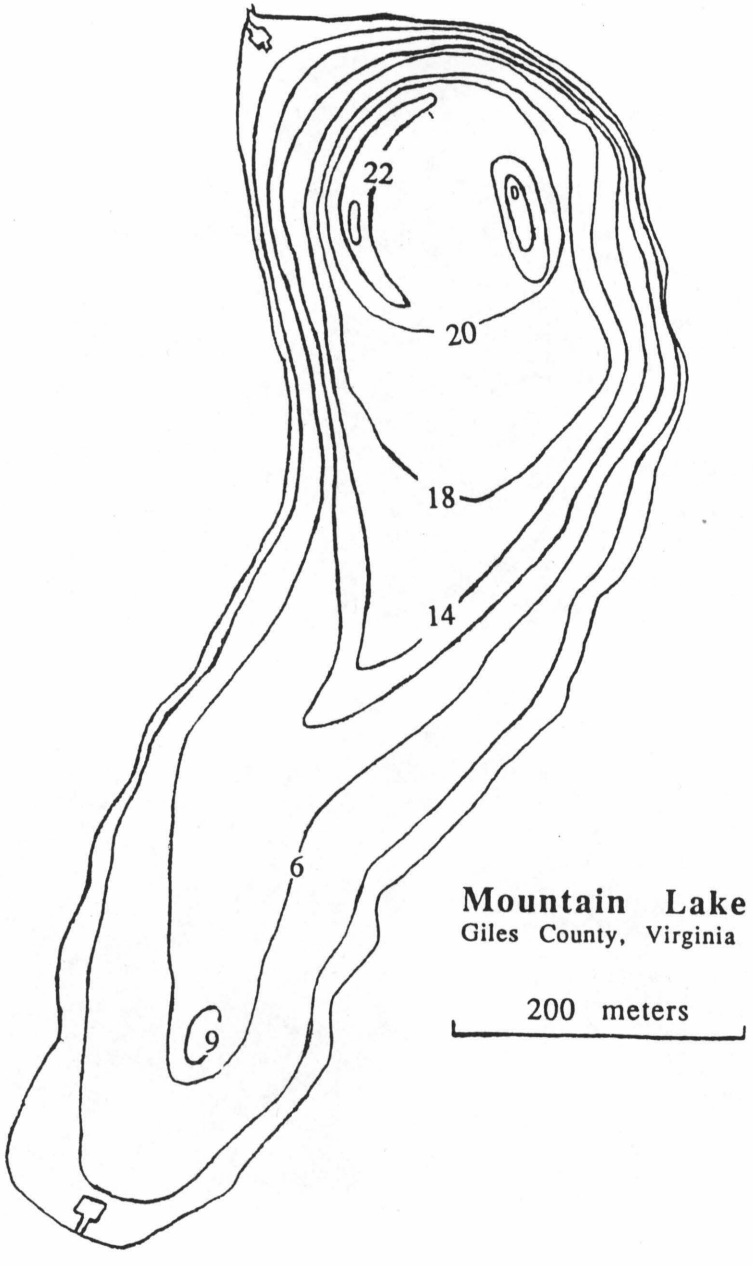


**Figure 5.** Portion of U.S. Geological Survey map (Eggleston, VA 1985) showing the Conservancy at Mountain Lake, Virginia, its approximate drainage basin (— — — — — —) and property owned by Mary Moody Northen, Inc. (————————).

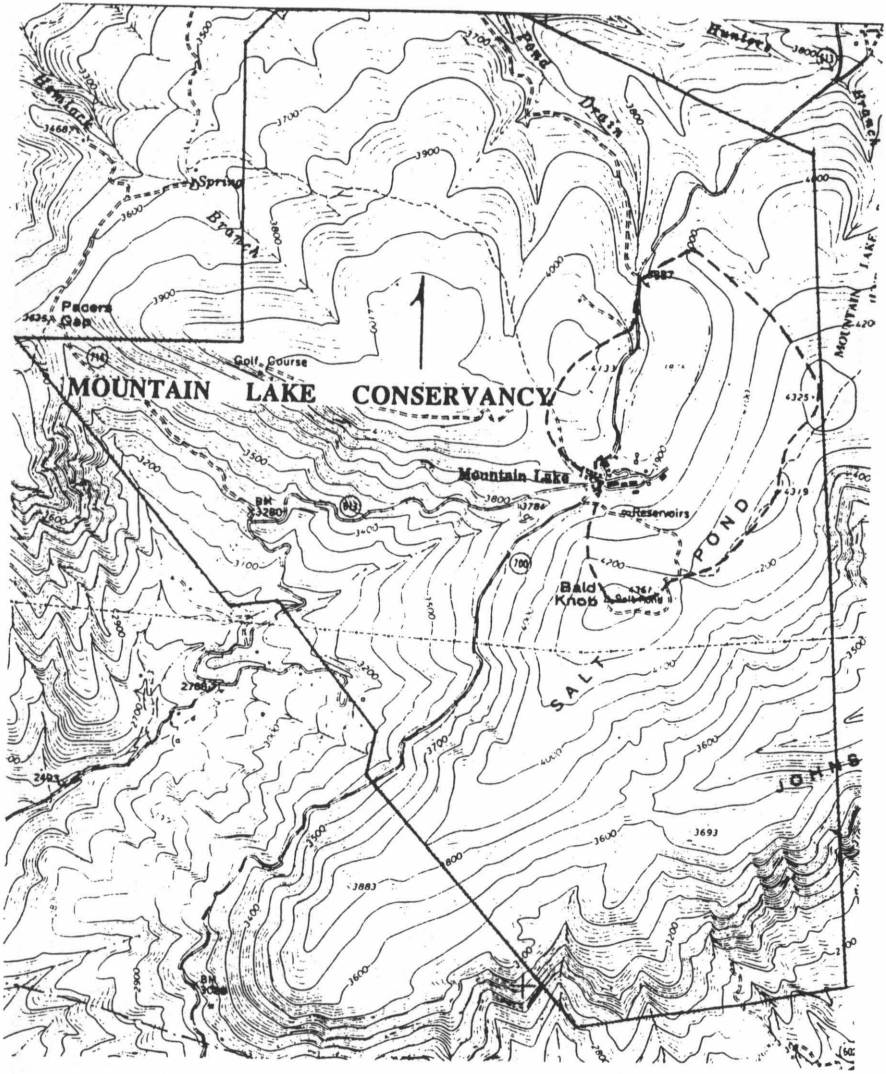


**Figure 6. Two major samplers used in the Mountain Lake research: (A) Kemmerer water bottle for collecting water at select depths; (B) Ekman dredge for collecting macrophytes and sediments from the lake bottom.**

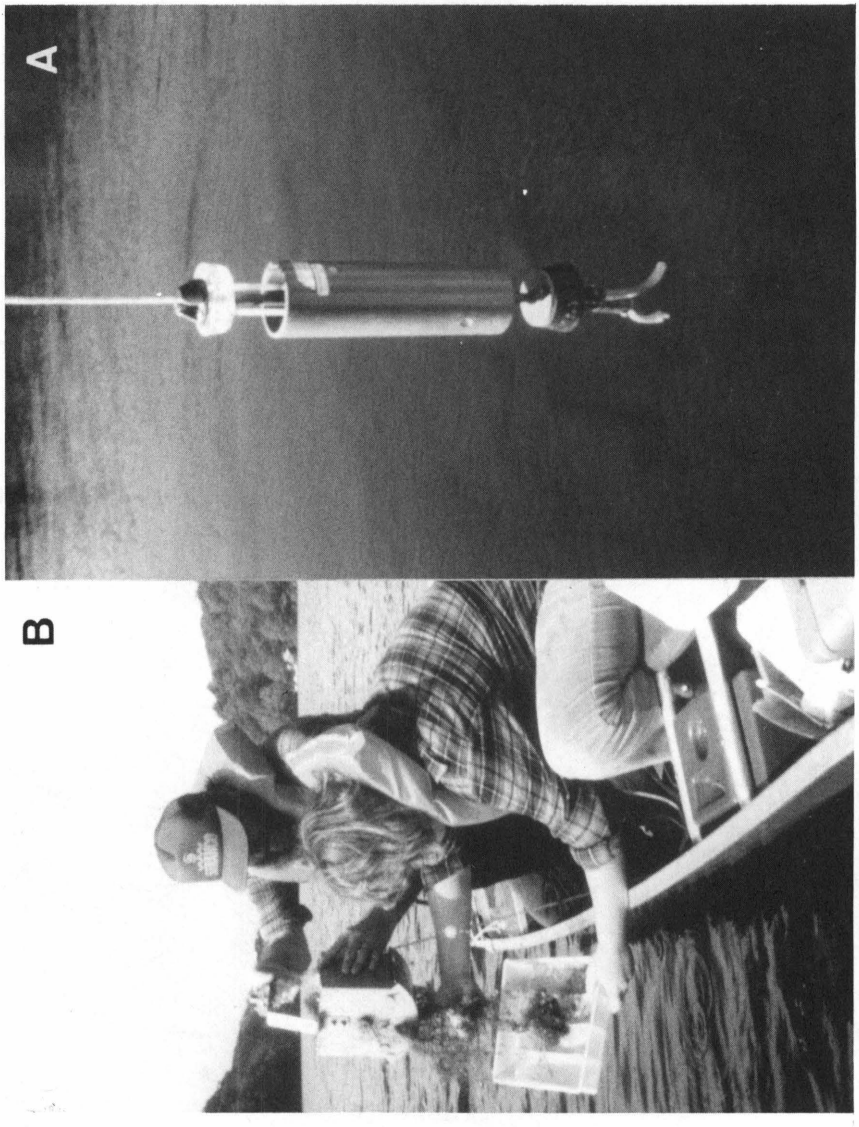


**Figure 7. Two instruments for measuring photosynthetically available light: (A) Pyrrono-graph measures light continuously at the lake surface; (B) Radiometer and attached submersible sensor (rear) measures light at various depths in Mountain Lake.**

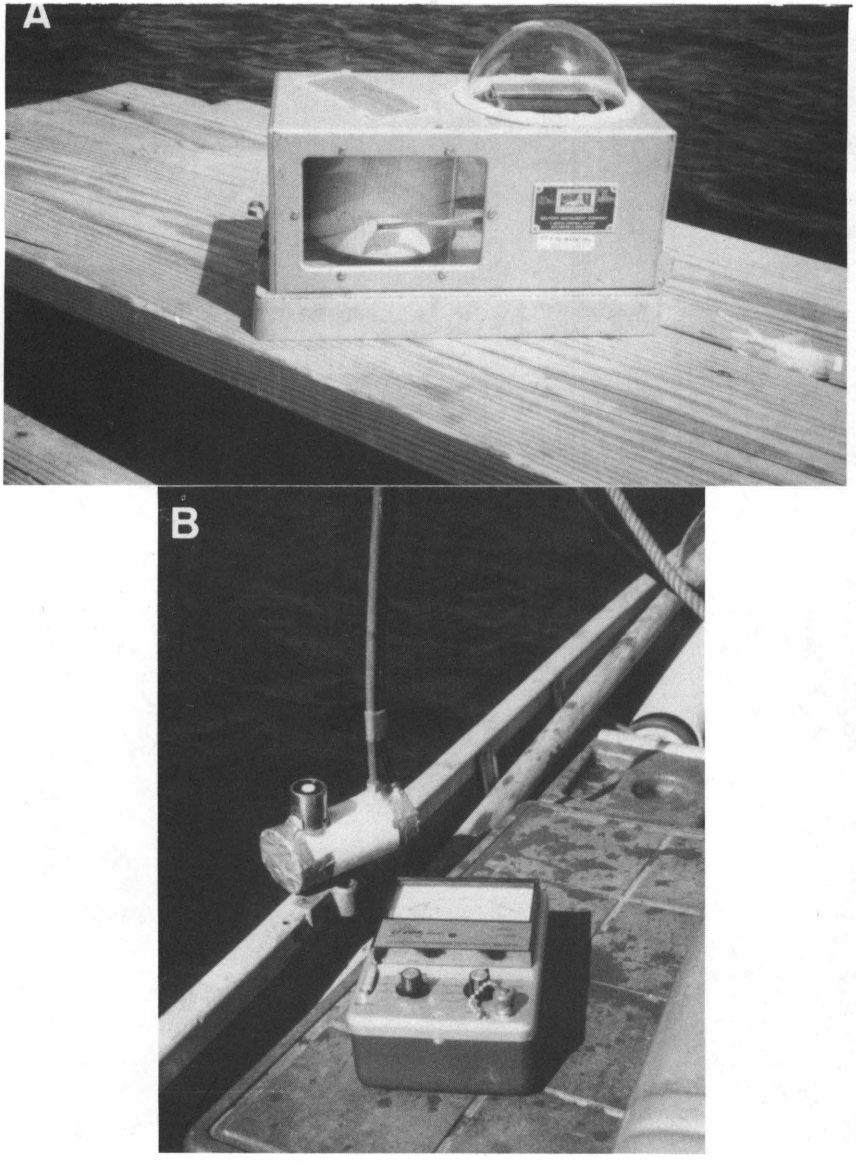


**Figure 8. Other instruments or devices used in Mountain Lake research: (A) pH and redox meter (upper left), temperature-conductivity-salinity meter (upper right); (B) Primary productivity bottles for measurements of phytoplankton photosynthesis rates at various depths.**

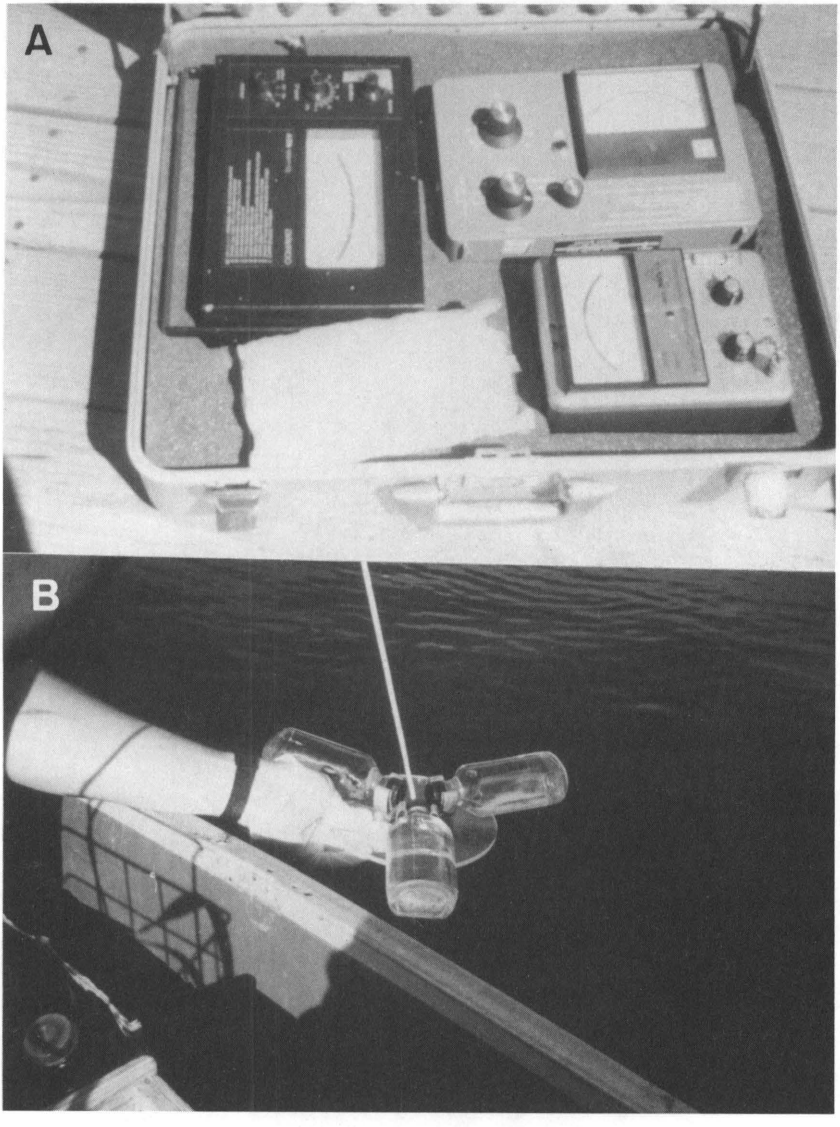


**Figure 9. Annual mean concentrations of nitrate-nitrogen in Mountain Lake. Line segments represent the ranges in monthly mean values.**

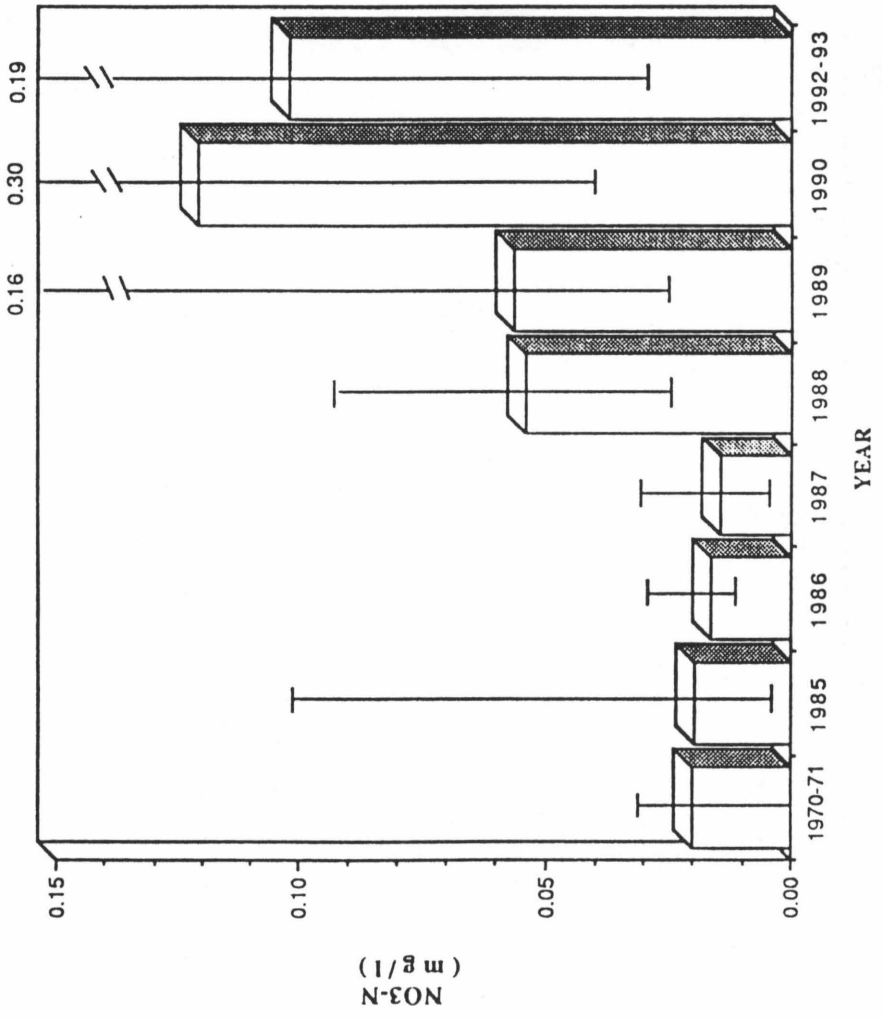


**Figure 10. Annual mean concentrations of ammonia-nitrogen in Mountain Lake. Line segments represent the ranges in monthly mean values.**

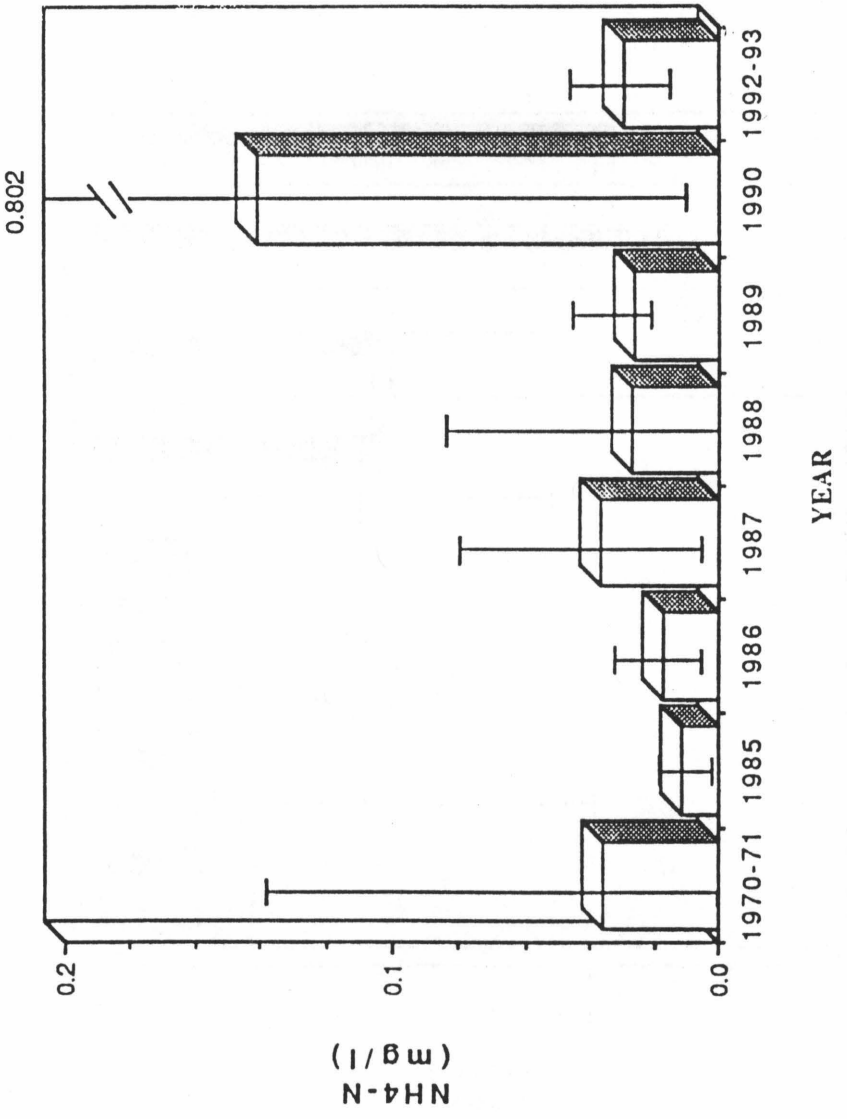


**Figure 11. Annual mean concentrations of orthophosphate-phosphorus in Mountain Lake. Line segments represent the ranges in monthly mean values.**

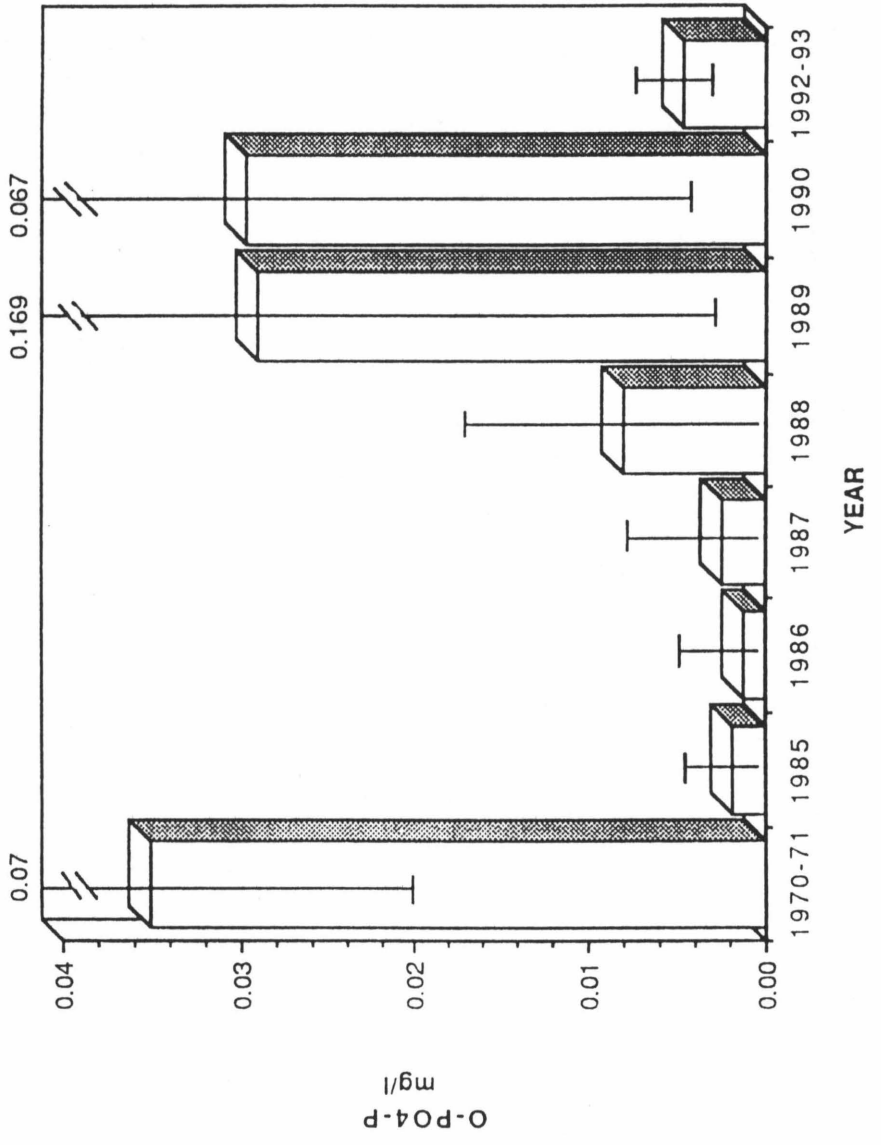


**Figure 12. Fecal coliform plate counts for surface samples at the north end of Mountain Lake. November 1988 - January 1990. Values are means of 6 replicates (Parker, unpubl.).**

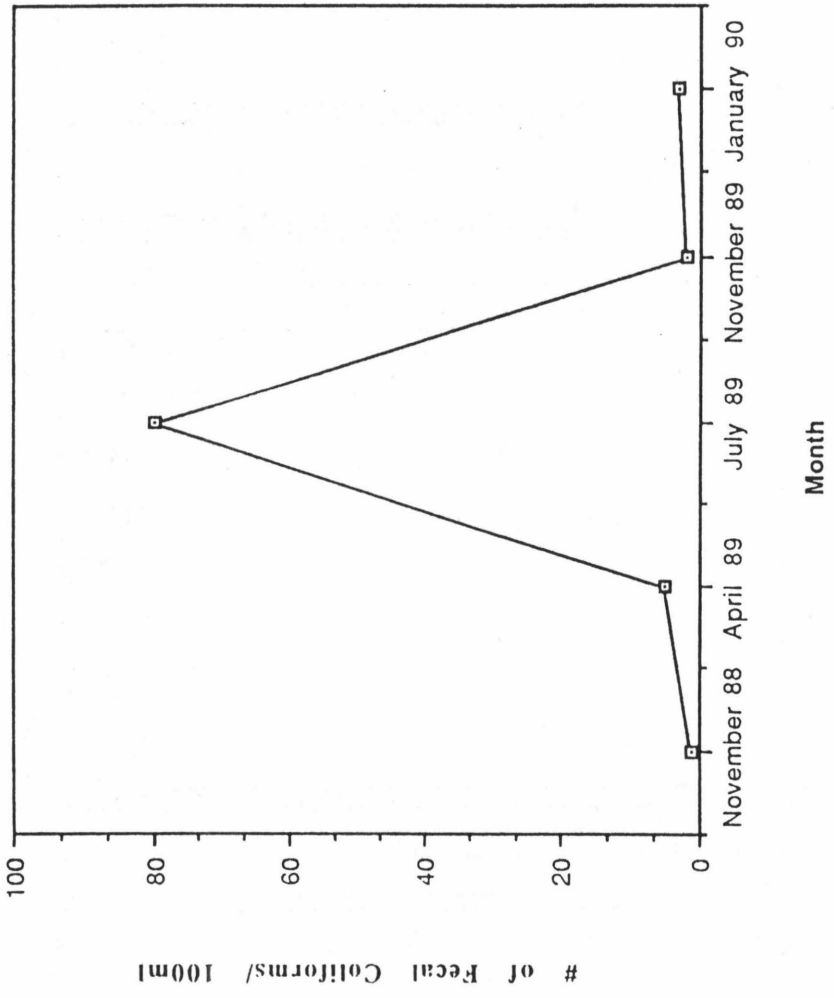
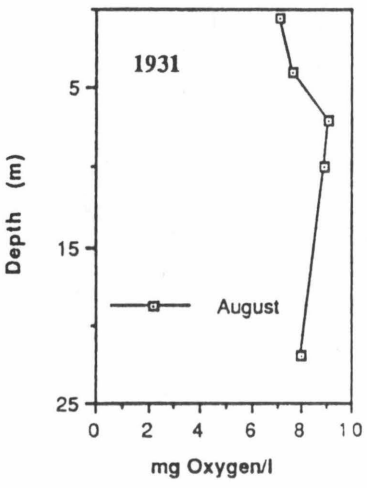
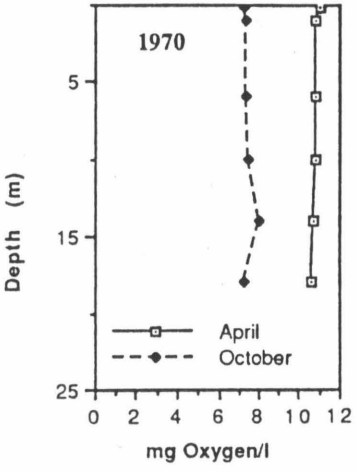


**Figure 13.** Representative oxygen profiles, 1931 to 1989, for Mountain Lake. Values for 1970 and 1989 are means of 2 replicates for each date. 1931 from Hutchinson and Pickford (1932), 1970 from Obeng-Asamoa (1971), and 1989 from Parker (unpubl.).



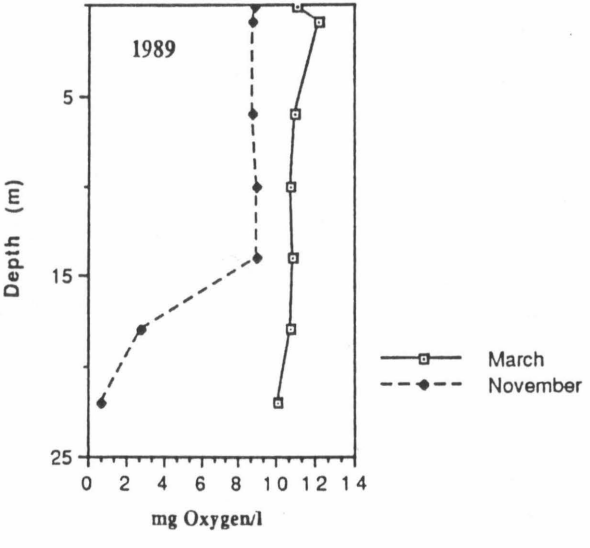
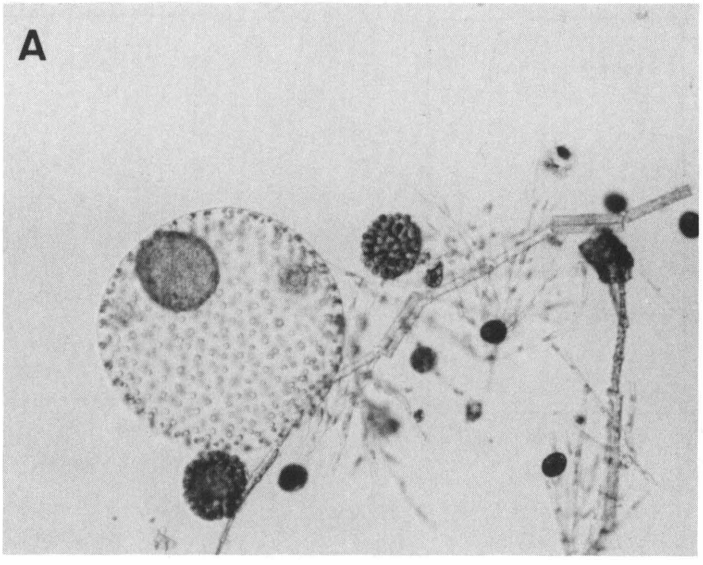



**Figure 14.** Some phytoplanktonic algae common during spring in Mountain Lake: (A) Typical algal community (343X); (B) *Volvox aureus* Ehrenberg (Chlorophyta, Chlorophyceae, Volvocales, Volvocaceae) (686X); (C) *Staurastrum ophiura* Lundell (Chlorophyta, Charophyceae, Zygnematales, Desmidiaceae) (1372X).



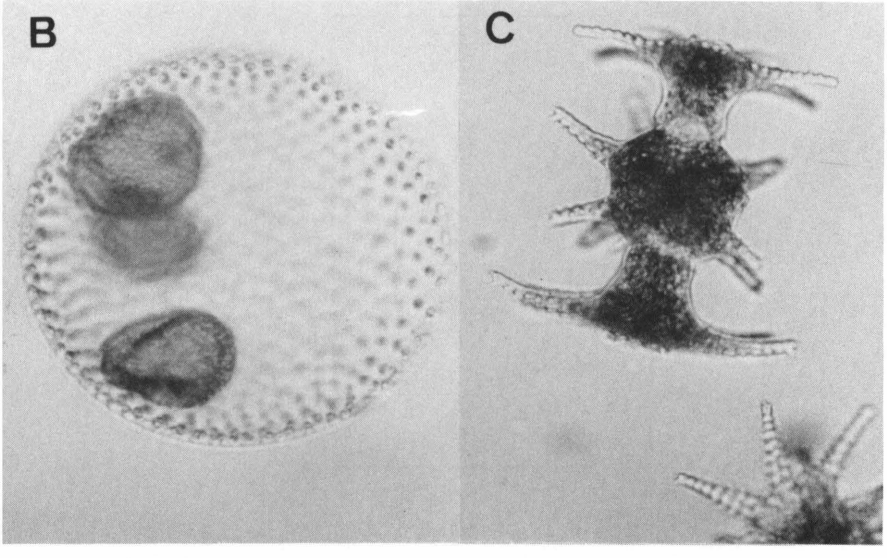



**Figure 15.** Some phytoplanktonic algae common during spring in Mountain Lake (1372X): (A) *Pandorina morum* (Muell.) Bory (Chlorophyta, Chlorophyceae, Volvocales, Volvocaceae); (B) *Sphaerocystis schroeteri* Chodat (Chlorophyta, Chlorophyceae, Chlorococcales, Palmellaceae); (C) *Quadrigula chodati* (Tanner-Fullman) G. M. Smith (Chlorophyta, Chlorophyceae, Chlorococcales, Oocystaceae); (D) *Gymnodinium* Stein (Dinophyta, Dinophyceae, Gymnodiniales, Gymnodiniaceae), which may be a new species.

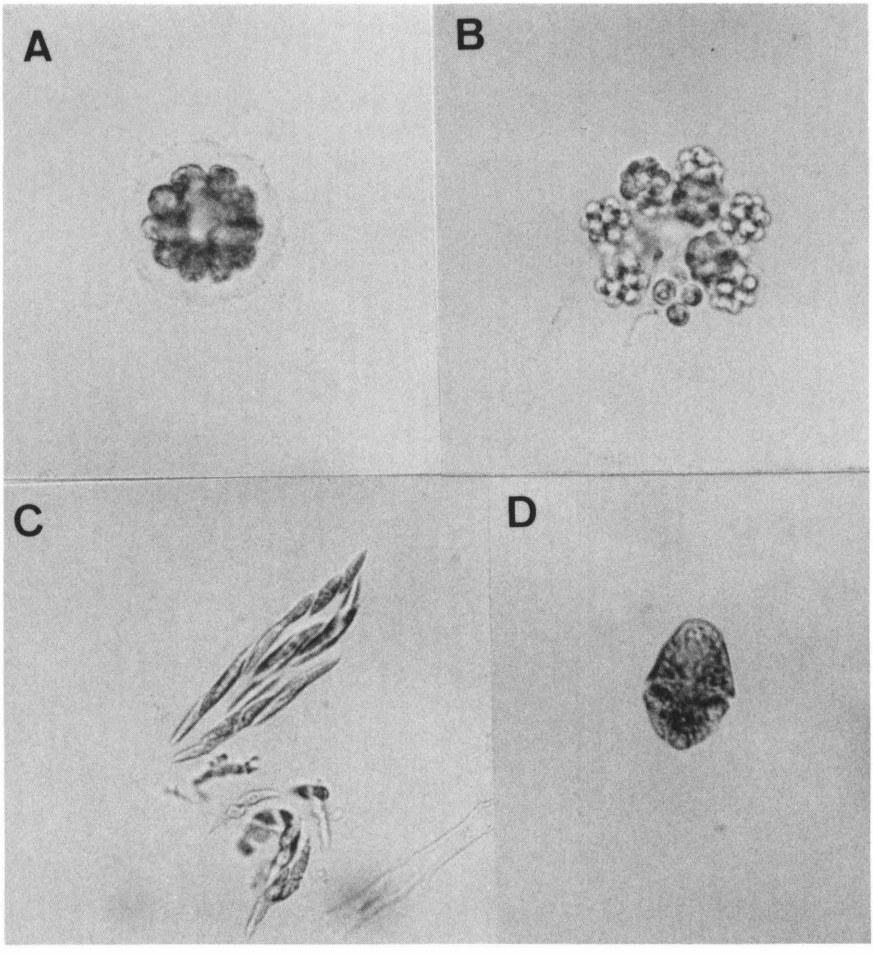


**Figure 16. Four heterokontophytan phytoplankton in Mountain Lake: (A) *Dinobryon cylindricum* Imhof (Chrysophyceae, Chromulinales, Dinobryaceae); (B) *Synura* sp. Ehrenberg (Synurophyceae, Synurales, Synuraceae); (C) *Tabellaria fenestrata* (Lyng.) Kuetzing (Bacillariophyceae, Pennales, Diatomaceae); (D) *Cyclotella meneghiniana* Kuetzing (Bacillariophyceae, Centrales, Thalassiosiraceae) (1372X).**

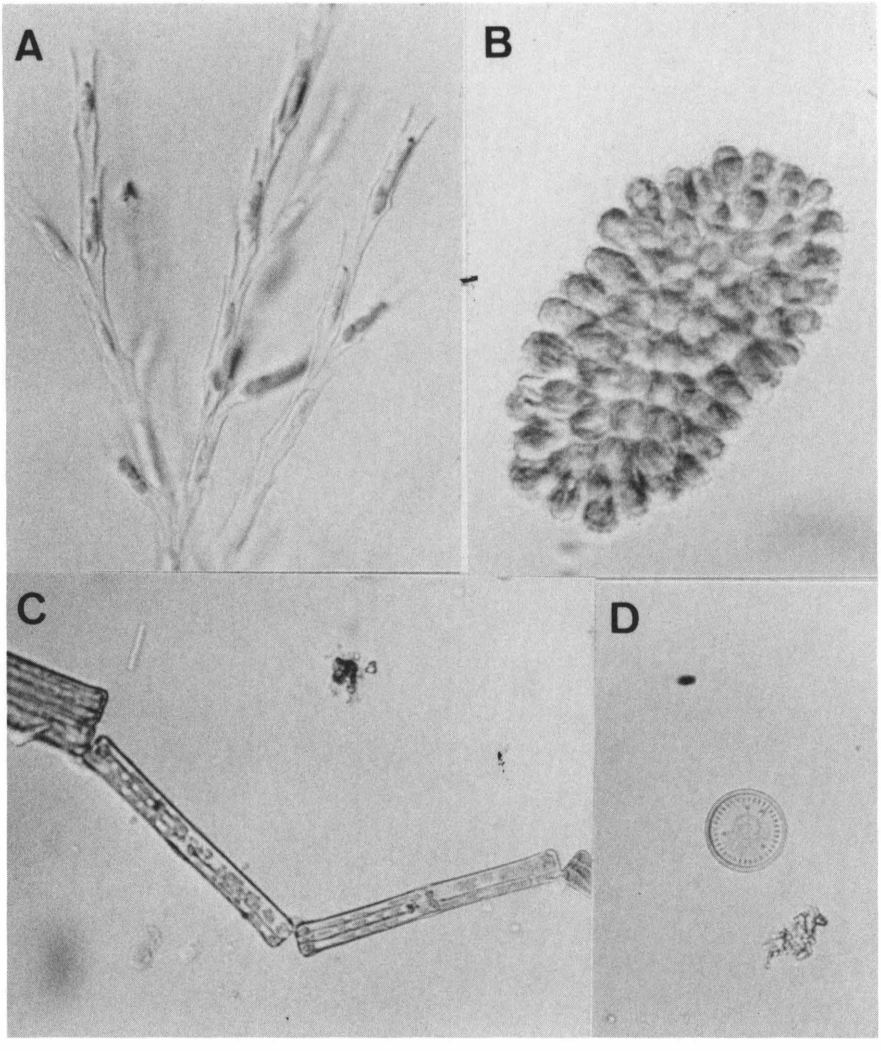


**Figure 17.** Some zooplankton common in Mountain Lake: (A) A rotifer resembling the genus *Keratella* (686X); (B) A copepod filled with orange pigment, presumably carotenoids derived from algae recently consumed (343X); (C) *Daphnia* with numerous attached *Vorticella* (343X).

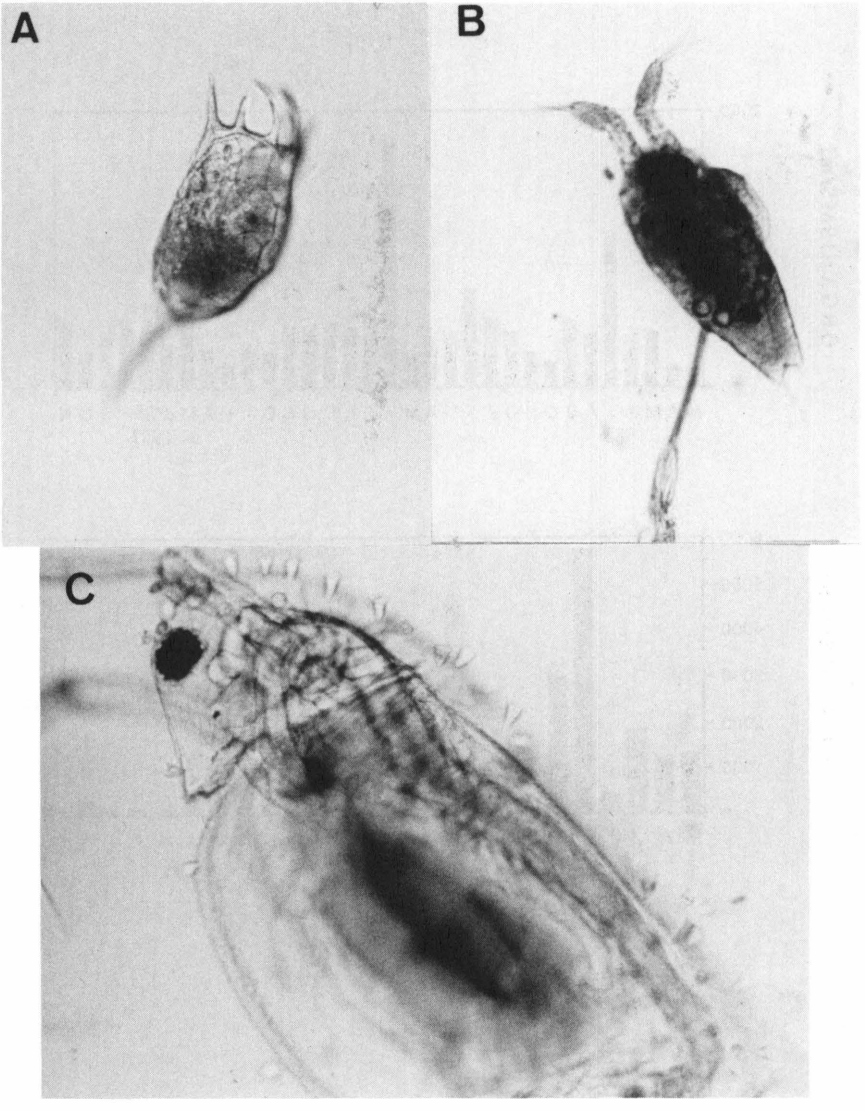
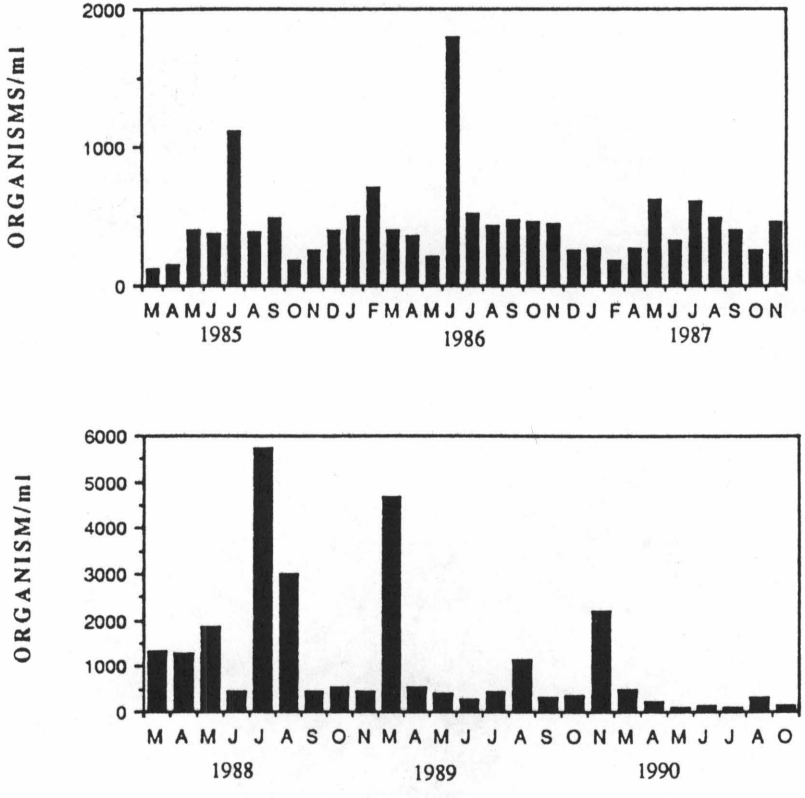


**Figure 18. Cell densities for Mountain Lake, Virginia from 1985 - 1990. 1985-87 data from Parson (1988); and 1988-90 data from Parker (unpublished).**



# Notes

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