THE TROPHIC STATE OF MOUNTAIN LAKE, GILES COUNTY, VIRGINIA

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Figure 1. Mountain Lake, Giles County Virginia--Aerial Infra-Red View Showing North End of Lake.

INTRODUCTION

Mountain Lake is a dimictic, subalpine, (and at least until recently) oligotrophic ecosystem located in the ridge and valley province of the southern Appalachians (37°21'56"N, 80°31'39"W) (Figure 1). This lake, when full of water, measures maximally 0.9 km long, 0.25 km wide, >25m deep, surface area 18.9 ha. It overlies three geological formations: Ordovician Martinsburg shale, Ordovician Juniata sandstone, and Silurian Clinch sandstone. Mountain Lake's unusual, if not unique, origin ≥ 6,000 years ago and its periodic lake level fluctuations primarily stem from a geological fracture or fault which crosses the lake bottom from southeast to northwest and includes an incompletely sealed hole at 33 meters depth through which about one-half of the lake's water can escape (Figure 2) (Cawley, Parker, and Perren, unpublished.)

EARLY SIGNS OF EUTROPHICATION

Despite a number of earlier references to various perturbations to Mountain Lake [Parson and Parker (1989a)], most investigators have viewed this ecosystem as "pristine" and "oligotrophic". However, Beaty and Parker (1994) for the first time warned that the lake might be entering early stages of eutrophication and that it had changed from oligotrophic in 1985-87 to oligomesotrophic by 1990. The bases for this assertion were:

(1) Increases in concentrations of orthophosphate (1988-93), ammonium (1990), nitrate (1988-93) and decreases in the N:P ratios (1988-1993) compared to values for 1985-87 (Table 1).
(2) Attention was also called to slightly reduced Secchi disk transparency values,
(3) A significant long-term increase in hypolimnetic oxygen deficit values (1962-93),
(4) The first observation of anoxic bottom water in October 1994,
(5) Relatively higher primary productivity in 1989, and possibly higher extractable chlorophyll (1985-89).

Subsequently Beaty and Parker (1996a) reported that microplankton algae (cells 20-200um) represented the dominant size fraction in terms of cell numbers and cell volume and contributed 95% of the total primary productivity. Beaty and Parker (1996b) also showed that phytoplankton primary productivity significantly increased two days after enrichments with K_2HPO_4+NH_4NO_3+ micronutrients, as well as K_2HPO_4 or NH_4NO_3 alone. Over two days PO_4^{-3} and NH_4^+, but not NO_3^-, decreased in the enrichment chamber solutions but phytoplankton cell numbers and species did not change. In short, these studies all suggested that eutrophication may have been occurring as a consequence of increases in the limiting nutrients orthophosphate -P and ammonium-N to Mountain Lake. Observations that the native attached Nitella megacarpa, the dominant macrophyte, had declined by 1990 to 10% of its 1973 biomass and that the invasive weed Ceratophyllum demersum may have increased (Parker et al., 1991) earlier had signaled probable deleterious changes in Mountain Lake.

Figure 2. Sonar Bathymetric Map of Mountain Lake in 1997 Showing Fracture Trace.

Table 1. Orthophosphate-P, Ammonium-N, Nitrate-N and N/P Ratios for Mountain Lake, 1985-93.

	PO_4-P		NH_4-N		NO_3-N		N/P Ratio
Year	Range	X	Range	X	Range	X	
1985	1.0-4.0	2.0	5-163	11.0	1-97	20.0	15.5:1
1986	1.0-4.0	1.0	6-30	18.0	10-24	16.0	34.0:1
1987	1.0-8.0	2.0	6-77	37.0	3-28	15.0	26.0:1
1988	0.0-17.	8.0	2-76	27.0	31-67	54.0	10.1:1
1989	3.0-169.	29.0	14-44	26.0	24-160	57.0	2.9:1
1990	4.0-67	27.0	4-802	139.0	37-300	114.	9.4:1
1993	3.0-19.	8.0	5-71	30.0	27-193	81.0	13.9:1

REVALUATION OF THE TROPHIC STATE

From 1996-99, Cawley and Parker undertook studies of the geomorphology, paleontology of sediment cores, and the origin of Mountain Lake. In addition to this research, they reexamined the trophic state of the lake and for the first time evaluated nutrient input sources. These investigations were conducted from June to October 1997 and April to October 1998. Monthly samples of lake water, five input streams, an adjacent marsh, and all major rainwater collections were examined for nutrient contents, whereas the lake was examined for certain other variables as listed in Table 2.

The magnitude of this study, which included input streams and rainwater, precluded additional measurements of primary productivity and extractable chlorophyll. Water samples, if turbid, were filtered through a Whatman GF/C, then all samples were frozen until needed for analysis.

Table 2. List of Variables, Methods, and Instruments Used at Mountain Lake in 1997-98.

Water Samples	
Lake-	**Kemmerer Bottle (Wildco Supply, Saginaw, Michigan) to Acid-Washed Polypropylene Bottles.**
Input Streams-	**Direct to Acid-Washed Polypropylene Bottles.**
Rainwater-	**From Calibrated Collectors to Acid-Washed Polypropylene Bottles.**
Temperature °C	**Yellow Springs S-C-T Meter, Model 33 (Yellow Springs Instruments Company, Yellow Springs, Ohio)**
Transparency	**Secchi Disk**
PH	**Indicator Dye Solution**
Hardness	**Titrimetric, EDTA (APHA-AWWA-WEF, 1995)**
Alkalinity	**Titrametric, Methyl Purple (APHA-AWWA-WEF, 1995)**
Dissolved Oxygen	**Modified Winkler (APHA-AWWA-WEF, 1995)**
Ammonium Nitrogen	**Phenate Method (Lind, 1979)**
Nitrate Nitrogen	**Cadmium Reduction Method (APHA-AWWA-WEF, 1995)**
Orthophosphate-P	**Ascorbic Acid Method; Isobutanol Extraction (Murphey and Riley, 1962)**
Dissolved Silica	**Molybdate Method (APHA-AWWA-WEF, 1995)**
Phytoplankton	**Acid Lugol's Fixation and Utermohl Settling (Vollenweider, 1969)**

RESULTS AND DISCUSSION

Temperature. Water column temperature showed a similar pattern in 1997 and 1998 as with previous years. Temperatures ranged from 23˚C maximum at the surface (July) to 4-5˚C at and below 18m. Mountain Lake was dimictic, turning over and fully mixing in March and November, as usual.

Transparency. Secchi disc values ranged from 3.2-8.5m (mean 5.5m) in 1997 and from 3.7-6.5m (mean 4.5m). These values are slightly less than values recorded from 1985-93 (mean 5.8m) (Beaty and Parker, 1994).

Alkalinity, Hardness, and pH. Lake bicarbonate alkalinity values also remained quite low, averaging 6.41 mg/L in the lake, 0.522 in rainwater, 35.07 in the marsh, and 14.23 in the input streams. Rainwater will reduce, whereas the marsh and input streams will increase the lake's alkalinity. Runoff from limestone ($CaCO_3$+Mg) used for construction at the south end will contribute to an increase in lake alkalinity.

Lake calcium and magnesium hardness values also remained low within the relatively undisturbed lake basin. Mean values for the lake (20.84 mg/L), rainwater (16.0), marsh (52.67) and input streams (34.67) show that the marsh and streams are presently sources for increased lake water hardness. Many of these higher values no doubt come from solution of the limestone ($CaCO_3$+Mg) introduced near the south end of the lake.

Table 3. Orthophosphate-P, Ammonium-N, Nitrate-N and N/P Ratios for Mountain Lake, 1997-98.

	PO_4-P		NH_4-N		NO_3-N		N/P Ratio
Year	Range	Mean	Range	Mean	Range	Mean	
1997	0.1-2.4	1.5	0.6-48.	17.0	17-600.	200	143.:1
1998	0.1-8.0	2.2	0-92.	16.0	0-618.	500	244.:1

Lake pH ranged from <6.0 to 6.8. The range for marsh (6.8-7.4) reflects both a limestone contribution and high productivity of the marsh plants. Whereas marsh input to Mountain Lake will slightly raise the lake water pH, many rains (<4.0-6.0) and some input streams (4.0-7.2) will slightly lower the lake water pH.

Dissolved Oxygen Depletion. The lowest lake-bottom oxygen values detected were of 0.4 mg/L at 20m in October, 1997 and 1.0 mg/L at 19m in October 1998. We cannot state that the lake bottom had anoxic conditions during either the 1997 or 1998 season. Localized anoxia may have been present, had we been able to locate and sample depths >23m in the water column. Still, lake bottom anoxia may have been less developed during these two seasons than it has been in the recent past (Beaty and Parker, 1994).

Table 4. Phytoplankton Counts (as organisms/ml) by Depth and Month for Mountain Lake, Virginia during Summers of 1997 and 1998.

Depth	May	June	July	August	September	October
1997						
1.0 m		788	825	408	4120	382
6.0 m		657	668	336	3030	5710
1998						
1.0 m	497	6084	14579	5241	1300	307
6.0 m	842	1122	1353	12431	2450	1053
10.0 m	216	754	6908	6764	600	261
17.0 m		150	1527	7351	4331	568

Dissolved Silica. The mean values for dissolved silica (as SiO_2) in Mountain Lake (0.385 mg/L), rainwater (0.38), marsh (0.070) and input streams (0.412) were quite low and probably limiting to growth of some diatoms with silicious cell walls. The literature and earlier studies at Mountain Lake suggested that <1.0 mg SiO_2/L were limiting to planktonic diatoms. Other algae with lower silica requirements, such as the silicious scaled Synura or the silicious spined Mallomonas probably were not limited in Mountain Lake. Also, most other phytoplankton algae (bluegreens, greens, etc.) have little or no silica requirement. The attached Aufwuchs, periphytic, epiphytic) diatoms in Mountain Lake may have been less limited by SiO_2, because they received higher volumes of water flowing past their cells and thus may have extracted more dissolved silica from the water (Figure 3). Silica was not determined during 1997.

Table 5. Phytoplankton Taxa in Mountain Lake, Virginia in 1997 and 1998 (Dominant taxa shown in bold).

Cyanoprokaryota (Bluegreen Algae):
Chroococcus dispersus var. minor
Gloeocapsa halmatodes
Aphanothece microscopica
Anabaena sp.

Chlorophyta (Green Algae)
Chlamydomonas sp.
Scourfieldia complanata
Pandorina morum
Eudorina elegans.
Chlorella vulgaris
Chlorococcum sp.
Oocystis pusilla
Scenedesmus bijuga
Gloeocystis planktonica
Selenastrum sp.
Crucigenia quadrata
Quadrigula chodatii
Chodatella sp.
Arthrodesmus quadratus
Mesotaenium sp.
Cosmarium phaseolus
Staurastrum limneticum
Mougeotia sp.
Pediastrum boryanum
Tetraedron sp.
Trochiscia (zygospore?)

Chrysophyta (Golden Algae)
Dinobryon elegantissimum
Synura sp.
Chromulina ovalis
Chlorochromonas minuta
Mallomonas caudata
Mallomonas acaroides

Bacillariophyta (Diatoms)
Navicula gracilis .
Cyclotella compta .
Synedra ulna
Achnanthes sp.
Gomphonema angustatum
Cymbella sp
Fragilaria sp
Tabellaria fenestrata
Tabellaria flocculosa

Dinophyta (Dinoflagellates)
Gymnodinium sp.
Peridinium inconspicuum

Euglenophyta (Euglenoids)
Phacus sp.
Trachelomonas sp.

Chryptophyta (Cryptophytes)
Chroomonas norstedii
Cryptomonas ovata

Orthophosphate-P, Ammonium-N, and Nitrate-N. As in the past, inorganic nitrogen and phosphorus have been considered the potential major limiting nutrients in Mountain Lake (Parson and Parker, 1989a, 1993; Beaty and Parker, 1994, 1996a, b). Table 3 lists the ranges and means for these nutrients during 1997 and 1998.

Lake ortho- or soluble reactive phosphate-phosphorus ranged slightly higher and showed a slightly higher mean (2.2 ugP/L) in 1998 than in 1997 (1.5). All phosphate values in 1998 and 1997 represent values for healthy oligotrophic lakes and an improvement from values reported by Beaty and Parker (1994) (8.7 ugP/L). The slightly higher input P values for 1998 probably resulted from the relatively wetter winter, spring, and early summer — thus more P input from rain, runoff, and springs. Rainwater collected in 1998 contained on the average 55 times the phosphate-P in the lake. Input streams and the marsh had several times the P occurring in the lake. The higher phosphate-P levels reaching the lake failed to show up in the lake, because as a major limiting nutrient, orthophosphate probably was rapidly taken up by cells.

The presence of one or more Dinobryon species in abundance during 1997 and 1998 is a biological indicator of low phosphate (Hutchinson, 1967). Also, the apparent spread of Nitella, another low phosphate genus, and retreat of the invasive Ceratophylum also points to a return to oligotrophic conditions similar to those measured in the past (Figure 4).

Table 6. Ranges and Means for Select Variables for Seven Input Sources to Mountain Lake During 1997-98.

Variable	1997		1998	
	Range	Mean	Range	Mean
PO_4-P (ug/l)	1.0-11.0	4.5	0.0-32.0	8.0
NH_4-N (ug/l)	1.0-230.0	23.4	0.0-2200.0	75.6
NO_3-N (ug/l)	27.0-4750.0	1141.0	0.0-5240.0	1198.0
pH	5.9-7.7	6.4	4.0-7.2	6.1
SiO_2 (mg/l)			0.0-2.2	0.44
Bicarbonate Alkalinity (mg/l)			0.0-75.0	14.2
Ca + Mg Hardness (mg/l)			8.4-200.0	34.7

Lake ammonium-nitrogen probably is the most important nitrogen nutrient in the lake (Parson and Parker, 1993). The range (0-92.0 ugN/L) and mean (16.0) for 1998 barely differed from the range (6-480) and mean (14.0) for 1997. These values corresponded well with those of Beaty and Parker (1994). Again as with phosphate, the primary outside source of ammonium-N is rainfall with a mean (503 ugN/L) 31 times that for the lake, suggesting that ammonium entering the lake was quickly assimilated, as shown by Parson and Parker (1993) and Beaty and Parker (1996b). The marsh and input streams also contributed some ammonium-N to the lake, particularly early in the season, possibly from road salt.

These concentrations of ammonium will be inhibitory to nitrogen fixation, which in part explains why certain nitrogen-fixing bluegreen algae (e.g. Anabaena) were seen only rarely in our phytoplankton samples. Similarly, a decrease in ammonium input to the lake would likely cause an increase in these heterocystous bluegreen algae.

Lake nitrate-N ranged (0 to 3,200 ugN/L) and averaged (500) in 1998, higher than it ranged (17-600) and averaged (200) in 1997. Both rainwater and input streams were sources of nitrate-N, and probably also springs in the lake, which would have flowed extensively during the wetter 1998 year. Our nitrate values for 1998 and 1997 are 8 times and 4 times higher than those of Beaty and Parker (1994). However, the input of nitrate need not be higher than for Beaty and Parker; rather the lake biota may be consuming less nitrate than during the earlier Beaty and Parker study. Although nitrate is not presently the limiting nutrient to this system, it will be prudent to control nitrate input to the lake wherever possible.

N:P Ratios. Ratios of N:P for 1997 (143) and 1998 (244) show that phosphorus, and not nitrogen, is the severely limiting nutrient. Beaty and Parker (1994) had lower NO_3-N and higher PO_4-P values, which led to N:P ratios approaching 20:1. Ratios of 20:1 to 10:1 usually cause growth limitations for both P and N. Redfield (1958) proposed 16:1, and Hillebrand and Sommer (1999) suggested 17:1 . So, presently P is the key limiting nutrient by far in Mountain Lake with an N:P ratio of >100:1.

Phytoplankton Counts and Taxa in Mountain Lake, 1997 and 1998. Table 4 shows the ranges and means for individual cell counts for the years 1997 and 1998. These numbers are similar to those observed in 1985-87 and no more than 20% of the phytoplankton cell densities observed in 1988-1990 (Beaty and Parker, 1994). Table 5 lists the phytoplankton taxa identified from samples taken in 1997-1998. Only 5 of the 41 taxa listed were not previously reported in Mountain Lake (Parson and Parker, 1989b) and their common occurrence in freshwaters of the southeastern U.S. gives no reason to suspect that a major change in the phytoplankton community structure has occurred.

Input Stream Variables to Mountain Lake, 1997 and 1998. Table 6 summarizes variables measured on water samples collected from seven input sources to Mountain Lake. Input streams and runoff from a marsh contributed a small amount of phosphate-P, a moderate amount of ammonium-N, and a large amount of nitrate-N to the lake in both 1997 and 1998. The pH of input water was slightly acid and close to that for the lake itself. Inputs of dissolved silica, alkalinity, and hardness also were similar to the lake itself.

Table 7. Ranges and Means for Select Variables in Mountain Lake Rainfall During 1997-98.

Variable	1997		1998	
	Range	Mean	Range	Mean
PO_4-P (ug/l)	1.0-29.0	20.8	0.5-700.	114.2
NH_4-N (ug/l)	21.0-580.0	269.7	7.0-2400	517.2
NO_3-N (ug/l)	80.-2000.	993.9	200.-8400.	2624.3
pH	4.7-7.2	5.0	4.0-6.6	4.6
SiO_2 (mg/l)			0.0-17.6	0.38
Bicarbonate Alkalinity (mg/l)			0.0-6.1	0.5
Ca + Mg Hardness (mg/l)			0.0-28.4	16.0

Table 7 summarizes the variables measured for major rainwater collections near Mountain Lake. Obviously rainwater represents a major contributor of PO_4-P, NH_4-N, NO_3-N, and acidity to Mountain Lake. Dissolved silica, alkalinity and hardness contributions by rainfall are of little consequence.

Figure 3. Diatoms *Navicula* and *Cyclotella.*

CONCLUSIONS

Our studies have shown that by 1997 and 1998, phosphate levels had returned from higher oligomesotrophic values of 8-29µg P/L (1988-93) to lower oligotrophic values of 1.5-2.2µg P/L commensurate with the earlier 1980s. This return to low phosphate and the increase in nitrate has created an N:P ratio of >100:1, clearly making phosphate the key limiting nutrient responsible for the oligotrophic state of Mountain Lake. Of the nutrient sources entering the lake, the streams contribute little enrichment. However, precipitation provides a major source of PO_4 P, NH_4-N, NO_3-N, and acidity. In contrast to the warning of Beaty and Parker (1994), we now suggest that Mountain Lake is not undergoing eutrophication.

Figure 4. *Dinobryon*, *Nitella* and *Ceratophyllum.*

REFERENCES

American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF). 1995. Standard Methods for the Examination of Water and Wastewater (18th ed.). APHA, Washington, D.C.

Beaty, M. H. and B. C. Parker, 1994. Investigations of eutrophication in Mountain Lake, Giles County, Virginia. Virginia Water Resour. Res. Center Bull. 184 and the Wilderness Conservancy at Mountain Lake Occasional Paper No. 1: i-x, 1-66.

Beaty, M. H. and B. C. Parker, 1996a. Relative importance of pico-, macro-, and microplankton to the productivity of Mountain Lake, Virginia. Hydrobiologia. 331: 121-129.

Beaty, M. H. and B. C. Parker, 1996b. Response of phytoplankton primary productivity to nutrient enrichment at Mountain Lake, Virginia. J. Freshw. Ecol. 11(4): 421-431.

Hillebrand, H. and U. Sommer. 1999. The nutrient stoichiometry of benthic microalgal growth: Redfield proportions are optimal. Limnol. Oceanogr. 44(2):440-446.

Hutchinson, G. E. 1967. A Treatise on Limnology. Vol. II. Introduction to Lake Biology and the Limnoplankton. John Wiley & Sons, Inc., New York.

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

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.

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.

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.
Redfield, A. C. 1958. The biological control of chemical factors in the environment. Am. Sci. 46:205-221.
Vollenweider, R.A. 1969. A Manual on Methods for Measuring Primary Production in Aquatic Ecosystems. Blackwell Scientific Pub., Oxford. 213 pp.

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