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# THE TROPHIC STATUS AND NUTRIENT CONCENTRATIONS OF CENTER HILL LAKE 1988

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Abstract

The collection and subsequent analysis of embayment and main channel data over an 11-month period for Center Hill Lake, a 40-year old U.S. Army Corps of Engineers reservoir constructed for flood control and hydroelectric power production in Middle Tennessee, indicates that the overall water quality has improved significantly over the past ten years. From the physical and chemical (nutrient) characterization of the Caney Fork River Basin it was concluded that: 1) anoxic conditions developed in both embayments, 2) the abundance of essential nutrients is significantly greater in the embayments than in the lake's main channel, 3) significant main channel trends between nutrient concentrations, depth, time and length exist, and 4) the main channel of the lake is mesotrophic and phosphorus-limited, and the embayments are eutrophic.

## Introduction

Over a ten-year period a number of studies have documented various physical and chemical water quality parameters for Center Hill Lake as well as its degree of eutrophy. Center Hill Lake has evolved during the last decade from a hydropower/flood control impoundment in a drainage basin subject to mining and agriculture to a multipurpose lake that supports a variety of recreational uses in a drainage basin characterized by silviculture and small communities. This study presents the 1988 summer nutrient concentrations for Center Hill Lake and the 1988 trophic states of the lake's main channel and embayments.

## Materials and Methods

### *Field Collection*

Water samples were collected and dissolved oxygen (DO) concentrations and Secchi disk depths were measured for four main channel stations at Caney Fork River Miles (CFRM) 27.2, 31.9, 48.8, and 61.1 and for two embayment stations, influenced primarily by the stream inflow, at Falling Water River Mile 5.1 and Mine Lick Creek Mile 2.0. At each main channel station water samples were collected from the epilimnion, metalimnion, and hypolimnion. At each embayment station water samples were collected at the following depths: 1) 0.5 meters below the water surface, 2) halfway between the water surface and the thermocline, 3) 1.0 meter above the thermocline, 4) 1.0 meter below the thermocline, 5) halfway between the thermocline and the bottom of the lake, and 6) 0.5 meters above the lake's bottom. All water samples were pumped into sterile plastic containers, transported in ice, and held at 4°C until analysis. DO concentrations were measured at each depth using a Hydrolab Surveyor II (Model SVR2-SU).

### *Laboratory Analyses*

All water samples were chemically analyzed by Tennessee Technological University Water Center staff using U.S. Army Corps of Engineers and/or EPA-approved methods. Total and ortho-phosphate phosphorus concentrations were measured by a persulfate digestion/ascorbic acid colorimetric technique. Nitrite and nitrate-nitrogen concentrations were measured using a Technicon Auto Analyzer II cadmium-reduction procedure. Total nitrogen analyses followed the same procedure as that for nitrite-nitrate, but water samples were first digested with persulfate. Ammonia concentrations were also measured on the Technicon Auto Analyzer II. Organic nitrogen concentrations were calculated by subtracting inorganic nitrogen from total nitrogen. Blanks, spikes, and standards were run on more than 5% of the samples for quality assurance.

*Mathematical Analyses*

The 1988 trophic state of Center Hill Lake was determined using criteria set forth by Gakstatter, Dillon, and Carlson. Gakstatter (1975) assessed a variety of physical and chemical parameters associated with lake trophic conditions in order to develop criteria by which the trophic state of a lake could easily be judged. Gakstatter's trophic state criteria are based upon commonly measured parameters and are listed in Table 1 [Gakstatter, et al., 1975]. Dillon's trophic state model considers the hydraulics of the lake, the areal total phosphorus loading, and the phosphorus retention in the lake. Dillon's loading factor is defined by the following equation:

Table 1 Gakstatter's Key Parameter Values Associated with Three Lake Trophic Conditions

| Parameter | Oligotrophic | Mesotrophic | Eutrophic |
|---|---|---|---|
| Total Phosphorus (μg/l) | <10 | 10-20 | >20-25 |
| Chlorophyll $a$ (μg/l) | <4 | 4-10 | >10 |
| Secchi Disk (meters) | >3.7 | 2.0-3.7 | <2.0 |

$$\text{Effective Loading}=L(1-R)/p \quad (4)$$

where p, the annual flushing rate, is the annual discharge to lake volume ratio, L is the areal loading expressed in terms of grams total phosphorus per square mile per year, and R, the total phosphorus retention in the lake, is that fraction of the input phosphorus not lost through the outflow [Dillon, 1975]. Figure 1 is a representation of Dillon's model [Dillon, 1975]. In comparison to Gakstatter's and Dillon's criteria, which may be used in any region, Carlson's Trophic State Indices (TSI) are used to rate measured in-lake variables on a scale so that the severity of lake problems can be compared to other lakes in the area. Carlson's TSI equations are as follows [Carlson, 1977]:

TSI=60-14.41*ln(Secchi transparency, meters); (5)

TSI=9.81*ln(Chloro $a$, μg/l)+30.6; and (6)

TSI=14.42*ln(Total phosphorus, μg/l)+4.15. (7)

According to Carlson (1977), index values greater than 50 indicate a degree of eutrophy, between 35 and 50 a degree of mesotrophy, and below 35 a degree of oligotrophy.

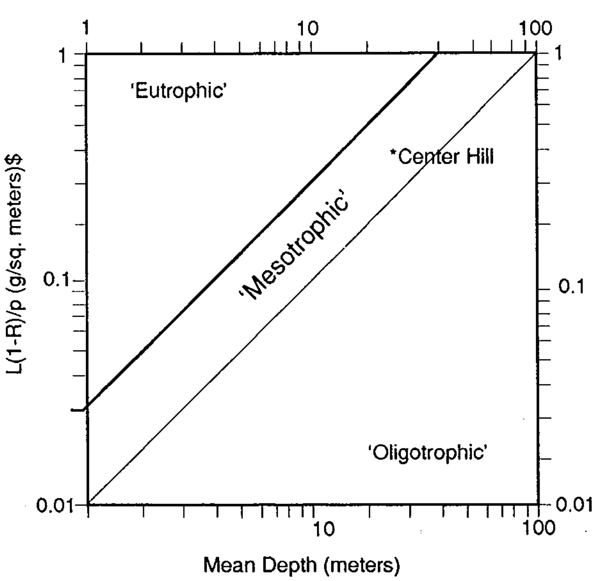


Figure 1. Dillon's Relationship for Center Hill Lake.

## RESULTS

*Nutrient Concentrations*

Monthly nutrient concentration/water quality sampling for Center Hill Lake embayment and main channel stations was performed from June through October 1988. Tables 2 and 3 list the nutrient and DO concentrations for the Falling Water River and Mine Lick Creek Embayments, respectively. Tables 4 through 7 list the nutrient and DO concentrations for Stations 2, 3, 4, and 5 of Center Hill Lake main channel. In order to better compare the water quality of the

Table 2. Nitrogen and Phosphorus Concentrations in Falling Water Embayment

| Depth (m) | DO (mg/l) | NO2/NO3 (mg/l) | NH3 (mg/l) | Total N (mg/l) | Organic N (mg/l) | Total P (μg/l) | Ortho P (μg/l) |
|---|---|---|---|---|---|---|---|
| 6/15/88 | | | | | | | |
| 0.6 | 13.0 | 0.01 | 0.15 | 0.38 | 0.23 | 51 | <10 |
| 3 | 15.3 | 0.62 | 0.15 | 0.77 | 0.01 | 29 | <10 |
| 5 | 5.8 | 0.01 | 0.18 | 0.42 | 0.23 | 67 | <10 |
| 7 | 0.6 | 0.01 | 0.18 | 0.47 | 0.29 | 44 | <10 |
| 15 | 1.5 | 0.66 | 0.20 | 0.86 | 0.01 | 55 | 23 |
| 23 | 1.4 | 0.01 | 0.03 | 0.46 | 0.43 | 40 | <10 |
| 7/8/88 | | | | | | | |
| 2 | 9.5 | 0.01 | 0.10 | 0.23 | 0.13 | 21 | <10 |
| 3 | 9.2 | 0.01 | 0.20 | 0.24 | 0.03 | 21 | <10 |
| 6 | 1.3 | 0.27 | 0.08 | 0.44 | 0.09 | 10 | <10 |
| 8 | 0.9 | 0.01 | 0.08 | 0.22 | 0.13 | 16 | <10 |
| 12 | 0.8 | 0.61 | 0.33 | 0.94 | 0.01 | 10 | <10 |
| 16 | 0.7 | 0.59 | 0.09 | 0.68 | 0.01 | 10 | <10 |
| 8/9/88 | | | | | | | |
| 1 | 10.3 | 0.01 | 0.03 | 0.31 | 0.27 | 25 | <10 |
| 3 | 8.8 | 0.24 | 0.18 | 0.42 | 0.01 | 20 | 13 |
| 5 | 2.7 | 0.01 | 0.06 | 0.36 | 0.30 | 19 | <10 |
| 12 | 0.5 | 0.07 | 0.15 | 0.41 | 0.19 | 29 | 24 |
| 15 | 0.5 | 0.01 | 0.06 | 0.062 | 0.56 | 36 | 24 |
| 20 | 0.5 | 0.06 | 0.22 | 0.61 | 0.33 | 71 | 57 |
| 9/8/88 | | | | | | | |
| 1 | 6.1 | 0.04 | 0.01 | 0.18 | 0.14 | 11 | <10 |
| 4 | 5.8 | 0.02 | 0.01 | 0.18 | 0.15 | 10 | <10 |
| 8 | 5.5 | 0.02 | 0.01 | 0.15 | 0.13 | 10 | <10 |
| 14 | 0.3 | 0.02 | 0.15 | 0.31 | 0.14 | 29 | 27 |
| 17 | 0.3 | 0.04 | 0.27 | 0.45 | 0.14 | 59 | 57 |

Table 3. Nitrogen and Phosphorus Concentrations in Mine Lick Embayment

| Depth (m) | DO (mg/l) | NO2/$NO_3$ (mg/l) | $NH_3$ (mg/l) | Total N (mg/l) | Organic N (mg/l) | Total P (µg/l) | Ortho P (µg/l) |
|---|---|---|---|---|---|---|---|
| 6/15/88 | | | | | | | |
| 0.5 | 13.9 | 0.01 | 0.15 | 0.42 | 0.27 | 44 | <10 |
| 2 | 16.2 | 0.02 | 0.09 | 0.51 | 0.40 | 55 | 11 |
| 6 | 2.3 | 0.49 | 0.18 | 0.74 | 0.07 | 40 | <10 |
| 8 | 1.5 | 0.89 | 0.12 | 1.00 | 0.01 | 45 | <10 |
| 14 | 3.0 | 0.82 | 0.16 | 0.99 | 0.01 | 68 | 32 |
| 18 | 3.3 | 0.84 | 0.16 | 1.00 | 0.01 | 68 | 34 |
| 7/8/88 | | | | | | | |
| 2 | 9.9 | 0.01 | 0.08 | 0.28 | 0.20 | 22 | <10 |
| 4 | 9.8 | 0.01 | 0.09 | 0.28 | 0.19 | 23 | <10 |
| 6 | 6.3 | 0.01 | 0.10 | 1.50 | 0.40 | 30 | <10 |
| 8 | 0.6 | 0.07 | 0.15 | 0.38 | 0.16 | 35 | 22 |
| 14 | 0.5 | 0.06 | 0.27 | 0.42 | 0.09 | 64 | 43 |
| 18 | 1.0 | 0.41 | 0.27 | 0.78 | 0.10 | 104 | 83 |
| 8/10/88 | | | | | | | |
| 1 | 8.2 | 0.01 | 0.04 | 0.39 | 0.35 | 40 | 11 |
| 3 | 7.9 | 0.01 | 0.09 | 0.41 | 0.32 | 32 | <10 |
| 5 | 5.4 | 0.02 | 0.20 | 0.71 | 0.49 | 71 | 28 |
| 11 | 0.4 | 0.01 | 0.57 | 0.88 | 0.31 | 223 | 200 |
| 14 | 0.4 | 0.01 | 0.42 | 0.67 | 0.25 | 116 | 97 |
| 17 | 0.4 | 0.01 | 0.69 | 0.96 | 0.27 | 10 | <10 |
| 9/7/88 | | | | | | | |
| 1 | 7.3 | 0.03 | 0.09 | 0.35 | 0.23 | 22 | <10 |
| 4 | 6.9 | 0.03 | 0.06 | 0.36 | 0.27 | 21 | <10 |
| 8 | 0.7 | 0.03 | 0.05 | 0.28 | 0.20 | 20 | 11 |
| 13 | 0.6 | 0.02 | 0.59 | 0.77 | 0.16 | 177 | 188 |
| 15 | 0.5 | 0.21 | 0.84 | 1.08 | 0.03 | 243 | 231 |
| 18 | 0.5 | 0.06 | 1.17 | 1.43 | 0.20 | 327 | 295 |
| 10/13/88 | | | | | | | |
| 1 | 7.8 | 0.01 | 0.21 | 0.38 | 0.17 | 26 | 12 |
| 7 | 7.0 | 0.01 | 0.05 | 0.60 | 0.55 | 29 | 12 |
| 12 | 4.4 | 0.01 | 0.07 | 0.52 | 0.45 | 10 | 18 |
| 14 | 0.4 | 0.01 | 1.10 | 1.35 | 0.25 | 378 | 46 |
| 15 | 0.4 | 0.01 | 1.23 | 1.55 | 0.32 | 456 | 62 |
| 16 | 0.4 | 0.01 | 1.39 | 1.78 | 0.39 | 521 | 81 |

embayments to that of the main channel, means and standard deviations were calculated for each nutrient species at each depth. These analyses were based upon the composited data for the two embayment stations and upon the composited data for the four main channel stations. The statistics are listed in Table 8.

*Trophic State*

The trophic state of Center Hill Lake was determined using three analytical methods. Dillon's relationship is shown in Figure 1, and Carlson's TSIs are listed in Table 9. For comparison to Gakstatter's Criteria, the total phosphorus concentration for the lake was estimated to be 18.4 µg/1, the average Secchi transparency to be 2.3 meters, and the average chlorophyll $\alpha$ concentration to be 7.4 µg/1, all three indicating mesotrophic conditions.

Table 4. Nitrogen and Phosphorus Concentrations in Station 2

| Depth (m) | DO (mg/l) | NO2/NO3 (mg/l) | NH3 (mg/l) | Total N (mg/l) | Organic N (mg/l) | Total P (µg/l) | Ortho P (µg/l) |
|---|---|---|---|---|---|---|---|
| 3/17/88 | | | | | | | |
| 2 | 11.6 | 0.20 | 0.10 | 0.68 | 0.30 | 13 | <10 |
| 10 | 11.3 | 0.22 | 0.05 | 0.73 | 0.51 | 10 | <10 |
| 36 | 10.5 | 0.30 | 0.05 | 0.86 | 0.56 | 10 | <10 |
| 6/15/88 | | | | | | | |
| 3 | 13.8 | 0.01 | 0.12 | 0.36 | 0.24 | 37 | <10 |
| 11 | 7.7 | 0.45 | 0.12 | 0.57 | 0.01 | 16 | <10 |
| 45 | 8.5 | 0.65 | 0.09 | 0.74 | 0.01 | 36 | <10 |
| 7/8/88 | | | | | | | |
| 3 | 10.4 | 0.20 | 0.17 | 0.43 | 0.06 | 10 | <10 |
| 12 | 4.1 | 0.49 | 0.08 | 0.62 | 0.05 | 10 | <10 |
| 21 | 6.4 | 0.71 | 0.09 | 0.80 | 0.01 | 10 | <10 |
| 8/10/88 | | | | | | | |
| 2 | 8.4 | 0.01 | 0.05 | 0.38 | 0.33 | 17 | <10 |
| 10 | 0.6 | 0.01 | 0.03 | 0.23 | 0.19 | 10 | <10 |
| 22 | 4.6 | 0.60 | 0.04 | 0.80 | 0.16 | 10 | <10 |
| 9/7/88 | | | | | | | |
| 2 | 7.0 | 0.03 | 0.01 | 0.24 | 0.21 | 10 | <10 |
| 10 | 0.4 | 0.02 | 0.01 | 0.17 | 0.15 | 10 | <10 |
| 28 | 3.7 | 0.77 | 0.01 | 0.85 | 0.08 | 10 | <10 |
| 10/13/88 | | | | | | | |
| 2 | 7.8 | 0.01 | 0.02 | 0.46 | 0.44 | 13 | <10 |
| 10 | 7.6 | 0.01 | 0.01 | 0.28 | 0.28 | 13 | <10 |
| 24 | 2.4 | 0.69 | 0.01 | 0.82 | 0.13 | 13 | <10 |

Table 5. Nitrogen and Phosphorus Concentrations in Station 3

| Depth (m) | DO (mg/l) | $NO_2/NO_3$ (mg/l) | $NH_3$ (mg/l) | Total N (mg/l) | Organic N (mg/l) | Total P (µg/l) | Ortho P (µg/l) |
|---|---|---|---|---|---|---|---|
| 3/17/88 | | | | | | | |
| 2 | 11.7 | 0.30 | 0.05 | 0.95 | 0.65 | 17 | <10 |
| 10 | 11.1 | 0.32 | 0.05 | 0.99 | 0.67 | 18 | <10 |
| 36 | 10.2 | 0.45 | 0.05 | 1.10 | 0.65 | 23 | 17 |
| 6/15/88 | | | | | | | |
| 2 | 13.3 | 0.01 | 0.07 | 0.44 | 0.37 | 47 | <10 |
| 10 | 5.7 | 0.55 | 0.11 | 0.69 | 0.03 | 31 | <10 |
| 36 | 8.4 | 0.64 | 0.16 | 0.80 | 0.01 | 34 | <10 |
| 7/8/88 | | | | | | | |
| 4 | 10.3 | 0.13 | 0.28 | 0.41 | 0.01 | 16 | <10 |
| 12 | 3.1 | 0.54 | 0.59 | 1.10 | 0.01 | 13 | <10 |
| 22 | 6.4 | 0.82 | 0.11 | 0.93 | 0.01 | 14 | <10 |
| 8/10/88 | | | | | | | |
| 2 | 8.4 | 0.01 | 0.06 | 0.36 | 0.29 | 17 | <10 |
| 10 | 0.5 | 0.01 | 0.05 | 0.30 | 0.25 | 12 | <10 |
| 22 | 4.3 | 0.69 | 0.02 | 0.86 | 0.15 | 10 | <10 |
| 9/7/88 | | | | | | | |
| 2 | 7.2 | 0.04 | 0.01 | 0.26 | 0.22 | 10 | <10 |
| 10 | 0.4 | 0.02 | 0.01 | 0.15 | 0.13 | 10 | <10 |
| 27 | 3.0 | 0.79 | 0.01 | 0.79 | 0.01 | 10 | <10 |
| 10/13/88 | | | | | | | |
| 3 | 7.9 | 0.01 | 0.01 | 0.37 | 0.37 | 14 | <10 |

Table 6. Nitrogen and Phosphorus Concentrations in Station 4

| Depth (m) | DO (mg/l) | $NO_2/NO_3$ (mg/l) | $NH_3$ (mg/l) | Total N (mg/l) | Organic N (mg/l) | Total P (µg/l) | Ortho P (µg/l) |
|---|---|---|---|---|---|---|---|
| 3/17/88 | | | | | | | |
| 2 | 11.5 | 0.61 | 0.05 | 1.70 | 1.09 | 39 | <10 |
| 10 | 10.9 | 0.65 | 0.05 | 1.50 | 0.85 | 27 | <10 |
| 32 | 9.7 | 0.73 | 0.07 | 1.60 | 0.80 | 36 | 19 |
| 6/15/88 | | | | | | | |
| 2 | 13.0 | 0.28 | 0.15 | 0.51 | 0.08 | 56 | 12 |
| 10 | 5.7 | 0.70 | 0.19 | 0.89 | 0.01 | 24 | <10 |
| 38 | 7.3 | 0.21 | 0.14 | 0.78 | 0.43 | 39 | <10 |
| 7/8/88 | | | | | | | |
| 1 | 10.3 | 0.13 | 0.28 | 0.41 | 0.01 | 16 | <10 |
| 9 | 3.1 | 0.54 | 0.59 | 1.10 | 0.01 | 13 | <10 |
| 20 | 6.4 | 0.82 | 0.11 | 0.93 | 0.01 | 14 | <10 |
| 8/10/88 | | | | | | | |
| 2 | 9.2 | 0.01 | 0.08 | 0.29 | 0.21 | 20 | <10 |
| 10 | 3.3 | 0.63 | 0.10 | 0.73 | 0.01 | 18 | <10 |
| 22 | 5.3 | 0.89 | 0.29 | 1.50 | 0.30 | 18 | <10 |
| 9/7/88 | | | | | | | |
| 2 | 9.1 | 0.01 | 0.05 | 0.32 | 0.26 | 12 | <10 |
| 10 | 0.7 | 0.26 | 0.03 | 0.44 | 0.15 | 11 | <10 |
| 22 | 2.6 | 0.71 | 0.05 | 0.88 | 0.12 | 10 | <10 |
| 10/13/88 | | | | | | | |
| 2 | 7.3 | 0.01 | 0.01 | 0.24 | 0.24 | 12 | <10 |
| 10 | 7.0 | 0.01 | 0.01 | 0.26 | 0.26 | 12 | <10 |
| 22 | 0.4 | 0.01 | 0.01 | 0.26 | 0.26 | 12 | <10 |

Table 7. Nitrogen and Phosphorus Concentrations in Station 5

| Depth (m) | DO (mg/l) | $NO_2/NO_3$ (mg/l) | $NH_3$ (mg/l) | Total N (mg/l) | Organic N (mg/l) | Total P (µg/l) | Ortho P (µg/l) |
|---|---|---|---|---|---|---|---|
| 3/17/88 | | | | | | | |
| 2 | 13.1 | 0.66 | 0.05 | 1.80 | 1.14 | 27 | <10 |
| 10 | 11.6 | 0.71 | 0.05 | 1.60 | 0.89 | 15 | <10 |
| 30 | 10.2 | 0.81 | 0.07 | 1.70 | 0.82 | 25 | <10 |
| 6/15/88 | | | | | | | |
| 2 | 14.1 | 0.07 | 0.15 | 0.37 | 0.15 | 46 | <10 |
| 10 | 7.0 | 0.86 | 0.08 | 0.94 | 0.01 | 31 | <10 |
| 28 | 6.1 | 0.81 | 0.02 | 0.94 | 0.11 | 31 | <10 |
| 7/8/88 | | | | | | | |
| 2 | 9.1 | 0.01 | 0.09 | 0.26 | 0.17 | 16 | <10 |
| 8 | 4.6 | 0.25 | 0.09 | 0.40 | 0.06 | 15 | <10 |
| 17 | 4.0 | 0.91 | 0.08 | 0.99 | 0.01 | 16 | <10 |
| 8/10/88 | | | | | | | |
| 2 | 8.6 | 0.01 | 0.04 | 0.28 | 0.23 | 16 | <10 |
| 10 | 0.5 | 0.25 | 0.03 | 0.49 | 0.21 | 10 | <10 |
| 22 | 0.6 | 0.44 | 0.12 | 1.61 | 0.05 | 10 | <10 |
| 10/13/88 | | | | | | | |
| 2 | 7.5 | 0.01 | 0.01 | 0.33 | 0.33 | 13 | <10 |
| 10 | 0.5 | 0.01 | 0.01 | 0.39 | 0.39 | 14 | 11 |
| 24 | 0.3 | 0.02 | 0.38 | 0.68 | 0.28 | 36 | 33 |

Table 8. Statistics for the Embayments and the Main-channel

| Parameter | Lake Stats Mean | Lake Stats Std. Dev. | Embayment Stats Mean | Embayment Stats Std. Dev. |
|---|---|---|---|---|
| NO2/NO3 (mg/l as N) | | | | |
| Epilimnion | 0.122 | 0.180 | 0.056 | 0.138 |
| Metalimnion | 0.293 | 0.278 | 0.100 | 0.214 |
| Hypolimnion | 0.615 | 0.247 | 0.227 | 0.294 |
| NH3 (mg/l as N) | | | | |
| Epilimnion | 0.068 | 0.060 | 0.090 | 0.063 |
| Metalimnion | 0.074 | 0.116 | 0.216 | 0.253 |
| Hypolimnion | 0.086 | 0.089 | 0.447 | 0.393 |
| Total Nitrogen (mg/l as N) | | | | |
| Epilimnion | 0.494 | 0.410 | 0.365 | 0.137 |
| Metalimnion | 0.590 | 0.400 | 0.588 | 0.354 |
| Hypolimnion | 0.880 | 0.334 | 0.865 | 0.359 |
| Organic Nitrogen (mg/l as N) | | | | |
| Epilimnion | 0.323 | 0.271 | 0.227 | 0.131 |
| Metalimnion | 0.238 | 0.252 | 0.278 | 0.282 |
| Hypolimnion | 0.219 | 0.246 | 0.197 | 0.160 |
| Total Phosphorus (µg/l as P) | | | | |
| Epilimnion | 20.8 | 13.3 | 26.6 | 12.1 |
| Metalimnion | 16.1 | 10.5 | 65.6 | 89.5 |
| Hypolimnion | 18.5 | 10.5 | 139.0 | 146.0 |
| Ortho Phosphorus (µg/l as P) | | | | |
| Epilimnion | <10 | NA | 10.4 | 0.086 |
| Metalimnion | <10 | NA | 35.2 | 54.0 |
| Hypolimnion | <10 | NA | 71.7 | 78.4 |

## DISCUSSION

*Nutrient Concentrations*

Monthly water quality and nutrient data for Falling Water River and Mine Lick Creek embayments reveal that significant differences exist between the two embayment's ammonia-nitrogen, total nitrogen, and orthophosphorus concentrations. Ammonia-nitrogen concentrations were nearly the same in both embayments during June 1988. However, due to low inflows to the Mine Lick Creek embayment, stagnant conditions developed causing low hypolimnetic DO conditions and significant increases in ammonia concentrations by mid-summer. Increases in hypolimnetic ammonia concentrations also occurred in the Falling Water embayment, but they were not as pronounced due to larger inflows and a greater embayment flushing rate mitigating the DO depletion. Anaerobic conditions in the Mine Lick Creek embayment, confirmed by near zero DO concentrations and negative ORP values, also caused increased orthophosphorus concentrations in the metalimnion and hypolimnion. These concentrations decreased during fall overturn due to an increase in DO concentrations. Similar, but smaller, responses were observed in the Falling Water River embayment.

Table 9 Carlson's Trophic State Indices for Center Hill Lake's Main Channel and Two Embayments

| Station | Secchi Disk TSI | Chloro α TSI | Total-P TSI |
|---|---|---|---|
| Falling Water River Embayment | 53 (eutrophic) | 46 (mesotrophic) | 58 (eutrophic) |
| Mine Lick Embayment | 53 (eutrophic) | 44 (mesotrophic) | 72 (eutrophic) |
| Main Channel | 48 (mesotrophic) | 50 (mesotrophic) | 46 (mesotrophic) |

Table 10. Total Nitrogen to Total Phosphorus Ratios in the Upper 12 Meters of Center Hill Lake According to Location and Time

| Station | 3/17/88 | 6/15/88 | 7/8/88 | 8/10/88 | 9/7/88 | 10/13/88 |
|---|---|---|---|---|---|---|
| CFRM | | | | | | |
| 27.2 | 61.3 | 17.5 | 52.5 | 22.6 | 20.5 | 28.5 |
| 31.9 | 55.4 | 14.5 | 52.1 | 22.7 | 20.5 | 14.8 |
| 48.8 | 48.5 | 17.5 | 26.8 | 33.0 | 20.0 | 20.8 |
| 61.1 | 91.9 | 17.0 | 21.3 | 29.6 | - | 26.7 |
| FWRM | | | | | | |
| 5.1 | - | 10.7 | 16.2 | 17.0 | 15.0 | 20.9 |
| MLC | | | | | | |
| 2.0 | - | 14.5 | 22.2 | 6.5 | 15.7 | 23.1 |

Significant trends in the main channel nutrient data were observed to occur with depth, time and distance along the lake's axis. Depth trends were insignificant for the nutrient species except for the nitrite and nitrate-nitrogen concentrations; at each station these concentrations increased significantly with depth throughout the summer month sampling dates.

Time trends were significant for nitrogen species and total phosphorus. Inorganic nitrogen concentrations in the epilimnion and metalimnion were greater than organic nitrogen concentrations in June and July. By mid-August, organic nitrogen concentrations in the epilimnion and metalimnion had become greater than inorganic nitrogen concentrations, and continued to increase through the fall overturn in October 1988. Total phosphorus concentrations peaked in June 1988, decreased during the summer and increased slightly during the fall overturn. Orthophosphorus concentrations were observed to be less than 10mg/l over the entire study period.

Nutrients trends, with regard to the length of Center Hill Lake , were significant for both total nitrogen and total phosphorus. In March and June 1988, total nitrogen and total phosphorus concentrations increased with distance upstream from the dam. In July, total nitrogen and total phosphorus concentrations were relatively constant throughout the lake. By mid-August both total nitrogen and total phosphorus concentrations decreased with distance from the dam. These nutrient concentration/distance trends indicate that the greatest nutrient loads enter Center Hill Lake through its tributaries during the spring and early summer when rain events are more frequent.

Based upon mean total nitrogen and mean total phosphorus concentrations measured during this study in the upper 12 meters, Center Hill Lake has a nitrogen to phosphorus ratio of 20:1. Literature has indicated that nitrogen to phosphorus ratios above 20:1 represent phosphorus-limited lakes (Tsai and Huang, 1979; NALMS, 1988).

Table 10 shows how the nitrogen to phosphorus ratios in the upper 12 meters varied with time and location. The ratios are not strongly related to sampling location, but do appear to change with time. The March data showed a phosphorus limited situation. This shifted by mid-June to ratios less than 20 indicating nitrogen limitations and then returned to a phosphorus limited state by July.

Compared to the lake's main channel, the Falling Water River and Mine Lick Creek embayments contain higher average concentrations of total and orthophosphorus and lower average concentrations of dissolved oxygen. Orthophosphorus concentrations were high in the hypolimnion in the embayments due to anoxic conditions and anaerobic activity. Anaerobic conditions were not observed within the main channel of the lake. Additional evidence that oxygen was limiting in the embayments was the observation that nitrite and nitrate-nitrogen concentrations were low in comparison to their corresponding ammonia concentrations. The opposite scenario was observed for the epilimnion and metalimnion of the lake which had satisfactory DO concentrations.

Dissolved oxygen concentrations in Center Hill Lake at stations 2, 3, and 4 show a pronounced metalimnetic minimum condition which has been previously described by Gordon (1976) and studied by Morris (1978). Morris (1978) concluded that this metalimnetic DO minimum was largely caused by phytoplankton and zooplankton respiration with a minor, but significant, contribution from 28-day BOD.

Long term trends in nutrient concentrations were noted in Center Hill Lake by Hunter (1987). He reported that a marked decline in total phosphorus and inorganic nitrogen was evident between 1971 and 1984. He noted a decrease in total inorganic phosphorus between a 1971-73 period which had 60 μg/l and a 1976-83 period which had less than 10 μg/1. Total nitrogen levels similarly dropped from 0.7 to 0.3 mg/l during the late March to early April pre-stratification period. The writers are aware that the Nashville District U.S. Army Corps of Engineers have subsequently questioned the quality of the phosphorus data from the early 1980's. However, the data taken during these studies substantiate the conclusions of Hunter (1987).

*Trophic State*

When compared to Gakstatter's criteria, Center Hill Lake's main channel can be classified as mesotrophic in view of a total phosphorus average of 18.4 μg/l, an average Secchi transparency of 2.3 meters and an average chlorophyll α concentration of 7.4 mg/l. Center Hill Lake embayments, Falling Water River and Mine Lick Creek, can be classified as eutrophic based upon average total phosphorus concentrations of 43.8 and 110.7 μg/l, average Secchi transparencies of 1.7 and 1.9 meters, and average chlorophyll α concentrations of 5.0 and 4.1 mg/l, respectively.

An attempt to assess Dillon's Model for the main channel of Center Hill Lake resulted in the following values:

p=1.016 year $^{-1}$ (1988 was a dry year);

L=0.408 gms/TP/sq mi/yr; and 1-R=0.2432.

The mean depth of Center Hill Lake is approximately 22 meters (72 feet). The Dillon relationship for the lake in 1988 is 0.305 which places the lake in the mesotrophic classification as shown by Figure 1.

Carlson's TSIs for the lake's main channel, Falling Water River (FWR) embayment and Mine Lick Creek (MLC) embayment are listed in Table 9. The TSIs imply that the main channel of the lake is slightly mesotrophic while the embayments are eutrophic. Indices calculated from average chlorophyll $\alpha$ concentrations are significantly lower than the other indices while total phosphorus indices are generally higher. An explanation might be the presence of suspended materials that reduce light attenuation and therefore algal productivity.

## CONCLUSIONS

Based upon this study's 1988-89 database and the previous studies of Center Hill Lake by Hunter (1987), Morris (1978), and Gordon (1976), the following statements may be concluded:

1. The main portion of Center Hill Lake is low in essential nutrients and is usually phosphorus limited based upon N:P ratios. The mean orthophosphorus concentration was less than 10 micrograms per liter. Late spring appeared to be the only time that the lake was not phosphorus limited.

2. Embayments had higher concentrations of the essential nutrients and phosphorus was more abundant in the metalimnion and hypolimnion.

3. Dissolved oxygen values are much lower in the metalimnion and hypolimnion in the embayments, and are well below concentrations required by aerobic organisms, such as fish, at all depths below the epilimnion in the embayments.

4. The main lake portion of Center Hill Lake has good dissolved oxygen concentrations except for a pronounced zone of low DO termed the metalimnetic minimum.

5. This information suports the conclusions of Hunter (1987) who noted that Center Hill Lake is lower in nitrogen and phosphorus than it was in the early 1970s.

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