THE PHYSICAL-CHEMICAL LIMNOLOGY OF A NEW RESERVOIR (Beaver) AND A FOURTEEN YEAR OLD RESERVOIR (Bull Shoals) LOCATED ON THE WHITE RIVER, ARKANSAS AND MISSOURI

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ABSTRACT

This paper compares limnological conditions of two reservoirs in the same drainage to determine whether there is a significant difference in basic fertility associated with age. Bull Shoals, the older reservoir of the study, filled in 1952, contains 45,440 acres at top of power pool, and has been under intensive study since June 1963. Beaver Reservoir, located upstream, began filling in December 1963 and reached 16,210 acres in 1965. At top of the designed power pool, it will encompass 28,220 acres. This new reservoir has been under study since June 1964.

All the more commonly assayed physical and chemical parameters, dissolved organic matter content and trace elements, were monitored at designated stations on a year-round basis. Results of these tests through August 1965, proved inconclusive in demonstrating a significantly higher nutrient base in the new reservoir.

INTRODUCTION

The objective of the National Reservoir Research Program is to study the natural processes of change with time in the chemical, physical and biological character of reservoirs so that these processes can be identified, predicted and subject to control. In the pursuit of this objective a major question concerns the cause of the exceptional sport fish harvest generally associated with young impoundments — whether attributable to an initial flush of basic fertility, chronological changes in fish population densities, fish behavior, or a combination of these factors. Construction of a series of reservoirs on the upper White River in the Arkansas-Missouri Ozarks presents an unusual opportunity to examine this question.

This paper describes some of the differences existing in a new and older reservoir bearing on limnological succession.

RESERVOIR DESCRIPTIONS

Bull Shoals Reservoir, filled in 1952, is the lowermost impoundment on the White River (Figure 1). Extending 140 kilometers (87 miles) upstream and incorporating 18,400 hectares (45,440 acres) at elevation 654 (top of power pool), at high water it extends to the dam forming Lake Taneycomo. The latter is the oldest (1913) and in the chain smallest [890 hectares (2,200 acres) at elevation 697 and 37 kilometers (23 miles) long]. Lake Taneycomo is essentially a cold tailwater to Table Rock Reservoir which became operational in 1958, and encompasses 129 kilometers (80 river miles) and 17,440 hectares (43,100 acres) at elevation 745. Immediately above Table Rock lies new Beaver Reservoir, which began filling in December 1963 and will ultimately contain 11,420 hectares (28,220 acres) stretching upstream for 118 kilometers (73 miles) at elevation 1,120. Its drainage constitutes 25 percent of the drainage of Bull Shoals.

Bull Shoals Reservoir's larger volume, area, and partially regulated inflow would appear to preclude comparison with Beaver. However, they are much alike. At power pool level, Beaver and Bull Shoals Reservoirs will be characterized by mean depths of 17.7 and 20.4 meters (58 and 67 feet), maximum depths of 65.9 and 61.3 meters (216 and 201 feet), bottom slopes of 0.5 and 0.6 meters per kilometer (2.7 and 2.9 feet per mile), shoreline development factors of 19.1 and 24.8, and deepwater outlets located at the 42.7 and 36.3 meter (140- and 119-foot) mid-depth

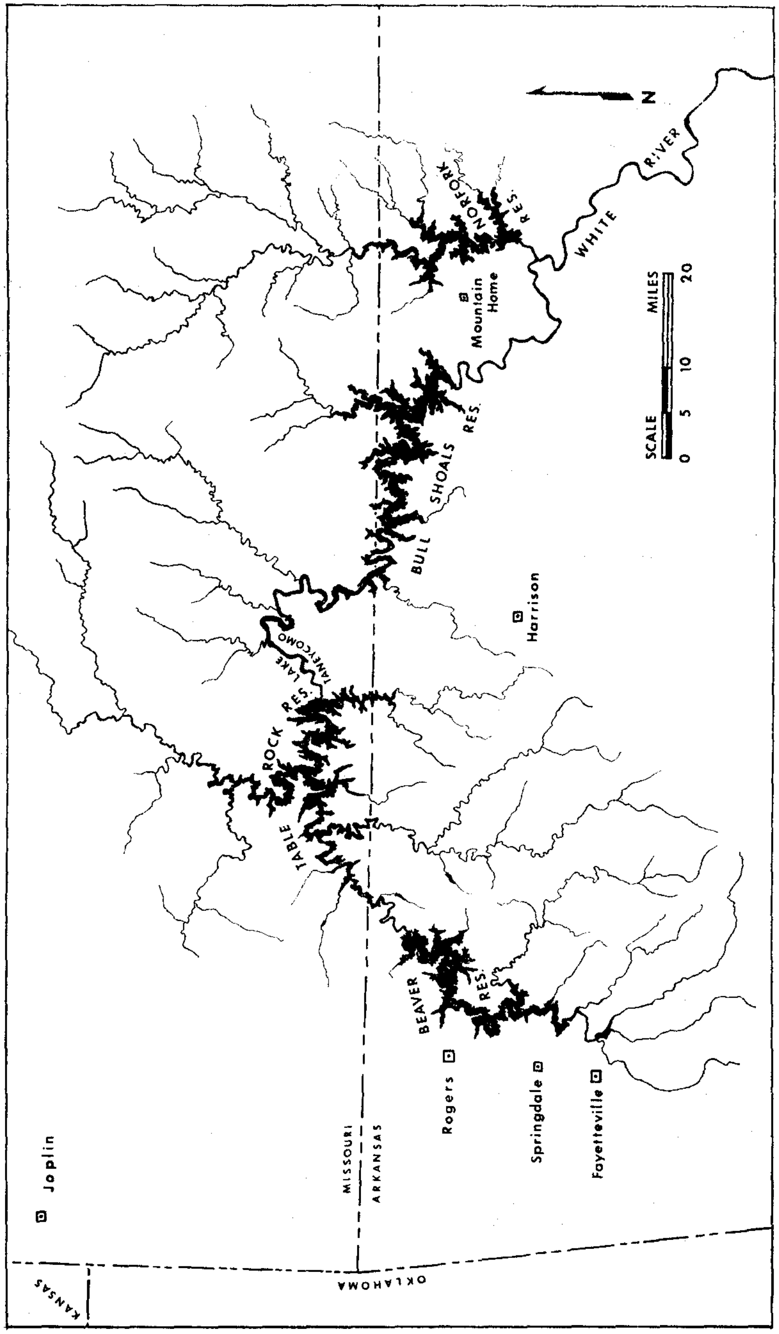

Figure 1. Depth profiles of temperature, heat content, and dissolved organic matter in Beaver and Bull Shoals Reservoirs.

levels, respectively. The impounded basins are narrow, steep-sided and meandering, the product of mature stream dissection of a peneplain elevated by the Ozark Uplift. Shaped like Chinese dragons, Beaver trends in a north-northeast direction and Bull Shoals east-southeast, each with maximum widths of about three kilometers (two miles). These similarities suggest that Beaver Reservoir is essentially comparable physically to Bull Shoals Reservoir.

The drainage area of both receives 107-127 centimeters (42-50 inches) of annual precipitation, which about equals mean annual evaporation over the forested watershed. However, there are distinct differences in watershed lithology. The Boston Mountains above Beaver Reservoir are capped by sandstones, shales, and siltstones of Pennsylvanian age and underlaid by Mississippian sandstone, shales, and some limestone. This is the principal source of the waters of the White River above Beaver, normally classified as "soft." Northward lies the Springfield Structural Plain, site of Beaver Reservoir, developed on Boone cherty limestone which enriches the drainage with calcium bicarbonates. To the east is the Salem Plateau, site of Bull Shoals Reservoir, developed largely on Ordovician dolomites and limestones, which contribute both calcium and magnesium bicarbonates to the water (Horn et al., 1964, and Huffman, et al., 1963).

METHODS

Temperature, dissolved oxygen, and conductivity were measured at 1.5- or three-meter (five- or 10-foot) intervals at nine or more stations on Bull Shoals Reservoir at four- to six-week intervals from June 1963 through August 1965. Other chemical analyses requiring laboratory facilities were run on refrigerated samples collected about one-half as frequently at six- or 12-meter (20-or 40-foot) depth intervals, at four stations (upper, middle, lower reservoir, and a major arm). A similar effort at seven stations on Beaver Reservoir has been operative since June 1964.

The Winkler method and a Jarrell-Ash analyzer were used in oxygen determinations. Conductance was measured in-situ with an Industrial Instruments conductivity bridge. Temperatures were taken with electrical Jarrell-Ash and Industrial Instruments thermometers, pH with a Hellige comparator, and the fluorometer-rhodamine B dye technique was used in studying water movements. Colorimetric determinations were made of total phosphate, nitrate, chloride, sulfate and turbidity employing a Hellige Aqua Analyzer, silica with a Hach colorimeter, nitrate nitrogen with a Hellige Aqua Tester, and hydrogen sulfide with a Hach matching chart. Titrametric determinations were made of total alkalinity and total calcium and magnesium hardness, using Hach reagents.

Dissolved organic matter analyses were by the quantitative dichromate oxidation micro method (Maciolek, 1962), using Millipore GS filters. Two seasonal analyses for 24 elements from both reservoirs were made by the Taft Center, USPHS, Cincinnati, employing appropriate spectrographic or standard wet chemical methods. The Ohio Agricultural Experiment Station similarly analyzed, spectrographically or flame photometrically, fifteen sample series for 14 elements.

SECCHI DISK TRANSPARENCY

Maximum transparency of Bull Shoals Reservoir was reached in late summer-early fall, with Secchi disk readings from 7 meters (23 feet) at the dam to 1.5 meters (5 feet) in upstream extremities. Minimum values were of the magnitude of 3.7 to 0.3 meters (12 to 1 feet), occurring in early spring. Corresponding values for Beaver Reservoir were only 30 to 65 percent that of the older impoundment, with the maximum transparency recorded being 4 meters (13 feet).

THERMAL CHARACTERISTICS

Each reservoir circulates once each year during the winter and has a warm monomictic cycle as classified by Hutchinson (1957), even though temperatures in upstream extremities occasionally drop below the 4°C. (39.2°F.) criterion of this definition.

Minimum temperatures (3.5-7.2°C.) were reached in Bull Shoals

Reservoir in February, 1964 and March, 1965. By late March or early April surface temperatures reached 10°C. (50°F.), 15.5°C. (60°F.) by late April, 21.1°C. (70°F.) in May, and 26.6°C. (80°F.) in June. Stratification began in May. In early summer, with the metalimnion between the 6-7.6 (20-25 feet) to 18.3-24.4 (60-80 feet) meter depth levels, the epilimnion, metalimnion, and hypolimnion each constituted about one-third of total reservoir volume. By mid-October the epilimnion had about doubled. Accelerated deepening of the metalimnion followed, and stratification disappeared about January 1 in both years.

Beaver Reservoir maintained about 2,585 hectares (6,390 acres) (23 percent of ultimate area and 14 percent of volume) between late May and December, 1964. Average and maximum depths were 10.8 and 35.4 meters (35.5 and 116 feet). Stratification was acute by late June, with the thermocline at 3.0 to 4.6 meters (10 to 15 feet). By late August the thermocline was depressed to 4.6 to 6 meters (15 to 20 feet), and by mid-October to 9.1 meters (30 feet). Stratification disappeared in November.

Between January and May, 1965, the water level rose 15.2 meters (50 feet), resulting in a pool of 6,560 hectares (16,210 acres) (57 and 47 percent of ultimate area and volume), which was maintained through August, the last sampling covered in this report. Average and maximum depths reached were 14.6 and 50.6 meters (48 and 166 feet).

Surface warming approximated that of Bull Shoals except that by late April 1965, a metalimnion existed at the 7.6 to 12.1 meter (25 to 40 foot) depth levels (Figure 2). This discontinuity layer apparently resulted from warmer inflows overriding the indigenous, colder "winter" water but not before some warming had occurred in the latter.

By the first week in June a true thermocline began at a depth of 3.7 meters (12 feet) (Figure 2). The metalimnion extended to about 15.2 meters (50 feet), and considering an additional 2.1 meter (seven-foot) rise in reservoir level, represented run-off or surface waters that had been exposed to vernal warming. The hypolimnion maintained temperatures recorded in March. Subsequent position of the thermocline in July and August was the same as found in 1964.

Estimated annual heat budgets for Bull Shoals Reservoir were 27,800 gram-calories in 1964 and 28,300 gram-calories in 1965. The corresponding heat budget for Beaver Reservoir in 1965 was 20,700 gram-calories.

Warming of hypolimnetic waters in Beaver lagged noticeably behind that of Bull Shoals at comparable depths, suggesting less vertical distribution of the energy received. This is confirmed by comparison of energy content per unit volume at three meter (10 foot) depth levels for August temperature series (Figure 3).

To provide a more meaningful thermal comparison between reservoirs, and one expressing biological time relationships, temperature summations as prescribed by Reimers, et al. (1956) were calculated. Day-degree totals (time x temperature above the minimum mean temperature of 42°F.) for Bull Shoals Reservoir for the period March 8 to August 23, 1965 were 2,460 and for Beaver Reservoir during the interval March 22 to August 16, 1965 were 2,620. If the Beaver data are expanded from 151 to a comparable 170 days, Beaver surpasses Bull Shoals by 490 day-degrees.

WATER EXCHANGE AND MOVEMENT

Varying, but sluggish water movement through Bull Shoals Reservoir is indicated by cumulative discharge volumes for the period July 1963 - June 1964 and July 1964 - June 1965: 44 and 67 percent of the total storage. The difference between years is accounted for by heavier discharges during January - June 1965 correlated with heavier inflows and normal to above normal rainfall. Outflow equaled inflow over the two-year period (water exchange rate of about 1.9, compared to average rate of 0.7) with maximum and median fluctuations below power pool level of only 14 and eight feet.

Dye-marked inflowing water moved 88.6 kilometers (55 miles) in Bull Shoals Reservoir in 30 days during May and June, 1964.

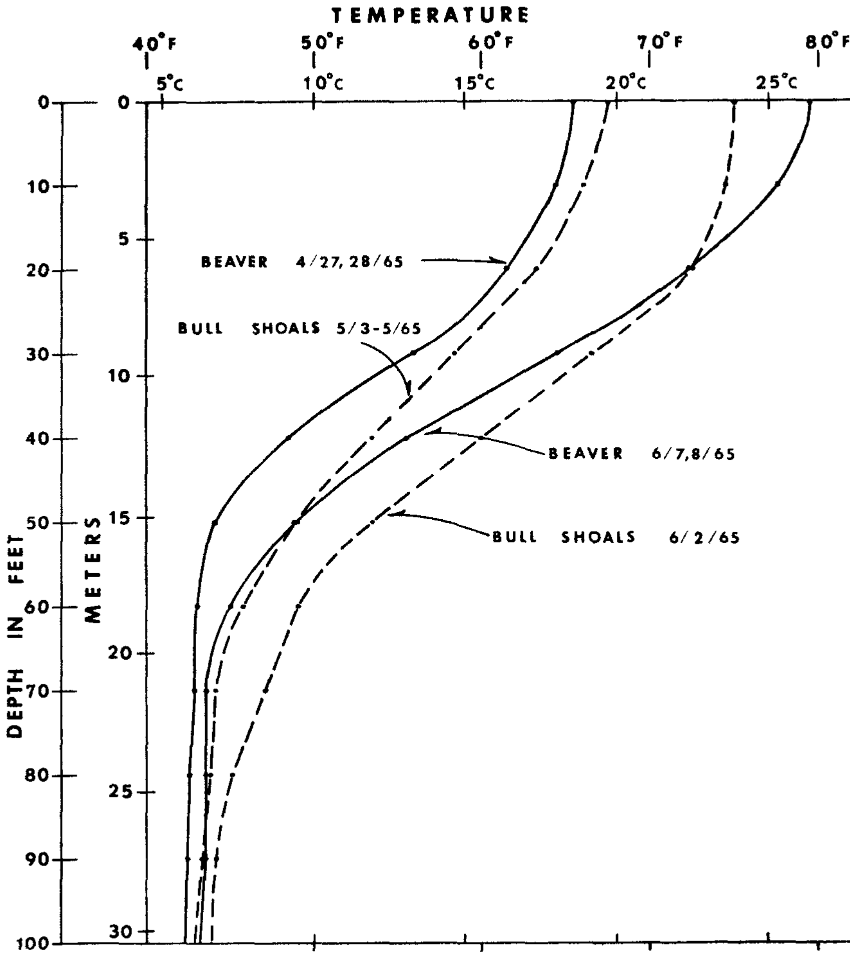

Figure 2. Depth profiles of temperature, Beaver and Bull Shoals Reservoirs.

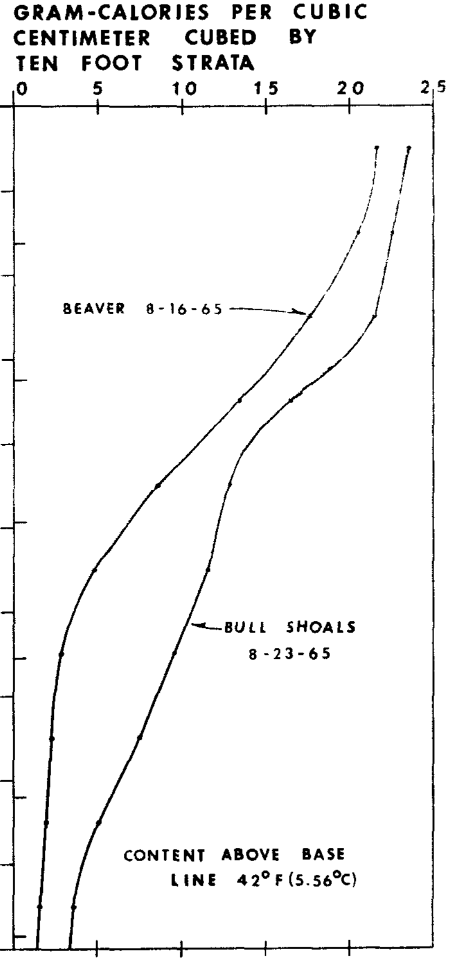

Figure 3. Depth profiles of heat content, Beaver and Bull Shoals Reservoirs.

Differences in dye concentrations indicated major water movement under the thermocline between depths of six and 24.4 meters (20 and 80 feet), settling out below 24.4 meters (80 feet) and pocketing in eddies. The 17.2°C. (63°F.) dye-laden inflow was surface oriented only for the first eight kilometers (five miles) of the river-like confluence, after which it disappeared to deeper strata of comparable temperature and density. This evidence and observations regarding seasonal patterns of conductance and dissolved oxygen suggest virtually a cessation in flow rate in the drought years of 1963 and 1964 below mid-reservoir. Introduction of dye between the 9.1 and 30 meter (30 and 100 foot) depth levels in mid-reservoir in 1965 confirmed that the water movement in the lower reservoir during increased inflow was faster than in 1964.

Discharges from Beaver Reservoir were minimal, with a daily regulated outflow of 50 c.f.s. and occasional test discharges to 2,500 c.f.s accounting for a theoretical water exchange of only 15 percent during the period July 1964 - June 1965.

Although major water movement was confined to surface strata in Beaver, both reservoirs were similar in reflecting exponential slowing of inflows with passage through the reservoir and deposition of allochthonous materials prior to reaching the lower portions of the reservoirs. This was depicted in Beaver not only by the seasonal patterns of transparency, conductance, dissolved oxygen, and most other chemical determinations but by a layering of allochthonous materials indicated by echo-sounding.

In late April 1965, following the surge in silty inflows earlier in the month, echograms suggested metalimnetic layering (25 to 40 feet) in the upper two-thirds of Beaver Reservoir but not in the lower section. The echogram traces could have been attributable to the temperature discontinuity associated with the density underlay of cold winter water, except that they could not be replicated in the lower reservoir with nearly identical thermal conditions. Concentrations of plankton or fish as causative factors were eliminated because of the spatial sameness and character of the echogram trace and the fact that plankton appeared in no greater density in the layer than in other strata sampled. Possibly causative of the echogram layering trace was the dichotomic distribution of turbidity at mid-reservoir. A metalimnetic maximum of 38 mg/1 (as mg/1 SO_2) existed, whereas values in the lower reservoir ranged between 2 and 4 mg/1.

WATER CHEMISTRY

Ionic Composition. The water in both reservoirs is classified as the bicarbonate type. By arranging the major electrolytes into equivalents per million which present their reacting weight, major anions exist in the order of HCO_3, SO_4, Cl. The major cations exist in the order Ca, Mg, Na, K (Table 1). Prior to impoundment above Beaver Dam, Na preceded Mg in the order of abundance in most waters of the upper White River (U. S. Geological Survey, 1964; Horn and Garner, 1964). Bull Shoals Reservoir had one-third more calcium and between 3 and 5.5 times the magnesium content of Beaver Reservoir. The Ca:Mg to Na:K ratios are relatively low in Bull Shoals.

Of the essential trace elements measured, there appeared to be no appreciable differences between reservoirs in concentrations of copper and zinc. Cobalt and molybdenum values were lower, and iron and manganese values were higher in the younger reservoir (Table 1). Median values for copper, cobalt, and zinc increased in 1965 in both reservoirs. Manganese increased, molybdenum remained unchanged, and iron decreased in Bull Shoals. All three declined in Beaver during 1965.

Phosphorus and aluminum concentrations in Beaver showed less acute inverse clinograde distribution during 1965. Phosphorous concentrations in Beaver during 1964 averaged double that of Bull Shoals, but in 1965 the difference was considerably less. Nitrogen values in Beaver averaged but a fraction of those in Bull Shoals in 1964, but were significantly higher in 1965.

Constituents generally found in appreciably higher concentrations in Beaver included silica, sulfate, and hydrogen sulfide; the latter occurring up to 5.0 mg/1. In Bull Shoals, hydrogen sulfide occurred only as a trace. Nickel, lead and chromium were more frequently detected in Beaver than in Bull Shoals. Barium and chloride values were higher in Bull Shoals. No appreciable differences were noted in concentrations of strontium and boron between reservoirs.

Bull Shoals was decidedly more alkaline than Beaver; during 1965 the median pH in the former was 7.9, 7.0 in the latter.

Conductivity. Water conductivity best reflects the gross ion concentration. Median values for Bull Shoals Reservoir were: 1963, 260 micromhos (at 25°C.); 1964, 260 micromhos; and 1965, 285 micromhos (Table 1). The range was 190 to 330 micromhos. Concentrations of ions invariably increased below the thermocline, in metalimnetic or hypolimnetic waters of the upper-middle reservoir, and in bottom waters of the distal portions of arms and coves. Median values for Beaver Reservoir in 1964 and 1965 were 156 micromhos (85 to 315 micromhos), 60 and 55 percent of that recorded for Bull Shoals Reservoir.

Dissolved oxygen. In 1963 and 1964, as summer progressed through fall, the sequence in oxygen distribution in the lower reaches of Bull Shoals Reservoir was positive heterograde, orthograde, and negative heterograde, whereas in 1965 negative heterograde distribution prevailed from the onset of stratification. Aside from the metalimnion minimum in which values ranged down to 2.8 mg/1 in August at the dam, and to 0.0 mg/1 upstream, oxygen was not reduced below 4.0 mg/1 in the clinolimnion and hypolimnion until early fall, and some oxygen (1-2 mg/1) remained until the overturn. Acute depletion below the thermocline typified the arms and upper reservoir, with the mid-reservoir mainstem displaying intergrades between these two extremes.

Oxygen depletion occurred below the thermocline in Beaver Reservoir by late June 1964, except for a temporary hypolimnetic cell at the dam. In 1965, accelerated depletion in the metalimnion began in April in the upper two-thirds of the reservoir and was virtually complete by early June. Content of the hypolimnion, 15.2 to 50 meters (50 to 166 feet) in depth, ranged between 4.0 and 6.0 mg/1 at this time, but by August was largely depleted.

During the summer of 1964, surface oxygen in Beaver Reservoir averaged 80-90 percent of saturation (6.0-8.0 mg/1), but by October was reduced to the 40-50 percent level at the dam. Upstream for 20 miles, surface values ranged from 2.9 to 3.8 mg/1, then in the next six miles, dropped to 1.6 to 0.8 mg/1 (6 to 17 percent saturation), after which they increased, reaching 100 percent saturation at the inflowing White River. In mid-December, the area of lowest oxygen content, 1.2 to 1.8 mg/1, was located six miles above the dam. Values then were 2.0-2.7 mg/1 in the latter area (18-24 percent saturation), and replenishment continued to lag through mid-January.

Dissolved organic matter. Median dissolved organic matter content of Bull Shoals Reservoir in 1964 was 6.1 mg/1 (range 4.1-10.6 mg/1) and 5.4 mg/1 (range 4.2-7.3 mg/1) in 1965. These values were 86 and 83 percent of the medians of 7.1 mg/1 (range 4.5-9.1 mg/1) and 6.5 mg/1 (range 3.2-7.7 mg/1) recorded in these same years in Beaver Reservoir (Table 1).

Hutchinson (1957) recognizes two theoretical categories of organic matter in solution, which complicates between-lake comparisons of this parameter. Autochthonous matter, containing about 24 percent crude protein, with a C:N ratio of 12:1, and largely derived from the decomposition of plankton, is undoubtedly characteristic of the clear water of Bull Shoals Reservoir. Allochthonous matter, containing about six percent crude protein, with a C:N ratio of 45-50:1, is derived from vegetation and imparts the brown color of Beaver Reservoir water.

Citing the findings of Birge and Juday, Welch (1935) states there is no great variation in dissolved organic matter with depth or season. In contrast, results of this study show an orthograde minimum vertical distribution in the early spring and a heterograde maximum distribution in late spring or summer, with the exception of arrested orthograde and clinograde distribution in the lower and mid-reservoir, respectively, at Beaver Reservoir between June and August, 1965 (Figure 4).

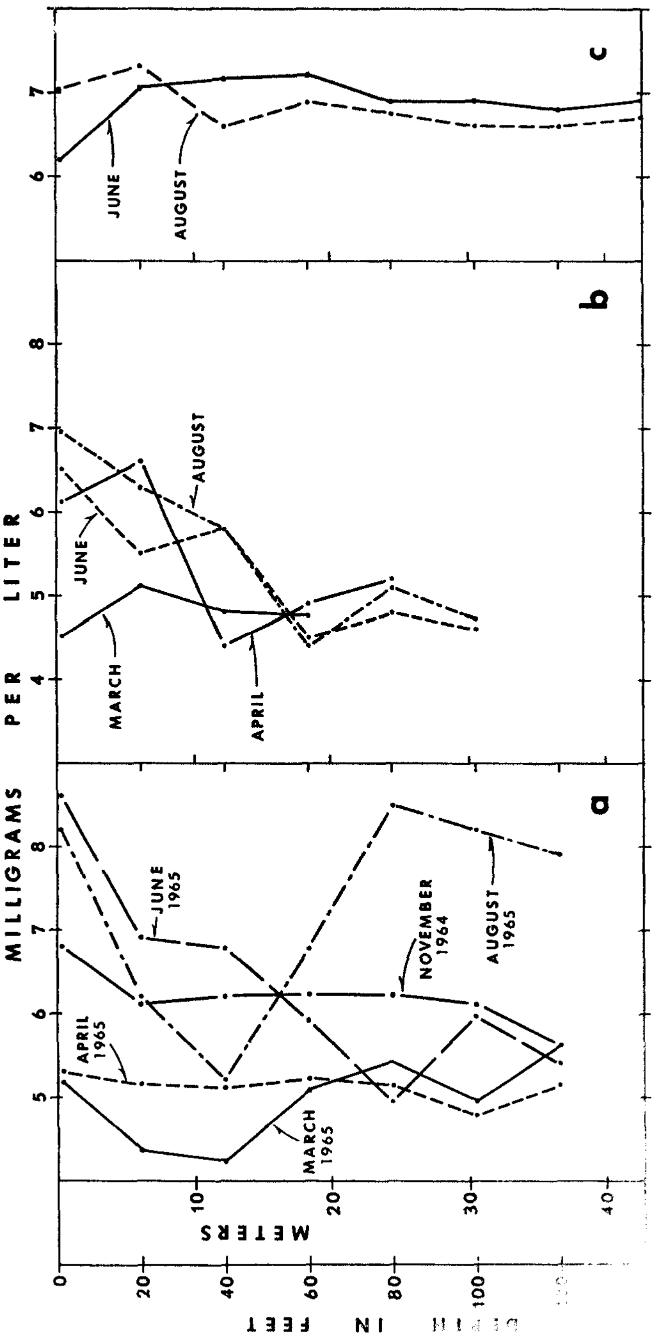

Figure 4. Depth profiles of dissolved organic matter, Beaver and Bull Shoals Reservoirs: (a) Typical seasonal cycling of dissolved organic matter at mid-reservoir, Bull Shoals; (b) Spring through summer, 1965, vertical distribution of dissolved organic matter at mid-reservoir, Beaver; (c) Arrested cycling of dissolved organic matter in the lower portion of Beaver, 1965.

DISCUSSION

Several possible comparisons are suggested by these data, bearing in mind that the salinity of the reservoirs, which approximates the 100 p.p.m. worldwide mean of river water (Conway in Hutchinson, 1957) in Beaver and double this in Bull Shoals, are relatively fixed by geochemical location.

Initial inorganic enrichment attributable to inundation of Beaver Reservoir basin as reflected by the parameters measured is not clear cut. The major salts, although undoubtedly regulatory, are only marginally involved in the enrichment. However, the slightly higher contents of nitrogen, phosphorus, dissolved organic matter, and possibly some of the trace elements found in Beaver may indicate greater nutrient availability.

In reservoirs similar to Beaver, filling slowly in annual increments, additional time may be required before the added nutrients are fully assimilated and evident. For example, the water mass has not yet reached an equilibrium with its shoreline — a process involving additional erosion, redeposition, and solution. In the deeper waters, decomposition of vegetation flooded in the spring of 1964 was no doubt very incomplete under prevailing anaerobic conditions of the summer and fall. Maximal mixing coincided with minimal, inhibiting temperatures of late winter. These waters were effectively "isolated" at the bottom of the reservoir following the spring rise in water levels. The step-like morphometrical distribution of PO_4, NO_3, Al, Fe, Mo, and Mn, especially in 1964, plus the arrested distribution pattern of dissolved organic matter in the summer of 1965, infers slow cycling (Hutchinson, 1957).

It may be impossible to document accurately the nutrient base of a reservoir with the approach taken, due to the rapid self-regulating uptake of nutrients by flooded vegetation, organisms, and sediments. Furthermore, the effects generally attributed to initial nutrient enrichment may be due to a mix of factors, both chemical and physical. Physical dissimilarities between reservoirs arising from varying light and thermal characteristics, extent of littoral erosion and difference in flooded terrestrial vegetation, represent influences on fish production yet to be adequately described.

In conclusion, measures of all the more commonly assayed chemical parameters, plus dissolved organic content and trace elements, failed to demonstrate a significantly higher nutrient base in Beaver Reservoir waters due to initial inundation when compared to 14-year-old Bull Shoals Reservoir.

LITERATURE CITED

Geurin, J. W. and H. G. Jeffery (1957). Chemical quality of surface waters of Arkansas, 1945-1955. A summary. U. S. Geological Survey and University of Arkansas Engineering Experiment Station, Bulletin No. 25, 79 pp.

Horn, M. E. and D. E. Garner (1964). Soil and water chemistry in the Beaver Reservoir Area, White River, Arkansas. University of Arkansas, 87 pp. (mimeographed).

Huffman, George G., Tyson A. Cathey, James E. Humphrey (1963). Parks and scenic areas in the Oklahoma Ozarks. Oklahoma Geological Survey. University of Oklahoma, Norman. 95 pp.

Hutchinson, G. Evelyn (1957). A treatise on limnology. Volume 1, Georgraphy, Physics, and Chemistry. John Wiley & Sons, New York. 1015 pp.

Maciolek, John A. (1962). Limnological organic analyses by quantitative dichromate oxidation. U. S. Fish and Wildlife Service, Research Report 60. 61 pp.

Reimers, Norman and Bobby D. Combs (1956). Method of evaluating temperature in lakes with description of thermal characteristics of Convict Lake, California. U. S. Fish and Wildlife Service, Fishery Bulletin No. 105, Volume 56, pp. 535-553.

U. S. Geological Survey (1964). Quality of surface waters of the United States 1962, Parts 7 and 8. Lower Mississippi River Basin and Western Gulf of Mexico Basins. U. S. Geological Survey, Water-Supply Paper No. 1944. 645 pp.

Welch, Paul S. (1935). Limnology. McGraw-Hill Book Company, New York and London. 471 pp.