WATER CONDITIONS AFFECTING AQUATIC LIFE IN ELEPHANT BUTTE RESERVOIR[1]

◆

By M. M. Ellis, Ph. D., Sc. D., *In Charge Interior Fisheries Investigations, United States Bureau of Fisheries, and Professor of Physiology and Pharmacology, University of Missouri.*

CONTENTS

INTRODUCTION[2]

The impounding of both river and run-off waters has become an accepted engineering procedure in connection with hydroelectric, water supply, irrigation, navigation, and flood-control projects, and a large number of reservoirs, artificial lakes, and river pools have been created. Differing in several particulars from natural lakes and ponds of comparable size, these bodies of impounded waters biologically are usually very productive for the first few years after the impoundment is accomplished, during which period fish and other aquatic life flourish. As the several environmental factors which were disturbed or changed by the creation of the impoundment become partially adjusted the various groups of aquatic animals in these artificial lakes and reservoirs achieve an unsettled balance of species, which, because of the frequent changes in water level in these impounded waters, rarely attains the degree of stability presented by the faunae of many natural lakes.

---

[1] Bulletin No. 34. Approved for publication May 20, 1939.

[2] The writer is particularly indebted to Messrs. L. R. Fiock, W. F. Resch, George Shannon and J. A Jackson, of the U. S. Bureau of Reclamation, for their helpful interest and generous cooperation, to Mr. Elliott S. Barker, of the New Mexico Game and Fish Department, for the loan of records and other courtesies, to Dr. H. L. Motley, Dr. B. A. Westfall, Dr. Paul Pierce, and Mrs. M. M. Ellis, and the junior members of the staff of the Columbia, Mo., field unit of the U. S. Bureau of Fisheries who have carried forward both in the field and in the laboratory, the many analyses, assays, and experiments required for these studies.

Although this unsettled balance of species is determined directly by competition and other ecological factors, basically it is dependent upon physical and chemical conditions existing in the impounded waters and along their margins, some of which conditions are subject to the abrupt changes attendant upon the necessary utilization of the waters for industrial, agricultural, or commercial purposes.

The fluctuating water level which necessarily is raised and lowered over a wider range of depths and at more frequent and more irregular intervals in impounded waters than in most natural lakes imposes, therefore, certain limitations on the biological productivity of impounded waters. These changes in water level often not only constitute catastrophies for the existing aquatic fauna but also disturb the physical and chemical characteristics of the waters themselves so that environmental conditions are seriously altered.

Some of the interrelations of these physical and chemical complexes have been followed during the past 4 years in the waters of Elephant Butte Reservoir, N. Mex. The data and findings presented here are not only descriptive of specific local situations, but also show some of the physical and chemical conditions which may be encountered in various impounded waters.

Created by the construction of Elephant Butte Dam, the reservoir is approximately 40 miles long and receives the entire flow of the Rio Grande River. This impoundment, closely flanked along the east shore by the Fra Cristobal range and bounded on the west by broken mesas, is divided by natural features of the topography into an upper and a lower lake. (See fig. 1.) The shallow upper lake, which is about 2 miles wide when the reservoir is filled to the spillway elevation of 4,400 feet, extends from the upstream limit of backwater near San Marcial, N. Mex., southward for approximately 25 miles to the Narrows. Here the width of the reservoir is greatly reduced, as the water is confined in a steep-walled canyon some 4 miles long. The Narrows open out at the south end into the deep lower lake which is roughly 15 miles long and from 2 to 4 miles wide.

The impounding of water in Elephant Butte Reservoir was begun in 1914 and the water almost reached the top of the spillway in 1920, despite the draw-off made for irrigation, so the reservoir had 15 years for general adjustment before the present studies were begun. Therefore, the data presented here cover conditions in a large impoundment in which the major physical and chemical adjustments had been made.

As the average surface elevation of the water in Elephant Butte Reservoir has fluctuated around the 4,350 foot elevation level since 1924, dropping to the 4,300 foot level in 1935 and 1936, and as the 4,300 foot contour passes through the lower end of the Narrows (see fig. 2), the upper lake has extensive shallow areas which vary greatly with the stage of water in the lower lake. Consequently, conditions characteristic of impounded waters are evident for the most part only in the deep lower lake, although the effects of the upper lake on the lower lake are very evident. Unless otherwise specified the graphs and discussion will refer to the lower lake of Elephant Butte Reservoir.

FIELD OPERATIONS

The field operations on which this report is based were begun in July 1935. Four major surveys by parties of 6 or more were made in July 1935, July 1937, December 1937, and July 1938. Supplemental observations and samples were taken by smaller groups at other times throughout this period. During each of these major surveys 2 laboratory trucks equipped with apparatus for water analyses and hydrobiological

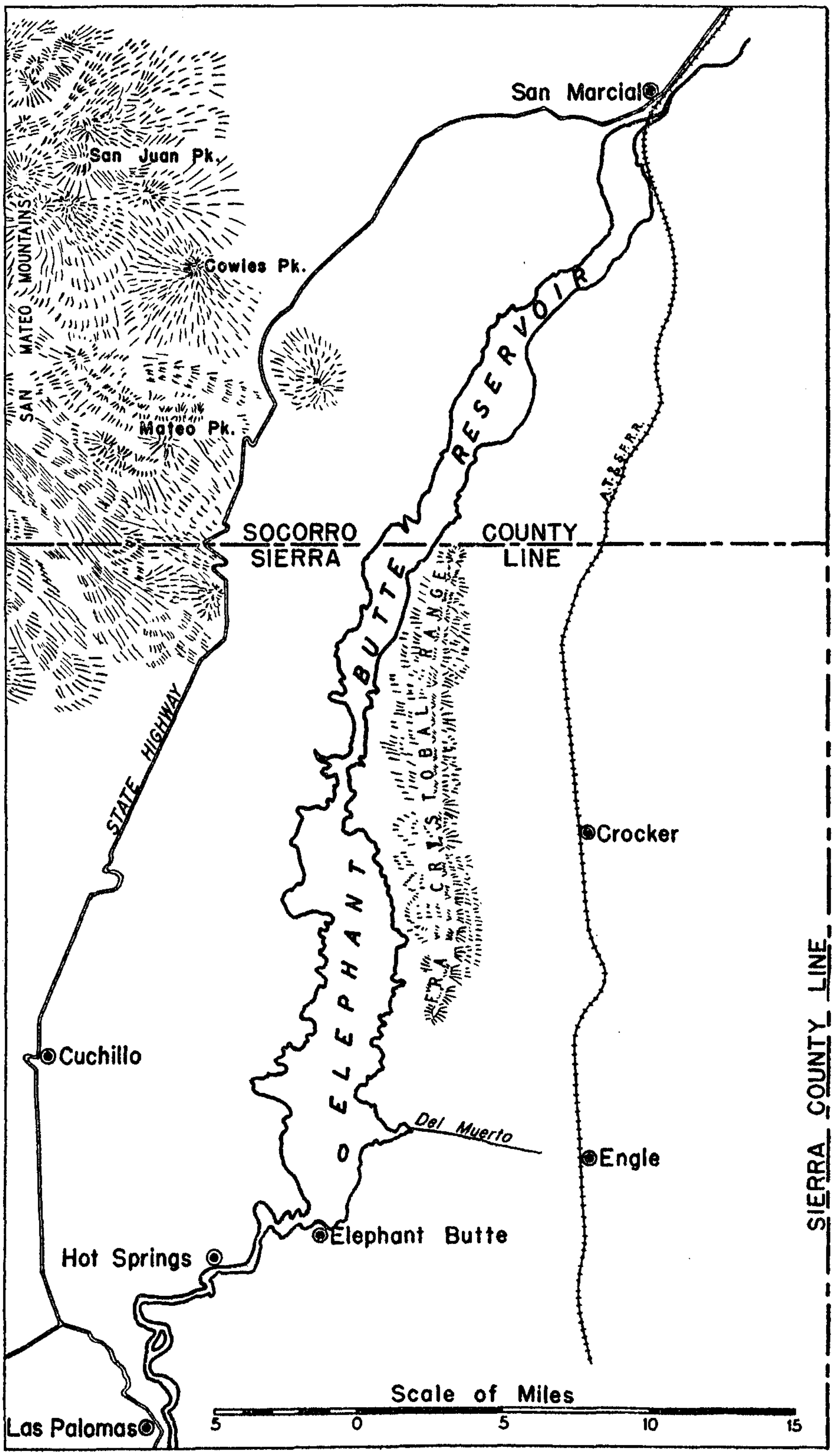

FIGURE 1.—Map of Elephant Butte Reservoir area.

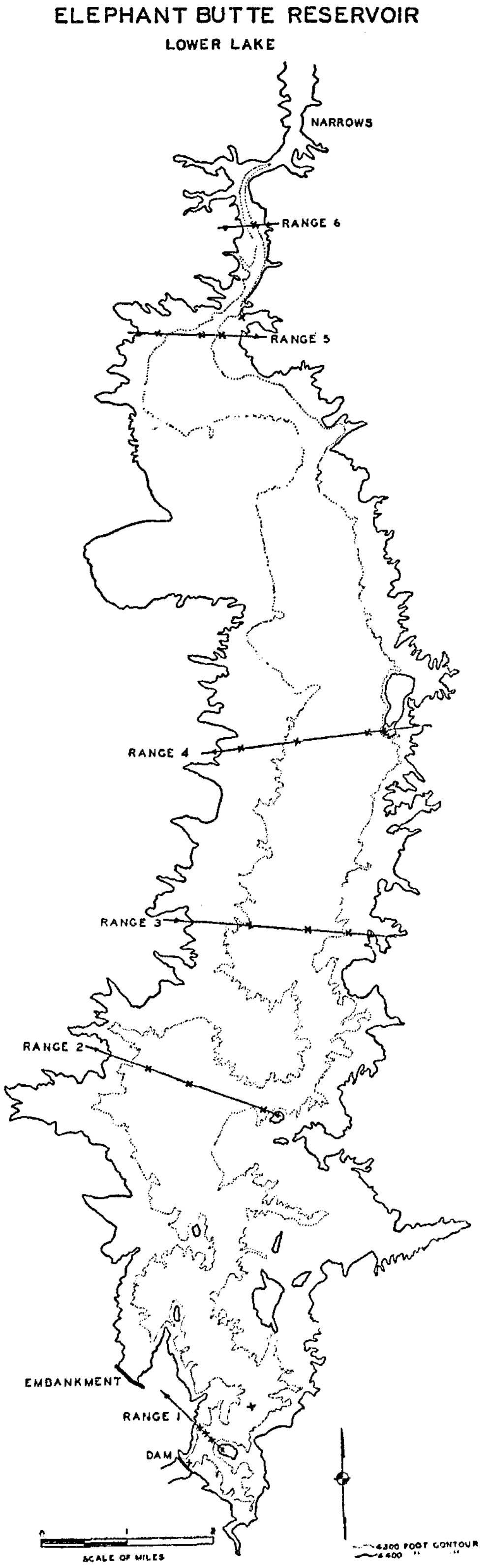

FIGURE 2.—Contour map of the lower lake of Elephant Butte Reservoir, showing ranges and principal stations at which sampling operations were conducted.

studies were used, and a temporary laboratory was maintained at Elephant Butte in a cottage furnished by the United States Reclamation Service.

The sampling and sounding operations in Elephant Butte Reservoir were conducted from a Reclamation Service cruiser. On this boat a drum and steel cable were installed for use in lowering a self-sealing brass water-sampler, an electric thermometer, a photo-electric turbidity meter, and such other apparatus as occasion demanded. Bottom samples were taken with a self-closing Peterson dredge. In this cruiser portable chemical and electrical units were carried for immediate determinations of dissolved gases, hydrogen-ion concentration, and specific conductivity.

Properly prepared samples were returned from the cruiser to the shore laboratory at Elephant Butte and to the laboratories of the Columbia, Mo., field unit of the Bureau of Fisheries for various other analyses. The details of the analytical procedures are given under subsequent topic headings.

In the spring of 1937 the Reclamation Service, in connection with a joint project of the committee on density currents of the National Research Council, in which both the Reclamation Service and Bureau of Fisheries were concerned, erected a series of monuments establishing definite ranges across the lower lake of Elephant Butte Reservoir. These surveys have been recorded and, as far as possible in the field work presented here, the sampling stations were located on these ranges or at points readily recognized from the designated ranges so that observations may be continued over a period of years. A list of these ranges and the major sampling stations follows. (See also fig. 2.)

RANGE 1

From monument on Elephant Butte Island, just over the elephant's right ear, west 4,750 feet to monument on Long Ridge on peninsula between dam and embankment. This range runs NW. to SE. parallel to the face of the dam about 2,000 feet NE. of the dam.

Station 1.—Approximately one-fourth of the distance from Elephant Butte Island to the shore line on the west. U.S.B.F. Lno. 1414.[3]

Station 2.—Halfway between Elephant Butte Island and the shore line on the west. This station is in the old river channel. U.S.B.F. Lno. 1415.

Station 3.—Two-thirds of the distance from Elephant Butte Island to the shore line on the west. U.S.B.F. Lno. 1416.

RANGE 2

From survey monument 76I on Indian Grave Butte to survey monument 76W, Oxbow, on west shore of lake. This range cuts the long axis of the reservior about 5 miles above the dam.

Station 1.—On the east side of the range in north and south line with Long Point Island and Summit Point, just off Indian Grave. U.S.B.F. Lno. 1418.

Station 2.—About midway between Indian Grave and the water tower at Puerto de Luna on the west shore. U.S.B.F. Lno. 1419.

Station 3.—Two-thirds of distance from Indian Grave to the shore line off Oxbow. U.S.B.F. Lno. 1420.

RANGE 3

From survey monument 72E on Olivine Peak, east shore, to survey monument 72W on Cedros, west shore. This range crosses the long axis of the reservoir approximately 7 miles above the dam.

Station 1.—About 1,200 feet off east shore, U.S.B.F. Lno. 1428.

Station 2.—In old channel of Rio Grande about one-third distance from the east shore line to the west shore line. U.S.B.F. Lno. 1429.

Station 3.—About two-thirds of the distance from east shore to the west shore. U.S.B.F. Lno. 1888.

RANGE 4

From survey monument 68E at Alamocita, on east shore, to survey monument 69W at Terrano de Publico on west shore. This range crosses the long axis of the reservoir about 9 miles above the dam.

Station 1.—In old Rio Grande channel, about 200 yards from the east shore. U.S.B.F. Lno. 1426.

Station 2.—About midway between east and west shore. U.S.B.F. Lno. 1889.

Station 3.—About 200 yards off the west shore. U.S.B.F. Lno. 1427.

RANGE 5

From survey monument 60E, Sandy, at Sand Point on east shore, to survey monument 60W, Dandy, on west shore. This range crosses the long axis of the reservoir just below the Narrows and about 14½ miles above the dam.

Station 1.—About 200 yards off east shore. U.S.B.F. Lno. 1421.

Station 2.—In old Rio Grande Channel, about 300 yards off east shore. U.S.B.F. Lno. 1422.

Station 3.—200 yards off the west shore. U.S.B.F. Lno. 1423.

---

[3] Abbreviation for U. S. Bureau of Fisheries locality number.

RANGE 6

Crosses the Narrows 1 mile above the lower lake from survey monument 57E, Diner, on the east shore, to survey monument 57W, Stiner, on the west shore.

Station 1.—Midchannel in the old Rio Grande bed. U.S.B.F. Lno. 1424.

In addition to the principal stations on the designated ranges, several other sampling stations were established during the course of these investigations. For convenience all of the major sampling stations are listed in table 1, according to the U.S.B.F. locality numbers.

TABLE 1.—*List of the major sampling stations, Elephant Butte Reservoir investigations*

Locality No. (Lno.)	Description of station	Locality No. (Lno.)	Description of station
829	Lower lake, about 150 feet above dam.	1429	Lower lake, range 3, station 2.
830	Lower lake, 1 mile above dam, old channel.	1430	Rio Grande, San Marcial, N. Mex.
831	Rio Grande, Hot Springs, N. Mex.	1431	Rio Grande, 6 miles north of Socorro, N. Mex.
1414	Lower lake, range 1, station 1.	1432	Rio Puerco, near Bernardo, N. Mex.
1415	Lower lake, range 1, station 2.	1526	Rio Grande, Isleta, N. Mex.
1416	Lower lake, range 1, station 3.	1546	Lower lake, bathing beach, west shore between embankment and range 2.
1418	Lower lake, range 2, station 1.		
1419	Lower lake, range 2, station 2.	1547	Rio Grande, 2 miles east of San Antonio, N. Mex.
1420	Lower lake, range 2, station 3.	1548	Rio Grande, 4 miles east of Bernardo, N. Mex.
1421	Lower lake, range 5, station 1.	1659	Lower lake, Rock Canyon west end of range 2.
1422	Lower lake, range 5, station 2.	1660	Upper lake, ½ mile from east shore, opposite San Jose Canyon.
1423	Lower lake, range 5, station 3.		
1424	Up the Narrows, range 6, station 1.	1661	Upper lake, 1 mile south from Lno. 1660.
1425	Lower lake, between range 5 and mouth of Narrows, side canyon east shore.	1662	Upper lake, ¾ mile north of the Narrows.
		1663	In the Narrows, 1 mile south of lower end of upper lake.
1426	Lower lake, range 4, station 1.		
1427	Lower lake, range 4, station 3.	1888	Lower lake, range 3, station 3.
1428	Lower lake, range 3, station 1.	1889	Lower lake, range 4, station 2.

WATER CHARACTERISTICS, ELEPHANT BUTTE RESERVOIR

TEMPERATURE

The detailed temperature readings were taken electrometrically with a Brown resistance thermometer (galvanometric resistance 247 ohms; bulb type 940A), lowered on a steel cable from a drum attached to an odometer on which the exact depth to one-tenth of a foot could be read at all times. For rapid work standardized glass, mercury-bulb thermometers were used and temperatures were recorded in degrees Centigrade.

In addition to the climatic conditions of the region and the physical features of the basin, which jointly regulate water temperatures in natural lakes, the position of the dam and the draw-off from the reservoir are also major factors in determining water temperatures in impounded waters. Consequently the temperature cycles which obtain in many natural lakes with surface outlets are modified in impounded waters by the volume of the outflow, the level from which this water is removed, and the type of draw-off, i. e., constant or intermittent. These variables, individually and collectively, can disturb temperature relations and other conditions in the several layers of water throughout any impoundment.

The outflow from Elephant Butte Reservoir leaves the bottom of the reservoir approximately 160 feet below the level of the spillway gates, and usually at least 100 feet below the surface of the water in the reservoir. As a minimal outflow is maintained constantly to meet various needs farther down the Rio Grande, and as the total volume of the outflow for irrigation purposes is intentionally as large as seems consistent with the expected intake, an overflow through the spillway gates, that is,

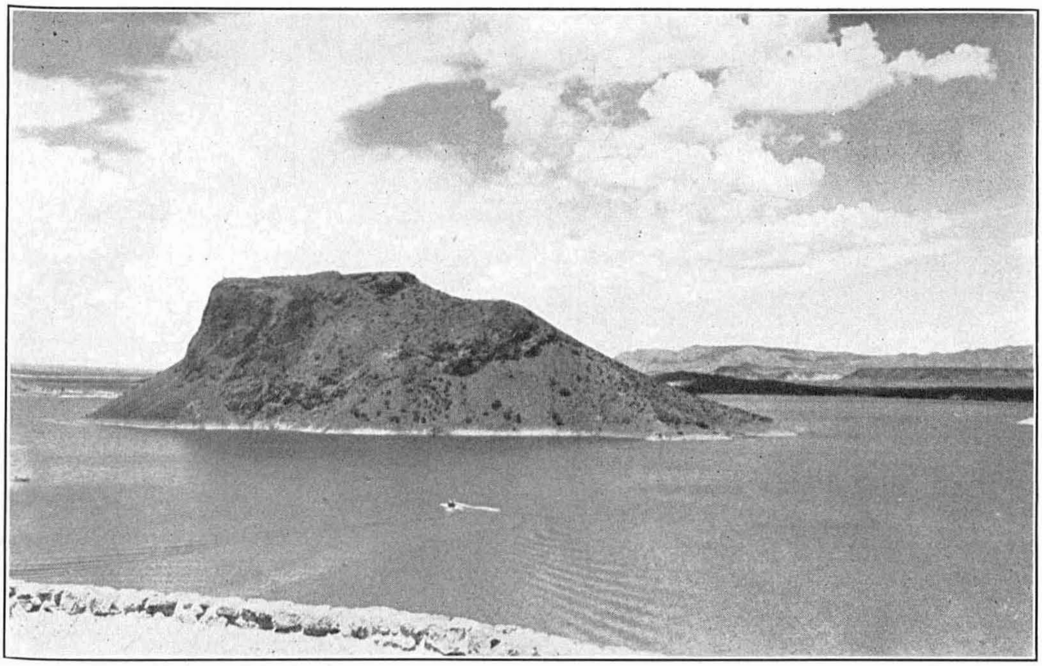

FIGURE 3.—Elephant Butte Island, Elephant Butte Reservoir, looking north from the south end of the reservoir.

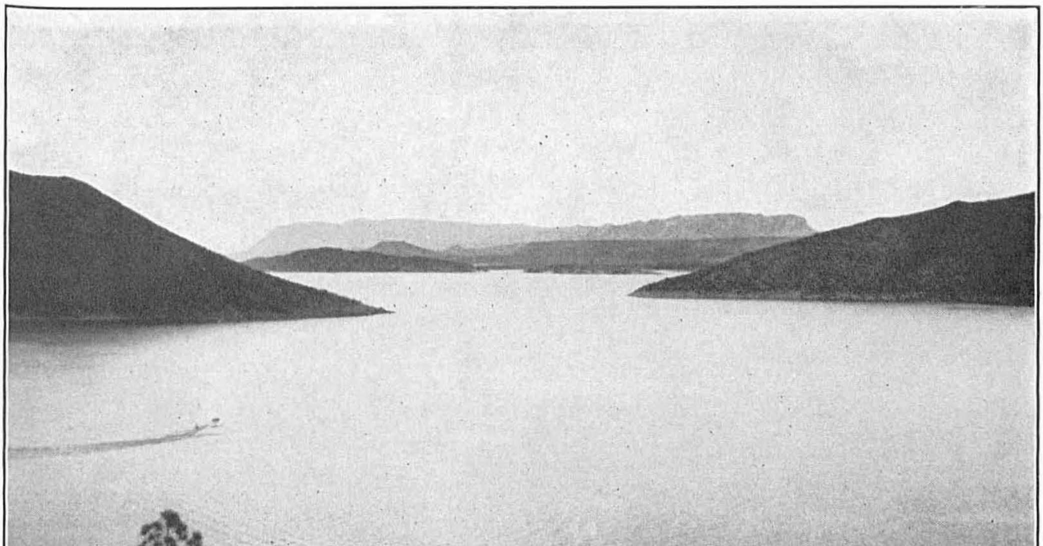

FIGURE 4.—East side of Elephant Butte Reservoir. East channel in foreground, Kettle Butte in midbackground, and Fra Cristobal Range in the distance.

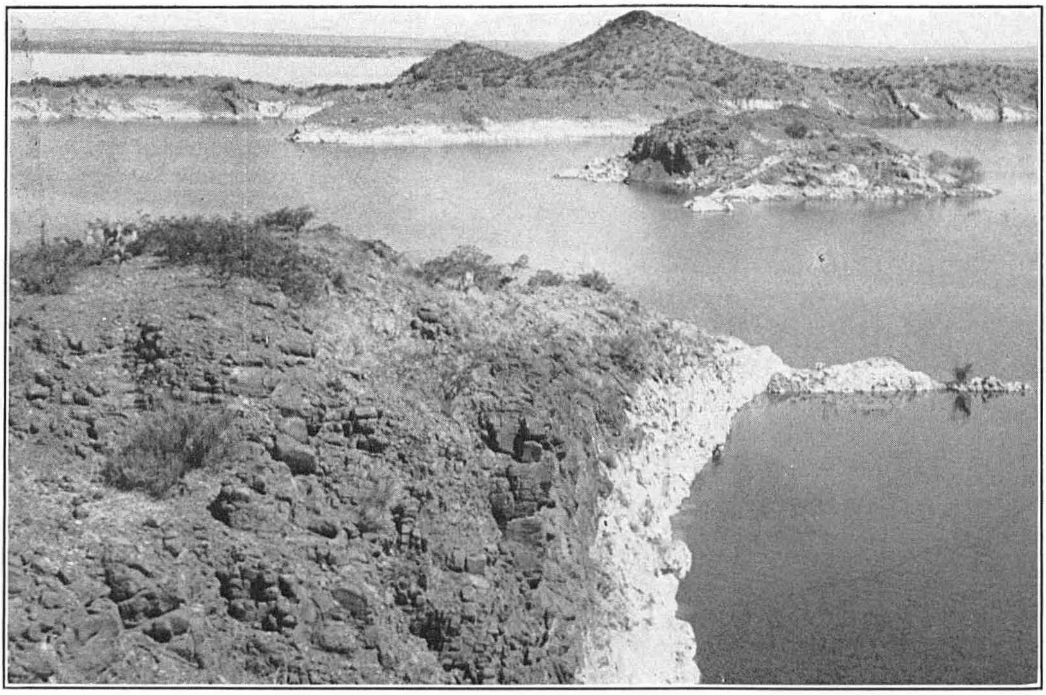

FIGURE 5.—East shore of the lower lake, Elephant Butte Reservoir, showing the steep rocky banks bearing white incrustations indicating the extent of the draw-down. The west shore of the lower lake can be seen in the left background.

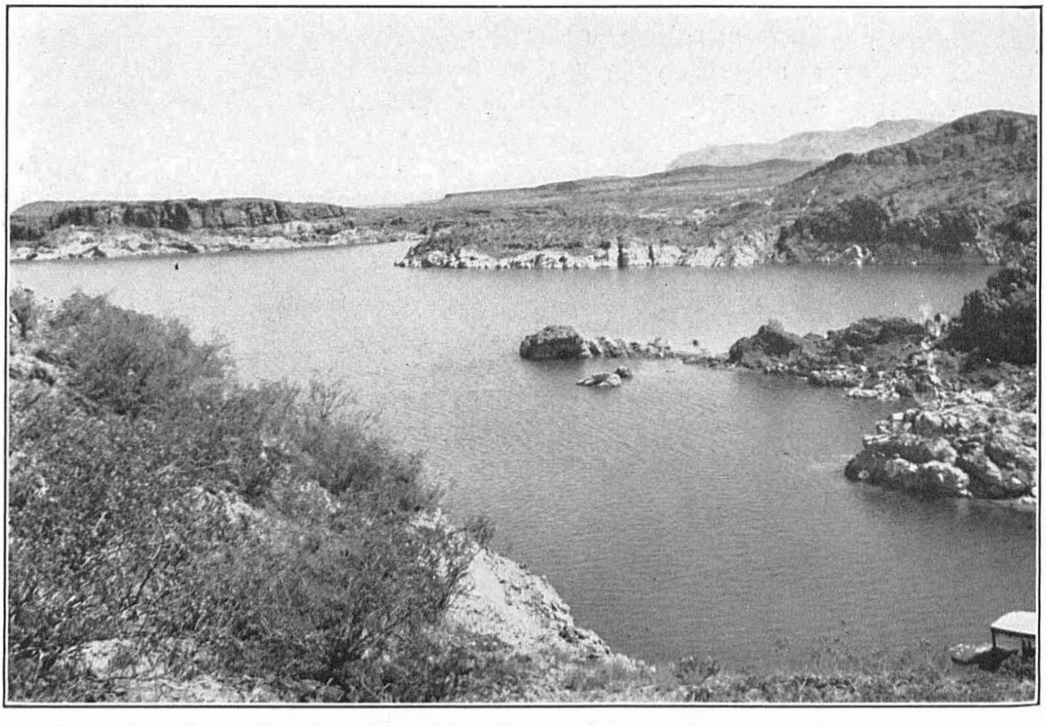

FIGURE 6.—East shore of lower lake, Elephant Butte Reservoir, looking north across one of the many rock coves.

an outflow comparable in position to the outflow of most natural lakes, rarely exists at Elephant Butte Reservoir. This control of the water level by a deep draw-off and the presence of a barrier on the floor of the reservoir between ranges 2 and 3 (see fig. 2) brings about conditions in the lower lake of the reservoir quite different from those usually found in natural lakes.

The annual temperature cycle for Elephant Butte Reservoir, as shown by a large series of observations made at the dam by the United States Reclamation Service over a period of years, has a gamut of approximately 20°C. for the surface and 12°C. for the outflow water (which as previously noted is drawn from the bottom of the reservoir in the region of greatest depth). In figure 7 the surface and outflow temperatures July 1, 1934, to July 1, 1935, have been graphed from data supplied by the Reclamation Service. This period was chosen because during those 12 months a fairly low water level, near the 4,330 foot elevation level, was maintained rather consistently.

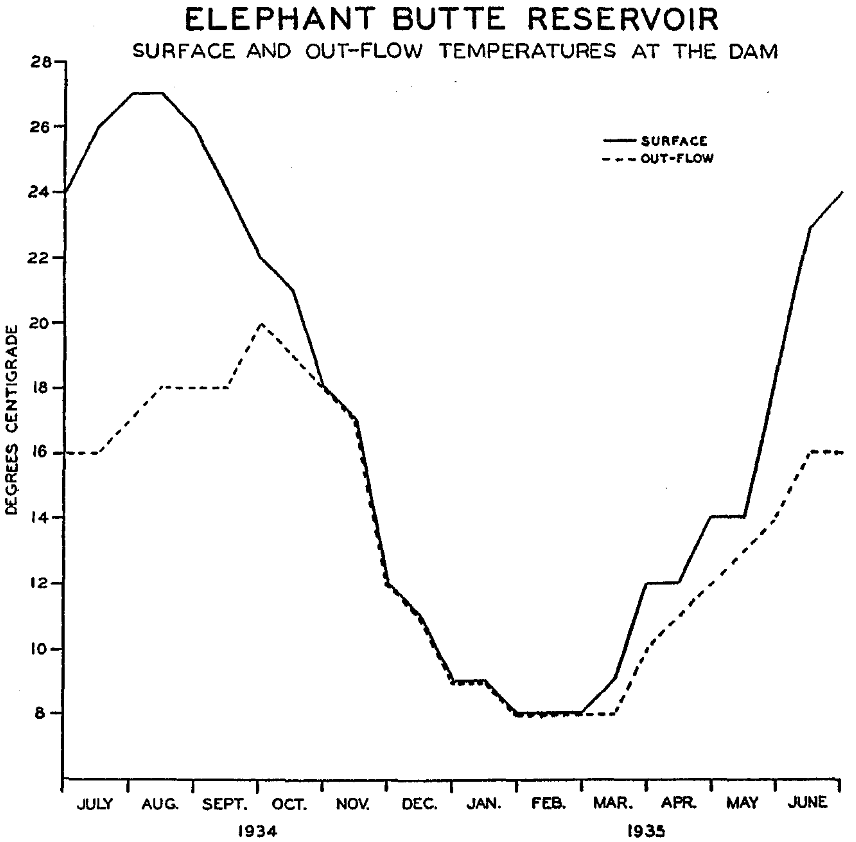

FIGURE 7.—Annual temperature cycles of surface and out-flow waters, Elephant Butte Reservoir, July 1934 to July 1935, from data supplied by the U. S. Reclamation Service.

From figure 7 it can be seen that the maximal surface temperature approaching 28°C. can be expected in July or August, and that the surface temperature begins to fall around the first of September. The maximal bottom temperature, however, is not reached until about the first of October, that is, nearly a month after the surface temperature has started to decline. By the middle of November the surface and bottom temperatures are essentially the same at a common level near 15°C. and they continue to decline to the common annual low of approximately 8°C. in February.

The surface-water temperature begins to rise early in March and continues to rise at an increasing rate to the annual maximum in August, making the greatest gain in May or June. The bottom temperature lags behind the surface temperature from the middle of March but increases slowly and rather uniformly to the annual maximum in October.

In view of the annual temperature cycles just described for the surface and bottom waters at the dam, the July 1937, the late December 1937, and the July 1938, observations throughout the reservoir have been selected from the present studies for detailed comparisons of the extremes in the temperature gamut. In connection with these comparisons it must be noted that the surface elevation in the lower lake during the four major surveys was 4,340 feet in June 1935, 4,380 feet in July 1937, 4,370 feet in December 1937, and 4,376 feet in July 1938. (Data supplied by U. S. Reclamation Service.)

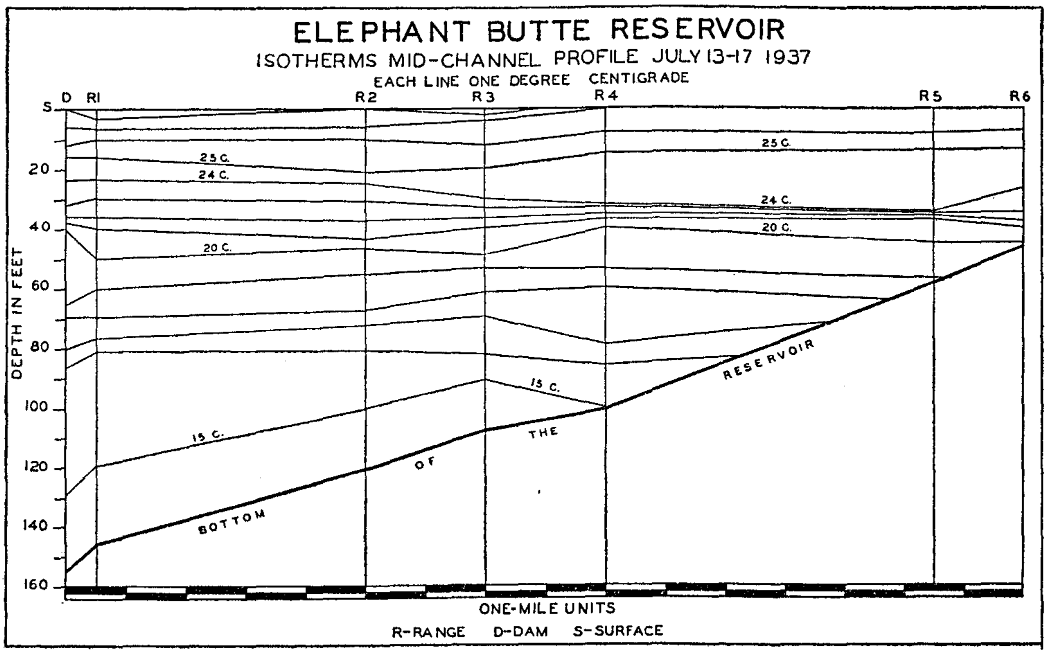

FIGURE 8.—Isotherms, lower lake, Elephant Butte Reservoir, midchannel profile, midsummer, 1937.

The July data portrays conditions at the beginning of the period of maximal surface temperature and the late December data conditions during the period of minimal surface and bottom temperatures. Only the midchannel profiles [4] are presented (see figs. 8, 9, and 10), as these stations included the maximal depths. Temperature readings and samples for analyses were taken at all stations, however, and from these data it may be stated that the temperature stratifications and zones found in the midchannel studies obtained in general up to the 10-foot level for all

---

[4] The midchannel profile follows the old bed of the Rio Grande and in this and subsequent sections is drawn from observations at the following stations: 150 feet upstream from the dam, Lno. 829; range 1, station 2, Lno. 1415; range 2, station 2, Lno. 1419; range 3, station 2, Lno. 1429; range 4, station 1, Lno. 1426; range 5, station 2, Lno. 1422; and range 6, station 1, Lno. 1424. Supplementary observations were made between these stations whenever the findings on the principal ranges suggested the need of such sampling. (See fig. 2 and table 1 for list of ranges.)

stations. In water less than 10 feet deep at the stations near shore the influence of shore conditions was evident in the higher, late afternoon temperatures at the surface during the summer season. Near shore, in shallows to a depth of 3 feet, midsummer afternoon water temperatures were found occasionally as high as 33°C. (See tables 2 to 11 inclusive.)

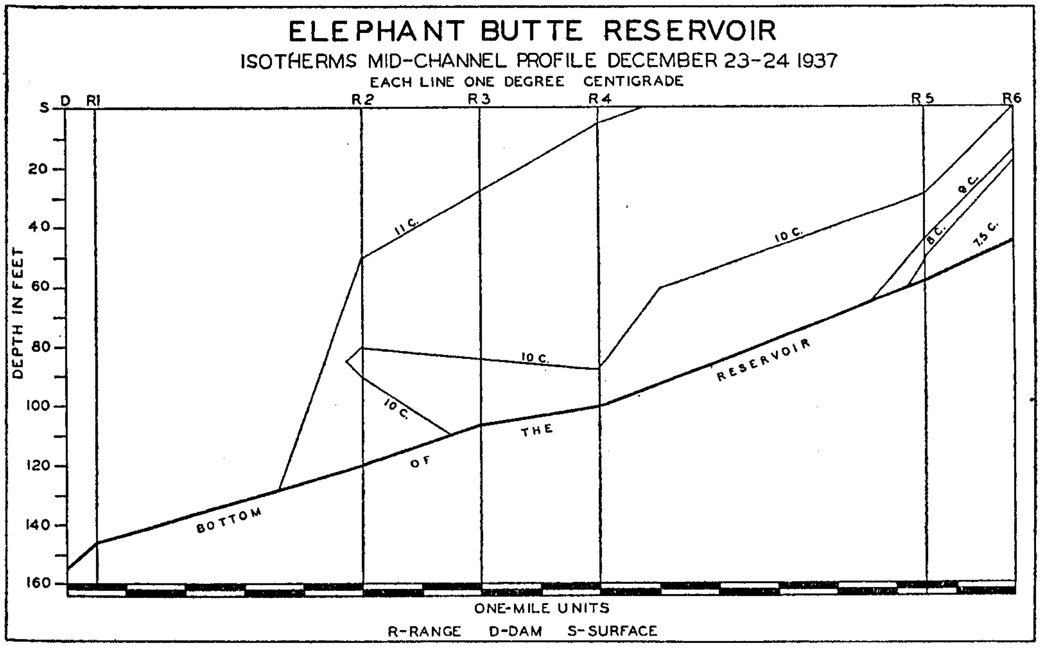

FIGURE 9.—Isotherms, lower lake, Elephant Butte Reservoir, midchannel profile, midwinter, 1937.

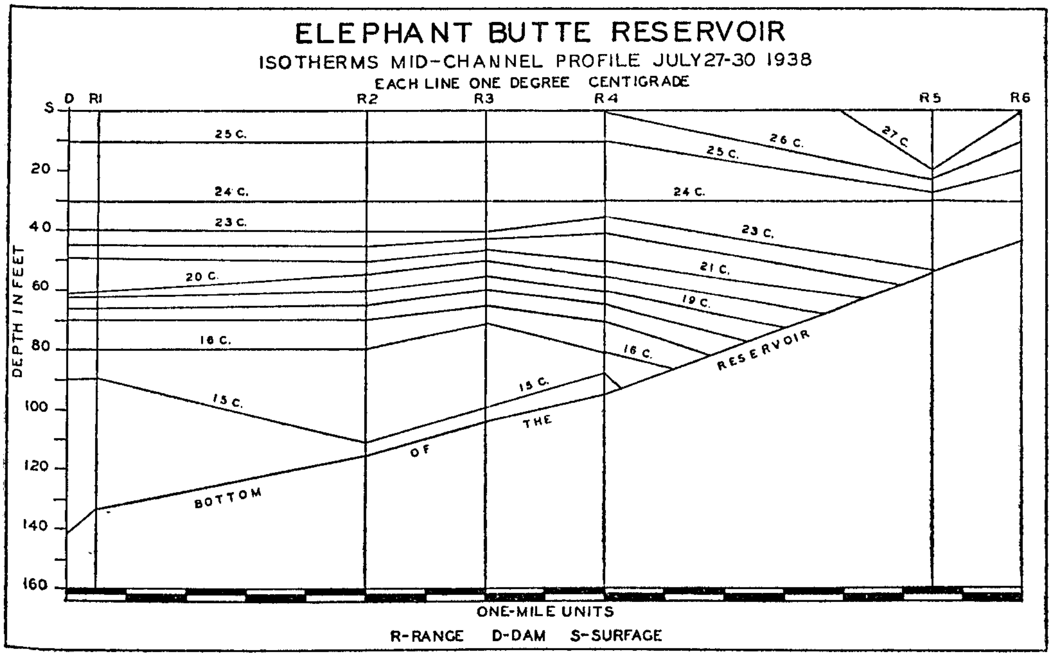

FIGURE 10.—Isotherms, lower lake, Elephant Butte Reservoir, midchannel profile, midsummer, 1938.

TABLE 2.—*Physical and chemical data at station 829, 150 feet upstream from Elephant Butte Reservoir dam, June 15, 1935*

[Air temperature 33°C. Time, 1:30–2:10 p. m. Surface elevation of reservoir 4,340 feet]

Depth in feet	Water temperature degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho $\times 10^{-6}$ at 25°C.	pH	Carbonate (CO_3), parts per million		Free carbon dioxide, parts per million	Turbidity, parts per million
					Phenolphthalein alkalinity	Methyl-orange alkalinity		
0	33.0	7.1	1,009	8.4	5.6	70.6	0	12.8
3	33.0	7.2	1,062	8.3	4.0	68.8	0	12.8
6	23.0	5.9	1,024	8.3	4.0	69.0	0	6.1
10	23.0	5.5	1,017	8.2	3.2	67.4	0	7.0
13	23.0	6.6	1,019	8.1	1.6	64.6	0	2.8
16	22.8	6.1	1,022	8.1	1.6	69.2	0	2.8
20	22.8	6.1	----------	8.1	1.6	68.0	0	3.2
23	22.0	6.2	1,051	8.1	1.6	67.0	0	2.8
26	21.9	6.8	1,062	8.1	1.2	67.8	0	2.8
29	21.5	5.9	1,081	7.8	0	70.4	2.8	2.8
33	20.5	6.6	1,096	7.6	0	69.6	2.2	2.8
36	20.4	6.6	1,077	7.6	0	68.6	3.6	1.3
38	19.8	6.2	1,107	7.6	0	69.8	1.4	1.2
49	19.6	6.5	1,068	7.6	0	70.2	2.2	1.2
59	18.8	6.6	1,070	7.6	0	69.6	4.8	1.2
68	18.0	6.8	996	7.6	0	71.0	4.8	1.3
78	17.8	5.1	1,067	7.6	0	71.6	5.4	1.3
88	17.6	5.1	1,045	7.6	0	72.4	8.0	1.2
98	17.1	5.3	1,059	7.6	0	73.6	7.4	1.2
107	16.9	5.1	1,052	7.6	0	73.0	4.8	1.3
120	16.9	4.7	1,023	7.5	0	73.8	6.4	1.2

TABLE 3.—*Physical and chemical data, lower lake, Elephant Butte Reservoir, at dam (Lno. 829) July 14, 1937. Time, 9:40–11:47 a. m. Air temperature 29.5–30°C.*

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho$\times$10-6 at 25°C.	pH	Carbonate (Co_3), parts per million (methyl-orange alkalinity)
0	28.0	7.0	623	8.4	64.4
10	26.3	7.4	595	8.4	66.0
20	30.0	6.7	607	8.3	65.4
30	23.8	3.8	607	8.1	67.4
40	20.8	3.1	631	7.8	67.2
50	19.8	3.5	664	7.9	70.2
60	19.3	3.6	656	7.9	72.0
70	18.0	3.8	684	7.9	73.2
80	17.0	4.2	694	7.9	75.0
90	15.8	4.2	717	7.9	72.0
100	17.0	3.7	720	7.8	75.6
110	15.8	3.3	733	7.9	76.4
120	15.2	3.7	737	7.8	72.0
130	15.0	3.1	762	7.9	75.0
140	15.3	3.9	767	7.8	63.0
150	15.0	3.7	791	7.8	73.4
153	14.9	2.9	793	7.8	73.8

TABLE 4.—*Physical and chemical data, lower lake, Elephant Butte Reservoir July 13 and 14, 1937*

Depth in feet	Water temperature, degrees Centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho $\times 10^{-6}$ at 25°C.	pH	Carbonate (CO$_3$), parts per million (methyl-orange alkalinity)
	Range 1, station 1, east side (Lno. 1414), July 13, 1937. Time 8:50-10:45 a. m. Air temperature 27.5-33.8°C.				
0	26.6	6.0	601	8.4	69.0
16	25.3	9.4	610	8.3	65.2
32	23.6	5.9	617	8.2	67.2
49	21.0	4.6	678	8.0	68.0
65	17.8	5.2	720	8.0	73.4
81	17.0	5.0	772	8.1	73.8
99	15.5	4.6	786	8.2	73.8
114	14.9	4.6	792	8.3	74.6
130	14.9	4.6	818	8.2	74.6
140	15.0	4.2	810	8.2	87.0
	Range 1, station 2, midchannel (Lno. 1415), July 13, 1937. Time 11:22 a. m.-4:25 p. m. Air temperature 32-32.2°C.				
0	29.0	7.0	555	8.4	67.0
10	26.0	6.1	474	8.5	60.8
20	24.7	6.4	596	8.4	64.6
30	23.0	5.2	611	8.2	64.6
40	21.0	4.6	657	8.0	67.8
50	20.0	3.5	697	8.0	71.6
60	19.0	5.8	698	8.0	70.0
70	18.0	5.0	725	8.0	72.6
80	18.7	5.7	751	8.0	73.2
90	16.0	5.7	791	8.0	74.0
100	15.3	4.6	787	8.0	74.8
110	15.2	4.8	809	7.9	74.8
120	16.0	4.2	804	8.0	77.2
130	15.0	5.2	814	7.5	74.0
138	15.0	5.0	798	7.9	81.4
140	14.9	5.7	806	7.9	89.2
146	14.8	5.3	740	7.8	113.4
	Range 1, station 3, west side (Lno. 1416), July 14, 1937. Time 8:20-9:16 a. m. Air temperature 27°C.				
0	27.5	6.1	618	8.5	61.2
10	26.0	6.7	612	8.4	61.2
20	25.0	6.0	607	8.4	63.0
30	24.0	5.0	603	8.3	63.2
40	21.0	2.8	636	7.8	64.2
50	19.5	2.8	677	7.8	67.0
60	18.8	3.4	700	7.8	68.6
63	18.5	3.9	681	7.8	68.4

TABLE 5.—*Physical and chemical data, lower lake, Elephant Butte Reservoir, June 14 and 15, 1937*

Depth in feet	Water temperature, degrees Centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho × 10^{-6} at 25°C.	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)
	Range 2, station 1, east side (Lno. 1418), July 14, 1937. Time 2:12–3:23 p. m. Air temperature 34°C.				
0	28.8	6.2	595	8.4	63.0
10	25.5	6.7	578	8.3	66.0
20	25.0	5.2	600	8.2	66.0
30	24.0	3.8	601	7.9	66.0
40	22.0	1.9	595	7.6	70.2
50	20.0	2.3	597	7.7	70.4
60	22.3	6.7	642	7.8	71.4
70	18.0	3.2	664	7.8	70.8
80	18.0	3.1	679	7.8	72.6
90	15.5	2.9	705	7.8	77.4
100	15.1	3.1	712	7.8	76.4
110	15.0	2.9	714	7.8	78.0
114	15.1	2.9	735	7.8	79.2
	Range 2, station 2, midchannel (Lno. 1419), July 15, 1937. Time 9:40–11:30 a. m. Air temperature 33°C.				
0	28.0	7.6	598	8.4	62.6
10	26.0	7.6	593	8.4	63.0
20	25.0	5.7	595	8.3	60.6
30	23.0	3.8	592	8.1	62.2
40	22.5	6.4	583	8.3	60.0
50	20.7	7.9	589	7.9	66.0
60	18.8	3.4	633	7.8	66.4
70	18.0	5.9	656	7.9	68.2
80	16.2	3.6	718	7.9	68.2
90	15.2	3.3	587	7.9	61.2
100	15.5	2.9	777	7.9	73.6
110	14.8	2.9	800	7.8	73.2
120	14.5	2.6	714	7.7	72.8
	Range 2, station 3, west side (Lno. 1420), July 15, 1937. Time 1:10–2:36 p. m. Air temperature 34°C.				
0	28.5	7.0	606	8.4	60.6
10	27.0	7.0	613	8.4	61.4
20	25.0	5.5	597	8.4	61.4
30	24.0	5.3	593	8.2	61.4
40	21.0	2.0	618	7.8	64.4
50	19.8	2.9	643	7.8	68.2
60	19.0	3.1	667	7.8	66.4
70	18.0	3.3	695	7.8	69.0
80	16.5	3.4	705	7.8	69.0
90	16.0	3.1	973	7.7	72.0
100	15.0	3.3	761	7.7	72.0
110	14.9	3.1	779	7.8	72.4
122	14.9	2.5	730	7.8	75.8

TABLE 6.—*Physical and chemical data, lower lake, Elephant Butte Reservoir, July 17, 1937*

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho × 10^{-6} at 25°C.	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)
	Range 3, station 1, east side (Lno. 1428), July 17, 1937. Time 1:02–1:50 p. m. Air temperature 34°C.				
0	28.8	8.6	585	8.4	59.6
10	26.0	8.4	630	8.5	60.6
20	25.3	6.7	603	8.5	62.6
30	24.0	3.8	682	8.1	66.8
40	21.0	2.2	627	7.8	68.4
50	20.0	2.7	647	7.7	68.8
60	19.3	3.2	625	7.8	68.4
70	17.8	3.6	671	7.8	71.8
75	17.0	3.7	699	7.8	73.2
	Range 3, station 2, midchannel (Lno. 1429) July, 17, 1937. Time 2:10–3:45 p. m. Air temperature 37°C.				
0	28.5	7.7	603	8.3	63.0
10	26.3	8.0	547	8.3	59.6
20	25.0	6.1	592	8.2	62.6
30	24.0	4.5	571	8.1	62.6
40	21.0	1.9	608	7.8	65.4
50	20.0	2.6	616	7.8	66.0
60	18.8	2.5	637	7.8	67.8
70	17.5	3.8	686	7.8	70.0
80	16.5	3.8	726	7.7	72.8
90	15.5	3.3	764	7.7	62.0
100	14.9	2.5	717	7.7	69.4
107	14.9	2.8	768	7.7	76.2

TABLE 7.—*Physical and chemical data, lower lake, Elephant Butte Reservoir, July 17, 1937*

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho × 10^{-6} at 25°C.	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)
	Range 4, station 1, midchannel (Lno. 1426), July 17, 1937. Time 9:05–10:55 a. m. Air temperature 30°C.				
0	27.0	7.8	582	8.4	60.6
10	25.3	6.9	566	8.3	63.4
20	24.8	6.2	500	8.4	64.4
30	24.5	3.8	476	8.0	63.0
40	20.5	1.8	610	7.8	66.0
50	19.5	2.5	627	7.9	66.4
60	18.3	2.9	645	7.8	67.4
70	17.8	2.6	680	7.9	68.4
80	17.0	3.3	690	7.9	68.8
90	15.5	2.9	736	7.8	70.8
100	15.0	1.9	756	7.7	75.2
	Range 4, station 3, west side (Lno. 1427), July 17, 1937. Time 12:16–12:30 p. m. Air temperature 36°C.				
0	28.3	6.9	566	8.3	59.0
10	26.0	8.5	552	8.3	1.0
23	24.5	5.4	571	8.1	64.0

TABLE 8.—*Physical and chemical data, lower lake, Elephant Butte Reservoir, July 16, 1937*

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho $\times 10^{-6}$ at 25°C.	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)
	Range 5, station 1, east side (Lno. 1421), July 16, 1937. Time 1:50–2:28 p. m. Air temperature 35.5° C.				
0	27.3	6.8	657	8.2	64.4
10	25.3	6.2	599	7.8	63.0
20	24.5	3.4	585	7.8	62.6
30	22.8	1.5	588	7.7	64.8
40	21.5	0.8	601	7.6	64.4
50	19.8	1.8	598	7.6	63.2
54	19.3	1.6	612	7.6	65.2
	Range 5, station 2, midchannel (Lno. 1422), July 16, 1937. Time 10:56–11:45 a. m. Air temperature 34.3° C.				
0	26.5	7.1	585	8.2	66.2
10	25.3	6.5	585	7.8	63.0
20	24.8	3.1	588	7.7	64.4
30	25.0	1.4	583	7.7	63.0
40	20.3	0.8	605	7.6	63.8
50	19.8	1.4	616	7.5	65.2
57	19.0	1.3	636	7.6	66.8
	Range 5, station 3, west side, (Lno. 1423), July 16, 1937. Time 9:50–10:30 a. m. Air temperature 34° C.				
0	26.5	6.4	577	8.2	60.0
10	25.3	5.3	586	7.9	61.4
20	24.5	3.8	602	7.8	61.4
30	23.0	1.2	590	7.6	63.8
40	20.8	0.8	599	7.6	64.4
50	19.5	1.4	620	7.5	67.4
56	19.5	0.8	620	7.6	69.4

TABLE 9.—*Physical and chemical data*

[In the Narrows, Elephant Butte Reservoir, range 6, station 1 (Lno. 1424), July 16, 1937. Time 12:55–1:33 p. m. Air temperature 35.5° C.]

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho $\times 10^{-6}$ at 25°C.	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)
0	27.0	7.1	680	8.0	62.2
10	25.5	7.0	664	8.1	64.4
20	24.8	3.6	641	7.8	62.6
30	23.3	1.5	604	7.6	64.8
40	21.0	0.7	605	7.5	66.0
46	20.0	0.3	605	7.5	65.4

It must be noted throughout these studies on Elephant Butte Reservoir, particularly in those made during the summer months, that masses of water varying from a few cubic feet to several thousand cubic feet in volume were frequently found which differed from the surrounding water in temperature, dissolved oxygen, or other characteristics. These masses of water, which were observed at various depths, often seemed rather sharply delimited as if they had been detached from the strata to which they belonged by convection currents, flow currents, or obstacles on the floor of the reservoir. These nonconformities, although they have been disregarded in drawing the principal isotherms, will be discussed more fully under dissolved oxygen.

From figure 8, which presents the isotherms for July 1937, it may be seen that between ranges 4 and 5 a well-defined thermal stratification existed. As this portion of the reservoir is about 5½ miles long and some 2 miles wide the temperature readings indicate a rather stable temperature balance for this part of the impoundment. There was a clearly delimited epilimnion above the 30-foot level in which the temperature range is less than 3°C. Below the epilimnion in a rather narrow thermocline, some 8 to 10 feet thick, the temperature dropped from 24 to 21 degrees, a change just sufficient to define this zone as a thermocline according to current limnological usage which requires a fall of at least 1°C. per meter of depth. From approximately the 40-foot level to the bottom a hypolimnial unit can be designated in which the temperature fell gradually but rather uniformly to 15°C.

From range 4 to the dam the thermoclinal band spread into the epilimnion and hypolimnion so that even on range 3 the temperature gradients were too small to define a true thermocline. Between range 2 and the dam the isotherms are quite evenly spaced down to the 90-foot level, where the temperature was 16°C.

Upstream from range 5 in the Narrows the isotherms show that the water delivered from the upper lake to the lower lake was approximately 27°C. at the surface and 24°C. at the 25-foot level.

During the July 1937 period the waters of the Rio Grande above the upper lake were warm, as shown by the following temperature readings taken July 18, 1937: Rio Puerco near the junction with Rio Grande, 34.5°C.; Rio Grande at Socorro, N. Mex., 31°C.; and Rio Grande at San Marcial, 25°C. (See table 12.) As there was no cold water in the shallow upper lake at this time the water received by the lower lake from the Rio Grande, by way of the upper lake, left the Narrows at a temperature of between 27° and 24°C. Under this layer of warm water, which was some 25 feet in depth, a smaller layer of cold water extended up the Narrows, along the bottom, to range 6. The temperature span in this colder water was too small to define a thermocline, however, and temperature readings upstream from range 6 showed that the spread of the isotherms became even greater as the upper lake was approached.

The late December 1937 temperature profile (see fig. 9) is quite different. The river temperatures for the Rio Grande on December 23, 1937, were 1°C. at Isleta, N. Mex.; 2.5°C. in the Rio Puerco near the junction with Rio Grande; 5°C. in the Rio Grande at Socorro, N. Mex., and 5.8°C. at San Marcial, N. Mex. (See table 12.) With the cold waters of the Rio Grande pouring into the upper lake, the water temperatures in the Narrows ranged from a scant 10°C. at the surface to 7.5°C. at the bottom, in approximately 55 feet of water The cold water entering the lower lake from the Narrows (see fig. 9) moved under the warmer water of the lower lake and could be followed on the bottom 11½ miles downstream, to a point below range 2. Figure 9 indicates that in late December the warmer water of the lower lake was being pushed toward the dam by the more dense cold water from the Narrows and that the draw-off at the bottom of the dam was, at the same time, pulling this water to the bottom of the reservoir between the dam and range 2. The resultant of these two forces is indicated by the position of the 11° isotherm.

The abrupt change in slope of the 11° isotherm near the 50-foot level on range 2 and the reentrant path of the 10° isotherm between ranges 2 and 3, indicating the position of a zone of warmer water near the bottom just above range 2, suggest that flows moving down the lower lake below the 4,350-foot contour are interrupted or deflected by the submerged barrier between ranges 2 and 3.

Although the midchannel profile indicates a rather gradual downward slope of the reservoir bottom from the Narrows to the dam, as this particular profile intentionally follows the old river channel on the map of the lower lake (see fig. 2), it may be seen that the 4,300-foot contour swings out from the west shore between ranges 2 and 3 and indicates the position of a submerged mesa which almost blocks the bottom of the reservoir in this region. From contour maps made before the reservoir was filled it was found that the main top of this mesa rises to an elevation of 4,390 feet. The old river bottom and the floor of the reservoir immediately north of this submerged mesa, however, have an elevation of only 4,250 feet. Consequently, water moving down the lower lake along the bottom through the 8 or 9 miles of rather broad open basin between ranges 5 and 3 encounters, a little south of range 3, an abrupt wall at least 100 feet high—excepting the narrow opening near the east shore where the old river channel cut around this mesa only to be turned abruptly west a short distance south by a similar mesa on the east. It is not surprising, therefore, that the nonconformities in water masses, as shown in the vertical sections of the lower lake, were common in the region of range 2 in view of these features of the submerged terrain.

The surface zone—water down to a depth of 20 to 30 feet—was not affected by this submerged mesa nor by the configuration of the tortuous old river channel during the December 1938 survey, as the surface elevation of the water at that time was 4,370 feet. The surface was approximately 20 feet above the top of the major portion of the submerged mesa. During periods of lower water, as in June 1935, when a considerable portion of this mesa was exposed because the surface elevation of the water had dropped at that time to the 4,340-foot level, the lower lake is rather sharply divided into two basins—one north of range 3 and the other south of range 2. At such times the temperature relations and the isotherms may differ very definitely in the two basins.

The combined action of the draw-off and the bottom flow of the water entering the lower lake from the Narrows continues through January and February until the bottom end of the 8° isotherm has moved down the reservoir to beyond range 1. At that time the annual low in the temperature cycle has been reached and a considerable portion of the water between range 3 and the dam has a temperature of approximately 8° C. The exact position of the surface end of the 8° isotherm depends largely upon three major factors, namely, the volume of the outflow removed by the draw-off, the volume of the inflow from the Narrows, and the constancy of the prevailing low-air temperatures of this December to February period.

The instability of the temperature pattern in the two basins of the lower lake may be seen by a comparison of the July 1937 (see fig. 8) and the July 1938 (see fig. 10), midchannel temperature profiles. During the latter part of July 1938 [5] very warm muddy water filled the upper lake and this water was moving down the Narrows and out into the lower lake. Due to differences in specific gravity between the muddy water and the clearer water of the lower lake, warm water from the upper lake and Narrows was accumulating in the upper basin of the lower lake between ranges 5 and 3.

As a result of this condition the bottom temperature in nearly 60 feet of water on range 5 was raised to 23° C., as the cooler water was crowded down the basin by the incoming warm muddy water of higher specific gravity. The thermoclinal stratification which was so prominent in the upper basin of the lower lake in the profile of July 1937 consequently was entirely obliterated. In fact no true thermocline was found in Elephant Butte Reservoir during the July 1938 survey.

South of range 3 the waters of the lower lake could be grossly divided on the basis of the July 1938 isotherms, into an epilimnial zone extending from the surface to about

---

[5] See discussion of turbidity, p. 293.

the 40-foot level, a very broad pseudo-thermoclinal zone some 40 feet thick in which the temperature fell only 7° C., and an hypolimnial unit in which the temperature was fairly constant near 15° C. from the 80-foot level to the bottom.

The temperature studies of Elephant Butte Reservoir collectively point out that, although the seasonal cycle of air temperatures tends to develop in the waters of this reservoir a seasonal cycle of temperature changes similar to that found in many natural lakes of the depth and size of Elephant Butte Reservoir, many factors such as the draw-off from the bottom of the dam, the sudden introduction of flood waters with heavy silt loads, following storms in the surrounding arid region, and the large area of shallow water in the upper lake, which may become very warm during the summer months or very cold during the winter season, all combine to disturb the regularity of the expected temperature cycle and foster temperature crises in the reservoir at unpredictable intervals.

DISSOLVED OXYGEN

Dissolved oxygen was determined by the Winkler process as standardized by the American Public Health Association (1938). Water below the surface was collected in a brass, self-closing sampler (Foerst modification of Kemmerer type) and drawn directly from the sampler without bubbling via the valved tube into the test bottle, which was always flooded to overflowing. The reagents were added at once and the titration made without delay.

The dissolved oxygen in the waters of Elephant Butte Reservoir during the middle of July 1937 varied from a minimum of 0.3 part per million to a maximum of 9.4 parts per million. Table 13, in which the summarized midchannel oxygen data are presented as typical of the dissolved oxygen findings during the July 1937 survey, shows that the dissolved oxygen values held or decreased slightly between 8.0 and 6.1 parts per million from the surface to a depth of 10 feet, as would be expected from the aeration of the surface waters by wind and wave action. Somewhere below the 10-foot level and above the 50-foot level the dissolved oxygen content of the water fell to below 4 parts per million. This break in dissolved oxygen came between 10 and 20 feet on ranges 5 and 6; between 20 and 30 feet at dam station 829 and on ranges 2 and 4; between 30 and 40 feet on range 3; and between 40 and 50 feet on range 1.

TABLE 10.—*Physical and chemical data, lower lake and Narrows, Elephant Butte Reservoir, midchannel stations, Dec. 23 and 24, 1937*

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho × 10^{-6} at 25°C	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)	Free carbon dioxide, parts per million	Sulphate (SO_4), parts per million	Phosphate (PO_4), as phosphorus, parts per million	Chloride as chlorine parts per million
	At dam, (Lno. 829), Dec. 24, 1937. Time 11:05 am.–12:50 pm. Air temeprature 14°C.								
0	11.6	7.2	696	7.5	97.2	4.4	152	0.008	25.0
12	11.5	7.3	695	7.5	90.6	4.4	134	.013	24.8
22	11.5	7.3	693	7.5	93.6	3.8	158	.004	25.3
32	11.5	6.3	699	7.6	92.8	4.4	166	.009	25.8
42	11.5	6.9	696	7.6	89.8	3.8	144	.011	25.0
52	11.5	6.9	694	7.6	93.6	3.8	158	.015	24.8
62	11.5	7.0	692	7.6	89.8	4.4	159	.010	24.9
72	11.5	6.9	699	7.6	92.8	5.0	168	.015	25.9
82	11.5	6.9	693	7.6	89.8	4.4	172	.015	25.3
92	11.5	6.5	695	7.6	94.2	4.4	169	.008	25.6
102	11.5	6.5	685	7.6	93.6	5.0	173	.015	25.7
112	11.5	6.1	693	7.6	89.8	4.4	157	.005	25.6
122	11.5	5.4	697	7.5	94.2	4.4	168	.013	25.8
132	11.5	6.5	697	7.5	92.8	4.4	152	.014	24.8
142	11.5	6.9	699	7.5	90.6	4.4	171	.015	24.9

TABLE 10.—*Physical and chemical data, lower lake and Narrows, Elephant Butte Reservoir, midchannel stations, Dec. 23 and 24, 1937*—Continued

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho × 10^{-6} at 25°C	pH	Carbonate (CO_3), parts per million (methyl-orange alkalinity)	Free carbon dioxide, parts per million	Sulphate (SO_4), parts, per million	Phosphate (PO_4), as phosphorus, parts per million	Chloride as chlorine, parts per million
	Range 1, station 2, (Lno. 1415), Dec. 24, 1937. Time 8:50–10:30 a. m. Air temperature 8°C.								
0	11.2	7.3	688	7.5	97.2	5.0	156	0.023	25.3
8	11.5	7.5	670	7.5	89.8	3.8	156	.014	25.8
18	11.5	7.8	672	7.6	93.6	4.4	166	.013	25.7
28	11.5	7.7	669	7.5	89.8	4.4	135	.010	25.8
38	11.5	7.7	686	7.5	91.2	5.0	180	.014	25.6
48	11.5	7.1	682	7.6	87.6	4.4	189	.012	25.6
58	11.5	7.8	678	7.5	94.2	5.0	154	.021	25.7
68	11.5	7.6	690	7.5	89.8	4.4	161	.014	25.3
78	11.5	7.4	704	7.4	93.6	4.4	135	.010	25.0
88	11.5	7.6	685	7.4	90.6	4.4	189	.013	25.7
98	11.5	7.7	704	7.4	92.8	3.8	135	.014	25.7
108	11.3	7.7	706	7.6	89.8	5.0	150	.012	25.9
118	11.3	7.8	703	7.6	94.2	5.6	135	.009	25.8
128	11.2	6.7	703	7.5	97.2	5.0	219	.010	25.3
	Range 2, station 2, (Lno. 1419), Dec. 23, 1937. Time 5:45–7:00 p. m. Air temperature 14.8°C.								
0	11.1	8.0	702	7.6	92.8	8.0	123	0.009	25.7
10	11.1	7.6	698	7.6	91.2	7.6	166	.012	25.0
20	11.1	7.7	693	7.6	92.8	8.0	135	.009	25.7
30	11.1	7.7	702	7.6	90.6	7.6	114	.005	25.8
40	11.1	8.0	695	7.6	92.8	8.0	161	.010	26.3
50	11.0	7.9	700	7.6	93.6	7.6	199	.015	25.7
60	11.1	7.9	696	7.6	91.2	6.2	180	.010	26.0
70	11.1	7.8	700	7.6	94.2	5.0	193	.020	25.8
80	10.0	7.9	700	7.6	92.8	4.4	186	.010	25.0
90	10.0	7.5	699	7.6	92.0	5.0	200	.012	25.8
100	10.9	7.7	706	7.6	92.8	8.0	209	.010	25.8
110	10.9	7.7	733	7.5	98.0	8.8	199	.025	26.7
	Range 3, station 2 (Lno. 1429), Dec. 23, 1937. Time 3:40–5:00 p. m. Air temperature 14.8°C.								
0	11.1	8.2	704	7.6	92.8	8.4	140	0.012	25.7
10	11.1	7.8	696	7.6	92.8	7.6	158	.011	25.8
20	11.1	7.7	693	7.6	92.8	5.4	154	.009	26.0
30	10.9	7.7	702	7.6	90.2	5.4	133	.008	25.8
40	10.8	7.9	706	7.6	90.2	9.8	129	.009	26.0
50	10.6	7.9	712	7.6	93.8	7.6	140	.012	26.1
60	10.4	7.9	708	7.6	91.2	6.8	150	.013	26.5
70	10.2	7.9	713	7.6	92.8	7.6	133	.014	26.6
80	10.2	7.7	710	7.6	92.8	7.6	126	.011	25.8
90	9.8	7.5	704	7.6	96.8	7.3	140	.009	25.9
100	9.7	7.6	717	7.5	99.2	8.0	147	.010	25.9
	Range 4, station 1 (Lno. 1426), Dec. 23, 1937. Time 1:30–2:40 p. m. Air temperature 14.8°C.								
0	11.1	8.3	708	7.5	85.4	9.4	166	0.013	25.7
13	10.8	8.1	695	7.5	93 0	7.6	172	.010	26.3
23	10.8	7.8	708	7.5	93 0	3.8	178	.010	26.8
33	10.7	7.3	703	7.5	94.2	3.8	174	.017	25.9
43	10.7	7.7	709	7.6	88.8	11.2	172	.010	25.7
53	10.8	7.6	705	7.5	92.4	6.8	172	.015	26.4
63	10.6	7.9	703	7.6	103.2	7.6	180	.019	27.0
73	10.6	7.9	710	7.5	87.2	8.0	161	.006	26.8
83	10.4	8.0	713	7.6	88.2	7.6	180	.006	26.8
	Range 5, station 2, (Lno. 1422), Dec. 23, 1937. Time 11:30 a. m.–12:30 p. m. Air temperature 12°C.								
0	10.2	8.3	721	7.6	92.8	6.2	144	0.004	25.7
5	10.2	8.5	712	7.6	88.8	7.6	166	.006	25.6
10	10.0	8.4	718	7.4	87.4	8.6	152	.006	26.6
25	10.0	7.8	713	7.6	88.8	11.2	144	.015	27.6
35	9.9	8.3	715	7.6	92.0	10.6	183	.014	26.8
45	8.0	8.5	801	7.4	101.8	17.6	198	.006	30.9
	Range 6, station 1, up the Narrows, (Lno. 1424), Dec. 23, 1937. Time 10:45-11:05 a. m. Air temperature 9.5°C								
0	10.0	8.2	715	7.4	93.2	12.6	157	0.014	24.0
12	9.8	8.4	719	7.6	92.0	10.6	152	.006	27.6
22	7.5	7.0	770	7.4	92.6	10.6	172	.003	30.4
32	7.5	8.7	820	7.9	102 0	10.6	231	.005	32.9

TABLE 11.—*Physical and chemical data, lower lake, Narrows, and upper lake, Elephant Butte Reservoir, midchannel stations, July 27–30, 1938*

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho×10⁻⁶ at 25°C.	pH	Carbonate (CO$_3$), parts per million		Free carbon dioxide, parts per million	Sulphate (SO$_4$), parts per million	Phosphate (PO$_4$) as phosphorus, parts per million	Chloride as chlorine, parts per million	Turbidity, parts per million
					Phenolphthalein alkalinity	Methyl-orange alkalinity					
	Lower lake, range 1, station 2 (Lno. 1415), July 30, 1938. Time 7:30–9:45 a. m. Air temperature 29°C.										
0	26.0	6.9	616	8.2	11.8	79.6	0	199	(1)	22.8	5.6
3	25.6	6.7	607	8.2	12.2	82.2	0	----------	0	----------	----------
4	25.5	7.0	621	8.2	13.2	80.4	0	----------	0	----------	----------
5	25.5	7.1	614	8.2	14.6	80.4	0	199	0	23.3	4.4
6	25.5	6.9	614	8.2	13.8	81.6	0	----------	0	----------	----------
7	25.4	7.0	611	8.2	13.2	82.2	0	----------	0	----------	----------
8	25.4	4.3	598	8.2	13.2	81.6	0	----------	0	----------	----------
9	25.0	6.9	593	8.2	13.0	82.2	0	----------	0	----------	----------
10	24.9	6.0	581	8.2	11.8	82.2	0	209	0	23.3	4.6
20	24.2	6.1	597	8.2	9.6	83.8	0	----------	0	23.3	5.1
30	23.5	4.1	614	8.1	6.8	82.4	0	208	0	23.8	9.1
40	22.5	4.1	630	7.8	0	87.4	3.4	208	0	24.5	5.1
50	20.5	3.6	655	7.7	0	89.6	4.0	219	0	26.0	5.0
60	18.9	3.6	692	7.7	0	91.2	5.6	225	0	26.8	6.1
70	16.5	3.9	678	7.8	0	93.0	9.4	252	(1)	26.9	7.9
80	16.0	3.9	702	7.6	0	94.2	7.8	----------	(1)	----------	6.3
90	15.3	3.9	698	7.6	0	95.6	8.4	240	0.011	28.0	7.9
100	15.0	3.6	704	7.7	0	96.4	7.8	238	0.015	28.0	8.5
110	15.1	3.7	703	7.7	0	96.4	9.0	264	0	25.6	9.1
120	15.0	3.7	712	7.7	0	97.8	11.2	252	0.028	28.0	10.7
130	14.9	2.9	692	7.7	0	96.4	9.6	252	0.010	27.7	10.7
133	15.1	3.1	720	7.6	0	96.4	10.2	----------	0.015	----------	33.0
	Lower lake, range 2, station 2 (Lno. 1419), July 29, 1938. Time 9:20–10:27 a. m. Air temperature 29°C.										
0	25.5	6.7	594	8.3	13.4	83.0	0	189	0	22.7	5.0
10	24.9	6.4	598	8.3	9.0	82.4	0	----------	----------	----------	----------
20	24.4	5.3	564	8.3	11.8	83.0	0	----------	----------	----------	----------
30	23.5	4.9	596	8.1	7.0	83.0	0	----------	----------	----------	----------
40	22.5	3.0	606	7.9	0	87.4	5.2	----------	----------	----------	----------
50	20.5	3.2	659	7.8	0	90.6	8.4	124	0	25.8	6.3
60	18.5	2.6	680	7.7	0	98.6	9.6	----------	----------	----------	----------
70	17.2	3.4	704	7.7	0	94.8	10.2	----------	----------	----------	----------
80	15.6	3.0	724	7.8	0	97.4	9.6	----------	----------	----------	----------
90	16.0	2.6	712	7.7	0	98.0	9.6	----------	----------	----------	----------
100	15.8	2.6	711	7.7	0	96.8	12.2	----------	----------	----------	----------
110	15.6	2.6	702	7.7	0	98.0	13.4	----------	----------	----------	----------
116	15.5	2.6	724	7.7	0	99.6	13.4	145	0.010	28.6	24.0
	Lower lake, range 3, station 2 (Lno. 1429), July 28, 1938. Time 10:35–11:50 a. m. Air temperature 30°C.										
0	26.1	6.9	577	8.4	13.0	84.0	0	114	(1)	24.4	3.0
10	24.8	7.1	582	8.4	13.0	82.4	0	161	(1)	22.7	3.6
20	24.0	6.2	586	8.2	11.8	84.0	0	166	(1)	22.0	2.2
30	23.5	4.1	595	8.1	4.6	84.4	0	135	(1)	21.8	3.6
40	23.0	4.6	615	7.9	0	84.0	0	180	0.015	22.0	5.0
50	20.2	2.7	653	7.8	0	90.6	12.1	161	.015	25.7	5.7
60	18.0	3.7	693	7.8	0	93.0	11.2	199	.012	26.9	6.3
70	16.2	2.3	708	7.7	0	93.6	11.2	131	.023	27.5	7.1
80	16.0	2.2	680	7.7	0	94.2	13.4	154	.034	28.0	16.4
90	15.6	2.8	707	7.7	0	95.4	17.8	199	.031	26.9	19.3
100	15.1	1.7	744	7.6	0	98.0	15.6	145	.027	27.8	31.0
104	15.0	1.7	677	7.7	0	99.2	10.0	----------	.018	----------	46.0
	Lower lake, range 4, station 1 (Lno. 1426), July 28, 1938. Time 8:40–9:55 a. m. Air temperature 28°C.										
0	25.5	7.5	580	8.5	13.0	81.8	0	189	0.010	21.8	5.0
10	24.9	6.0	578	8.6	8.8	82.4	0	119	0	21.3	3.6
20	21.3	5.9	586	8.3	10.6	83.0	0	169	(1)	21.6	6.3
30	23.8	5.3	594	8.1	6.0	82.4	0	120	0.010	22.3	5.0
40	21.7	3.6	642	7.7	0	87.4	4.4	161	.010	23.0	9.1
50	20.5	3.4	649	7.5	0	90.0	5.6	161	.010	25.0	10.7
60	19.0	3.6	691	7.7	0	94.8	3.4	----------	.011	----------	15.6
70	16.6	3.8	722	7.7	0	99.2	10.0	----------	.012	----------	14.3
80	16.1	3.6	704	7.9	0	95.4	7.4	----------	.020	----------	14.9
90	15.8	2.4	707	7.8	0	96.8	7.8	----------	.020	----------	38.0
95	15.3	2.2	646	7.9	0	96.2	5.6	----------	.019	----------	60.0
	Lower lake, range 5, station 2 (Lno. 1422), July 27, 1938. Time 1:00–1:45 p. m. Air temperature 32°C.										
0	26.9	7.5	580	8.3	8.6	82.4	0	113	(1)	21.2	5.0
10	26.5	7.4	592	8.3	18.8	82.8	0	119	(1)	21.8	5.0
20	26.5	7.0	470	8.3	15.0	82.8	0	109	0	20.2	6.3
30	24.1	5.8	646	8.1	9.0	83.8	0	144	0	22.7	38.0
40	23.3	4.5	687	7.8	0	83.2	5.6	157	0.028	23.2	127.0
50	23.0	3.1	786	7.8	0	88.4	4.4	124	.040	22.1	280.0
53	22.5	2.9	740	7.7	0	90.6	4.4	189	.045	24.8	204.0

[1] Trace; less than 0.010 part per million.

TABLE 11.—*Physical and chemical data, lower lake, Narrows, and upper lake, Elephant Butte Reservoir, midchannel stations, July 27–30, 1938*—Continued

Depth in feet	Water temperature, degrees centigrade	Dissolved oxygen, parts per million	Specific conductivity, mho×10⁻⁶ at 25°C.	pH	Carbonate (CO₃), parts per million: Phenolphthalein alkalinity	Carbonate (CO₃), parts per million: Methyl-orange alkalinity	Free carbon dioxide, parts per million	Sulphate (SO₄), parts per million	Phosphate (PO₄) as phosphorus, parts per million	Chloride as chlorine, parts per million	Turbidity, parts per million
	In the Narrows, 1 mile above lower lake, range 6, station 1, (Lno. 1424), July 27, 1938. Time 11:45 a. m.–12:15 p. m. Air temperature 32°C.										
0	26.7	6.2	594	8.2	8.6	93.2	0	131	0.011	22.6	3.6
10	26.4	5.9	587	8.2	15.	84.2	0	----	.011	----	5.0
20	24.8	5.4	606	8.2	12.	83.8	0	144	.010	22.7	9.1
30	23.8	3.5	772	7.8	0	84.2	5.8	205	[1]	25.6	16.4
40	23.0	4.9	825	7.7	0	86.4	5.6	189	[1]	25.8	46.0
43	22.9	3.6	838	7.6	0	86.6	2.2	205	0.020	25.6	116.0
	In the Narrows, 1 mile below upper lake (Lno. 1663), July 30, 1938. Time 4:20–4:50 p. m. Air temperature 32°C.										
0	28.0	7.8	693	8.3	15.2	81.8	0	171	0.011	22.7	6.3
38	23.0	1.9	908	7.6	0	89.0	3.4	221	.062	26.8	382.0
	Upper lake, ¾ mile above the Narrows (Lno. 1662), July 30, 1938. Time 3:30–3:50 p. m. Air temperature 32.9°C.										
0	29.0	7.0	823	8.3	17.2	82.0	0	199	0	25.7	10.7
23	25.1	6.1	767	8.2	9.6	83.8	0	209	[1]	25.3	24.0
	Upper lake, about 3½ miles above the Narrows (Lno. 1661), July 30, 1938. Time 2:50–3:00 p. m. Air temperature 35.5°C.										
9	30.5	7.1	874	8.3	17.2	85.2	0	231	[1]	26.8	53.0
	Upper lake, opposite San Jose Canyon, about 5 miles above the Narrows (Lno. 1660), July 30, 1938. Time 2:20–2:30 p. m. Air temperature 35.5°C.										
0–3	33.5	6.4	749	8.06	13.4	96.2	0	169	0.063	26.0	366.0

[1] Trace; less than 0.010 part per million.

TABLE 12.—*Physical and chemical data, Rio Puerco and Rio Grande above and below Elephant Butte Reservoir*

Lno.	Locality	Date	Temperature, degrees centigrade: Air	Temperature, degrees centigrade: Water	Specific conductivity, mho×10⁶ at 25° C.	pH	Carbonate (CO₃), parts per million (methyl-orange alkalinity)	Sulphate (SO₄), parts per million	Phosphate (PO₄) parts per million	Chlorides as chlorines, parts per million
1526	Rio Grande, Isleta, N. Mex.	Dec. 22, 1937	7.0	1.0	497	7.2	110.2	90	0.041	13.8
1548	Rio Grande, 4 miles east of Bernardo, N. Mex.	Apr. 12, 1938	----	----	782	8.1	----	182	----	26.0
1432	Rio Puerco at U. S. highway 60 south of Bernardo, N. Mex.	July 18, 1937	39.5	34.5	----	8.3		----	----	91.0
1432	do	Dec. 22, 1937	6.0	2.5	6,088	----	147.0	2,197	.008	367.5
1431	Rio Grande 6 miles northeast of Socorro, N. Mex.	July 18, 1937	39.0	31.0	----	8.1	120.0	----	----	31.8
1431	do	Dec. 22, 1937	6.0	5.0	800	----	127.0	540	.040	31.5
1547	Rio Grande 2 miles east of San Antonio, N. Mex.	Apr. 12, 1938	----	----	1,004	8.1	----	219	----	39.4
1430	Rio Grande, San Marcial, N. Mex.	July 18, 1937	36.0	26.0	----	8.1	115.3	----	----	36.7
1430	do	Dec. 22, 1937	7.5	5.8	808	----	140.2	193	.038	44.7
1665	Rio Grande, just below Elephant Butte Dam	July 31, 1938	29.0	16.0	716	7.7	86.8	----	----	----
831	Rio Grande, Hot Springs, N. Mex.	June 16, 1935	27.2	16.8	860	7.5	74.2	----	----	----
831	do	Apr. 12, 1938	----	----	747	8.2	----	----	.017	----
831	do	July 26, 1938	28.5	18.4	----	----	136.4	----	----	----
1658	Rio Grande, Hatch, N. Mex.	July 26, 1938	34.0	28.8	762	----	123.8	----	----	----
1545	Rio Grande, 16 miles north of Las Cruces, N. Mex.	Apr. 12, 1938	----	----	797	7.9	----	----	----	----
828	Rio Grande, Las Cruces, N. Mex.	June 15, 1935	24.0	22.6	616	7.5	78.0	----	----	----
1527	Rio Grande, El Paso, Tex.	Dec. 22, 1937	6.0	8.0	1,939	7.6	175.8	----	.030	----

TABLE 13.—*Dissolved oxygen in parts per million, Elephant Butte Reservoir*

Depth in feet	Dam, station 829	Range 1, station 2	Range 2, station 2	Range 3, station 2	Range 4, station 1	Range 5, station 2	Range 6, station 2
	July 13-17, 1937						
0	7.0	7.0	7.6	7.7	7.8	7.1	7.1
10	7.4	6.1	7.6	8.0	6.9	6.5	7.0
20	6.7	6.4	5.7	6.1	6.2	3.1	3.6
30	3.8	5.2	3.8	4.5	3.8	1.4	1.5
40	3.1	4.6	6.4	1.9	1.8	0.8	0.7
50	3.5	3.5	7.9	2.6	2.5	1.4	0.3
60	3.6	5.8	3.4	2.5	2.9	1.3	----------
70	3.8	5.0	5.9	3.8	2.6	----------	----------
80	4.2	5.7	3.6	3.8	3.3	----------	----------
90	4.2	5.7	3.3	3.3	2.9	----------	----------
100	3.7	4.6	2.9	2.5	1.9	----------	----------
110	3.3	4.8	2.9	2.8	----------	----------	----------
120	3.7	4.2	2.6	----------	----------	----------	----------
130	3.1	5.2	----------	----------	----------	----------	----------
140	3.9	5.0	----------	----------	----------	----------	----------
150	3.7	----------	----------	----------	----------	----------	----------
	July 27-30, 1938						
0	----------	6.9	6.7	6.9	7.5	7.5	6.2
10	----------	6.0	6.4	7.1	6.0	7.4	5.9
20	----------	6.1	5.3	6.2	5.9	7.0	5.4
30	----------	4.1	4.9	4.1	5.3	5.8	3.5
40	----------	4.1	3.0	4.6	3.6	4.5	4.9
50	----------	3.6	3.2	2.7	3.4	3.1	----------
60	----------	3.6	2.6	3.7	3.6	----------	----------
70	----------	3.9	3.0	2.3	3.8	----------	----------
80	----------	3.9	3.4	2.2	3.6	----------	----------
90	----------	3.9	2.6	2.8	2.4	----------	----------
100	----------	3.6	2.6	1.7	----------	----------	----------
110	----------	3.7	2.6	----------	----------	----------	----------
120	----------	3.7	----------	----------	----------	----------	----------
130	----------	2.9	----------	----------	----------	----------	----------

In the upper basin of the lower lake between ranges 3 and 6 the dissolved oxygen dropped to a minimum of less than 2 parts per million at the 40- to 50-foot level, but in the lower basin, range 2 to the dam, the dissolved oxygen remained above 2.6 and for the most part above 3.0 parts per million. During July 1937, on ranges 1 and 2, the vertical distribution of dissolved oxygen was even more irregular; on range 1 there being a low at 50 feet, a high at 80 feet, a low at 120 feet and a rise to the bottom; and on range 2 a low at 30 feet, a high at 50 feet, a low at 60 feet, and a high at 70 feet, followed by a progressive decline to the bottom.

As 3 parts per million is approximately the lower limit of dissolved oxygen at which fresh-water fish can survive, and as waters carrying 5 parts per million or more dissolved oxygen are favorable for fishes as regards oxygenation (Ellis, 1937), three groups of dissolved oxygen values, which include the major variations in dissolved oxygen distribution just discussed, have been plotted in figures 11, 12, 13, and 14, namely, 0.3–2.9 parts per million (dissolved oxygen too low for survival of fishes); 3.0–4.9 parts per million (oxygenation unfavorable for fish life although such conditions can be tolerated by some fish for varying periods); and 5.0–9.4 parts per million (dissolved oxygen ample and favorable for fish life), to ascertain the probable limits of fish distribution throughout the lower lake.

From tables 3 to 9 and figures 11 and 12 for the July 1937 survey it may be seen that in a surface zone varying from 15 to 30 feet deep over the entire lower lake the dissolved oxygen content was above 5 parts and in general above 6 parts per million. although it must be noted that in this surface zone only 1 dissolved oxygen value above 9 parts and 7 above 8 parts per million were recorded in the entire July 1937 series of several hundred observations. However, high levels of dissolved oxygen are not to be expected in Elephant Butte Reservoir during the summer season as this impoundment is practically devoid of aquatic vegetation which could add to the supply of oxygen and produce the localized zones of supersaturation which have been noted in some natural lakes with abundant aquatic vegetation. Complete saturation of the water in Elephant Butte Reservoir with dissolved oxygen from the air would necessarily be less than 8.38 parts per million (saturation at 760 mm. pressure and 25° C.) in view of the 4,400-foot altitude of this reservoir and high midsummer surface-water temperatures of 25° to 33° C.

Under the surface zone of well-oxygenated water, a second zone some 10 to 20 feet deep carrying from 3.0 to 4.9 parts per million of dissolved oxygen extended rather uniformly over the entire lower lake. Below the 20-foot level on range 6 and below the 40-foot level on range 4 the water of the upper basin of the lower lake carried less than 2.9 parts per million of dissolved oxygen, excepting two small masses of water near the east shore on range 4 at depths of 60 and 80 feet, respectively.

On range 3 the water of the upper basin was divided from shore to shore into five vertical zones, namely, a surface zone between the surface and the 25-foot level, in which the dissolved oxygen was above 5 parts per million; a second zone from 25 to 35 feet, carrying dissolved oxygen between 3.0 and 4.9 parts per million; a third zone from 35 to 65 feet, having less than 2.9 parts per million dissolved oxygen; a fourth zone from 65 to 90 feet, with dissolved oxygen rising to between 3.0 and 4.9 parts per million; and a fifth zone from 95 feet to the bottom, in which the oxygen was again reduced to less than 2.9 parts per million. The approximate depth of these zones are given as of station 2. (See table 6 and fig. 12 for more exact details.) However, excepting the extra layers of water carrying 3.0 to 4.9 parts per million found in this region between range 3 and the submerged mesa, the distribution of dissolved oxygen in the upper basin of the lower lake during the July 1937 survey followed essentially the plan of natural lakes with an established thermoclinal stratification.

The distribution of dissolved oxygen in the lower basin of the lower lake during July 1937 was quite different. The surface zone of well oxygenated water was continuous with that extending over the entire lower lake to a depth of 20 to 30 feet. However, in the lower basin the second zone of water carrying from 3.0 to 4.9 parts per million of dissolved oxygen, noted on range 3 in the upper basin, extended to below the 100-foot level on ranges 2 and 1, and at station 829 just upstream from the dam, entirely to the bottom.

This second zone was broken on ranges 1 and 2 by intrusions from zone 3 of range 3 (water carrying less than 2.9 parts per million) and also by intrusions of water similar in dissolved oxygen content to that of the surface zone, i.e., water carrying more than 5 parts per million dissolved oxygen.

The fourth zone found on range 3 was apparently fused with the second zone on both ranges 1 and 2 and at station 829 near the dam. The fifth zone of water carrying less than 2.9 parts per million of dissolved oxygen lay across the bottom of the reservoir on range 2 below the 110-foot level, but disappeared about one-third of the distance between ranges 1 and 2 downstream from range 2.

The configuration of the two masses of water of high oxygen content, i.e., above 5 parts per million, which were found between range 2 and the dam in the lower basin can be approximated by an examination of both the mid-channel and cross-section profiles. It should be remembered that the width of the lower lake is much reduced between range 2 and range 1 so that the volumes of these two masses of water appear greater in the midchannel profile than the cross-sections actually warranted. During a period of relatively calm weather, July 13–17, 1937, the upper of these masses extended from the eastern half of the lower basin between the 40- and 80-foot levels on range 2 downstream almost to station 829, and practically across the entire basin between the 60- and 90-foot levels on range 1.

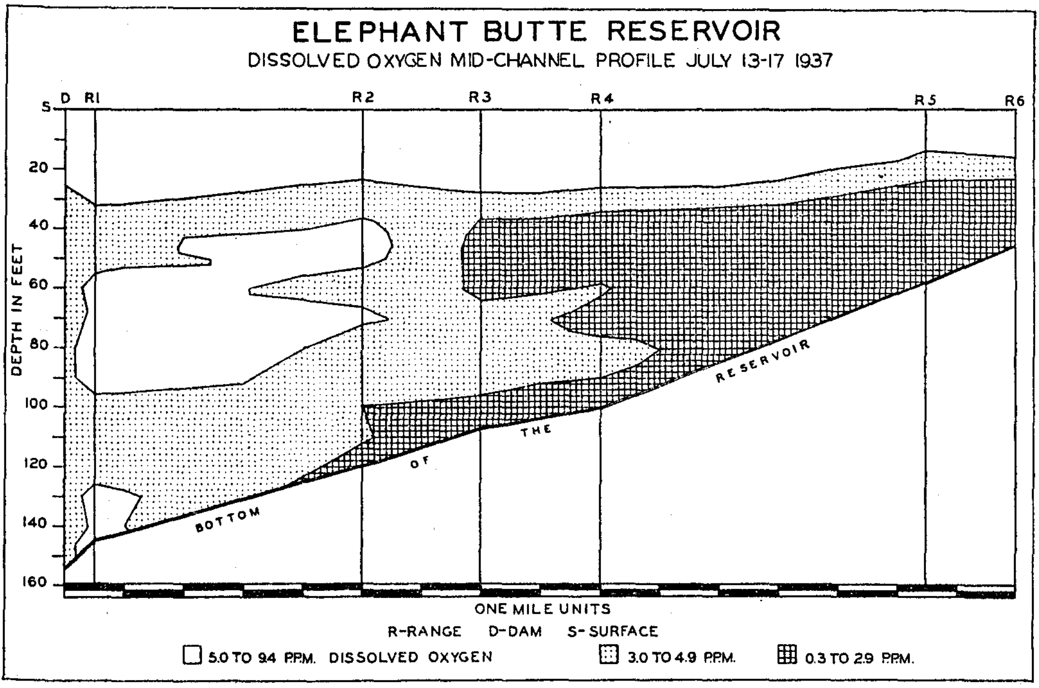

FIGURE 11.—Distribution of dissolved oxygen in the waters of the lower lake, Elephant Butte Reservoir, midchannel profile, midsummer, 1937.

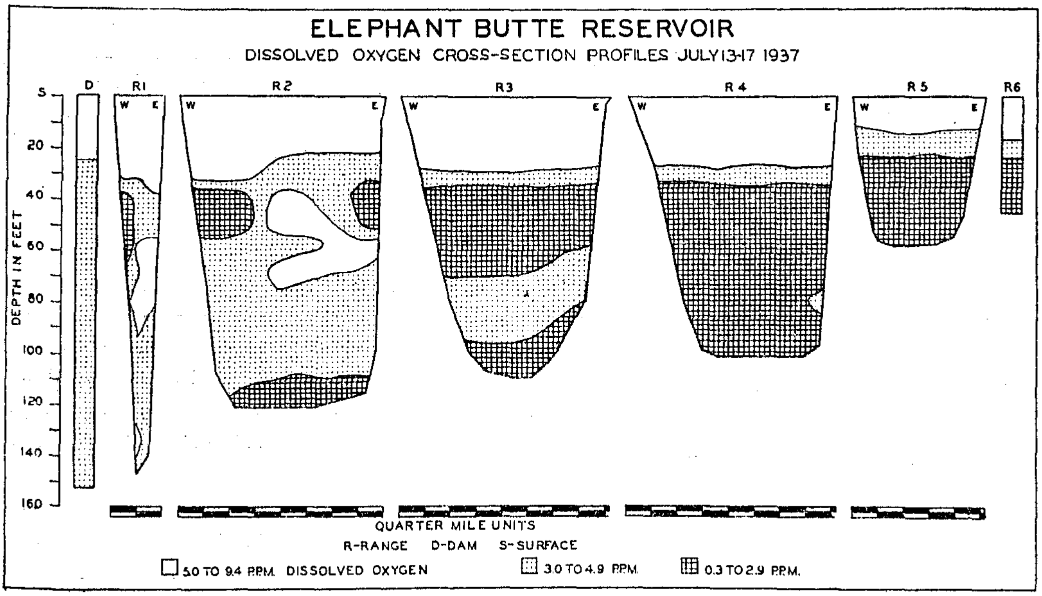

FIGURE 12.—Distribution of dissolved oxygen in the waters of the lower lake, Elephant Butte Reservoir, cross-section profile at the dam and across the six major ranges, midsummer, 1937.

The dissolved oxygen in this upper detached mass of water varied from 5.2 to 7.9, averaging 6.1 parts per million, that is, the oxygen content of this unit was essentially the same as that of the water in the surface zone above the 20-foot level.

The lower of these nonconforming masses of water was much smaller and extended upward from the bottom to about the 125-foot level on the west side of range 1. In this second unit the dissolved oxygen varried from 5.1 to 5.3 parts per million.

The distribution of dissolved oxygen in Elephant Butte Reservoir during midsummer of 1937, at the time of the maximum temperature phase of the temperature cycle, as just described, differs definitely from the expected oxygen distribution in natural lakes having thermoclinal stratification. In such natural lakes the dissolved oxygen content of the water drops rapidly in the region of the thermocline so that the hypolimnial unit is composed of water having a rather uniform but low dissolved oxygen content. The differences between this pattern of oxygen distribution and that found in the lower lake of Elephant Butte Reservoir, particularly the intrusion of masses of water having a higher oxygen content than the surrounding hypolimnial waters, in part at least, are the resultants of the interaction of three major factors, namely, flows produced by the draw-off at the foot of the dam, disturbances caused indirectly by the shape of the impoundment, and deflections by the submerged obstruction between ranges 2 and 3, together with the superimposed factor of variability in the composition and volume of the waters entering the lower lake from the upper lake.

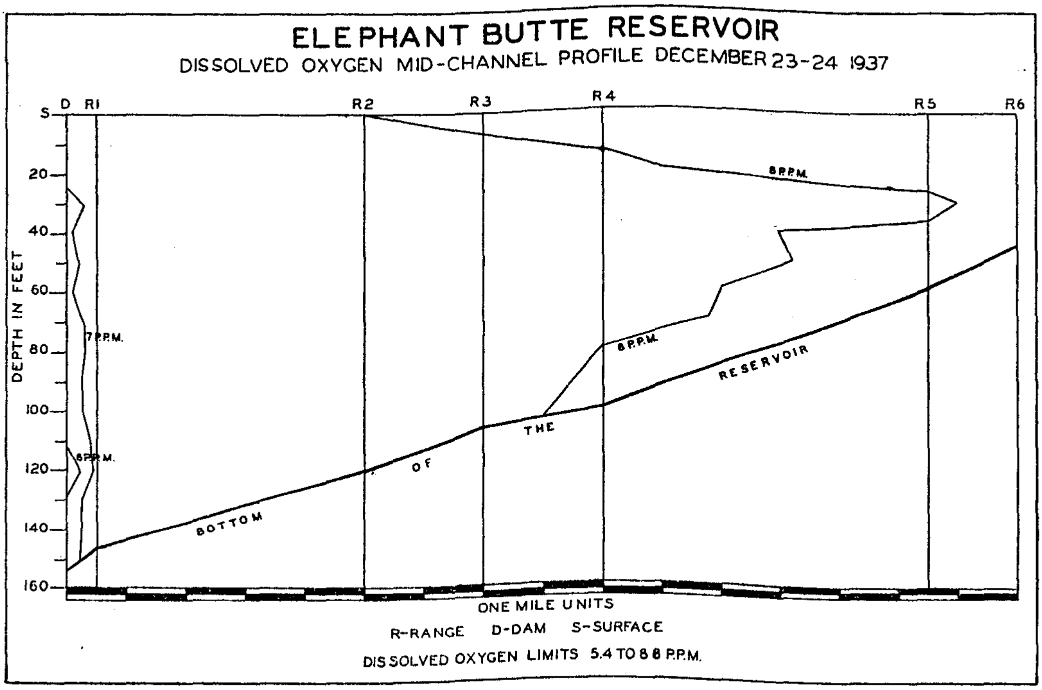

FIGURE 13.—Distribution of dissolved oxygen in the waters of the lower lake, Elephant Butte Reservoir, midchannel profile, midwinter, 1937.

Because of the submerged mesa which forms an irregular barrier between ranges 2 and 3, the upper basin of lower lake upstream from range 3 is rather free from the disturbances which occur downstream from range 2, and consequently a thermal stratification with the development of a definite thermocline is possible at times in this unit of the reservoir during the summer months, as has been pointed out in the previous section on temperature. (See fig. 8.) Once a thermoclinal band became established from the Narrows to range 3, the warm water entering the Narrows from the shallow upper lake could flow over the cold water near the bottom of the Narrows and, on leaving the Narrows, out into the epilimnial layer of this upper basin of the lower lake. As a result the dissolved oxygen in the undisturbed and isolated hypolimnion of the upper basin could be consumed and could approach zero, that is, this upstream unit of the lower lake would then possess, in general, the midsummer characteristics of a lake of the second order (Whipple, 1927), midway between the tropical and temperate classes. Such conditions were found in July 1937, but not in July 1938, as will be discussed later.

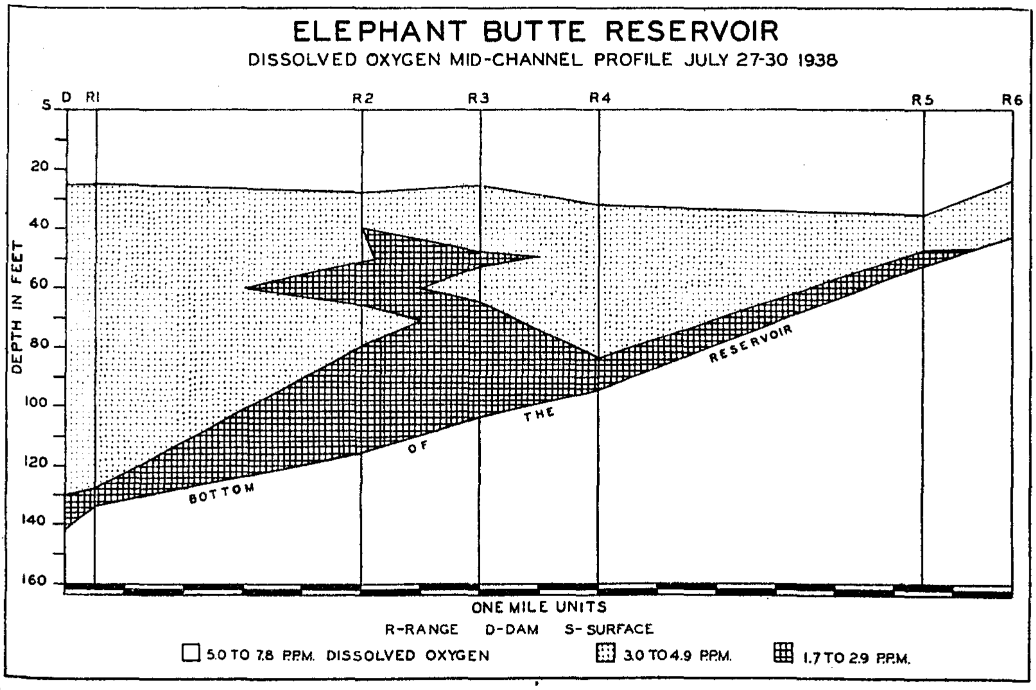

FIGURE 14.—Distribution of dissolved oxygen in the waters of the lower lake, Elephant Butte Reservoir, midchannel profile, midsummer, 1938.

The lower basin of the lower lake, that is, that portion between submerged mesa and the dam, could also develop the same thermal stratification and an almost oxygenless hypolimnion were it not for the interaction of two sets of conditions set up by certain intrinsic characteristics of Elephant Butte Reservoir, namely, the position of the draw-off opening and the shape of the impoundment.

In the average natural lake deep waters are generally well offshore, and around this more or less central mass of deep water the shallower waters are usually disposed with some degree of concentric symmetry. In artificial reservoirs and impoundments, however, often the deepest water is opposed directly by the sheer face of the almost vertical dam which also rises above the surface of the water like a cliff. By comparison with the average natural lake these impoundments therefore are only "half lakes" as regards their ground plan, Consequently, in such reservoirs as Elephant Butte, where there is an almost unobstructed downstream surface 15 miles long, sudden downstream movements of surface water as the result of strong winds, storms, or short heavy rains, will produce a piling up of water at the dam and over the mass of deep water. In a natural lake a similar movement of surface water would raise the water level in the shallows along the opposite shore, and this displacement of water from the surface of the lake would be dissipated by seiches, tilting of the thermocline, and other oscilations around the deep central portion of the lake with little basic disturbance of the thermal stratifications, as all of these movements would be confined largely to the epilimnial portion of the natural lake.

However, in the reservoir the piling up of waters at the dam forces the epilimnial waters down, breaking such thermal stratification as may exist, and finally driving these surface waters in an upstream direction back through what would have been the upper hypolimnial or lower epilimnial zone. The severity of the disturbances produced by the movement of surface water against the dam is increased in many reservoirs by natural features of the bounding shores for usually, wherever opportunity offers, construction engineers place the dam across a narrowing canyon in which the movements of surface water down the reservoir are concentrated on the dam by the funneling action of the canyon walls.

As the outlet may or may not be open at the time of these movements of surface water, the subsequent fate of the surface water which is forced down into the lower levels at the dam varies. If the outlet be open and the draw-off currents are well established, surface water may be carried to the bottom by the downward pressure of the water as it piles up at the dam and the suction currents which are pulling water toward the outlet; or detached masses of surface water may remain in the hypolimnial zone at various levels where even after they have made temperature adjustments they still may be detected for some time by their higher dissolved oxygen content. If the combination of forces be violent enough there may be a rather general mixing of surface and deep waters, with resultant elevation in both the temperature and dissolved oxygen levels of the water in the hypolimnial portion of the basin. Since both the surface and draw-off currents are subject to much variation, and as the disturbances produced by these two variables may or may not be synchronized, conditions in this mass of deep water which may be designated conveniently as the adclaustral portion of the impoundment, because of proximity to the dam, are very unstable.

In Elephant Butte Reservoir the submerged barrier between ranges 2 and 3 seems to confine the disturbances produced in the adclaustral zone by movements of surface water down the lower lake, to the lower basin. This was to be expected, as the depth of the water covering the top of this submerged mesa is rarely more than 30 feet and may be much less.

As the summer progresses and the bottom temperatures rise to the annual maximum the dissolved oxygen content of water near the bottom of the upper part—range 4 to range 6—of the upper basin becomes very low, if this portion of the basin is not disturbed by large flows of warm water from the upper lake as the result of sudden rains in the Rio Puerco district or elsewhere above San Marcial.

As there was no large inflow from the upper lake at the time of the July 1937 survey, the stratification of the water of the upper basin of the lower lake on the basis of dissolved oxygen content was very evident. However, due to the pull of the draw-off, water from the upper basin was slowly progressing down the lower lake toward the dam.

From figure 11 and tables 8 and 9 it may be seen that the waters entering the upper basin of the lower lake from the Narrows were well aerated to a depth of 20 feet, poorly oxygenated between the 20- and 30-foot levels, and below 30 feet, that is, from the 30-foot level to the bottom, 56 feet, were almost devoid of dissolved oxygen. During July 1937 there was a very definite thermal stratification of the waters in the upper basin of the lower lake for at least 6 miles below the Narrows, i. e., from the Narrows to range 4. (See fig. 11.) Waters moving into the upper basin of the lower lake from the Narrows tended to maintain the same density stratifications existing up the Narrows at range 6, as these waters spread out into the upper basin. The layers thus produced were evident down the lake to range 4 or beyond.

During the summer months the upper lake is practically the sole source of supply for the lower lake, and to a large extent determines the characteristics of the waters of the upper basin of the lower lake. As the upper lake is relatively shallow and contains large quantities of silt and some vegetation, water entering the upper end of the Narrows during the summer is usually much more turbid and has a larger load of organic matter than the waters of the lower lake. In its journey through the Narrows the silt in this water from the upper lake begins to settle out, carrying with it much of the organic detritus acquired in the upper lake. As the waters of the upper lake are quite warm when they enter the Narrows the settling out of the silt-detritus load creates an oxygen demand below the 20-foot level in the Narrows.

This oxygen demand results in a reduction of the dissolved oxygen to a very low level and a simultaneous rise in free carbon dioxide, so that the alkalinity of the water in the Narrows drops from around pH 8.0 at the surface to pH 7.6 at 30 feet and pH 7.5 near the bottom. However, the silt-detritus deposit is swept out of the Narrows by frequent water surges and currents which pass through this canyon when the upper lake is raised by heavy rains in the Rio Puerco or upper Rio Grande districts. Consequently the incompletely oxidized silt-detritus mixture is carried out into the upper basin of the lower lake. Turbidity studies and bottom samplings showed that the settling out of the silt load in the upper part of the upper basin of the lower lake between ranges 5 and 4 progresses quite rapidly when this portion of the Lake is not disturbed by sudden inflows.

The combined observations on dissolved oxygen, pH, free carbon dioxide, and turbidity show that the deposition of silt and detritus in the upper basin creates a definite oxygen demand which depletes the oxygen supply of the waters along the floor of the upper basin—which waters were completely oxygenated during the cold season—down the lake at least to range 4 or beyond. This oxygen demand becomes progressively less because the total load of organic material in these waters is not large, being very much less than the load in many natural lakes. Consequently, free carbon dioxide is generally absent from the waters of the lower lake between range 4 and the dam, the alkalinity in this portion of the lower lake usually being greater than pH 7.7.

In the vicinity of range 3 other factors combine to alter the distribution of dissolved oxygen in the waters of the lower lake. The submerged barrier lying between ranges 2 and 3 was covered to a depth of 20 feet or more during July 1937, and the movements of the surface and subsurface layers of water down the lower lake over both the upper and lower basins were unobstructed. As a result the surface zone of well-oxygenated water spread over the entire lower lake, as did also the second zone of poorly aerated water between the 20 and 30 foot levels. In the upper basin of the lower lake the hypolimnial mass of water, low in dissolved oxygen, did not flow over this submerged barrier but was drawn around it through the tortuous and narrow old river channel by the down-lake current near the east side of the reservoir. Near range 3 the oxygen demand on the floor of the reservoir also is much reduced for, as previously pointed out, the oxygen demand becomes less and less as the silt-detritus deposits become smaller on the bottom and the depth of the water, with a concurrent fall in temperatures, becomes greater downstream from range 3.

As a result of the combined action of these several factors operating during midsummer in the upper basin of the lower lake between range 4 and the submerged barrier, the hypolimnial stratum is broken somewhere downstream from range 4 into from 2 to 5 substrata which carry different quantities of dissolved oxygen.

Several conditions contribute to the irregular and uneven distribution of dissolved oxygen in the hypolimnial portion of the upper basin. Among these are the spreading of layers of water of different densities and different dissolved oxygen content from the Narrows over the upper basin of the lower lake, which in general tend to maintain their identity and to lie above the colder water in the deeper portions of the upper basin; the creation of an oxygen demand by silt-detritus deposits along the bottom, grading from a maximum near the Narrows to an almost negligible demand near range 3, which depletes the dissolved oxygen in the lower portions of the well-aerated waters left in the upper basin during the cold season; the gradual displacement of all waters left in the upper basin during the cold season by the incoming warmer waters from the upper lake; the free flow of the surface and subsurface layers above the hypolimnion over the submerged barrier between ranges 2 and 3; and the deflection of the currents in the hypolimnial portions in the upper basin by the submerged barrier.

In the lower basin the distribution of dissolved oxygen becomes still further complicated by the disturbances in the adclaustral portion of the lower basin due to surface currents sweeping down the lake during times of storm and high water; by the reduction of the bottom oxygen demand of the bottom silt-detritus deposits to an almost negligible factor in the lower end of the lower basin; and by the positive action of the draw-off current.

Downstream from the submerged barrier, i. e., in the lower basin of the lower lake, the draw-off current was found to exert a very positive action on the movement of water along the bottom and down the sides of the narrowed but deep portion of this basin between the dam and range 1. The drawing in of water from the sides and surface of the lake in this portion of the reservoir is evident in the cross section profiles at the dam and across range 1 (see fig. 12 and tables 3 and 4), which show the trend of the subsurface layer of the water toward the bottom of the reservoir. Evidence of the positive pull of the draw-off current was found upstream as far as range 2. Up the lake from range 2 the currents, excepting those resulting from inflows at the Narrows, were ascribable to the gradual movements of the water into the lower basin to replace the outflow. In general the denser bottom layers of water tended to move more rapidly than the upper layers, with the single exception of the surface layers which, although lighter than the layers below, are subject to rather rapid downstream movements at times because of wind and wave action.

The combined action of these several sets of factors is so variable in Elephant Butte Reservoir that even in late summer the position of the downstream end of the hypolimnial water of low dissolved oxygen content is hardly predictable.

The July 1938 data presented in table 11 and figure 14 show the effect of a flow of warm water which was moving in at the time from the upper lake, and which had disturbed the waters of the upper basin of the lower lake so that no marked thermal stratification existed, on the distribution of dissolved oxygen in the lower lake. In table 11 it may be seen that the warm muddy water entering the lower lake from the upper lake via the Narrows carried more dissolved oxygen than the water entering the lower lake in July 1937, the lowest dissolved oxygen value in the Narrows at range 6 during July 1938 being 3.5 parts per million.

Following down the ranges it is evident that the sharp break in dissolved oxygen noted in July 1937 was absent in July 1938, the dissolved oxygen decreasing more gradually from the surface to the 40- or 50-foot level. Below the 50-foot level the variations in dissolved oxygen are too small to be significant other than indicating that the inflow of warm muddy water was pushing the water in the upper basin down the lake, as has been observed in the discussion of water temperature.

Between ranges 2 and 3 the mixing of bottom and midhypolimnial units is evident from the queer configuration of the layer of water carrying less than 3 parts per million dissolved oxygen. The projections of this later shown in the midchannel profile are actually intrusions, but of smaller size than those found in July 1937.

The dissolved oxygen findings collectively emphasize the fact that a predictable and uniform oxygen stratification comparable to that found in many natural deep lakes in the United States cannot be expected during the warm season in Elephant Butte Reservoir and similar western impoundments. The shape of these artificial basins, the draw-off, the sudden inflow following heavy storms, and natural barriers in the basin individually and collectively alter the distribution of dissolved oxygen in such impounded waters. As these factors are for the most part variables, both the upper and lower basins of the lower lake of Elephant Butte Reservoir may be subjected to sudden and often severe fluctuations in the dissolved oxygen content of their waters, particularly during the midsummer season. Consequently the distribution of dissolved oxygen is much more irregular and the movements of flow currents carrying different loads of dissolved oxygen much more broken in Elephant Butte Reservoir than has recently been described for Norris Reservoir, in the mountains of Tennessee, by Wiebe (1938; 1939).

In the fall after the annual maximal bottom temperature has been attained the thermal recession to winter conditions proceeds rapidly and the shallow upper lake becomes an important factor in the reoxygenation of the deep lower lake basin. The water in the upper lake cools rapidly and its oxygen-carrying power rises. The cold water entering the upper basin of the lower lake from the Narrows now carries more dissolved oxygen than the hypolimnion, and the water of low dissolved oxygen content in this unit of the basin is removed partly by a thermal over-turn, such as occurs in many temperate lakes, and partly through the direct displacement by cold water of high oxygen content flowing in from the Narrows along the bottom. (See fig. 13 and table 10.) The combination of these two factors, both of which vary, depending upon the extent of the fall rains and storms, the number and time of abrupt temperature changes in the air and the amount of draw-off at the time, mix the water of the lower lake so that by late December the dissolved oxygen throughout the entire lower lake has risen to above 6 parts per million.

The reoxygenation of the lower basin of the lower lake, particularly in the adclaustral portion, accomplished during the cold season, is sufficient to maintain the dissolved oxygen above 5 parts per million for indefinite periods after these factors cease operation and the water temperatures have risen several degrees from the midwinter low. For example, on June 15, 1935, at station 829, 150 feet upstream from the dam (see table 2), the dissolved oxygen at the surface was 7.2 parts per million and dropped rather regularly to 5.1 parts per million at 107 feet, i. e., all of the water above 110 feet carried 5 parts per million or more dissolved oxygen. The water temperature at the time these samples were taken varied from 24°C. at the surface to 16.9° C. at 110 feet.

HYDROGEN-ION CONCENTRATION (pH)

Routine hydrogen-ion concentration (pH) determinations were made colorimetrically with a Hastings hydrogen-ion colorimeter (Bausch and Lomb type) standardized against a glass electrode. The critical pH readings, and many of the routine measurements as well, were taken electrometrically with a Beckman pH meter, glass electrode (National Technical Laboratories, model F).

The summer hydrogen-ion concentration of the waters of Elephant Butte Reservoir (see tables 2, 3 to 9, and 11, and fig. 15), varied from pH 8.6 at the 10-foot level, range 4, station 1, July 28, 1938, to pH 7.4 near the bottom at 120 feet, station 829, June 15, 1935. However, as can be seen from the midchannel profile for July 1937, very little of the water in this reservoir was less alkaline than pH 7.7, and water less alkaline than pH 7.7 was found for the most part near the bottom in the upper basin of the lower lake where the silt-detritus deposit was creating an oxygen demand and liberating free carbon dioxide. In general the surface water was more alkaline than pH 8.4 and there was some stratification on the basis of hydrogen-ion concentration from the surface to the thermoclinal zone. Below this level the hydrogen-ion concentration ranged from pH 8.0 to pH 7.7, with few exceptions throughout the reservoir.

As the surface waters entering the reservoir from the Narrows varied between pH 8.3 and pH 7.7, and as no readings less alkaline than pH 7.5 were taken in the midsummer studies, the waters of Elephant Butte Reservoir may be characterized as fairly alkaline and as rather well adjusted by the intrinsic buffer system. The absence of any zones near the bottom of the reservoir in which the waters approach definite acidity, or even neutrality, points to two conditions of importance to the aquatic life, namely, the waters are well buffered by comparison with many natural waters, and the mud on the floor of this reservoir carries much less decomposing organic matter than is found on the floor of many impoundments. Both of these conditions are to be expected in Elephant Butte Reservoir since the waters of the Rio Grande have, in part at least, drained areas rich in calcium and magnesium salts, and because this portion of the Rio Grande receives very little organic matter either from the land drained or as effluents from industries and municipalities.

During the winter season, after winter conditions have become established, the waters of Elephant Butte Reservoir have essentially the same hydrogen-ion concentration throughout the lower lake as the waters entering at the Narrows. The hydrogen-ion concentration, once the thermal stratification of the summer season is broken, changes rather rapidly to pH 7.7, and thereafter more gradually toward pH 7.4. However, the pH values throughout the reservoir vary so little at any given time during the winter season that they have not been graphed (see table 10), although a specific example is given for comparison. The 78 pH readings taken on December 24, 1937 (not all given in table 10), throughout the reservoir from surface to bottom ranged from pH 7.4 to pH 7.65, and 50 of these readings lay between pH 7.5 and pH 7.6.

Toward the end of February the average hydrogen-ion concentration value may become slightly less alkaline than pH 7.4 depending upon the combination of weather conditions, water stage, and the draw-off demands. When the surface-water temperature begins to rise again in the spring the pH of the surface water shifts rather rapidly back toward the midsummer alkaline limit near pH 8.5 and the differences between the hydrogen-ion concentrations of the surface and bottom waters are reestablished.

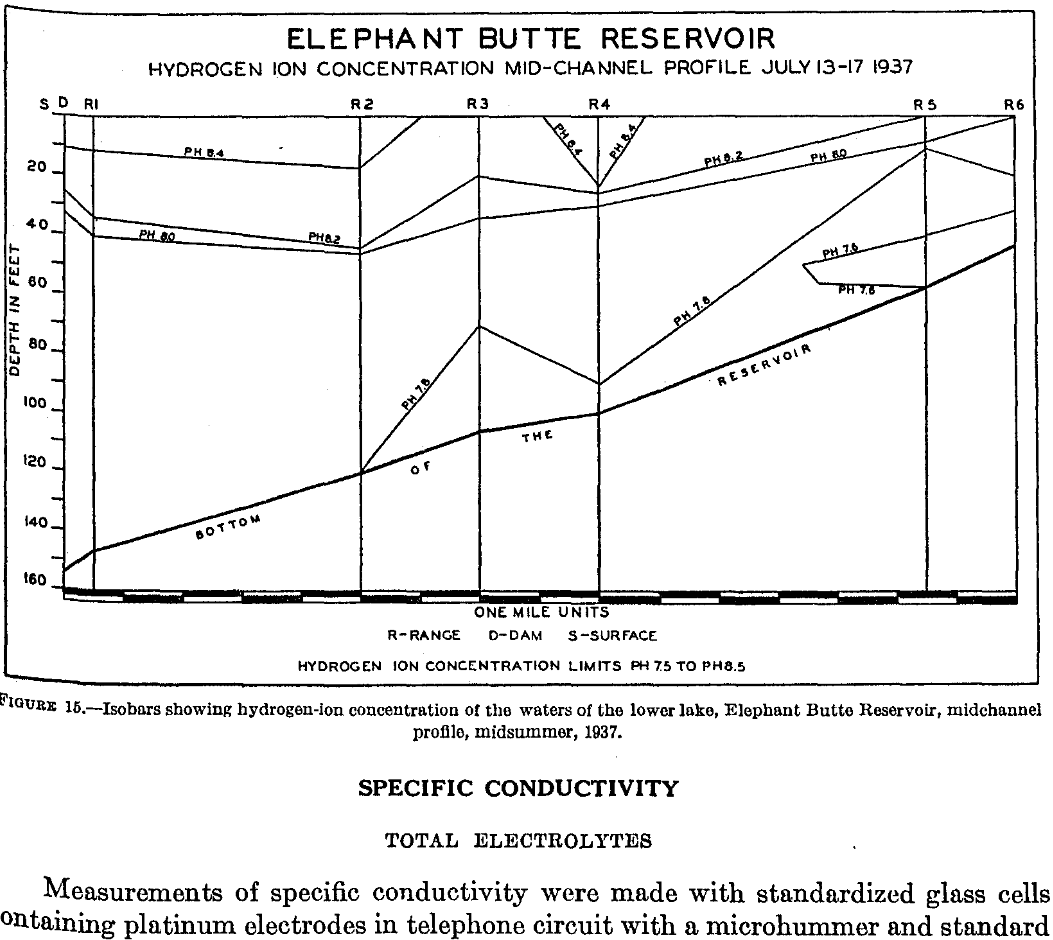

FIGURE 15.—Isobars showing hydrogen-ion concentration of the waters of the lower lake, Elephant Butte Reservoir, midchannel profile, midsummer, 1937.

SPECIFIC CONDUCTIVITY

TOTAL ELECTROLYTES

Measurements of specific conductivity were made with standardized glass cells containing platinum electrodes in telephone circuit with a microhummer and standard variable resistance units. Several readings were taken on each sample and temperature corrections made. For purposes of comparison all values have been reduced to 25° C., and the specific conductivity data presented as $\text{mho} \times 10^{-6}$ at 25° C. From this basic figure other computations can be made if desired.

Specific conductivity measurements during the summer months showed a gradual increase in total electrolytes from the surface to the bottom of Elephant Butte Reservoir when no unusual conditions, such as those accompanying silt flows, were in progress. The actual gamut of specific conductivity varies from time to time over a rather wide spread. For example, at range 1 on June 15, 1935 (see tables 2, 4, and 11), the specific conductivity varied from 996 to 1,107; on July 14, 1937, from 474 to

818; and on July 30, 1938, from 581 to 720 mho×10^{-6} at 25° C., although the vertical relations of lower specific conductivity at the surface and higher at the bottom were maintained on all of these dates. For comparison with the other data the specific conductivity determinations throughout the reservoir during the July 13–17, 1937, period have been graphed in figure 24.

The spread of values just given for range 1 on July 14, 1937, included the maximal and minimal conductivity determinations for the reservoir during that period. However, at that time the water in the Narrows ranged from 680 (the warmer water above 20 feet) to 604 mho×10^{-6} at 25° C. (the colder water near the bottom). As the warmer water spread out into the epilimnion of the upper basin of the lower lake the conductivity dropped rapidly to a little less than 600, so that the epilimnial water above 30 feet between ranges 4 and 5 was fairly uniform as regards total electrolytes. Between range 4 and the dam the surface water varied in conductivity from 474 to 600, although there seemed to be a fairly well defined mass of water between the 10- and 20-foot levels, extending from ranges 1 to 4, in which the conductivity was less than 500 surrounded both above and below by water having conductivity between 500 and 600. (See fig. 20.) As the water temperatures were higher in this portion of the surface zone than in any other part of the deep basin, evaporation from the surface water and the diurnal circulation of the surface water may have been factors in the distribution of electrolytes in this surface zone between range 4 and dam. The data on hydrogen-ion concentration offer some confirmation at least of this suggestion. (See fig. 15.)

Below the 30- to 40-foot level, that is, below the thermocline when it was clearly defined or below its horizontal continuation, the thermoclinal band, the specific conductivity increased gradually from about 600 to slightly more than 800 at the bottom, although the isobars ran more nearly parallel to the surface than to the bottom of the reservoir. The bends in these isobars between ranges 4 and 2, although probably of little significance, at least follow the directions expected in view of the disturbances by surface currents as discussed in connection with the distribution of dissolved oxygen in the adclaustral portion of the reservoir.

The detached masses of water which were recognized by their dissolved oxygen content in the adclaustral portion as far upstream as range 2 could not be delimited by specific conductivity, pH, or fixed carbonates. As previously noted, differences in water temperatures were observed in some cases of these detached masses having higher dissolved oxygen than the surrounding water, but in general the minimal variations were not great enough to materially influence the trend of the isotherms in that region. However, some of these detached masses could be identified by the turbidity of the water.

It seems, therefore, that the intrusions and detached nonconforming masses of water, whether they be masses of surface water forced down in the adclaustral portion of the reservoir or separated portions of the various flow strata moving down from the upper basin, tend to assume the character of the surrounding water rather rapidly except as regards dissolved oxygen and to a lesser degree as regards suspensoid content.

Radiation and convection could readily account for the loss of heat into the surrounding water, and diffusion of ionizable material could explain the balance in both conductivity and pH. All of these adjustments could take place rather rapidly. However, the very slow rate of diffusion of dissolved oxygen in water is well established as is also the slow dispersion of very finely divided colloidal material. Apparently the differences in ionized substances and temperature between the detached masses of

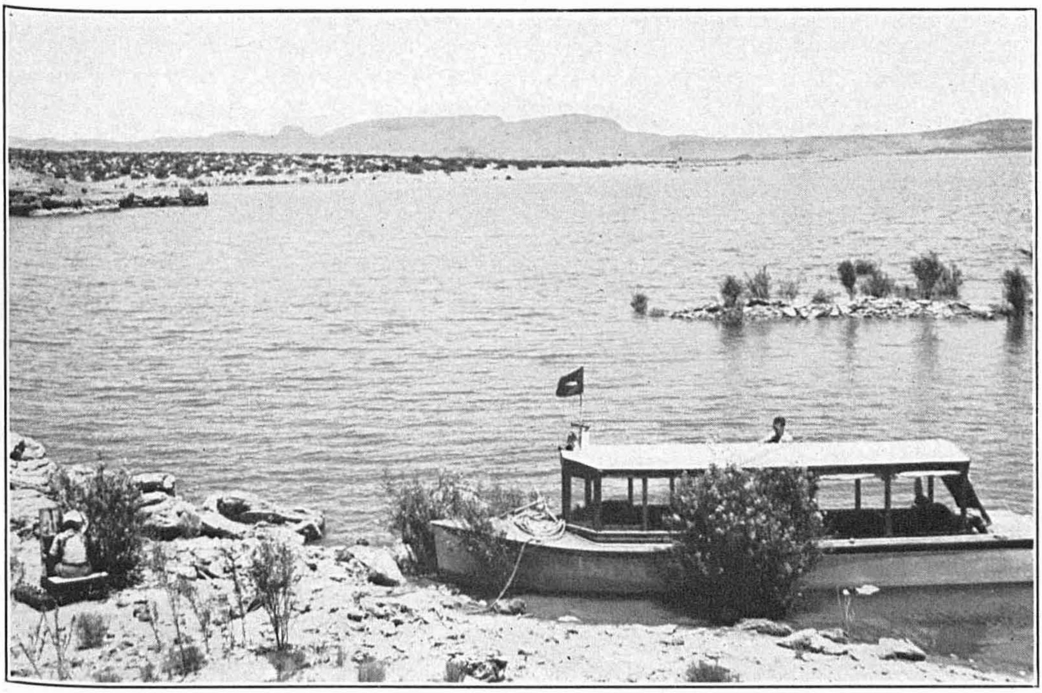

FIGURE 16.—Looking southeast across the lower lake of Elephant Butte Reservoir from near the west end of Range 5.

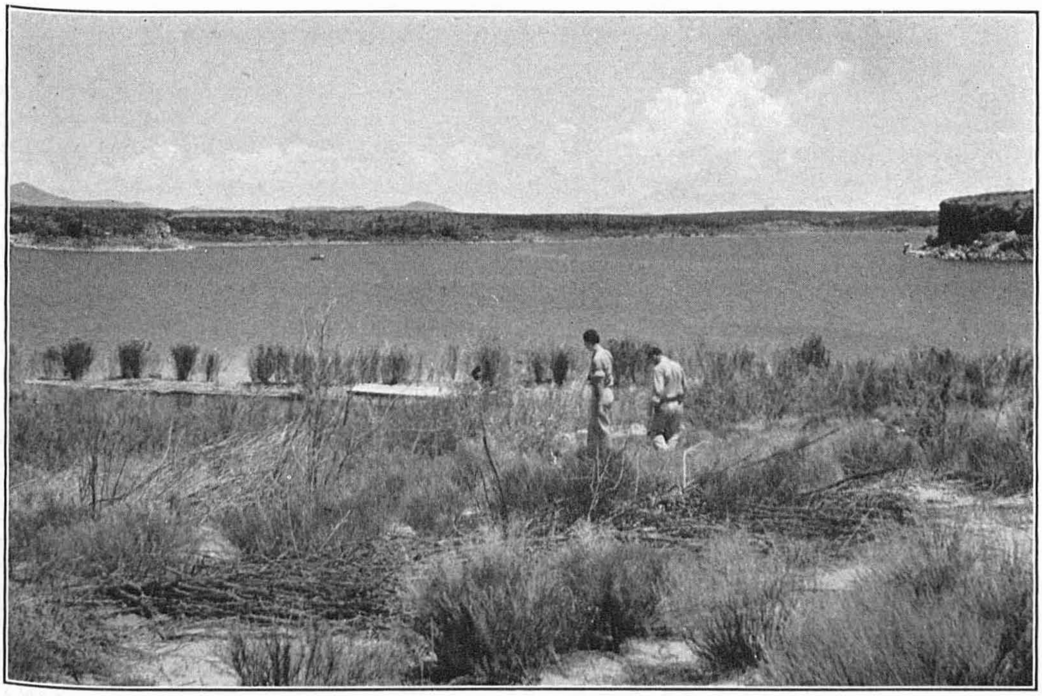

FIGURE 17.—Mouth of the Narrows looking northwest from the east end of Range 5, lower lake, Elephant Butte Reservoir.

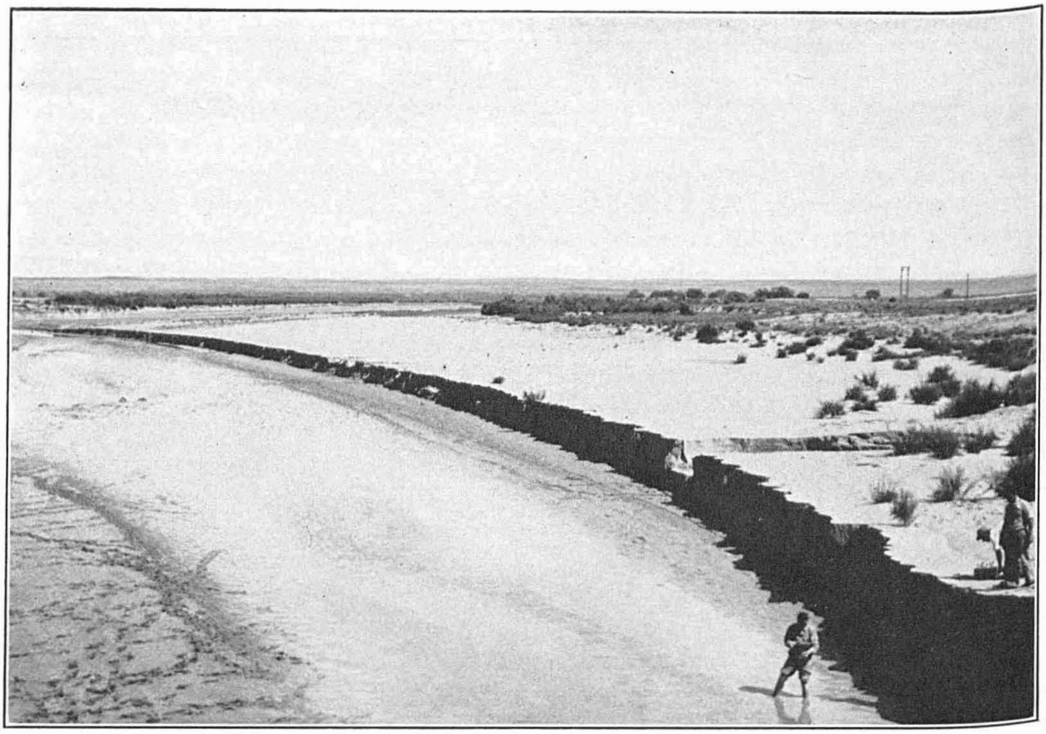

FIGURE 18.—Rio Puerco, showing the abrupt adobe banks and soft mud bed of this stream which contributes much silt to the waters of Elephant Butte Reservoir. About two miles above the junction of the Rio Puerco with the Rio Grande, near Bernardo, New Mexico.

FIGURE 19.—The photoelectric and illumination units of the submersible apparatus for continuous determination of turbidity. In actual use these two units are mounted facing each other in a rigid cage. See text, p. 293, for details of operation.

water and the surrounding water into which they were projected or separated were obliterated rather rapidly by physical and chemical processes which do not call for rapid movement of the water itself, but the slowly diffusable dissolved oxygen and to a lesser extent the colloidal suspensoids remained as markers of the original detached masses. These observations also indicate that currents flowing through the lower lake resulting from the draw-off, for the most part move very slowly unless these flows be accelerated by large inflows from the Narrows.

In July 1938, the specific conductivity of the waters in the lower lake varied from 470 on range 5 at 20 feet, to 838 at the bottom on range 6. Up the Narrows at station 1663, conductivities exceeding 900 were found. The July 1938 data (see table 11) show that the inflow of warm turbid water which was entering the lower lake at that time from the upper lake and the Narrows, in spite of its temperature, was moving forward along the bottom of the reservoir to a depth of about 50 feet. These conductivity values, confirming the observations made in previous sections on temperature and dissolved oxygen, indicate that the inflow water was crowding all of the water in the upper basin forward and that the flow had reached range 5 at the time the samples were taken.

Following the various thermal changes which have already been described for the annual temperature cycle, the vertical stratification of electrolytes found during the summer season gives way in the winter to an oblique stratification down the reservoir from the Narrows to the dam. (See fig. 21.) In midwinter the higher specific conductivities were found in water near the bottom up the Narrows and the low conductivities from the surface of the reservoir on range 2 to the bottom near the dam. In the winter season the coldest water, which lies at the bottom of the Narrows, carries the largest load of electrolytes, consequently the conductivity and thermal profiles in midwinter are somewhat similar.

As the specific conductivity values are resultants of the combined action of all of the electrolytes in solution at any particular station, it seemed desirable to resolve this electrolyte complex in part by studies of the distribution of carbonates, calcium hardness, sulphates, phosphates, chlorides, fluorides, and ammonia. From these studies it was observed that the specific electrolytes determined were rather uniformly distributed throughout the waters of the lower lake despite the various stratifications and slowly moving flow currents previously discussed, and that there was a gradual but consistent increase in these electrolytes at most stations from the surface to the bottom of the reservoir; that is, in general the distribution of these specific electrolytes followed that of the total electrolytes as determined by specific conductivity. Exception to this pattern of electrolyte distribution must be made in the case of the rapidly moving silt flows in which the salt content may be much higher than in the surrounding water and of the shallow waters of the upper lake which are rather uniformly mixed by wind and wave action except at times of silt flows, and have therefore no increase in electrolyte content toward the bottom.

The data concerning the distribution of these specific electrolytes are given in the general tables (excepting the calcium hardness, the fluorides, and ammonia), and are summarized in the following paragraphs.

CARBONATES

Because of their importance to living organisms the carbonates were determined by the methyl-orange alkalinity method (American Public Health Association, 1938) routinely on all samples taken at Elephant Butte Reservoir. The results have been

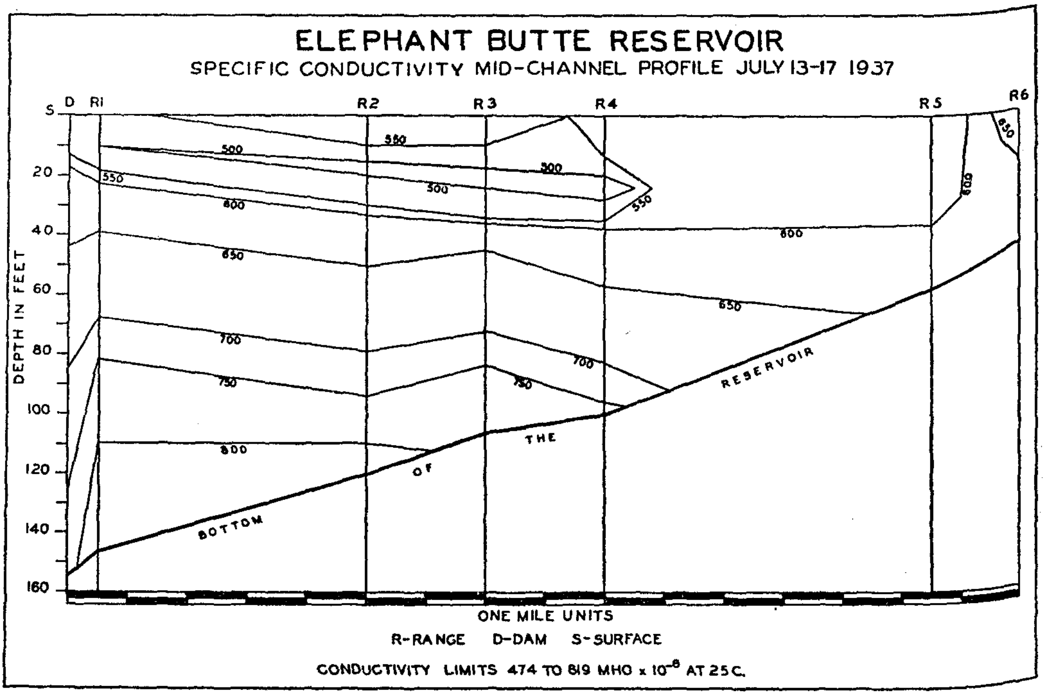

FIGURE 20.—Isobars showing the specific conductivity of the waters of the lower lake, Elephant Butte Reservoir, midchannel profile, midsummer, 1937.

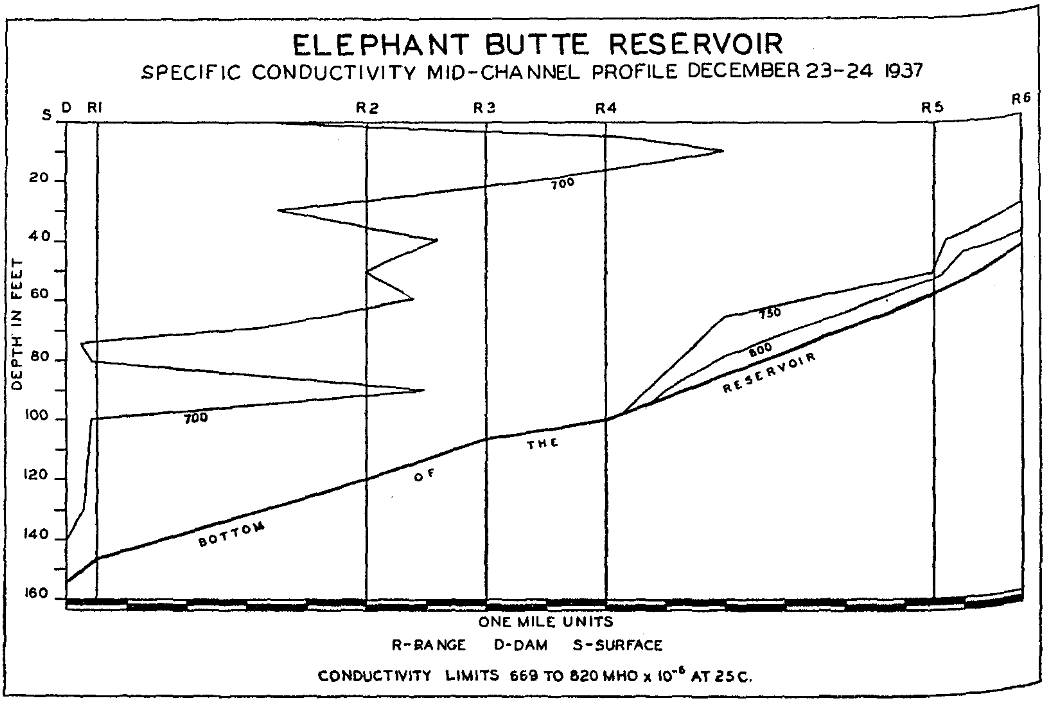

FIGURE 21.—Isobars showing the specific conductivity of the waters of the lower lake, Elephant Butte Reservoir, midchannel profile, midwinter, 1937.

expressed as carbonate (CO_3), in parts per million, so that direct comparisons could be made with sulphate (SO_4) and phosphate (PO_4). If it is desired to transform the CO_3 parts per million to $CaCO_3$ parts per million the figures given should be multiplied by 1.6. The methyl-orange alkalinity as carbonate parts per million throughout the reservoir varied from 59.0 to 99.2 parts per million in the summer determinations and from 85. 4 to 103.2 parts per million in the winter determinations. Exception to these figures must be reserved in cases of water in direct contact with the bottom and of silt flows. These findings place Elephant Butte Reservoir in the class of hard-water lakes (Birge and Juday, 1911) since the fixed carbonates computed as cubic centimeters of carbon dioxide exceeded 22 cc. per liter. This classification is in line with previously reported data (Ellis, 1937) showing that the Rio Grande below the Colorado mountains is essentially a hard-water stream.

Following the midchannel profile, in the midsummer distribution of methyl-orange alkalinity, a fairly well defined stratification may be noted which in general parallels the surface of the reservoir from range 5 to the dam. During the winter season the stratification of carbonates, like that of specific conductivity, becomes more oblique and parallels the bottom of the reservoir. The similarity between the summer conductivity and carbonate stratifications and the winter conductivity and carbonate stratifications is of course based on the obvious relation between these two characteristics of the impounded water.

CALCIUM HARDNESS

The calcium hardness was obtained by the soap method (American Public Health Association, 1938) and computed as parts per million of calcium carbonate. For Elephant Butte waters, excepting silt flows, the calcium hardness ranged from 126 in winter and 176 in summer at the surface to 232 in winter and 282 in summer at the bottom. As the Rio Puerco is known to be one of the chief contributors of salts and silt to the waters of this reservoir it is interesting to note that the calcium hardness of the waters of the Rio Puerco near its junction with the Rio Grande was 2,215 parts per million as calcium carbonate on December 23, 1937.

SULPHATES

The sulphate determinations followed the gravimetric procedure as outlined by American Public Health Association (1938), and have been reported as parts per million of SO_4.

The range of sulphates in the waters of Elephant Butte Reservoir, excepting those in immediate contact with the bottom, extended from 109 to 264 parts per million in the summer and 114 to 209 in the winter. In the lower lake a general and progressive increase in the amount of sulphates from surface to bottom was noted in both the midsummer and midwinter studies. From table 12 it may be noted that the Rio Puerco is the major contributor of sulphates to the waters of Elephant Butte Reservoir as the sulphates in Rio Puerco waters may at times rise to 2,050 parts per million in contrast to the much lower sulphate content at Isleta and Bernardo, N. Mex.

PHOSPHATES

Total phosphates in the waters of Elephant Butte Reservoir were determined colorimetrically by the molybdate method of Deniges (1920), which was modified and adapted for use with the photelometer. This procedure gave very satisfactory results when 50-cc. samples were used and the readings made with large glass cells. The values have been expressed as parts per million of PO_4.

During the midwinter season of 1937 the soluble phosphates in the waters of Elephant Butte Reservoir ranged from a trace to 0.025 part per million, although only three exceeded 0.020 parts per million and the majority lay between 0.010 to 0.015 part per million. In July 1938 the phosphate values lay between zero and 0.045 part per million. These values are comparable to those found in the soft-water lakes of Wisconsin by Juday, Birge, Kemmerer, and Robinson (1927), although the waters of Elephant Butte Reservoir were hard in terms of fixed carbonates and contained much more ionizable material than the Wisconsin lakes.

The distribution of phosphates in the lower lake followed the same general plan of the other electrolytes in that there was an increase in phosphates from the surface to the bottom of the reservoir. During the summer of 1938 the waters of the lower lake, to a depth varying from 30 to 80 feet, were almost devoid of phosphates. Below these levels the phosphates were generally higher in the more turbid waters than in the surrounding clearer waters, as may be seen at range 3, station 2. The analyses of waters from the Rio Puerco and the Rio Grande at various stations above the reservoir suggest that the phosphates are contributed by the Rio Grande. (See table 12.)

CHLORIDES

Chlorides in Elephant Butte Reservoir waters were determined by the Dupray (1923) modification of the Isaacs (1922) silver chromate method, adapted to 25 or 50 cc. samples which were read in the photelometer. By standardizing the reagents and using a carefully measured aliquot part of the filtrate a high degree of accuracy was obtained with this procedure. The data have been stated as chlorine (Cl) in parts per million.

The chlorides showed the most uniform distribution throughout the waters of the lower lake of any of the electrolytes studied. In general, however, there was a graded increase in chlorides from the surface to the bottom of the reservoir. Comparisons with the chlorides of the Rio Puerco and the Rio Grande (see table 12) above Elephant Butte suggest that the Rio Puerco is the chief source of the chlorides received by Elephant Butte Reservoir.

The chloride content of the waters of this reservoir varied from 20 to 29 parts per million (as chlorine) during the misdummer period, and from 24 to 33 parts per million during December 1937.

FLUORIDES

Eleven sets of fluoride determinations at representative stations in the lower lake of Elephant Butte Reservoir were made during the summer of 1938, and three during December 1937, by the alizarin-zirconium method (Elvove, 1933). This method was adapted for use with the photelometer and proper consideration was given to substances interfering with the reaction. The findings are reported as parts per million of fluorine.

Although the data are too few to give any information concerning distribution of fluorides in the waters of this reservoir, in view of the biological hazards presented by fluorides it is imporant to report that all of the summer tests were positive, with fluorine values ranging from 0.6 to 1.2 parts per million. Recent work at the Columbia (Mo.) Laboratories of the Bureau of Fisheries has shown that much smaller quantities of fluorine as fluoride can be detrimental to fish and some aquatic invertebrates.

AMMONIA

Using standard nesslerization procedures 58 analyses were made for ammonium compounds in water taken from representative stations in the lower lake during July 1937 and July 1938. Although large samples were used, only 8 of the 58 were positive, the ammonia values ranging from 0.001 to 0.087 and averaging 0.003 part per million. These values for ammonia are very low as compared with most inland rivers in the United States (Ellis, 1937) and are lower than the ammonia content of various English lake waters as reported by Pearsall (1930) or of Wisconsin lakes as given by Domogalla, Juday and Peterson (1925). The low ammonia content of Elephant Butte Reservoir waters is significant not only in pointing out the absence of organic pollution but also when taken with the very low total nitrogen content of this water found during these studies, as indicating the small amount of nitrogen available for the production of food organisms in Elephant Butte Reservoir.

TURBIDITY

Routine turbidity measurements were made photoelectrically both in the field and in the laboratory, with a photelometer (Cenco type 12340), standardized against known turbidity suspensions. By varying the filters and water containers this instrument could be used over a wide range of turbidities and for the clearer waters was found sensitive to less than 0.5 parts per million turbidity.

For the detailed studies of vertical silt distribution in the waters of Elephant Butte Reservoir and other impoundments, a submersible photoelectric apparatus was devised. (See fig. 19) This apparatus consisted of two heavy walled brass boxes, one 4 by 4 by 4 inches and the other 4 by 4 by 2½ inches, carrying, respectively, a light unit and a photoelectric unit. The face of each box was covered by a square of thick plate glass which was held in position between two rubber gaskets by a brass frame bolted to a flange on the box. Inside the smaller box a Weston photronic unit was mounted, and in the larger box a parabolic reflector carrying an electric bulb. Connections with the photronic cell and the electric bulb were made through brass tubes perforating the top of each box. Two rubber-covered cables of fine, multiple strand, flexible copper wire were introduced into each box through the brass tube and this tube subsequently sealed with fiber packing and melted rubber. An open tube of dessicated calcium chloride, lightly plugged with cotton, was placed in each box before sealing to free the enclosed air from moisture which might fog the glass when the units were cooled in the deeper waters.

The insulated copper wire cables from each box were fastened to a steel cable which carried the load of both apparatus and copper wires. Through its copper wire cables the photronic cell was attached to a sensitive microammeter, and the electric light to batteries mounted on the deck of the boat. As both the battery current to the light and the photoelectric current from the photronic cell passed through the entire length of their respective cables, the internal resistence of the apparatus was essentially constant.

In actual operation the two brass boxes were bolted securely to a carrier (not shown in fig. 19). As the distance between the light and the photronic unit could be varied, adjustment could be made for the amount of turbidity to be studied as the apparatus was always standardized in distilled water. By altering the distance between the light and the photoelectric unit, and by using electric light bulbs of different wattage, the apparatus is serviceable over a wide range of turbidities. In the clearer waters when the two units are set well apart turbidity readings of 0.5 part per million or less can be made.

When the apparatus was lowered into the water an electric thermometer was attached to the carrier and to the supporting steel cable so that it was possible to make simultaneous and continuous observations on turbidity and temperature from the surface to the bottom. In the upper layers of water, where sunlight was a factor, two readings with the photoelectric unit were taken at each point, namely, the microammeter deflection with the electric light off, that is, the photoelectric reading due to light penetration in the water, and a second reading with the electric light on. Correction could be made in this way for light other than that produced by the electric light bulb of the apparatus.

By means of the standardization factors which were determined for the various settings of the light and the photronic cell, the microammeter readings were transformed directly into turbidity as parts per million, using the American Public Health Association standards (1938). From these values in parts per million, light reduction in percent and light penetration in millionth intensity depth (Ellis, 1936a) could be computed as desired.

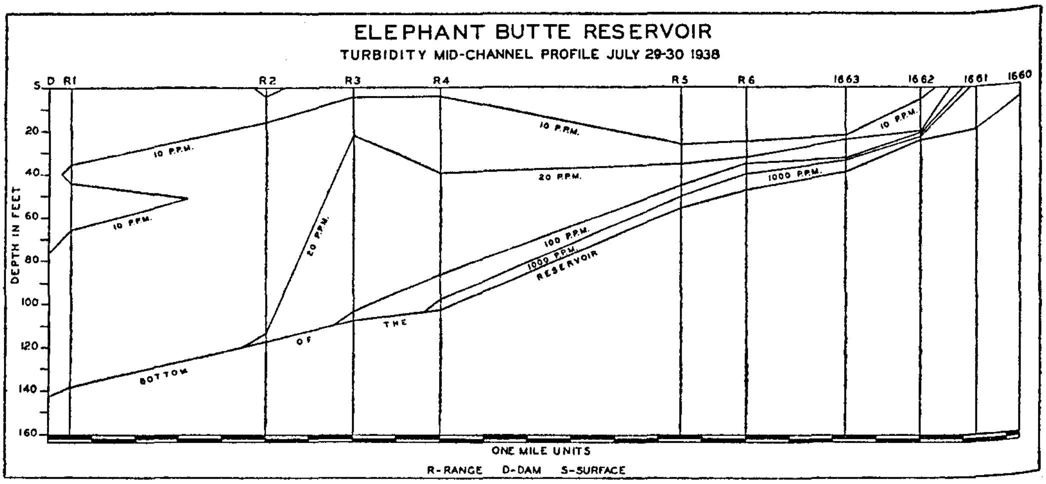

FIGURE 22.—Isobars showing turbidity of waters of both upper and lower lakes of Elephant Butte Reservoir, July 29-30, 1938.

The determinations of turbidity presented here as made with either of the two instruments described are "total turbidity," that is, all of the suspensoids are measured collectively with such color as the water may have. However, when the suspensoids in Elephant Butte waters were removed by direct sedimentation, by colloidal filter under 80 pounds pressure, or by centrifuging, the water was found to be colorless, consequently, as the waters of this reservoir are very poor in plankton, the turbidities reported were produced almost entirely by silt and organic detritus. As has already been noted the organic load of the waters of Elephant Butte Reservoir is also very low so the turbidity values for these waters are essentially measurements of silt turbidity.

As the Rio Grande may entirely cease flowing at times above Elephant Butte Reservoir during the period between July and October, and through such tributary streams as the Rio Puerco it receives much silt in times of high water following the

TABLE 14.—*Turbidity in parts per million, midchannel profile for upper lake, the Narrows, and lower lake, Elephant Butte Reservoir, July 29–30, 1938*

Depth in feet	Lno. 829	Range 1, station 2	Range 2, station 2	Range 3, station 2	Range 4, station 1	Range 5, station 2	Range 6, station 2	Lno. 1663	Lno. 1662	Lno. 1661
1	4.5	5.5	84.0	7.8	7.8	6.7	4.0	4.5	9.0	2,100
2	9.0	7.8	84.0	7.8	10.5	4.3	4.5	3.8	10.5	1,600
3	6.6	10.5	90.0	10.5	10.5	4.5	4.5	4.5	9.0	1,600
4	6.6	14.0	90.0	10.5	10.5	4.3	5.0	3.8	9.0	1,600
5	4.5	12.0	90.0	10.5	10.5	4.7	5.5	4.0	9.0	1,500
6	5.5	10.5	14.0	10.5	10.5	5.6	5.5	4.5	10.5	2,100
7	6.6	7.8	14.0	10.5	10.5	5.6	5.5	3.6	10.5	2,900
8	6.6	9.0	14.0	10.5	12.0	5.6	5.5	7.8	9.0	[1]5,000
9	5.5	6.6	14.0	14.0	12.0	5.5	5.5	6.6	10.5	[1]5,000
10	6.6	6.6	6.6	14.0	12.0	6.6	5.5	6.6	10.5	
11	6.6	9.0	6.6	14.0	12.0	6.6	5.5	6.6	9.0	
12	6.6	6.6	6.6	14.0	12.0	5.4	5.5	4.5	9.0	
13	5.5	6.6	6.6	14.0	12.0	5.6	4.6	5.5	9.0	
14	5.5	6.6	6.6	14.0	12.0	5.0	6.0	5.5	9.0	
15	6.6	6.6	6.6	14.0	12.0	5.6	6.0	5.5	9.0	
16	6.6	7.8	6.6	16.0	13.5	5.6	7.1	6.6	7.8	
17	7.8	6.6	6.6	16.0	14.0	8.0	6.0	5.5	7.8	
18	5.5	5.5	10.5	20.0	14.0	7.8	7.1	5.5	7.8	
19	6.6	6.6	10.5	20.0	14.0	7.8	8.3	5.5	10.5	
20	6.6	6.6	10.5	20.0	14.0	6.6	8.3	6.6	14.0	
21	5.5	6.6	10.5	20.0	14.0	6.6	8.3	6.6	20.0	
22	5.5	6.6	10.5	20.0	14.0	6.6	8.3	6.6	60.0	
23	6.0	6.0	10.5	20.0	14.0	7.8	5.5	7.8	[1]5,000.0	
24	6.0	5.5	10.5	20.0	14.0	9.0	7.8	7.8		
25	4.1	5.5	10.5	20.0	14.0	9.0	7.8	9.0		
26	4.1	6.6	10.5	20.0	14.0	9.0	7.8	7.8		
27	4.5	5.5	10.5	20.0	14.0	9.0	7.8	10.5		
28	4.5	6.6	10.5	20.0	16.0	10.5	10.5	20.0		
29	4.5	6.6	10.5	23.0	16.0	10.5	12.0	32.0		
30	4.5	7.8	10.5	20.0	18.0	10.5	16.0	54.0		
31	4.5	7.8	10.5	23.0	18.0	12.0	20.0	76.0		
32	4.5	7.8	10.5	20.0	18.0	12.0	23.0	90.0		
33	4.5	9.0	10.5	23.0	18.0	14.0	23.0	124.0		
34	4.5	9.0	10.5	20.0	18.0	18.0	23.0	180.0		
35	4.5	9.0	10.5	20.0	20.0	18.0	29.0	1,100.0		
36	5.5	10.5	10.5	29.0	20.0	18.0	40.0	3,800.0		
37	7.8	10.5	10.5	29.0	20.0	20.0	105.0	[1]5,000.0		
38	7.8	10.5	10.5	29.0	20.0	32.0	142.0	[1]5,000.0		
39	7.8	10.5	10.5	29.0	20.0	32.0	340.0	[1]5,000.0		
40	7.8	10.5	10.5	29.0	20.0	36.0	1,150.0			
41	7.8	10.5	10.5	54.0	29.0	40.0	[1]5,000.0			
42	6.6	10.5	10.5	54.0	29.0	44.0	[1]5,000.0			
43	7.8	10.5	10.5	44.0	26.0	60.0	[1]5,000.0			
44	7.8	10.5	10.5	49.0	26.0	208.0	[1]5,000.0			
45	9.0	10.5	10.5	44.0	26.0	380.0	[1]5,000.0			
46	7.8	10.8	10.8	54.0	26.0	570.0				
47	7.8	9.0	10.5	49.0	36.0	940.0				
48	5.5	10.5	10.5	49.0	32.0	1,400.0				
49	7.8	9.0	10.5	49.0	29.0	1,500.0				
50	7.8	9.0	10.5	49.0	29.0	1,300.0				
51	7.8	9.0	10.5	49.0	29.0	860.0				
52	7.8	9.0	10.5	49.0	29.0	940.0				
53	7.8	10.5	10.5	49.0	29.0	1,400.0				
54	7.8	9.0	10.5	36.0	29.0	[1]5,000.0				
55	7.8	9.0	10.5	36.0	32.0					
56	7.8	9.0	10.5	36.0	32.0					
57	7.8	9.0	10.5	36.0	32.0					
58	7.8	9.0	10.5	36.0	32.0					
59	7.8	9.0	10.5	36.0	36.0					
60	7.8	9.0	10.5	36.0	36.0					
61	9.0	10.5	10.5	36.0	40.0					
62	9.0	10.5	10.5	36.0	44.0					
63	9.0	9.0	10.5	36.0	54.0					
64	9.0	10.5	10.5	36.0	54.0					
65	9.0	10.5	10.5	36.0	54.0					
66	9.0	9.0	10.5	36.0	54.0					
67	9.0	10.5	10.5	36.0	54.0					
68	9.0	10.5	10.5	36.0	54.0					
69	9.0	10.5	10.5	36.0	54.0					
70	9.0	10.5	14.0	36.0	60.0					
71	9.0	10.5	14.0	36.0	64.0					
72	9.0	10.5	14.0	36.0	60.0					
73	9.0	10.5	14.0	36.0	60.0					
74	9.0	10.5	14.0	36.0	60.0					
75	9.0	10.5	18.0	36.0	60.0					
76	9.0	12.0	18.0	36.0	54.0					
77	9.0	12.0	18.0	36.0	54.0					
78	9.0	10.5	18.0	36.0	54.0					
79	9.0	10.5	18.0	36.0	54.0					
80	10.5	12.0	18.0	36.0	54.0					
81	10.5	12.0	18.0	36.0	60.0					
82	9.0	12.0	18.0	44.0	64.0					
83	9.0	12.0	18.0	44.0	76.0					
84	9.0	12.0	29.0	44.0	76.0					
85	9.0	12.0	29.0	44.0	76.0					
86	9.0	12.0	29.0	70.0	76.0					
87	9.0	12.0	29.0	54.0	90.0					
88	9.0	12.0	29.0	54.0	90.0					
89	9.0	12.0	29.0	54.0	98.0					
90	9.0	12.0	18.0	54.0	105.0					
91	9.0	12.0	18.0	54.0	105.0					
92	10.5	14.0	18.0	54.0	105.0					
93	10.5	14.0	14.0	54.0	105.0					
94	10.5	14.0	14.0	64.0	105.0					
95	9.0	14.0	14.0	60.0	105.0					
96	10.5	12.0	14.0	64.0	940.0					
97	10.5	12.0	14.0	64.0	[1]5,000.0					
98	9.0	12.0	14.0	64.0	[1]5,000.0					
99	9.0	10.5	14.0	64.0	[1]5,000.0					
100	14.0	12.0	16.0	76.0	[1]5,000.0					
101	14.0	14.0	16.0	76.0	[1]5,000.0					
102	18.0	14.0	16.0	90.0	[1]5,000.0					
103	18.0	14.0	16.0	90.0						
104	18.0	14.0	16.0	90.0						
105	18.0	14.0	16.0	105.0						
106	18.0	14.0	16.0	340.0						
107	14.0	14.0	16.0							
108	14.0	14.0	16.0							
109	14.0	14.0	16.0							
110	14.0	14.0	16.0							
111	14.0	14.0	16.0							
112	14.0	14.0	16.0							
113	18.0	14.0	16.0							
114	18.0	14.0	16.0							
115	18.0	14.0	16.0							
116	18.0	14.0	16.0							
117	18.0	14.0	36.0							
118	14.0	14.0								
119	14.0	14.0								
120	14.0	14.0								
121	14.0	14.0								
122	14.0	14.0								
123	14.0	14.0								
124	14.0	14.0								
125	940.0	14.0								
126		14.0								
127		14.0								
128		14.0								
129		14.0								
130		14.0								
131		14.0								
132		14.0								
133		14.0								
134		16.0								

---

[1] The submersible photoelectric apparatus was not calibrated for turbidities greater than 5,000 parts per million.

sudden heavy rains which often occur in this area, silt is an important factor in the physical and chemical complexes regulating the conditions of the water in Elephant Butte Reservoir. For example, as has already been pointed out under the discussion of dissolved oxygen, silt by laking down organic detritus at times creates an oxygen demand in the waters near the bottom of the upper basin of the lower lake.

The extent of the silting in Elephant Butte Reservoir may be seen from data supplied by the United States Reclamation Service, which show a deposition of 365,186 acre-feet during the first 20 years (1915–35) of the existence of this reservoir, that is, about 18,260 acre-feet per year. This load of silt is brought into Elephant Butte Reservoir very largely by the Rio Grande, as there are no other permanent streams entering this reservoir; although on occasion heavy rains of short duration can bring silt into this reservoir by way of the many arroyas which lead directly into the deep basin. The silt inflow into the reservoir is even more variable than the inflow of water, consequently the waters of the lower lake, although generally rated as clear to cloudy, on occasion become quite turbid.

From the data collected on silt turbidity through the past 4 years at Elephant Butte Reservoir a series of observations made during 30 hours beginning at noon on July 29, 1938, have been selected (see tables 14 and 15, and fig. 22) as presenting the principal features of the turbidity findings. In these two tables the turbidity in parts per million and the water temperatures are given at 1-foot intervals for the complete vertical section at each of the stations in the midchannel profile from the middle of the upper lake, through the Narrows, and down the lower lake to the dam.

From table 14 it may be seen that the turbidity throughout the entire reservoir on July 29–30, 1938, varied from 3.6 to over 5,000 parts per million, which constituted a wide spread from clear to very turbid, although in much of the water the turbidity did not exceed 16 parts per million. The data in table 14 also show, as was brought out repeatedly in the studies with the submersible photoelectric unit, the marked irregularity of the turbidity pattern from surface to bottom in the waters of Elephant Butte Reservoir. Even the clearer waters often varied 100 percent or more in turbidity within a span of a few feet, and frequently the transition was very abrupt either to more or less turbid water.

On the other hand, some masses of water were found in which the turbidity remained quite constant for many feet, as at range 2, station 2, where the water held consistently at a turbidity of 10.5 parts per million for 51 feet between the 18- and 69-foot levels, although from the surface to a depth of 6 feet at this same station the water was definitely cloudy with a turbidity between 84 and 90 parts per million. These and similar comparisons of turbidity at different vertical levels throughout Elephant Butte Reservoir confirm the statements made previously in other sections of this discussion concerning the lack of uniformity in composition of the waters of the lower lake, particularly downstream from range 3 and in the adclaustral portion where various physical and chemical factors disturb the waters of the reservoir.

TABLE 15.—*Water temperatures in Elephant Butte Reservoir, in degrees centigrade, July 29–30, 1938*

Depth in feet	In the lower lake					In the Narrows		In the upper lake		
	Lno. 1415, range 1, station 2	Lno. 1419, range 2, station 2	Lno. 1429, range 3, station 2	Lno. 1426, range 4, station 1	Lno. 1422, range 5, station 2	Lno. 1424, range 6, station 1	Lno. 1663	Lno. 1662	Lno. 1661	Lno. 1660
Work started	2:05 p. m.	8:50 a. m.	8:08 a. m.	7:18 p. m.	6:14 p. m.	5:38 p. m.	4:32 p. m.	3:23 p. m.	3:07 p. m.	2:35 p. m.
Work completed	2:50 p. m.	9:30 a. m.	8:40 a. m.	7:42 p. m.	6:31 p. m.	5:58 p. m.	4:52 p. m.	3:57 p. m.	3:18 p. m.	2:47 p. m.
1	26.0	25.5	27.2	28.9	30.0	30.0	31.7	31.7	31.7	33.6
2	------	25.5	27.5	28.9	29.4	29.4	30.6	30.9	31.1	32.8
3	25.6	25.5	27.5	28.6	29.3	28.9	30.0	29.8	30.0	32.2
4	25.5	25.5	27.8	28.6	29.2	28.3	29.4	29.4	28.7	------
5	25.5	25.5	27.8	28.3	28.9	28.0	28.9	28.9	27.2	------
6	25.5	25.5	27.8	28.3	28.3	27.8	28.3	28.3	26.7	------
7	25.4	25.5	27.5	28.3	27.8	27.2	28.3	27.8	26.5	------
8	25.4	25.5	27.2	28.0	27.5	27.5	28.3	27.2	26.1	------
9	25.0	25.5	27.2	28.0	26.7	26.7	27.8	26.7	26.1	------
10	24.9	24.9	27.2	27.9	27.5	26.6	27.2	26.5	------	------
11	------	24.9	27.5	27.8	26.7	26.1	26.6	26.1	------	------
12	------	24.9	26.7	27.5	26.6	26.1	26.5	26.1	------	------
13	------	24.9	26.7	27.2	26.6	26.0	26.5	25.9	------	------
14	------	24.9	26.7	27.2	26.4	26.0	26.5	25.9	------	------
15	------	24.9	26.7	27.5	26.1	25.6	26.1	25.6	------	------
16	------	24.9	26.7	26.7	26.1	25.6	26.1	25.6	------	------
17	------	24.9	26.7	26.7	26.1	25.6	26.0	25.3	------	------
18	------	24.9	26.7	26 7	26.0	25.5	26.0	25.3	------	------
19	------	24.9	26.7	26.6	25.6	25.5	25.6	25.0	------	------
20	24.2	24.2	26.7	26.6	25.6	25.5	25.6	25.0	------	------
21	------	24.2	26.7	26.5	25.5	25.5	25.5	25.1	------	------
22	------	24.2	26.7	26.1	25.5	25.0	25.3	25.3	------	------
23	------	24.2	26.7	26.1	25.0	25.0	25.0	25.5	------	------
24	------	24.2	26.6	26.1	25.0	25.0	24.7	25.5	------	------
25	------	24.2	26.1	26.1	24.9	24.9	24.7	------	------	------
26	------	24.2	26.1	26.0	24.7	24.7	24.4	------	------	------
27	------	24.2	26.1	25.6	24.7	24.7	24.4	------	------	------
28	------	24.2	26.1	25.6	24.6	24.6	24.3	------	------	------
29	------	24.2	26.1	25.3	24.4	24.4	24.4	------	------	------
30	23.5	23.5	26.1	25.0	24.4	24.4	24.4	------	------	------
31	------	23.5	26.0	25.0	24.4	24.4	24.4	------	------	------
32	------	23.5	26.0	25.0	24.4	24.4	24.6	------	------	------
33	------	23.5	25.8	24.7	24.3	24.3	24.4	------	------	------
34	------	23.5	25.6	24.5	24.2	24.3	24.4	------	------	------
35	------	23.5	25.6	24.4	24.2	24.2	23.9	------	------	------
36	------	23.5	25.5	24.4	24.4	24.0	23.6	------	------	------
37	------	23.5	25.0	24.3	24.0	23.9	23.3	------	------	------
38	------	23.5	24.9	24.3	23.9	23.9	23.1	------	------	------
39	------	23.5	24.4	24.2	23.9	23.9	23.2	------	------	------
40	22.5	22.5	24.4	24.0	23.9	23.6	------	------	------	------
41	------	22.5	23.9	23.9	23.9	22.9	------	------	------	------
42	------	22.5	23.9	23.9	23.9	22.8	------	------	------	------
43	------	22.5	23.9	23.9	23.7	22.8	------	------	------	------
44	------	22.5	23.4	23.6	23.9	22.6	------	------	------	------
45	------	22.5	23.3	23.3	23.7	22.6	------	------	------	------
46	------	22.5	23.3	23.1	23.7	------	------	------	------	------
47	------	22.5	23.3	22.8	23.3	------	------	------	------	------
48	------	22.5	23.1	22.8	23.3	------	------	------	------	------
49	------	22.5	22.8	22.5	23.1	------	------	------	------	------
50	20.5	20.5	22.8	22.2	23.1	------	------	------	------	------
51	------	20.5	22.8	21.9	23.1	------	------	------	------	------
52	------	20.5	22.4	21.9	22.6	------	------	------	------	------
53	------	20.5	22.2	21.7	22.6	------	------	------	------	------
54	------	20.5	22.2	21.7	22.2	------	------	------	------	------
55	------	20.5	22.2	21.6	------	------	------	------	------	------
56	------	20.5	21.9	21.6	------	------	------	------	------	------
57	------	20.5	21.7	20.6	------	------	------	------	------	------
58	------	20.5	21.5	20.6	------	------	------	------	------	------
59	------	20.5	21.1	20.3	------	------	------	------	------	------
60	18.9	18.5	21.1	20.1	------	------	------	------	------	------
61	------	18.5	20.8	20.1	------	------	------	------	------	------
62	------	18.5	20.6	19.5	------	------	------	------	------	------
63	------	18.5	20.3	19.4	------	------	------	------	------	------
64	------	18.5	20.2	19.4	------	------	------	------	------	------
65	------	18.5	20.0	19.2	------	------	------	------	------	------
66	------	18.5	19.8	19.2	------	------	------	------	------	------
67	------	18.5	19.4	18.9	------	------	------	------	------	------
68	------	18.5	19.3	18.9						
69	------	18.5	19.2	18.6						
70	16.5	17.2	18.9	18.3						
71	------	17.2	18.9	18.3						
72	------	17.2	18.6	18.3						
73	------	17.2	18.4	18.3						
74	------	17.2	18.3	18.3						
75	------	17.2	18.2	18.1						
76	------	17.2	17.8	17.8						
77	------	17.2	17.6	17.8						
78	------	17.2	17.5	17.7						
79	------	17.2	17.5	17.5						
80	16.0	15.6	17.3	17.2						
81	------	15.6	17.3	17.2						
82	------	15.6	17.2	17.2						
83	------	15.6	17.2	17.0						
84	------	15.6	17.2	16.7						
85	------	15.6	17.2	16.7						
86	------	15.6	17.2	16.7						
87	------	15.6	17.2	16.7						
88	------	15.6	17.1	16.6						
89	------	15.6	16.9	16.4						
90	15.3	16.0	16.9	16.1						
91	------	16.0	16.8	16.1						
92	------	16.0	16.8	16.1						
93	------	16.0	16.7	16.1						
94	------	16.0	16.7	16.1						
95	------	16.0	16.7	16.1						
96	------	16.0	16.7	16.1						
97	------	16.0	16.7	16.1						
98	------	16.0	16.7	16.1						
99	------	16.0	16.7	16.1						
100	15.0	15.8	16.5	16.1						
101	------	15.8	16.4	16.1						
102	------	15.8	16.4	16.1						
103	------	15.8	16.4	------						
104	------	15.8	16.4	------						
105	------	15.8	16.4	------						
106	------	15.8	16.2	------						
107	------	15.8	16.1	------						
108	------	15.8	------	------						
109	------	15.8	------	------						
110	15.1	15.6	------	------						
111	------	15.6	------	------						
112	------	15.6	------	------						
113	------	15.6	------	------						
114	------	15.6	------	------						
115	------	15.6	------	------						
116	------	15.5	------	------						
117	------	15.5	------	------						
118	------	15.5	------	------						
119	------	------	------	------						
120	15.0	------	------	------						
121	------	------	------	------						
122	------	------	------	------						
123	------	------	------	------						
124	------	------	------	------						
125	------	------	------	------						
126	------	------	------	------						
127	------	------	------	------						
128	------	------	------	------						
129	------	------	------	------						
130	14.9	------	------	------						
131	------	------	------	------						
132	------	------	------	------						
133	15.1	------	------	------						
134	------	------	------	------						

NOTE.—The temperatures given in this table were taken synchronously with the turbitidy readings given in table 14.

This particular turbidity profile was taken on July 29–30, 1938, and the waters of the upper lake were very muddy and had been so for some time. At Lno. 1661, near the middle of the upper lake, where the water was only 10 feet deep at that time the turbidity varied from 1,500 to over 5,000 parts per million, the silt load being so great that visible swirls were produced wherever the muddy water was disturbed. As water was being removed continuously from the lower lake at this time by the draw-off there was a very slow but steady movement of water into the lower lake from the upper lake via the Narrows, and as this water entered the lower lake the progression of the silt-laden water could be followed downstream with the submersible photo-electric unit.

Approximately 2½ miles downstream from Lno. 1661 the upper lake becomes much deeper, owing to the sloping floor of this basin, so that on July 29–30, 1938, over 20 feet of water were found at Lno. 1662. Here the vertical distribution of silt showed a rather rapid settling out of the heavier silt particles in the deeper and consequently less disturbed water, for the turbidity varied irregularly between 7.8 and 10.5 parts per million in the upper 19 feet of water. Below this level there was a band some 4 feet deep in which the turbidity increased rather abruptly from 14 parts to over 5,000 parts per million.

As the movement of water down the lake toward the dam was quite slow during July 29–30, 1938, and as there was no marked slit flow moving in from the Rio Grande or Rio Puerco, the same stratification established in the quieter waters at Lno. 1662 was found in the upper part of the Narrows Canyon at Lno. 1663. At this station, which is approximately 2 miles downstream from Lno. 1662, the sedimentation of the finer silt particles had progressed still farther as the turbidity of the upper 25 feet of water at Lno. 1663 was less than 10 parts per million, the actual values ranging from 3.6 to 9.0 parts per million with an average turbidity of less than 6 parts per million. Below the 26-foot level the turbidity increased in the next 8 feet from 10.5 to 180 parts per million at the 34-foot level, and abruptly at 35 feet to 1,100 parts per million. From the 35-foot level to the bottom, at approximately 40 feet, the turbidity rose to over 5,000 parts per million.

Near the lower end of the Narrows at range 6, station 2, the turbidity stratification was essentially the same as that at the upper end of the Narrows, the water above the 27-foot level being quite clear, with a turbidity of less than 10 parts per million, and averaging less than 6 parts per million. Below the 27-foot level the turbidity increased progressively to 340 parts per million at 39 feet, followed by an abrupt rise to 1,150 parts per million at 40 feet. Below 40 feet there was a band some 5 feet deep extending to the bottom in which layer the turbidity was greater than 5,000 parts per million.

A similar distribution of silt turbidity was found at range 5, station 2, which was to be expected because this station, although located in the upper basin of the lower lake, is less than 1 mile from the mouth of the Narrows. At range 5, station 2, the water above the 27-foot level remained clear with a turbidity of 4.3 to 9.0 parts per million. Below the 27-foot level the turbidity increased gradually to 60 parts per million at 43 feet, abruptly at 44 feet to 208 parts per million and rapidly from 44 feet to the bottom at 54 feet where the turbidity exceeded 5,000 parts per million, i. e., the quantities of water having turbidity greater than 10 and greater than 100 parts per million increased at this station, by comparison with the Narrows stations.

However, in the 5 to 6 miles between ranges 5 and 4, the vertical turbidity pattern of the waters of the upper basin of the lower lake changed definitely. At range 4, station 1, the turbidity had risen so that only in the surface 12 inches was water found with a turbidity less than 10 parts per million. From the 1-foot level the turbidity increased progressively and rather rapidly to 105 parts per million at 90 feet. At 96 feet the turbidity changed abruptly to 940 parts per million and to more than 5,000 parts per million at 97 feet. From 97 feet to the bottom, at 102 feet, turbidity exceeded 5,000 parts per million. The same general vertical pattern obtained at range 3, station 2, 2 miles farther down the lake, with these differences the progressive increase in turbidity was less regular at range 3, station 2, and the maximal turbidity at the bottom at this station was only 340 parts per million; that is, the bottom layer of water having a turbidity greater than 1,000 parts per million disappeared between range 4 and range 3 although the main mass of water at range 3, station 2, particularly above 40 feet, had become slightly more turbid than the water at comparable levels at range 4, station 1.

Having established the pattern of silt distribution in the upper basin of the lower lake, a comparison with the distribution of dissolved oxygen becomes pertinent as in the upper basin the dissolved oxygen stratification was more definite than elsewhere in the reservoir and the silt detritus deposits play an important part in the removal of some of the dissolved oxygen from the water. Such a comparison shows that the vertical distribution patterns of dissolved oxygen and silt turbidity are not the same, as the silt tends to settle through the various strata to the lower levels unless there be very definite differences in density or temperature at times of silt flows. Consequently silt turbidity is a less accurate marker for the delimitation of the slowly moving density currents than is dissolved oxygen.

In the lower basin of the lower lake the turbidity of the major mass of water was definitely lower than in the upper basin. In the lower basin little water was found with a turbidity greater than 16 parts, very little greater than 20 parts, and no turbidity greater than 90 parts per million was recorded, even at the bottom. This major difference between the general turbidity of the upper and lower basins of the lower lake is, in part at least, due to the submerged barrier between range 3 and range 2, which tends to hold back the deeper waters in a sort of settling basin, although the clearer surface waters pass freely over the barrier.

The description of the silt distribution in the waters of Elephant Butte Reservior for July 29–30, 1938, presents the silt-turbidity pattern at a time when muddy, silt-laden water was moving slowly but steadily into the lower lake from the upper lake. However, at irregular intervals the particular combination of water level, temperature, and inflows of turbid water heavily laden with silt give rise to silt flows in Elephant Butte Reservoir, Lake Mead, and various other impounded waters which can receive on occasion large volumes of water carrying exceptionally heavy silt loads.

In the case of Elephant Butte Reservoir these silt flows enter the upper basin of the lower lake at the Narrows. There the muddy water in midsummer may establish a density current which will then proceed through the reservoir at levels determined by the interaction of several factors, among which are temperature, the specific gravity of the silt-water mixture, and the velocity of this particular mass of silt-laden water.

As has been pointed out under specific conductivity the electrolyte content and silt loads of waters entering the Rio Grande from the Rio Puerco are often much higher than those of either the waters of the Rio Grande or of Elephant Butte Reservoir. Consequently muddy waters, particularly from the Rio Puerco region, may arrive at the Narrows with a relatively high density and subsequently may break through the thermoclinal band in the upper basin of the lower lake between ranges 5 and 4, with the result that a silt flow may move along at a level quite out of keeping with the temperature of the water in the flow. If the combination of the various characteristics of the flow water is such that the flow does not break through the thermoclinal barrier the silt flow may move as a hyperlimnorrheum in the lower portion of the epilimnial zone. Similar relations between silt stratification and temperature of the water have been pointed out by Kindle (1927) in experimentally produced thermal stratification for water and reported for river-lakes and impounded waters by Ellis (1936b, 1937).

In either event the subsequent fate of the silt flow depends upon the complex of factors controlling the adclaustrial portion of the lower lake, and the turbidity of the reservoir between range 4 and the dam will vary accordingly. Some silt flows have been recorded by the Reclamation Service as moving through this reservoir from the Narrows to the dam, but other flows of lesser magnitude are usually dissipated somewhere downstream below range 4. Silt flows, although occurring at irregular intervals, add another factor of uncertainty concerning the turbidity of the waters in the lower lake.

During the winter season, due to various physical changes attendant on the establishment of the winter temperature levels, the waters of the reservoir mix quite completely and the turbidity rises to a density more nearly approximating that of the inflow waters from the Rio Grande.

BIOLOGICAL ASPECTS

At present (1938) at least 12 species of fishes are known to inhabit the waters of Elephant Butte Reservoir. It is possible that several of the smaller species have escaped notice and that other species will work down the Rio Grande into the reservoir. Several species not included in the list below have been planted in this reservoir and have failed to establish themselves in these waters. The list of species as verified during these studies follows:

Catfish, *Siluridae.*
  1. Blue, or channel cat, *Ictalurus furcatus* (Le Sueur).
  2. Mud, or yellow cat, *Opladelus olivaris* (Rafinesque).
Suckers and buffalo, *Catostomidae.*
  3. Small-mouthed buffalo, *Ictiobus bubalus* (Rafinesque).
  4. Carp sucker, *Carpiodes tumidus* Baird and Girard.
Minnows and carp, *Cyprinidae.*
  5. German carp, *Cyprinus carpio* Linnaeus.
  6. Goldfish, *Carassius auratus* (Linnaeus).
Top minnows, *Poeciliidae.*
  7. Top minnow, *Gambusia patruelis* Girard.
Gizzard shad, *Dorosomidae.*
  8. Gizzard shad, *Dorosoma cepedianum* (Le Sueur).

Sunfish and bass, *Centrarchidae.*

9. Blue gill, *Helioperca incisor* (Cuvier and Valenciennes).
10. White crappie, *Pomoxis annularis* Rafinesque.
11. Largemouth black bass, *Huro floridans* (Le Sueur).

Perch, *Percidae.*

12. Yellow perch, *Perca flavescens* (Mitchill).

A review of this list shows that all of the above species are warm-water fish, and that trout and other salmonids are not present in spite of the fact that they have been planted in Elephant Butte Reservoir. The temperature and dissolved oxygen data presented in previous sections of this paper readily explain the absence of cold-water fish in this reservoir, for trout prefer water below 18° C., and 21° C. (70° F.) is approximately the upper limit in which trout can be successfully maintained. Many writers (see Ellis, 1937) have pointed out that trout require higher dissolved oxygen than warm-water fish.

The figures and tables which furnish data on temperature and dissolved oxygen for Elephant Butte Reservoir show that in midsummer the mass of water below the 21° C. isotherm is so variable in composition, and frequently carries so little oxygen, that regardless of temperature the deep waters of the lower basin of the lower lake are at times definitely unsuited even for warm-water fish. These observations point out the reason for the failure of trout in these waters and indicate that Elephant Butte Reservoir is not suitable for them, although the adclaustral portion of the deep basin may at times contain sufficient dissolved oxygen. Shifting conditions in this part of the reservoir may bring in large masses of water almost devoid of oxygen at any time during the summer season. As an added hazard to trout in the adclaustral portion of the reservoir the occasional warm-water silt flows which pass through this part of the lower lake must also be borne in mind.

Turning to the warm-water fishes, for which group the variations in dissolved oxygen, temperature, and turbidity in Elephant Butte Reservoir are less severe hazards, the physical and chemical conditions in this impoundment may be regarded as satisfactory for adult fish. However, the physical and chemical complexes, through their effects on the food supply, may seriously limit the warm-water species.

The combination of uncertain water levels in this reservoir, due to the uneven adjustment between inflow and draw-off, and the arid climate of the region in which Elephant Butte is situated almost inhibits the natural development of shore vegetation and of either emergent or submergent vegetation in the shallower portions of the impoundment, yet both littoral and aquatic vegetation are important in supplying insects and other types of fish foods. The almost complete absence of vegetation near the water or in the shallow parts of the reservoir has been mentioned previously under dissolved oxygen, and was noted in both the reports of Hazzard (1935) and Greenbank (1937). This feature of Elephant Butte Reservoir is well shown in many of the figures submitted in the present discussion, particularly figure 6.

A review of the findings on substances associated with plankton production in natural lakes shows that Elephant Butte Reservoir waters, under existing conditions, could not be expected to be rich in plankton. The ammonia content of these waters was almost negligible and the total and nonprotein nitrogen were both very low, which together with the low phosphate content, indicates conditions which would at least greatly restrict the production of plankton. Chemical tests and bioassays also revealed combinations of electrolytes unfavorable to the growth of plankton.

Actually the plankton production in the waters of Elephant Butte Reservoir was found to be low throughout the present studies of this impoundment, confirming the previous observations of Hazzard (1935) who reported the plankton as "slightly below average" (p. 8), and of Greenbank (1937) who states that "the plankton is rather small in amount as compared with that of many bodies of water and the fish food is diminished thereby" (p. 97).

The other main source of basic food for fishes in Elephant Butte Reservoir is the bottom mud, since this reservoir supports almost no vegetation. The bottom mud in the lower lake, as noted under the discussions of hydrogen-ion concentration and turbidity, carries relatively little organic matter and for a considerable portion of the summer is covered by a layer of water which is low in dissolved oxygen. As a result of this combination of conditions at the bottom, the bottom fauna in the reservoir was found to be very sparse. Besides, due to the large silt load carried by the waters entering the reservoir at irregular intervals, both following heavy storms and during silt flows, conditions on the bottom are too unstable in many parts of the reservoir to support a good bottom fauna even were ample food for these animals available.

Most of the organic detritus introduced into the lower lake comes from the upper lake, and the lower lake is very largely dependent upon these fresh supplies of organic matter for its basic food constituents, since the reuse from year to year of the organic matter, which is possible in many natural lakes, is greatly limited in Elephant Butte Reservoir by the constant draw-off which removes a large volume of water from the lower levels each year. Consequently the lower lake is subject to irregular variations in fish food supply as the result of fluctuations in the amount of organic matter brought into the lower lake from the upper portions of the upper lake and from the sloughs near San Marcial. These fluctuations in food supply in part explain the good years which the fishermen report now and then for the lower lake.

With the invertebrate food supply definitely limited by existing physical and chemical conditions, the productivity as regards fish will of course be restricted as long as these conditions obtain. As Elephant Butte Reservoir has had over 15 years for adjustment there will probably be little change in the present balance of physical and chemical factors unless man makes some radical change in the operation of this reservoir, or in the waters received from the Rio Grande.

From the physical and chemical data presented for Elephant Butte Reservoir several deductions can be made which have bearing on the expected biological productivity of impounded waters. In evaluating the effects of the physical and chemical characteristics of these waters on biological productivity the impoundments of the United States can be grouped rather readily into two classes, the shallow and the deep, although this classification is to some extent difficult of definition. In general the shallow reservoirs and river-lakes have a maximal depth of 30 to 50 feet and in these shallow impoundments the river or inflow currents are usually sufficient to keep the waters rather completely mixed, even in the summer months. The waters of such shallow reservoirs, or so-called lakes, are usually without stratification of any sort and differ little from the inflow water if the inflow volume be reasonably large. Shallow impoundments are, however, particularly subject to the catastrophies of stream pollution, and, if the inflow volume is inadequate, to stagnation during the summer months.

Deep reservoirs, those in which there is a considerable mass of water approaching or exceeding 80 feet in depth, may be divided into two subclasses; namely, those with the draw-off at the bottom of the basin and those with the draw-off well above the floor. This single feature of construction is responsible for marked differences between conditions in the adclaustral portions of impoundments of these two subclasses. Both types of deep impoundments may develop a rather well-defined thermal stratification in the summer season, with the attendant variations in the distribution of dissolved oxygen, electrolytes, and silt as described for Elephant Butte Reservoir. However, in those impoundments having a draw-off at the bottom the disturbances in the epilimnial layer, due to the piling up of water at the dam and the flow currents moving down the reservoir, are projected to the bottom of the basin; while in those impoundments from which the outflow leaves at a level well above the bottom there is a mass of water below the draw-off level which remains almost undisturbed during the summer season.

After the main features of the physical and chemical conditions in impoundments have been ascertained, the factors of submerged barriers, silt flows, and even the electrolyte complexes must be determined before the biological productivity of the reservoir can be predicted with any degree of finality. However, since impounded waters differ so definitely from natural lakes in several particulars, as has been pointed out in this discussion of Elephant Butte Reservoir, not only should the principal physical and chemical features be determined but the distribution of density currents, detached masses of water, and flow trends should also be ascertained before extensive programs of fish planting and stocking are attempted.

LITERATURE CITED

American Public Health Association. 1936. Standard methods for the examination of water and sewage. Ed. 8. New York.

Birge, E. A. and C. Juday. 1911. The inland lakes of Wisconsin. The dissolved gasses of the water and their biological significance. Bull. Wis. Geol. and Nat. Hist. Surv., No. 22. Madison, Wis.

Denigès, G. 1920. Réaction de coloration extrêmement sensible des phosphates et des arséniates. Ses applications. Comptes Rendus de l'académie des sciences. Tome 171, pp. 802–804. Paris.

Domogalla, B. P., C. Juday and W. H. Peterson. 1925. The forms of nitrogen found in certain lake waters. Jour. Biol. Chem., vol. 63, pp. 269–285. Baltimore, Md.

Dupray, M. 1923. A modification of Isaacs' colorimetric determination of blood chlorides. Jour. Biol. Chem., vol. 58, pp. 675–679. Baltimore, Md.

Ellis, M. M. 1936a. Erosion silt as a factor in aquatic environments. Ecology, vol. 17, pp. 29–42. Lancaster, Pa.

Ellis, M. M. 1936b. Some fishery problems in impounded waters. Trans. Amer. Fish. Soc., vol. 66, pp. 63–71. Hartford, Conn.

Ellis, M. M. 1937. Detection and measurement of stream pollution. Bull. No. 22, U. S. Bureau of Fisheries, vol. 48, pp. 365–437. Washington.

Elvove, E. 1933. Estimation of fluorides in waters. U. S. Public Health Repts., vol. 48, No. 40, 1219–1222. Washington.

Greenbank, J. 1937. A chemical and biological study of the waters of Elephant Butte Reservoir as related to fish culture. Manuscript thesis, University of New Mexico. Albuquerque, N. Mex.

Hazzard, A. S. 1935. A preliminary fisheries survey of Elephant Butte Lake, N. Mex. Manuscript report to U. S. Commissioner of Fisheries. Washington.

Isaacs, M. L. 1922. A colorimetric determination of blood chlorides. Jour. Biol. Chem., vol. 53, pp. 17–19. Baltimore, Md.

JUDAY, C., E. A. BIRGE, G. I. KEMMERER and R. J. Robinson. 1927. Phosphorus content of lake waters of northeastern Wisconsin. Trans. Wis. Acad. of Sciences, Arts, and Letters, vol. 23, pp. 233–248. Madison, Wis.

KINDLE, E. M. 1927. The role of thermal stratification in lacustrine sedimentation. Trans. Roy. Soc. of Canada, Sec. IV, vol. 21, pp. 1–36. Ottawa.

PEARSALL, W. H. 1930. Phytoplankton in the English lakes. I. The proportions in the waters of some dissolved substances of biological importance. Jour. Ecol., vol. 18, pp. 306–320. London.

WHIPPLE, G. C. 1927. The microscopy of drinking water. Ed. 4. John Wiley and Sons. New York.

WIEBE, A. H. 1938. Limnological observations on Norris Reservoir, with special reference to dissolved oxygen and temperatures. Trans. 3d N. Amer. Wildlife Conf., Amer. Wildlife Inst., pp. 440–457. Washington.

WIEBE, A. H. 1939. Dissolved oxygen profiles at Norris Dam and in the Big Creek sector of Norris Reservoir (1937), with a note on the oxygen demand of the water (1938). Ohio Jour. Sci., vol. 39, pp. 27–36. Columbus, Ohio.

⁂