Dissolved-Oxygen Depletion and Other Effects of Storing Water in Flaming Gorge Reservoir, Wyoming and Utah

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By E. L. BOLKE

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DISSOLVED-OXYGEN DEPLETION AND OTHER EFFECTS OF STORING WATER IN FLAMING GORGE RESERVOIR, WYOMING AND UTAH

By E. L. Bolke

ABSTRACT

The circulation of water in Flaming Gorge Reservoir is caused chiefly by insolation, inflow-outflow relationships, and wind, which is significant due to the geographical location of the reservoir. During 1970–75, there was little annual variation in the thickness, dissolved oxygen, and specific conductance of the hypolimnion near Flaming Gorge Dam. Depletion of dissolved oxygen occurred simultaneously in the bottom waters of both tributary arms in the upstream part of the reservoir and was due to reservoir stratification. Anaerobic conditions in the bottom water during summer stratification eventually results in a metalimnetic oxygen minimum in the reservoir.

The depletion of flow in the river below Flaming Gorge Dam due to evaporation and bank storage in the reservoir for the 1963–75 period was 1,320 cubic hectometers, and the increase of dissolved-solids load in the river was 1,947,000 metric tons. The largest annual variations in dissolved-solids concentration in the river was about 600 milligrams per liter before closure of the dam and about 200 milligrams per liter after closure. The discharge weighted-average dissolved-solids concentration for the 5 years prior to closure was 386 milligrams per liter and 512 milligrams per liter after closure. The most significant changes in the individual dissolved-ion loads in the river during 1973–75 were the increase in sulfate (0.46 million metric tons), which was probably derived from the solution of gypsum, and the decrease in bicarbonate (0.39 million metric tons), which can be attributed to chemical precipitation.

The maximum range in temperature in the Green River below the reservoir prior to closure of the dam in 1962 was from 0°C in winter to 21°C in summer. After closure until 1970 the temperature ranged from 2° to 12°C, but since 1970 the range has been from 4° to 9°C.

During September 1975, a massive algal bloom was observed in the upstream part of the reservoir. The bloom covered approximately 16 kilometers of the lower part of the Blacks Fork arm, 23 kilometers of the lower part of the Green River arm, and 15 kilometers of the main reservoir below the confluence of the two arms. By October 1975 the algal bloom had disappeared. Nutrient loading in the reservoir was not sufficient to maintain a rate of algal production that would be disastrous to the reservoir ecosystem. However, should the nutrient loading increase substantially, the quality of the reservoir water could probably deteriorate rapidly, and its use for recreation and water supply could be severely limited.

INTRODUCTION

Flaming Gorge Reservoir is on the Green River, a tributary to the Colorado River, in northeastern Utah and southwestern Wyoming (fig. 1). The water in the reservoir, at maximum storage, extends about 145 km upstream from the dam. Maximum storage is about 4,674 hm^3 at a pool level of 1,841 meters above mean sea level. Dead storage is about 49 hm^3 at a pool level of 1,750 meters. The deepest point in the reservoir, which is near the dam, is about 133 meters below maximum pool altitude. Construction of the dam began in 1959, and storage in the reservoir began in November 1962.

Flaming Gorge Reservoir is an important part of the Colorado River Storage Project, which is a long-range basinwide program of the U.S. Bureau of Reclamation to develop the water resources of the upper Colorado River system. The reservoir regulates the flow of the Green River, thereby storing water to meet downstream commitments, providing flood control and recreational facilities, and allowing for production of electric power.

The U.S. Geological Survey participates in studies of the quality of water of the Colorado River Basin, which are reported biennially to Congress by the Department of the Interior. Madison and Waddell (1973) evaluated the chemical quality of surface water in the Flaming Gorge Reservoir area for the period prior to 1969.[1] That report indicated that the increase in dissolved-solids concentration of the Green River below Flaming Gorge Dam was due chiefly to leaching of soluble minerals from the area inundated by the reservoir. Bolke and Waddell (1975), in addition to continued evaluation of the leaching rate in the reservoir and the effect on the downstream water quality, described some of the elements of the limnological cycle in the reservoir and evaluated the occurrence of anaerobic conditions in the reservoir. They also discussed the variations of streamflow, dissolved-solids concentrations, and dissolved-solids load of the major tributaries to the reservoir. Their findings indicated that the major tributaries, Green River, Blacks Fork, and Henrys Fork (fig. 1), contribute about 97 percent of the total streamflow and about 82 percent of the total load of dissolved solids. The principal constituents in the tributary streamflow are calcium and sulfate during periods of lowest flow and calcium and bicarbonate during periods of highest flow.

Based on these studies and as part of the continuing program of participation by the Geological Survey in the assessment of water

[1]Water years are used throughout this report. A water year is the 12-month period from October 1 through September 30, and it is designated by the calendar year in which it ends.

quality in the Colorado River Basin, a more detailed study, the subject of this report, was undertaken during the period July 1973-September 1977 with the following principal objectives: (1) delineate the extent and frequency of occurrence of oxygen depletion in the

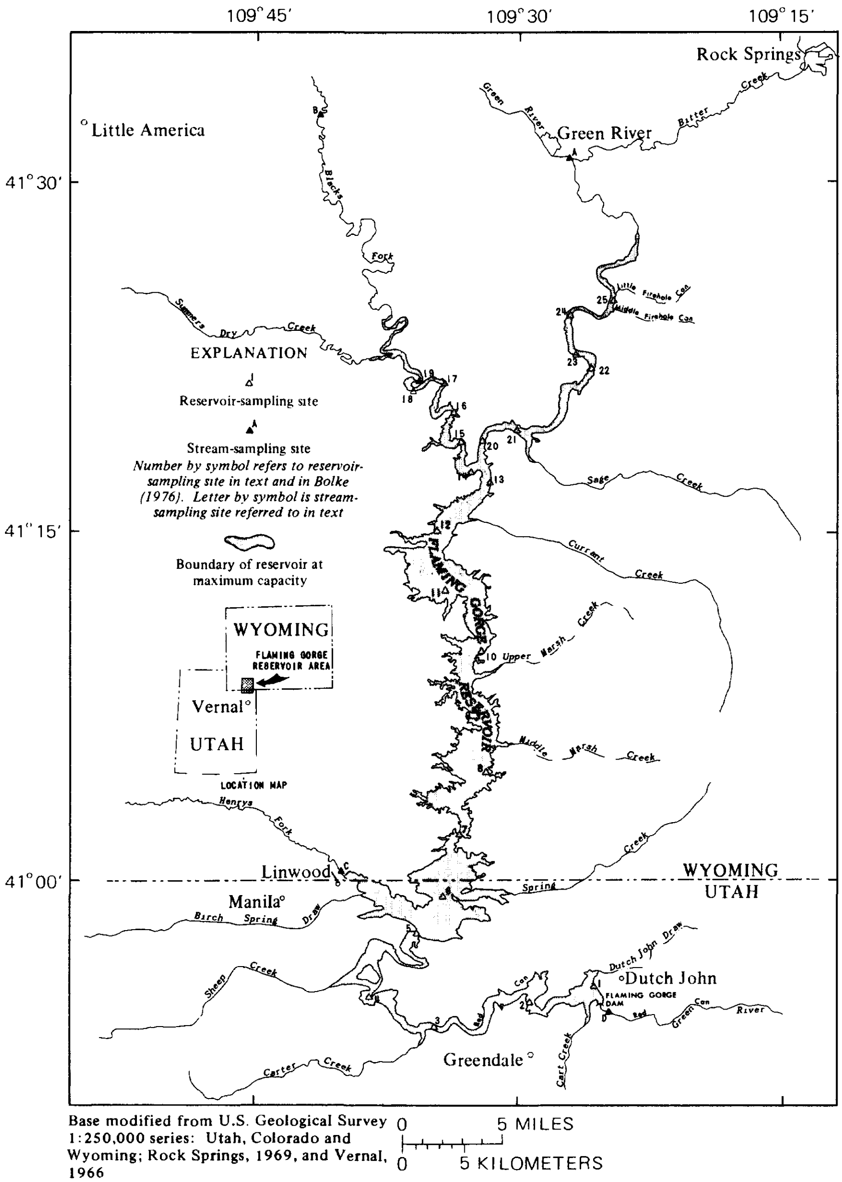


FIGURE 1.—Map showing Flaming Gorge Reservoir and data-collection sites.

reservoir; (2) describe processes that control circulation in the reservoir; (3) evaluate downstream effects of storing water in the reservoir; and (4) evaluate potential effects of upstream development with regard to increased salinity. The data collected and the study methods used are reported by Bolke (1976).

The cooperation and assistance of personnel of the U.S. Bureau of Reclamation who provided records of storage and area-capacity data are gratefully acknowledged.

Values given in this report are in metric units. Divide metric units by the conversion factors given below to obtain their English equivalents.

Metric		*Conversion factor*	*English*	
Unit	*Abbreviation*		*Unit*	*Abbreviation*
Cubic hectometer	hm^3	0.0012334	Acre-foot	acre-ft
Meter	m	.3048	Foot	ft
Kilometer	km	1.6093	Mile	mi
Metric ton	t	.90718	Ton (short)	ton

Chemical concentration is given in milligrams per liter (mg/L). Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation: $°F=1.8(°C)+32$.

CIRCULATION PROCESSES IN THE RESERVOIR

Circulation of water in reservoirs is due mainly to temperature differences caused either by heating or cooling of the water mass or by wind-induced turbulence. Heating or cooling is due chiefly to insolation, back radiation, evaporation, and advection of water to and from the reservoir. The integrated effect of these processes is shown by monthly temperature-depth profiles in figure 2. The profiles were taken at site 13, which is near the confluence of the Green River and Blacks Fork (fig. 1). During 1975, data were available only for ice-free months. However, data for 1971 for part of the winter period were obtained from the Utah Division of Wildlife Resources, and these data are shown together with 1975 data in figure 2. Although the reservoir level was lower in January and February of 1971 than during 1975, the profiles for these months are assumed to show typical winter conditions.

HEATING AND THERMAL STRATIFICATION

During the winter, Flaming Gorge Reservoir is ice covered and is weakly stratified. (See fig. 2.) In the spring, the water in the reservoir, primarily by insolation, is isothermal, thus allowing free circulation from top to bottom. The profile for May 1975 shows the first significant change due to heating. At temperatures above 4°C, water decreases in density with increasing temperature. The inflow water in spring is warmer and thus less dense than the water in the reservoir; therefore, the inflow water flows over the colder water in the reservoir (fig. 3). This heat input, combined with insolation, is the beginning of summer stratification.

Stratification results in the formation of three distinct zones in the reservoir which are delineated by temperature differences. The water in the uppermost zone, the epilimnion, is generally isothermal, warmer than the underlying water, and circulates freely within the zone. From the beginning of the heating season until the time when the profile was taken in May, the epilimnion formed to about 9 meters in depth (fig. 2). The middle zone, or metalimnion, is the zone with the greatest temperature gradient, and it effectively separates the uppermost and lowermost zones. In May 1975 the metalimnion was about 3 meters thick. The lower zone, or hypolimnion, is generally isothermal like the epilimnion, but it does not mix with overlying water except by the process of diffusion or by wind-induced turbulence.

The temperature profile for June would normally show a transition between the May and July profiles, but because Flaming Gorge Reservoir is in an area that receives periodic violent windstorms, the profile for June 1975 is somewhat atypical. Wind-induced turbulence causes abnormally rapid mixing of the reservoir water, and the amount of mixing increases with the intensity of the wind and decreases with increasing reservoir stratification. Turbulent wind action destroyed the thermocline that had formed in May. Thus, the temperature profile taken on June 24 (fig. 4) shows that the reservoir was only weakly stratified, thus allowing for easier mixing.

Between June 24 and June 26, the reservoir was subjected to strong winds for about 24 hours, with gusts in excess of 80 km/h. The mixing that resulted from wind action extended to the entire depth of the reservoir, which was 26 meters at site 13 (fig. 4). The conditions at site 13 are assumed to be typical for the upstream part of the reservoir. The temperature difference between the top and bottom waters changed from 6°C before the storm to 2.8°C after the storm.

The July temperature profile represents the greatest seasonal difference in temperature between the epilimnion and hypolimnion (maximum thermal stratification). The profile also shows the epilimnion to be about 8 meters thick, a strongly developed metalimnion of about 7 meters, and a hypolimnion of approximately 12 meters. The greatest rate of change in temperature in the metalimnion was about 2°C/m. The thermal stratification helped contribute to a deterioration of water quality in the hypolimnion, particularly with respect to dissolved oxygen, by preventing circulation with overlying water.

COOLING AND DESTRATIFICATION

After the period of maximum heating, the water in the reservoir gradually cools. The process begins in the epilimnion where cooling

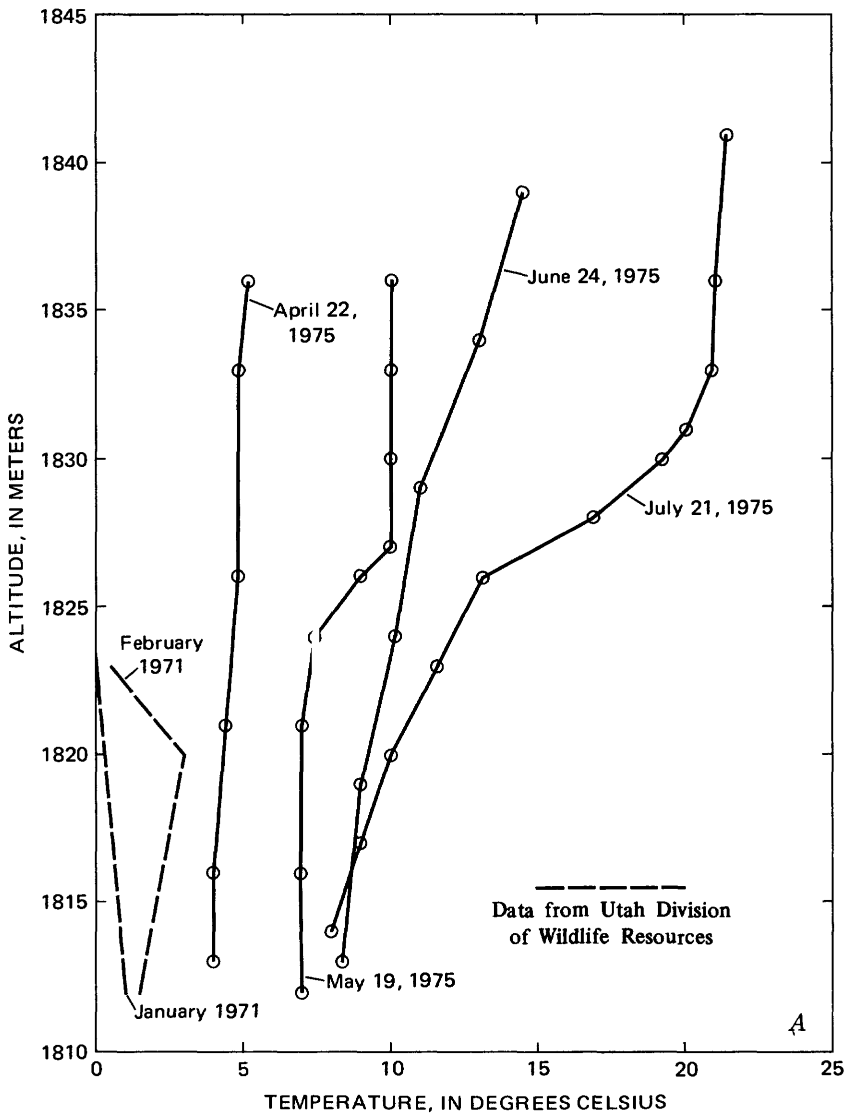
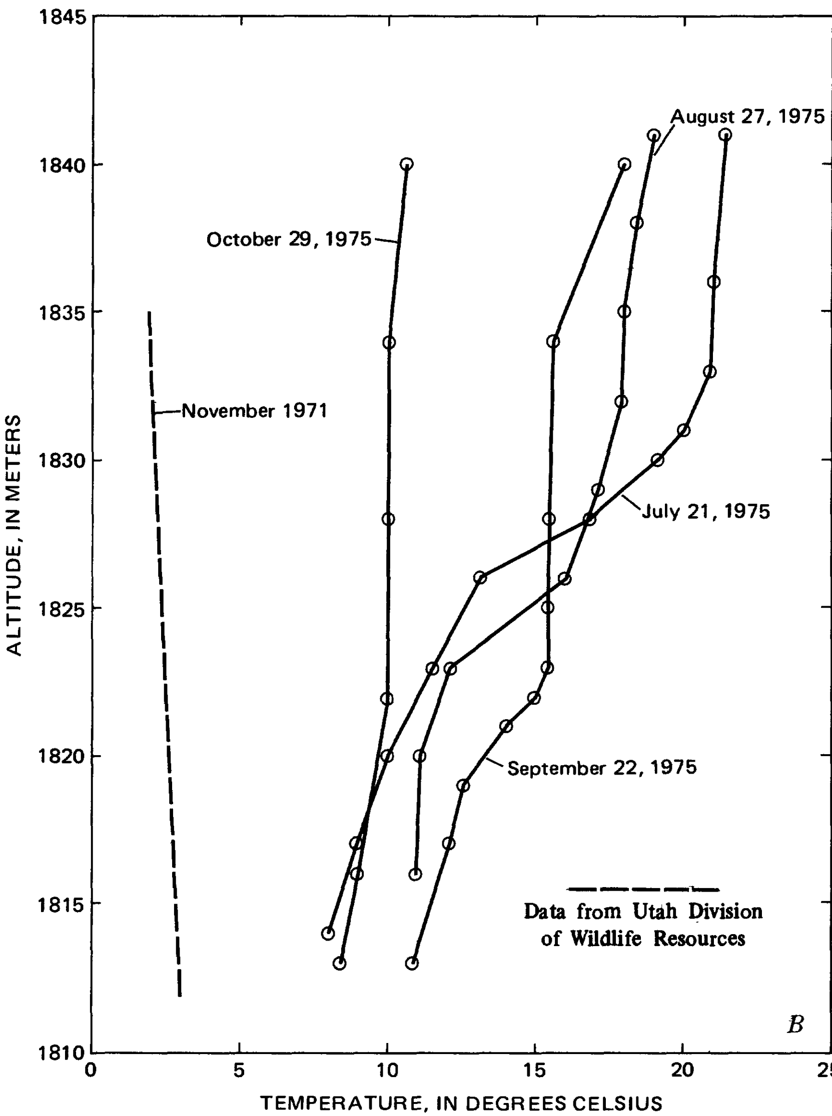


FIGURE 2.—Monthly temperature profiles at site 13.

of the surface water causes it to increase in density, whereupon it displaces the warmer water below, thereby causing circulation. The temperature gradient in the metalimnion is gradually weakened by this mixing action, and warm water is exchanged with cool hypolimnetic water, thereby warming the hypolimnion and cooling the epilimnion (fig. 2). In July 1975, the thickness of the actively



A, Reservoir heating period. *B*, Reservoir cooling period.

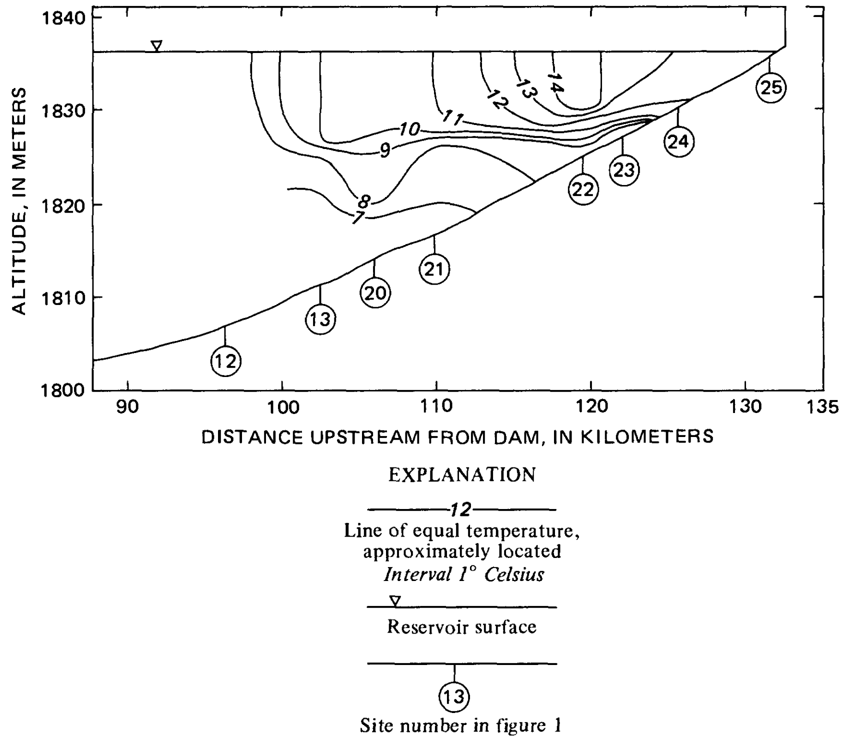


FIGURE 3.—Longitudinal temperature profile of the upstream part of Flaming Gorge Reservoir, May 1975.

mixing zone or epilimnion was about 8 meters, in August the thickness increased to about 15 meters, and in October to about 27 meters—the total depth of the reservoir at site 13.

After the profile for October 1975 was determined, continued cooling caused the temperature gradient to reverse; the colder water was above the warmer water. The November 1971 profile, although not in chronological order, shows this effect, which results from the density of water decreasing as the water temperature falls below 4°C.

The movement of cold water into the reservoir during late fall causes additional cooling. The cold water, being denser than the water in the reservoir, flows below the warmer reservoir water (fig. 5) until the temperature of the inflow is below 4°C. It then enters the reservoir as either interflow or overflow, depending upon the rela-

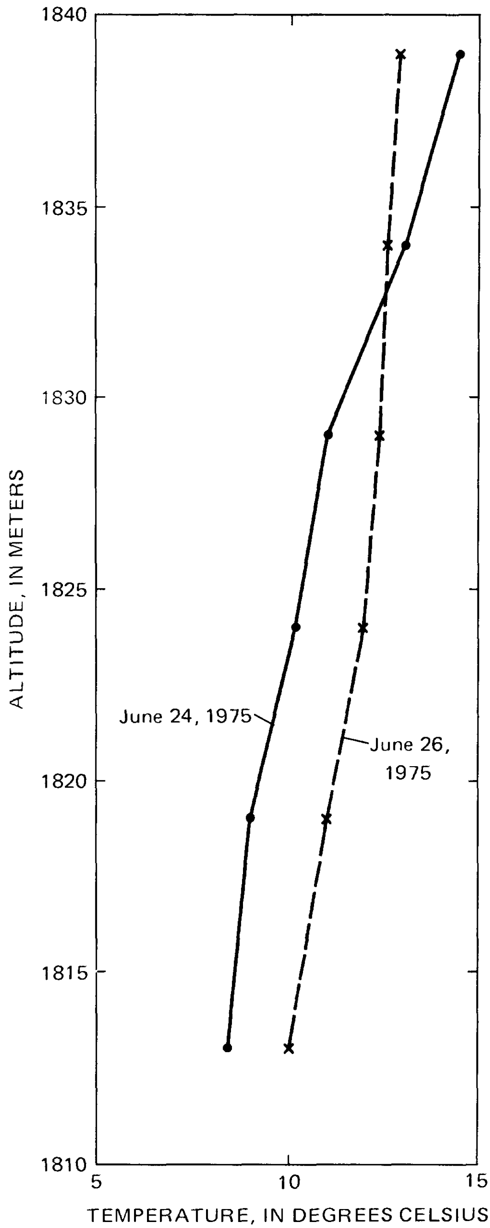


FIGURE 4.—Temperature change due to wind effect at site 13.

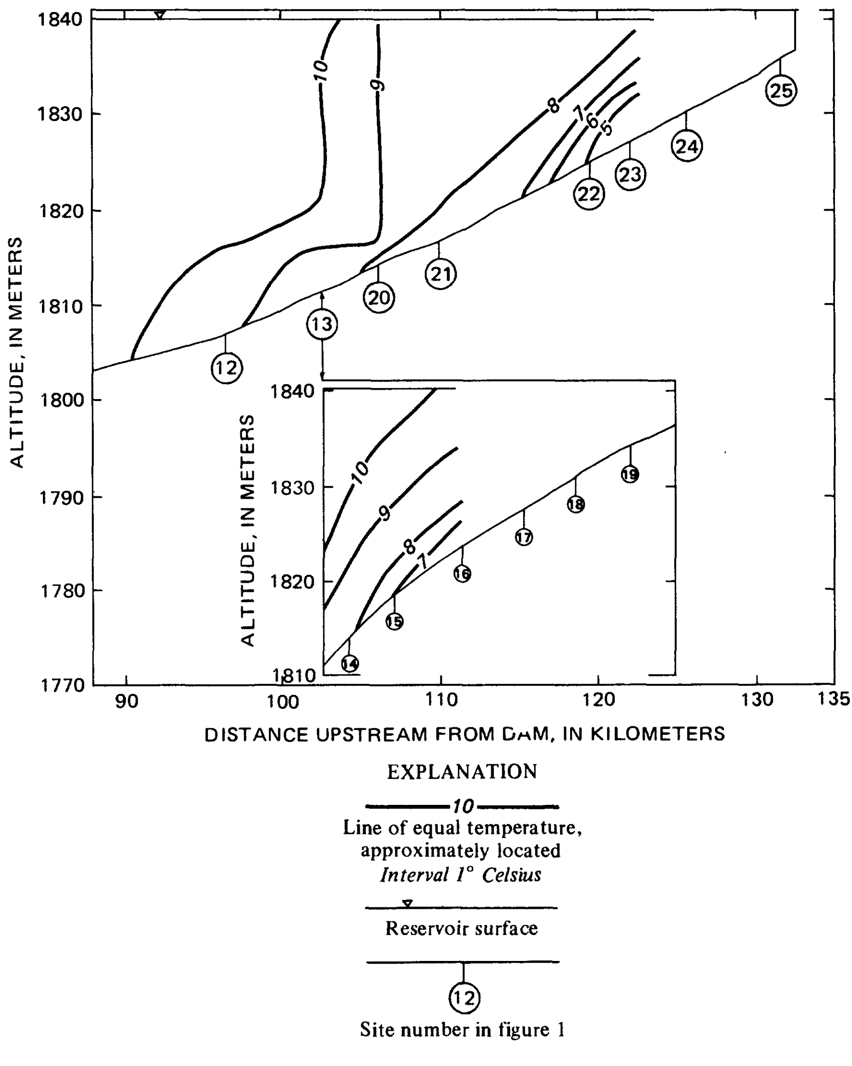


FIGURE 5.—Longitudinal temperature profile of the upstream part of Flaming Gorge Reservoir, October 1975.

tive densities of inflow and reservoir water. When overflow occurs, continued cooling causes ice formation on the reservoir.

In summary, the water in Flaming Gorge Reservoir circulates from top to bottom during both the spring and fall (dimictic), except in the deepest part of the reservoir near the dam where the water apparently does not circulate. Between these circulation periods, the reservoir is thermally stratified. The maximum stratification is in the summer; whereas the reservoir is only weakly stratified during the winter. Circulation is caused chiefly by insolation and inflow-outflow relationships, but wind has a significant effect in the circulation process.

DEPLETION OF DISSOLVED OXYGEN IN THE RESERVOIR

Oxygen dissolved in water is derived chiefly from air in contact with water, but it also is a byproduct by photosynthesis by aquatic plants. The concentration of dissolved oxygen at saturation is inversely proportional to temperature and altitude, and so cold-water, low-altitude reservoirs generally contain more oxygen than high-altitude, warm-water reservoirs. The amount of oxygen in water is also dependent upon the depletion of oxygen by bacterial decomposition of organic matter.

Previous studies by Bolke and Waddell (1975) showed that in the deepest part of Flaming Gorge Reservoir, which is near the dam, there is a chemically stable zone where the dissolved-oxygen content is nil. They indicated that water in this zone most probably does not mix with overlying water except by diffusion. Temperature profiles taken at site 1 during 1970–75 show little annual variation in the thickness of the hypolimnion, although a slight modification of the dissolved-oxygen concentration and specific conductance within the hypolimnion has occurred. (See fig. 6.) The top of the hypolimnion as determined from the temperature profiles varied from about 1,764 meters to about 1,770 meters during the 1970–75 period. During 1970–72 the dissolved-oxygen concentration was essentially nil in the hypolimnion, but during 1973–75 a slight increasing trend in dissolved-oxygen concentration to about 1 mg/L (milligram per liter) was measured. The specific conductance in the hypolimnion increased slightly during 1970–72 but decreased during 1973–75. The changes during 1973–75 may be due to dilution from currents flowing along the bottom of the reservoir.

Bolke and Waddell (1975) also pointed out that oxygen depletion occurs during the summer-stratification period in the upstream part of the reservoir and that an oxygen minimum occurs in the metalimnion during summer stratification. More detailed information has been collected in the upstream part of the reservoir since these earlier findings, and the following discussion concerns that part of the system.

CONDITIONS IN SPRING

Mixing of water in Flaming Gorge Reservoir occurs from top to bottom during the spring circulation period in most of the reservoir. At this time, the reservoir is isothermal and can be mixed easily by

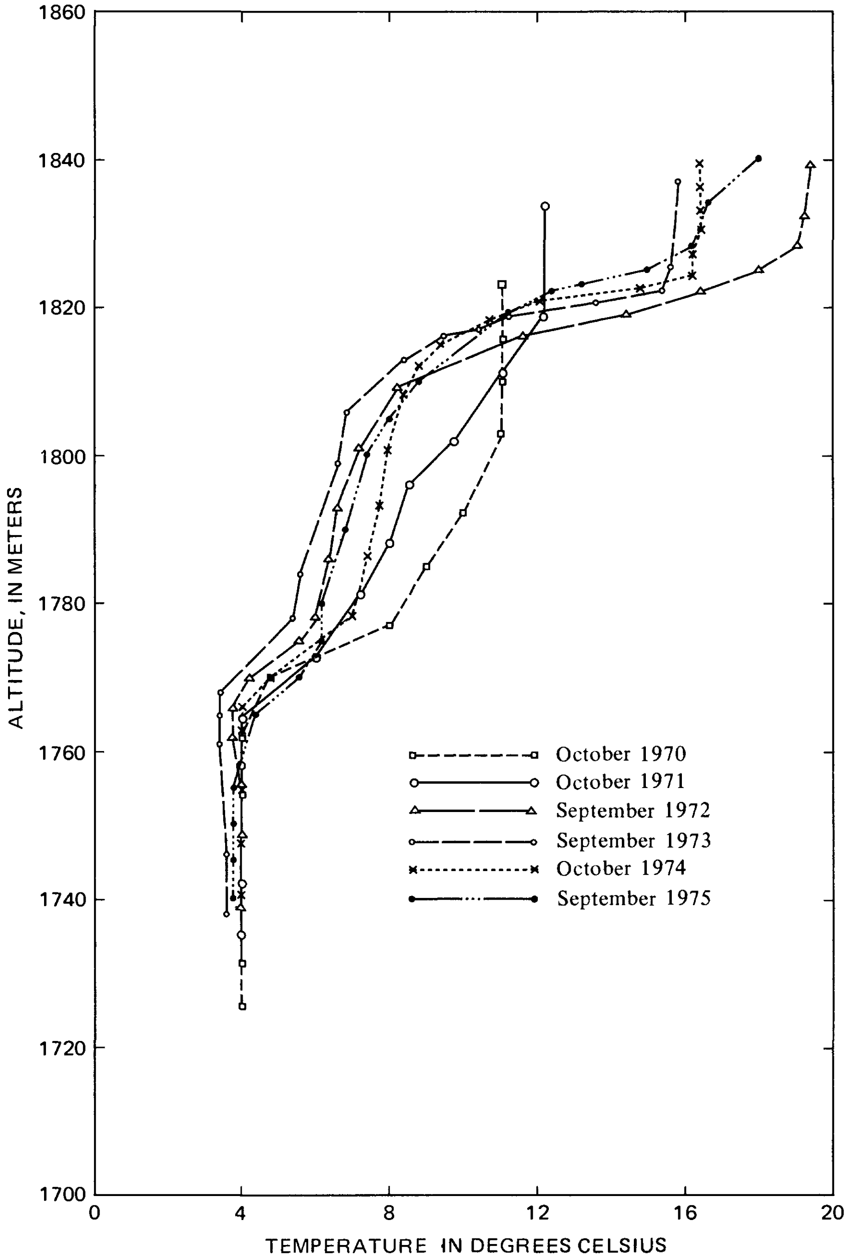
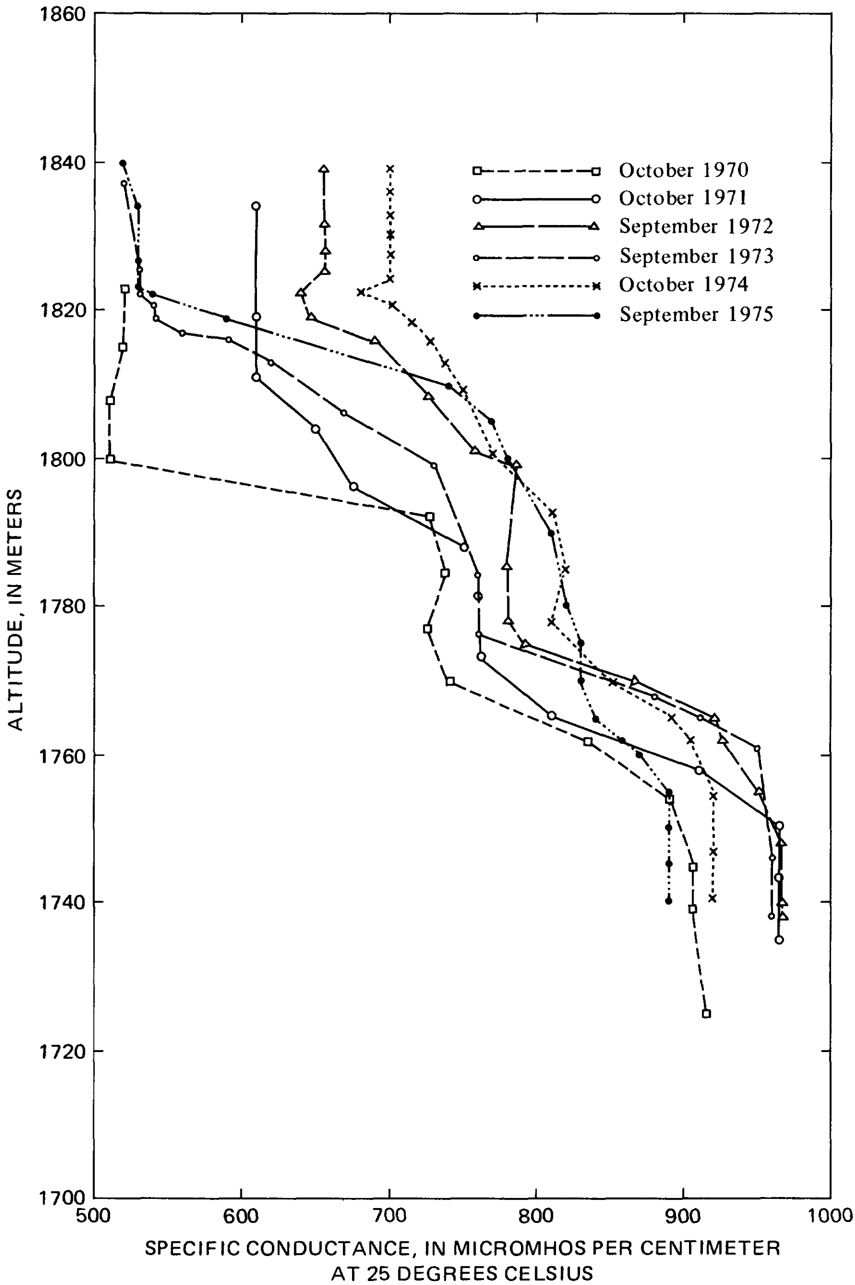


FIGURE 6.—Temperature, dissolved-oxygen concentration, and



specific-conductance profiles at site 1 in Flaming Gorge Reservoir.

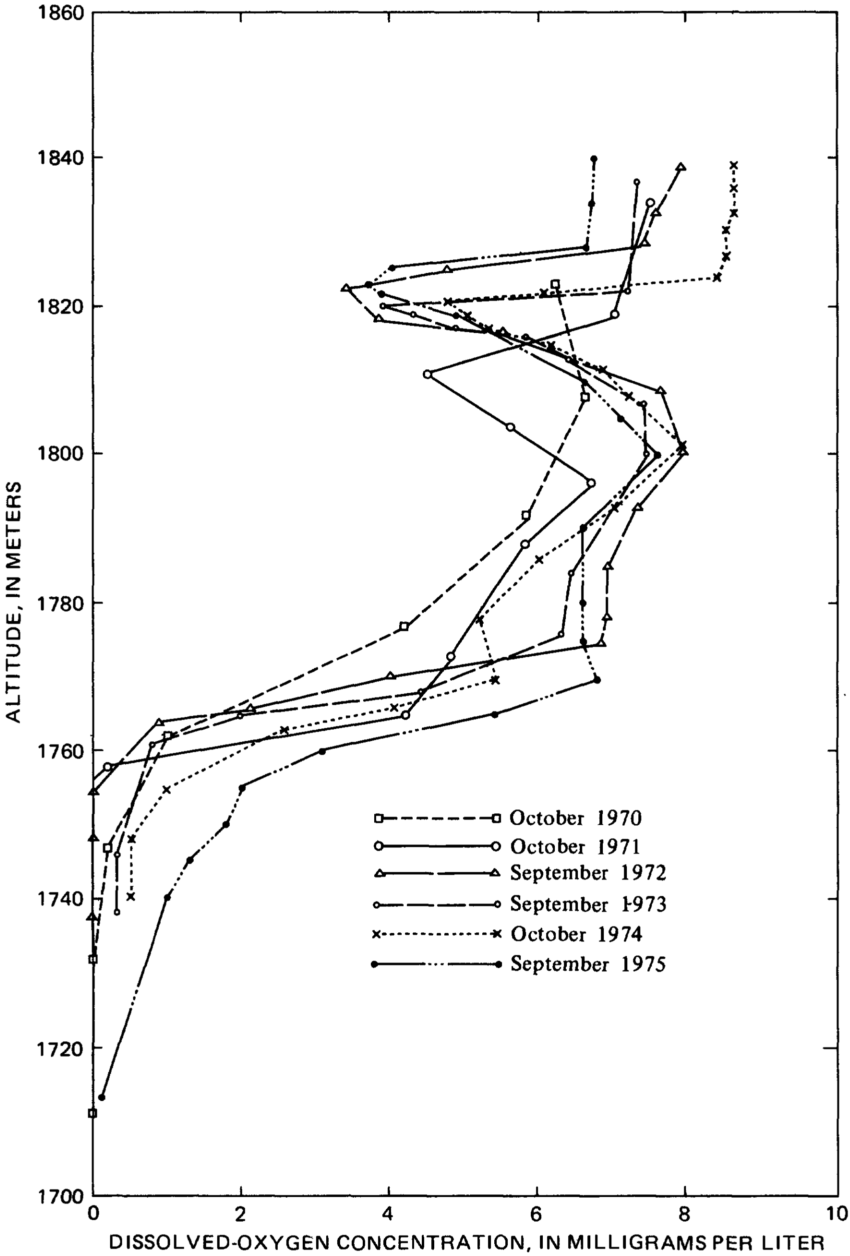


Figure 6.—Continued.

disturbances, such as by wind. Because of the mixing and because of the increased solubility of oxygen at low water temperatures (table 1), the reservoir is well oxygenated in the spring. Dissolved-oxygen concentration profiles for the central and upstream part of the reservoir are shown in figure 7. The temperature profile for April 1975 (fig. 2), which was the earliest seasonal data after icemelt that could be obtained during the study, shows that the reservoir was nearly isothermal at about 4°–5°C. The saturated dissolved-oxygen concentration in water for a water temperature of 4°–5°C is 10.5–10.2 mg/L (table 1). In April 1975 most of the reservoir, except the deeper part, was supersaturated with respect to dissolved-oxygen concentration (fig. 7). These concentrations were the highest observed in the reservoir for any period of the year.

Supersaturation generally implies photosynthetic activity in the euphotic zone, which in the upstream part of the reservoir in April 1975 was estimated to be about 5 meters deep. The estimate is based on Secchi-disk measurements for April 1975, which averaged about 1 meter (Bolke, 1976, table 3), and the assumption that the euphotic zone is five times the limit of vertical visibility of the water as determined from measurements. (See Verduin, 1956, fig. 1.) The depth to which supersaturation extended in April 1975, however, was about four to five times the depth of the euphotic zone. Thus, any increase in dissolved-oxygen concentration due to photosynthetic activity probably occurred further upstream in the area of inflow; the oxygen-enriched water was mixed perhaps by wind-induced turbulence, with the deeper reservoir water.

Later in spring as the reservoir warms, oxygen solubility in water decreases. The lower dissolved-oxygen concentration observed in

TABLE 1.—*Solubility of oxygen in water exposed to water-saturated air at a pressure of 609 millimeters*

[Adapted from American Public Health Association and others (1975, p. 446)]

Temperature (°C)	Dissolved oxygen (mg/L)	Temperature (°C)	Dissolved oxygen (mg/L)
4	10.5	15	8.1
5	10.2	16	8.0
6	10.0	17	7.7
7	9.8	18	7.6
8	9.5	19	7.5
9	9.3	20	7.3
10	9.0	21	7.2
11	8.9	22	7.0
12	8.6	23	6.9
13	8.5	24	6.8
14	8.3	25	6.7

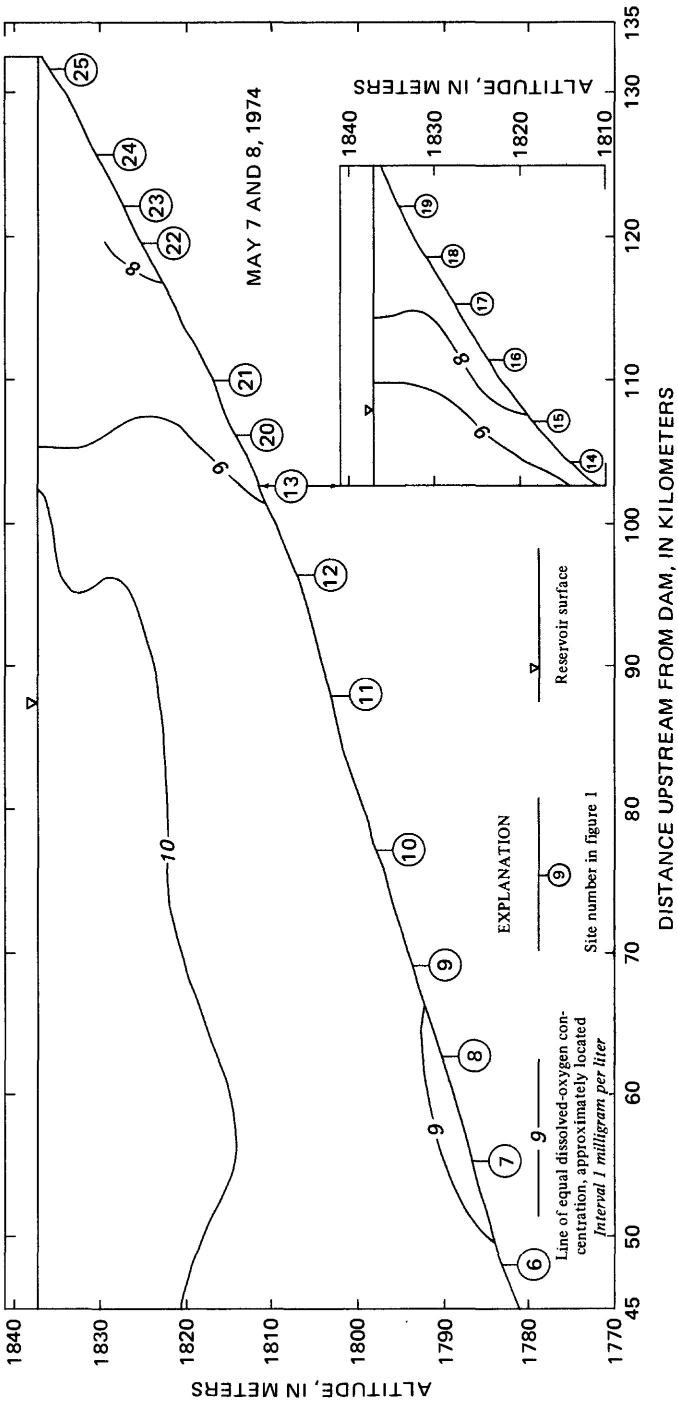


FIGURE 7.—Profiles of dissolved-oxygen concentration in Flaming Gorge Reservoir.

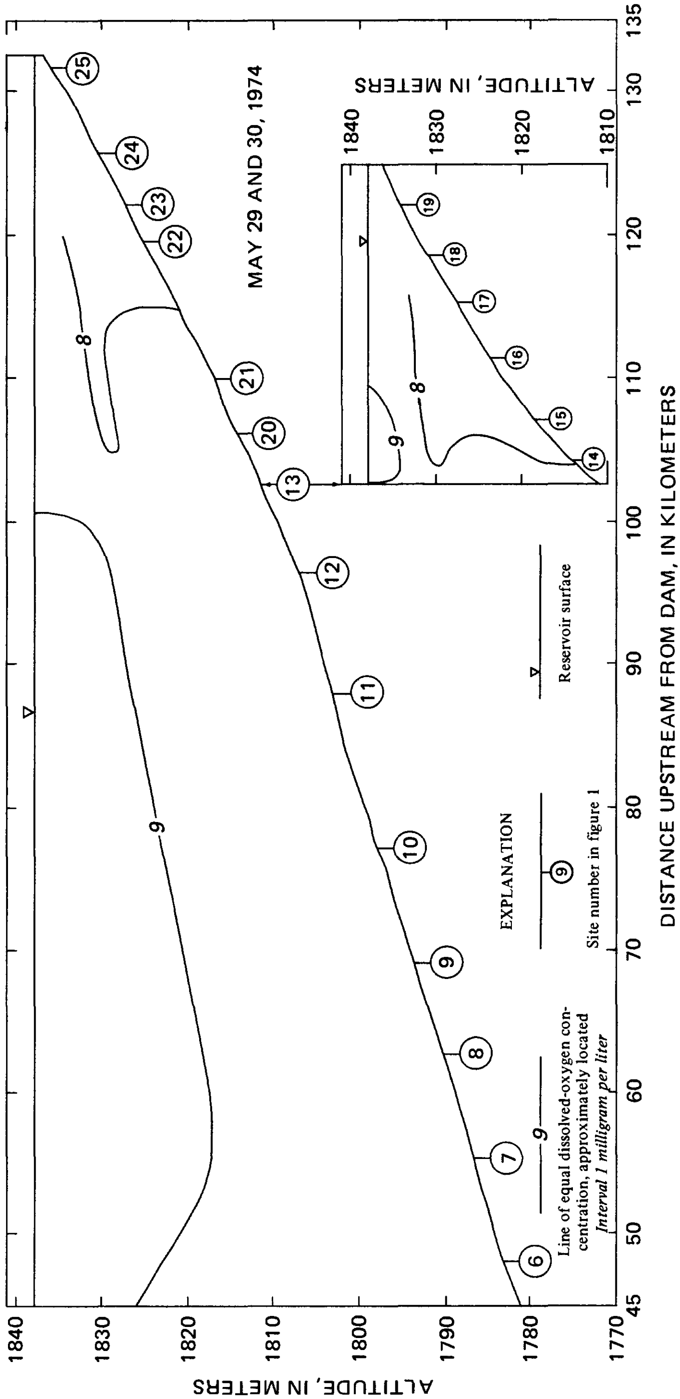


FIGURE 7.—Continued.

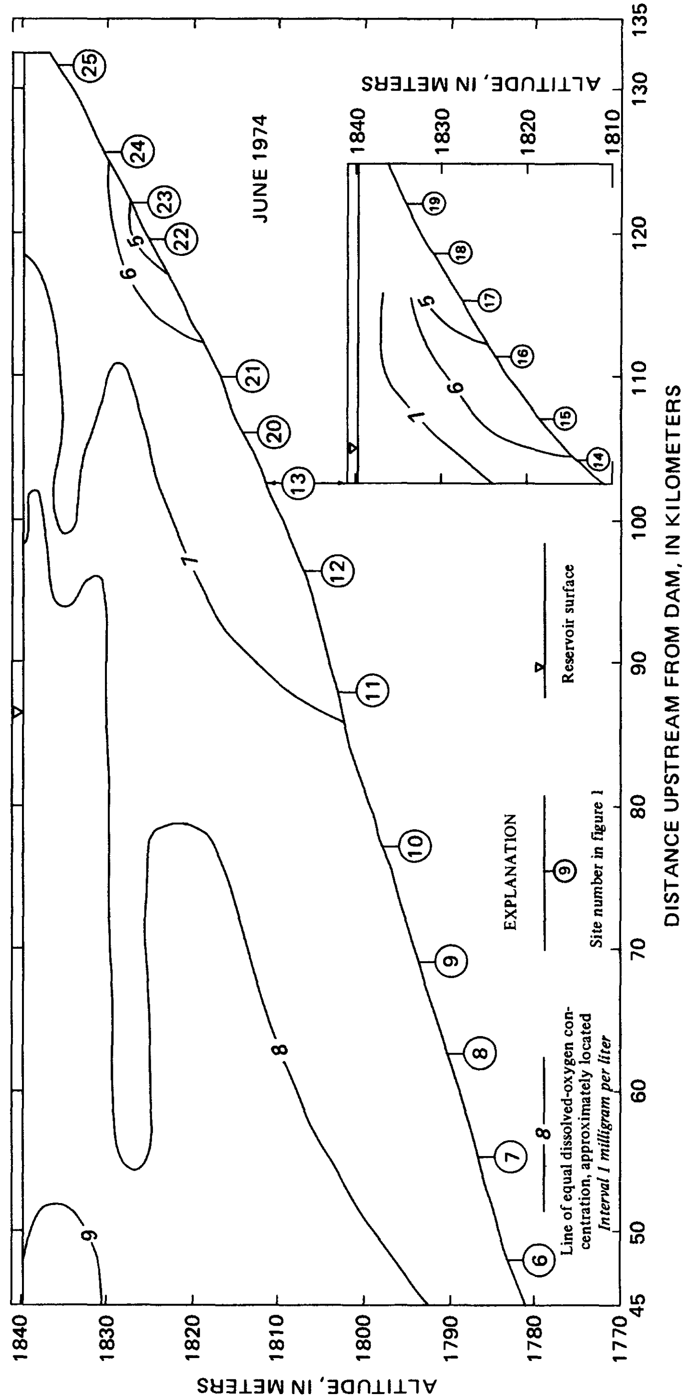
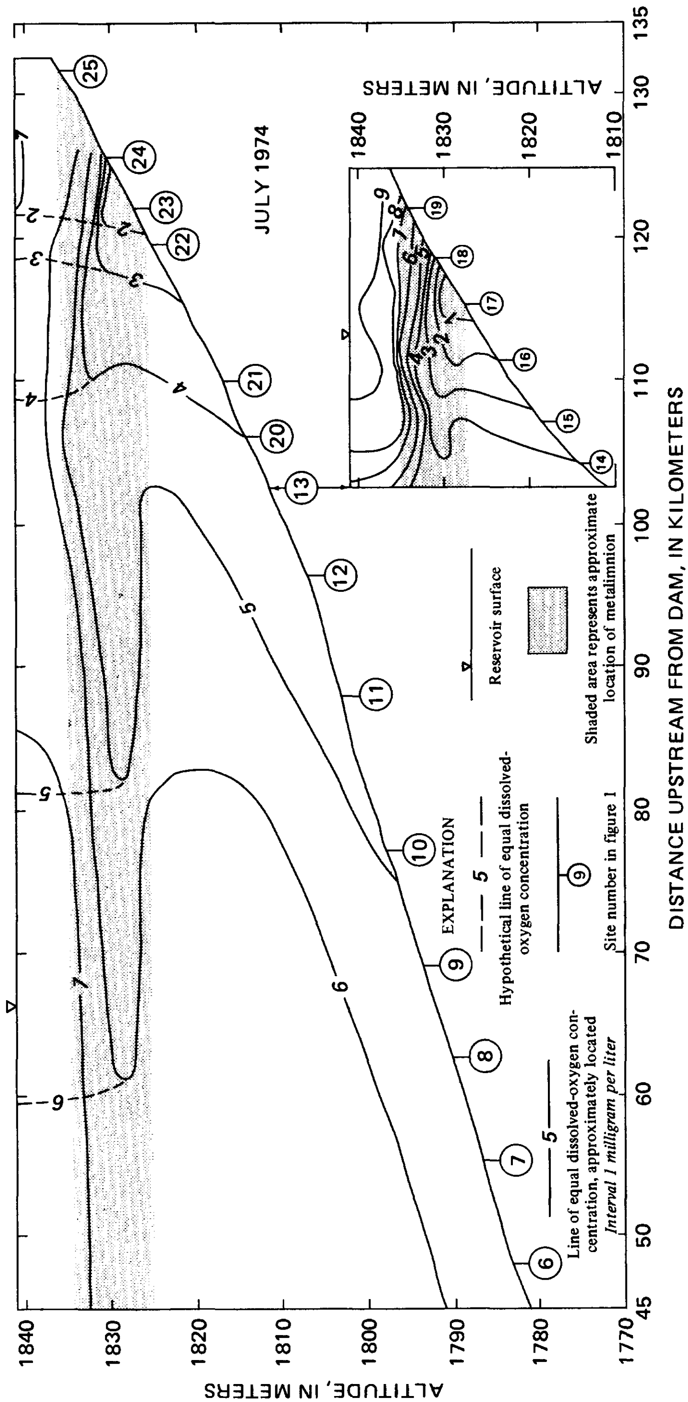


FIGURE 7.—Continued.



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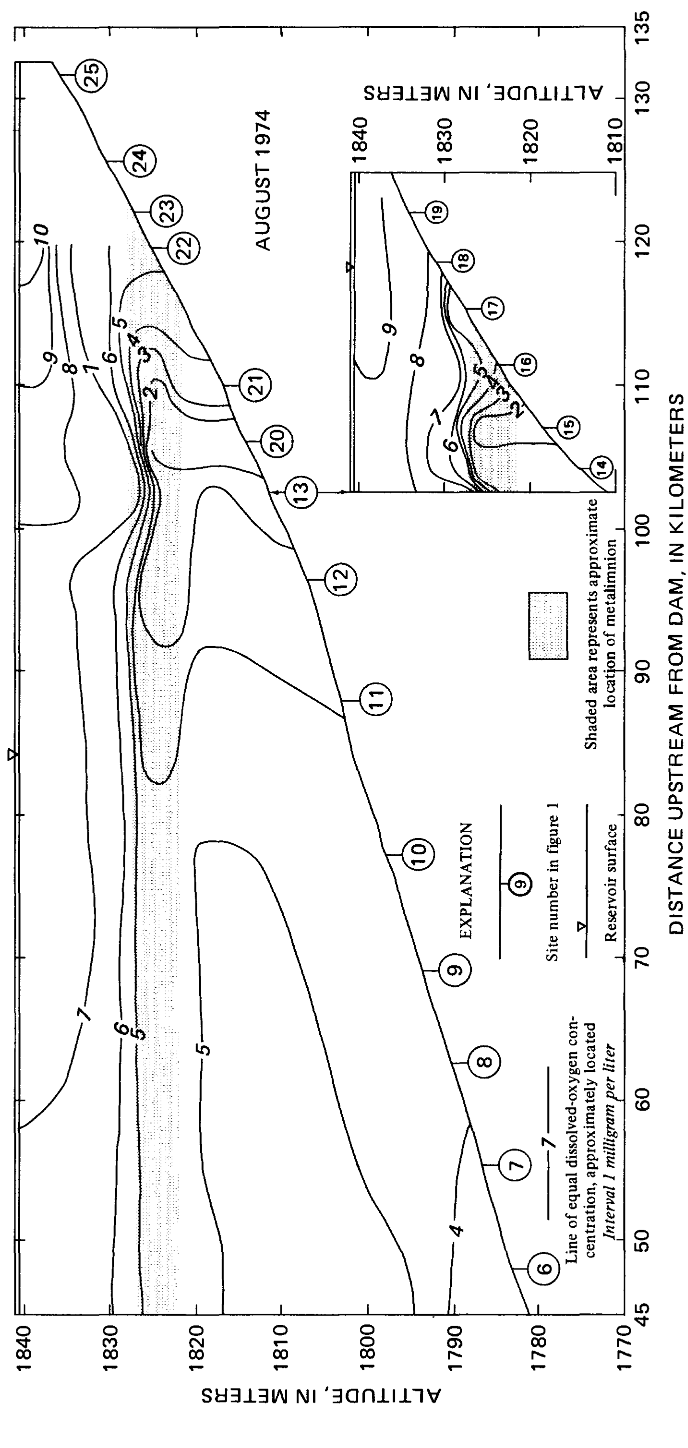

FIGURE 7.—Continued.

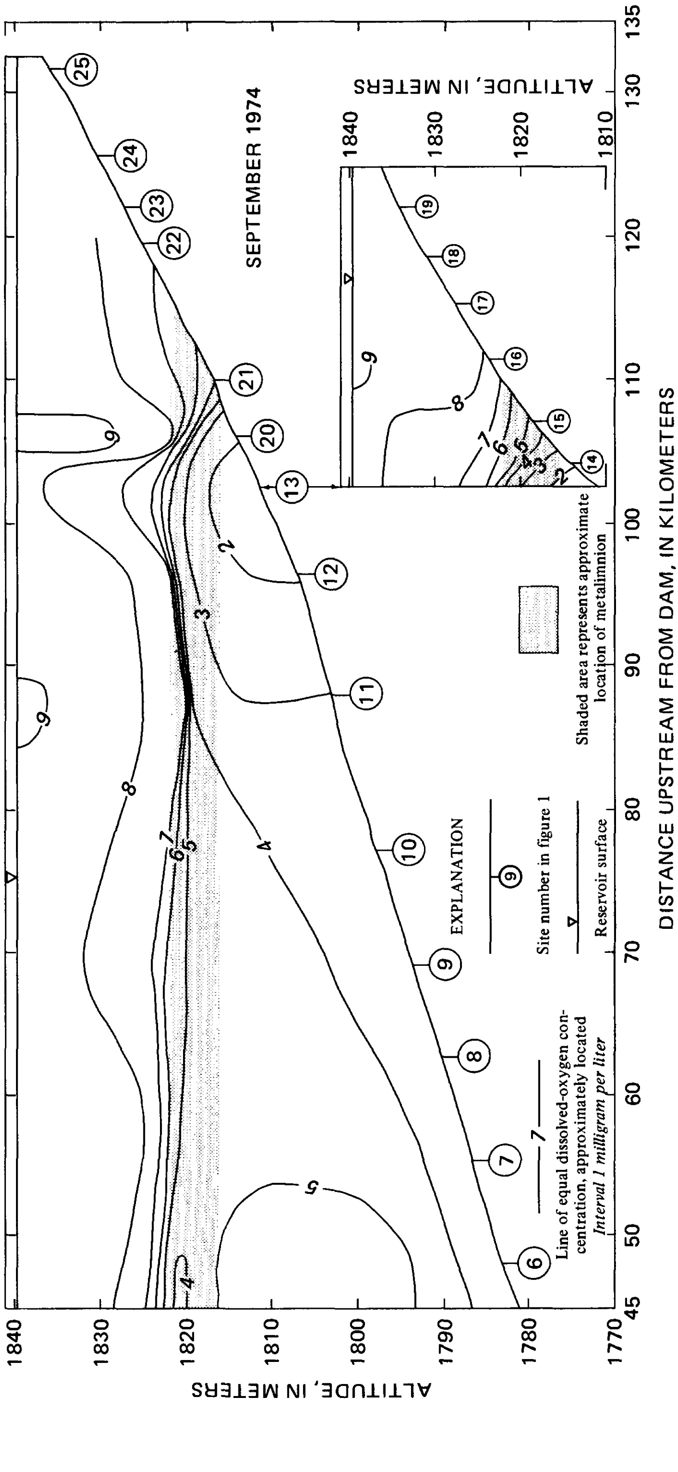

FIGURE 7.—Continued.

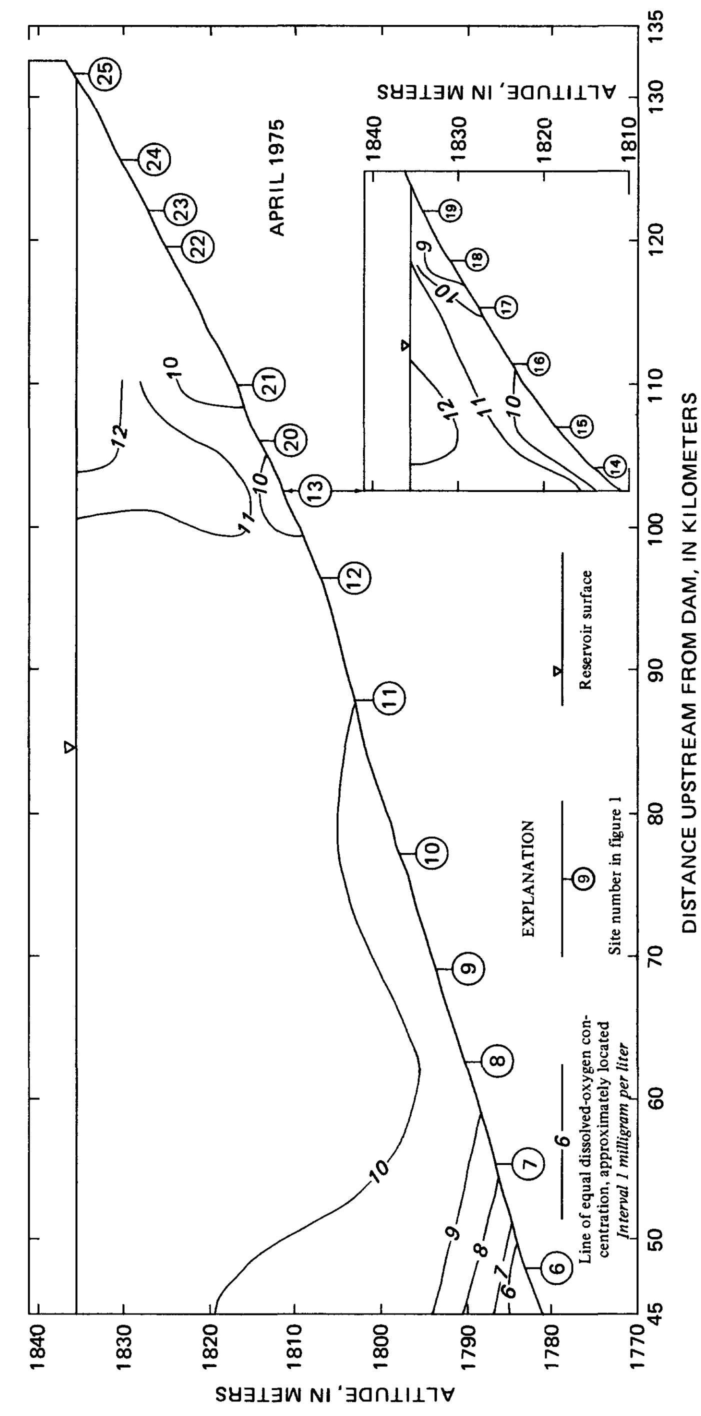

FIGURE 7.—Continued.

May 1974 is due mainly to the decrease in oxygen solubility. Thus, while the absolute dissolved-oxygen concentration decreases from initial conditions in early spring, the percentage saturation is still near 100 for most of the near-surface water in the reservoir. (See table 2.) Aside from the decrease in concentration of dissolved oxygen that is due to oxygen solubility, a somewhat localized decrease is apparent in the bottom waters of the Green River and Blacks Fork arms of the reservoir in late spring.

TABLE 2.—*Dissolved-oxygen concentration in near-surface water in Flaming Gorge Reservoir, in percentage of saturation*

Site No.	May 7–8, 1974	May 29–30, 1974	June 24–25, 1974	July 30–31, 1974	Aug. 26–27, 1974	Sept. 30–Oct. 2, 1974	Apr. 21–22, 1975
6	109	107	125	105	89	112	98
7	114	108	114	101	94	109	—
10	110	102	114	102	107	—	—
12	115	104	113	94	98	105	100
13	112	103	105	—	112	103	113
15	—	—	113	120	114	108	125
16	99	105	109	143	116	114	—
17	92	101	101	132	122	—	118
18	—	—	—	—	—	—	117
19	92	—	—	143	122	—	—
20	97	100	100	97	105	110	124
21	—	106	103	100	120	103	119
22	104	104	92	95	143	109	—

FORMATION, DEVELOPMENT, AND MOVEMENT OF ZONE OF OXYGEN DEPLETION

In June 1974, most of the water in the epilimnion was saturated with dissolved oxygen, and water in the hypolimnion was undersaturated. Dissolved-oxygen consumption by decomposition of organic material probably caused the undersaturated conditions. Any photosynthetic activity is probably effectively arrested by suspended material, including sediment, which considerably reduces transparency. Secchi-disk readings in June 1974 in the upstream part of the reservoir ranged from 2.1 meters at site 13 to 0.3 meter at site 25.

As shown in the profile for June 1974 (fig. 7), the lowest dissolved-oxygen concentration occurred simultaneously in bottom waters of both tributary arms of the reservoir. This simultaneous occurrence—and because each tributary has a different hydrologic makeup in terms of streamflow characteristics such as size of drainage area, channel geometry, runoff rates and periods, and chemical constituents—leads to the conclusion that dissolved-oxygen depletion is a function of reservoir stratification.

Organic material is either (1) carried into the reservoir during spring runoff and its heaviest part deposited on the bottom of the reservoir because of the abrupt decrease in stream velocity as the water enters the reservoir or (2) deposited on the bottom of the reservoir during a receding stage and then inundated during a rising reservoir stage (fig. 10). The deposition and subsequent decomposition of organic material probably results in the dissolved-oxygen depletion in the bottom waters as shown in the June 1974 profile (fig. 7). Since no replenishment of dissolved oxygen occurs in the bottom water from either overlying water or from inflow water, the available dissolved oxygen in the hypolimnion is gradually depleted. The lowest dissolved-oxygen concentration observed in the upstream part of the reservoir for June 1974 was about 5 mg/L.

From June to July 1974, the dissolved-oxygen concentration in the reservoir changed appreciably. The near-surface water, although containing less dissolved oxygen than in June, remained saturated, but the entire deeper part of the reservoir was undersaturated. In July in the upstream part of the reservoir, the dissolved-oxygen concentration decreased with depth until the minimum concentration was observed near the bottom of the reservoir. The minimum dissolved-oxygen concentration in the bottom water decreased from about 5 mg/L in June to less than 1 mg/L in July (fig. 6). The 5 mg/L isopleth extended about 50 km further downstream along the bottom in July than in June.

Downstream from the point of minimum dissolved-oxygen concentration on the bottom, the dissolved-oxygen concentration in the metalimnion is inversely distributed with depth. This condition is known as the metalimnetic oxygen minimum, and it is most apparent in the July profile (fig. 7). The metalimnetic minimum cannot be explained on the basis of analysis of water samples for phytoplankton (Bolke and Waddell, 1975, p. A15) nor can it be explained on the basis of analysis of water samples for seston that were taken during this study, but it might be due to flow characteristics of the reservoir.

The most probable cause for the metalimnetic oxygen minimum is an interflowing current in the reservoir. Water movement during the summer for the most part is limited to horizontal movement, because water entering the reservoir seeks its own density level and then moves horizontally through the reservoir. The July profile either suggests an interflow at about a depth of 13 meters, with apparent shear zones above and below the interflow, or the profile suggests relatively fast movement of water at 13 meters compared to the water above or below that depth. The "tongue-shaped" appearance of the specific-conductance profile in the Blacks Fork arm of the reservoir (fig. 8) is additional evidence of the interflowing current. Water with a specific conductance of about 1,300 micromhos per centimeter at 25°C enters the reservoir from Blacks Fork and seeks its own density level at about 10 meters.

Another possible cause for the metalimnetic oxygen minimum in July is the replenishment of dissolved oxygen in the epilimnion and thence to the upper metalimnion from the air above the reservoir. Without replenishment from the air, the dissolved oxygen in the epilimnion would be depleted by continued organic decomposition and might appear as shown by the dashed lines on the July profile. (See fig. 7.)

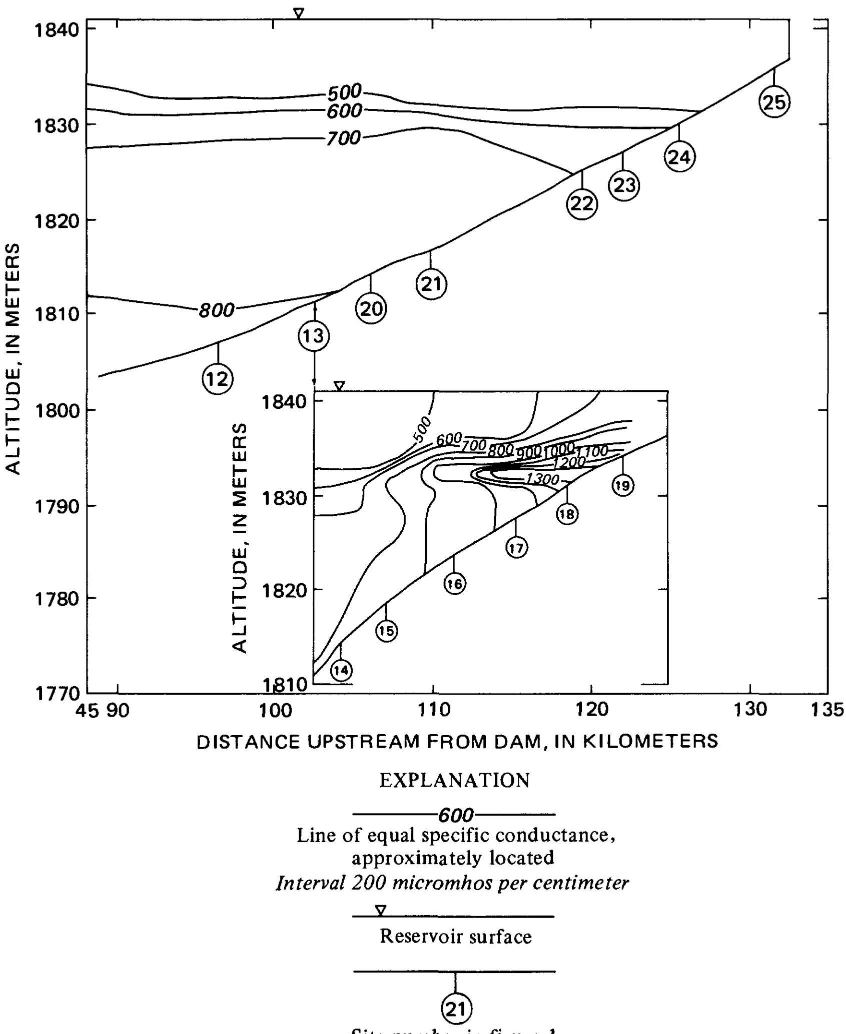

FIGURE 8.—Longitudinal profile of specific conductance in the upstream part of Flaming Gorge Reservoir, July 1974.

The shape of the dissolved-oxygen profile along the bottom of the reservoir, rather than being caused by underflow, is probably due to decomposition of organic material deposited on the bottom during spring runoff and bacterial decomposition of sinking algal cells. An underflowing current during July is not likely, because the inflowing water is warmer than the water in the reservoir and hence less dense than the bottom water. The deposition of organic material along the bottom and its subsequent decay could account for the shape of the dissolved-oxygen profile along the bottom of the reservoir. As shown in figure 7, by August 1974 continued depletion of dissolved oxygen had affected a larger part of the lower metalimnion and the hypolimnion.

The effects of fall circulation (destratification) are shown in the profile for September 1974 (fig. 7). The thickness of the epilimnion increased from about 13 meters in August to about 20 meters in September. During September, cooling of the epilimnion below temperatures in the metalimnion cause vertical circulation in the reservoir, thus enriching the metalimnion with dissolved oxygen. In addition, cooler water flowing into the reservoir displaced the water with low dissolved-oxygen concentration downstream from the confluence of Blacks Fork and the Green River. The low dissolved-oxygen concentration also was raised somewhat by dilution.

Although no data were collected after September 1974, partial data for the last part of October 1975 shows continued movement of the water with low dissolved-oxygen concentration along the bottom of the reservoir. Also, data collected in late October 1970 (Bolke and Waddell, 1972) showed a zone of water with low dissolved-oxygen concentration along the bottom as far downstream as site 6. This suggests that the water with low dissolved-oxygen concentration moves along the bottom of the reservoir until it either is mixed by circulation in the late fall or ultimately is trapped in the deepest part of the reservoir near the dam.

DOWNSTREAM EFFECTS OF STORING WATER IN THE RESERVOIR

Storage of water in Flaming Gorge Reservoir has resulted in the following effects in the Green River downstream from the reservoir: decrease in total flow of water, increase in dissolved-solids load, and decrease in overall temperature.

DEPLETION OF FLOW

Storage of water in Flaming Gorge Reservoir has caused a depletion of flow in the Green River because of evaporation and bank storage. These losses were estimated by means of a water budget, wherein for a given time period the change in storage (DS) in the reservoir is equal to inflow (IN) minus outflow (OT) minus evaporation (EV) minus bank storage (BS), or,

$$DS = IN - OT - EV - BS. \tag{1}$$

Inflow (IN) to the reservoir consists of tributary streamflow plus precipitation on the reservoir surface. The major tributary inflow was measured, and minor tributary inflow and precipitation were estimated as follows:

Prior to closure of Flaming Gorge Dam in November 1962, the measured flow of the Green River near Greendale, at a gaging station just below the damsite (site D in fig. 1), was equal to the total inflow of the Green River, Blacks Fork, and Henrys Fork (gaged at sites A, B, and C, fig. 1) plus the unmeasured inflow of minor tributaries, plus the precipitation that falls between the Greendale and the upstream gaging stations. The average relationship of the outflow (OT) measured at site D to the measured inflow (MIN) at sites A, B, and C for the 1952–62 period was

$$OT = IN = 1.06\ MIN. \tag{2}$$

The difference between the total inflow (IN) and the measured inflow (MIN) was the unmeasured inflow surface and ground water plus precipitation.

After 1964, MIN was adjusted for storage and estimated evaporation at Fontenelle Reservoir (SEF) in order to keep the relationship valid for estimating unmeasured inflow to Flaming Gorge Reservoir. After the unmeasured inflow was estimated using the above relationship, then storage and evaporation at Fontenelle Reservoir (SEF) were subtracted to give the actual storage change in Flaming Gorge Reservoir, or,

$$DS = IN - OT - EV - BS - SEF. \tag{3}$$

Substituting for IN from equation 2 and solving for ($EV + BS$),

$$(EV + BS) = 1.06\ MIN - OT - DS - SEF. \tag{4}$$

Fewer data were available for evaporation and bank storage than for the other terms in the water budget, so they were first computed as a single residual in the budget ($EV + BS$). Then by estimating evaporation from pan data, the bank storage was computed as a second residual.

For the period 1963–75, values of $(EV + BS)$ were computed as shown in table 3. Total $(EV + BS)$ for 1963–75--1,320 hm³—represents the depletion of flow in the river system due to evaporation and bank storage in Flaming Gorge Reservoir.

The volume of evaporation was estimated using data from National Weather Service class A evaporation pans. Data from three sites—Flaming Gorge Dam, Manila, Utah, and Green River, Wyo.—were used to estimate evaporation. Using a method of Kohler, Nordenson, and Baker (1959), the monthly data from May through October for these three sites were averaged, adjusted by a factor of 0.81 to obtain annual pan evaporation, and then corrected by a factor of 0.71 to obtain annual lake evaporation. The average annual lake evaporation thus computed for the 1963–75 period was about 1,067 mm. The volume of evaporation was then obtained by multiplying the average surface area of the reservoir for each year by the average annual evaporation rate. These volumes are given in table 4.

Comparison of total evaporation for 1963–75, based on an annual evaporation rate of 1,067 mm, and total evaporation plus bank storage computed from the water budget for the same period shows a difference of 210 hm³. Assuming that the water-budget calculation for evaporation is more accurate than the direct calculation of evaporation, the annual evaporation rate of 1,067 mm calculated from pan data is too high.

An earlier analysis by Iorns, Hembree, and Oakland (1965, pl. 6), using the same method, showed that the average annual evaporation rate was about 864 mm. The total volume of evaporation computed using this rate (table 4) was about 80 hm³ less than the total of evaporation and bank storage from the water budget. Assuming that the evaporation rate of 864 mm is the more realistic, because some water undoubtedly enters bank storage, the latter is then computed as a residual as shown in table 5.

TABLE 3.—*Estimates of evaporation plus bank storage, in cubic hectometers, for Flaming Gorge Reservoir*

[See text for explanation of symbols]

Year	*MIN*	*OT*	*DS*	*SEF*	*EV+BS*
1963	1,331	206	+1,063	0	+142
1964	1,880	1,034	+817	+26	+116
1965	3,116	1,988	+1,219	+16	+80
1966	1,581	1,459	−22	+15	+224
1967	2,272	1,932	+321	−2	+157
1968	1,819	2,262	−731	+373	+24
1969	2,030	2,404	−366	+5	+109
1970	1,438	1,649	−40	−27	−58
1971	2,853	1,264	+1,407	+123	+230
1972	3,080	2,387	+653	+46	+179
1973	2,040	2,599	−350	+17	−104
1974	2,297	1,752	+489	−1	+195
1975	2,240	2,227	+81	+41	+25
Total (rounded)					1,320

TABLE 4.—*Evaporation estimates for Flaming Gorge Reservoir*

Year	Average surface area (hm²)	Volume of evaporation: Evaporation rate 1,067 mm/yr (hm³)	Volume of evaporation: Evaporation rate 864 mm/yr (hm³)
1963	625	6.7	5.4
1964	7,225	77.1	62.4
1965	7,650	81.6	66.1
1966	12,615	134.6	109.0
1967	12,305	131.3	106.3
1968	11,550	123.2	99.8
1969	10,425	111.2	90.1
1970	9,525	101.6	82.3
1971	11,655	124.4	100.7
1972	14,285	152.4	123.4
1973	14,935	159.4	129.0
1974	15,210	162.3	131 4
1975	15,615	166.6	134.9
Total (rounded)		1,530.0	1,240.0

TABLE 5.—*Estimates of bank storage, in cubic hectometers*

EV: Evaporation rate 864 mm/yr.
BS: Positive values indicate water moves into bank storage, and negative values indicate water returns to the reservoir.

Year	*EV+BS*	*EV*	*BS*
1963	+142	5.4	+137
1964	+116	62.4	+54
1965	+80	66.1	+14
1966	+224	109.0	+115
1967	+157	106.3	+51
1968	+24	99.8	−76
1969	+109	90.1	+19
1970	−58	82.3	−140
1971	+230	100.7	+129
1972	+179	123.4	+56
1973	−104	129.0	−233
1974	+195	131.4	+64
1975	+25	134.9	−110
Total (rounded)	1,320	1,240	80

INCREASE IN DISSOLVED-SOLIDS LOAD

One of the effects of storing water in the reservoir is that the concentration of dissolved solids, and hence the dissolved-solids load, is increased in the river below the reservoir. The increase is due to leaching of soluble salts from the rocks and soils that are inundated by the reservoir. Figure 9 shows the variations in dissolved-solids concentrations in the Green River below Flaming Gorge Dam both before and after closure of the dam. The largest annual variation was about 600 mg/L before closure, and except for 1965, only about 200 mg/L after closure. In 7 of the 13 years since closure, the variation between the maximum and minimum was 100 mg/L or less. The discharge weighted-average dissolved-solids concentration for the 5 years prior to closure was 386 mg/L, and the discharge weighted average was 512 mg/L after closure. Thus, the effect of the reservoir has been to decrease the amount of variation between the maximum and minimum dissolved-solids concentrations and to increase the

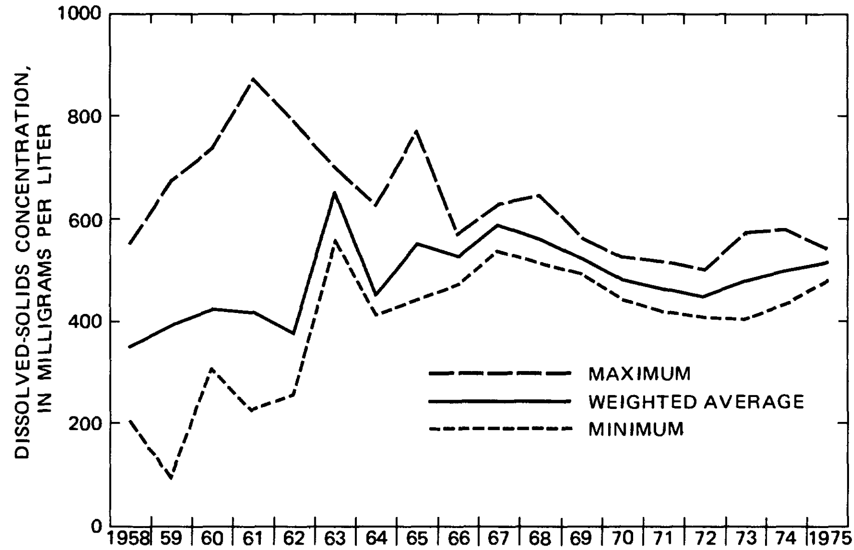

FIGURE 9.—Annual maximum, minimum, and weighted-average dissolved-solids concentration of the Green River below Flaming Gorge Reservoir before and after closure of the dam.

weighted-average dissolved-solids concentrations in the river below the reservoir.

A budget for dissolved-solids load (*DSL*) was used to estimate the change in the river below the reservoir. Thus, like the relationship for the water budget discussed above, for a given time period the change in load (*DSL*) in the reservoir is equal to inflow load (*INL*) minus outflow load (*OTL*) plus the net load change due to leaching and chemical precipitation (*LL*), or

$$DSL = INL - OTL + LL. \qquad (5)$$

Inflow load to the reservoir is the total load from the major and minor tributaries. The inflow load from the major tributaries was estimated by correlating monthly analyses of specific conductance and dissolved solids. Daily values of specific conductance also were available for each of the major tributaries. Thus, the weighted-average specific conductance was computed, and the dissolved solids load was then estimated from the relationship between specific conductance and dissolved solids.

The inflow load from minor tributaries was estimated as follows: Prior to closure of Flaming Gorge Dam in November 1962, the dissolved-solids load of the Green River at side D (fig. 1) was equal to the sum of the measured load of the Green River (site A), Blacks

Fork (site B), and Henrys Fork (site C), plus the unmeasured load from minor tributaries. The average relationship of the dissolved-solids load at site D (*OTL*) to the measured dissolved-solids load at sites A, B, and C (*MINL*) for the 1957–62 period was

$$OTL = INL = 1.20\ MINL. \tag{6}$$

The difference between the total inflow load (*INL*) and the measured inflow load (*MINL*) was the unmeasured inflow load.

After 1964, *MINL* was adjusted for change in dissolved-solids load stored in Fontenelle Reservoir (*DLF*). After the unmeasured load was estimated using equation 6, then the stored load (*DLF*) was subtracted to give the actual storage load change in Flaming Gorge Reservoir, or,

$$DSL = INL - OTL + LL - DLF. \tag{7}$$

Substituting for *INL* from equation 6 and solving for *LL*,

$$LL = DSL + OTL + DLF - 1.20\ MINL. \tag{8}$$

The term *LL* represents the net change of dissolved-solids load due to leaching and chemical precipitation. Values of *LL* were computed for the 1963–75 period and are shown in table 6.

Year-by-year comparisons of the change in dissolved-solids load (*LL*) for the 1963–69 period were not possible because of insufficient data. Thus, a longer period was used in order to compare the change of dissolved-solids load with time and with changes in reservoir contents. Changes in reservoir contents affect the volume of rocks and soils inundated. The average change of *LL* was about 170,000 metric tons per year for the 1963–66 period, compared with about 120,000

TABLE 6.—*Estimates of net change of dissolved-solids load in the river system due to leaching and chemical precipitation, in metric tons*

[See text for explanation of symbols]

Year	*DSL*	*OTL*	*DLF*	*MINL*	*LL* (rounded)
1963	—	134,300	0	488,100	—
1964	—	465,400	+4,540	646,800	—
1965	—	1,108,600	−450	1,123,100	—
1966	+1,678,300	783,800	+2,720	656,800	[1]+680,000
1967	—	1,145,800	−2,900	840,000	—
1968	−317,500	1,294,500	+92,600	714,900	[1]+347,000
1969	—	1,290,000	−21,000	738,400	—
1970	−315,700	800,100	−4,090	611,400	[1]+130,000
1971	+460,800	586,000	+14,600	952,500	−82,000
1972	+432,700	1,070,500	−2,010	994,300	+308,000
1973	−98,000	1,261,900	+10,800	831,000	+178,000
1974	+263,100	876,300	−3,070	843,700	+124,000
1975	+90,700	1,163,000	−1,920	824,600	+262,000
Total (rounded)					+1,947,000

[1]Computations based on 2- or 4-year totals because data are lacking for computation of dissolved-solids load in the reservoir (*DSL*) during intervening years.

metric tons per year during 1967–70, and about 160,000 metric tons per year during 1971–75. The largest change in LL occurred during initial filling of the reservoir. The contents of the reservoir at the end of June 1966 (fig. 10) was about 3,300 hm^3, compared with the design capacity of 4,674 hm^3. The smallest change in LL occurred from 1967 to 1970 during an overall decrease in reservoir contents. The increase of dissolved-solids load from 1971 to 1975 was due to the large increase in contents which resulted in the flooding of rocks and soils not previously covered by reservoir waters. It appears likely, therefore, that if the volume of the reservoir were to remain stable, then the dissolved-solids load (due to leaching and chemical precipitation) in the river below the reservoir would be less than the loads estimated for the period 1971–75.

CHANGES IN INDIVIDUAL ION LOADS

The changes in the individual ion loads in the river below the reservoir were calculated for the 1973–75 period using a dissolved-ion load budget. The calculations are shown in the following table in millions of metric tons:

Ion	(1) Calculated reservoir load Sept. 1972	(2) Inflow load 1973–75	(3) Outflow load 1973–75	(4) Theoretical reservoir load Sept. 1975 (1+2−3)	(5) Calculated reservoir load Sept. 1975	(6) Increase(+) or decrease(−) of ion load (5−4)
Calcium (Ca)	0.29	0.46	0.45	0.30	0.30	0.00
Magnesium (Mg)	.10	.15	.18	.07	.14	+.07
Sodium (Na)	.23	.33	.37	.19	.24	+.05
Bicarbonate (HCO_3)	1.69	2.91	2.52	2.08	1.69	−.49
Sulfate (SO_4)	.81	1.16	1.46	.51	.97	+.46
Chloride (Cl)	.06	.09	.11	.04	.07	+.03

Most of the ion loads increased during the period, particularly the sulfate load. The only decrease in load was for bicarbonate. The increases were due to the leaching of soluble minerals from the rocks and soils inundated by the reservoir, and the decrease in bicarbonate is attributed to chemical precipitation.

The source of the increased sulfate load is probably gypsum ($CaSO_4 \cdot 2H_2O$). An equivalent amount of calcium presumably was leached, and this is estimated by multiplying the sulfate load by the ratio of the atomic weight of calcium to the atomic weight of sulfate, or,

$$\text{calcium load} = 0.46 \text{ million tons } (40/96) = 0.19 \text{ million tons.}$$

The budget analysis shows no increase of calcium load, thus 0.19 million tons of calcium is estimated to be lost by precipitation, probably as calcium carbonate. Using this assumption, the equivalent load of carbonate is estimated by multiplying the calcium load by

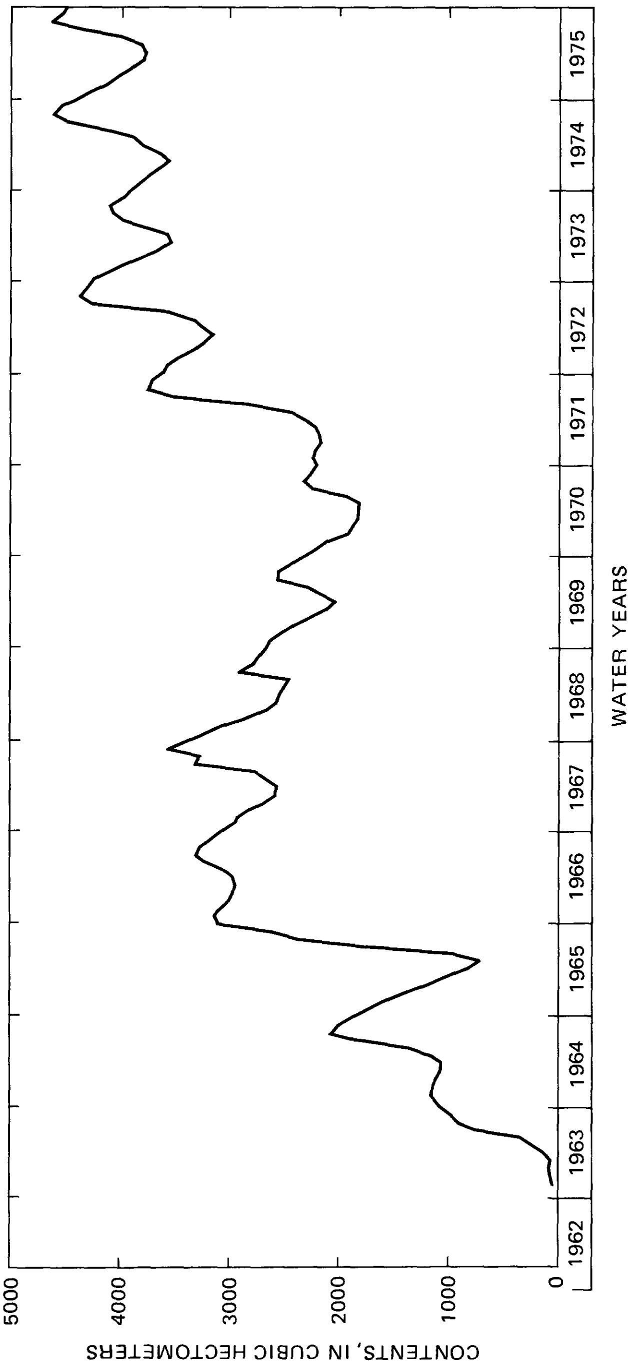

FIGURE 10.—End-of-month contents in Flaming Gorge Reservoir.

the ratio of the atomic weight of carbonate to the atomic weight of calcium, or,

carbonate load = 0.19 million tons (60/40) = 0.28 million tons.

The dissolved bicarbonate calculated in the load budget was 0.39 million tons. Subtracting the 0.28 million tons of carbonate leaves 0.11 million tons unaccounted for. This may be released as carbon dioxide and water.

TEMPERATURE VARIATIONS

The storage of water in a deep reservoir, such as Flaming Gorge, has a considerable effect on the temperature regime in the river below the reservoir. Prior to closure of Flaming Gorge Dam in November 1962, the maximum range in temperature at site D (fig. 1) was from 0°C in winter to 21°C in summer (fig. 11). After closure until 1970, the average monthly temperature ranged from 2°C to 12°C, but since 1970 the range has been from 4°C to 9°C. Prior to closure, the maximum average monthly temperature was in July or August, whereas after closure the maximum was in October, November, or December. The minimum average monthly temperature prior to closure was during December, January, or February, whereas after closure the minimum was during February or March. After 1967, however, the minimum has held constant for from 2 to 5 consecutive months; for instance, during 1973, the minimum temperature of 4.5°C persisted from February through June.

The large change in range between the maximum and minimum average monthly temperatures and the change in time period when the maximum and minimum occurs are due primarily to the retention time of water in the reservoir. Prolonged storage causes a lag in cooling in the fall and also a lag in heating of the reservoir in the spring. The change in range also is due to the fact that water cannot be selectively withdrawn from the reservoir for downstream release. Currently (1977) water is released only from the power inlet at altitude 1,783 meters, compared with the maximum pool altitude of 1,841 meters. Release from this altitude precludes discharge of any water from the epilimnion that has been seasonally warmed. Thus, the water released downstream is the cold hypolimnetic water or the slightly warmer metalimnetic water, depending on the season.

EFFECTS OF UPSTREAM DIVERSIONS ON DISSOLVED-SOLIDS CONCENTRATION

Large-scale upstream diversions of water from the Green River, which is the major tributary to Flaming Gorge Reservoir, in addi-

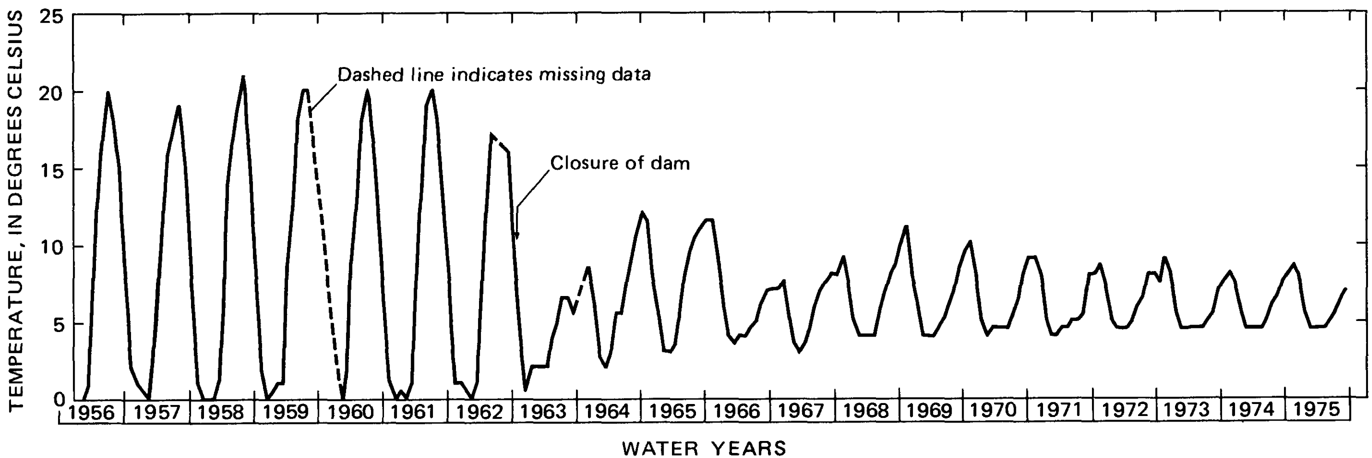

FIGURE 11.—Variations of average monthly temperature of the Green River about 0.8 kilometer below Flaming Gorge Dam.

tion to decreasing the flow of the river, would (1) decrease the dissolved-solids load in the river and (2) increase the dissolved-solids concentration of the inflow to the reservoir.

For the 1957–75 period, the discharge-weighted average dissolved-solids concentration of the inflow in the Green River to Flaming Gorge Reservoir was about 420 mg/L. If during this period about 250 hm^3 of water had been diverted, the resulting concentration of the inflow would have increased only to about 425 mg/L. If twice that amount (500 hm^3) had been diverted, the resulting concentration would have been about 440 mg/L. (See fig. 12.)

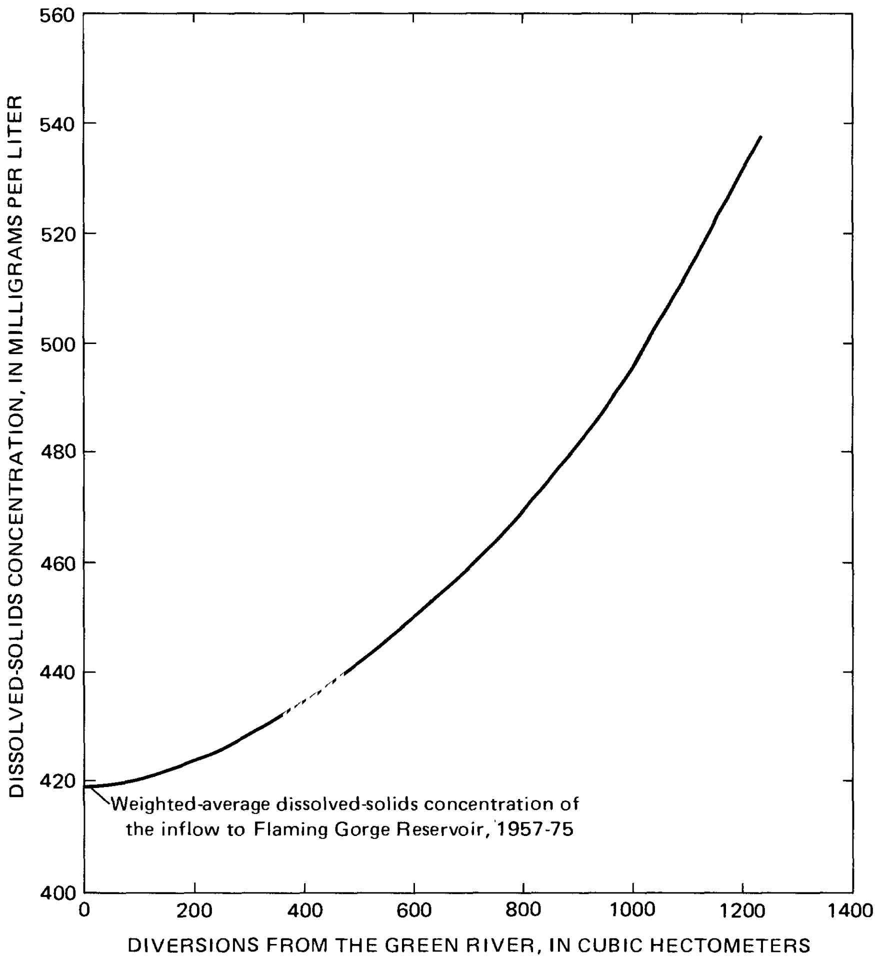

FIGURE 12.—Effect of diverting water from the Green River on the dissolved-solids concentration of the inflow to Flaming Gorge Reservoir.

PRODUCTION OF ALGAE IN THE RESERVOIR

Although a biological study was not within the scope of this project, some general observations were made of algal growth during the late summer and fall sampling trips on the reservoir. These observations were stimulated by reports of excessive algal production each fall in the upstream part of the reservoir. These algal blooms were of great concern to reservoir users.

During September 1974, algae were observed only in isolated clusters. Phytoplankton samples were taken at three sites for identification of organisms. At site 10, the codominant genera were *Oscillatoria, Dinobryon,* and *Onacystis;* at site 13, the codominants were *Oscillatoria, Aphanizomenon,* and *Lyngbya;* and at site 18 the codominants were *Anabena, Aphanizomenon,* and *Asterionella.*

During September 1975, a massive algal bloom was observed to extend from about site 11 in the main part of the reservoir to site 18 in the Blacks Fork arm and to near site 24 in the Green River arm (fig. 1). During August 1975, algae had been seen only in isolated clusters throughout the same area. The bloom in September turned the upper reservoir the color of "pea soup" and extended to both banks. Below site 11, above site 18, and above site 24 the algae were scant. Water samples were collected and filtered for seston analysis from top to bottom at site 15 in September in order to estimate the depth of the algal bloom. As determined from the color and density of filtered material, the bloom extended to a depth of at least 8 meters and possibly to almost 15 meters. The absence of green color in the filtered samples at 15 meters and below indicates a low algal concentration. Furthermore, 15 meters corresponds to the depth of the euphotic zone as determined from Secchi-disk readings (Bolke, 1976, p. 35). During October 1975 no extensive algal production was observed in the reservoir.

Massive algal blooms are disastrous to reservoirs in that the algae eventually die and the resulting decomposition depletes the oxygen supply. This has not been known to occur on a large scale as yet in Flaming Gorge Reservoir, because of the relatively low nutrient loading in the reservoir. Also, the large volume of the reservoir, coupled with its high flow-through capacity, discourages accumulation and concentration of nutrients. However, should the nutrient loading increase substantially, the quality of the reservoir water could deteriorate rapidly, and its use for recreation and water supply could be severely limited.

RECOMMENDATIONS FOR FUTURE STUDIES

The quality of the water that enters Flaming Gorge Reservoir is affected by upstream agriculture, industrial activities including those related to energy development, and impoundments. In turn, the reservoir affects the downstream quality of the Colorado River, which is a matter of major local, national, and international concern. The reservoir also is an important regional recreational area centered on water-based activities such as boating and fishing. Further studies are needed to:

1. Identify the organisms that comprise the aquatic biological community and determine their temporal and spatial distribution in the reservoir. Identify the source of nutrients that has supported massive algal blooms observed during the fall in the upstream part of the reservoir. Determine whether or not the nutrients occur naturally and how algal production can be controlled. Biological studies should include sampling and analysis for the following: Bacteria, plankton, periphyton, tripton, benthos, macrophytes, productivity, nutrients, turbidity, and light penetration.
2. Evaluate the effect of future coal and oil-shale mining within the Green River basin upon water quality. Current and future mining may contribute to the deterioration of water quality, not only by direct runoff of dissolved and suspended substances to streams, but also indirectly from the impact of increased population and related development.
3. Evaluate the effect of proposed industrial development in the Green River basin. The proposed development would deplete both water and dissolved solids from the river above Flaming Gorge Reservoir, which would in turn affect the inflow to the reservoir. Alteration of the present tributary inflow to the reservoir with respect to variables such as dissolved solids, temperature, or nutrients could adversely affect the reservoir environment.
4. Continue evaluation of leaching rates in the Flaming Gorge Reservoir area as they affect the downstream water quality. Past and present studies show that a substantial amount of minerals are added to the Colorado River system by leaching of rocks and soils inundated by the reservoir.
5. Estimate more accurately the load and composition of dissolved solids contributed by the minor tributaries. This unmeasured load currently is estimated as 18 percent of the total inflow to the reservoir, and the composition is assumed to be the same as that of the major tributaries. Systematic gaging and sampling of ephemeral and unmeasured perennial inflow would be required to provide more accurate estimates.
6. Monitor depletion of dissolved oxygen in the bottom waters in the upstream part of the reservoir during periods of summer res-

ervoir stratification. Surface waters are replenished with oxygen from the air above the reservoir and from inflowing water, but stratification effectively eliminates mixing of top and bottom waters. Dissolved oxygen in concentrations of less than 5 mg/L are known to be detrimental to fish, and during maximum summer stratification (July, August, and September), the deeper two-thirds of the reservoir contains less than 5 mg/L of dissolved oxygen.

7. Delineate the patterns of inflow of suspended and bedload material from the major tributaries and ascertain the time and space distribution of these materials in the reservoir. During periods of spring runoff, suspended material lessens light penetration in the reservoir, which decreases the effective depth of photosynthesis. Large accumulations of sediment destroy the habitat of the benthic organisms in the reservoir. Oxygen depletion first occurs in the shallow bottom waters where there is undoubtedly an abundance of organic material deposited during spring runoff. Turbidity measurements, dye studies, and sediment analyses would facilitate the delineation of the flow patterns and the distribution of sediment in the reservoir.

SUMMARY

Flaming Gorge Reservoir, an important part of the U.S. Bureau of Reclamation's Colorado River Storage Project, regulates the Green River and also affects the amount of flow, chemical quality, and temperature of water in the river below the reservoir.

The water in the reservoir circulates from top to bottom during both the spring and fall, but in the deepest part of the reservoir near the dam, the water apparently does not circulate. At other times the reservoir is thermally stratified. The maximum stratification is in the summer, and the reservoir is weakly stratified in the winter. Circulation is caused chiefly by insolation and differences in temperature and density of inflow and of water in the reservoir, but wind is also a significant cause of circulation.

The reservoir is well oxygenated in the spring, but dissolved oxygen is depleted in the bottom of both tributary arms of the reservoir by early summer and in the entire deeper part of the reservoir later in the summer. Oxygen depletion is related to reservoir stratification and decomposition or organic material.

Storage of water in Flaming Gorge Reservoir has depleted the flow in the Green River because of evaporation and bank storage. The net depletion was 1,320 hm^3 for the 1963–75 period, of which more than 90 percent was due to evaporation.

Another result of the presence of the reservoir is that there is less variability in dissolved-solids concentration and temperature and an increase in dissolved-solids concentration in water in the river below the dam. Dissolved solids varied as much as 600 mg/L prior to closing of the dam but, except for 1965, only up to 200 mg/L since. Temperature of water varied from 0° to 21°C before closing but has varied from 2° to 12°C since, and only from 4° to 9°C since 1970. The discharge weighted-average concentration of dissolved solids was 386 mg/L prior to closing and 512 mg/L since, mostly because of leaching of soluble salts from rocks and soil covered by the reservoir. The net increase in dissolved-solids load for the 1963–75 period was 1,947,000 metric tons. The largest increase among the individual ions was in sulfate, probably because of solution of gypsum, and the only decrease was in bicarbonate, probably because of precipitation of calcium carbonate.

If large volumes of water were diverted from the Green River above Flaming Gorge Reservoir, the dissolved-solids load of the river would decrease, but the dissolved-solids concentration of the combined inflows to the reservoir would increase slightly.

During September 1975 a massive algal bloom occurred in the upstream part of the reservoir but was not studied in detail.

Further studies are needed of the aquatic life of Flaming Gorge Reservoir to estimate effects of potential coal and oil-shale mining and industrial development upstream; to refine estimates of the quality of inflow, leaching, and oxygen depletion; and to estimate inflow of sediment.

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