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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2039-A

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By E L BOLKE *and* K M WADDELL

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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CHEMICAL QUALITY AND TEMPERATURE OF WATER IN FLAMING GORGE RESERVOIR, WYOMING AND UTAH, AND THE EFFECT OF THE RESERVOIR ON THE GREEN RIVER

By E L BOLKE and K M WADDELL

ABSTRACT

The major tributaries to Flaming Gorge Reservoir contribute an average of about 97 percent of the total streamflow and 82 percent of the total load of dissolved solids The Green River is the largest tributary, and for the 1957-72 water years it contributed 81 percent of the total streamflow and 70 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

Flaming Gorge Dam was closed in November 1962, and the most significant load changes of chemical constituents due to the net effect of inflow, outflow, leaching, and chemical precipitation in the reservoir have been load changes of sulfate and bicarbonate The average increase of dissolved load of sulfate in the reservoir for the 1969-72 water years was 110,000 tons (99,790 t) per year, which was 40,000 tons (36,287 t) per year less than for the 1963-66 water years The average decrease of dissolved load of bicarbonate in the reservoir for 1969-72 was 40,000 tons (36,287 t) per year, which was the same as the decrease for 1963-66

Anaerobic conditions were observed in the deep, uncirculated part of the reservoir near the dam during the 1971 and 1972 water years, and anaerobic or near-anaerobic conditions were observed near the confluence of the Blacks Fork and Green River during the summers of 1971 and 1972

The water in Flaming Gorge Reservoir is in three distinct layers, and the upper two layers (the epilimnion and the metalimnion) mixed twice during each of the 1971-72 water years The two circulation periods were in the spring and fall The water in the deepest layer (the hypolimnion) did not mix with the waters of the upper zones because the density difference was too great and because the deep, narrow shape of the basin probably inhibits mixing

The depletion of flow in the Green River downstream from Flaming Gorge Dam between closure of the dam and the end of the 1972 water year was 4,500,000 acre-feet (5,550 8 hm^3) Of this total, water stored in the reservoir accounted for 3,500,000 acre-feet (4,317 2 hm^3), evaporation consumed 700,000 acre-feet (863 4 hm^3), and 300,000 acre-feet (370 0 hm^3) went into bank storage

The net load of dissolved solids added to the river system during the 1963–72 water years, due to leaching and chemical precipitation, was 1,730,000 tons (1,569,421 t) The leaching rate was 200,000 tons (181,436 t) per year for 1963–68, 115,000 tons (104,326 t) per year for 1969–70 and 150,000 tons (136,077 t) per year for 1971–72 It appears that the leaching rates should decrease in the future since the reservoir level in 1972 was near maximum pool level

The most significant increase in concentration of the chemical constituents in the water below the reservoir involved the sulfate ion, which increased from about 115 milligrams per litre (42 percent of the anions) in 1957 to about 200 milligrams per litre (54 percent), in 1972 But the highest concentration, about 290 milligrams per litre (58 percent), occurred in 1963, immediately after closure of the dam

Prior to closure of the dam, the average monthly temperature of the Green River below the damsite ranged from 0°C to 19 5°C as compared to 3 5°C to 10 0°C after closure

INTRODUCTION

Flaming Gorge Reservoir is on the Green River, a tributary to the Colorado River, in northeastern Utah and southwestern Wyoming (pl 1) The damsite is about 30 miles (48.3 km) north of Vernal, Utah The water in the reservoir, at maximum storage, extends about 90 miles (144 8 km) upstream from the dam The pool altitude at maximum storage—3,788,900 acre-feet (4,673 6 hm^3)—is 6,040 feet (1,840 0 m) above mean sea level The pool altitude at dead storage—39,700 acre-feet (49 0 hm^3)—is 5,740 feet (1,749 6 m) The deepest point in the reservoir at maximum pool altitude, which is near the dam, is about 435 feet (132 6 m) 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 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 The results of these studies prior to 1969[1] were evaluated in a report by Madison and Waddell (1973) for the chemical quality of surface water in the Flaming Gorge Reservoir area The report indicated that the average dissolved-solids concentration increased in the Green River below Flaming Gorge Dam during the 6 years following closure (1963–68) The increase in dissolved-solids concentration was due chiefly to leaching of soluble minerals (calcium and sulfate) from the area inundated by the reservoir

Based on these findings, the Geological Survey made a more detailed

[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

study during July 1970–June 1973 with the following principal objectives· (1) to determine the rates of leaching of minerals in the reservoir area during 1969–72 for comparison with rates determined for 1963–68, (2) to determine the effect of the leached minerals on downstream quality, and (3) to define the annual limnologic cycle of the reservoir Chemical and physical data were collected from the reservoir during six sampling runs from October 1970 to September 1972 The entire sampling period encompassed two annual limnologic cycles. A portable water-quality monitoring instrument was used to make in situ measurements of temperature, dissolved-oxygen concentration, specific conductance, and pH at 34 sites (pl 1) in the reservoir during each sampling run

The results of the basic-data collection during the six sampling runs in the reservoir are reported separately by Bolke and Waddell (1972) That report also includes chemical-quality data for the major inflowing streams to the reservoir and the outflow below the dam that were obtained in 1969–72 at previously established sites as part of the Geological Survey's basic-data collection program

The cooperation and assistance of the following organizations and individuals is gratefully acknowledged the U S Bureau of Reclamation, which provided records of storage and area-capacity data for Flaming Gorge Reservoir; O. P Zabarsky of Martek Instruments, Inc , who provided technical assistance for the portable water-quality monitoring instrument; and R. C. Witherspoon, who provided information and assistance for safe and timely boat operation on the reservoir

Most numbers are given in this report in English units followed by metric units parentheses Multiply the English units by the conversion factors given below to obtain their metric equivalents The conversion factors used are

English			*Metric*	
Unit	*Abbreviation*	*Conversion factor*	*Unit*	*Abbreviation*
Acre-foot	acre-ft	0 0012335	Cubic hectometre	hm^3
Foot	ft	3048	Metre	m
Mile	mi	1 6093	Kilometre	km
Ton	ton	90718	Metric ton	t

Chemical concentration and water temperature are given only in metric units Chemical concentration is given in milligrams per litre (mg/l). For concentrations less than 7,000 mg/l, the numerical value is about the same as for concentrations in parts per million

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit by the following equation·

$$°F = 1 8(°C) + 32$$

CHEMICAL QUALITY OF INFLOW WATER TO THE RESERVOIR

The major tributaries to Flaming Gorge Reservoir are the Green River, Blacks Fork, and Henrys Fork. The major tributaries and their sampling locations, together with numerous minor tributaries, are shown on plate 1. Madison and Waddell (1973, p 4, 5) showed that for the 6-year period 1956–62 prior to closure of Flaming Gorge Dam, the three tributaries contributed an average of 97 percent of the total streamflow to the reservoir area and 82 percent of the total dissolved-solids load The streamflow, dissolved-solids concentration, and dissolved-solids load of these major tributaries fluctuate both annually and seasonally

ANNUAL VARIATION

The annual variation of dissolved-solids load in the water entering Flaming Gorge Reservoir in the three major tributaries is in direct proportion to the quantity of streamflow, whereas the dissolved-solids concentration generally fluctuates inversely with the quantity of flow (fig 1) The causes for the anamolous relationships during 1959, 1961, and 1965 are not known

Of the major tributary streamflow and dissolved-solids load for 1957–72, the Green River contributed 81 percent of the flow and 70 percent of the load, Blacks Fork contributed 14 percent of the flow and 22 percent of the load; and Henrys Fork contributed 5 percent of the flow and 8 percent of the load The average annual streamflow in the three major tributaries that entered the reservoir during 1957–72 was 1,530,000 acre-feet (1,887 3 hm^3), compared to 1,870,000 acre-feet (2,306.6 hm^3) during 1969–72, which was about 120 percent of the 1957–72 average The average annual inflow of dissolved-solids load during 1957–72 was 760,000 tons (689,457 t) compared to 900,000 tons (816,462 t) during 1969–72, which also was about 120 percent of the 1957–72 average

SEASONAL VARIATION

The dissolved-solids concentration in the water entering Flaming Gorge Reservoir in the three major tributaries is highest during late fall and winter when streamflow is at a minimum and lowest during late spring and early summer when streamflow is at a maximum Seasonal variations for the 1969–72 period are shown in figure 2 Madison and Waddell (1973, pl. 1) showed that the same seasonal variations occurred during the period 1966–68. In contrast, the three major tributaries contribute about 65 percent of the annual streamflow and about 55 percent of the annual dissolved-solids load during the period April-July (fig. 2).

The seasonal variation of concentration of individual ions is similar to that of the seasonal variation of the dissolved-solids concentration

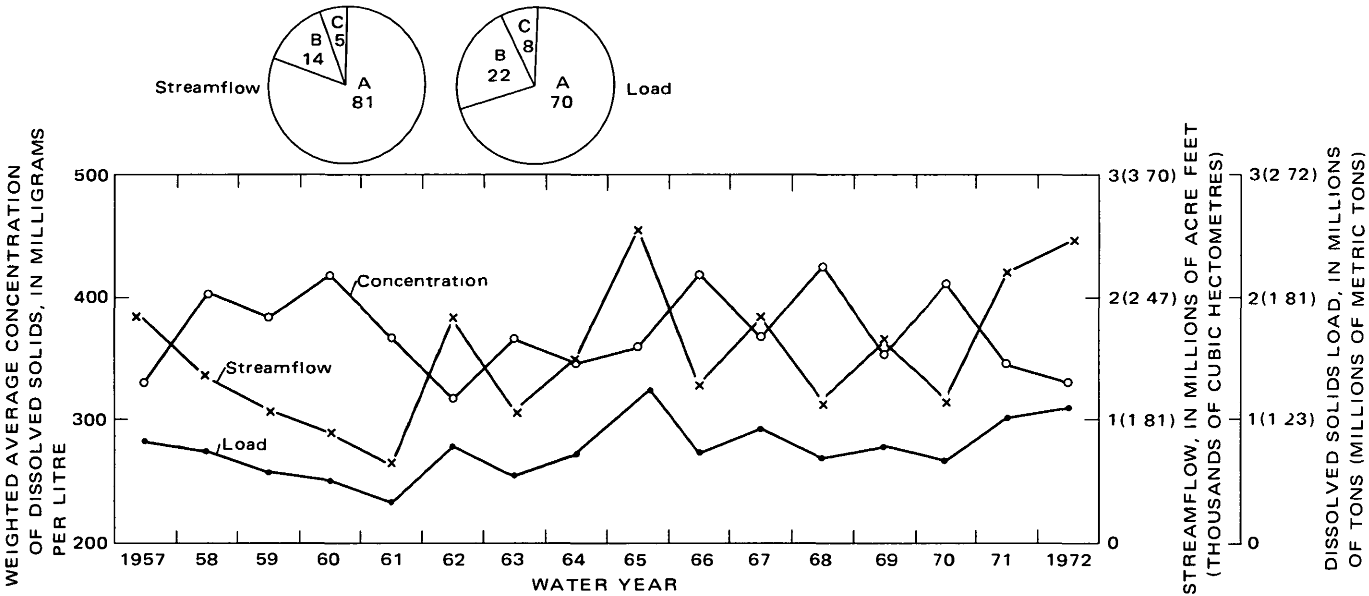


FIGURE 1 — Dissolved-solids concentration, dissolved-solids load, and streamflow during 1957–72 in the three major tributaries to Flaming Gorge Reservoir Circles represent 1957–72 average major tributary streamflow or load Numbers in circle are percentages of streamflow or load contributed by each major tributary A, Green River, B, Blacks Fork, C, Henrys Fork

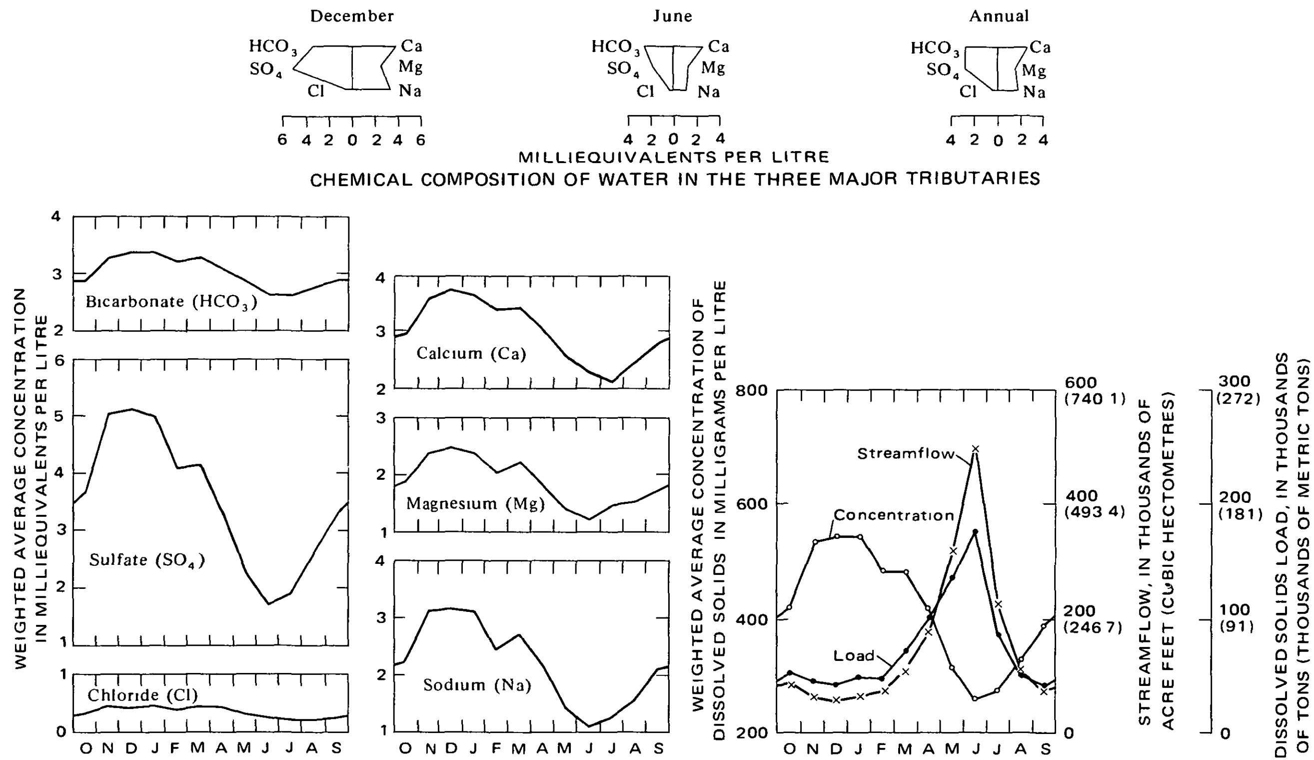


FIGURE 2 — Weighted-average monthly variation of chemical constituents and dissolved-solids load, streamflow, and chemical composition of water in the three major tributaries to Flaming Gorge Reservoir for 1969–72

(fig 2) The sulfate ion shows the largest seasonal variation and the chloride ion the least The principal constituents in the tributary streamflow during late fall and winter are calcium and sulfate, and during periods of highest streamflow in late spring and early summer the principal constituents are calcium and bicarbonate

CHEMICAL QUALITY OF WATER IN THE RESERVOIR

Among the processes that affect the chemical and physical properties of water impounded in a reservoir are (1) the relationship among inflow, outflow, and storage in the reservoir, (2) the leaching of minerals from rocks and soils inundated by the reservoir, (3) the precipitation of minerals from the water in the reservoir, (4) the annual limnologic cycle, and (5) the concentration of minerals due to evaporation The effects of items 1 to 4 on the water in Flaming Gorge Reservoir are discussed in later parts of this section, and the effect of item 5 is discussed in the section "Increase of Dissolved-Solids Concentration Below the Reservoir

EFFECTS OF INFLOW-OUTFLOW-STORAGE RELATIONSHIP, LEACHING AND CHEMICAL PRECIPITATION

Large changes that occur in the quality of the water in Flaming Gorge Reservoir in relatively short periods, are attributed to the high ratio of annual inflow to reservoir-storage capacity The maximum storage in the reservoir is 3,788,900 acre-feet (4,673 6 hm^3), whereas, the average annual inflow to the reservoir during 1957–72 was 1,530,000 acre-feet (1,887.3 hm^3), or about 40 percent of the capacity of the reservoir

The effects of the inflow-outflow-storage relationship, leaching, and precipitation on the chemical quality of the water in Flaming Gorge Reservoir are shown in figure 3 for 1969–72 With the exception of sulfate and bicarbonate, the relative proportion of individual ions in the inflow and water in the reservoir did not change greatly during 1969–72, although the dissolved-solids concentration of the inflow was quite variable for the 1969–72 period (fig 1) For this reason, the ratios of dissolved-sulfate and -bicarbonate loads to total dissolved load were computed and are shown in figure 3 so that a comparison can be made between inflow to the reservoir and water in storage

During water years 1969, 1970, and the early part of 1971, the water in storage in the reservoir fluctuated only slightly, as compared with the latter part of 1971 and 1972, because inflow and outflow were nearly the same During 1970, the ratios of sulfate load and bicarbonate load to total dissolved load were about the same for the inflow water and the water in storage The dissolved-solids concentration in the water in the reservoir was greater than that in the inflow water and was partly attributed to concentration by evaporation and partly to leaching From

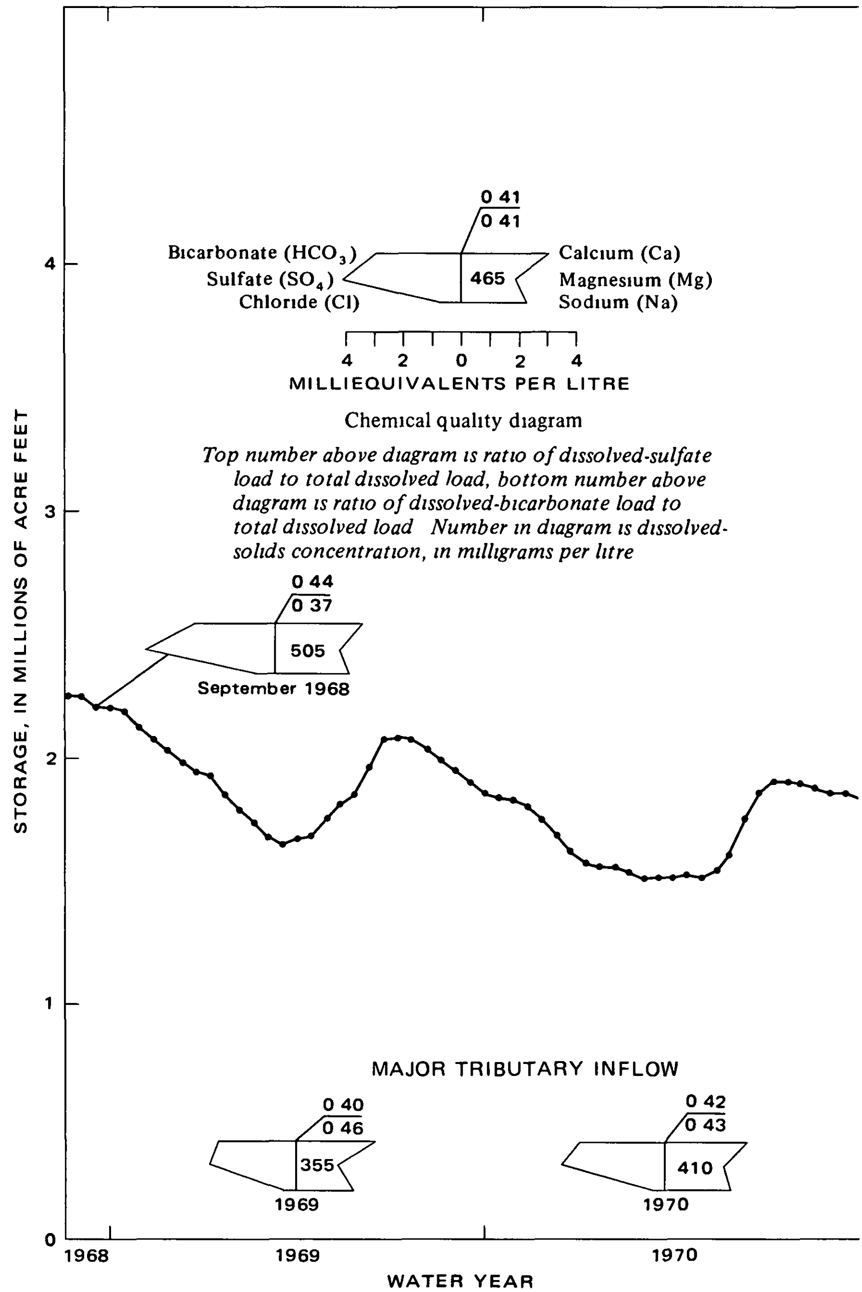
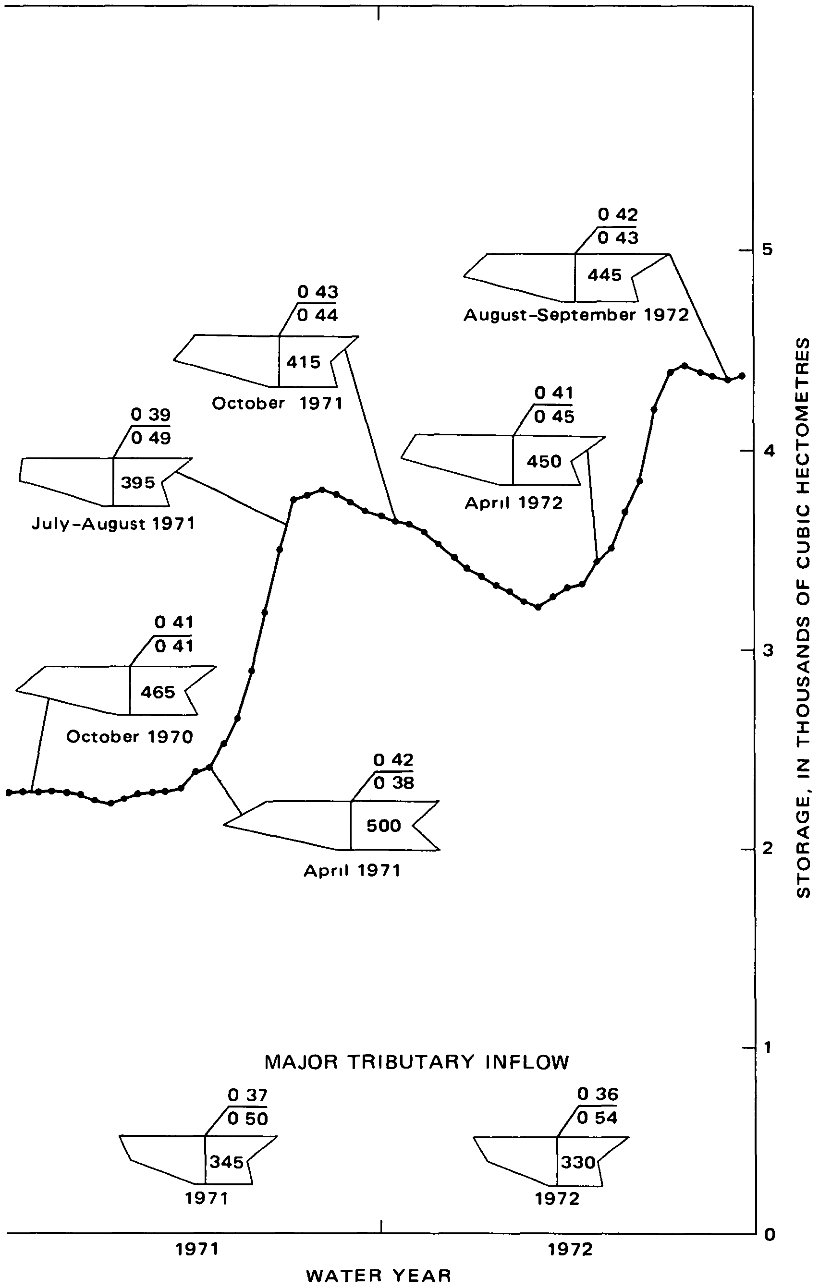


FIGURE 3 — Changes in storage in Flaming Gorge Reservoir and weighted-average major tributaries and of



concentration and dissolved-load ratios of chemical constituents of inflow in the three water in storage, 1969–72

October 1970 to April 1971, the amount of water in storage was nearly unchanged, but the sulfate concentration, dissolved-solids concentration, and the ratio of sulfate load to total dissolved load increased. These increases are indicative of leaching, because evaporation and inflow were minimal during this period of the year

From April 1971 to July–August 1971, the storage content of the reservoir increased by about 1 million acre-feet (1,233 5 hm^3) (fig 3), and the above-average runoff during this period (fig. 1) contained water with a relatively low dissolved-solids concentration and significantly lower sulfate concentration than in the previous year The ratio of sulfate load to total dissolved load in the stored water during this period decreased from 0 42 to 0 39, while the ratio of bicarbonate load to total dissolved load increased from 0.38 to 0 49 This indicates that during periods of above-average runoff the inflow to the reservoir contains proportionately more bicarbonate than sulfate load During such periods of above-average runoff, the stored water is diluted, and the ionic concentration of water in the reservoir becomes similar to that of the inflow water—except that the sulfate and dissolved-solids concentrations remain higher in the reservoir

From July–August 1971 to October 1971, the quantity of water stored in the reservoir remained fairly constant, and no appreciable changes occurred in the chemical quality of the water The dissolved-solids concentration increased from 395 to 415 mg/l, and the ratio of dissolved-sulfate load to total dissolved load increased from 0 39 to 0 43 The increased concentration was due partly to evaporation and partly to leaching, but the increased load ratio indicates solely the effect of leaching

From October 1971 to April 1972, the quantity of water stored in the reservoir decreased slightly, the dissolved-solids concentration increased from 415 to 450 mg/l, and the concentration of most of the ions increased proportionately During this period, evaporation and inflow are usually minimal, therefore, the increased concentrations are attributed mostly to the more concentrated inflow water

From April 1972 to August–September 1972, the storage content of the reservoir increased by about 700,000 acre-feet (863 4 hm^3) as a result of above-average inflow (fig 1) The inflow water during this period had the lowest concentration of dissolved solids observed during the 1969–72 period The dissolved-solids concentration of the 1972 inflow was 330 mg/l, as compared to 445 mg/l for the reservoir for the August–September 1972 period The ratio of sulfate load to total dissolved load in the inflow was 0 36, whereas in the reservoir this ratio increased from 0 41 to 0 42 from April to August-September By contrast, the ratio of dissolved-bicarbonate load to total dissolved load in the inflow was 0 54, and it decreased from 0 45 to 0 43 in the reservoir during the same period The increase in sulfate ratio is indicative of the leaching effect in the reservoir, while the decrease in bicarbonate ratio is indicative of chemical precipitation.

The overall net effect of leaching, chemical precipitation, inflow, and outflow on loads of individual dissolved ions in the reservoir for the period from September 1968 to September 1972 are given in millions of tons in the following table·

Ion	(1) Calculated reservoir load Sept 1968	(2) Inflow load 1969–72	(3) Outflow load 1969–1972	(4) Theoretical reservoir load Sept 1972 (1+2−3)	(5) Calculated reservoir load Sept 1972	(6) Increase(+) or decrease(−) of ion load (5−4)
Calcium (Ca)	0 18	0 62	0 52	0 28	0 32	+0 04
Magnesium (Mg)	09	18	21	06	11	+ 05
Sodium (Na)	18	53	51	20	25	+ 05
Bicarbonate (HCO_3)	53	2 12	1 56	1 09	92	− 17
Sulfate (SO_4)	64	1 59	1 79	44	89	+ 45
Chloride (Cl)	07	18	15	10	07	− 03

The theoretical reservoir load represents the load in the reservoir exclusive of leaching and chemical precipitation

The above calculations involve an unknown amount of error because of (1) the lack of detailed chemical-quality sampling during seasons of rapidly fluctuating tributary inflow, and because (2) the unmeasured inflow load from minor tributaries is about 18 percent of the total inflow load of dissolved solids (Madison and Waddell, 1973, fig 2)

The most significant differences between the theoretical and the calculated dissolved-ion loads in September 1972 were the increase in sulfate and the decrease in bicarbonate The load of dissolved sulfate ion increased by 0 45 million tons (0 41 million t) during 1969–72, or an average of about 0 11 million tons (0 10 million t) per year The load of dissolved bicarbonate ion decreased by 0 17 million tons (0 15 million t) during 1969–72, or a decrease of about 0 04 million tons (0 04 million t) per year The dissolved load of sulfate increased on the average about 0 15 million tons (0 14 million t) per year during the 1963–66 period (Madison and Waddell, 1973, p 8), or about 135 percent of the average annual increase for the 1969–72 period The dissolved load of bicarbonate decreased on the average about 0 04 million tons (0 04 million t) per year for the 1963–66 period, which is the same rate of decrease as observed during 1969–72 Most of the leached load is believed to be due to solution of gypsum ($CaSO_4 \cdot 2H_2O$) (Madison and Waddell, 1973, p 7)

EFFECTS OF THE ANNUAL LIMNOLOGIC CYCLE

The limnologic cycle is a series of related events occurring during the year that describe (1) the circulation patterns or lack of circulation (stratification) patterns in bodies of water such as reservoirs, and (2) the thermal and chemical processes that are associated with circulation or lack of circulation in the reservoir.

CIRCULATION OF WATER

The following general discussion describes the typical circulation patterns of deep reservoirs, such as Flaming Gorge, due to seasonal variation in solar radiation in the temperate zone (See Ruttner, 1963, p 34–37) In the fall the circulation process begins as seasonal cooling of the uppermost water in the reservoir causes it to become more dense than the warmer water immediately below. The more dense water then displaces the underlying warmer water, which is cooled in turn The circulation is localized near the surface at the beginning of the cooling period, but as cooling and wind mixing continue through the season, the circulation gradually reaches nearly all depths in the reservoir Eventually, the temperature in the reservoir is nearly uniform at about 4°C and complete or nearly complete circulation has occurred This circulation period is known as the fall turnover

Additional cooling may result in ice formation on the surface, and, because of the anomalous expansion of water below 4°C, the water on the surface, though colder, is less dense than the underlying water Thus, the period of ice cover is characterized by a mild thermal gradient ranging from 0°C near the surface to 4°C at the bottom in the deeper zones of the reservoir When the ice cover disappears in the spring, the warming of surface waters from 0°C to 4°C results in another period of complete circulation known as the spring turnover After the reservoir has warmed above 4°C stratification occurs and continues until the fall turnover

Flaming Gorge Reservoir differs from the typical reservoir in that it apparently does not circulate to the bottom in the deepest part of the reservoir near the dam. The evidence for this lack of complete circulation is given in the following section on thermal and chemical stratification.

THERMAL AND CHEMICAL STRATIFICATION

Variations of temperature, dissolved-oxygen concentration, specific conductance, and pH in Flaming Gorge Reservoir in 1971–72 indicated the presence of three distinct layers or zones (pl. 1).

The uppermost zone, the epilimnion, was delineated from the data shown on plate 1 as the shallow part of the reservoir, which was nearly homogeneous with regard to the parameters mentioned above. The homogeneity resulted from mixing caused by convection and wind-generated currents. The average thickness of this zone during the 1971–72 water years ranged from about 30 feet (9.1 m) during the summer to about 150 feet (45.7 m) during the spring.

The middle zone, the metalimnion, was delineated as a poorly mixed zone that showed stratification of some of the parameters mentioned above. The average thickness of the metalimnion ranged from about 80 feet (24.4 m) in the spring to about 210 feet (64.0 m) in the summer.

The deepest zone in the reservoir, the hypolimnion, was delineated as a relatively stable zone, the thickness of which was affected only slightly by seasonal variations. The average thickness in this zone ranged from about 85 feet (25.9 m) to about 105 feet (32.0 m) during 1971–72 and was limited to the deepest part of the reservoir. Mixture of water in this zone with the overlying waters is partly inhibited by the deep and narrow shape of the reservoir basin near the dam.

TEMPERATURE

The seasonal changes in the temperature regime in the reservoir are shown on plate 1. Maximum thermal stratification occurred during the summer months when temperatures ranged from about 4°C in the hypolimnion to about 23°C in the epilimnion. The maximum thermal gradient (thermocline) observed in the metalimnion during 1971-72 was 1.6°C/m. During the fall, the reservoir was stratified but less so than during the summer, as temperatures ranged from about 4°C in the hypolimnion to 13°C in the epilimnion. During the spring, before any appreciable amount of seasonal heating, most of the water in the reservoir was of nearly uniform temperature, ranging from about 3°–5°C in the downstream part of the reservoir to 5°–9°C in the upstream part.

DISSOLVED-OXYGEN CONCENTRATION

Oxygen dissolved in water is necessary for propagation of aquatic life, and among the factors that control oxygen solubility are atmospheric pressure and temperature. Because of the reduced pressure, high-altitude reservoirs generally contain less oxygen than do low-altitude reservoirs, but the effect is partially offset by the decrease in temperature. Dissolved-oxygen solubility in water varies inversely with temperature, increasing as temperature decreases. Dissolved-oxygen concentration is increased by photosynthesis of aquatic plants and decreased by respiration of plants and other aquatic life, including the micro-organisms that decompose organic matter in the water.

The seasonal changes of dissolved-oxygen concentrations in Flaming Gorge Reservoir are shown on plate 1 and in table 1. The data indicate that anaerobic to slightly supersaturated conditions existed in the

TABLE 1 – *Dissolved-oxygen concentration in near-surface water in Flaming Gorge Reservoir, in percentage of saturation*

[Leaders (---) indicate no data]

Site No	Oct 1970	Apr 1971	July–Aug 1971	Oct 1971	Apr 1972	Aug -Sept 1972
1	73	95	111	91	117	111
2	---	93	---	---	---	---
3	78	95	113	---	117	106
4	---	96	113	---	---	107
5	---	95	103	92	106	107
6	---	96	102	---	---	92
6 5	---	---	100	90	---	---
7	78	98	103	84	107	95
8	82	99	106	---	---	92
9	91	96	105	94	108	95
10	---	93	107	91	---	---
10 5	---	95	100	93	---	97
11	58	93	106	90	112	90
12 5	---	---	105	---	---	95
13	85	91	---	---	---	---
15	83	92	99	89	104	93
17	83	92	102	83	---	93
18	81	95	105	90	105	90
19	91	95	98	92	---	90
20	83	102	94	95	118	95
22	94	94	96	98	---	93
23	98	93	90	100	103	115
24	98	97	117	102	107	---
28	90	90	84	100	108	---
29	98	92	92	93	---	87
30	---	---	90	---	122	---

reservoir during the 1971-72 water years, with concentrations ranging from zero to about 11 mg/l The highest values generally were observed in the epilimnion during the spring coincident with the lowest observed water temperatures The lowest values were observed in the hypolimnion throughout all sampling periods

The percentage of saturation of dissolved oxygen was computed for near-surface waters in the reservoir for all sampling periods, using the altitude and temperature data of Hutchinson (1957, p 582) (See table 1) Supersaturated conditions were more common during the July–August 1971 and April 1972 periods than during the other sampling periods During the July–August 1971 period, the supersaturated conditions were due partly to photosynthesis, but it is not known what caused these conditions in April 1972

During the summer, anaerobic or near-anaerobic conditions were observed in the bottom waters of the reservoir near the confluence of Blacks Fork and the Green River These conditions may be due directly or indirectly to the decomposition of naturally occurring organics in the water or pollutants brought in by either or both Blacks Fork or the Green River During the 1965–72 water years, the backwater of the reservoir has fluctuated above and below the confluence of Blacks Fork and the Green River, thus reducing the velocities of the two streams The reduced velocities are conducive to deposition of organic debris transported by the rivers, and organic decomposition would be accelerated at the summer temperatures During the fall, these conditions, somewhat modified, were observed downstream near Henrys Fork Even though the total volume of water affected was not large, a great distance along the reservoir was affected by these conditions (pl. 1)

An inverse distribution of dissolved-oxygen concentration was observed in the upper part of the metalimnion during the July-August and October 1971 and August-September 1972 periods According to Hutchinson (1957, p. 623–625):

> The most widely known theory of the metalimnetic minimum is that it represents a region into which oxidizable material, such as dead plankton, faeces, and perhaps living plankton metabolizing its reserves or living saprobiotically, has fallen from the epilimnion * * *
>
> Actually, it is obvious that in the turbulent epilimnion the sinking speed will be determined solely by the turbulence, throughout the entire freely circulating layers, any tendency to abstract oxygen will be counterbalanced by turbulent diffusion from the surface, if not by photosynthesis Most small particles that reach the bottom of the epilimnion will be returned by turbulent movements to the upper layers Only when a particle descends below the epilimnion * * * is its downward descent assured Only then can initial decomposition of easily oxidizable material produce a metalimnetic minimum * * *
>
> It must also be borne in mind that not only is a particle inherently likely to have a higher rate of oxygen uptake early in its descent while the most unstable materials are still present, but in the metalimnion the temperature is somewhat higher than in the lower layers, so that oxidation will proceed faster * * *

During August–September 1972, phytoplankton samples were collected above, at, and below the point of minimum dissolved-oxygen concentration. The concentration of phytoplankton was extremely low and probably contributed little to the lowering of the dissolved-oxygen concentration (K V Slack, U S Geol Survey, oral commun , 1972) However, oxidizable materials such as dead plankton may have caused the metalimnetic minimum, but such data were not collected The simultaneous occurrence of anaerobic conditions in the upstream part of the reservoir suggests that the upstream source of low oxygen water may in some way be related to, although somewhat modified, the inverse distribution of dissolved oxygen in the shallow downstream part of the reservoir

Further study is required to identify the factors responsible not only for the metalimnetic minimum, but also for the occurrence of anaerobic conditions in the reaches of the reservoir near the tributaries

Anaerobic conditions were observed in the hypolimnion during all sampling periods The lack of mixing of the water in this zone with the overlying waters was conducive to a reducing environment, which resulted in a complete removal of dissolved oxygen The volume of water in the hypolimnion appeared constant, and the volume represented by the hypolimnion was less than 5 percent of the total volume of the reservoir Mixing of the hypolimnetic waters with overlying waters or the release downstream of such mixed water, however, would be detrimental to aquatic life in the river system should the resulting mixture contain less than about 5 mg/l of dissolved oxygen (McKee and Wolf, 1963, p. 181)

SPECIFIC CONDUCTANCE

The seasonal changes of specific conductance in the reservoir are shown on plate 1 The specific conductance in the two uppermost zones of the reservoir ranged from about 400 to 900 micromhos/cm at 25°C The lowest values were observed in the upper reaches of the reservoir, and the highest values were observed near the bottom of the metalimnion. Data collected during this study, as well as during previous years indicate that the specific conductance of the water in the hypolimnion remains essentially unchanged from season to season. The specific conductance in the hypolimnion during 1966–72 ranged from about 800 to 1,000 micromhos/cm at 25°C

The reservoir was more stratified with respect to specific conductance in the summer than in the spring. This was partly due to the spring inflow, which had a lower specific conductance and a higher temperature (thus lower in density) than the water in the reservoir Hence, the lower density inflow probably flowed over the more dense water in the reservoir The stratification was also partly due to the temperature gradient The lack of the temperature gradient in the spring allowed for deep circulation and most of the reservoir was nearly homogeneous with respect to specific conductance in the spring

HYDROGEN-ION ACTIVITY (pH)

Except for the hypolimnion and the lower metalimnion, the pH in the reservoir during 1971–72 ranged from 8.0 to about 8 9 The pH values in the reservoir above the hypolimnion were lower in the summer than in the spring The lower pH values probably resulted from precipitation of calcium carbonate when the water in the reservoir was heated during the summer

An inverse distribution of pH was observed in the upper part of the metalimnion during the summer and fall, coinciding with an inverse distribution of dissolved-oxygen concentration. These inversions are undoubtedly related, in that decomposition of organic matter decreased the dissolved-oxygen concentration and increased the carbon-dioxide concentration in the process, which in turn was indicated by the lower pH values.

The pH values were relatively unchanged in the hypolimnion during 1971–72, ranging from 7 5 to 7 7 The drop in pH values from the upper zones probably results from decomposition of organic matter as described above, but the values have remained nearly unchanged due to lack of mixing of the waters of the hypolimnion with overlying water

DOWNSTREAM EFFECTS OF CLOSURE

DEPLETION OF FLOW

At the end of the 1972 water year, the amount of water that passed the damsite[2] was about 4,500,000 acre-feet (5,550.8 hm^3) less than the calculated amount that would have passed the site if the dam had not been constructed (fig. 4). The depletion in flow represents water stored in the reservoir, water lost by evaporation, and water that is in bank storage Approximately, 3,500,000 acre-feet (4,317 2 hm^3) of water was stored in the reservoir at the end of 1972 The total evaporation for the 1963–72 period was estimated from Iorns, Hembree, and Oakland (1965, pl 6) to be about 700,000 acre-feet (863.4 hm^3) Therefore, about 300,000 acre-feet (370.0 hm^3) was in bank storage at the end of the 1972 water year

INCREASE OF DISSOLVED-SOLIDS CONCENTRATION BELOW THE RESERVOIR

An increase in the weighted-average dissolved-solids concentration was observed in the river below the reservoir after closure of the dam (fig. 5). The highest weighted-average dissolved-solids concentration was in 1963, when a minimum of water was released as the reservoir filled With the exception of 1965 and 1967, the weighted-average dissolved-solids concentration decreased from the 1963 high until 1972 when the weighted-average dissolved-solids concentration was only slightly greater than it was prior to closure of the dam.

The increase of dissolved-solids concentration after closure was due to leaching and evaporation. The weighted-average dissolved-solids concentration of the water that passed the sampling site below the dam (site D on pl 1), plus the water in the reservoir for the 1963–72 period, was about 505 mg/l (from figs 4 and 6) The evaporation from the reservoir during 1963–72 was about 700,000 acre-feet (863 4 hm^3) If the total volume of the river and the reservoir were increased by that amount, the weighted-average dissolved-solids concentration of the water that

[2] The discharge is actually measured at a gaging station on the Green River near Greendale, which is at site D on plate 1

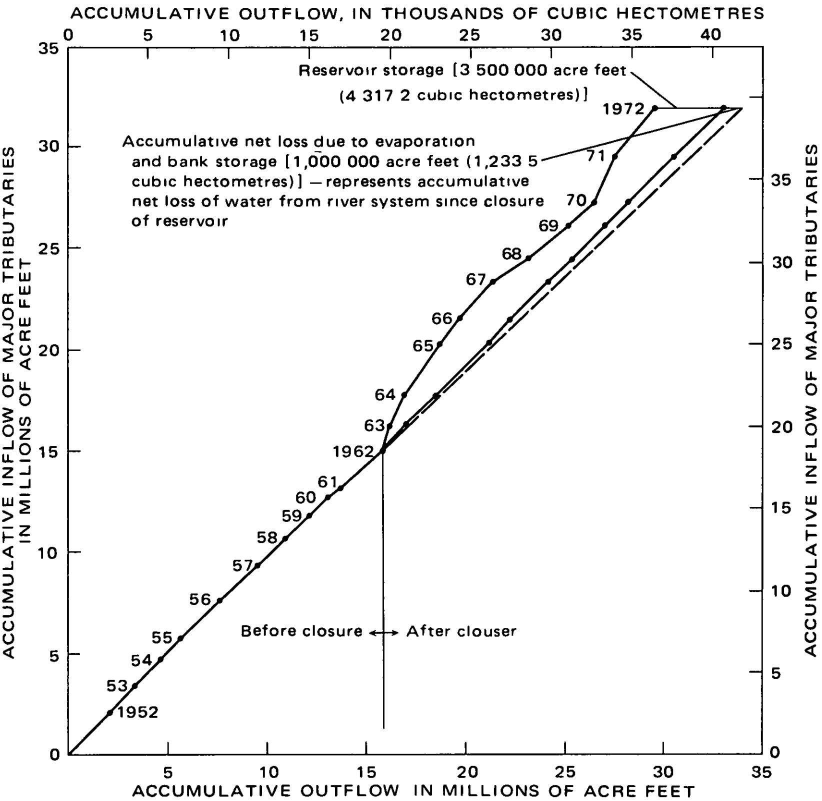


FIGURE 4 — Mass balance of major tributary inflow, outflow, and storage for Flaming Gorge Reservoir, 1952–72

would have passed sampling site D below the dam during 1963–72 would have been about 485 mg/l Comparison with the actual figure of about 505 mg/l indicates an increase of about 20 mg/l in dissolved-solids concentration due to evaporation during 1963–72 Madison and Waddell (1973, p 13) showed that for the 1963–68 period the weighted-average dissolved-solids concentration increased by about 15 mg/l as a result of evaporation Thus, the increase during 1969–72 due to evaporation was about 5 mg/l

The weighted-average dissolved-solids concentration that would have passed sampling site D below the dam during 1963–72 without the reservoir is about 405 mg/l (from figs 4 and 6), thus leaching and evaporation accounted for approximately a 100 mg/l increase in dissolved-solids concentration in the river below the reservoir The increased concentration due to leaching for 1963–72, therefore, was about 80mg/l, or about 80 percent of the total increase in dissolved-solids concentration after closure of the dam

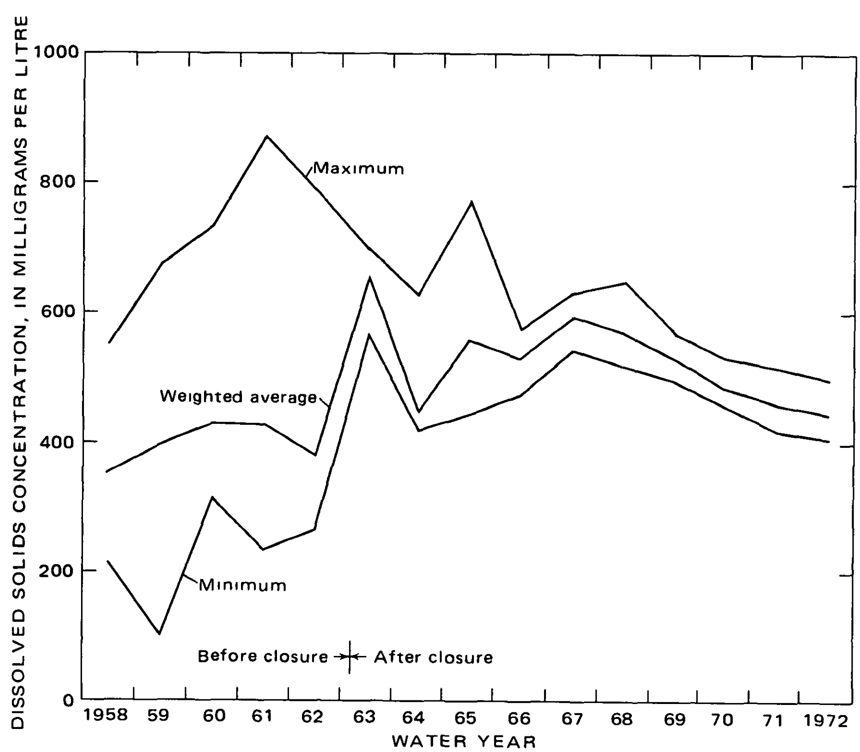


FIGURE 5 — Annual maximum, minimum, and weighted-average dissolved-solids concentration of the Green River below Flaming Gorge Reservoir (site D on pl 1) before and after closure of the dam

DISSOLVED-SOLIDS LOAD BALANCE

The loads of dissolved solids in the reservoir, the inflow and outflow loads, and the changes in net dissolved load due to leaching and chemical precipitation for the 1957–72 period are shown in figure 6 The load of dissolved solids in bank storage was not included in figure 6 because the average reservoir level does not change much after the initial filling of the reservoir, thus, the load loss due to bank storage does not change much either

The load of dissolved solids in the reservoir for the 1970–72 period was calculated using data from vertical sampling sites in the reservoir together with area-volume curves for the reservoir The inflow and outflow loads were calculated from streamflow and chemical-quality data for the major tributaries

The accumulative load of dissolved solids that should have passed sampling site D on the Green River (pl 1) without the reservoir at the end of 1972 was 14,530,000 tons (13,181,325 t) (dashed line in fig 6)

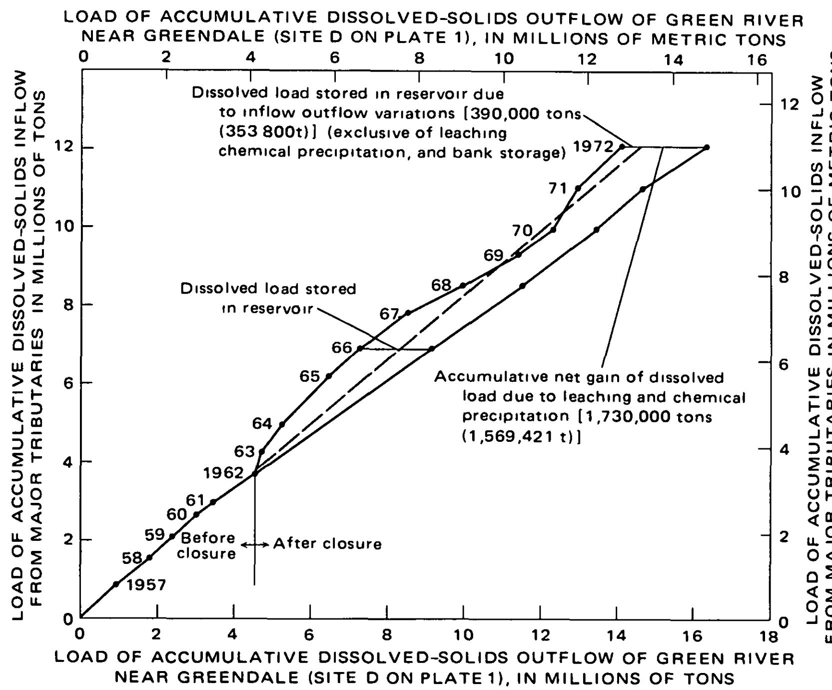


FIGURE 6 — Mass balance of inflow, outflow, and reservoir load of dissolved solids for Flaming Gorge Reservoir, 1957-72

The accumulative load of dissolved solids that did pass the sampling site at the end of 1972, plus the dissolved load in the reservoir, was 16,260,000 tons (14,750,747 t) Thus, the net gain to the river system resulting from the effects of leaching and chemical precipitation was 1,730,000 tons (1,569,421 t), all of which accumulated since 1963 Periodic net load changes, in millions of tons, are shown in the following table·

Time period (water year)	(A) Calculated reservoir load, end of period	(B) Calculated reservoir load, beginning of period	(C) Inflow load during period	(D) Outflow load during period	Net load change due to leaching and chemical precipitation end of period (A−B−C+D)
1963-66	---	---	---	---	[1]+0 80
1967-68	---	---	---	---	[1] + 40
1969-70	1 15	1 50	1 72	2 30	+ 23
1971-72	2 14	1 15	2 52	1 83	+ 30

[1]From Madison and Waddell (1973, pl 1)

The rate of leaching during 1969-70 was only about 115,000 tons (104,326 t) per year, or about 60 percent of the rate for 1963-68 (200,000 tons (181,436 t) per year) The rate decreased because during 1969-70 the water fluctuated through a range of levels previously occupied, levels where most of the readily soluble minerals had already been dissolved The leaching rate increased during 1971-72 to about 150,000 tons (136,077 t) per year, owing to the leaching of readily soluble minerals from rocks and soils that had not been previously inundated, as the reservoir water levels rose to alltime highs.

The leaching rate should decrease in the future, because the reservoir level during 1972 was within about 5 feet (1.5 m) of maximum pool level The area of rocks and soils in the remaining 5 feet (1 5 m) not yet inundated is a small percentage of the total area of rocks and soils affected by the reservoir water

VARIATION OF INDIVIDUAL IONS BELOW THE RESERVOIR

The weighted-average concentration of all the major dissolved inorganic constituents in the river below the reservoir for 1957-72 is shown in figure 7 The highest concentration of all the major ions, except magnesium, was in 1963, immediately after closure of the dam, and was probably due to initial inundation and leaching of rocks and soils in the reservoir area.

The sulfate ion showed the greatest variation—from about 115 mg/l and 42 percent of the anions in 1957 to a high of about 290 mg/l and 58 percent in 1963, and then to about 200 mg/l and 54 percent in 1972 The chloride ion showed the least variation—from about 12 mg/l and 6 percent of the anions in 1957 to about 23 mg/l and 7 percent in 1963, and then to about 19 mg/l and 5 percent in 1972 Although the concentration of the bicarbonate ion remained relatively constant within the range of 170 to 190 mg/l (except for 1963) in percentage of anions, it decreased from about 50 percent in 1957 to 40 percent in 1972 because of proportionately more leached sulfate in the water

VARIATIONS OF TEMPERATURE BELOW THE RESERVOIR

The range of average monthly temperatures of the Green River below the reservoir has been reduced considerably since closure of the dam (fig 8) Prior to closure the average monthly temperatures ranged from 0°C to 19 5°C as compared to 3.5°C to 10 0°C after closure The reservoir not only reduced the magnitude of variation in temperature but also changed the time period of the high and low temperatures Prior to closure the lowest temperature was in the period December to February and the highest in July, after closure the lowest temperature was in March and the highest was in November

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FIGURE 7 (next pages) — Annual weighted-average percent composition and concentration of major dissolved constituents of the Green River below Flaming Gorge Reservoir (site D on pl 1) before and after closure of the dam

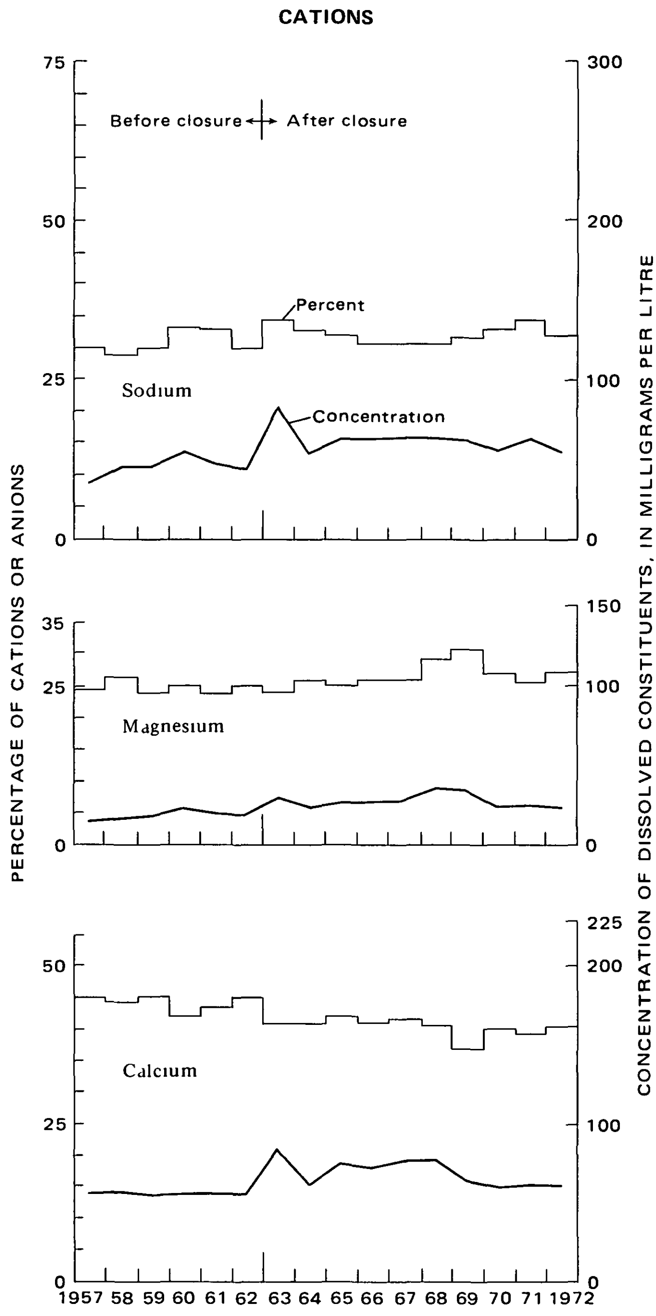

FIGURE 7 (caption on previous page)

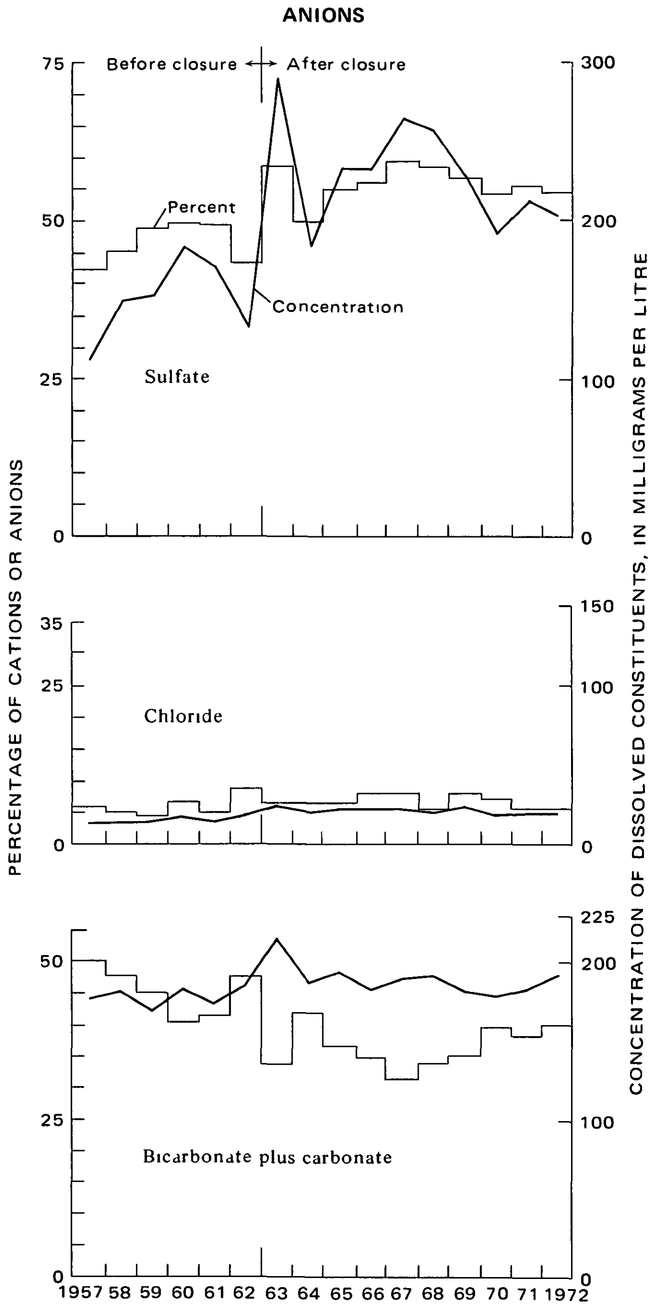

FIGURE 7 — Continued

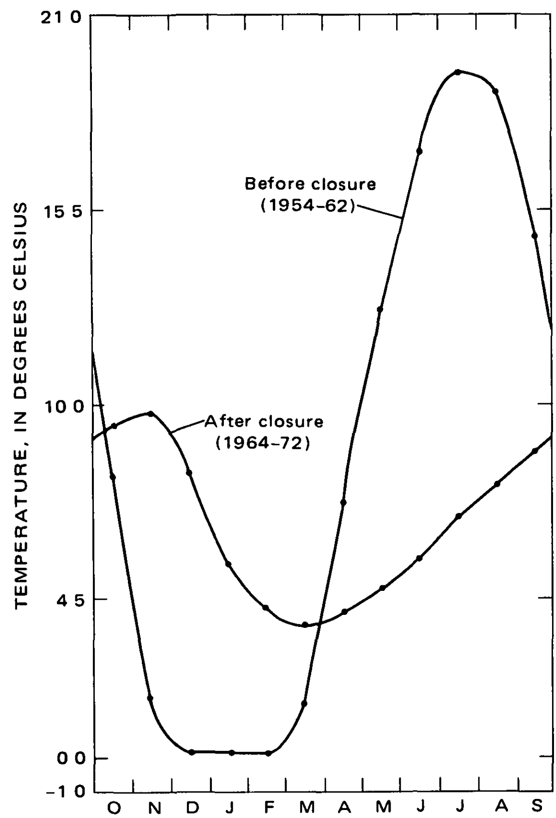

FIGURE 8 — Average monthly temperature of the Green River below Flaming Gorge Reservoir (site D on pl 1) before and after closure of the dam

RECOMMENDATIONS FOR FUTURE STUDIES

Flaming Gorge Reservoir is an important regional recreational area centered on water-based activities such as boating and fishing Even more importantly, the reservoir affects the downstream quality of the Colorado River, a matter of major national and international concern Further studies are needed in Flaming Gorge Reservoir to:

1 Continue evaluation of leaching rates in the Flaming Gorge Reservoir area as they affect the downstream water quality. Past and present studies of the reservoir show that a substantial amount of minerals are added to the Colorado River system by leaching of rocks and soils inundated by the reservoir Evaluation of leaching rates, together with the other aspects of water quality, form the basis for the U S Geological Survey's contribution to the biennial

report to Congress on the quality of water in the Colorado River basin

2 Evaluate the effect of possible irrigation development on the inflowing tributaries to Flaming Gorge Reservoir A proposed irrigation development project on the headwaters of Blacks Fork has caused much local concern This tributary contributes a high percentage of solutes to the reservoir (relative to its water discharge) Also anaerobic conditions have been observed in the upper part of the reservoir near the confluence of Blacks Fork and the Green River during part of the summer months Proposed reservoirs for irrigating land in the Blacks Fork drainage area would most likely alter the chemical quality of water impounded by the proposed reservoirs as well as the water in the river downstream from the irrigated areas, which in turn would affect the water quality in Flaming Gorge Reservoir

3 Determine the source of anaerobic or near-anaerobic conditions existing in the shallow parts as well as the upstream reaches of the reservoir Because of the importance of dissolved oxygen to the propagation of fish and other aquatic life in the reservoir, the source and extent of the dissolved-oxygen depletion should be delineated

4 Construct a model to evaluate and predict effects on the reservoir of such occurrences as upstream irrigation development and oil shale processing The model will allow for evaluation of these effects by first establishing how the reservoir reacts to historic inflow data, and then by varying the inflow volumes and loads observe the reaction in the reservoir model The model will also facilitate evaluation of downstream effects of the reservoir and provide a basic tool that will aid in evaluating projects in other areas of the utilized upper Colorado River system.

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