RESERVOIR SEDIMENT-WATER MICROCOSM SIMULATION: PRE-IMPOUNDMENT PREDICTIONS VS. OBSERVED WATER QUALITY AT RIDGWAY RESERVOIR, RIDGWAY, COLORADO

Science and Technology Program Research Report

by

Douglas Craft and Jerry Miller

September 2001

U.S. Department of the Interior
Bureau of Reclamation

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
September 2001

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Reservoir Sediment-Water Microcosm Simulation: Pre-Impoundment Predictions vs. Observed Water Quality at Ridgway Reservoir, Ridgway Colorado

5. FUNDING NUMBERS
.

6. AUTHOR(S)
Douglas Craft and Jerry Miller

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Bureau of Reclamation
Denver Federal Center
P.O. Box 25007
Denver, CO 80225-0007

Bureau of Reclamation
Upper Colorado Regional Office
125 South State Street, UC-242
Salt Lake City, UT 84138-1102

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Available from the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Sediment-water microcosm simulation was used to predict post-impoundment hypolimnetic water quality at Ridgway Reservoir, Ridgway, Colorado, U.S.A. Reservoir basin soils and one river sediment were combined with Uncompahgre River water in 55-gal tanks, and water was sampled and analyzed before and after bacterially mediated reducing conditions developed. After completion of Ridgway Dam, the inflow streams, the reservoir, and outflow were sampled and analyzed on a monthly schedule from March 1987 to October 1996 for major ions, nutrients, and trace elements. Ridgway Reservoir contains 59,400 acre-ft (7.33×10^7 m^3) of active water storage, has a surface area of 1,030 acres (417 Ha) at normal water surface elevation of 6,871 ft. (2,094 m), and is approximately 200 ft (61 m) deep behind the dam. Despite extensive mine wastes and acidic drainage in the upper elevation reaches of the watershed, Ridgway Reservoir is an oligotrophic lake that has very low algal productivity and very good water quality. Reservoir median pH was 8.14 and dissolved solids ranged from 200 to 500 mg/L. Generally low total phosphorus concentrations (median = 8.0 µg/L) and elevated total nitrogen:total phosphorus ratios (median ratios for unfiltered samples ranging from 26 to 52) suggest that the lake is phosphorus-limited. The post impoundment data also suggest that the reservoir improves downstream water quality by reducing inflow concentrations of trace elements and nutrients, with total nitrogen loading reduced by 38 percent and total phosphorus loading reduced by 77 percent. Because of a lake bottom outlet in the dam and hypolimnion mixing from outlet operations, anoxic and reducing conditions at depth were not commonly observed during summer sampling. A comparison of simulation data with post impoundment chemistry revealed that microcosm simulation reasonably predicted median reservoir behavior. Both simulation and post-impoundment chemistry data are presented, and modifications of simulation methodology and considerations regarding differences between soils and sediments are discussed.

14. SUBJECT TERMS- - reservoir simulation, microcosms, water quality, prediction, sediments, hypolimnion, lake chemistry

15. NUMBER OF PAGES
103

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UC	UC	UC	UC

RESERVOIR SEDIMENT-WATER MICROCOSM SIMULATION: PRE-IMPOUNDMENT PREDICTIONS VS. OBSERVED WATER QUALITY AT RIDGWAY RESERVOIR, RIDGWAY, COLORADO

Science and Technology Program Research Report

by

Douglas Craft[1] and Jerry Miller[2]

September 2001

[1] U.S. Department of the Interior - Bureau of Reclamation
Technical Service Center
Fisheries Applications Research Group, D-8290
PO Box 25007, Denver CO 80225-0007

[2] U.S. Department of the Interior - Bureau of Reclamation
Upper Colordo Regional Office
125 South State Street, UC-242
Salt Lake City, UT 84138-1102

MISSION STATEMENTS

The Mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

TABLE OF CONTENTS

Page

Tables

Table of Contents - continued

Page

Figures

Table of Contents - continued

Table of Contents - continued

Page

Table of Contents - continued

Page

EXECUTIVE SUMMARY

This study compares reservoir water quality predicted using the technique of sediment-water microcosm simulation (Gunnison, et al., 1980; Craft, 1985) with post-impoundment water quality from inflow streams, lake, and reservoir outflow. The microcosm simulation study was performed during construction of Ridgway Dam to assess the environmental effects of a proposed design change from a multi-level outlet to a single bottom outlet. During dam construction, soils and river sediments were collected from the empty basin of Ridgway Reservoir and combined with water collected from the Uncompahgre River. Soils, sediment and river water were combined in 55-gallon microcosm tanks to simulate the future lake bottom. Microcosms were sealed, and the simulation water was sampled and analyzed as bacterial activity in the sediment-water systems progressively changed the water chemistry from aerobic and oxidizing to anaerobic and reducing. The results of the microcosm simulation experiment were then compared with statistical summaries of post-impoundment chemistry data from water samples collected and analyzed from 1987 to 1996.

Ridgway Reservoir was completed in 1987 and first filled to capacity in 1990. The current active storage capacity of Ridgway Reservoir is 59,400 acre-ft (7.33×10^7 m^3), and the surface area of the reservoir at normal water surface elevation of 6,871 ft. (2,094 m) is 1,030 acres (417 Ha). Behind the dam, the reservoir is approximately 200 ft (61 m) deep (Bureau of Reclamation, 2000), and the reservoir currently operates with a single-level outlet positioned near lake bottom.

Runoff in the watershed is dominated by the annual spring snowmelt, which peaks in late May through mid-June, with average daily inflow peaks ranging from 700 to 1,800 cfs (20,000 to 50,000 L/s). Occasional summer storm events also produce localized episodic runoff. Streamflow data from the U.S. Geological Survey (USGS) indicate that the upper elevation Uncompahgre River sub basin accounts for about 70 percent of runoff, with the Dallas Creek sub basin contributing about 22 percent of annual runoff. Streamflow discharge data from gage stations were used to calculate flow-weighted loadings from nutrient and trace element concentrations.

Despite widespread abandoned mine wastes in the upper elevations of the Uncompahgre River sub basin, post-impoundment chemistry data revealed that water quality in Ridgway Reservoir is very good. Total dissolved solids (TDS) in Ridgway Reservoir ranged from 205 to 478 mg/L, and pH varied from 7.64 to 8.47. Major ions in the water are dominated by calcium (Ca), magnesium (Mg), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-). The SO_4^{2-} derives from oxidation of sulfide minerals, and the Ca, Mg, and HCO_3^- come from dissolution of limestone conglomerate deposits abundant in the watershed geology.

Algal productivity and dissolved phosphorus (P) concentrations are currently very low (filtered P average = 0.006 mg/L), and the total nitrogen (N) to total P (TN:TP) ratio (Downing and McCauley,1992) ranges from 26 to 52. Insoluble mineral forms of phosphorus (as apatite and hydroxyapatite) were also observed in reservoir sediments, suggesting that Ridgway Reservoir is phosphorus limited and oligotrophic. Although some trace elements were occasionally observed at elevated concentrations in the Uncompahgre River and Dallas Creek, particulate settling and denitrification in the lake appears to improve downstream water quality for both nutrients and trace elements. Loading data revealed that Ridgway Reservoir is currently a net sink for nutrients (N and P) and trace elements, with about 38 percent of TN and 78 percent of TP being removed by reservoir processes. Few exceedances of water quality standards were observed.

Ridgway Reservoir does thermally stratify during summer; however, complete anoxia and chemically reducing conditions were not observed during post-impoundment sampling. Sediment-water simulation suggested that the hypolimnion would not rapidly develop anoxia and reducing conditions during thermal stratification episodes. Concentrations for the major ions and nutrients in the microcosms were greater than median, but less than maximum concentrations observed in post-impoundment waters. The simulation data suggest that phosphorus releases from reducing sediments will probably not be significant, and that denitrification is active before reducing conditions develop.

The post-impoundment reservoir data generally support the simulation concentrations for iron (Fe), manganese (Mn), and zinc (Zn). Both Fe and Mn showed increased concentrations as reducing conditions in the microcosms intensified, but Zn appeared to fall in concentration after anoxia developed. Reservoir dissolved Fe ranged from <3.0 to 100 µg/L, which compared with <1.00 to 332 µg/L in the microcosms. Reservoir dissolved Mn ranged from <4.00 to 549 µg/L whereas microcosm water ranged from <1.00 to 690 µg/L. Reservoir dissolved Zn ranged from <4.00 to 50.0 µg/L whereas microcosm Zn ranged from 6.10 to 125 µg/L. No other measured trace elements were significantly above detection limits in the microcosms, including the microcosm that contained Uncompahgre River sediments. Except for Zn, simulation results suggest that filling basin soils and river sediment will only contribute minor amounts of toxic trace metals to hypolimnetic waters under reducing conditions.

Reservoir sediments, however, do contain elevated trace element concentrations compared with the simulation soils, so sediments may provide a source of toxic metals if reservoir productivity and anoxia in the hypolimnion increase. Measurable dissolved concentrations of arsenic were rarely observed in the reservoir (maximum = 3.00 µg/L), but As was routinely detected in inflow water (median = 4.16 µg/L). Dissolved Pb was observed in inflows, but rarely in reservoir water (maximum = 3.00 µg/L), but was mostly below detection limits in the microcosms.

Although water quality is currently very good at Ridgway Reservoir, development and land use in the near vicinity of the lake could eventually lead to eutrophication and associated water quality problems. Besides nuisance algal blooms and odor, eutrophication and increased deposition of plankton could produce greater hypolimnetic anoxia and releases of other trace elements that currently remain bound to reservoir sediments. Given the reliable detection of Hg in the Uncompahgre River, Hg bioaccumulation through the food chain may be a problem if productivity increases significantly. Consequently, it would be wise to continue to monitor water quality at Ridgway Reservoir.

Despite the problems associated with tank leaks and temperature control in this study, microcosm simulation produced a reasonably accurate prediction of reservoir conditions that was supported by subsequent post-impoundment data. This study suggests that microcosm simulation, within reasonable limitations, is a valid water quality assessment tool. The authors recommend that researchers planning simulation experiments consider a smaller scale and more cost-effective approach that uses many smaller (500 mL) microcosms (Craft, 1985). Smaller vessels allow reliable sealing of microcosms, handling convenience, better and cheaper temperature control, and less alteration of *in situ* redox conditions.   Redox potentials in anaerobic samples are maintained by preparing samples in a controlled-atmosphere glove box.

The issues surrounding use of soil vs. sediments should also be considered by researchers planning reservoir simulations. Soils and sediments may have very different physical and chemical properties that affect trace element and nutrient adsorption and releases under reducing conditions.

INTRODUCTION

This study compares post-construction reservoir water quality with the chemistry predicted prior to filling using sediment-water microcosm simulation. The simulation approach involves combining reservoir basin soils and river sediments with river water in sealed tanks. Then water samples are collected and analyzed over time as the sediment-water systems become anoxic and develop reducing conditions. Microcosm simulation (Gunnison, et al., 1980; Messer, et al., 1984) has been applied to assess sediment-water processes, and was used here to predict whether sediments would contribute trace elements to the hypolimnion when anoxic conditions formed in the reservoir hypolimnion after filling.

The original design for Ridgway Dam specified a multi-level outlet structure for downstream temperature control to enhance cold water fishery habitat. Because of the amount of past mining activity in the upper reaches of the Ridgway Reservoir watershed and the potential for toxic trace element transport by acid mine drainage, there was concern regarding trace element inputs to the reservoir and what might happen if the reservoir remained stratified for extended periods. Microcosm simulation was performed to support a design change to a less expensive, single-level, hypolimnion outlet which was proposed during the early phases of construction.

Ridgway Dam and Reservoir

Ridgway Dam, seen in figure 1, was constructed for the Bureau of Reclamation's Dallas Creek Project and was authorized by Congress in 1968 as part of the Colorado River Storage Project. The Dallas Creek Project is named after a tributary of the Uncompahgre River whose confluence is near the reservoir inflow zone. The project was constructed to provide water for irrigation, municipal and industrial use, and snowmelt runoff flood control for ranches, farms, and towns in Montrose, Delta, and Ouray counties. This water is distributed through existing facilities by the Tri-County Water Conservancy District or other water users (Bureau of Reclamation, 2000). The annual water supply for irrigation averages 11,200 acre-ft (1.38×10^7 m^3) and 28,100 acre-ft (3.47×10^7 m^3) are available for municipal and industrial uses in the towns of Colona, Montrose, Olathe, and Delta, and the surrounding rural areas. The primary water sources for the Dallas Creek Project include the Uncompahgre River, Dallas Creek, and Alkali Creek.

The Colorado map (figure 2a) and shaded relief watershed map (figure 2b) show the geographic features of the Dallas Creek Project. The reservoir is located on the Uncompahgre River near the western Colorado town of Ridgway at latitude 38˚09' N, longitude 107˚45' W. The dam is a rolled earthfill structure that was constructed from 1978 to 1987. Ridgway Dam contains 10,900,000 cubic yards (8.33×10^6 m^3) of compacted earthfill and rises to a height of 234 ft (71.3 m) above the original Uncompahgre River streambed. The dam crest, at elevation 6,886 ft (2,099 m), is 2,460 ft (750 m) long and 30 ft (9.1 m) wide. Figures 3a, 3b and 3c show several scenic views of Ridgway Reservoir.

The reservoir basin was cleared of vegetation and graded before impoundment, and was first operated at capacity during 1990. The reservoir has a maximum storage capacity of 84,410 acre-ft (1.04×10^8 m^3) and extends southward up the Uncompahgre River for

Figure 1.—Aerial view looking south at Ridgway Dam and reservoir (Bureau of Reclamation, 2000).

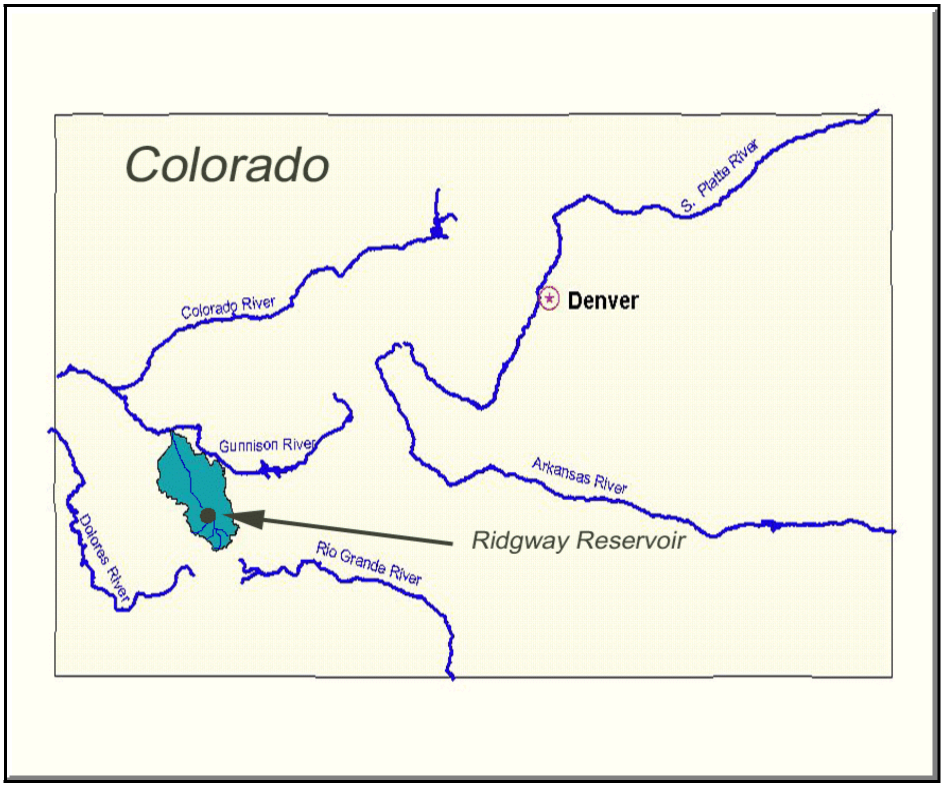


Figure 2a.—Colorado map showing general location of Ridgway Reservoir.

Figure 2b - Watershed Map

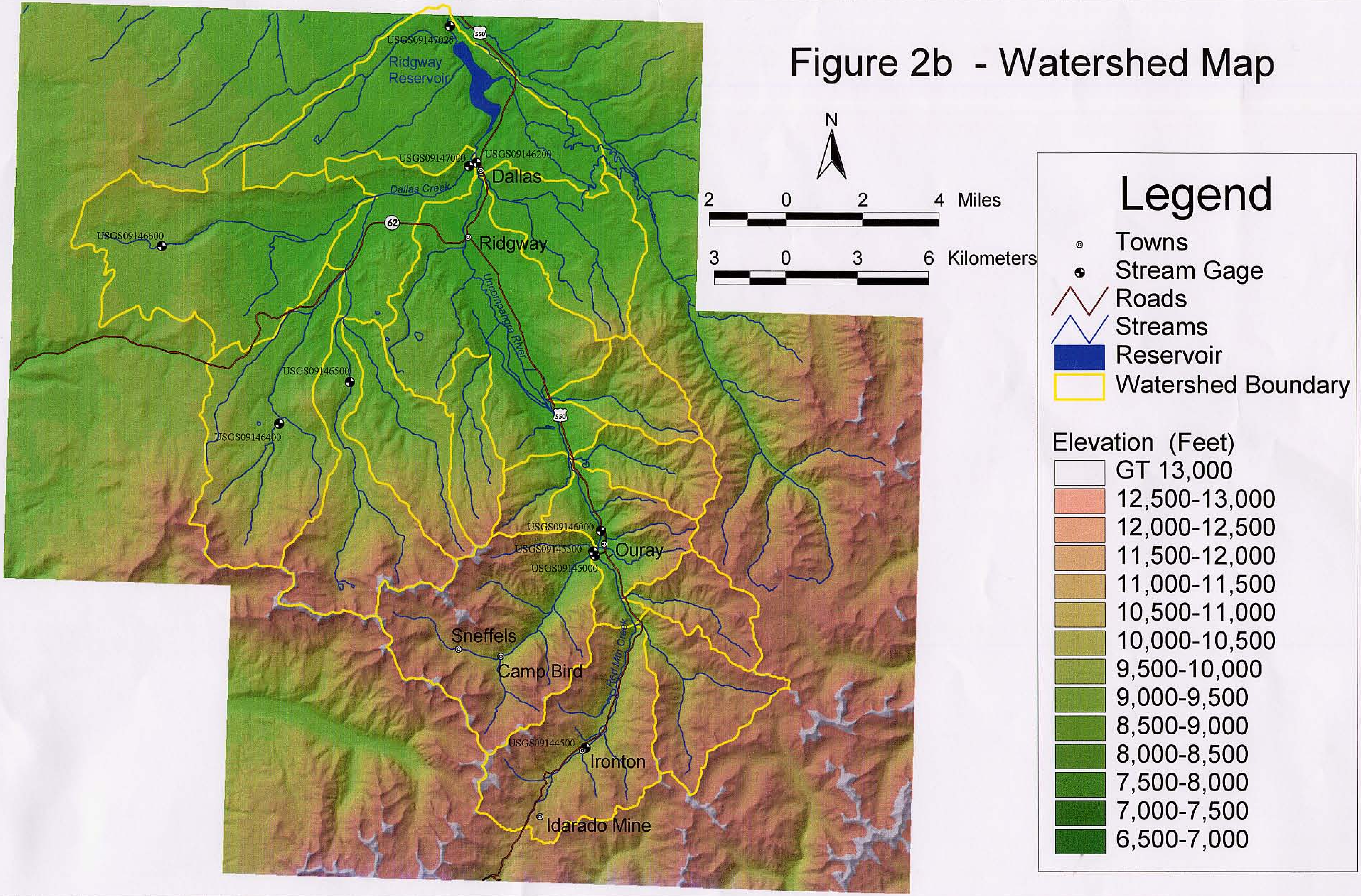


Figure 3a.—View of Ridgway Reservoir looking north from the camping area.

Figure 3b.—View of Ridgway Reservoir looking south from the Overlook Path towards the San Juan Mountains.

Figure 3c.—View of the inflow mixing zone where the Uncompahgre River enters Ridgway Reservoir, looking north.

4.6 mi (7.40 km), with a 1-mile (1.61-km) branch up the drainage of Alkali Creek. Active storage capacity is 59,400 acre-ft (7.33 X 10^7 m^3) and inactive capacity is 25,000 acre-ft (3.08 X 10^6 m^3). The surface area of the reservoir at the normal water surface elevation of 6,871 ft (2,094 m) is 1,030 acres (417 Ha), and the reservoir is approximately 200 ft (61 m) deep behind the dam (Bureau of Reclamation, 2000).

Ridgway Reservoir also provides recreational facilities for fishing, picnicking, camping, boating, swimming, and hiking. Park facilities, including a waste treatment plant for campground sewage, are administered by the State of Colorado Division of Parks and Outdoor Recreation. Figures 4a, 4b, and 4c, respectively, show the main boat ramp, the marina, and swimming beach at Ridgway Reservoir. Total visitation was 629,000 during 1996.

Fishing at Ridgway Reservoir is generally reported as “slow,” and the reservoir is usually stocked in the spring with rainbow trout, *Salmo gairdneri*, along with kokanee salmon, *Oncorynchus nerka kennerlyi*, from the National Fish Hatchery in Hotchkiss, Colorado. The reservoir also has a population of brown trout, *Salmo trutta*, which existed prior to impoundment in the Uncompahgre River and Dallas Creek.

Watershed Topography, Climate, and Land Use

The watershed drainage area above Ridgway Reservoir (figure 2b) covers approximately 260 mi^2 (673 km^2) and consists of the main stem and tributaries of the Uncompahgre River to the south and southeast and Dallas Creek and its tributaries to the southwest.

Figure 4a.—The main boat launching ramp at Ridgway Reservoir, looking north.

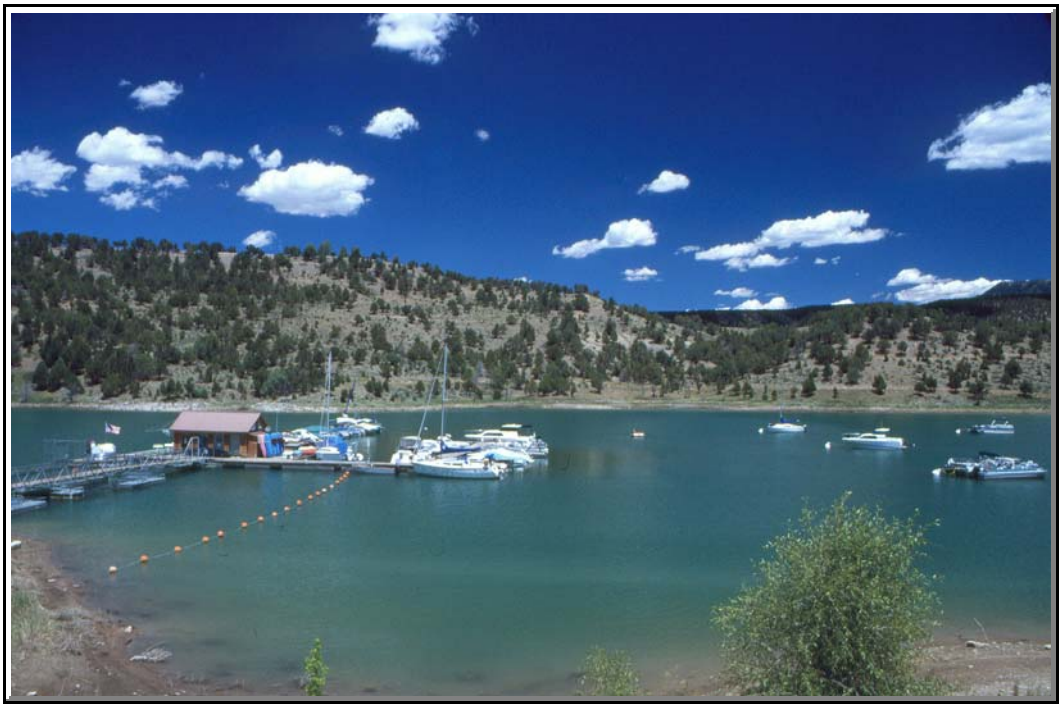


Figure 4b.—View of the marina at Ridgway Reservoir, looking east.

Figure 4c.—The swimming beach and recreation area at Ridgway Reservoir.

Production of livestock, predominantly cattle and sheep, is the leading land use in the watershed at elevations below 7,500 ft (2,290 m). These lowlands cover approximately 133 mi^2 (345 km^2), 51 percent of the watershed area. Lower elevation crops consist primarily of livestock feeds such as alfalfa, meadow hay, pasture, and small grains. Irrigated lands in the area also produce pinto beans, malt barley, shelling and ensilage corn, alfalfa, onions, and fruit. The climate near the reservoir is semi-arid with annual precipitation (based on weather data from Montrose, Colorado, from 1961 to 1990) ranging from 5.6 to 15 in. (14.2 to 38.1 cm), with an average of 9.7 in. (24.6 cm). The mean annual temperature, based on Montrose data from 1900-1996, is 48.8˚F (9.33˚C), with extremes of -27˚F (-32.8˚C) in 1905 and 106˚F (41.1˚C) in 1947. The average growing season is 150 days for irrigable lands at elevations from 4,950 ft (1,509 m) to 6,400 ft (1,951 m) (Bureau of Reclamation, 2000). Since its filling, Ridgway Reservoir has experienced significant ice formation only during the winters of 1991-1992 and 2000-2001.

South of Ouray, Colorado, and southwest up the Dallas Creek sub basin, the topography is mountainous and rises to elevations above 14,000 ft (4,267 m), giving the watershed an elevation gradient of approximately 7,200 ft (2,195 m). Uplands above 7,500 ft (2,290 m) account for approximately 127 mi^2 (329 km^2), or approximately 49 percent of the watershed. The climate in the uplands is alpine and most precipitation falls as snow producing spring snowmelt runoff inflows. Summer thunderstorms also produce episodic runoff events.

The southern uplands of the watershed were extensively mined for silver, gold, lead, and zinc beginning in the late 1800s. A notable example of historic mining activity is the Idarado Mine. This site was the first large Superfund hazardous waste site cleanup project in a basin extensively contaminated by mine tailings and mill waste deposits (figs. 5a, 5b, 5c). This area is drained by the upper reaches of the Uncompahgre River, Red Mountain Creek, Canyon Creek, Bear Creek,

Figure 5a.—Mine wastes in the upper elevations of the watershed along Red Mountain Creek. This view is looking northwest near the site of Ironton, Colorado, visible from Highway 550.

Figure 5b.—Uncompahgre River just below the confluence with Red Mountain Creek in the upper elevations of the watershed. Note the brown-yellow cast of the water associated with acid mine drainage.

Figure 5c.—A tailings deposit remediation project north of the Idarado Mine. The materials have been covered, revegetated, and a drainage system has been installed (lined channels in the foreground).

and several small creeks and drainage gulches. Most of the streams and gulches receive acidic mining activity and remediation of several major tailings deposits, the mine drainages continue to contribute acidity and toxic metals to the watershed. This sub basin contains 47 peaks above 13,000 ft (3,960 m) and 67 peaks from 12,000 to 13,000 ft (3,660 to 3,960 m). Notable peaks above 13,000 ft include Mt. Potosi, Gilpin Peak, Mt. Emma, United States Mountain, Chicago Peak, Trico Peak, Hurricane Peak, Tuttle Mountain, Houghton Mountain, Siegal Mountain, and Engineer Mountain.

In the Dallas Creek sub basin (figs. 6a and 6b), mining was much less intensive and current mining activity is nearly nonexistent. Principal land use in this 97 mi^2 (250 km^2) sub basin is ranching and recreation on national forest lands. This area contains many springs and geothermal sources that contribute mineralized runoff to the watershed. The uplands of this sub basin include 13 peaks above 13,000 ft, including Mears Peak, Wolcott Mountain, Mt. Sneffels (elevation 14,150 ft, 4,313 m) (fig. 6b), Potosi Peak, Cirque Mountain, Teakettle Mountain, Mt. Ridgway, and Whitehouse Mountain.

Watershed Geology

The Ridgway Dam site is in the southeast quarter of the Uncompahgre plateau near the boundary between the Uncompahgre Plateau and the San Juan Mountains. The Uncompahgre Plateau, a subdivision of the Colorado Plateau physiographic province, is an uplifted fault block that is tilted to the northeast and extends 75 mi (121 km) to the northwest from the base of the San Juan Mountains. The Uncompahgre Plateau is composed of sedimentary rocks ranging in age from the upper Jurassic to the upper Cretaceous. It also includes units of the Entrada sandstone, the

Figure 6a.—A view of the Dallas Creek watershed and the San Juan Mountains looking south from near the Dallas Divide.

Figure 6b.—Mt. Sneffels (center left) and Potosi Peak (far left), two intrusive volcanic mountains in the upper elevation reaches of the Dallas Creek sub basin.

Morrison Formation, the Dakota Group, and the Mancos Shale. These sedimentary rocks are intruded locally by granodiorite and quartz monzonite stocks, sills, and dikes of upper Cretaceous and Eocene ages (Bureau of Reclamation, 1979).

During the Pleistocene Epoch, glaciers from the San Juan Mountains moved northward into the portion of the Uncompahgre Plateau south of Ridgway Reservoir. Unsorted bouldery till deposits and sorted outwash sands and gravels from several glacial episodes are present in the area between the towns of Ridgway and Montrose. Post glacial deposits consist of Holocene and Pleistocene landslide deposits and Holocene alluvium. At the dam site, the Holocene alluvium deposited by the Uncompahgre River has been eroded through the Mancos shale and Dakota Group, cutting deeply into the Morrison Formation.

South of the town of Ouray, metamorphosed and tilted Precambrian sedimentary deposits are covered by Tertiary volcanic rocks from several periods of volcanism that formed the San Juans Mountains. Magma intruding into marine limestones (such as the Leadville Limestone) and older sedimentary deposits associated with the Laramide Orogeny helped create some of the richly mineralized veins of precious metals at intrusive contact boundaries. A visible example of such an intrusion is the “blowout” of yellow-brown limonite seen on the canyon wall east of Ouray.

Uplift of the area and subsequent erosion before Oligocene times helped create extensive deposits of the Telluride Conglomerate, which is as deep as 350 ft in places. The Telluride Conglomerate is a loosely-consolidated matrix of limestone-rich rocks and gravel that represents ideal sites for mineralization and for neutralizing acidic mine drainage. The volcanic geology and faulting of the San Juans also created numerous hydrothermal groundwater sources and springs. Notable examples include the Ouray Municipal Hot Springs, Orvis Hot Springs along the Uncompahgre River, and numerous small springs in the Dallas Creek sub basin.

Watershed Hydrology

The Ridgway Reservoir watershed is located within the upper elevations of the Uncompahgre River Basin, U.S. Geological Survey's (USGS) hydrologic unit code 14020006 (see fig. 2a map). Average annual discharge at Ridgway Dam is 167,000 acre-ft (2.06 X 10^8 m^3). This discharge is currently monitored by USGS gaging station 09147025 (Uncompahgre River below Ridgway Reservoir, Colorado). Upstream of Ridgway Reservoir, stream flows are monitored at USGS gaging stations 09147000 (Dallas Creek near Ridgway, Colorado) and 09146200 (Uncompahgre River at Ridgway, Colorado). Figures 7a, 7b and 7c show graphs of flow discharges and reservoir elevations for water-years 1993 through 1996.

Table 1 provides area and flow data for additional watershed sub basins obtained from historical stream flow monitoring data (U.S. Geological Survey, 1999). All area and discharge percentages were calculated using area and discharge information reported for the USGS gage on the Uncompahgre River downstream of Ridgway Dam (09147025). Since Ridgway Reservoir was not completely filled until 1990, a 1992 -1995 period of record was chosen to calculate median and minimum flows. Because historical stream flow data cover several different periods of record with varying precipitation years, comparisons of median and minimum average flows are qualitative. Figure 8 plots monthly average daily discharge for several table 1 stream gages. June is the month of maximum runoff flow for the Ridgway Reservoir watershed.

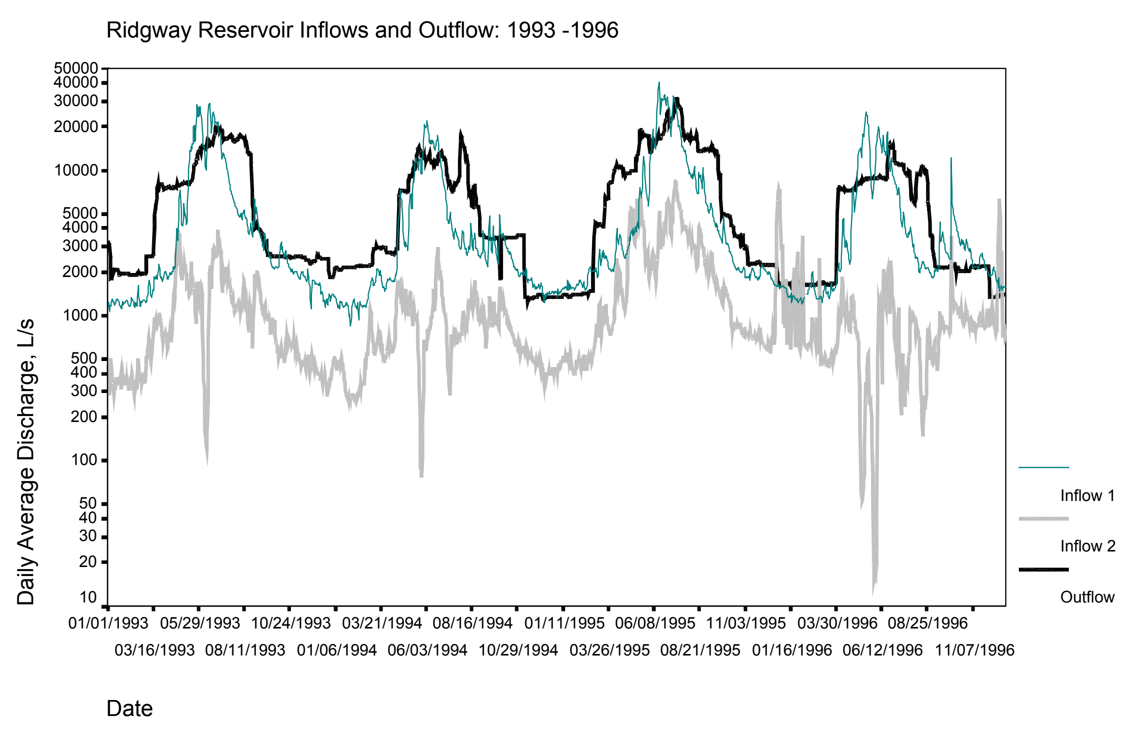


Figure 7a.—Daily average flow discharge measured at USGS gagling stations for Inflow 1 (Uncompahgre River), Inflow 2 (Dallas Creek) and Outflow (below Ridgway Dam).

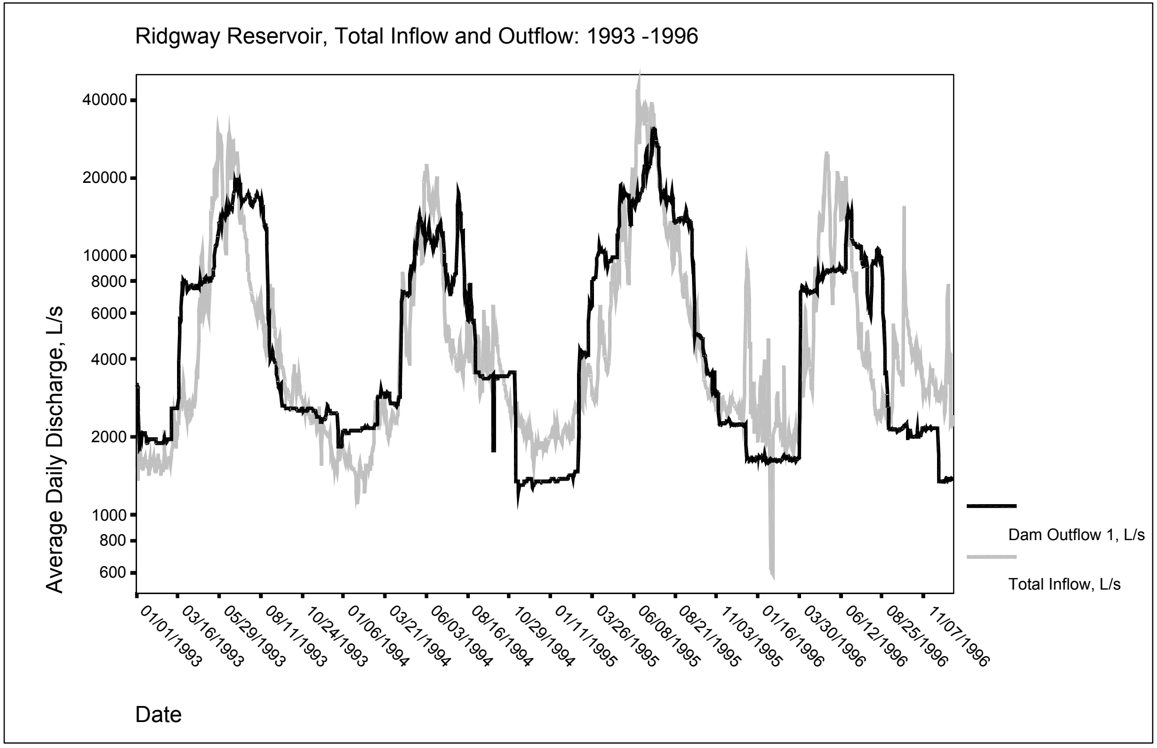


Figure 7b.—Daily average flow discharge measured at USGS gagling stations for all inflows (Inflow 1 + Inflow 2) and the outflow below Ridgway Dam.

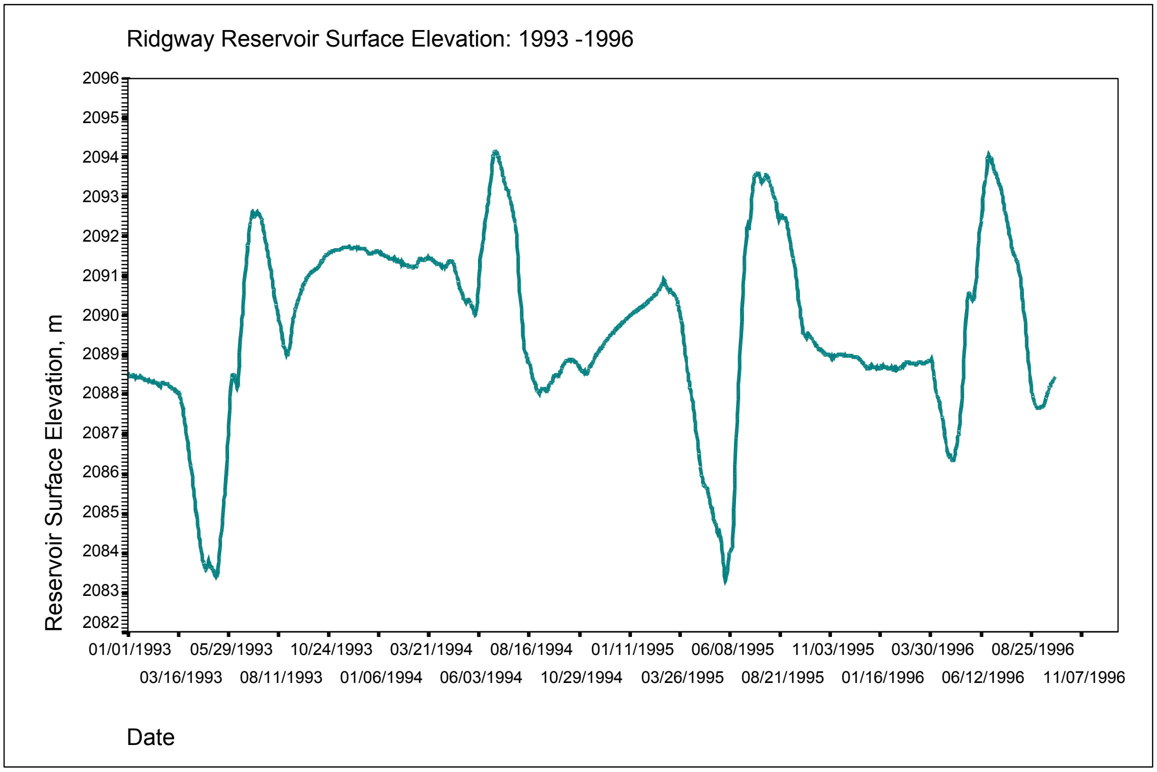


Figure 7c.—Daily average reservoir surface elevations, in m.

Table 1.—Sub basins in the Ridgway Reservoir watershed. Basins within sub basins are indented. Flow comparisons are based on median and minimum calculations for daily average flow in cfs for the indicated period of record. Flow percentages are based on comparison to the summed flows

Sub Basin Description	USGS Gage Station	Gage Elevation ft.	Sub Basin Area		Daily Summary Streamflow				Period of Record
					Median Flow		Minimum Flow		
			mi^2	Percent	cfs	Percent	cfs	Percent	
Uncompahgre River below Ridgway Dam	9147025	6,550	260.00	100.00	125.0	100.0	41.50	100.0	1992-1995
> Dallas Creek near Ridgway	9147000	6,980	97.20	37.40	27.0	21.6	0.410	0.990	1988-1995
>> East Fork Dallas Creek	9146500	7,980	16.80	6.50	--	--	--	--	1960-1967
>> West Fork Dallas Creek	9146400	8,400	14.10	5.40	--	--	--	--	1960-1967
>> Pleasant Valley Creek	9146600	8,680	8.20	3.10	--	--	--	--	1960-1967
>> Misc. Lower Elevation	see above	<7,980	58.10	22.40	--	--	--	--	NA
>Uncompahgre River near Ridgway	9146200	6,880	149.00	57.30	88.0	70.4	28.00	67.50	1988-1995
>> Uncompahgre River at Ouray	9145000	7,800	24.00	9.20	28.0	22.4	6.00	14.50	1911-1915
>>> Red Mountain Ck at Ironton	9144500	9,590	18.00	6.90	13.0	10.4	3.00	7.23	1947-1955
>> Canyon Creek at Ouray	9145500	7,750	25.80	9.90	18.0	14.4	2.00	4.82	1911-1915
>> Beaver Creek near Ridgway	9146550	7,680	12.20	4.70	--	--	--	--	1960-1968
>> Miscellaneaous Upper Elevation	no gage	>7,670	7.40	2.80	--	--	--	--	NA
>> Miscellaneous Lower Elevation	no gage	<7,680	61.60	23.70	--	--	--	--	NA
> Alkali Creek and near reservoir	no gage	<6,880	13.80	5.30	--	--	--	--	NA

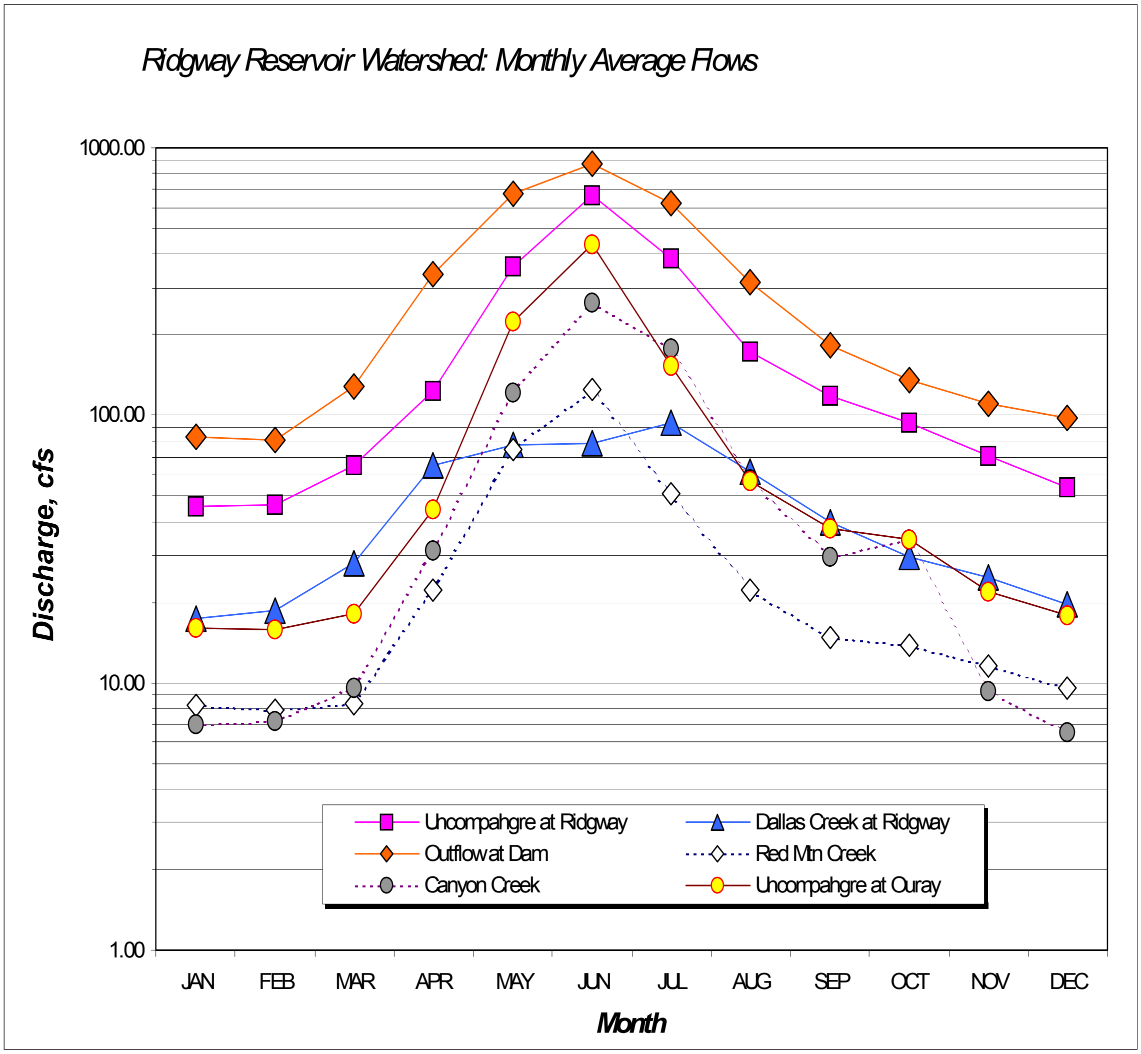


Figure 8.—Monthly average discharge flows from several USGS Gaging stations in the Ridgway Reservoir watershed.

During normal precipitation years, approximately 22 percent of the runoff flow originates in the Dallas Creek sub basin, whereas the upper Uncompahgre River accounts for approximately 70 percent of the runoff. Historical data suggest that the Dallas Creek sub basin would not be a significant inflow source during low precipitation water years. A significant proportion of runoff drains the higher elevation southern sub basins of the watershed where mine waste is prevalent. Flow data from USGS gage stations on Red Mountain Creek at Ironton (09144500), Uncompahgre River at Ouray (09145000), and Canyon Creek at Ouray (09145500) suggest that these higher elevation sub basins account for 26 percent of the watershed area (68 mi^2, 175 km^2) and about 47 percent of median runoff flow.

METHODOLOGY

Reservoir Simulation Methodology

The sediment-water interface and conditions in the reservoir hypolimnion may be simulated in the laboratory using microcosms which combine soils or sediment with river or reservoir water in sealed chambers. This general simulation approach has been applied to assess the release of metals and phosphorus from anaerobic sediments by several other investigators (Brannon, et al., 1978; Brannon, et al., 1980, Gunnison and Brannon, 1981; Gunnison, et al., 1980; Messer, et al., 1984). In this study, a “static” simulation was performed. Uncompahgre River water was combined with Ridgway Reservoir basin soils and river sediments in 55-gal polypropylene tanks (figs. 9a and 9b). These tanks were sealed and then allowed to develop anaerobic conditions. Static simulation will produce conditions similar to the "worst case" scenario where a reservoir experiences prolonged stratification, stagnation, and high biological productivity. Bacterial respiration and metabolism lead to anaerobic reducing conditions that may release toxic metals into the hypolimnion (Cole, 1992; Schindler and Stumm, 1987; Morel and Hering, 1993; Myers and Nealson, 1988; Horowitz, 1985).

Figure 9a.—Sediment-water simulation microcosms under construction.

Figure 9b.—Completed simulation tank with circulation sidearm and instrumentation. These items were removed for the anaerobic portion of the simulation.

Simulation Soil Collection and Preparation

Eight soil samples and Uncompahgre River water were obtained from the Ridgway Reservoir basin in July of 1980. The reservoir basin map (fig. 10) locates and table 2 describes the sampling locations. Four 5-gal. plastic buckets were filled with surficial soil or river sediments at each site and then sealed for transport to Denver. Uncompahgre River water was pumped near the project construction office into a 220-gal. fiberglass tank, which was aerated until water was introduced into the microcosm tanks.

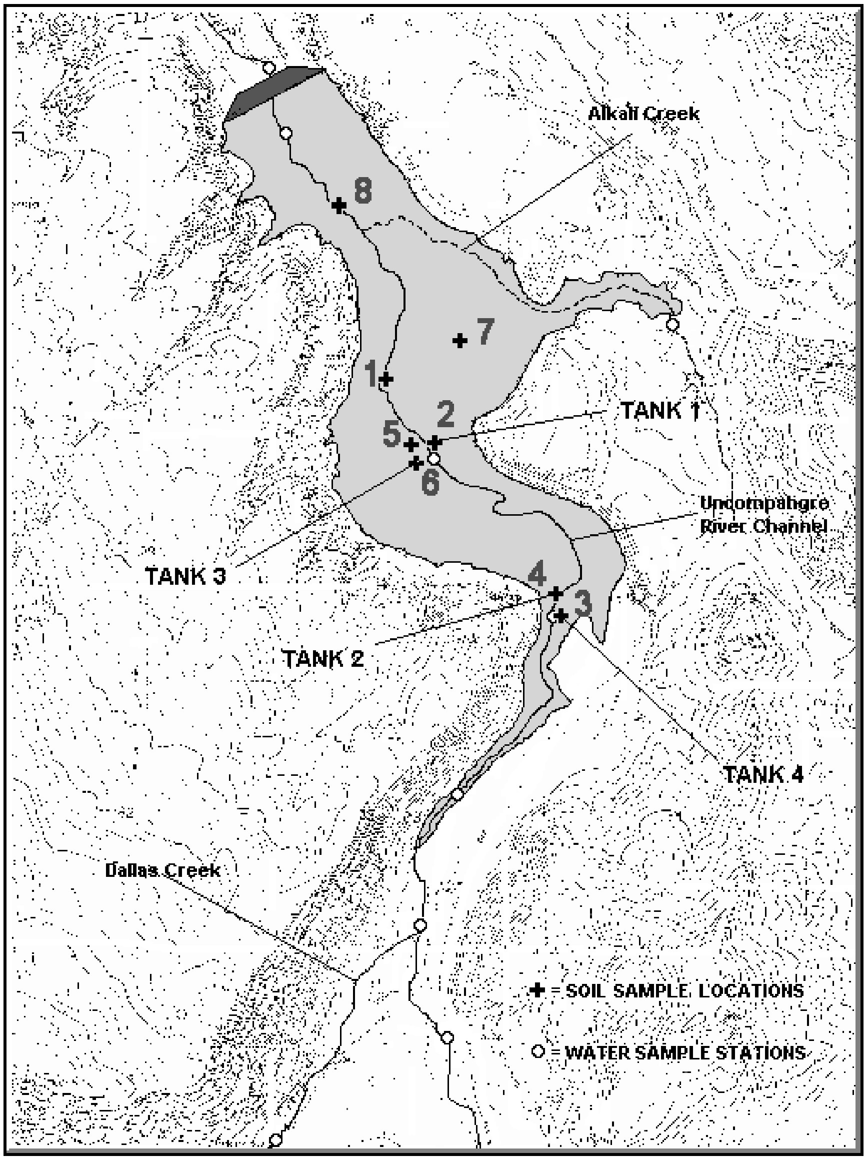


Figure 10.—Map showing the locations of surface soils and river sediments collected for the 1981 simulation study.

Table 2.—Location of soil and sediment samples collected from Ridgway Reservoir basin for sediment-water simulation. Refer to the map in figure 10 for specific locations of simulation samples

Sample Number	Description
1	Surface soil collected downstream of aggregate processing plant.
2	Surface soil collected upstream of concrete batch plant near river at road crossing.
3	Fill material for re-routed Hwy 550 collected upstream from Cookie Tree Ranch site.
4	Dried pond sediments from old watering hole on southwest edge of Cookie Tree Ranch.
5	River bank material from west side of Uncompahgre river near bridge.
6	River mud-sand near collected near bridge.
7	Surface soil from Alkali Creek borrow area.
8	River bank material collected at Alkali Creek-Uncompahgre River confluence.

Samples from each site were sieved to remove rocks and other objects greater than No. 4 mesh (U.S. Standard Sieve sizes). Plus-4-sized soil clods were broken to pass the No. 4 screen and the resulting minus-4 material was thoroughly blended on a 12-ft X 12-ft rubberized cloth blend pad, then split into quarters using a bulk riffle. The blend pad was cleaned with compressed air between samples to prevent cross-contamination. One quarter of each soil sample was then blended and split to a manageable size for further blending and splitting of representative fractions for petrographic and chemical tests. The small representative fractions reserved for chemical analysis were ground to pass a 2-mm screen, then blended and split to obtain the desired sample size.

Characterization of Simulation Soils and Sediments

Before the simulation experiment, representative fractions of all eight samples were submitted for petrographic and chemical analysis to characterize the materials. Petrographic examination used x-ray diffraction and optical microscopy (megascopic and microscopic) to identify minerals and estimate volume percentages.

Trace metal analyses on the eight samples were performed after the following digestion: approximately 1 g of each representative sample was placed in a Parr, teflon-lined, digestion bomb with 10 mL of 20 percent (by volume) nitric acid ($HN0_3$), then sealed and heated in a 105˚C drying oven for 3 hours. Samples were then filtered through an acid-washed, deionized water-rinsed filter, diluted to 100 mL with distilled-deionized water, then analyzed by graphite furnace atomic absorption spectrophotometry (GFAAS) using a Perkin Elmer Model 370 GFAA instrument with deuterium lamp background correction.

The four soils with the highest concentrations of trace metals were selected for simulation. These sample locations are also near reservoir sampling stations RES02 and RES03. Representative subsamples were analyzed for leachable major ions using a 1:10 soil:water (weight to weight) extraction that used Uncompahgre River water as the extractant. This extraction provided a simulation of first flushing of basin soils. The river water extractant and soil extracts were filtered and analyzed for major ions using consensus methods listed in table 3.

Table 3.—Analytical techniques and reference methods for soil, sediment and water analyses performed by the Reclamation Denver Laboratory during this study

	Up to 1985		1986-1989		1990-1993		After 1994	
Analyte	**Technique**	**Method**	**Technique**	**Method**	**Technique**	**Method**	**Technique**	**Method**
MAJOR IONS								
pH	electrometric	SM15 423	electrometric	SM16 423	electrometric	SM17 4500-H+B	electrometric	EPA 150.1
Total Dissolved Solids	gravimetric	SM15 209C	gravimetric	SM16 209D	gravimetric	SM17 2540C	gravimetric	EPA 160.1
Total Suspended Solids	gravimetric	SM15 209D	gravimetric	SM16 209C	gravimetric	SM17 2540D	gravimetric	EPA 160.2
Calcium	EDTA titration	SM15 311C	EDTA titration	SM16 311C	ICP-ES	SM17 3120B	ICP-ES	EPA 200.7
Magnesium	EDTA titration	SM15 314B	EDTA titration	SM16 318C	ICP-ES	SM17 3120B	ICP-ES	EPA 200.7
Sodium	flame photometry	SM15 325B	flame photomentry	SM16 325B	ICP-ES	SM17 3120B	ICP-ES	EPA 200.7
Potassium	flame photometry	SM15 322B	flame photomentry	SM16 322B	ICP-ES	SM17 3120B	ICP-ES	EPA 200.7
Alkalinity	potentiometric titration	SM15 403	potentiometric titration	SM16 403	potentiometric titration	SM17 2320B	potentiometric titration	EPA 10.1
Sulfate	gravimetric	SM15 426A	IC	EPA 300.0	IC	EPA 300.0	IC	EPA 300.0
Chloride	color titratiion	SM15 407A	IC	EPA 300.0	IC	EPA 300.0	IC	EPA 300.0
NUTRIENTS								
Total Phosphorus	auto colorimetric	SM15 424G	auto colorimetric	SM16 424G	auto colorimetric	SM17 4500PF	auto colorimetric	EPA 365.1
Ortho-Phosphorus	auto colorimetric	SM15 424G	auto colorimetric	SM16 424G	auto colorimetric	SM17 4500PF/B	auto colorimetric	EPA 365.1
Nitrate	auto colorimetric	SM15 418F	auto colorimetric	SM16 418F	auto colorimetric	SM17 4500NO3-F	auto colorimetric	EPA 353.2
Nitrite	auto colorimetric	SM15 419	auto colorimetric	SM16 419	auto colorimetric	SM17 4500NO2-B	auto colorimetric	EPA 354.1
Ammonia	auto colorimetric	SM15 417F	auto colorimetric	SM16 417G	auto colorimetric	SM17 4500NH3-H	auto colorimetric	EPA 350.1
Total Kjeldahl Nitrogen	auto colorimetric	SM15 420B	auto colorimetric	SM16 420B	auto colorimetric	SM17 4500Norg-C	auto colorimetric	EPA 351.2

Table 3.—Analytical techniques and reference methods for soil, sediment and water analyses performed by the Reclamation Denver Laboratory during this study - continued

	Up to 1985		1986-1989		1990-1993		After 1994	
Analyte	**Technique**	**Method**	**Technique**	**Method**	**Technique**	**Method**	**Technique**	**Method**
TRACE ELEMENTS								
Trace (Fe Mn, Al, Si)	flame AA	SM15 303	flame AA	SM16 303A	ICP-ES	SM17 3120B	ICP-ES	EPA 200.7
Ultra Trace (Cd, Cu, Zn)	GFAA	SM15 304	GFAA	SM16 304	GFAA	SM17 3113B	GFAA	EPA 202-289
Selenium-Arsenic	hydride AA	SM15 303E	GFAA	SM16 304	GFAA	SM17 3113B	GFAA	EPA 202-289
Mercury	cold vapor AA	SM15 320A	cold vapor AA	SM16 303F	CVAFS	SM17 3112	CVAFS	EPA 245.2
Digestion	nitric acid/bomb	SM15 302D	nitric acid/bomb	SM16 302D	nitric acid	SM17 3030E	microwave HNO3	*EPA 3015B
SOIL ANALYSES								
Sample Preparation	blend/split	EM2, E-5	blend/split	EM2, E-5	blend/split	EM3 USBR 5205	blend/split	USBR 5205
Saturation Extracts	di H2O	Hndbk 60	di H2O	Hndbk 60	di H2O	Hndbk 60	di H2O	Hndbk 60
1:10 Leach Extraction	di H2O	Hndbk 60	di H2O	Hndbk 60	di H2O	Hndbk 60	di H2O	Hndbk 60

NOTES:

SM15	Standard Methods 15th Edition (American Public Health Association, 1981).
SM16	Standard Methods 16th Edition (American Public Health Association, 1985).
SM17	Standard Methods 17th Edition (American Public Health Association, 1989).
EPA	Methods for Chemical Analysis of Water and Wastes (Environmental Protection Agency, 1983).
*EPA	Test Methods for Evaluating Solid Waste, 3rd Edition, SW-846, (Environmental Protection Agency, 1986).
Hndbk 60	Diagnosis and Improvement of Saline and Alkali Soils (United States Department of Agriculture, 1953).
EM2	Reclamation Earth Manual, 2nd Edition (Bureau of Reclamation, 1974).
EM3	Reclamation Earth Manual, 3rd Edition (Bureau of Reclamation, 1990).

Temperature Control and Contamination

When this simulation was performed, the temperature-controlled calorimeter room used for the experiment (fig. 11) was approximately 45 years old and located in an active concrete materials testing laboratory. The age of the cooling system and location of the calorimeter room caused several problems that affected the accuracy of the simulation of the conditions expected in the reservoir hypolimnion. Both before sealing the tanks and during this experiment, the refrigeration system for the calorimeter room experienced several ammonia refrigerant leaks which may have contaminated initial test waters. Aggregate and concrete processing and routine operation of diesel forklifts may have also introduced minor contamination artifacts. After repeated temperature control problems, the calorimeter room temperature was raised to 25˚C to prevent further refrigeration system failures and minimize subsequent contamination. So the experiment that started as an attempt to simulate expected field conditions in the reservoir hypolimnion became a simulation of worst-case conditions of prolonged thermal stratification, lack of mixing with fresh recharge water, and prolonged anoxia and reducing conditions.

Figure 11.—View of the sediment-water microcosms located in an old calorimeter room at the Bureau of Reclamation's Denver facility. The pumps and sidearm plumbing were removed for sampling under anaerobic conditions.

Sediment-Water Microcosms and Sampling Technique

The simulation was conducted in four 55-gallon polypropylene acid neutralization batch tanks (Nalgene), which were located in a constant-temperature calorimeter room (fig. 11). Representative quarters from soils 2, 3, 4, and 6 were added to the tanks in whole-quarter units and allowed to settle prior to tank sealing. The approximate ratio of soil to water in the tanks was 1:10 (17.0 to 22.9 kg placed in approximately 190 L of river water), and sediment depth in the tanks was approximately 4 to 5 cm. The original tank design included a pump to circulate tank water through a PVC pipe sidearm external to the tank. Sampling for the first two simulation samples was performed using a valve located on the external plumbing (figure 9a). Air leaks in the tanks and external plumbing were a problem, and several attempts to seal the systems proved ineffective. When the pumps and circulation plumbing were suspected of injecting air into the system, a simpler design was implemented. The circulation sidearm plumbing and pump were sealed and the rubber gasket used to seal the tanks at the top was discarded. A new gasket made with silicone rubber and latex caulking proved effective sealing the tank covers.

The last three simulation samples were collected from the tanks using a purge tube (with air stone) and a siphon with a gas trap to prevent atmospheric oxygen contamination (fig. 9b). The siphons drew water from the tanks at a distance of approximately 14-16 cm from the sediment surface. The tanks were purged with oxygen-free nitrogen for 2 hours to stir the tank water. Microcosms were then allowed to sit quiescent for 90 minutes before sampling. Oxygen was removed from the N_2 purge gas by passing the gas through an ammonium vanadate-amalgamated zinc solution in a gas scrubber bottle.

Samples from the tanks for chemical analyses were collected into pre-cleaned high density polyethylene (HDPE) bottles (previously soaked in 20 percent HNO_3, then rinsed three-times with deionized water). The bottles were rinsed three times with drained or siphoned tank water before sample collection. During this experiment, simulation water from all tanks was clear and devoid of visible suspended particles, and samples were not filtered to minimize chemical changes during collection under anoxic conditions. Samples for trace elements were preserved to 0.2% HNO_3 (Ultrex) and nutrient samples were preserved to 0.2% HCl (Baker reagent grade) immediately after collection.

Analytes tested and methods followed for simulation soils, sediments and water are summarized in table 3 under the "up to 1985" table columns. Simulation water samples were analyzed by the Reclamation Denver Laboratory (the Denver Lab) for the following constituents: major ions including pH, conductivity, (EC), total dissolved and total suspended solids (TDS, TSS, or unfilterable and filterable residue), Ca, Mg, sodium (Na), potassium (K), SO_4^{2-}, chloride (Cl^-), HCO_3^-, and carbonate (CO_3^{2-}); trace elements including iron (Fe), manganese (Mn), aluminum (Al), arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), selenium (Se), silicon (Si), and zinc (Zn), among others; and nutrients including nitrate (NO_3^-) plus nitrite (NO_2^-) (analyzed as nitrate+nitrite), ammonia (NH_3), total Kjeldahl nitrogen (TKN), total phosphorus (total-P), and ortho-phosphate (o-PO_4^{3-} or ortho-P).

Immediately after collecting samples for chemical analyses, the pH and Eh (oxidation-reduction or redox potential) were measured using Orion combination pH and Eh electrodes and an Orion model 801 digital pH/mV meter. The pH electrode was calibrated using a two buffers, and the Eh probe was checked using Zobell's solution ($KFe(CN)_4$, potassium ferric cyanide). Dissolved oxygen (DO) was measured using an Orion electrochemical DO electrode and checked using a modified Winkler titration. Uniform measurements of pH and Eh during this sampling technique suggested that adequate stirring was provided by the nitrogen purge.

Results from the last three simulation samples reflect the addition of sucrose to the systems. None of the tanks spontaneously developed anoxic or reducing conditions, probably due to air leaks and the lack of a carbon food source for the bacteria. After the second sample showed positive DO and Eh readings, the external circulation plumbing was removed and after re-sealing, approximately 2 g of sucrose was added to each tank (approximately 10 mg/L) to speed the development of reducing conditions. Once the tanks were sealed and purged of dissolved oxygen, the Eh values began to drop to negative potentials, indicating that the anaerobic bacteria had a sufficient food supply to create reducing conditions in the tanks.

Post-Filling Water Sampling

Collection of inflow and outflow samples for water quality testing began in 1987, the year the dam was completed and filling was initiated, and reservoir samples were collected starting in 1988. As expected for a study of this duration, water samples were collected by several different field crews from Reclamation and State of Colorado offices, each of whom used slightly different designations for collection sites. Table 4 lists the uniform station names adopted for this report. The map in figure 12 shows the locations of post-filling sampling stations except for Outflow 2 (Uncompahgre River at Colona, Colorado), which is 6 miles (9.7 km) downstream (north) of Ridgway Dam.

Table 4.—Water sample collection stations used in this report

Station	Station Description	Decimal ° North Latitude	Decimal ° West Longitude
Inflow 1	Uncompahgre River at USGS Gage Station	38.183889	107.745278
Inflow 2	Dallas Creek at Old USGS Gage Station	38.177778	107.757778
Inflow 3	Alkali Creek Inflow near Reservoir	38.222500	107.730208
Inflow-Mix	River-Lake Mixing zone	38.196881	107.744967
Inflow Pore	Pore water from inflow zone river sediments	38.189853	107.747483
RES01	Ridgway Reservoir behind dam	38.233333	107.757639
RES02	Ridgway Reservoir at mid-lake	38.215194	107.746703
RES03	Ridgway Reservoir at upper-lake	38.206583	107.738278
Outflow 1	Uncompahgre River below Dam	38.238056	107.758611
Outflow 2	Uncompahgre River at Colona CO	38.331389	107.778889

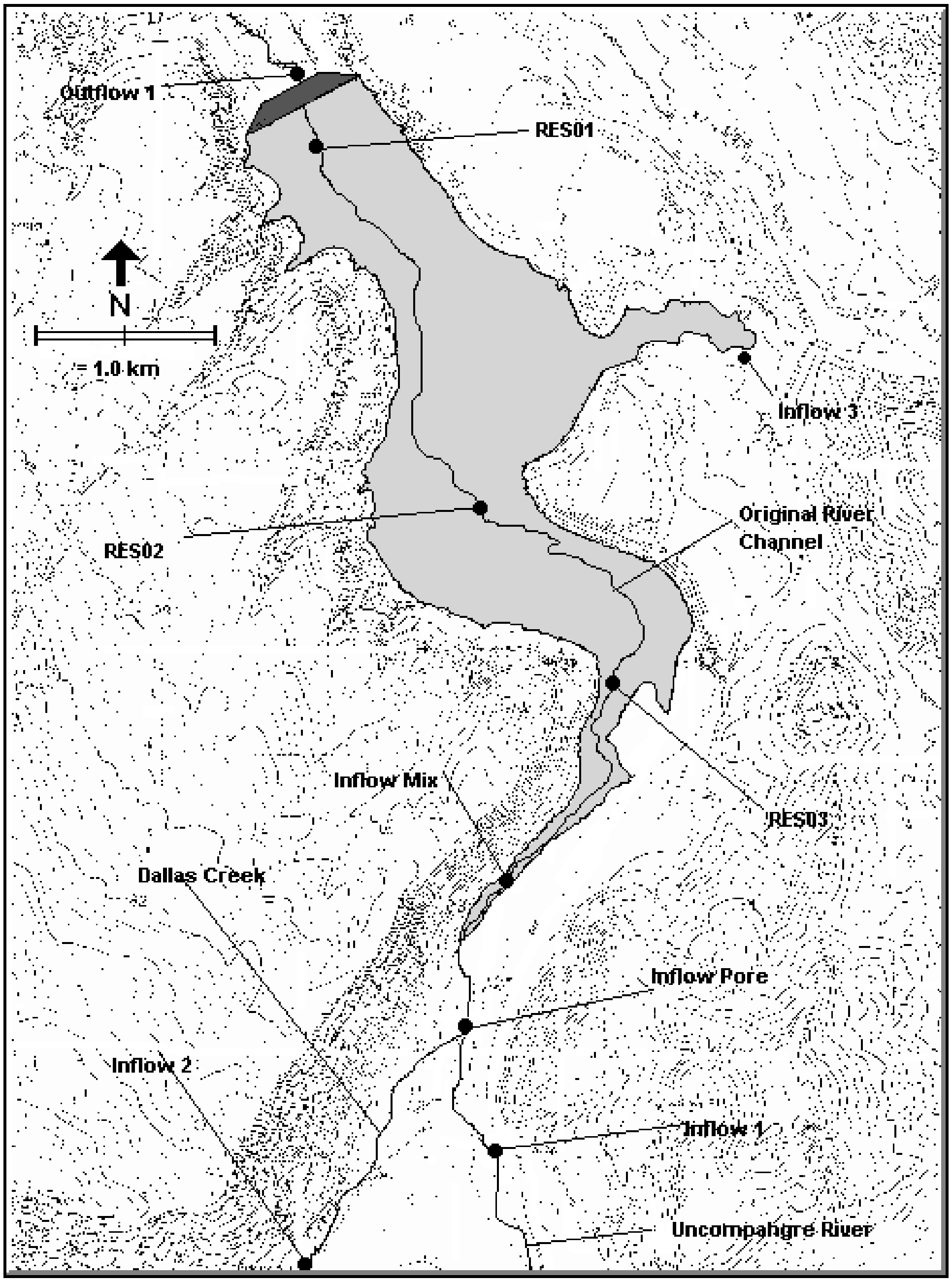


Figure 12.—Map of Ridgway Reservoir showing location of water sampling stations.

The largest and most consistent set of samples were collected for the inflows and outflows (stations Inflow 1, Inflow 2, Outflow 1, Outflow 2) from 1987 to 1991. The highest frequency sampling years for this study were 1988 and 1989. Reservoir stations were only sampled during 1988, 1989, 1991, and 1995, with the highest sampling frequency in the 1988 and 1989 first-filling period. No samples were collected during 1992, and very few samples in 1993 and 1994. Because of cold weather, relatively fewer samples were collected in late fall, winter, and early spring.

Water column data profiles for temperature (T), pH, dissolved oxygen (DO), conductivity (EC), and redox potential (Eh) were measured at each station where samples were collected, using various models of Hydrolab multi-probes and data loggers. All Hydrolab probes were calibrated prior to sampling. After 1992, calibration procedures were more rigorous and documented. EC was calibrated using a certified standard reference solution (ERA), pH was calibrated using a 2-buffer (VWR Scientific) calibration, and Eh was checked against Zobell's solution (VWR Scientific) or pH buffer. DO was calibrated using saturated air at the measured local barometric pressure. Hydrolab profile data, Secci disk depth, and sample notes were recorded on field forms archived by the authors.

Raw water samples for major ions, nutrients (N, P, silica - SiO_2), total organic carbon (TOC), and dissolved organic carbon (DOC) were collected as surface grab samples from the boat or using a van Dorn sampler (Wildco Supply) for deeper samples. Established sampling and preservation procedures (Environmental Protection Agency, 1982) were observed. Water samples were then transferred to pre-cleaned, labeled HDPE containers (Eagle-Pitcher) which were then placed on ice in coolers. These samples were filtered (0.45 µm polycarbonate filter disks - Millipore) and preserved at the end of the sampling day. Samples were then shipped to the Denver Lab the following day. Field quality assurance (QA) for these reservoir samples included collection of duplicate samples and field blanks submitted as blinds to the Denver Lab.

Ultra-clean sampling procedures and equipment were provided by Frontier Geosciences, Inc., Seattle, Washington (FGS), for 1995 mercury (Hg) analyses. This equipment included certified pre-cleaned and double-bagged Teflon sample bottles, and clean room gloves. Surface samples were collected as grab samples from a slowly moving boat following a procedure from FGS contained in EPA Method 1669 (Environmental Protection Agency, 1996a). This sampling method requires two people following the "clean hands/dirty hands" protocol to avoid contamination. Water samples were shipped to FGS on ice by overnight delivery using standard chain of custody forms and procedures.

Post-Filling Water Sample Analytical Methods

Post-filling water samples were analyzed for major ions, nutrients, and trace elements following consensus methods listed in table 3. Most of these samples were analyzed by the Denver Lab. Additional analyses were provided by the State of Colorado Laboratory (the State lab) and FGS which performed Hg analyses. Total Hg was analyzed by FGS using EPA Method 1631 (Bloom, 1995, Bloom, 1996; Environmental Protection Agency, 1996b). This method involves bromine monochloride (BrCl) oxidation of the sample, followed by stannous chloride ($SnCl_2$) reduction, purging volatile Hg onto a gold trap, and then thermal desorption before detection using cold vapor atomic fluorescence spectrophotometry (CVAFS). All analyses by FGS used statistical blank correction.

All analytical service labs used for post-filling samples had formal QA plans in place that included provisions for standard operating procedures, instrument calibration verification, duplicates, spikes, laboratory control samples, and defined corrective actions for each instrument run (Taylor, 1987; Environmental Protection Agency, 1972; American National Standards Institute, 1991). All data deliverable packages included QC reports that allowed evaluation and validation of data quality.

Complete sets of major ions analyses were almost all (306 out of 310) analyzed by the Denver Lab for 60 samples collected from the reservoir and 250 samples collected from inflow and outflow stations. The State Lab analyzed approximately 190 samples for total hardness and 188 samples for total alkalinity, mostly during 1988 and 1989. Reclamation field crews analyzed 71 samples for alkalinity using a Hach portable digital titrator with methyl orange indicator endpoint detection. The peak years for major ions samples were 1989-1991, and fewer samples collected 1994 to 1996. Because of the general regularity of inflow and outflow sampling, the distribution of major ions samples by month is fairly uniform. However, May was the month when most samples were collected.

Since 1987, 11,700 individual trace element analyses were performed on approximately 613 Ridgway water samples. A total of 134 samples were collected from the reservoir, and 479 were collected from inflow and outflow stations. The Denver Lab analyzed 84 percent of trace element data points, and the State Lab analyzed 16 percent. It should be noted that trace element analysis requests varied over the course of this study. Many samples were submitted as dissolved only (filtered through a 0.45 µm membrane), or analyzed for limited or varying sets of requested trace elements. More trace element samples were collected in May than any other month.

Approximately 442 samples were collected and 4400 nutrient analyses were performed. Field crews collected 62 samples from reservoir stations, and 380 samples from inflow and outflow stations. All nutrient samples were analyzed by the Denver Lab. Nutrient analysis requests, like trace element requests, varied over the course of this study. Not all samples collected were analyzed for the full suite of nutrients, and both filtered (dissolved) and unfiltered samples were not always submitted for analysis. The peak year for nutrient sampling was 1989, and May was the peak sampling month with increased samples collected during the peak runoff season of April through June.

Quality Assurance for Post-Filling Water Sampling

Routine inflow and outflow samples collected by Reclamation personnel did not include blind QA samples to check lab analysis results. Reservoir sampling, performed by Denver Reclamation personnel, included duplicate and spiked field samples and known concentration blind QA samples. State Lab sampling episodes included non-blinded duplicate inflow and outflow samples. The State Lab also collected several samples on the same dates Reclamation collected inflow and outflow samples.

1995 Reservoir Sediment Sample Collection, Preparation, and Analysis Procedures

Reservoir sediment grab samples were collected during October 1995 using a mini-Ponar dredge (Wildco Supply). Sediments were collected at the river-lake inflow mixing zone, and then at sites downstream from the mixing zone into the reservoir. Sediment samples were collected approximately 100 m, 200 m, 1200 m (near station RES03), and 2700 m (near station RES02) downstream from the inflow mix zone. The dredge was drained of excess water and sediment was then transferred from the dredge into acid-cleaned deionized water-rinsed plastic containers.

Excess standing water in the reservoir sediment samples was decanted, and large (plus-4 U.S. Standard Sieve material) rocks, sticks, and leaves were removed. Samples were then air dried in their plastic field containers (with covers slightly ajar to prevent contamination by fugitive dust).

Samples were not ground prior to blending to preserve the natural particle size distributions. Dried samples were blended for 10 minutes using a rotary split-cone blender. The plastic split-cone assembly was cleaned between samples using compressed air, a soap and water wash, hot water rinse, and then a triple rinse with ultra-pure deionized water. Blended samples were split and recombined four times using a riffle before final splitting to obtain representative subsamples using a micro splitter. Representative subsamples were then submitted for size analysis using a hydrometer test (Bureau of Reclamation, 1990), and minus-100 µm particles were analyzed using a Coulter Model LS 100 laser size analyzer. Each of the representative fractions were also subsampled for petrographic and chemical analyses.

Several sediment cores were also collected in 1.75-in (4.45 cm) inside diameter plexiglas tubes from river bank sediments upstream from the inflow mix zone (the Inflow Pore station identified in the figure 12 map). The purpose of these samples was to investigate whether river bank sediments still within maximum reservoir water levels could be a source of toxic trace metals during maximum runoff flows when these sediments would be eroded and transported into the reservoir. Pore water from these cores was separated and analyzed for trace elements, and solids were digested and analyzed for trace elements as well as examined for mineralogy and particle size distribution.

Petrographic examination of reservoir sediments used x-ray diffraction on a Scintag 2000 x-ray spectrometer and optical examination (megascopic and microscopic) to identify minerals. A Jeol 5400-LV scanning electron microscope (SEM) was used for electron micrograph imaging. Identification of sediment trace element occurrences on grain surfaces was performed using the SEM x-ray accessory energy dispersive spectrometer. For SEM analysis, a representative portion of the minus 100 sieve-size material was examined. The SEM work was performed on uncoated samples under low vacuum conditions using back-scattered electron imaging. The samples were prepared by affixing the minus 100 grains to double stick carbon tape adhered to brass specimen holders. SEM spectral analyses were performed at 15-kV accelerating voltage to detect elements of atomic number 26 (Fe) and lower.

Representative sediment subsamples were analyzed for trace elements, total and inorganic carbon, and total phosphorus. Trace element samples were digested using EPA method 3051B (Environmental Protection Agency, 1986), microwave-assisted nitric acid digestion followed by analysis using inductively coupled plasma emission spectrometry (ICP-ES) following EPA Method 200.6 (Environmental Protection Agency, 1982). Total and inorganic carbon and total phosphorus were analyzed by Huffman Laboratories, Golden, Colorado. Total carbon was determined using ASTM method D5373 (American Society for Testing and Materials, 1993), involving sample combustion and infrared detection with a Leco CR 12 Carbon Analyzer. Carbonate carbon was determined using ASTM method D4129 (American Society for Testing and Materials, 1992) involving acidic conversion of carbonate to CO_2 and coulometric detection using a UIC-Coulometrics System 140 Carbonate Carbon Analyzer. Total organic carbon was determined by subtracting carbonate carbon from total carbon. Total P was determined by ICP-ES analysis of a sample digested using nitric and perchloric acids (Guy, 1969).

Post-Filling Data Quality Issues, Analysis and Validation

Analytical methods, detection limits for trace elements and nutrients, laboratory quality control practices, and field sample collection procedures varied during this study, introducing complications in summarizing lower concentration data. In particular, post-filling water analysis data sets contained anomalous data (for example, a filtered sample having significantly greater concentration than the unfiltered sample) that were censored before statistical evaluation. Multiple detections limits for trace elements were also a problem that required censoring or recoding of higher detection limit non-detect data prior to analysis or graphing.

Post-filling data were collated from a variety of sources and formats: Lotus 123® computer spreadsheet files for the 1988-1990 reservoir data and State Lab-analyzed data; manually entered data from copies of Denver Lab memos reporting routine inflow-outflow data results; Reclamation Hydromet ASCII data files for reservoir surface elevation; and USGS ASCII files summarizing daily average gage station flows measured at Inflows 1 and 2 and Outflow 1. Mass loadings for individual analytes were calculated by multiplying the daily average discharge flow by the observed same-date concentration.

Data reported as below instrument detection limits were coded as the negative value of the reported detection limit. This approach was selected to preserve information on detection limits from several labs and instrumental techniques, and to facilitate identification of non-detects while keeping the non-detect designator a numeric variable. This approach will negatively bias the mean, especially for analytes with widely varying and higher detection limits. The median, a summary statistic based on rank, however, is less affected by this coding. A rank based summary statistic (such as a percentile) showing a negative value is simply interpreted as "less than the detection limit," which is the absolute value of the negative summary value.

Initial evaluation of trace metal and nutrient data revealed that almost all low-concentration (near detection limit) data were not normally distributed. Because of data non-normality and recoding of below detection data as negative values, the median was used as the preferred estimate of data central tendency (Keith, et.al., 1983). For more normally distributed data sets like those for major ions, the median and mean coincide as estimates of central tendency. Investigators wishing to perform further parametric evaluations of these data should consider alternate censoring and recoding of below-detection-limit data as suggested by Nehls and Ackland, (1967), and others (Gilbert, 1987; and Gilliom, et.al., 1984).

SPSS® (Statistical Package for the Social Sciences) for Windows, version 8.0 was used to calculate summary values. All-data summary values for the reservoir and adjacent inflows and outflows were based on combining data from stations Inflow 1, Inflow 2, the three reservoir stations, and Outflow 1 below the dam. Reservoir summaries were based on combined data from stations RES01, RES02, and RES03. Inflow summaries refer to combined data from stations Inflow 1 and Inflow 2. Outflow 2, Uncompahgre River at Colona, Colorado, was excluded from the all-data summaries because of its downstream distance from the dam (6 mi, 9.7 km). Otherwise SPSS® summary tables were based on individual station data sets.

After the SPSS® files were validated and anomalous data were removed, a relational data base was created using Microsoft Access 97®. SPSS® files for ions, nutrients, trace elements, sediments, stream flows, and reservoir surface elevations were entered as separate data base tables into the Access data base by converting the individual SPSS® files to Microsoft Excel® spreadsheet files that were then directly imported. Station identifiers, latitudes, and longitudes were entered manually into a separate data base table that conveniently linked station information, reservoir surface elevation, or stream flows with sample data by way of various query reports. Flow-weighted loading calculations of unfiltered and filtered analytes were performed by creating additional queries within the data base. These queries combined stream flow and concentration data. The data base is available on request from the authors.

RESULTS AND DISCUSSION

This section provides a general summary of the observed post-filling reservoir water chemistry data, a summary and comparison of pre-impoundment simulation soil samples with 1995 reservoir sediment samples, and then microcosm simulation results with comments on how simulation results compare with observed reservoir chemistry.

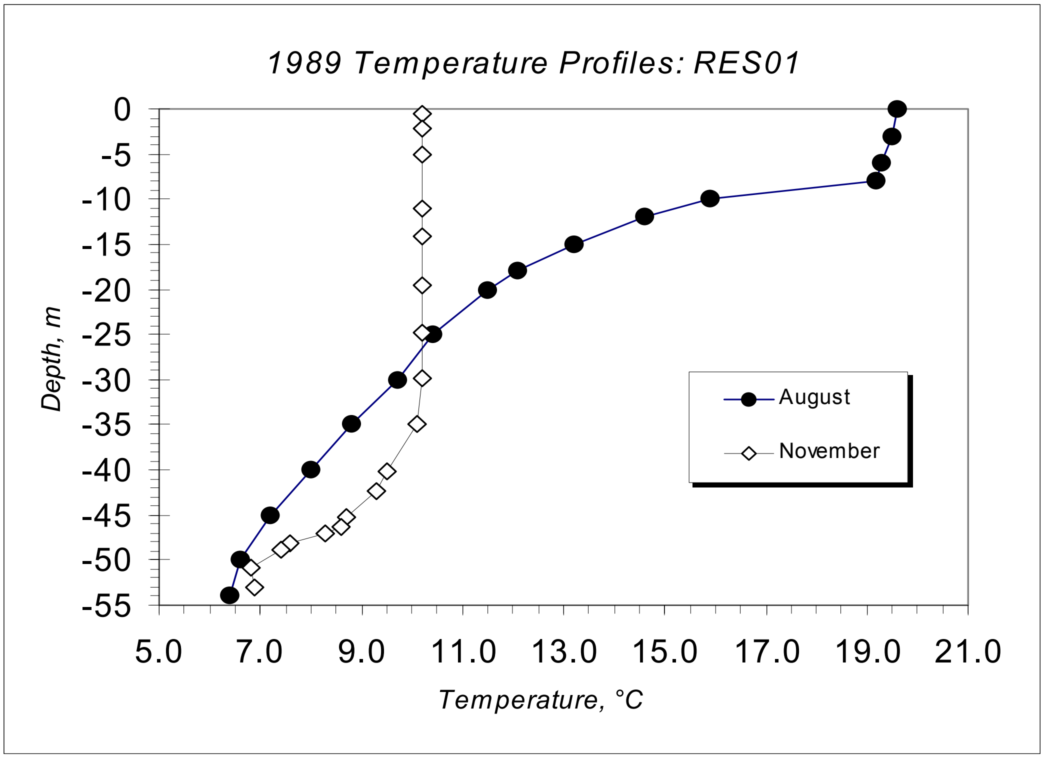
Productivity and Trophic Status

Ridgway Reservoir appears to be an oligotrophic lake with very low productivity. Algal blooms have not been observed as of this report. The water column is fairly transparent: 1989 median Secci depths ranged from 2.0 m during May to 4.8 m during November. Chlorophyll A measured in 1989 showed surface samples with a median concentration of 1.4 mg/m^3 (or µg/L) and a median concentration for at- depth composites of 1.9 mg/m^3. The maximum median chlorophyll A (2.4 mg/m^3) was observed in June 1989, and the minimum median value (1.4 mg/m^3) was observed in November 1989. The low productivity in the lake is the likely reason why fishing at Ridgway Reservoir is generally reported as "slow".

Reservoir Water Column Profiles

The lake thermally stratifies during summer. Figures 13 and 14 show Hydrolab probe profiles for T, DO, pH, and EC measured during August and November 1989. These profiles provide a contrast between late summer and fall post-turnover water columns. The August profiles all show a fairly well-defined boundary for the epilimnion at about 10 m depth with an overall ΔT of almost 14˚C. These profiles suggest minor DO depletion at depths greater than 40 m with a pH minima at the top of the mesolimnion during late summer. In contrast, the November profiles suggest a well defined hypolimnion boundary with a weak thermocline (ΔT about 3˚C) at a depth of about 45 m and a well-mixed water column above 40 m depth. Notably, fall profiles show almost complete DO depletion and accompanying drop in pH, usually associated with hypolimnetic microbial activity. The EC profiles (fig. 14, bottom) show the general increase in runoff concentrations from August to November. The fall profile shows substantially higher EC along the bottom compared with the summer profile. The November EC profile suggests that colder, higher concentration (and denser) river inflows are flowing along the bottom, probably following the original stream bed, beneath warmer and less concentrated water.

August 1989 releases from the river level outlet works at Ridgway Dam averaged 194 cfs whereas, the November average outflow was 45 cfs. During this same 1989 period, average total inflows were 129 cfs for August (65 cfs less than outflow) and 64.8 cfs for November (20 cfs *greater than* outflow). Perhaps the lower flow releases from the dam during November 1989 contributed to less-rapid water exchange and the observed hypolimnetic DO depletion (fig. 13). The profiles and discharge data suggest that stratification behind the dam is influenced by operation of the outlet works.



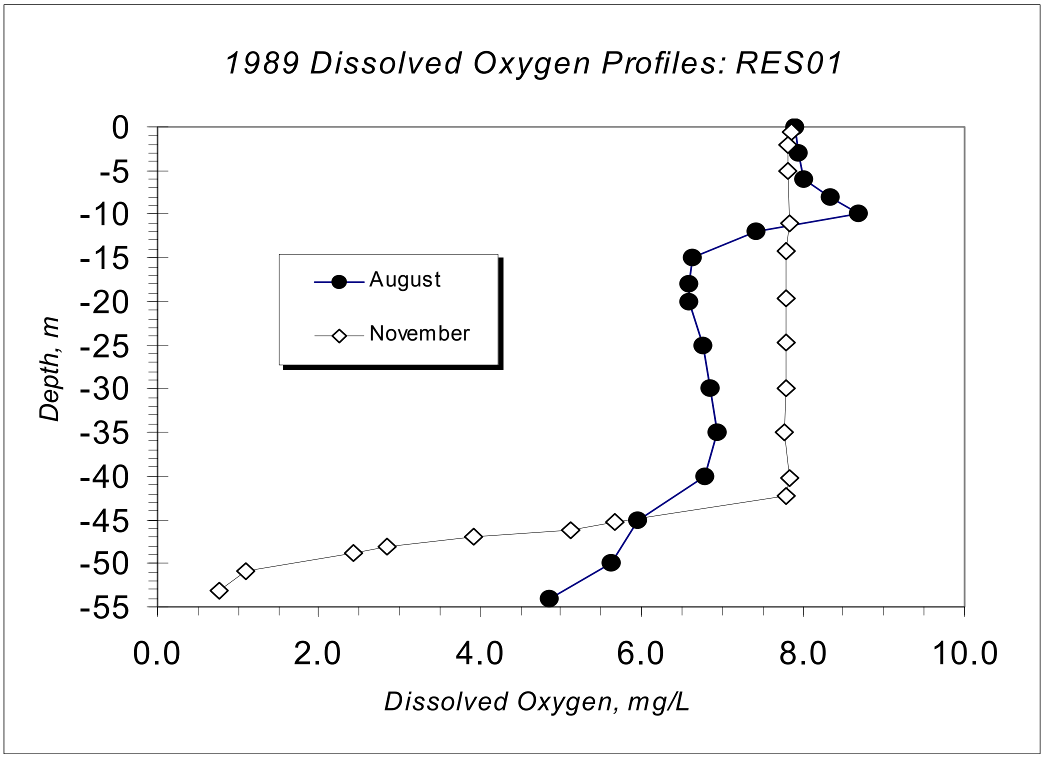
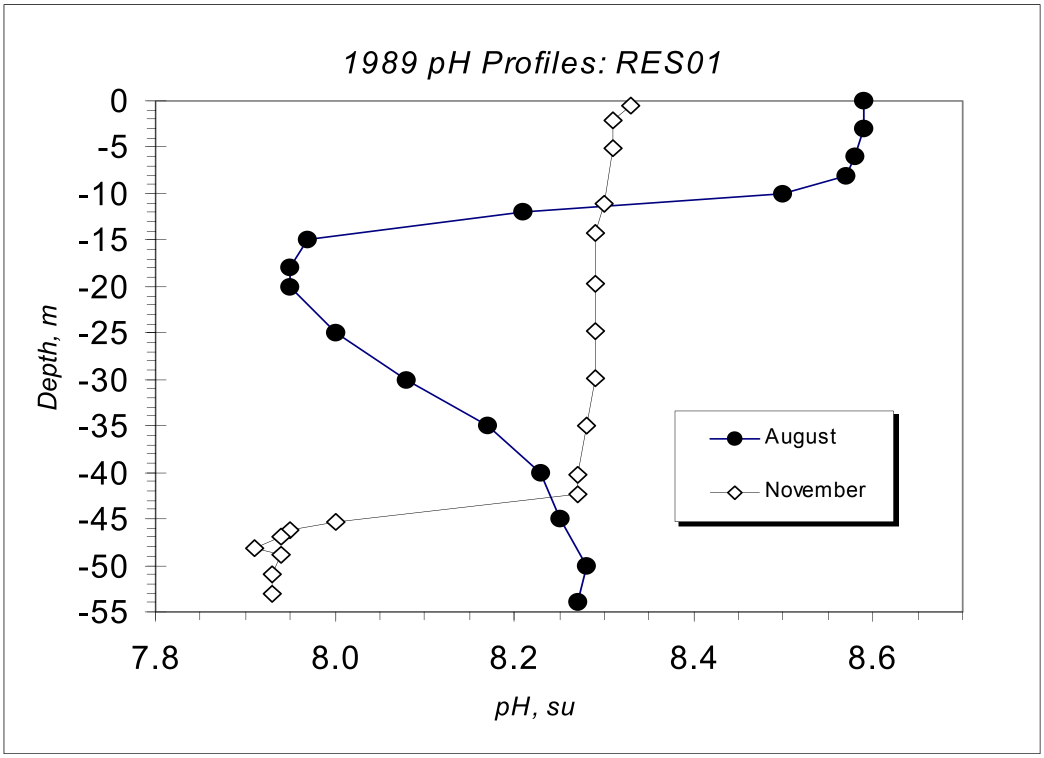


Figure 13.—Summer and fall 1989 temperature and dissolved oxygen profiles at station RES01 behind the dam.



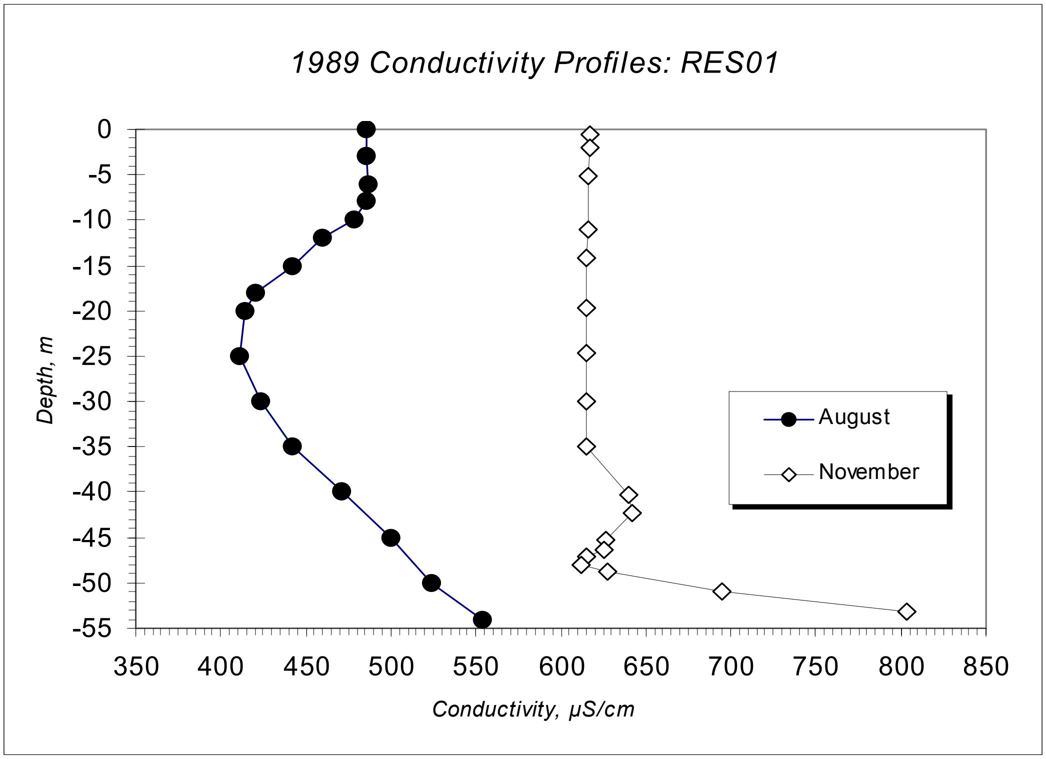


Figure 14.—Summer and fall 1989 pH and conductivity profiles at station RES01 behind the dam.

Generally, 1988-1996 discharge data indicate that August inflows average 236 cfs and November inflows average 95.4 cfs. If inflows are compared with 1992-1996 average outflows at the dam (fig. 8) (315 cfs during August and 111 cfs during November), average releases at the dam exceed inflows during both months. In normal runoff years, the lake profile data suggest that stratification and isolation of the hypolimnion leading to DO depletion and development of anaerobic, reducing conditions is probably unlikely during summer. However, DO depletion and anaerobic conditions may be more prominent during winter when inflows and releases are lowest, and denser bottom waters experience longer hypolimnion residence times.

Major Ions in Ridgway Waters

Table 5 summarizes the available data on major ions for Ridgway Reservoir, and its inflows and outflow. Note that the inflow stations and Outflow 1 summaries are based on a much larger data set and longer continuous period of record. Outflow 1 samples, collected below the dam from the Uncompahgre River, should be somewhat indicative of lower depth reservoir water. These data suggest that runoff and reservoir waters are calcium-sulfate-bicarbonate dominated with total dissolved ions (calculated as the sum of all major ions concentrations) ranging from 180 mg/L (Uncompahgre River) to above 1,000 mg/L (Dallas Creek), and pH ranging from 6.4 (Outflow 1) to above 8.5 (observed in Dallas Creek, RES01, and Outflow 1). Dallas Creek appears to have the highest major ions concentration inflows during low runoff volume years, suggesting a greater influence from groundwater in this sub basin during drier years. The average sum of ions concentration for all Ridgway waters is 475 mg/L with average pH of 7.95. The lowest concentrations and lowest pH waters are likely to be observed shortly after the onset of spring snowmelt runoff. Figure 15 shows Stiff diagrams (Stiff, 1951) that compare average major ions data for low (January) and high (June) runoff months at each of the sampling stations.

All waters contain similar concentrations of bicarbonate, ranging from 1 - 5 meq/L, indicating that these waters are very well buffered. The bicarbonate (and Ca) probably arise from runoff contact with limestones in the Precambrian sediments beneath the volcanic San Juan deposits and in the Telluride Conglomerate. These limestone deposits act to neutralize higher elevation acid mine drainage by the time runoff has reached the elevations of Ridgway Reservoir. The large proportions of sulfate are likely the result of oxidation of sulfide minerals exposed during mining and extraction activities in the upper elevations of the watershed (Drever, 1988). Hardness (the sum of Ca and Mg) ranges from about 2.1 meq/L (Uncompahgre River) up to 15 meq/L (Dallas Creek) and averages over 5 meq/L for all Ridgway waters. The observed major ions chemistry corroborates watershed land use and geology. The higher average pH and hardness should also ameliorate harmful effects from toxic trace elements transported into the reservoir (Forstner and Whitmann, 1979).

Nutrients in Ridgway Waters

The low productivity in Ridgway Reservoir is corroborated by the phosphorus and nitrogen concentrations observed in the water quality monitoring data. Table 6 provides an all-data summary of minimum, median, and maximum N and P concentrations by station. Note that P concentrations reported above 0.030 mg/L are suspected contamination artifacts for filtered samples. In all waters, P species are dominated by suspended and non-ortho-P forms, and N species are dominated by NO_3 and organic-N. Median outflow NO_3 (0.190 mg/L) is slightly higher than the inflow median (0.152 mg/L); however, the significance of this difference would

Table 5.—Summaries of major ions data for inflow, outflow and reservoir stations

Station ID	Summary	TDS, mg/L	Field pH su	Calcium mg/L	Magnesium mg/L	Sodium mg/L	Potassium mg/L	Carbonate mg/L	Bicarbonate mg/L	Sulfate, mg/L	Chloride, mg/L	Calculated Sum of Ions, mg/L
Inflow 1	N	86	41	87	87	87	87	87	87	87	87	64
	Mean	455	7.89	94.7	11.6	21.3	1.85	0.0280	122	211	5.01	467
	Minimum	164	6.57	36.8	3.00	4.78	0.00	0.00	51.6	62.9	0.00	182
	Maximum	714	8.52	145	19.1	45.0	3.60	2.46	197	385	14.2	718
Inflow 2	N	83	42	83	83	83	83	83	83	83	83	60
	Mean	535	7.99	113	21.7	16.9	2.17	0.00	206	217	3.69	596
	Minimum	157	7.04	54.1	8.79	6.13	0.00	0.00	114	65.5	0.00	279
	Maximum	1090	8.52	207	55.4	41.8	4.53	0.00	308	456	11.2	1060
Outflow 1	N	82	40	82	82	82	82	82	82	82	82	66
	Mean	422	7.87	86.0	13.3	19.2	2.00	0.00	129	186	5.10	430
	Minimum	227	6.39	47.0	5.55	6.88	0.00	0.00	76.9	80.1	0.00	221
	Maximum	796	8.53	112	20.9	54.0	4.31	0.00	155	265	25.2	610
RES01	N	23	13.00	23	23	23	23	23	23	23	23	22
	Mean	389	8.00	80.8	13.1	17.4	1.93	0.00	124	175	3.86	416
	Minimum	205	7.64	64.8	8.49	12.3	1.21	0.00	97.9	137	2.27	327
	Maximum	511	8.47	101	22.8	23.6	2.59	0.00	144	242	7.20	543
RES02	N	26	11.00	26	26	26	26	26	26	26	26	26
	Mean	384	8.09	81.1	11.7	17.4	1.77	0.00	125	169	3.31	409
	Minimum	321	7.72	67.3	8.33	12.5	1.09	0.00	96.7	134	1.84	328
	Maximum	450	8.46	98.7	14.7	21.5	2.16	0.00	142	202	4.09	483
RES03	N	12	10.00	12	12	12	12	12	12	12	12	12
	Mean	405	8.18	81.1	11.9	18.1	1.92	0.00	125	171	3.60	413
	Minimum	340	8.00	69.1	10	14.0	1.46	0.00	103	149	2.85	359
	Maximum	478	8.40	107	15.4	25.1	2.40	0.00	152	217	4.29	517
ALL	N	312	157.00	313	313	313	313	313	313	313	313	250
	Mean	455	7.95	94.6	14.8	18.8	1.98	0.0800	147	198	4.40	475
	Minimum	157	6.39	36.8	3.03	4.78	0.00	0.00	51.6	62.9	0.00	182
	Maximum	1090	8.53	207	55.4	54.0	4.53	2.46	308	456	25.2	1060

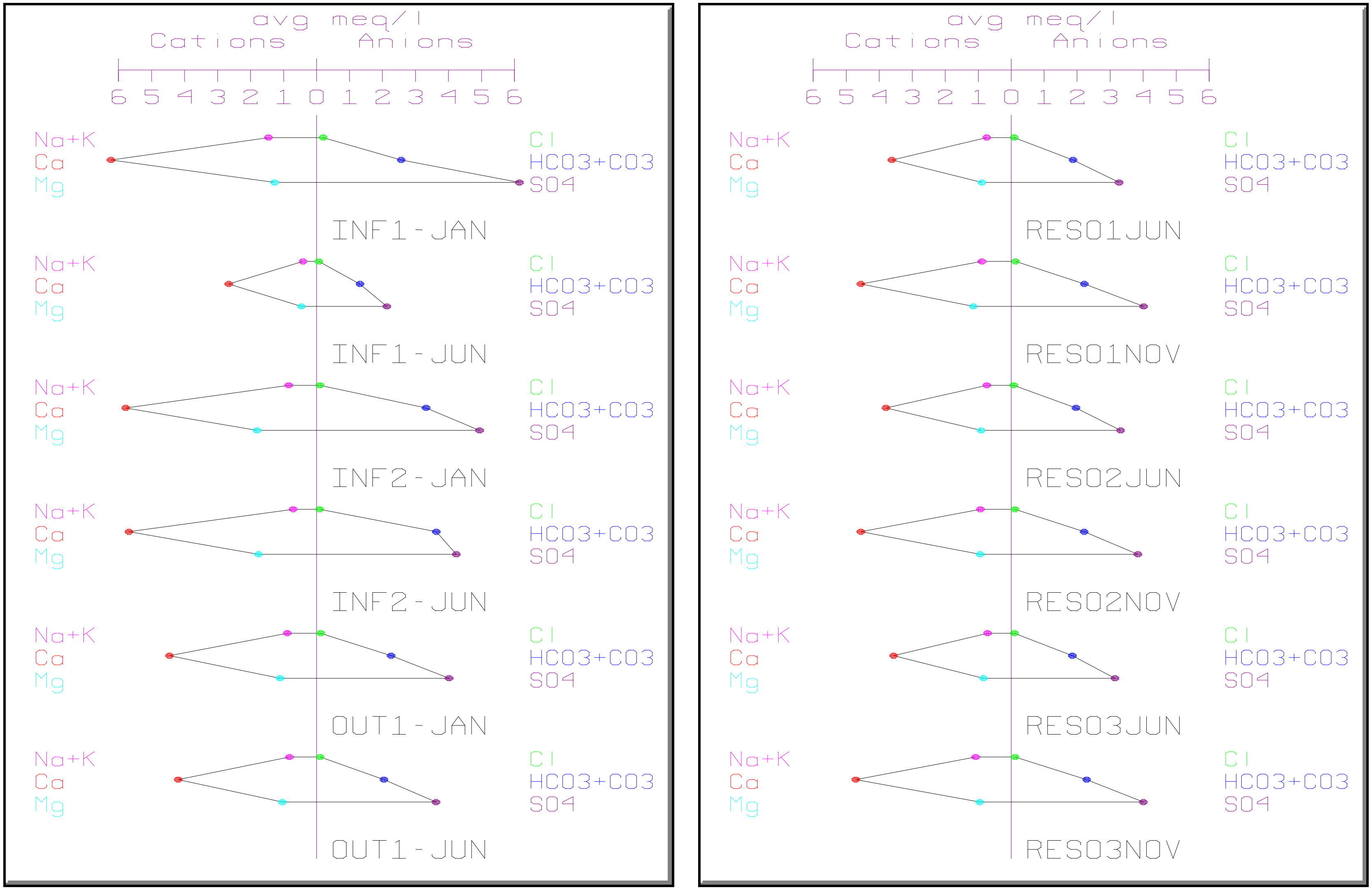


Figure 15.—Stiff diagrams showing average major ions for inflow and outflow during January and June, and reservoir station average ions for June and November.

Table 6.—Summary of nutrient data by sample collection station

Station	Summary	Total P Unfiltered, mg/L as P	Total P Filtered, mg/L as P	Ortho-P Filtered, mg/L as P	NH3 Filtered, mg/L as N	NO3 Filtered, mg/L as N	NO2 Filtered, mg/L as N	NO3+NO2 Filtered, mg/L as N	TKN Unfiltered, mg/L as N	TKN Filtered, mg/L as N	Organic-N Filtered-calc mg/L as N
Inflow 1	N	96	95	100	111	96	98	61	105	102	99
	Mean	0.0110	0.00600	<0.00100	<0.0100	0.205	<0.00100	0.194	0.0950	0.0715	0.0700
	Minimum	<0.00500	<0.00500	<0.0100	<0.0100	0.0900	<0.00100	0.0800	<0.0500	<0.0500	<0.0860
	Maximum	0.170	0.0420	0.0600	0.0360	0.540	0.00500	0.371	0.551	0.510	0.520
Inflow 2	N	98	98	105	116	99	99	69	100	99	96
	Mean	0.0110	0.00900	<0.00100	<0.0100	0.0960	<0.00100	0.0995	0.195	0.179	0.177
	Minimum	<0.00500	<0.00500	<0.0100	<0.0100	<0.0300	<0.00100	<0.0300	<0.0500	<0.0500	<0.0680
	Maximum	0.150	0.0560	0.0300	0.0430	0.367	0.0110	0.331	0.752	0.673	0.683
Outflow 1	N	59	106	111	116	99	99	66	64	110	108
	Mean	0.00600	0.00500	<0.00100	<0.0100	0.190	<0.00100	0.199	<0.0500	0.101	0.111
	Minimum	<0.00500	<0.00500	<0.0500	<0.0100	<0.0300	<0.00100	0.0155	<0.0500	<0.0500	<0.0680
	Maximum	0.0330	0.0500	0.0900	0.0430	0.410	0.00700	0.413	0.242	0.548	0.558
RES01	N	5	19	19	19	19	19	14	4	18	18
	Mean	0.00900	0.00600	0.00100	0.0130	0.234	<0.00100	0.171	0.0940	0.0555	0.0410
	Minimum	0.00500	0.00200	<0.00100	<0.0100	<0.0300	<0.00100	0.0155	0.0730	<0.0500	<0.0630
	Maximum	0.0100	0.0190	0.0100	0.0710	0.753	0.00300	0.720	0.117	0.500	0.487
RES02	N	7	26	26	26	25	26	19	7	26	26
	Mean	0.00800	0.00500	<0.00100	0.0120	0.158	<0.00100	0.182	0.102	0.0835	0.0830
	Minimum	0.00600	<0.00100	<0.00100	<0.0100	<0.0300	<0.00100	0.0155	0.0650	<0.0500	<0.0680
	Maximum	0.0560	0.0520	0.0490	0.0590	0.373	0.0180	0.374	0.186	0.462	0.441
RES03	N	5	15	17	17	17	15	12	5	15	15
	Mean	0.00600	0.00700	0.00300	<0.0100	0.132	<0.00100	0.127	0.0710	0.105	0.112
	Minimum	0.00250	<0.00100	<0.00100	<0.0100	<0.0300	<0.00100	0.0155	<0.0500	<0.0500	<0.0660
	Maximum	0.0120	0.0850	0.080	0.0750	0.269	0.0310	0.281	0.114	0.416	0.404

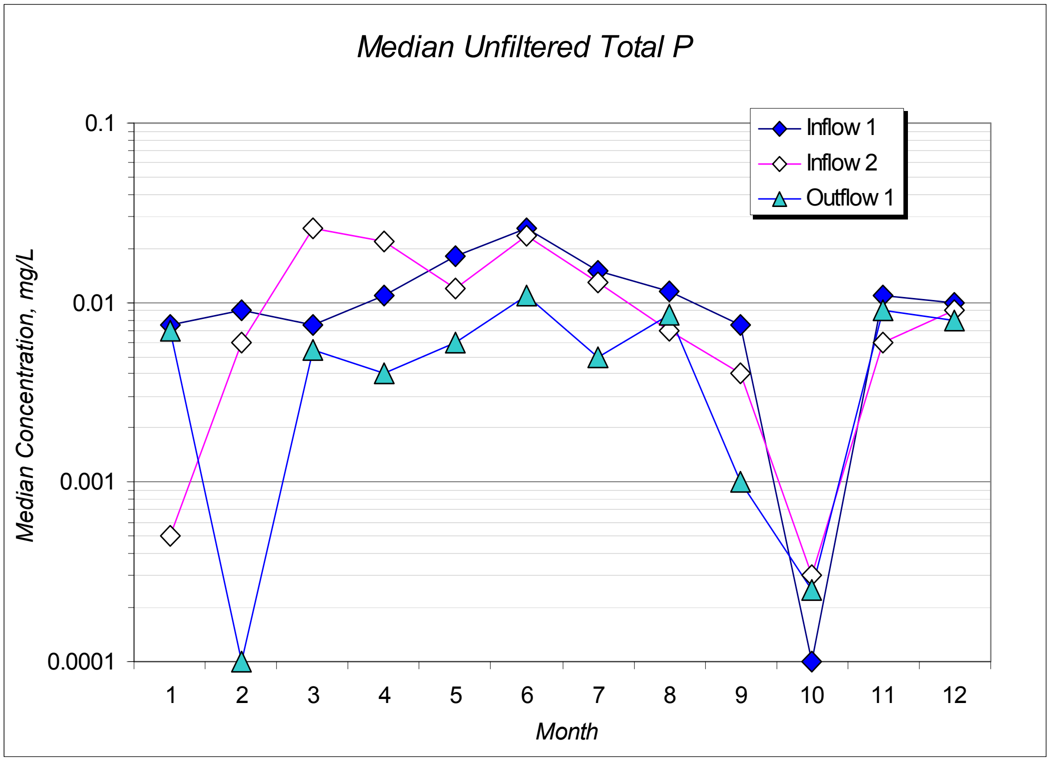
need to be evaluated after additional sampling and analysis. Perhaps there are some minor NO_3 inputs contributed by Alkali Creek or in the immediate vicinity of the reservoir. Dissolved NH_3 was infrequently observed above detection limit (about 0.01 mg/L) in inflow waters, in at-depth reservoir samples (median = 0.013 mg/L, with only 4 out of 36 reported above the 0.03 mg/L limit of quantitation), or in outflow samples (98 out of 116 samples below detection limit). The low NH_3 concentrations, consistent with the observed lack of anaerobic conditions in the hypolimnion, suggest that almost all TKN is associated with organic-N. Likewise, NO_2, a product of bacterially mediated nitrate reduction, was seldom observed above detection limits, though most of the NO_2 analysis data are likely suspect because of extended holding times prior to analysis.

Figure 16a shows plots of monthly median unfiltered total-P (top graph) and filtered ortho-P (bottom graph) concentrations for the inflow and outflow stations. Values plotted at or below 0.001 mg/L represent concentrations below detection limits. Uncompahgre River (Inflow 1) unfiltered P concentrations show a maximum for June (the maximum runoff flow month), whereas Dallas Creek (Inflow 2) data suggest a spring concentration maximum, perhaps associated with early thawing and flushing of soluble P forms in this sub basin, and another peak in June. All Outflow 1 median monthly unfiltered total-P concentrations are below most inflows, suggesting that the reservoir acts as a net sink for suspended P. The much lower filtered ortho-P concentrations in the bottom graph suggest that most P is associated with particulates, and consistently low dissolved ortho-P concentrations suggest that Ridgway Reservoir is phosphorus limited.

Flow-weighted monthly average P loading data in kg/day are plotted in figure 16b. Unfiltered loadings are shown in the top graph and dissolved loadings in the bottom graph. Non-detect data were recoded as 0.1 times the reported detection limit prior to calculation of loading values and monthly averages. The greatest unfiltered loadings were observed for the Uncompahgre River during June, approaching 60 kg/day. Dissolved loadings show a July maximum of about 35 kg/day for the Uncompahgre River. In both unfiltered and filtered loadings, Dallas Creek shows the lowest loadings, which are consistent with lower observed runoff flows in this sub-basin. Outflow unfiltered P loadings show an August spike with a September spike for dissolved P.

Both the concentration and loading data suggest that P inputs to the reservoir are likely particulates associated with suspended inorganic mineral forms that are transported mechanically by turbulent spring runoff flows. Within the lake beyond the inflow sediment settling zone, however, most suspended P is likely associated with biota.

Figure 17a plots median monthly filtered NO_3 (top plot) and organic-N (bottom plot) concentrations for the Uncompahgre River and the outflow. Although some NO_3 and TKN appears to be associated with suspended particulates, almost all of the N is dissolved. Dallas Creek N concentrations (omitted from these graphs) are much lower than those of the Uncompahgre River. The Uncompahgre River data show a NO_3 maximum in April followed by a drop through the summer, and subsequent concentration spikes in late summer and fall. The April maximum may be related to initial spring snowmelt flushing of soluble NO_3. Outflow NO_3 appears to follow Uncompahgre River NO_3 concentrations, with August-October outflow concentrations exceeding inflow. Median organic-N concentrations in the outflow appear to consistently exceed inflow concentrations except during winter low-flow months.



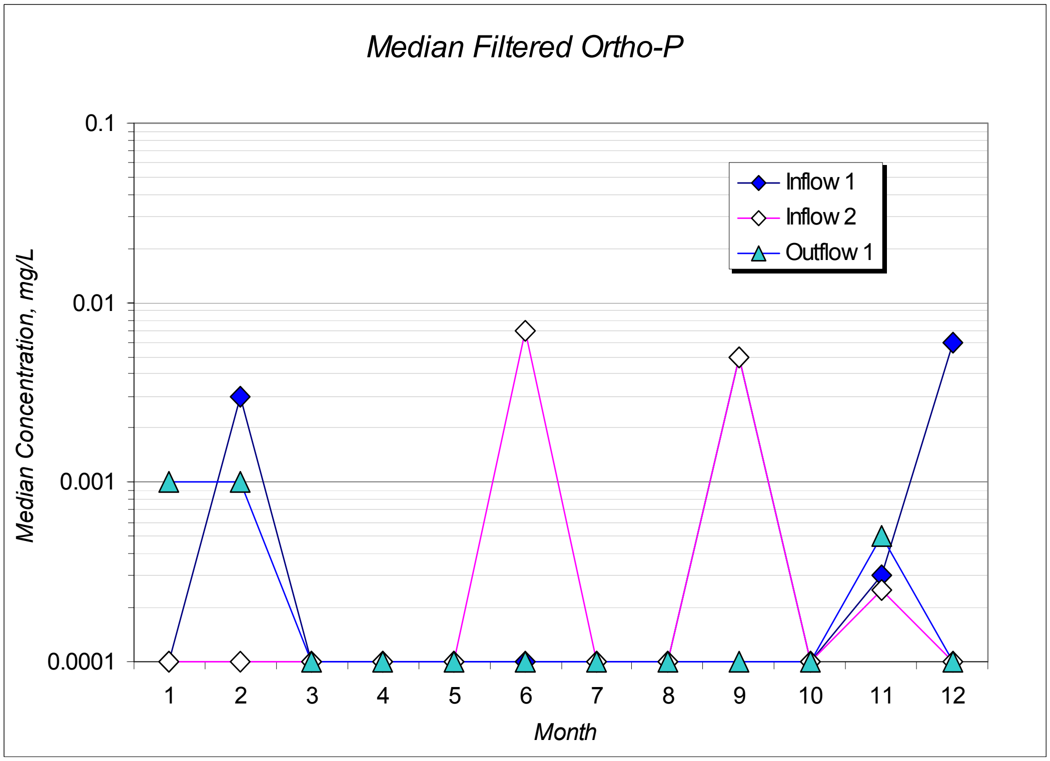
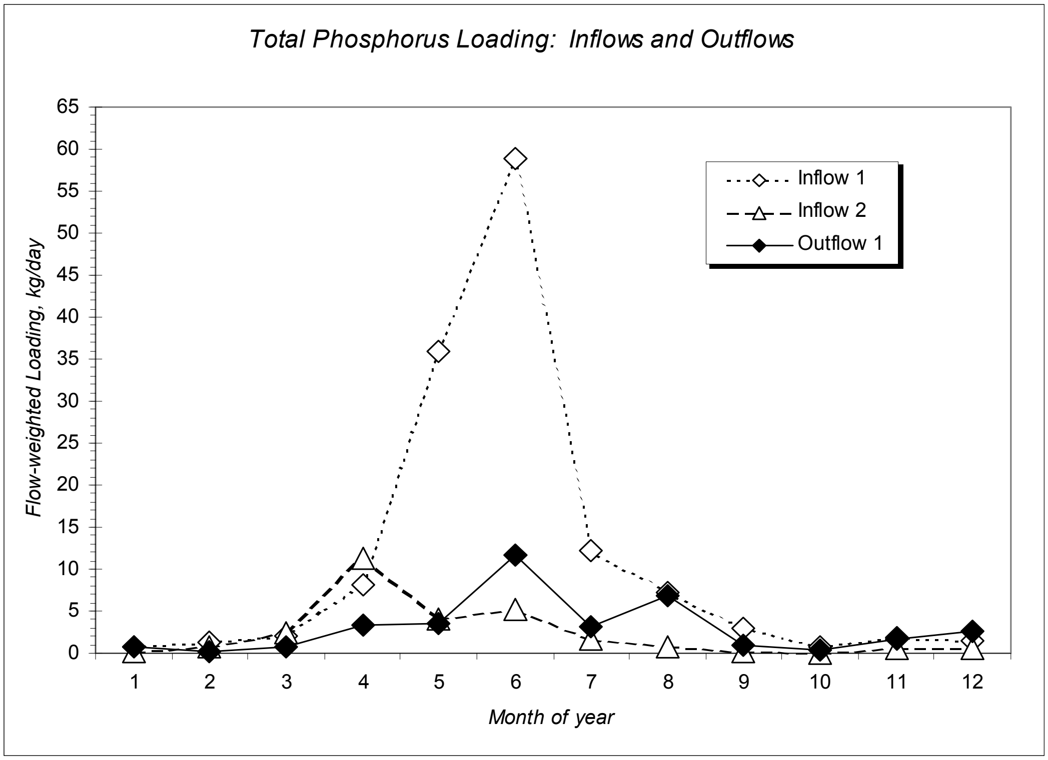


Figure 16a.—Median monthly phosphorus concentrations for stations Inflow 1, Inflow 2, and Outflow 1. Values below 0.001 µg/L are below reported detection limits.



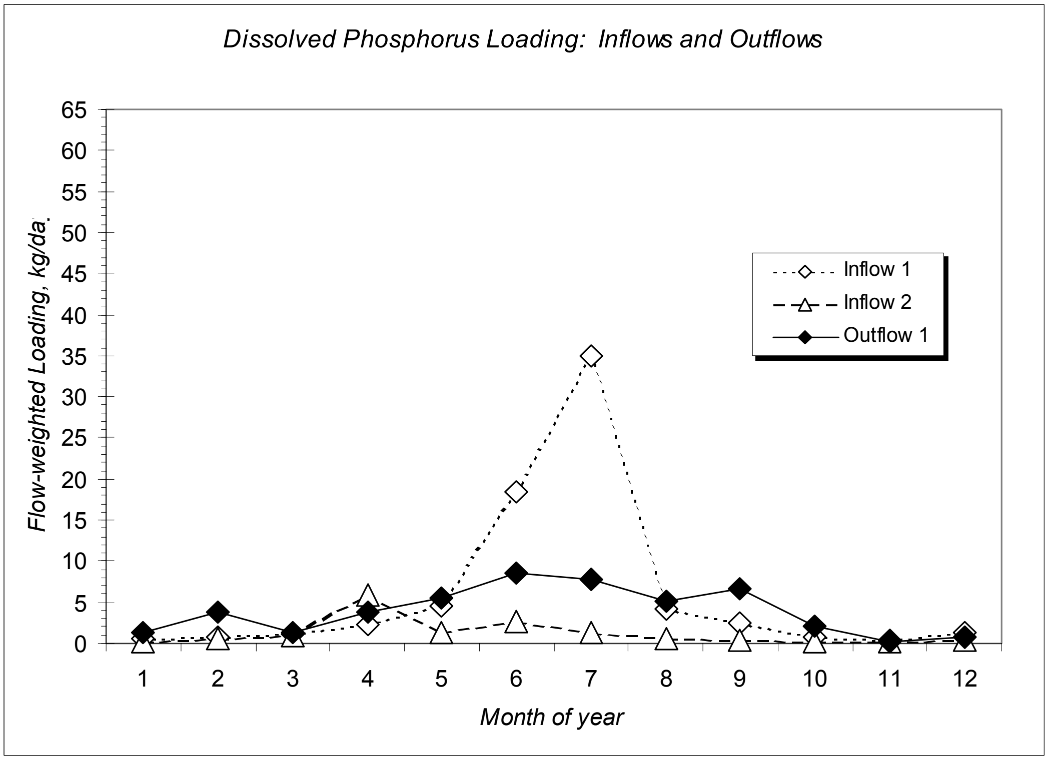
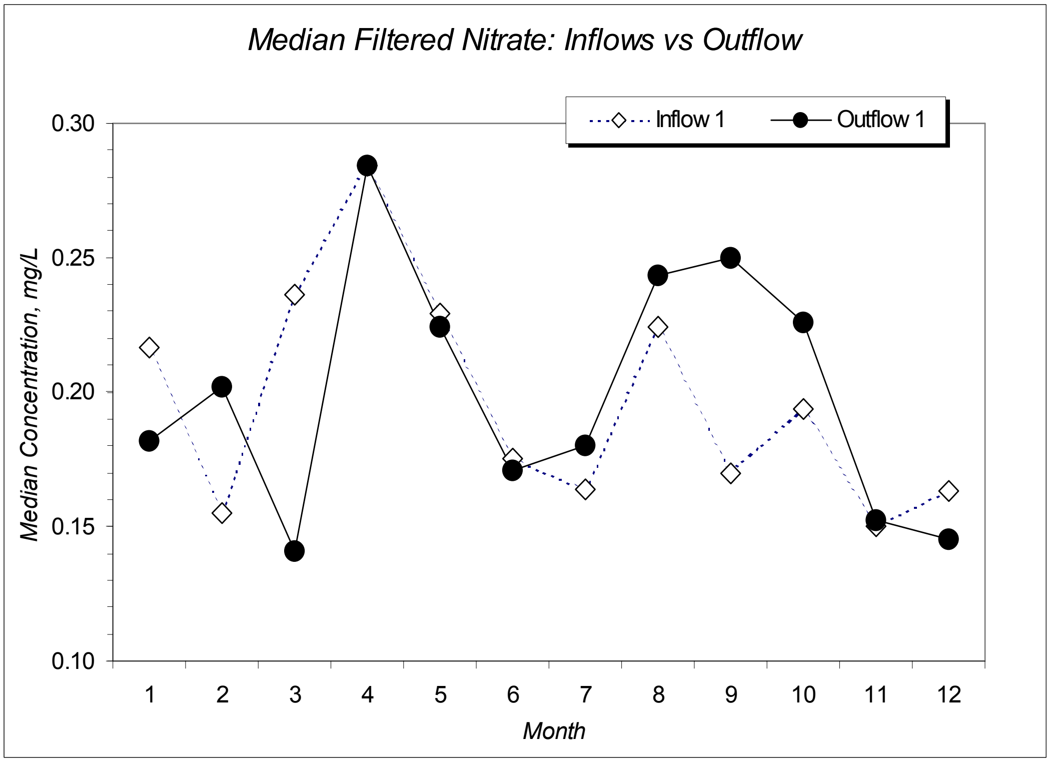


Figure 16b.—Average flow-weighted P loading for Ridgway inflows and outflow, 1987-1996. Top graph is for unfiltered data, bottom graph is for filtered data.



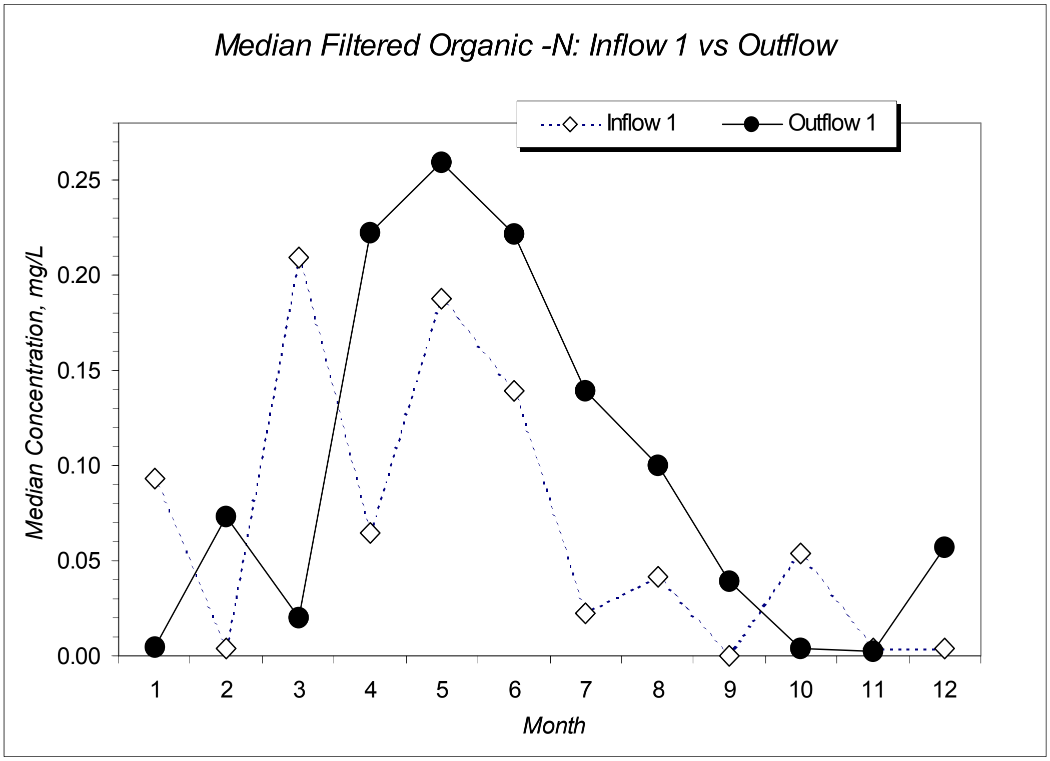


Figure 17a.—Median monthly dissolved nitrate and organic-N concentrations for Inflow 1 and Outflow.

Flow-weighted loadings for total-N (calculated as the sum of NO_3+NO_2+TKN) plotted in figure 17b, show maxima for both unfiltered and dissolved total-N for the Uncompahgre River during June. The outflow, while showing a June peak, exhibits loading maxima during August, the only month when reservoir release loadings exceed inflows. The monthly loading graphs also show a shift in maxima compared with the figure 17a concentration plots, which show peaks for dissolved NO_3 and organic-N from March through May.

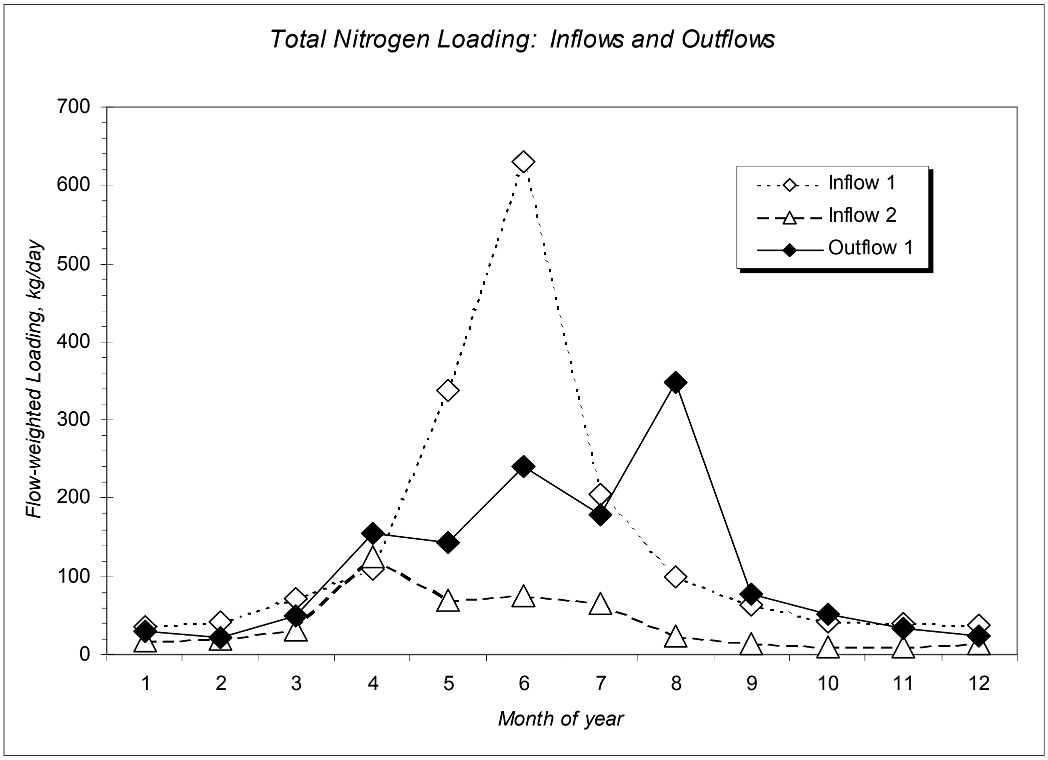
Table 7 compares annual average inflow nutrient loadings to annual average reservoir outflow loadings based on both unfiltered and filtered analytical results. The data analyzed in this study suggest that Ridgway Reservoir is a net sink for both N and P. Although this is the expected effect of a reservoir and represents a net improvement in downstream water quality, it also suggests that reservoir sediments may eventually contribute a much greater source of internal nutrient loading to the reservoir and its outflows if the trophic status changes from oligotrophic to eutrophic.

Table 7.—A comparison of of total-N and total-P loading for Ridgway Reservoir

	ANNUAL AVERAGE LOADINGS			
	Total Nitrogen		**Total Phosphorus**	
Loading Source	**Unfiltered, kg/day**	**Dissolved, kg/day**	**Unfiltered, kg/day**	**Dissolved, kg/day**
Uncompahgre River	143.0	129.00	11.10	5.99
Dallas Creek	39.7	34.30	2.32	1.21
Total Inflow	183.0	163.00	13.40	7.20
Reservoir Outflow	113.0	151.00	2.97	3.94
Inflow - Outflow	69.9	11.60	10.50	3.26
Percent Entrained	38.3	7.15	77.90	45.20

Observed reservoir nutrient data are shown in figure 17c, which plots median (all-data) filtered N and P species concentrations for surface, mid-depth, and bottom reservoir samples. All median N and P concentrations show an increase with depth and approximately an order of magnitude greater concentrations of N compared with P. Median concentrations of NO_3 are only slightly greater than organic-N (as represented by the TKN plot).

The ratio of total nitrogen to total phosphorus (TN:TP) has been suggested as indicative of trophic status (Downing and McCauley, 1992), with high TN:TP ratios suggesting oligotropy and low TN:TP ratios suggesting eutrophy. TN:TP ratios for Ridgway samples, seen in table 8, are log-normally distributed, and median ratios ranged from 25.6 to 51.8 for unfiltered samples and ranged from 47.3 to 61.2 for filtered ratios. Interquartile ranges (boundary values for the 25th and 75th percentile ranks) for all reservoir associated waters (inflows, reservoir, and dam outflow samples) were 16.4 to 54.8 for unfiltered samples (n = 199), and 26.0 to 105 for filtered samples (n = 289). These values are associated with oligotrophic systems as summarized by Downing and Cauley (1992).



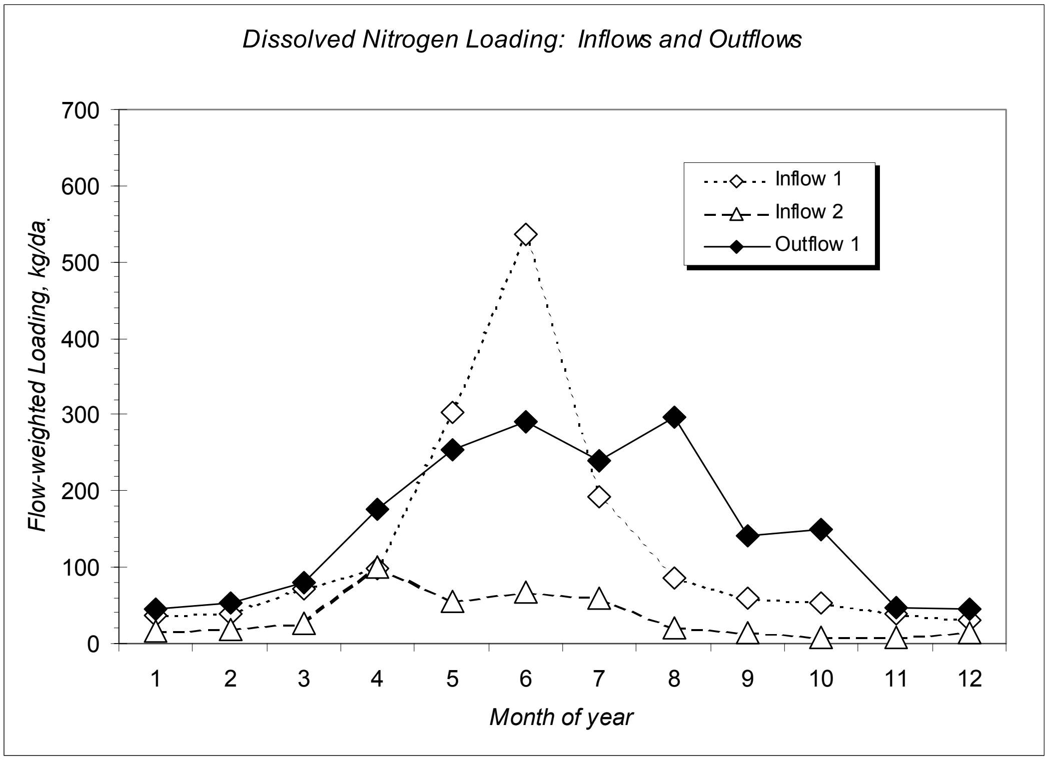


Figure 17b.—Average flow-weighted N loading for Ridgway inflows and outflow, 1987-1996. Top graph is for unfiltered data, bottom graph is for filtered data.

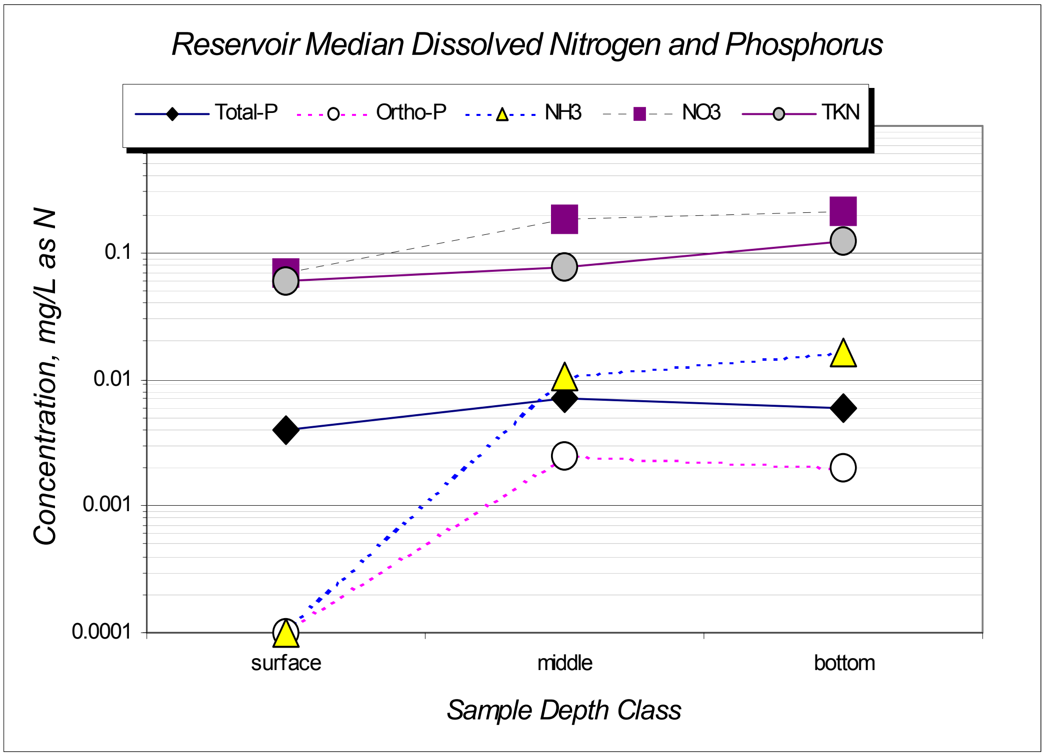


Figure 17c.—Median filtered nutrients in Ridgway Reservoir by sample depth class. Note logarithmic scale. Points below 0.001 were below reported detection limits.

Table 8.—Unfiltered and filtered N:P ratios calculated for different Ridgway water sources. Below detection limit data were recoded as half the detection limit

		Unfiltered TN:TP Ratio	Filtered TN:TP ratio
Inflow	n	147.0	145.00
Percentiles	25	14.0	23.80
	75	54.8	105.00
Outflow	n	39.0	86.00
Percentiles	25	19.7	26.80
	75	53.1	125.00
Reservoir	n	13.0	58.00
Percentiles	25	38.3	32.40
	75	56.4	104.00
Simulation	n	0	16.00
Percentiles	25		9.33
	75		58.00

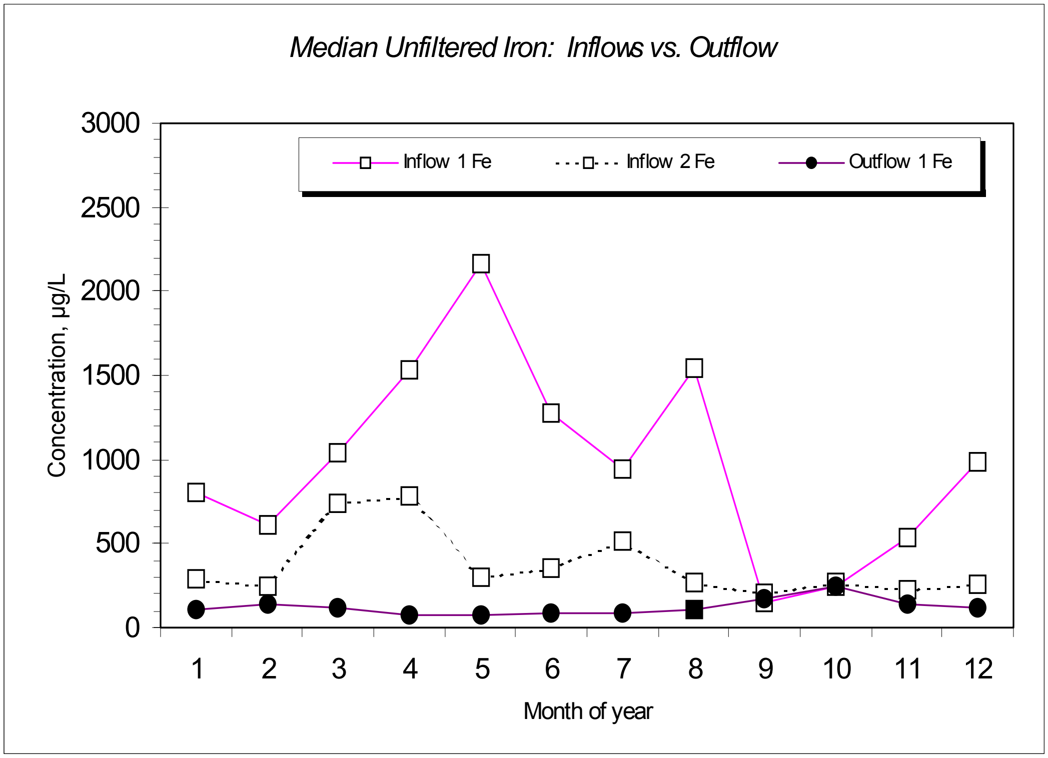
Trace Elements in Ridgway Waters

Given the amount of historical mining activity in the watershed, it is not surprising that trace elements have been observed in Ridgway waters. Like all chemical constituents in Ridgway waters, trace element behavior appears to be strongly influenced by runoff transport and the hydrologic cycle. All unfiltered trace elements show maximum mass loading during June and, as seen with the nutrient data, the Uncompahgre River is the dominant input source. The outflow mass loading data also suggest that Ridgway Reservoir generally reduces trace elements in downstream waters. This discussion will address trace elements as 2 groups: mineral elements, a higher concentration group composed of Si, Al, Fe, and Mn, and usually associated with suspended mineral particles and adsorbed coatings (Lion, et al., 1982; Stumm, 1987; Schindler and Stumm, 1987; Stone and Morgan, 1987) and toxic elements, including silver (Ag), arsenic (As), Cd, Cu, Hg, Pb, Nickel(Ni), Se, and Zn, which are present at much lower concentrations.

Mineral Elements

The pie charts in figure 18a show flow-weighted loading proportions for the mineral elements based on the overall median mass loadings for dissolved and suspended Si, Al, Fe, and Mn in the inflows and outflow. Notably, Si is largely dissolved in all waters, indicating presence of soluble amorphous silica glass in the volcanic geology of the watershed (Deer, et al., 1977). Inflow 1 shows the highest percentage (about 38 percent) of suspended mineral elements, over twice that observed in Inflow 2 (about 17 percent) and the outflow (about 14 percent). Suspended Al loading appears to be from 5- to 7-times greater than dissolved, and the ratio of suspended Al to Si suggests molar ratios on the order of 2:1. These data suggest an association of suspended Al and Si with transported aluminosilicate particulates, and that mechanical erosion of surface sediments along turbulent runoff flowpaths is the likely mode of transport for mineral (and toxic) elements in the Uncompahgre River. Both Al and Fe are mostly suspended in all waters, with significantly lower suspended:dissolved ratios for Fe observed in the outflow (suspended about 2.5 times dissolved) compared with the Uncompahgre River (suspended over 20-times dissolved).

Figure 18b shows monthly median unfiltered Fe and Mn concentrations in the inflows and outflow. These plots share some similarity to the nutrient plots (figure 17a) where concentration maxima (in May for Al and Fe, April for Mn) appear to precede maximum runoff and loading in June. Also prominent in the inflow plots are August peaks for Fe inflows, perhaps associated with late summer thunderstorm runoff events. Manganese does not show a similar late summer peak, suggesting that it is not as associated with sediment from runoff erosion. Notably, both concentration and mass loadings suggest that Ridgway Reservoir is a net sink for trace elements. The likely mechanism for lower suspended loadings in the outflow involves settling of heavier suspended materials and deposition on reservoir sediments. Dissolved concentrations may be reduced during water transport through the reservoir by adsorption of dissolved trace elements on suspended seston and fine particulates (Dzombak and Morel, 1990), which subsequently also settle on lake sediments.



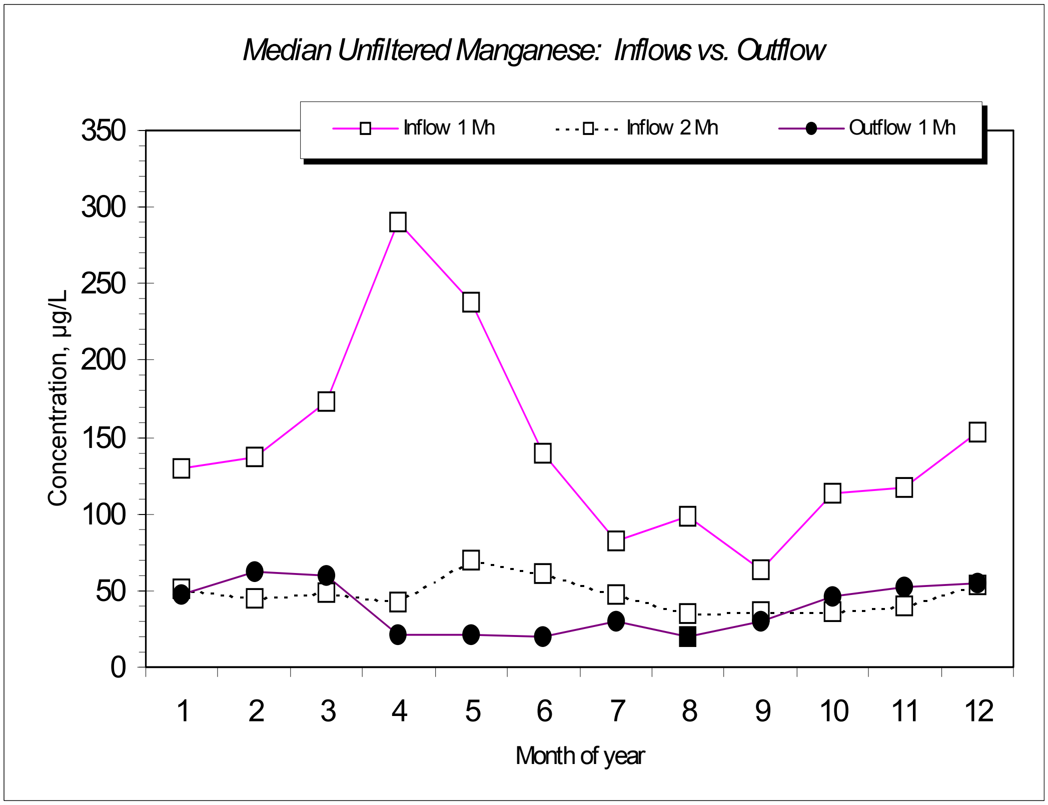
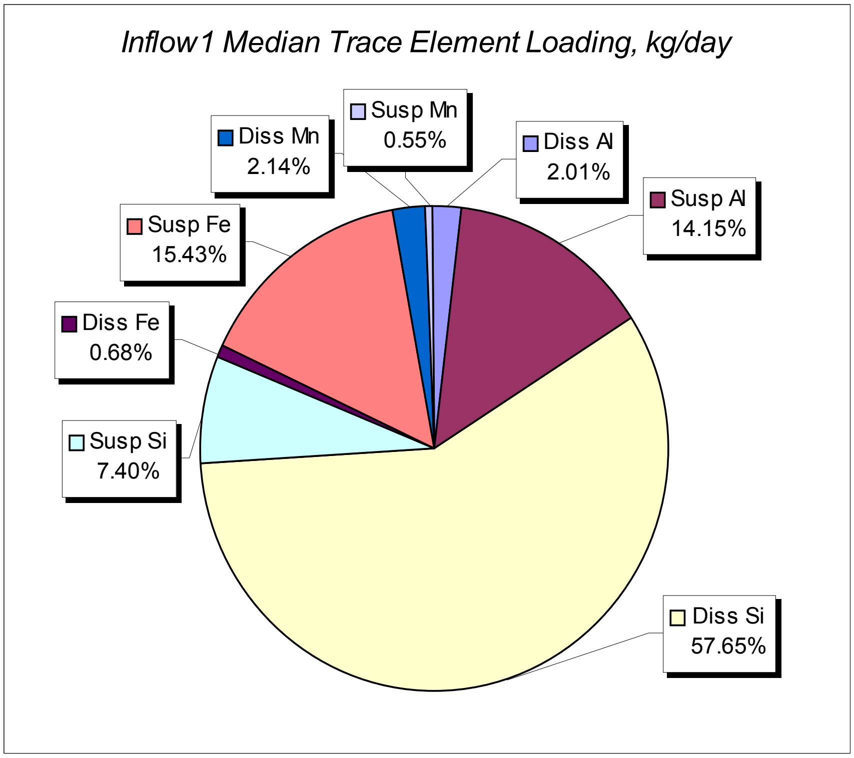


Figure 18.—Median monthly unfilterered Fe (top chart) and Mn (bottom chart) comparing Inflow stations with outflow.



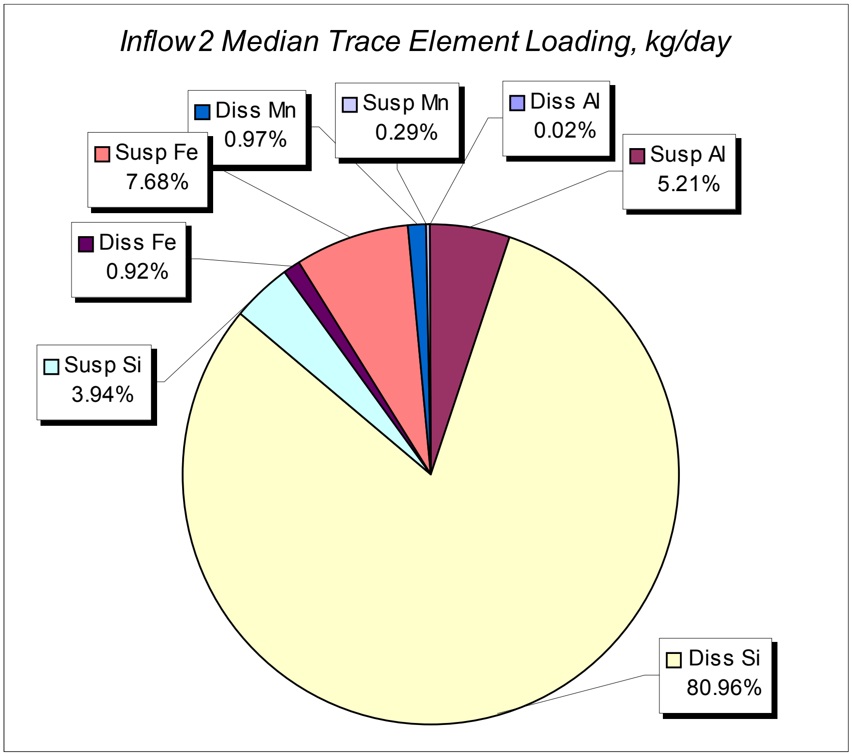


Figure 18a.—Overall median suspended trace element loading proportions for Inflow 1, Inflow 2, and the reservoir outflow.

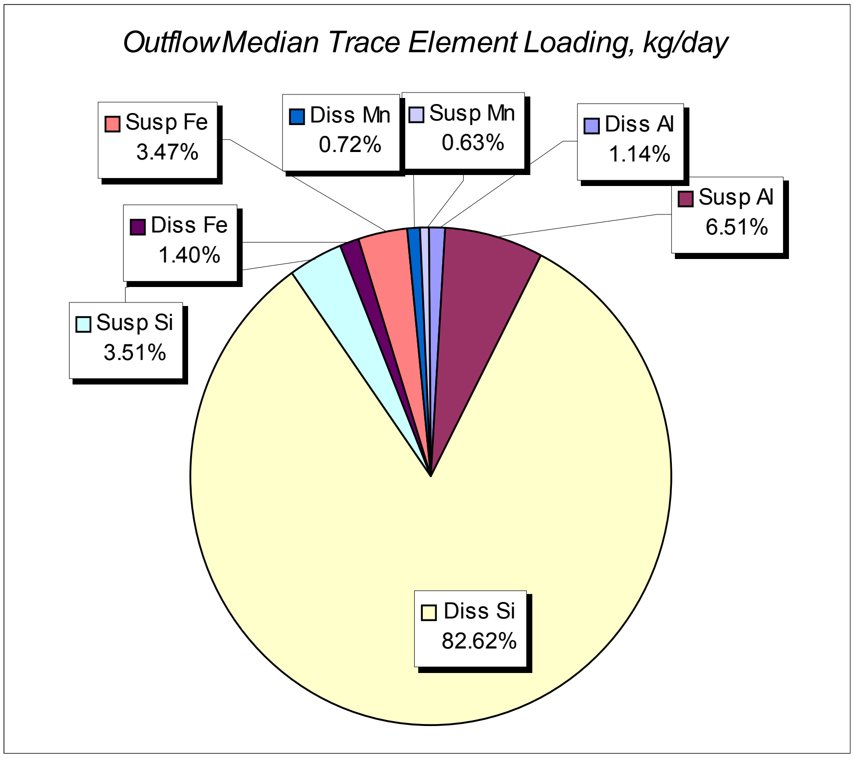
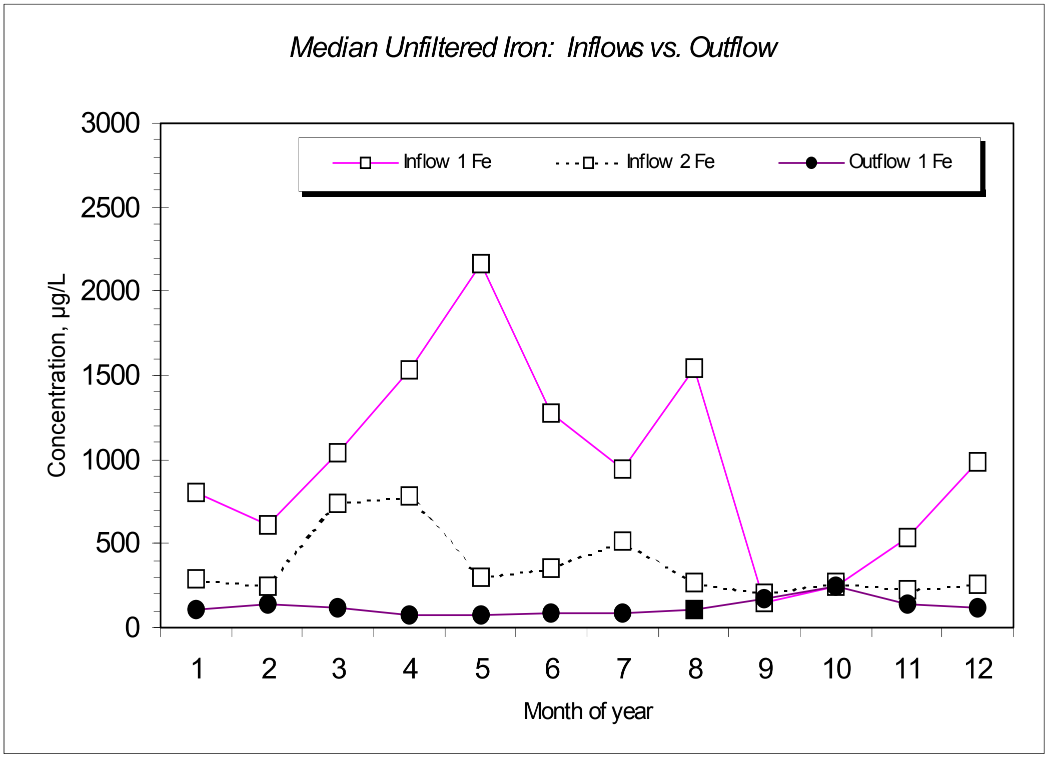


Figure 18a.—(continued) Overall median suspended trace element loading proportions for Inflow 1, Inflow 2, and the reservoir outflow.



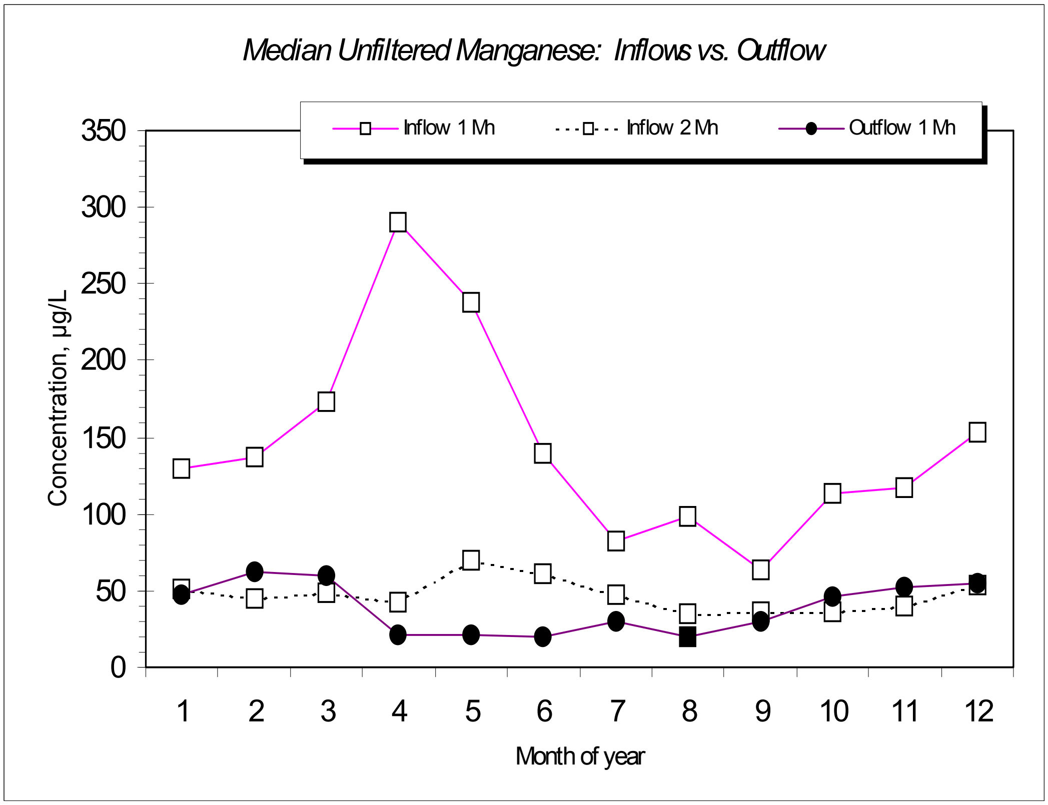


Figure 18b.—Median monthly unfilterered Fe (top chart) and Mn (bottom chart) comparing Inflow stations with outflow.

Toxic Elements

Although the validated and censored data sets suggest that toxic trace elements are present in inflows and outflows, conclusions regarding several elements should be considered tentative. Removal of unacceptably high detection limit data and recoding of non-detect data may introduce biases for minimum estimates, and some high observed unfiltered maxima may be the result of non-representative sampling. For these reasons, most of the conclusions are based on median values from censored data sets. Because of the lower concentrations observed in Dallas Creek samples, these data are more subject to interpretative bias, whereas the higher observed concentrations in the Uncompahgre River, well within the quantitation range of the analytical instruments for several elements, inspire greater confidence. Although inflows and outflow were sampled much more frequently compared with reservoir, the reservoir samples are less likely to be biased due to sampling problems or contamination.

Figure 19a shows log-scale radar diagrams that plot median total (unfiltered) and dissolved (filtered) toxic element concentrations for the inflows and outflow. These diagrams provide a visual way to compare the different source waters, both with respect to the distribution of elements (the overall shape of the polygons) and the relative median concentrations (the overall size or axial extension of the polygons). Inflow 2 shows the lowest median concentrations and an absence of Cd and dissolved Cu. The similarities in shape among Inflow 1 and the outflow polygons are indicative of the greater influence of the Uncompahgre River on Ridgway Reservoir chemistry. The lower median concentrations in the outflow polygon corroborate observations that the reservoir is a sink for toxic elements. The highest median monthly concentrations were observed for unfiltered Zn (> 100 µg/L in the Uncompahgre River), followed by unfiltered Cu, then unfiltered Pb, and unfiltered As. For Ni (not shown in fig. 19a) the median unfiltered concentration is about 14 µg/L and about 80 percent of Ni is in the dissolved form. Except for a small amounts of unfiltered Se, and some observed chromium (Cr, not plotted), most of the other median toxic elements were observed below or near instrument detection limits.

How unfiltered Zn and Cd vary in concentration and mass loading throughout the hydrologic season is shown in figure 19b. The top graph plots median monthly unfiltered Zn and Cd for the inflows and outflow stations. It shows an April maximum for Inflow 1 unfiltered Zn and Cd. The outflow Zn and Cd show reduced median concentrations. The lower graph plots unfiltered and dissolved mass loadings for Zn for the inflows and outflow. The June maximum is similar to that observed for nutrients (fig. 17b) and mineral elements (fig. 18b) mass loading plots. Figure 19c shows median monthly dissolved concentrations for As, Cd, Ni, Pb, Se, and Zn, for the Uncompahgre River (top graph) and the outflow (bottom graph). The Zn and Cd data, the most reliable of the toxic trace element measurements, show clear reductions in dissolved median monthly concentration between Inflow 1 and the outflow. Note that the censored data sets produce interpolation gaps for Se, As, Pb, and Ni, and these same elements often show below detection limit values (plotted < 0.10 µg/L) Despite the monthly data gaps, figure 19c shows lower dissolved concentrations for the outflow compared with Inflow 1, another indication that reservoir acts to reduce toxic trace element concentrations.

Concern is often voiced about Hg because of its inherent toxicity (Ostler, 1987), potential for methylation (Jensen and Jernelov, 1969, 1972; Zhang and Planas, 1994), bioaccumulation through the food chain (Ostler, 1987), and low regulated concentrations (0.01 µg/L for total Hg). Although several observations suggested that Hg may exceed the 0.010-µg/L water quality standard, an ultra-clean sampling in August 1995 followed by careful analysis by Frontier Geosciences, Inc., Seattle, Washington, provides the most reliable Hg measurements to date in Ridgway waters. Table 9, which presents data from this supervised sampling event, shows that

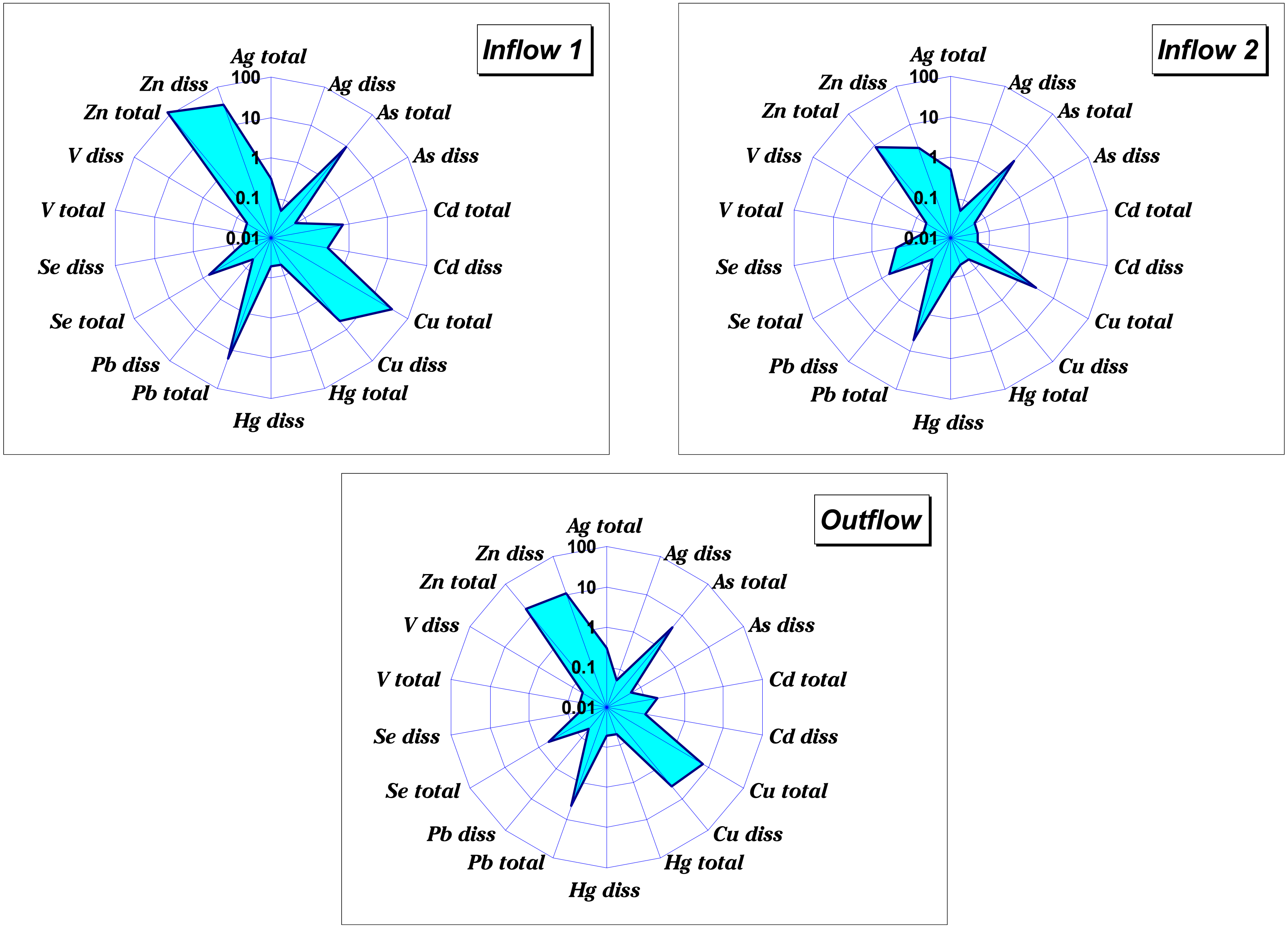
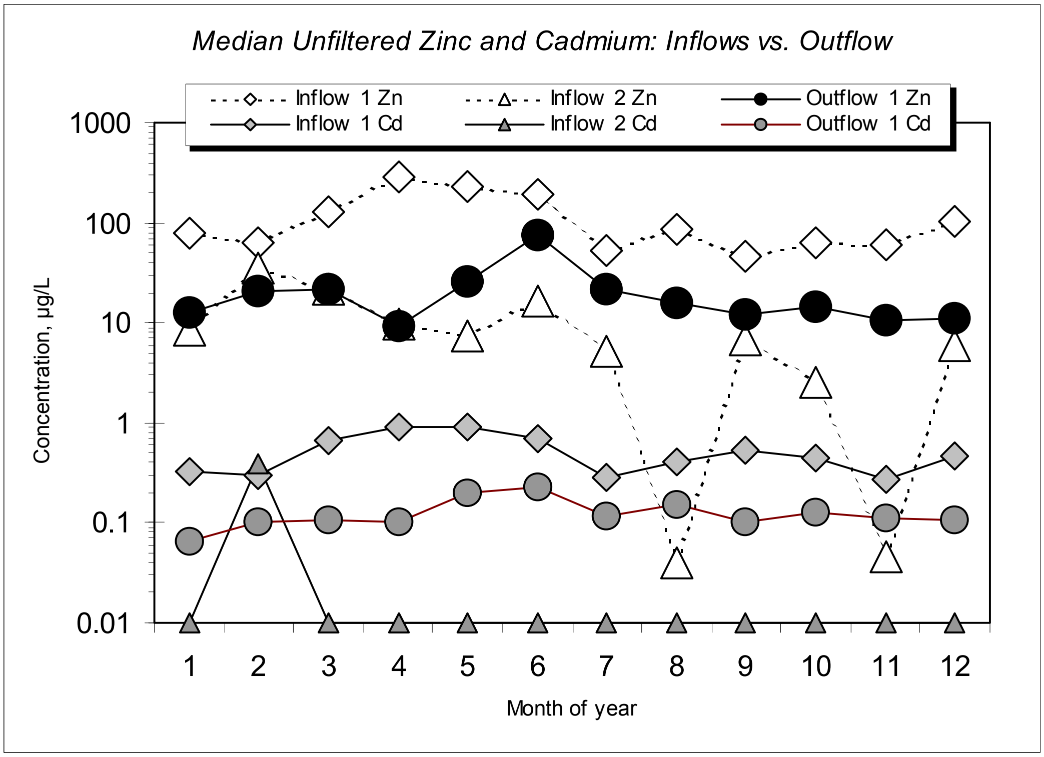


Figure 19a.—Median toxic element concentrations in µg/L plotted on radar diagrams for the Uncompahgre River, Dallas Creek, and reservoir outflow. Values plotted below 0.1 µg/L were below detection limits.



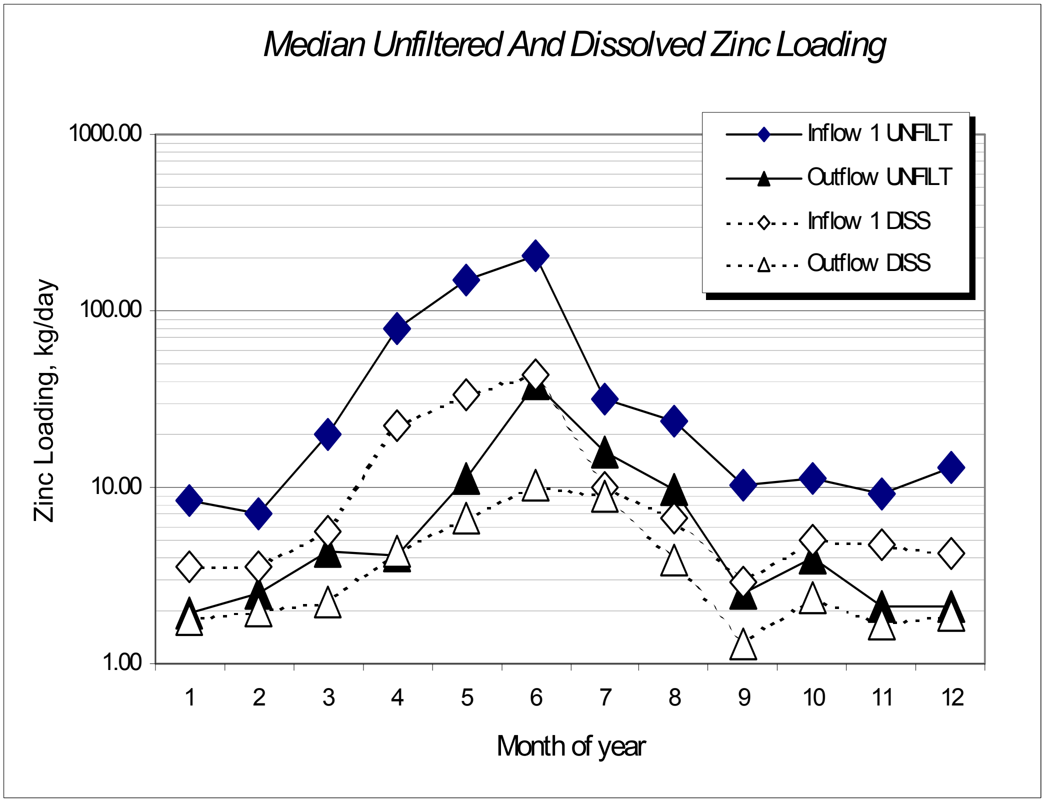
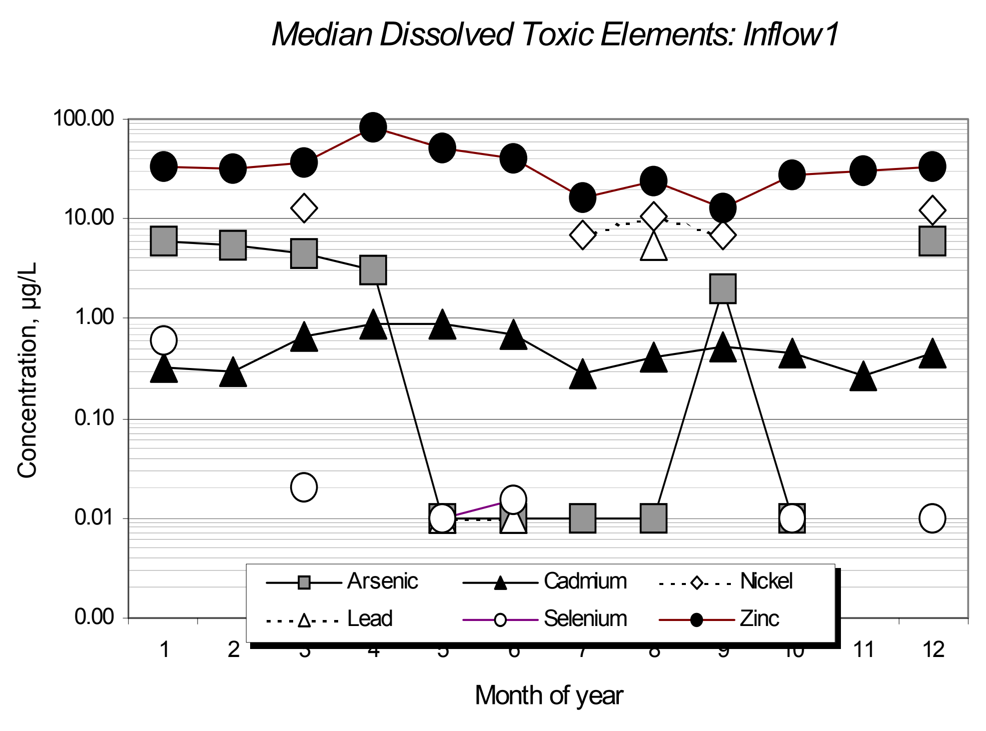


Figure 19b.—Median monthly unfiltered Zn and Cd concentrations (top graph) and median unfiltered and dissolved loading for Zn (bottom graph).



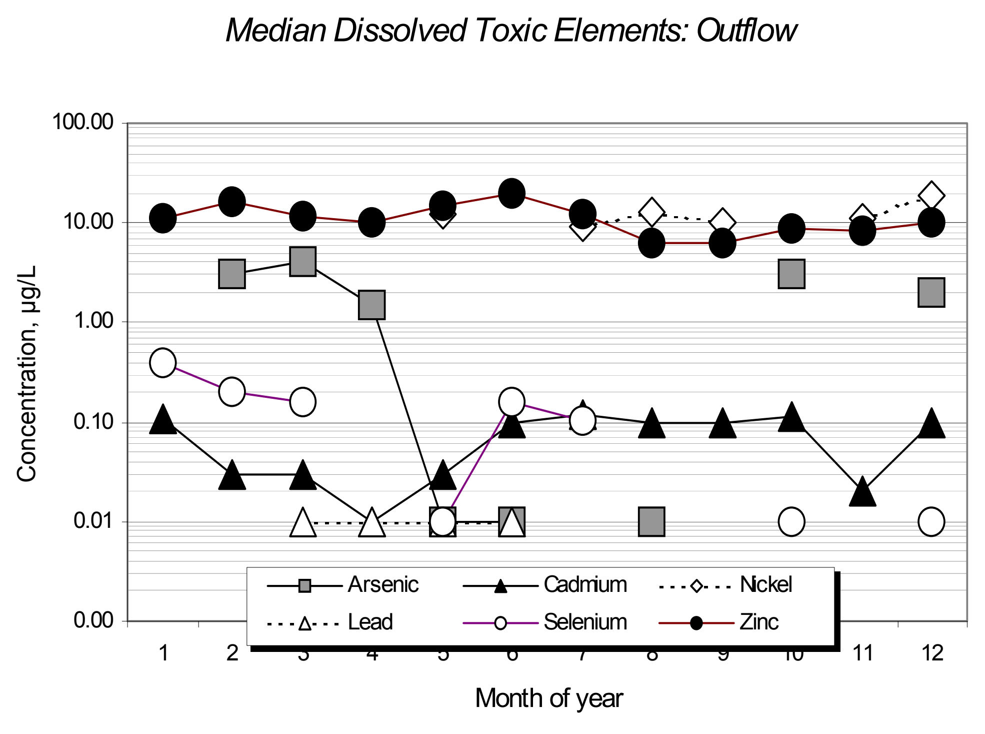


Figure 19c.—Median monthly dissolved trace element concentrations for more toxic elements. Inflow 1 is shown in the upper graph, and the reservoir outflow is shown in the bottom graph.

the Uncompahgre River does contain unfiltered Hg slightly above water quality limits. However, concentrations in Dallas Creek, surface samples in the reservoir, and the outflow are well below these limits. Though tentative and deserving of additional study, these data suggest that Hg was being transported into Ridgway Reservoir well past June maximum runoff flows at concentrations near and above regulated levels.

Notably, Osmundson (1992) reported Hg measured in Ridgway fish tissues for larger predator species approaching the 0.6 mg/kg level EPA recommends for issuance of fish consumption advisories (EPA, 1993, 1994). Although the current trophic status and low productivity of the reservoir will not encourage Hg bioaccumulation, this may be a legitimate concern if the lake becomes more eutrophic. Bryophytes exposed to river water in the upper, undisturbed reaches of the Uncompahgre River also showed detectable Hg (Nelson and Campbell, 1995), suggesting that Hg is a naturally occurring contaminant in the watershed.

Table 9.—Mercury concentrations in µg/L for August 1995 unfiltered samples collected using ultra-clean procedures

RES01	0.00201
RES02	0.00207
RES03	0.00149
Reservoir Outflow	0.00206
Dallas Creek at USGS gage	0.00239
Uncompahgre River at USGS gage	0.01209

Water Quality

Table 10 summarizes water quality standards applicable to Ridgway waters. The principal criteria are those established by the State of Colorado (State of Colorado, 1999) and are based on a system that implements regulated concentrations, called table value standards (TVS), based on intended water usage (agricultural, recreational, etc.). TVS concentrations are also adjusted for trace elements based on hardness in the water. The TVS values provide for acute and chronic exposure standards based on toxicity to aquatic organisms and fish. Hardness, the sum of Ca and Mg expressed in mg/L as $CaCO_3$, is known to ameliorate the toxic effects of trace elements (Forstner and Whitmann, 1979), and most TVS values are based on dissolved concentrations in recognition that suspended concentrations are not usually bioavailable. Colorado classifies the Uncompahgre River segment that includes Ridgway Reservoir (segment 3) as aquatic life cold water class 1 (suitable for cold water fish species such as trout), recreation class 1 (suitable for direct human contact as in swimming), and as agricultural water. For reference, table 10 also lists regulated concentrations established for public drinking water under the Clean Water Act (United States of America, 2000a, 2000b). These values do not apply to source waters used for public drinking water supply (such as Ridgway Reservoir), but rather treated water provided to the public by municipalities. Also provided in table 10 are National Recommended Water Quality Criteria defined under section 303(d) of the Clean Water Act (United States of America, 1998), which are similar to the Colorado TVS levels.

Table 10.—Summary of National and State water quality standards applicable to Ridgway Reservoir. All concentrations are dissolved unless otherwise noted: trec = total recoverable

		National Drinking Water Standards		National Recommended WQ Criteria for Priority Toxic Pollutants[3]		State of Colorado Table Value Standards[4]						
		Primary[1] 40 CFR 141	Secondary[2] 40 CFR 143	62 FR 42160 CMC[a]	62 FR 42160 CCC[b]	General Standard	Cold Water Acute	Warm Water Acute	Acute	Trout Acute	Chronic	Trout Chronic
pH	su		6.50 to 8.50			6.50 to 9.00						
DO	mg/L					6.00**						
TDS	mg/L		500									
Cl^-	mg/L		250			250*						
SO_4^{2-}	mg/L		250			250*						
NH_3^-	mg/L						0.257	0.370			20.0	
NO_3^-	mg/L	10.0				10.0*						
NO_2^-	mg/L	1.00				0.0500*						
As (trec)	µg/L	50.0		340	150					50.0	100	
Al	µg/L		50.0 to 200									
B	mg/L					0.750						
Ba	µg/L	2000										
Be	µg/L	4.00										
Cd (trec)	µg/L	5.00		4.30	2.20				32.0	12.7	2.57	
Cr total	µg/L	100										
Cr(III)	µg/L			570	74.0				4083		487	
Cr(VI)	µg/L			16.0	11.0				16.0		11.0	
Cu	µg/L	1300	1000	13.0	9.00				47.4		28.9	
Fe	µg/L		300								1100[c]	
Hg (total)	µg/L	2.00		1.40	0.770	0.0100						
Mn	µg/L		50.0								1000[d]	
Pb	µg/L	15.0		65.0	2.50				517		17.1	
Ni	µg/L	100		470	52.0				2045		211	
Se (trec)	µg/L	50.0			5.00				20.0		5.00	
Ag	µg/L		100	3.40					12.3		1.93	0.452
Zn	µg/L		5000	120	120				283		257	

NOTES:

[1] United States Code of Federal Regulations, 2000a

[2] United States Code of Federal Regulations, 2000b

[3] United States Federal Register, 1998

[4] State of Colorado, 1999

[a] CMC = Criterion Maximum Concentration (acute exposure maximum)

[b] CCC = Criterion Continuous Concentration (chronic exposure maximum)

[c] Lower TVS values in upstream segments: chronic dissolved = 300 µg/L; chronic total recoverable = 1000 µg/L

[d] 50 µg/L TVS listed for upstream segments of the Uncompahgre River

* Values for headwater stream segment No. 2: Uncompahgre River from Como Lake to confluence of Red Mountain Creek

** TVS for DO in spawning habitats = 7.0 mg/L

Table 11 summarizes the observed water quality standard exceedances and provides an estimate of the percentage of reliable data points in the censored data sets observed at concentrations higher than regulated levels. Almost all exceedances are observed infrequently, and in some cases such as trace elements, they may represent contaminated or non-representative samples. Several more obvious exceedances include TDS above 500 mg/L in 30 percent of samples; sulfate above the 250 mg/L Colorado general standard in 19 percent of samples; dissolved Al above 50 µg/L in 40 percent of samples; and dissolved Mn above 50 µg/L in 30 percent of samples. The TDS and sulfate exceedances were associated with low flow conditions and were more common in the Dallas Creek samples. Higher concentrations of Al and Mn were observed mostly during peak runoff months in the Uncompahgre River.

Table 11.—Summary of water quality in Ridgway waters based on existing water quality regulations and criteria

Regulated Constituent	Exceeded Standards	Percent of Samples Exceeding Standard
Dissolved Silver, µg/L	CO trout chronic 0.45 µg/L	5 percent
Dissolved Aluminum, µg/L	NSDWS 50 µg/L	40 percent (40 pct in lake)
Total Arsenic, µg/L	CO trout acute 50 µg/L NPDWS 50 µg/L	2.50 percent
Dissolved Arsenic, µg/L	NPDWS 50 µg/L	1.00 percent (0 pct in lake)
Dissolved Boron, µg/L	OK	0 percent
Dissolved Barium, µg/L	OK	0 percent
Dissolved Beryllium, µg/L	OK	0 percent
Total Cadmium, µg/L	CO acute 32 µg/L	1.00 percent
Dissolved Cadmium, µg/L	CO acute 12.7 mg/L CO chronic 2.5 µg/L	0 percent 1.00 percent
Dissolved Chromium, µg/L	OK	0 percent
Dissolved Copper, µg/L	CO acute 16 µg/L CO chronic 11 µg/L CMC 13 µg/L	5.00 percent 2.50 percent 2.50 percent
Dissolved Iron, µg/L	OK	<1.00 percent
Total Mercury, µg/L	CO General Std 0.010 µg/L	UNKNOWN
Dissolved Manganese, µg/L	NSDWS 50 µg/L	30.0 percent (10 pct in lake)
Dissolved Nickel, µg/L	OK	0 percent
Dissolved Lead, µg/L	CO Chronic 17.1 µg/L	2.50 percent
Total Selenium, µg/L	CCC 5.0 µg/L	5.00 percent
Dissolved Selenium, µg/L	CO acute 20 µg/L CO chronic 5.0 µg/L	2.50 percent 2.50 percent
Dissolved Zinc, µg/L	CMC and CCC 120 µg/L	1.00 percent (0 pct in lake)
Dissolved NO3, mg/L	OK	0 percent
Dissolved NO3+NO2, mg/L	OK	0 percent
Dissolved NH3, mg/L	OK	0 percent
Field pH, su	OK	0.2 percent low 0.8 percent high
Total Dissolved Solids, mg/L	NSDWS 500 mg/L	30.3 percent
Sulfate, mg/L	CO General Std 250mg/L	18.7 percent
Chloride, mg/L	OK	0 percent
Dissolved Oxygen, mg/L	CO General Std for surface waters 6.0 mg/L	OK - 20.1 percent in hypolimnion

NPDWS = National Primary Drinking Water Standards
NSDWS = National Secondary Drinking Water Standards

Toxic elements Cu, Cd, Pb, Se, and Zn were elevated above regulated levels in only 1 to 5 percent of censored data sets; and were most frequently associated with the Uncompahgre River. Despite the observed exceedances, it is notable that no N species and few toxic trace elements are observed at elevated concentrations. The overall conclusion is that the water quality in Ridgway Reservoir is very good, and that the reservoir tends to improve downstream water quality. EPA also rates waters in this drainage as having low vulnerability to pollutant loadings with an Index of Watershed Indicators score of 1 (best possible quality) (Environmental Protection Agency, 2001).

Mineralogy and Properties of Simulation Soils and Reservoir Sediments

The results of petrographic analysis for simulation soils are summarized in table 12a. These results are consistent with the expected erosion and weathering products from the local sedimentary and glacial geology near the reservoir basin. A comparison of the pre-filling samples with 1995 reservoir sediment sample mineralogy, seen in table 12b, reveals some notable differences, especially with respect to the relative amounts of feldspar and clay. Feldspar weathers to form clay minerals, so greater amounts of feldspar, as seen in reservoir sediments, are usually indicative of more recently transported and less weathered arkosic materials (Pettijohn, et al., 1972; Folk, 1974; Deer, et al., 1977). Reservoir sediment feldspar ranges from 25-40 percent, whereas the simulation soils show lower amounts in the range of 5-20 percent. Clays in the basin soils range from 13-30 percent whereas reservoir sediments show a range of 5-20 percent. Even for sediments from mid-lake, 2.6 km from the inflow where one would expect enrichment of finer clay-sized particles from sedimentation, total clay only ranges from 15-20 percent. Perhaps the feldspars in the basin soils weathered to clays since they were originally deposited during Holocene times, or the basin soils were more influenced by erosion of the local sedimentary geology.

Table 12a.—Mineralogical compositions and estimated percentages for soils and sediments collected in July 1980 from the reservoir basin

	Simulation Sample Numbers and Estimated Mineral Volume Percentages							
Mineral Class	**1**	**2****	**3****	**4****	**5**	**6****	**7**	**8**
Feldspar	15-20	15	10-15	5	5-10	15-20	5	5-10
Quartz	40-45	35-40	45-50	20-25	50-55	30-35	30-35	30
Mica-illite	5-10	5-10	5-10	10	5	5-10	5	5-10
Kaolinite	5	5	3-5	5-10	5	5	5-10	5-10
Smectite [1]	5	5-10	5-10	15	10	5-10	5-10	10
Clay [2]	**15-20**	**15-25**	**13-25**	**30-35**	**20**	**15-25**	**15-25**	**20-30**
Chlorite	1-2	2-3	3	2	1-2	2-3	2-3	2
Carbonate [3]	1-2	2-3	5	20-25	5	5-10	30-35	25-30
Iron oxide [4]	5-10	5-10	3-5	3-5	3-5	5-10	2-3	1-2
Zeolite	3	2-3	1-2	1-2	2	5	trace	trace
Amphibole	1-2	2-3	trace	trace	trace	trace	trace	1-2
Minor [5]	5-10	10	5-10	10	5-10	5-10	5	5

NOTES:

** Sample was used in simulation tanks

1 Smectite (montmorillonite) includes mixed-layer and poorly crystalline varieties.

2 Total clay is sum of mica/illite, kaolinite, and smectite

3 Carbonate includes calcite and dolomite, may include other varieties.

4 Iron oxide includes hematite, magnetite, spinel, and amorphous to poorly crystalline varieties.

5 Minor includes organic material, pyrite, pyroxene, water soluble sulfates, and -other accessory and unidentified detrital minerals.

Table 12b.—Mineralogical composition of 1995 Ridgway Reservoir sediments. Distance is the lateral distance from the river-lake mixing zone

Sample ID	**Cores**	**Mix-Zone**	**100m DS**	**200m DS**	**Bay/RES03**	**RES02**
Distance, m	**--**	**0**	**100**	**200**	**1200**	**2600**
Mineral Class	**Estimated Mineral Volume Percentages:**					
Feldspar [1]	35-40	40	35-40	30-35	35	25-30
Quartz	25	30	25-30	20-25	25	20-25
Clay [2]	**10**	**5-10**	**5-10**	**10-15**	**10**	**15-20**
Chlorite [3]	5-10	5-10	10	10-15	10-15	15
Carbonate [4]	2-3	trace	trace	trace	trace	trace
Iron Oxide [5]	2-3	5	5	5	5	5
Zeolite [6]	5	5	5	5	5	5
Amphibole [7]	5-10	trace	5	5	5	trace
Minor [8]	2-3	5	2-3	5	2-3	5-10

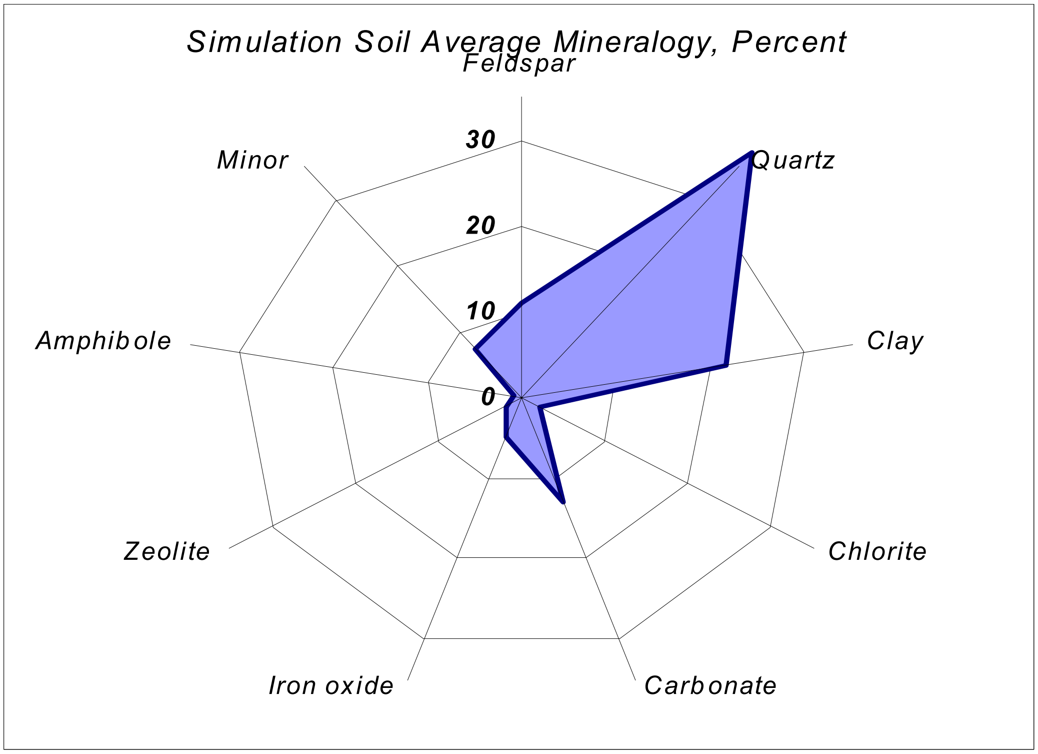
NOTES:

1 Includes both potassium and plagioclase varieties.
2 Chiefly illite/mica, includes mixed layer varieties; may include halloysite.
3 May include vermiculite.
4 Carbonate includes calcite and dolomite, may include other varieties.
5 Iron oxide includes hematite, magnetite, spinel, and amorphous to poorly crystalline varieties.
6 Chiefly laumontite and/or chabazite, may include other varieties.
7 Chiefly hornblende, may include other varieties.
8 Minor includes trace where indicated, apatite, magnetite, titanium-rich minerals such as sphene (titanite), rutile/anatase/brookite, and/or ilmenite, as well as other miscellaneous minerals.

Other differences noted between the pre-filling basin soils and reservoir sediments include much greater percentages of carbonate minerals (for example calcite and dolomite) in soils (up to 30-35 percent) compared with sediments (almost all at trace levels). The low carbonate content of sediments may be caused by the presence of acidic mine drainage in the upper elevations of the watershed. This possibility is supported by the observed elevated alkalinity (1-5 meq/L) of inflow waters. The chlorite and zeolite concentrations are also elevated in sediments relative to soils whereas quartz, perhaps originating from erosion and glacial transport of local sandstones, is elevated in soils compared with sediments. Figure 20 mineral class proportions. The differences in feldspar and clay percentages between soils and sediments are clearly visible in the polygon shapes.

Minor components revealed some other differences between basin soils and lake sediments. Unlike basin soils, the lake sediments contained several titanium (Ti) rich minerals (such as rutile, sphene, or anatase). Lake sediments also showed trace amounts of apatite (a fairly insoluble phosphorus mineral, $Ca_5(PO_4)_3OH$). These results suggest that titanium may be a marker associated with specific upper-elevation basin water sources and that the relatively insoluble apatite may account for the low observed P concentrations in the inflows and the lake.

SEM microprobe analysis of the reservoir sediments revealed the presence of Fe, Ti, and P in all sediment samples. Phosphorus was observed both as discrete apatite and as a sparse and/or disseminated surface coating on grains. Ti was detected in most samples, supporting petrographic observation of rutile and other Ti-containing minerals. Mapping of elements on several grains from each sample suggests that iron is present, for the most part, as hematite or other iron oxides. Iron-rich grains and coated areas on particles were noticeably reflective in the micrographs. Mn appeared to occur most frequently as an oxide coating on grain surfaces and was detected in all samples collected downstream of the inflow-mix zone. These data support the generally reported behavior of oxidized Fe and Mn oxyhydrates that coat surfaces of



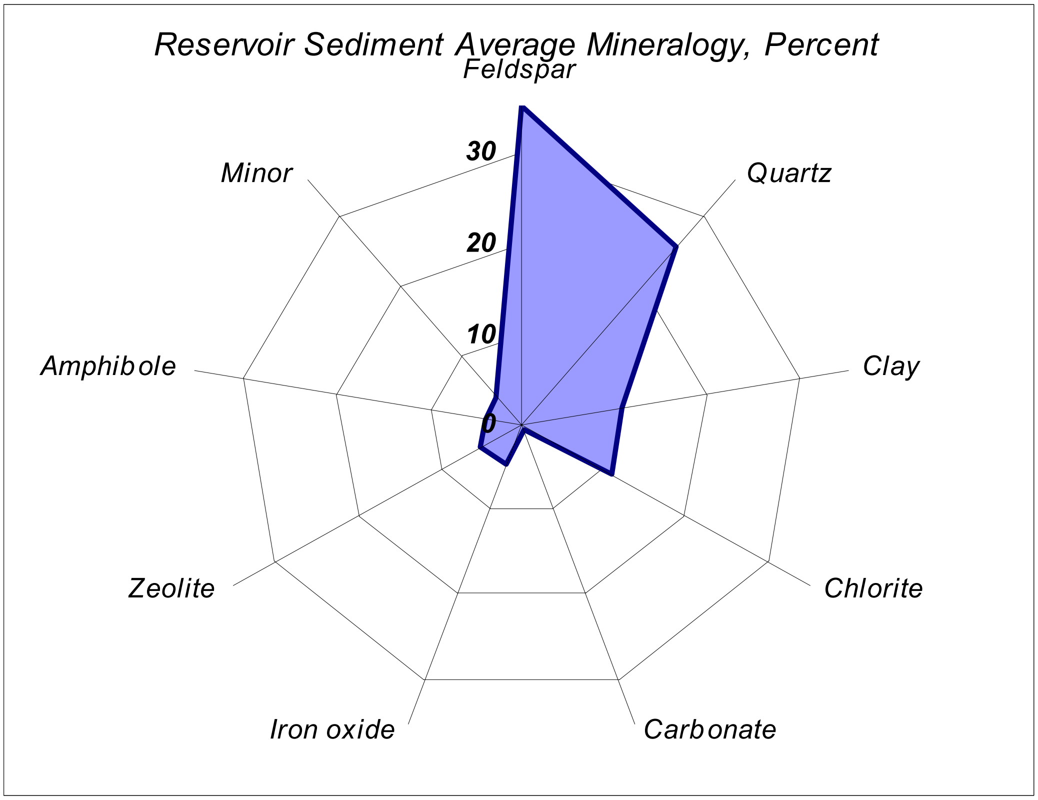


Figure 20.—Radar diagrams showing percent mineral classes for simulation soils (top) and reservoir sediments (bottom).

suspended particulates in water (Schindler and Stumm, 1987; Morel and Hering, 1993). Fe and Mn oxyhydrates are also very effective adsorptive surfaces for toxic trace elements, which are subsequently released from sediment particle surfaces under anaerobic, reducing conditions (Stone and Morgan, 1987; Myers, et al., 1988; Lion, et al., 1982; Dzombak and Morel, 1990).

Size Distributions of Reservoir Sediments

Size distributions were not determined for the simulation soil samples; however, particle size analysis results for the 1995 reservoir sediments are presented in tables 13a and 13b. Particle size fraction percentages from hydrometer tests and a more generalized fractionation of sediment into sand (>60 µm), silt (5-60 µm), and clay (<5 µm) size classes (Horowicz, 1985) are summarized in table 13a. More detailed particle size data for the minus 100-µm fraction, obtained from the Coulter size analyzer, are summarized in table 13b. These data reveal negligible amounts of the larger >2000-µm fraction material present in reservoir samples, and only the Mix-Zone sediment contained particles in the 1000-2000-, 500-1000-, and 250-500-µm, fractions.

The observed trend was for almost all sand-sized material to have settled after a lateral distance 200 m beyond the inflow-mix zone. Both the 500-1000 µm and 250-500 µm fractions appear to drop to negligible amounts after only 100 m of lateral distance from the inflow-mix zone. After 200 m of lateral distance, the 125-250-µm and 62-125-µm fractions also appear to have declined significantly, whereas the <62-µm fraction has reached approximately 92 percent at 200 m downstream. These results suggest that during autumn non-storm stream flow, larger sediment particles quickly settle within short distances from the inflow-mix zone. Once in the reservoir proper, the <62-µm silt and clay-sized fractions dominate the sediment size distributions, with steady increases observed in the very fine <10-µm fraction with increased distance from the inflow-mix zone.

A 20 percent reduction in the silt-sized fraction and a 20 percent increase in the clay-sized fraction were observed between the RES03 (1200 m) and RES02 (2600 m) samples. The table 12b data also show a 25 percent increase in the <10 µm fraction, a slight reduction in the 10-25 µm fraction, and approximately 10 percent reductions in the 25-50- and 50-75-µm fractions between RES03 and RES02 samples. These observations are consistent with expected settling behavior along reservoir inflow paths.

The size fraction data for the 1995 core samples collected from riverine bank sediments upstream of the reservoir are listed at the bottom of tables 13a and 13b. This sample represents sediments located within the maximum reservoir surface elevation influence zone that have accumulated since the reservoir was first filled. The hydrometer results suggest that these upstream river sediments were primarily in the sand- and silt-size ranges; 48 percent of the sample was associated with the <62 µm fraction. The small particle distribution seen in table 12b suggest that these sediments are most similar to the reservoir sediment sample collected 100 m downstream of the inflow-mix zone.

The sand/silt/clay sediment particle size distributions for reservoir sediments seen in table 13a appear congruent with the table 12a simulation soil mineralogy. Petrography results suggests that 15-35 percent of simulation soils are identified as clays (compared with 33 percent clay-sized particles at mid-lake RES02), and that 20-55 percent in soils were identified as quartz (compared with 59 percent as silt-sized particles at RES02). Despite the mineralogical differences, it appears that the size fractionation of pre-filling simulation soils and post-filling reservoir sediments appear roughly similar.

Table 13a.—Hydrometer particle size analysis results for 1995 sediments from Ridgway Reservoir

Sample	Distance m	Percentages Within Size Fraction Range in M							Percentages as		
		>2000	1000-2000	500-1000	250-500	125-250	62-125	<62	Sand	Silt	Clay
River-Lake Mix Zone	0	1.00	3.60	20.0	56.9	17.2	0.900	0.400	98.6	0.400	0.00
100m Downstream	100	0.00	0.200	0.300	0.500	19.1	50.1	29.8	70.2	27.8	2.00
200m Downstream	200	0.00	0.100	0.200	0.500	1.00	6.40	91.8	8.20	79.3	12.5
Inflow near RES03	1200	1.00	0.00	0.100	0.100	1.20	4.60	93.0	7.00	79.4	13.6
RES02	2600	0.300	0.600	1.40	1.00	0.700	1.90	92.1	6.60	59.0	33.2
River Inflow (3 cores)	NA	0.100	0.400	0.700	7.8.	20.7	22.3	48.0	51.9	41.0	7.00

Table 13b.—Coulter particle size analyzer results for 1995 sediments from Ridgway Reservoir

Sample	Distance m	Adjusted Percentages Within Size Fraction in m					
		<10	10-25	25-50	50-75	75-90	>90
River-Lake Mix Zone	0	0.00600	0.159	0.118	0.0650	0.0380	0.0250
100m Downstream	100	0.268	9.51	6.36	7.26	4.32	2.07
200m Downstream	200	38.1	17.8	16.8	11.1	5.32	2.67
Inflow near RES03	1200	40.0	17.3	16.6	11.3	5.27	2.43
RES02	2600	65.4	14.1	6.64	3.38	1.48	1.14
River Inflow (3 cores)	NA	19.4	8.91	9.72	6.13	2.56	1.29

Simulation Soil and Reservoir Sediment Trace Elements

Table 14 shows acid-digested trace elements for the simulation soils, which may be compared with analysis results for the reservoir sediments in tables 15a and 15b. Concentrations appear to be lower in soils than in sediments. However, some of these differences may be caused by the digestion methods used: the acid bomb digestion used for simulation soils had an acid:sample ratio of 0.03 moles/g, whereas the Method 3051 digestion used for the reservoir sediments had an acid:sample ratio of 0.30 moles/g. Although comparable digestion and analysis data for simulation soils are unavailable to resolve the observed differences, it seems reasonable that sediments transported from the upper elevations where mine wastes are widespread would have higher trace element concentrations. Figure 21 shows average mineral and toxic element concentrations as polygons on log-scale radar diagrams for the simulation soils (top diagram) and reservoir sediments (bottom). Except for Cd, the overall similarity in shape of the two polygons suggests that both soils and sediments share common proportions of trace elements, despite their different mineralogies.

Table 14.—Summary of trace element analyses for acid-digested samples for simulation experiment basin soils and river sediments collected in July 1980. Sample 6 collected from Uncompahgre River sediments

Sample Number	Simulation Soil Sample Concentrations in mg/kg							
	As	Cd	Cu	Fe	Mn	Pb	Se	Zn
1	12.0	0.0900	23.0	10600	535	33.0	<0.0750	89.0
2 **	13.0	<0.0200	35.0	12800	628	53.0	<0.0750	212.0
3 **	31.0	<0.0200	32.0	16300	522	38.0	<0.0750	119.0
4 **	45.0	0.110	41.0	18400	298	42.0	<0.0750	132.0
5	21.0	<0.0200	14.0	11100	200	19.0	<0.0750	76.0
6 **	33.0	1.54	.	16700	1660	.	<0.0750	665.0
7	16.0	<0.0200	18.0	16100	284	20.0	<0.0750	125.0
8	22.0	<0.0200	37.0	14600	459	56.0	<0.0750	159.0

** Samples used in simulation experiment

Sediment analysis results clearly show that trace metal, carbon, and phosphorus concentrations in the inflow-mix zone of the reservoir are lower than those in deeper sites in the reservoir. These results suggest that trace elements and nutrients are associated with the silt- and clay-sized suspended sediment fractions and the organic detritus associated with plankton that settle more slowly. The concentrations of almost all sediment trace elements appear to follow a similar trend with lateral distance from the inflow-mix zone - a trend also observed in the silt-sized fraction percentages found in table 12a. Relatively low concentrations were observed for the inflow-mix zone, with increasing concentrations up to 1,200 m from the inflow-mix zone, and then a slight drop in concentrations between RES03 and RES02.

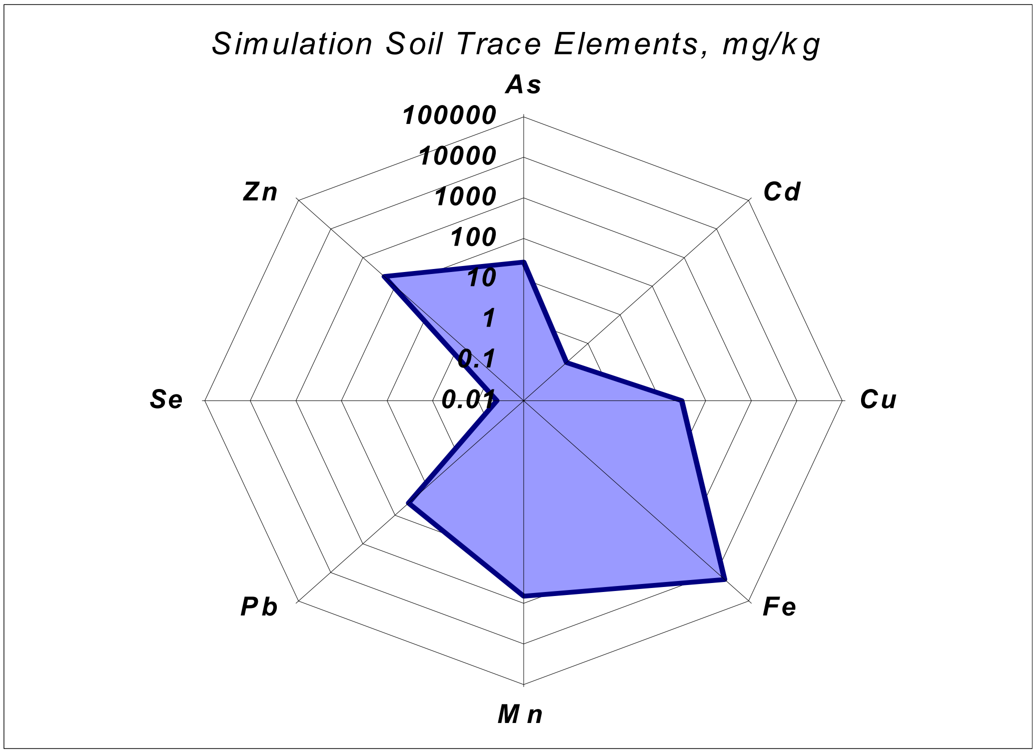
Given what is known regarding enhanced surface area and adsorption of trace elements for very fine particles (Stumm, 1986; Horowicz, 1985; Stumm and Morgan, 1996), why do RES02 sediment trace element concentrations drop when the same sediment showed a 25 percent increase in the smallest <10-µm size fraction? One possibility is that the acid-extractable toxic elements may be associated with larger sediment size fractions. The table 13b data show a 3-percent reduction in the 10-25-µm fraction, a 10-percent reduction in the 25-50-µm fraction, and an 8-percent reduction in the 50-75-µm fraction between RES03 and RES02. Another possibility is that the sediments at RES02, in a deeper part of the reservoir, may have experienced sediment bacterial activity that produced anaerobic reducing conditions leading to the loss of some trace elements.

Table 15a.—Method 3051 acid digestable cations and mineral elements for 1995 Ridgway Reservoir sediments

Downstream Distance, m	Sediment Concentrations in mg/kg										
	Ca	Mg	Na	K	Fe	Mn	Al	Si	B	Li	Sr
0	9790	5080	155	844	14100	1160	9900	801	<2.00	13.5	414
100	16400	5960	196	1390	26000	1100	13800	351	<2.00	16.9	600
200	16900	6580	223	2240	27400	1450	16700	326	<2.00	19.7	579
1200	18400	7710	265	2560	30400	1720	17500	2070	<2.00	22.5	649
2600	17100	7560	420	3450	26600	986	18300	1610	<2.00	26.8	582
Inflow cores	20400	6700	233	1890	25900	1390	15900	466	<2.00	19.3	676

Table 15b.—Method 3051 acid-digestable toxic elements for 1995 Ridgway Reservoir sediments

Downstream Distance, m	Toxic Element Concentrations in mg/kg													
	Ag	As	Cd	Ba	Be	Co	Cr	Cu	Mo	Ni	Pb	Se	V	Zn
0	1.28	2.30	0.900	58.7	0.539	11.5	2.93	52.6	<2.00	5.58	91.1	<0.400	13.5	328
100	3.14	18.9	2.25	130	0.880	12.7	6.63	135	<2.00	8.14	155	<0.400	33.8	559
200	5.77	30.8	3.93	230	1.13	13.9	7.05	221	<2.00	10.5	263	0.461	30.5	739
1200	6.42	31.6	4.06	299	1.20	15.8	8.31	200	3.16	11.3	268	<0.400	36.7	719
2600	3.12	26.3	3.3	212	1.27	13.8	9.70	180	<2.00	15.0	191	<0.400	26.4	676
Inflow cores	2.74	24.5	3.07	173	1.03	13.2	6.99	171	<2.00	10.8	169	<0.400	31.1	648



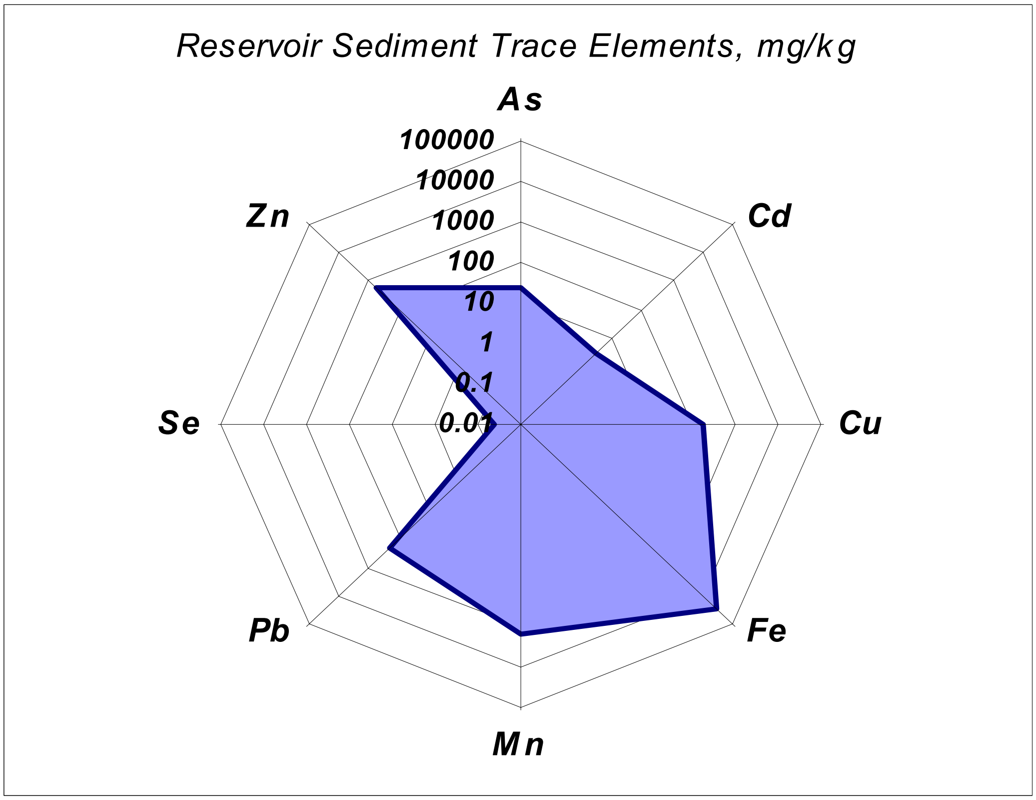


Figure 21.—Log-scale radar diagrams comparing average trace elements for simulation soils (top) and reservoir sediments (bottom).

Other sediment elements appear to be more associated with the smaller clay-sized fractions (the table 13b <10 µm fraction): Na, K, lithium (Li), and strontium (Sr), monovalent exchangeable ions often associated with clay minerals (Lindsay, 1979), and Al, Ni, and Cr, all of which showed progressive concentration increases with increasing lateral distance from the inflow-mix zone. The association of different elements with different particle size fractions and their mineral compositions in Ridgway Reservoir deserves additional study.

Underscoring the relationship between geology and water chemistry, there is a general correspondence between soil and sediment concentrations and those observed in Ridgway waters. For example, trace elements in elevated concentrations, such as Zn, Pb, Cu, Mn, and As, are also often observed in surface waters. Similarly, whereas Cd, Se, and beryllium (Be) were detected in sediments, they rarely were observed above detection limits in surface waters. The absence of measurable molybdenum (Mo) and Se in sediments and soils is consistent with similarly low concentrations observed for these elements in reservoir and inflow water, as well as bryophytes exposed to inflow water as part of an integrated biological toxicity assessment performed by Nelson and Campbell (1995).

The figure 22 radar diagram shows the same trace elements axes as figure 21, except here, unfiltered median water concentrations for combined inflows, reservoir, and outflow waters are plotted. Notably, the shape is very similar to the sediment and soil diagrams in figure 21.

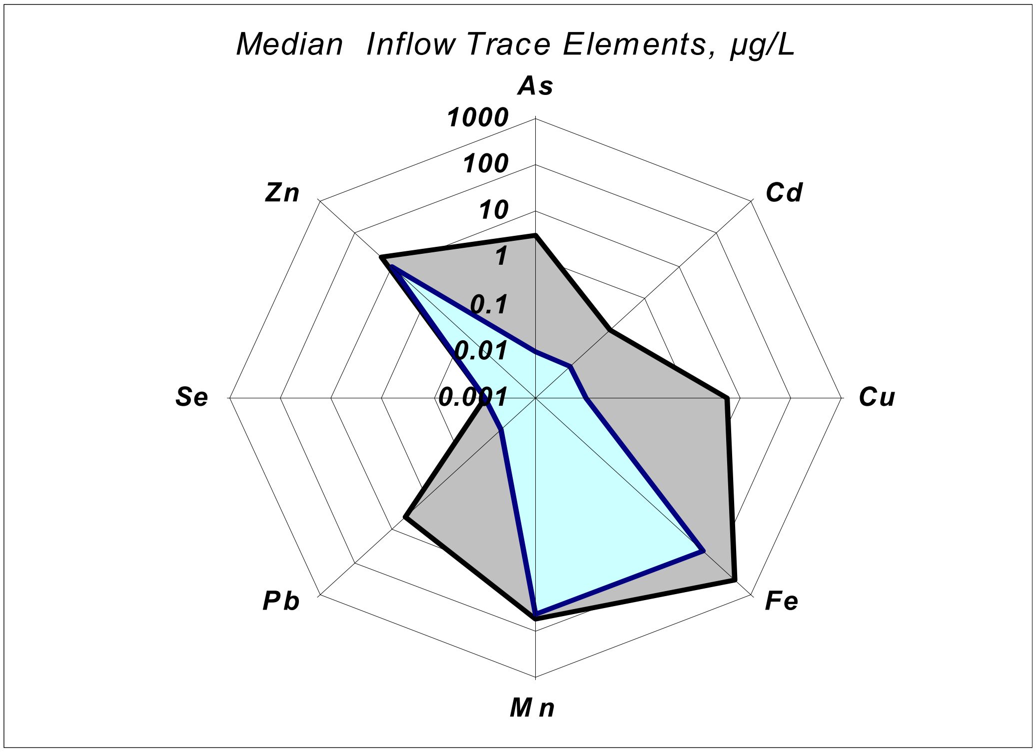


Figure 22.—Log-scale radar diagram showing median trace elements in Ridgway inflow waters. The inner polygon represents median filtered concentrations, the outer polygon represents unfiltered concentrations. Note how the outer polygon is similar to the sediment and soil analysis polygons.

Sediment Carbon and Phosphorus

Table 16 provides C and P analysis data for the reservoir sediments on a dry-weight basis. Total-P results show that the sediments in Ridgway Reservoir contain from 900 to 1,400 mg/kg (0.09 to 0.14 percent by weight). If the P were in a labile form, such as a phosphate adsorbed to Fe-Mn oxyhydrate particle coatings, an source of bioavailable P could influence primary productivity if Ridgway Reservoir experiences prolonged stratification and anaerobic reducing conditions in the sediments. However, the petrographic observation of apatite, a class of calcium phosphate minerals, suggests that not all P may be associated with readily available sediment forms. Simulation results suggest that only a small percentage of sediment P is available to overlying water under reducing conditions; however, soils and sediments may have very different distributions of P species. Additional sampling and analysis of sediments and local soils is recommended if these questions must be answered.

Table 16.—Phosphorus and carbon for 1995 Ridgway Reservoir sediments

Downstream Distance, m	**Sediment Concentrations in mg/kg**			
	Phosphorus	**Carbon**		
	Total	**Carbonate**	**Organic**	**Total**
0	917	0.120	0.0600	0.180
100	1080	0.320	0.790	1.11
200	1330	0.430	1.46	1.89
1200	1300	0.370	1.18	1.55
2600	1090	0.420	1.32	1.74
Inflow cores	1100	0.440	0.680	1.12

Total carbon in sediments is present at roughly order of magnitude concentrations less than P, and organic C is present at about 2-3 times inorganic C, ranging from 1.2 to 1.5 mg/kg in the reservoir. Despite having much lower concentrations than P, organic C tends to adsorb on suspended particle surface films (Lion, et al., 1982; Thurman, 1985), producing large effective surface areas per unit weight. Organic C concentrations in Ridgway Reservoir are also similar to those observed in Lake Owyhee, Oregon (Craft, et al., 2000), a eutrophic lake with anaerobic sediments. These factors suggest that reservoir sediments have adequate organic C as a potential food supply for bacteria to create anaerobic conditions.

Inorganic carbonate-C and organic-C show roughly inverse trends with lateral distance from the inflow-mix zone. Organic proportions increase with lateral distance to a plateau of about 75-80 percent after 200 m. The opposite trend occurs with carbonate-C where highest fractions are present in the inflow-mix zone and a decreasing trend to a fraction plateau of 20-25 percent is seen. Carbonate C data also suggest that calcite is present in reservoir sediments about 3 mg/kg, a corroboration of the "trace" observations in the petrography results (table 12b).

Inflow Zone River Bank Sediment and Pore Water

Analysis results for filtered pore water collected *in situ* from riverine sediments upstream of the inflow-mix zone show elevated concentrations of only a few trace elements compared with same date surface water samples. Concentrations of Mn and Sr are significantly elevated (orders of magnitude greater) compared with those in Uncompahgre River water. The high dissolved Mn suggests that reducing conditions were active in the sediment pore water; however, the lack of H_2S gas odor suggests that conditions were not severely reducing (Brannon, et al., 1978). The degree of reducing potentials may also increase with sediment depth in this inflow zone. Ca, Mg, barium (Ba), and Mo are somewhat elevated compared with the surface water. Some Pb is also present; however Ag, Cd, cobalt (Co), Si, Se, and Zn were similar to river concentrations.

The lower trace element concentrations observed in the reservoir inflow-mix zone sediments and the upstream riverine sediment cores suggest that resuspension of previously deposited sediments during the seasonal spring snowmelt runoff will probably not cause water quality problems for Ridgway Reservoir. The inflow-mix zone, which moves upstream or downstream depending on runoff flows and duration, contains coarser size fractions with lower organic carbon compared with fine reservoir sediments. Thus it would not be expected to introduce higher trace element or P concentrations during resuspension from higher inflows. It would be reasonable to expect a brief pulse of sediment pore-water Mn, Sr, and possibly Fe (depending on redox conditions in the pore-water at the time of the runoff episode); however, these trace elements should quickly adsorb onto suspended particles once mixed with oxygenated inflow waters.

Microcosm Simulation Water Chemistry Compared with Reservoir

The following sections will compare simulation microcosm water chemistry with the observed reservoir and inflow water data. Figures 23a and 23b show Stiff diagrams comparing simulation ions with reservoir and inflow summary data. Table 17 (nutrients) and table 18 (trace elements) provide simulation results and observed reservoir and inflow data. In these two tables, data are grouped by simulation tank and sorted in the sequence they were sampled. At the bottom of the tables, minimum, median, and maximum values are summarized for grouped reservoir and inflow stations. As previously mentioned, simulation water samples were not filtered but were consistently clear and contained no visible turbidity. Both unfiltered and filtered reservoir and inflow data summaries are provided for comparison with simulation samples. Figure 24 plots radar diagrams for median trace elements in simulation water, inflows and reservoir, using the same trace element axes and log-scale seen in figures 21 and 22 .

Major Ions Simulation Data

Figure 23a summarizes major ions data for Tank 1 (left) and Tank 2 (right), and figure 23b shows Tank 3 (left) and Tank 4 (right). At the top of each tank's figure is the Stiff diagram for the Uncompahgre River used in the simulation tanks. Below the river water diagrams are the 10:1 water:soil extractions of simulation soils with Uncompahgre River water, followed by the initial tank mixing sample, and then the subsequent samplings performed during the simulation. Each simulation diagram is labeled with the soil sample number (see table 2) and the simulation sampling sequence. Note that a fifth and final ions sample was not collected during this experiment. At the bottom of each figure is the median reservoir bottom water, derived from all available post-filling sampling data.

Table 17.—Nutrient analysis results for microcosm simulation experiment compared to water quality monitoring data

	DO	Eh	pH	Total- P	Ortho-P	NO3	NO2	NH3	Organic-N
Sample Description	**mg/L**	**mV**	**s.u.**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Tank 1 - Soil 2 Initial	**9.00**	**+175**	**8.34**	**0.0400**	**<0.00100**	**0.889**	**<0.00100**	**0.142**	**0.450**
Tank 1 - Soil 2 #2	4.80	+145	7.53	0.0140	0.00700	0.619	0.00100	0.0200	0.400
Tank 1 - Soil 2 #3	0.00	+204	7.67	0.0560	0.0170	0.195	0.0250	0.0700	0.530
Tank 1 - Soil 2 #4	0.00	-61.0	7.99	0.0700	0.0250	<0.00100	<0.00100	0.0880	0.0320
Tank 1 - Soil 2 #5	0.00	-177	8.01	0.0520	0.0320	<0.00100	<0.00100	.	.
Tank 2 - Soil 4 Initial	**9.00**	**+171**	**8.46**	**0.0600**	**0.00800**	**0.895**	**<0.00100**	**0.0650**	**0.460**
Tank 2 - Soil 4 #2	4.60	+105	7.83	0.0400	0.0210	0.838	0.00200	0.0100	0.440
Tank 2 - Soil 4 #3	0.00	+189	8.08	0.0380	0.0240	0.382	0.0180	0.0600	0.510
Tank 2 - Soil 4 #4	0.00	-86.0	7.94	0.0460	0.0120	<0.00100	<0.00100	0.0480	0.192
Tank 2 - Soil 4 #5	0.00	-154	8.22	0.0250	0.0200	<0.00100	<0.00100	.	.
Tank 3 - Soil 6 Initial	**9.00**	**+166**	**8.29**	**0.0300**	**<0.00100**	**0.961**	**<0.00100**	**0.0830**	**0.370**
Tank 3 - Soil 6 #2	3.40	+128	7.75	0.00600	<0.00100	0.916	0.00400	0.0300	0.360
Tank 3 - Soil 6 #3	0.00	+199	7.81	0.0140	0.00300	0.455	0.00500	0.0300	0.480
Tank 3 - Soil 6 #4	0.00	-45.0	7.97	0.0240	0.0100	<0.00100	<0.00100	0.0220	0.0680
Tank 3 - Soil 6 #5	0.00	-162	8.35	0.00700	0.00300	<0.00100	<0.00100	.	.
Tank 4 - Soil 3 Initial	**9.00**	**+155**	**8.42**	**0.0400**	**<0.00100**	**1.00**	**<0.00100**	**0.122**	**0.460**
Tank 4 - Soil 3 #2	3.80	+132	7.81	0.0120	0.00500	0.979	0.00500	0.0200	0.580
Tank 4 - Soil 3 #3	0.00	+186	7.88	0.0780	0.00600	0.447	0.00300	0.0500	0.550
Tank 4 - Soil 3 #4	0.00	-38.0	7.97	0.0290	0.0100	<0.00100	<0.00100	0.0490	0.101
Tank 4 - Soil 3 #5	0.00	-133	7.97	0.0100	<0.00100	<0.00100	<0.00100	.	.
Reservoir UNFILT N	**412**	**338**	**412**	**17**	**15**	**14**	**15**	**15**	**14**
Minimum	0.740	127	7.30	0.00300	<0.00100	0.133	<0.00100	<0.0100	0.0600
Median	7.56	218	8.14	0.00800	<0.00100	0.224	<0.00100	<0.0100	0.0890
Maximum	9.70	344	8.69	0.0560	0.0520	0.772	0.0200	0.0850	0.130
Reservoir FILT N				**60**	**62**	**61**	**60**	**62**	**54**
Minimum				<0.00100	<0.00100	<0.0300	<0.00100	<0.0100	<0.0500
Median				0.00600	0.00150	0.158	<0.00100	0.0115	0.0690
Maximum				0.0850	0.0800	0.753	0.0310	0.0750	0.490
Inflows UNFILT N	**0**	**0**	**63**	**156**	**167**	**150**	**152**	**186**	**123**
Minimum	.	.	6.57	<0.00500		<0.0300	<0.00100	<0.0100	0.0100
Median	.	.	8.04	0.0110	<0.00100	0.120	<0.00100	<0.0100	0.250
Maximum	.	.	8.52	0.170	0.100	0.522	0.0220	0.0900	0.740
Inflows FILT N				**156**	**168**	**150**	**152**	**187**	**115**
Minimum				<0.00500	<0.0100	<0.0300	<0.00100	<0.0100	0.0200
Median				0.00700	<0.00100	0.173	<0.00100	<0.0100	0.247
Maximum				0.420	0.0600	0.540	0.0110	0.0430	0.660

Table 18.—Trace Element concentrations from simulation experiment compared to water quality monitoring data

	pH	Eh	DO	As	Cd	Cu	Fe	Mn	Pb	Se	Zn
Sample Description	**s.u.**	**mV**	**mg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**
Tank 1 - Soil 2 Initial	8.34	+175	9.00	2.00	<0.100	<1.00	0.800	0.400	<0.200	<1.00	41.0
Tank 1 - Soil 2 #2	7.53	+145	4.80	<1.00	0.200	4.00	43.0	2.10	0.500	<1.00	9.70
Tank 1 - Soil 2 #3	7.67	+204	0.00	1.10	<0.100	<1.00	20.0	21.0	<0.200	<1.00	42.0
Tank 1 - Soil 2 #4	7.99	-61.0	0.00	14.3	<0.100	1.00	123	715	<0.200	<1.00	11.8
Tank 1 - Soil 2 #5	8.01	-177	0.00	.	0.200	<1.00	266	690	.	<1.00	19.2
Tank 2 - Soil 4 Initial	8.46	+171	9.00	2.00	<0.100	<1.00	2.60	1.10	<0.200	<1.00	40.0
Tank 2 - Soil 4 #2	7.83	+105	4.60	<1.00	0.100	4.00	89.0	0.800	<0.200	<1.00	14.0
Tank 2 - Soil 4 #3	8.08	+189	0.00	<1.00	<0.100	<1.00	14.0	5.10	<0.200	<1.00	13.0
Tank 2 - Soil 4 #4	7.94	-86.0	0.00	2.60	<0.100	1.20	119	117	0.500	<1.00	95.0
Tank 2 - Soil 4 #5	8.22	-154	0.00	.	0.200	<1.00	332	150	.	<1.00	8.40
Tank 3 - Soil 6 Initial	8.29	+166	9.00	1.00	<0.100	<1.00	2.70	1.90	<0.200	<1.00	125
Tank 3 - Soil 6 #2	7.75	+128	3.40	<1.00	0.100	5.00	1.70	1.20	<0.200	<1.00	21.0
Tank 3 - Soil 6 #3	7.81	+199	0.00	1.00	<0.100	.	10.0	1.70	<0.200	<1.00	125
Tank 3 - Soil 6 #4	7.97	-45.0	0.00	3.80	0.250	4.00	59.0	654	<0.200	<1.00	53.9
Tank 3 - Soil 6 #5	8.35	-162	0.00	.	0.200	3.00	291	610	.	<1.00	31.2
Tank 4 - Soil 3 Initial	8.42	+155	9.00	2.00	<0.100	2.00	2.30	1.40	<0.200	<1.00	56.0
Tank 4 - Soil 3 #2	7.81	+132	3.80	<1.00	0.100	5.00	2.60	0.300	<0.200	<1.00	6.10
Tank 4 - Soil 3 #3	7.88	+186	0.00	<1.00	<0.100	5.30	9.00	1.80	<0.200	<1.00	6.70
Tank 4 - Soil 3 #4	7.97	-38.0	0.00	2.10	0.250	2.90	52.0	667	0.200	<1.00	12.5
Tank 4 - Soil 3 #5	7.97	-133	0.00	.	<0.100	2.00	191	690	.	<1.00	22.1
Reservoir UNFILT N	412	338	412	46	105	88	71	107	30	17	89
Minimum	7.30	127	0.74	<2.00	<3.00	2.00	9.44	<1.00	<1.40	<2.00	<4.00
Median	8.14	218	7.56	2.00	0.0800	5.00	77.1	20.0	2.00	<1.00	10.0
Maximum	8.69	344	9.70	9.00	8.00	110	2150	1160	10.0	<1.00	190
Reservoir FILT N				47	106	74	22	92	30	17	84
Minimum				<2.00	<3.00	<1.00	<3.00	<4.00	<1.40	<2.00	<4.00
Median				<2.00	0.0500	3.00	37.8	8.42	<1.00	<1.00	6.50
Maximum				3.00	5.00	20.0	100	549	3.00	<1.00	50.0
Inflows UNFILT N				100	212	129	114	244	101	56	205
Minimum				<2.00	<3.00	<2.00	<3.00	<2.00	<1.40	<2.00	<4.00
Median				<1.00	<0.100	4.10	41.9	64.2	<1.00	<0.200	20.0
Maximum				240	60.6	40.8	1370	334	329	219	2220
Inflows FILT N	83	.	.	44	172	121	168	189	61	35	171
Minimum	6.57	.	.	<2.00	<3.00	<1.00	40.1	19.0	<0.400	<2.00	<4.00
Median	8.04	.	.	4.16	0.223	28.2	680	90.0	12.0	0.600	80.00
Maximum	8.52	.	.	421	75.8	108	5960	633	162	370	600

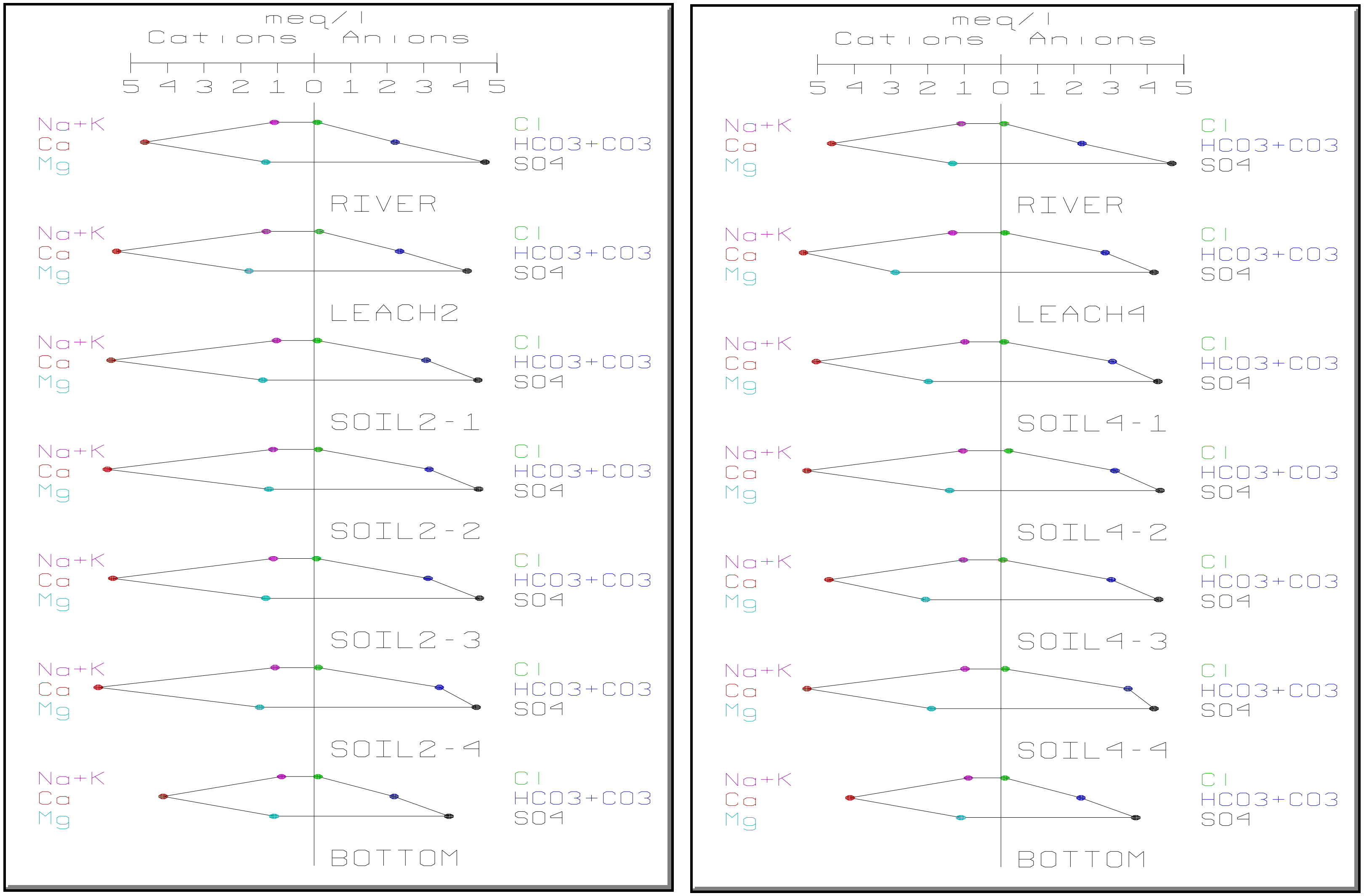


Figure 23a.—Major ions data for simulation Tank 1 (left - using soil sample 2) and Tank 2 (right - using soil sample 4). Uncompahgre River water is shown in the top diagram, followed by the 10:1 river:soil leaching extraction, the simulation samples, and the median reservoir bottom sample ions.

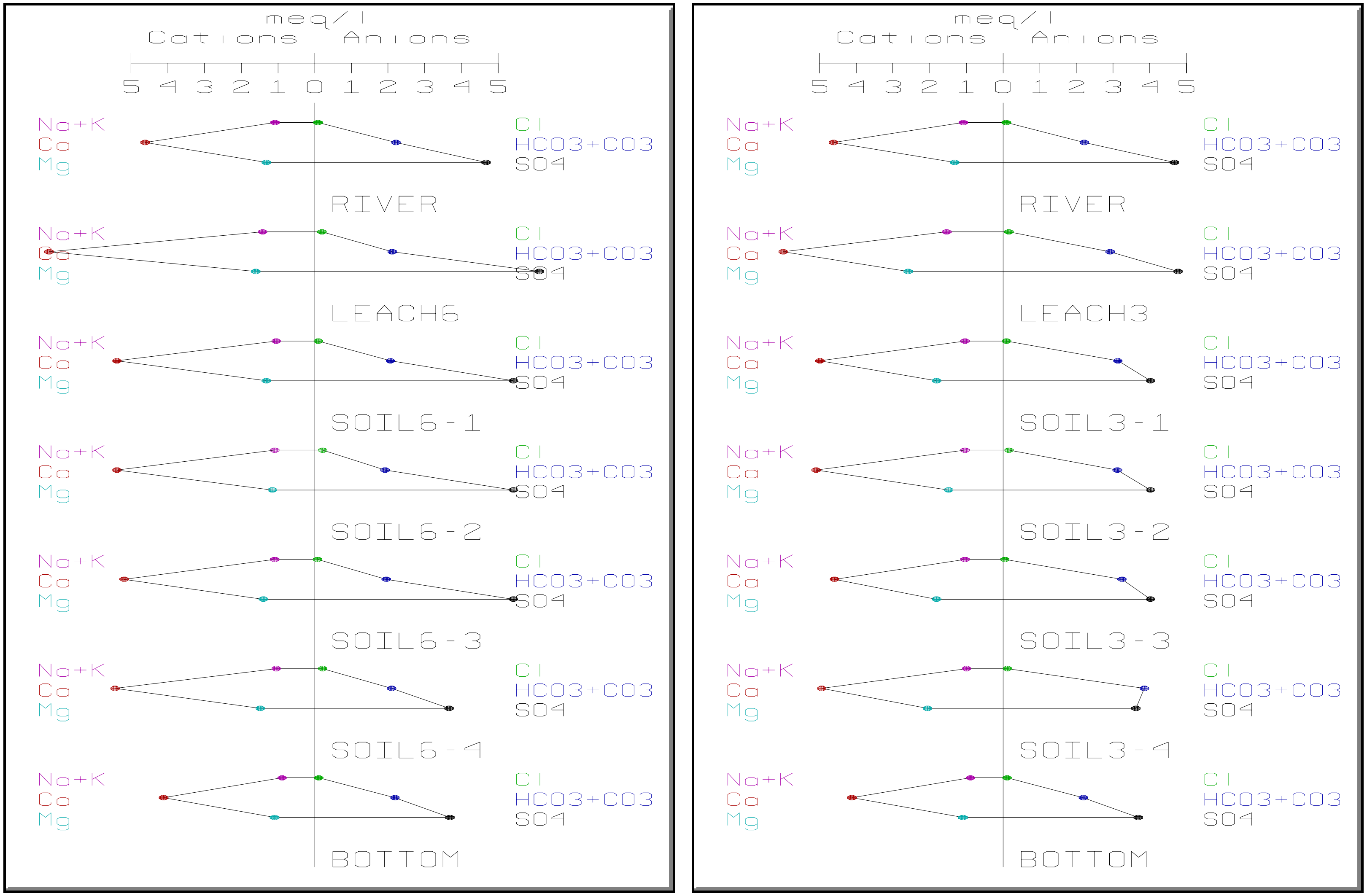
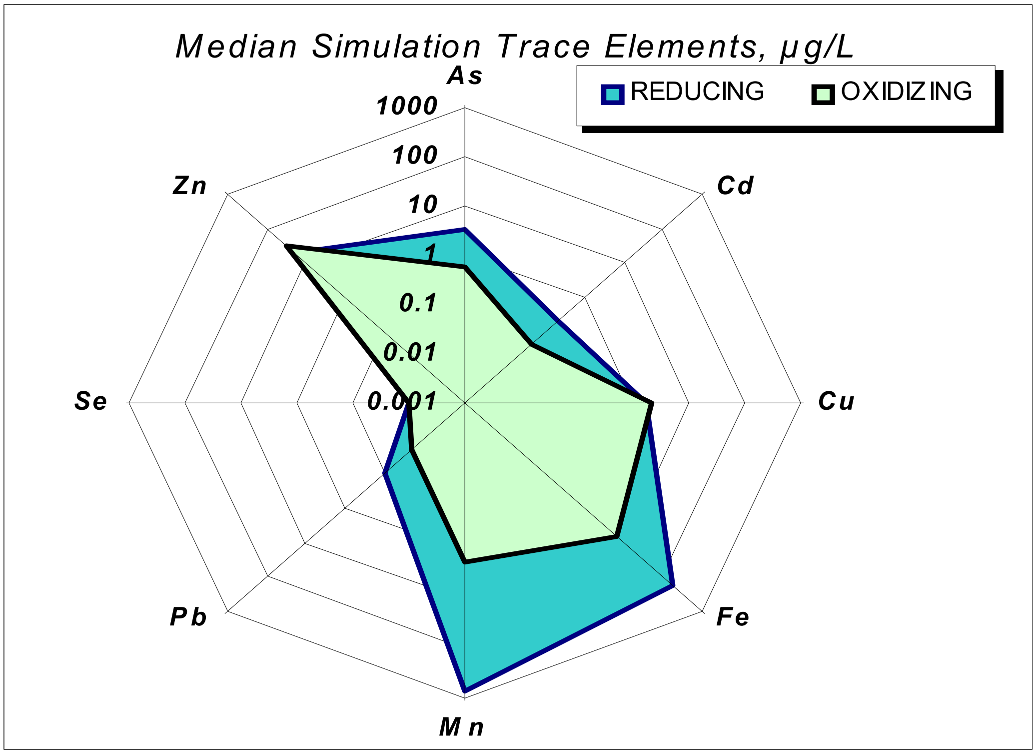


Figure 23b.—Major ions data for simulation Tank 3 (left - using soil sample 6) and Tank 4 (right using soil sample 3). Uncompahgre River water is shown in the top diagram, followed by the 10:1 river:soil leaching extraction, the simulation samples, and the median reservoir bottom sample ions.



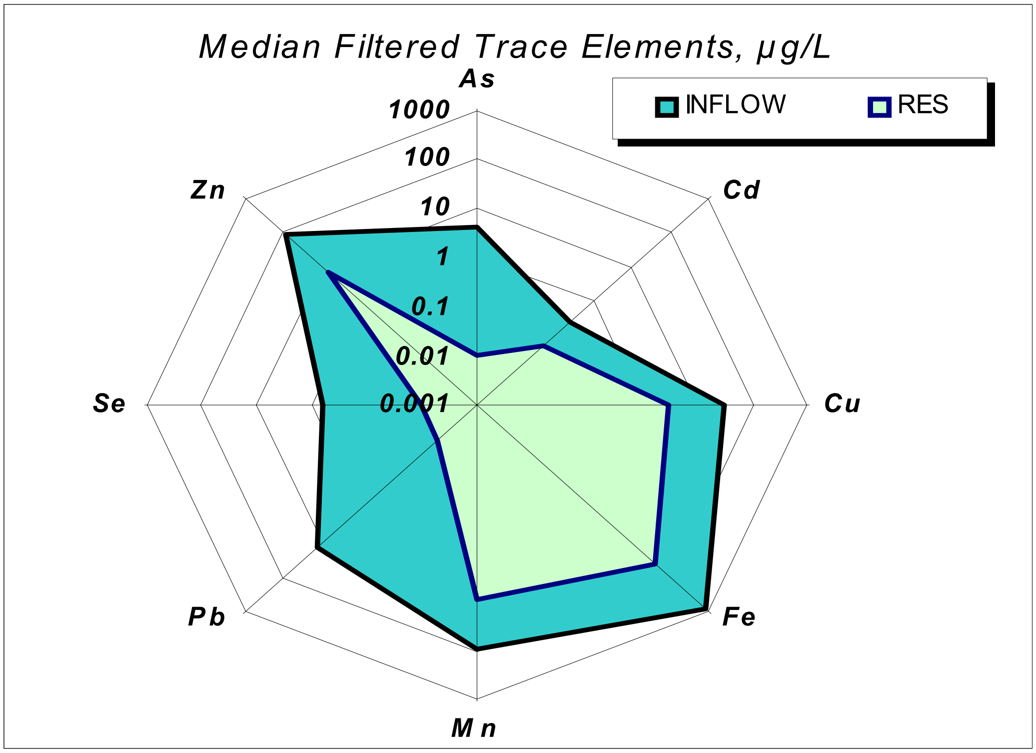


Figure 24.—Median trace element concentrations for oxidizing (inner polygon) and reducing conditions in simulation tank waters (top), and median dissolved inflow and reservoir (inner polygon) concentrations (bottom), plotted on log-scales. Values at or below 0.01 µg/L are below detection limits

The first observation worth noting is that the Ca, Mg, and HCO_3^- concentrations are elevated for Tanks 1, 2, and 4 in the 10:1 extraction water and in most simulation samples relative to the river water. This observation is consistent with dissolution of carbonate minerals observed in these soil samples during mineralogical examination (table 12a). Tank 3, containing the river sediment sample, is the exception to this observation and shows very little change in HCO_3^- (although Ca and Mg are elevated). All simulation samples are elevated in ions concentrations compared with the median reservoir bottom water; however, the simulation total ions are less than maximum observed reservoir and inflow water concentrations.

Changes in SO_4 and HCO_3 concentrations were observed between simulation sample sequence 3 (DO = 0, but still showing positive oxidizing Eh values) and sample 4 (all tanks showing negative Eh). Note that in every tank, SO_4 decreases slightly and bicarbonate increases slightly once reducing conditions develop. The loss of SO_4 is consistent with the odor of H_2S (hydrogen sulfide) gas observed during sampling events 4 and 5. Production of HCO_3 is also known to be associated with bacterial metabolism (oxidation) of dissolved organic material (Drever, 1988; Thurman, 1985; Stumm and Morgan, 1995).

Nutrient Simulation Data

The organic-N in table 17 (org-N in the column heading) was determined by subtracting NH_3 from TKN. Note that comparison of simulation samples with actual reservoir samples may be biased by unequal numbers of filtered and unfiltered samples. For example, the filtered maximum concentration exceeds the unfiltered maximum value for the reservoir total-P summaries (17 unfiltered vs. 60 filtered samples). This apparent anomaly is caused by larger numbers of filtered samples for nutrients where a greater concentration range would be expected.

The highest NO_3 concentrations were observed in the initial samples for all simulation tanks. Initial NO_3 concentrations were greater than or comparable with the maximum observed reservoir concentration of 0.772 mg/L. Nitrate data show the clearest response to absence of DO and development of reducing (negative) Eh conditions, with 50-70 percent NO_3 losses observed after 0 mg/L DO was attained in the tanks at sample 3. Once negative Eh conditions developed, both NO_3 and NO_2 dropped below detection. Because NO_2 samples were analyzed beyond the currently recommended 48-hour holding time, these data are of unknown accuracy. However, the NO_3 data clearly show that denitrification occurs in both anaerobic and reducing sediment-water systems. Denitrification is also supported by calculated total-N data (NO_3+NO_2+NH_3+org-N), which show a progressive loss of total nitrogen throughout the simulation experiment. Initial samples from all tanks show total-N greater than maximum observed reservoir and inflow concentrations, whereas sample 4, under reducing conditions, shows values less than, or comparable with, median reservoir and inflow total-N concentrations.

Initial concentrations of NH_3 were comparable with or greater than the observed reservoir maximum of 0.085 mg/L. The elevated initial concentrations, as mentioned in the methodology, may reflect some contamination from refrigerant leaks in the simulation calorimeter room. The tanks containing basin soils (1, 2, and 4) all show a significant NH_3 loss between initial and second simulation samples, followed by a slight concentration increase as reducing conditions developed. The NH_3 rebound observed in these tanks and the simultaneous loss of NO_3 may suggest an intermediate conversion of NO_3 to NH_3. The riverine sediment system in tank 3 did not follow the NH_3 concentration rebound observed in the soil systems after sample 2, and low concentrations relative to initial values persisted in this tank throughout the experiment.

Initial simulation samples show elevated organic-N concentrations compared with reservoir and inflow median concentrations, but less than or comparable with observed maximum concentrations. Between samples 2 and 3, a slight concentration increase was observed in all systems except Tank 4. Once DO was removed at simulation sampling 3, organic nitrogen concentrations fell 62-94 percent in all tanks. These results corroborate denitrification suggested by NO_3 data under anaerobic and reducing conditions.

As observed for N data, P simulation concentrations exceed observed reservoir and inflow median values, but are comparable with, or less than observed maximums. All systems show high initial total-P and low initial ortho-P, followed by lower total-P concentrations for sample 2, suggesting settling of fine particulates or adsorption after initial mixing. Simulation total-P and ortho-P concentrations are similar in the three soil systems (Tanks 1, 2, and 4), and generally lower concentrations are observed in the riverine sediment system in Tank 3. These results suggest that river-transported sediments will have lower available P compared with flooded soils. All tanks show a drop in total-P concentration between samples 4 and 5, perhaps caused by precipitation of PO_4^{3-} ion by Fe and Mn released under reducing conditions; however, no dramatic concentration losses (as seen for NO_3) were observed under reducing conditions.

If the total-P in 1995 reservoir sediment samples (table 16), which ranged from 900-1,400 mg/kg, were completely dissolved under the approximate 10:1 water:soil ratios of the simulation experiment, then the maximum measured simulation water total-P concentrations represent less than 0.5 percent of phosphorus potentially available in existing reservoir sediments. It appears that prolonged anaerobic reducing conditions do not release significant quantities of P. This suggests that a large portion of the P is not adsorbed onto Fe- and Mn-oxyhydrate particle coatings that are labile under reducing conditions. This hypothesis is supported by petrographic observation of trace amounts of fairly insoluble apatite and hydroxyapatite (table 12b) found in reservoir sediments.

Trace Element Simulation Data

Higher detection limit ICP-ES data were removed from the data sets for the table 18 and figure 24 inflow and reservoir comparison summaries. For most trace elements present in the <10-µg/L range, this censoring favors results using GFAA, which are thought to be the more accurate values. Once again, anomalous summary results for unfiltered and filtered data should be considered in light of unequal sample sizes.

All simulation systems show a increase in Fe and Mn with the development of anaerobic and reducing conditions, visible in the larger shaded polygon in the top radar diagram in figure 24. These observed simulation concentrations may be compared with the median filtered reservoir and inflow concentrations in the bottom radar diagram of figure 24, the median unfiltered inflow concentration in figure 22, with the acid digestion results in table 13, and with the sediment trace element radar diagrams in figure 21. A notable difference between the trace element proportions in sediment and filtered water and the simulation systems (except for Tank 2), is the significantly higher Mn concentrations relative to Fe during reducing conditions (top radar diagram, figure 24). All other sediments, soils, and waters indicate that Fe $\geq$ Mn.

The higher Mn simulation concentrations could be the result of the shorter overall duration of low Eh conditions sufficient to reduce Fe oxides and oxyhydrates. Mn reduction ($p\varepsilon^\circ(w) = +8.9$) may occur at higher (more oxidizing) Eh than Fe ($p\varepsilon^\circ(w) = -0.8$) (Stumm and Morgan, 1995). Since Mn will begin to be reduced at higher Eh values (comparable with NO_3 reduction), there is more time available for Mn to accumulate in the water above the sediments; well before bacterial exergonic processes lower the Eh sufficiently to initiate Fe^{3+} to Fe^{2+} reduction reactions. These results imply that the trace element concentrations in an anaerobic simulation water (or a real sediment:water system), depend on both the severity of reducing conditions (how negative the Eh becomes) as well as the duration of reducing conditions.

Other Simulation Trace Elements

Only Zn shows appreciable releases from simulation sediments that exceed the median dissolved inflow concentration of 20 µg/L. This suggests that Zn is associated with reducible Fe and Mn oxyhydrates. The general Zn behavior in all tanks shows an increase with initial mixing, followed by a decline in sample 2, and then an increase in concentration observed during initial reducing conditions at sample 4. The final sample at maximum reducing conditions shows another decline in Zn concentration, perhaps caused by concurrent precipitation with S^{2-} (sulfide ion) produced by the bacterial reduction of SO_4 (supported by observed H_2S gas odor during reducing condition sampling), or adsorption to tank or sediment surfaces. The Tank 3 simulation using river sediments suggests that reservoir sediments will be a source of Zn for Ridgway Reservoir.

With regard to other trace elements, Cu, As, Pb, and Cd were observed, but mostly near or below GFAA detection limits. However, all these elements were observed at quantitative levels in soils, reservoir sediments, and inflow waters. For example, median filtered Pb in the inflows (fig. 24, bottom) was about 10 µg/L; however, Pb was very low in simulation waters. Perhaps the proportions of these elements associated with labile Fe and Mn particle coatings were low, or the lower concentrations were more affected by precipitation with S^{2-} or CO_3 (except for anionic As), or adsorption to tank surfaces. Another possibility involves the greater proportions of clay in simulation soils compared with inflow and reservoir sediments. Could binding and ion exchange of trace metals with clays reduce the lability of these elements under reducing conditions? Se was not observed in simulation waters, simulation soils, or reservoir sediments, and was only rarely observed above detection in inflow waters. The lack of Se is consistent with absence of marine shales in the upper elevations of the watershed.

CONCLUSIONS AND RECOMMENDATIONS

Ridgway Reservoir

Despite the widespread presence of abandoned mine wastes in the upper elevations of the watershed, analysis of post-impoundment chemistry data revealed that water quality in Ridgway Reservoir is very good. Few exceedances of regulated concentrations were observed. Algal productivity and dissolved phosphorus concentrations are very low, TN:TP ratios are elevated (>10), and observation of insoluble mineral forms of phosphorus in reservoir sediments all indicate that Ridgway Reservoir is phosphorus limited and oligotrophic. Although some trace elements were occasionally observed at elevated concentrations (mostly Fe, Mn, and Zn) in the Uncompahgre River and Dallas Creek, particulate settling and denitrification in the lake appears to improve downstream water quality for both trace elements and nutrients.

Although the reservoir water column does thermally stratify during summer, complete anoxia and reducing Eh conditions were not encountered during the post 1987 reservoir and stream sampling portion of this study. This is probably caused by the combination of (1) the clearing and burning of biomass in the reservoir basin before lake impoundment, which reduced *in situ* available organic carbon; (2) the additional hydraulic mixing and hypolimnion water exchange produced by a single lower level outlet works; and (3) cold river inflows during summer that promote hypolimnetic mixing by providing oxygenated waters that sink and flow beneath warmer surface water.

Simulation Summary

Microcosm simulation results suggested that the reservoir hypolimnion would not rapidly develop anoxia and reducing conditions during thermal stratification episodes. Concentrations for the major ions and nutrients in the microcosms were greater than median, but less than maximum concentrations observed in post-impoundment waters. The simulation data suggests that P releases from reducing sediments will probably not be significant, and that the sediments may act as a net phosphorus sink. Denitrification was observed both before and after reducing conditions developed, with dramatic reductions in NO_3 observed after anaerobic conditions developed.

The post-impoundment trace element concentrations generally support the simulation concentrations for Fe, Mn, and Zn. No other measured trace elements were observed significantly above detection limits in the microcosms, including the microcosm that contained Uncompahgre River sediments. However, it appears that the reservoir sediments contain higher trace element concentrations compared with the simulation soils, and measurable (but usually below regulated) concentrations of As, Pb, Cd, Cr, Co, and Hg were also observed in Ridgway waters. Notably, Pb did not increase in microcosms with the onset of reducing conditions. Except for Mn and Zn, the simulation suggests that reservoir sediments will not constitute a major source of toxic trace metals to hypolimnetic waters unless reducing conditions intensify, persist, and produce conditions not encountered in this study. The simulation results also suggest that reducing conditions may concurrently release S^{2-} and CO_3^{2-} anions that suppress trace element accumulation in the hypolimnion through precipitation of insoluble complexes.

Post-impoundment data support the results from microcosm simulation using basin soils, and produced a reasonable simulation of initial reservoir flooding conditions. This study suggests that, given reasonable limitations, microcosm simulation is a valid predictive water quality tool deserving wider application for both studying existing hypolimnetic environments and for predictive purposes.

Considerations for Future Simulation Experiments

The problems encountered in this study with air leaks and temperature control are associated with the relatively large tanks used for the Ridgway simulation. Future simulation experiments performed by the authors will utilize smaller scale microcosms (Craft, 1985), rather than a few large tanks. Smaller vessels allow reliable sealing of microcosms, handling convenience, better and cheaper temperature control, and less alteration of redox conditions by preparing anaerobic samples in a controlled-atmosphere glove box. Since many of the small microcosms may be conveniently prepared, additional sites may be simulated to improve basin representativeness, and a larger variety of perturbation scenarios (for example, spiking with varying levels of organic carbon or trace elements) may be contemplated.

The issues surrounding scope of prediction and the use of soil vs. sediments should also be considered by researchers considering reservoir simulations. Soils and sediments may have different properties that affect trace element and nutrient adsorption and release under varying redox conditions. Differences in mineralogy, particle size distribution, and particle surface chemistry will affect the applicability of microcosm simulation results. For example, if longer-term predictions of reservoir behavior are needed, sediments would be a better choice for microcosms. The basin soils used in this study were an appropriate choice for simulating initial filling conditions, but may not be as accurate for a 30-year old Ridgway Reservoir with sediment-dominated substrate.

Before impoundment, riverine sediments could be collected from oxbow sand-mud bars located in the filling basin, or by building settlement labyrinths that intercept river flows containing suspended particles. Appropriate design of the settlement labyrinth would allow collection of known particle size fractions that could be analyzed to determine various contaminant particle size and mineralogy associations. The different fractions could then be combined in varying proportions to create microcosm sediments that more accurately mimic the size distribution changes expected between inflow zones and deeper reservoir sites. This attention to matching sediment properties should improve the overall accuracy of simulations, allow more reasonable estimates of flux rates to and from sediments, and allow particle size and mineralogical associations for inflow sediment loading to be investigated.

Future Studies: Although current water quality conditions at Ridgway Reservoir are encouraging and the reservoir is improving downstream water quality, future development and land use near the lake could lead to eutrophication and potential water quality problems. Besides nuisance algal blooms and odor, eutrophication could produce longer periods of hypolimnetic anoxia, more severely reducing conditions, and releases of other trace elements currently remaining in reservoir sediments. Given that reservoir sediments contained higher trace element concentrations than simulation soils, eutrophic conditions and prolonged anoxia could eventually cause Ridgway Reservoir to become a point source for some toxic trace elements. Another potentially serious water quality problem is Hg. Given the reliable detection of Hg in the Uncompahgre River, Hg may bioaccumulate through the food chain and require fish consumption advisories if productivity increases significantly. Because of these issues, it would be wise to continue to monitor water quality at Ridgway Reservoir every other year, and when obvious water quality issues arise.

ACKNOWLEDGMENTS

For technical advice and peer review of the original simulation experiment:
Dr. Douglas Gunnison and Jim Brannon, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

For assistance with simulation sample preparation and construction of microcosms:
Robert Shiller (rest in peace), and Cliff Stead, U.S. Bureau of Reclamation (USBR), Denver, Colorado.

For financial and administrative support of simulation experiment and follow up analysis:
Jerry Miller, USBR, Salt Lake City, Utah; Ed Backstrom (retired), Howard Salman (retired), and Lloyd Timblin (retired), USBR Engineering and Research Center, Denver, Colorado; Dr. Diana Weigmann, USBR Fisheries Applications Research Group, Denver, Colorado; Shannon Cunniff, USBR Science and Technology Program manager, Washington, DC; and former Bureau of Reclamation research programs and managers.

For transcription of historical monitoring data:
Daryl Ciruli and Annette Turney, U.S. Bureau of Reclamation, Denver, Colorado.

For preparation of shaded relief watershed maps:
Bruce Whitesell, U.S. Bureau of Reclamation, Denver, Colorado.

For peer review and preparation of this manuscript:
Jim Sartoris, USGS Mid-Continent Ecological Science Center, Denver, Colorado; Rick Roline and Mark Nelson, USBR Technical Service Center, Ecological Research and Investigations Group, Denver, Colorado; Joe Carriero and Tina Armentrout, USBR Technical Service Center, Technical Communications Group, Denver, Colorado.

REFERENCES

American National Standards Institute, 1991, *Quality Management and Quality System Elements for Laboratory - Guidelines*, American National Standard ANSI/ASQC Q2-1991, American National Standards Institute/American Society for Quality Control, Milwaukee Wisconsin.

American Public Health Association, 1981, *Standard Methods for the Examination of Water and Wastewater,* 15th Edition, edited by Franson, M.A.H., Greenburg, A.E., Connors, J.J., and Jenkins, D., APHA-AWWA-WPCF, American Public Health Association, Washington, DC.

American Public Health Association, 1985, *Standard Methods for the Examination of Water and Wastewater,* 16th Edition, edited by Franson, Greenburg, A.E., Trussell, R.R., Clesceri, L.S., APHA-AWWA-WPCF, American Public Health Association, Washington, DC.

American Public Health Association, 1989, *Standard Methods for the Examination of Water and Wastewater,* 17th Edition, edited by Franson, M.A.H., Clesceri, L.S., Greenburg, A.E., Trussell, R.R., APHA-AWWA-WPCF, American Public Health Association, Washington, DC.

American Public Health Association, 1995, *Standard Methods for the Examination of Water and Wastewater,* 19th Edition, Edited by M.A.H. Franson, A.D. Eaton, L.S. Clesceri, and A.E. Greenburg, APHA-AWWA-WEF, American Public Health Association, Washington, DC.

American Society for Testing and Materials, 1980, *Standard Methods for Reducing Field Samples of Aggregate to Testing Size*, ASTM method C702, American Society for Testing and Materials, Philadelphia, Pennsylvania.

American Society for Testing and Materials, 1992, *Standard Test Method for Total and Organic Carbon in Water by High Temperature Oxidation and by Coulometric Detection Standard Methods for*, ASTM method D4129, American Society for Testing and Materials, Philadelphia, Pennsylvania.

American Society for Testing and Materials, 1993, *Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Laboratory Samples of Coal and Coke*, ASTM method D5373, American Society for Testing and Materials, Philadelphia, Pennsylvania.

Bloom, N.S., 1990, *On the chemical form of mercury in edible fish and marine invertebrate tissue,* Can. J. Aquat. Sci., Vol. 49, pp. 1010-1017.

Bloom, N.S. and M. Horvat, 1995, *Results of the International Aqueous Mercury Speciation Exercise*, Wat. Air, Soil. Pollut., Vol. 80, p. 1257.

Bloom, N.S., 1996, *Method 1631: Mercury in Water by Oxidation, Purge and Trap, and Cold Vapor Atomic Fluorescence Spectrometry*, US EPA Report Number 821-R-95-027, Environmental Protection Agency, Office of Water, Washington, DC.

Brannon, J.M., Gunnison, D., Butler, P.L., and Issac Smith, Jr., 1978, *Mechanisms that Regulate the Intensity of Oxidation-Reduction in Anaerobic Sediments and Natural Water Systems*, Technical Report Y-78-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Brannon, J.M., Plumb, Jr., R.H., I. Smith, Jr.,, 1980, *Long Term Release of Heavy Metals from Sediments*, in “Contaminants in Sediments”, Vol. 2, edited by R.A. Baker, Ann Arbor Science Publishers, Inc., Ann Arbor, MI, pp 221-266.

Bureau of Reclamation, 1974, *Earth Manual,* Second Edition, “Preparation of Soil Samples for Testing”, USBR method E-5, pp 419-424, U.S. Department of the Interior, Bureau of Reclamation.

Bureau of Reclamation, 1979, *Ridgway Dam, Stage 1*, Specifications No. DC-7395, Dallas Creek Project, Colorado.

Bureau of Reclamation, 1990, *Earth Manual,* Part 2, Third Edition, “Preparing Soil Samples by Splitting or Quartering”, USBR method 5205, pp 228-238, U.S. Department of the Interior, Bureau of Reclamation.

Bureau of Reclamation, 2000, *Project Dataweb,* Information and Specifications for Ridgway Dam and Reservoir, Website, http://dataweb.usbr.gov/.

Craft, D., 1985, *Predicting water quality data in an unfilled reservoir using microcosm sediment-water simulation*, Environmental Geochemistry and Health, 7(4).

Craft, D., Cannon, N., Zimmer, D., Krill, K. and L. DiMattia, 2000, *Water Quality and Mercury in Lake Owyhee, Southeastern Oregon*, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.

Deer, W.A., R.A. Howie, and J. Zussman, 1977, *An Introduction to the Rock-Forming Minerals,* Longman Group, Ltd., London.

Downing, J.A., McCauley, E., 1992, *The nitrogen:phosphorus relationship in lakes*, Limnol. Oceanogr., 37(5), pp. 936-945.

Drever, J.I., 1988, *The Geochemistry of Natural Waters,* Second Edition, Prentice Hall, Englewood Cliffs, NJ, p 310. p 310.

Dzombak, D.A., and F.M.M. Morel, 1990, *Surface Complexation Modeling: Hydrous Ferric Oxide*, John Wiley and Sons, New York, pp. 103-109.

Ostler, R., 1987, *Mercury Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review*, U.S. Department of the Interior, Fish and Wildlife Service, Biological Report 85(1.10), Laurel, Maryland.

Environmental Protection Agency, 1972, *Handbook for Analytical Quality Control in Water and Wastewater Laboratories,* U.S. Environmental Protection Agency, National Environmental Research Center, Cincinnati, Ohio.

Environmental Protection Agency, 1982*, Handbook for Sampling and Sample Preservation of Water and Wastewater*, EPA-600/4-82-029, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Cincinnati OH, 1982.

Environmental Protection Agency, 1983*, Methods for Chemical Analysis of Water and Wastes*, EPA-600/4-79-020, U.S. Environmental Protection Agency, Cincinnati OH.

Environmental Protection Agency, 1986*, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, SW-846, 3rd Edition: Proposed Update I and II, U.S. Environmental Protection Agency, Washington DC, November 1986.

Environmental Protection Agency, 1993, *Guidance for assessing chemical contaminant data for use in fish advisories, Volume 1: Fish Sampling and Analysis,* EPA/823/B-93/002.

Environmental Protection Agency, 1994, *Guidance for assessing chemical contaminant data for use in fish advisories, Volume 2: Risk Assessment and fish consumption limits,* EPA/823/B-94/004.

Environmental Protection Agency, 1996a, *Sampling Ambient Water for Trace Metals at EPA Water Quality Criteria Levels,* EPA Method 1669, EPA 821-R-96-011, Office of Water, Engineering and Analysis Division, Washington, DC.

Environmental Protection Agency, 1996b, *Mercury in Water by Oxidation, Purge and Traps, and Cold Vapor Atomic Fluorescence Spectrometry*, EPA Method 1631, USEPA Office of Water, Engineering and Analysis Division, Washington, DC.

Environmental Protection Agency, 2001, *Surf Your Watershed* water quality information website, http://www.epa.gov/surf3/hucs/14020006/

Folk, R.L., 1974, *Petrology of Sedimentary Rocks*, Hemphill Publishing Co., Austin, Texas, pp. 132-136.

Forstner, U. and G. Whitmann, 1979, *Metal Pollution in the Aquatic Environment*, Springer-Verlag, New York.

Gilbert, Richard O., 1987, *Statistical Methods for Environmental Pollution Monitoring,* Van Nostrand Reinhold, New York, pp 177-179.

Gilliom, R.J., Hirsch, R.M., and Gilroy, E.J.,, 1984, *Effect of censoring trace-level water-quality data on trend-detection capability*, Environmental Science and Technology, Vol. 5, pp 530-535.

Gunnison, D., Brannon, J.M., Smith, Jr, I., Burton, Jr., G.A., and K.M. Preston, 1980, *A Reaction Chamber for Study of Interactions between Sediments and Water Under Conditions of Static or Continuous Flow*, Water Research, Vol. 14, 1529-1532.

Gunnison, D, and J.M. Brannon, 1981, *Characterization of Anaerobic Chemical Processes in Reservoirs: Problem Description and Conceptual Model Formulation*, Technical Report E-81-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Guy, H., 1969, *Laboratory Theory and Methods for Sediment Analysis*, in “U.S. Geological Survey Techniques of Water Resources Investigations”, book 5, Chapter C1, U.S. Geological Survey, Reston, Virginia.

Hem, J.D., 1985, *Study and Interpretation of the Chemical Characteristics of Natural Waters,* 3rd Edition, USGS Water Supply Paper 2254, U.S. Government Printing Office, Washington, DC.

Horowitz, A.J., 1985, *A Primer on Trace Metal-Sediment Chemistry*, U.S. Geological Survey Water-Supply Paper 2277.

Jensen, S., and A. Jernelov, 1969, *Biological methylation of mercury in aquatic organisms,* Nature, Vol. 23, pp. 753-754.

Jensen, S., and A. Jernelov, 1972, *Behavior of Mercury in the Environment*, Chapter 4 in “Mercury Contamination in Man and the Environment”, United Nations World Health Organization, International Atomic Energy Agency, Vienna, Austria, Technical Report 9.

Keith, L.H., W. Crummett, J. Deegan, Jr., R.A. Libby, J.K. Taylor, and G. Wentler, 1983, *Principles of Environmental Analysis*, Analytical Chemistry, Vol. 55, pp. 2210-2218.

Lion, L.W., R.S. Altmann, and J.O. Leckie, 1982, *Trace metal adsorption characteristics of estuarine particulate matter: evaluation of contributions of Fe/Mn oxide and organic surface coatings*, Environ. Sci. Technol., Vol. 16 pp. 660-666.

Lindsay W.L., 1979, *Chemical Equilibria in Soils,* John Wiley and Sons, New York.

Messer, J.J., Ihnat, J.M., and D.L. Wegner, 1984, *Phosphorus Release from the Sediments of Flaming Gorge Reservoir, Wyoming, U.S.A.,* Verh. Internat. Verein. Limnol., Vol 22, 1457-1464.

Morel, F.M.M., and J.G. Hering, 1993, *Principles and Applications of aquatic Chemistry*, John WIley and Sons, New York, 1993, pp. 338-343.

Myers, C.R. and K.H. Nealson, 1988, *Microbial reduction of manganese oxides: Interactions with iron and sulfur*, Geochimica et Cosmochimica Acta, Vol. 52, pp. 2727-2732.

Nehls, G.J. and Akland, G.G., 1973, *Procedures for Handling Aerometric Data*, Journal of the Air Pollution Control Association, , Vol. 23, pp 180-184.

Nelson, S.M., and S.G. Campbell, 1995, *Integrated Assessment of Metals Contamination in a Lotic System Using Water Chemistry, Transplanted Bryophytes, and Macroinvertebrates*, J. Freshwater Ecology, vol. 10, no. 4, pp. 409-420.

Osmundson, B.C., 1992, *Inorganic Elements Detected in Sediments and Aquatic Biota from the Uncompahgre River and Ridgway Reservoir, Colorado, 1987-1990.* Contaminant Report No. R6/303J/92, U.S. Fish and Wildlife Service, Grand Junction, Colorado.

Pettijohn, F.J., Potter, P.E., and R. Siever, 1972, *Sand and Sandstone*, Springer-Verlag, Berlin, Germany, pp. 428-435.

Rogers, R.D., 1977, *Abiological Methylation of Mercury in Soils*, J. Environ. Qual., Vol. 6, No. 4, pp.463-467.

Schindler, P.W. and W. Stumm, 1987, *The Surface Chemistry of Oxides, Hydroxides, and Oxide Minerals,* Chapter 4 in "Aquatic Surface Chemistry: Chemical Processes at the Particle-Water Interface," edited by Werner Stumm, John Wiley and Sons, New York, pp.83-110.

Schmitt, C.J., and W.G. Brumbaugh, 1990, *Concentrations of arsenic, cadmium, copper, lead, mercury, selenium, and zinc in U.S. freshwater fish, 1976-1984,* Arch. Environ. Contam. and Toxicol., Vol. 19, pp. 731-747.

State of Colorado, 1999, *Classifications and Numeric Standards for Gunnison and Lower Dolores River Basins, Regulation No. 35,* Colorado Department of Public Health and Environment, Water Quality Control Commission, January 30, 1999.

Stiff, H.A.,Jr., 1951, *The Interpretation of Chemical Water Analysis by Means of Patterns*, Journal of Petroleum Technology, Vol. 3, pp. 15-17.

Stone, A.T. and J.J. Morgan, 1987, *Reductive Dissolution of Metal Oxides*, Chapter 9 in "Aquatic Surface Chemistry: Chemical Processes at the Particle-Water Interface," edited by Werner Stumm, John Wiley and Sons, New York, pp.221-254.

Stumm, W. (editor), 1987, *Aquatic Surface Chemistry: Chemical Processes at the Particle-Water Interface*, John Wiley and Sons, New York.

Stumm, W. and J.J. Morgan, 1996, *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters*, Third Edition, Wiley-Interscience, John Wiley and Sons, Inc, New York.

Taylor, J.K., 1987, *Quality Assurance of Chemical Measurements*, Lewis Publishers, Chelsea, Michigan.

Thurman, E.M., 1985, *Organic Geochemistry of Natural Waters*, Martinus Nijhoff/Dr W. Junk Publishers, Dordrecht, The Netherlands, 1985.

United States Department of Agriculture, 1953, *Diagnosis and Improvement of Saline and Alkali Soils*, Agriculture Handbook No. 60, U.S. Salinity Laboratory, Riverside, California.

United States Geological Survey, 2000, Hydrology and Stream flow Data Website, http://www.usgs.gov or http://waterdata.usgs.gov/nwis-w/US/.

United States of America, 1998, *Part 4 - Environmental Protection Agency, National Recommended Water Quality Criteria, Republication,* Federal Register, Volume 63, Number 237, pp. 68353-68364, December 10, 1998.

United States of America, 2000a, *Part 141 - National Primary Drinking Water Regulations*, Code of Federal Regulations, Title 40, Volume 15, Part 141, Subpart G, revised, July 1, 2000.

United States of America, 2000b, *Part 143 - National Secondary Drinking Water Regulations*, Code of Federal Regulations, Title 40, Volume 15, Part 143, revised, July 1, 2000.

Zhang, L. and D. Planas, 1994, *Biotic and Abiotic Mercury Methylation and Demethylation in Sediments*, Bull. Environ. Contam. Toxicol., Vol. 52, pp. 691-698.

GLOSSARY

Limnology and General Environmental Science Terms

acid mine drainage	acidic water associate with mining activities, created when sulfide minerals such as pyrite are exposed to oxygenated water, creating sulfuric acid.
acute	short-term or immediate, usually applied to toxicity or exposure to toxic compounds.
aerobic	in the presence of oxygen.
allochthonous	having an origin or formed outside the system of interest.
anaerobic	in the absence of oxygen.
autochthonous	originating from within the system of interest.
benthic	associated with sediments below the water column, or the bottom of a stream or lake.
bioaccumulation	the process whereby toxic compounds are taken up by living organisms and become concentrated in animal tissue over time, or magnify in organisms feeding at higher levels of the food chain.
bioavailability	a property of chemical compounds that describes how well the compound is taken up by living organisms.
biotic	associated with biological organisms.
chronic	long-term or of extended duration, usually applied to toxicity or exposure to toxic compounds.
delta-T, ΔT	change in temperature.
diatoms	microscopic, single-celled plant plankton that form cell walls of silica, called frustules.
eutrophic	trophic state of a lake having high productivity, generally low water transparency, abundant nutrients for plankton, and elevated concentrations of organic carbon.
epilimnion	the surface layer of a thermally stratified lake.
fugitive dust	wind-blown dust, fine soil, and sediment transported away from its point of origin.
hydrodynamics	the study of water flows and currents.
hydrology	the study of surface and ground water hydrodynamics.
hypolimnion	the cold and dense water pool in a thermally stratified lake, next to sediments and below the thermocline.
lacustrine	associated with a lake environment.
lentic	associated with still or calm water.
limnology	the study of the chemistry, biology, and physics of fresh water.
lotic	associated with flowing water.
mesolimnion	the depth region in a thermally stratified lake where temperature drops to a lower limit in the hypolimnion.
microfauna	the collection of microscopic animals in an ecosystem.

microflora	the collection of microscopic plants in an ecosystem.
non-point source	a diffuse source of pollution.
oligotrophic	trophic state of a lake having low productivity, generally higher water transparency, and low concentrations of nutrients and organic carbon.
phytoplankton	microscopic plants suspended in water, usually algae and diatoms.
plankton	microscopic plant and animal organisms suspended in water.
point source	a localized, well defined source of pollution.
productivity	the degree of biological activity in an ecosystem.
profile	the collection of measurements collected in a single location at many depths in a lake.
remote sensing	spectral or photographic imaging from a distance, usually from an aircraft or orbiting satellite.
riverine	associated with a river or flowing stream environment.
Secci depth	the depth below water surface at which a standard flat disk (the Secci disk) becomes invisible, a measure of water transparency.
seston	microscopic debris, sediments, and organisms suspended in a water.
spectrometer	an instrument that measures light intensity at different wavelengths.
spectrum	the collection of light intensity data measured over a continuous range of wavelengths.
thermal stratification	the tendency for deeper lakes to form temperature and density layers in the water column,
thermocline	the temperature transition zone in a thermally stratified lake, associated with the depth of the mesolimnion.
toxicity	the degree to which a compound harms a given organism, usually described using a dosage per unit body weight, or a concentration in water that causes mortality to a percentage of a population.
trophic state	a classification of a lake with respect to biological productivity. High productivity lakes are classified as eutrophic, low productivity lakes as oligotrophic.
turnover	the mixing of a thermally stratified lake, usually occurs in spring and fall.
zooplankton	microscopic animals suspended in water.

Geology Terms

agglomerates	clumps of loosely consolidated solid materials.
albite	a plagioclase feldspar enriched with sodium: $NaAlSi_3O_8$
alluvium	unconsolidated gravel, silt and sand deposited in recent geological times by flowing water: *alluvial deposit, alluvion.*
alteration, altered	change in the mineralogical composition of rock by physical or chemical means, usually applied to hydrothermal solution processes.
amphibole	a group of ferromagnesian silicate minerals, abundant in igneous and metamorphic rock: $(Mg,Fe^{2+},Ca,Na)_{2-3}(Mg,Fe^{2+},Fe^{3+},Al)_5(Si,Al)_8O_{22}(OH)_2$
anatase	a mineral containing titanium usually found with brookite and rutile: TiO_2
anorthite	a plagioclase feldspar enriched with calcium: $CaAl_2Si_2O_8$
apatite	a group of calcium phosphate-containing minerals, also containing carbonate, fluoride, chloride, or hydroxide.

arkose, arkosic	a feldspar-rich sandstone derived from rapid disintegration of granite.
basalt	an igneous volcanic rock
breccia	a coarse-grained rock composed of angular broken rock fragments held together with mineral cement.
brookite	a mineral containing titanium usually found with rutile and anatase: TiO_2
calcite	calcium carbonate, $CaCO_3$
Cambrian	rocks formed during the older period of the Paleozoic Era, from 570 to 510 million years ago.
carbonate	minerals containing carbonate, such as *calcite* or *dolomite*.
chabazite	a zeolite mineral: $CaAl_2Si_4O_{12}\cdot 6H_2O$
chlorite	a group of clay-like minerals of the general formula: $(Mg, Fe^{2+}, Fe^{3+})_6AlSi_3O_{10}(OH)_8$
cinnabar	mercuric sulfide: HgS
clastic	pertaining to a rock or sediment composed of broken fragments of rocks and minerals transported some distance from their points of origin. Sandstone and shale are considered “clastics.”
clay	a class of finely crystalline or amorphous single and multi-layered aluminosilicate minerals formed from the weathering of feldspars, pyroxenes, and amphiboles; or soil and sediment particles smaller than 0.004 µm containing clay minerals such as illite, smectite, or montmorillonite..
clinoptilolite	a zeolite mineral rich in potassium: $(Na,K,Ca)_{2\text{-}3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$
composite	a single sample composed of many combined individual subsamples, used to represent a larger population or area.
conglomerate	a coarse-grained clastic sedimentary rock composed of granules, pebbles, and cobbles larger than 2mm in diameter (gravel) in a matrix of fine sands and silts.
Cretaceous	rocks formed during the final period of the Mesozoic era, covering the span of time from 65 to 135 million years ago.
Dakota Sandstone	a sedimentary rock formation deposited during the early Cretaceous period, prominently exposed in the uplift along the Front Range of the Rocky Mountains. Usually observed above the Morrison shale and below the Mancos shale.
dikes	a vertical igneous intrusion that cuts across the bedding or foliation of the country rock: also *sill, dyke.*
diorite	a group of plutonic rocks of intermediate acid-base composition containing visible hornblende, acid plagioclase (oligoclase, andesine), pyroxene, and some quartz. Also *andesite*.
disaggregation	the process of breaking up soil or sediment solid aggregates.
dolomite	a carbonate mineral containing both calcium and magnesium: $Ca_aMg_b(CO_3)_{a+b}$

Entrada Sandstone	a sedimentary rock formation deposited during the middle Jurassic period, usually observed below the Morrison shale and above the Navajo Sandstone.
Eocene	the Eocene Epoch; rocks deposited or formed 55 to 35 million years ago, between the Oligocene (more recent) and the Paleocene (older) strata.
epithermal	pertaining to hydrothermal mineral deposits formed in the upper 1 km of the earth's surface at temperatures of 50°-200°C.
fault	a crack or fracture in rock, or a zone of fracturing with displacement of sides parallel to the fracture.
fault block	a crustal unit bounded by faults that tectonically behaves as a single unit.
feldspar	a class of metamorphic aluminosilicate minerals.
felsic	pertaining to a group of igneous rocks composed of light colored minerals such as quartz, feldspars, feldspathoids, or muscovite.
ferrihydrite	an iron hydroxide mineral: $Fe(OH)_3$
fractional spooning	a procedure for collecting representative subsamples using many small, randomly selected scoops of solid material.
frustules	the siliceous cell walls of diatoms.
geothermal	pertaining to heat from the interior of the earth.
glacier, glaciation	a large mass of ice formed mostly on land from the compression and recrystallization of snow, which slowly flows downhill; the process of glacier formation.
glass	a non-crystalline rock formed from the rapid cooling of magma.
gneiss	a foliated textured rock formed by regional metamorphism.
goethite	an iron oxide/hydroxide mineral: α-FeO-OH
granite	a hard plutonic rock, containing mostly quartz and feldspar.
granodiorite	a coarse-grained plutonic rock intermediate in composition between quartz diorite and quartz monzonite; a diorite containing quartz and alkali feldspar.
halloysite	a porcelain like clay with a tubular microstructure, $Al_2Si_2O_5(OH)_4 \cdot 2H_2O$
hematite	an iron oxide mineral: α-Fe_2O_3
heterogeneous	non-uniform and poorly mixed..
Holocene	an epoch of the Quaternary period, after the *Pleistocene*, approximately 8,000 years ago to the present.
homogeneous	uniform and well mixed.
hornblende	the most common mineral in the amphibole group, having a general formula: $Ca_2Na(Mg, Fe^{2+})_4(Al, Fe^{3+},Ti)$.
hydrated	a mineral or compound containing water.
hydrothermal	processes in igneous rock involving heated or superheated water.
hydroxyapatite	a variation of the mineral apatite, containing hydroxide: $Ca_5(PO_4)_3OH$
igneous	a rock or mineral formed from cooling of molten or partly molten material, such as magma.
illite	a general name for a group of triple-layer clays commonly found in marine shales.
ilmenite	the principal ore for titanium, a black, opaque, rhombohedral mineral: $FeTiO_3$.
interbedding	layering of different kinds of sedimentary rock or minerals.

intrusive	a rock different from surrounding rock that formed within or forced its way into the surrounding rock.
Jurassic	the second period of the *Mesozoic* era, after the *Triassic* and before the *Cretaceous*, covering a span of time from 135 to 190 million years ago.
kaolinite	a common clay mineral of the kaolin group: $Al_2Si_2O_5(OH)_4$.
Laramide Orogeny	the period of time when the eastern Rocky Mountains were uplifted and formed, from the late Cretaceous to the end of the Paleocene.
laumontite	a white zeolite mineral: $CaAl_2Si_4O_{12}\cdot 4H_2O$
limestone	a sedimentary rock containing more than 50 percent by weight of calcium carbonate; specifically, a carbonate mineral containing at least 95 percent calcite and less than 5 percent dolomite.
limonite	a general field term for a group of brown amorphous hydrous ferric oxides; a common secondary mineral formed by the weathering of iron or iron bearing minerals.
loess	small particle-sized wind-blown deposits.
mafic	pertaining to an igneous rock composed of dark-colored ferromagnesian minerals.
magma	naturally occurring mobile molten rock material generated within the earth and capable of extrusion and intrusion; parent material of all igneous rock.
magnesite	a carbonate mineral containing magnesium: $MgCO_3$
magnetite	a black, opaque, and magnetic mineral of the spinel group: $(Fe,Mg)Fe_2O_4$
Mancos Shale	a sedimentary shale rock formation deposited from inland seas during the middle Cretaceous period, observed throughout the great basin and Colorado, usually observed above the Dakota Sandstone and below the late-Cretaceous to early Tertiary Mesaverde Group coal, sandstones, and mudstones.
marble	a metamorphic rock formed from re-crystallized calcite and/or dolomite.
metamorphic	previously formed rock that is transformed in structure and mineralogy at higher pressure and temperature.
mica	a group of clay-like, layered aluminosilicate minerals that form elastic sheets and flakes in igneous or metamorphic rock.
mineralization	the processes whereby minerals are introduced into rock, and may involve hydrothermal solution processes, fissure filling, impregnation, or replacement.
minus No. 80 mesh	solid material smaller than 0.007 in. (178 µm), passing through a No. 80 U.S. Standard screen.
minus No. 10 mesh	solid material smaller than 0.079 in. (2,000 µm), passing through a No. 10 U.S. Standard screen.
monzonite	a group of intrusive plutonic rocks intermediate in composition between syanite and diorite, containing equal amounts of alkali feldspar and plagioclase, and very little quartz.
Morrison Formation	a sedimentary shale formation deposited from inland seas during the early Cretaceous period, prominently exposed in the uplift along the Front Range of the Rocky Mountains, and containing numerous dinosaur fossils. It is usually observed above the Entrada Sandstone and below the Dakota Sandstone.

Oligocene	an epoch of the early Tertiary period, after the Eocene and before the Miocene.
oligoclase	a plagioclase feldspar mineral enriched with sodium, but containing more calcium than albite.
olivine	a group of ferromagnesian silicate minerals formed from igneous rock: $(Mg,Fe,Mn,Ca)_2SiO_4$
orthoclase	an alkali feldspar enriched with potassium.
orogeny	the process of mountain formation.
oxyhydrate	hydrated oxide/hydroxide minerals usually containing iron and/or manganese.
Permian	rocks formed during the last period of the Paleozoic era, covering a span of time from 225 to 280 million years ago.
petrography	the branch of geology that determines the mineralogy of rock and soil.
physiography	a description of the surface features and landforms of the earth.
plagioclase	a group of triclinic feldspar minerals of the general formula: $(Na,Ca)Al(Si,Al)Si_2O_8$
Pleistocene	rocks and deposits formed during the Quaternary period, covering a span of time from 2-3 million to 8,000 years ago.
Precambrian	very old rock formed 570 million years ago, or older, before the Paleozoic Era, and composed of the Archeozoic (oldest rocks on the Earth) and Proterozoic (younger rocks)
pyrite	an iron sulfide mineral, FeS, which creates acidic mine drainage and sulfuric acid when oxidized by exposure to air.
pyroxene	a group of silicate minerals formed in igneous rock, similar to the amphiboles but lacking hydroxyl groups.
Quaternary	rocks formed during the second period of the Cenozoic Era, following the Tertiary, covering the span of time from 2-3 million years ago to the present time.
quartz	a crystalline silicon dioxide mineral: SiO_2
quartzite	a very hard but unmetamorphosed sandstone consisting chiefly of cemented quartz grains.
rhyolite	an extrusive igneous rock containing quartz and alkali feldspar.
rutile	a mineral containing titanium usually found with brookite and anatase: TiO_2
sandstone	a medium-grained clastic sedimentary rock containing large amounts of quartz, with some clay and cementing minerals.
screen, sieving	the process of separating solid samples into defined size fractions by sifting the sample through a series of mesh screens.
sediment	mineral particles carried by stream flows.
SEM	scanning electron microscope.
shale	a fine-grained and laminated detrital sedimentary rock composed of fine silt and clay, or mud; also called claystone, mudstone.
silica	amorphous silicon dioxide mineral: SiO_2
silicate	a mineral containing SiO_4
sill	a tabular igneous intrusion that parallels the planar structure of the surrounding rock.
silt, silt-sized	soil or sediment particles ranging from 0.002 to 0.05 mm in diameter; a particle size class smaller than fine sand but larger than clay-sized particles.

smectite	a group of multi-layered clay minerals with swelling properties and high cation exchange capacity. Also called *montmorillonite.*
soil	geological materials capable of sustaining plant growth.
sphene	a yellow or brown titanium-containing mineral $CaTiSiO_5$
spinel	a group of ferromagnesian minerals: AB_2O_4, where A can be any or all of Mg, Fe^{2+}, Fe^{3+}, Zn, or Mn, and B can be oxides of Al, Fe^{2+}, Fe^{3+}, or Cr.
stocks	and igneous intrusion that is less than 100 km^2 in size.
subsample	a portion of a larger sample collected to represent the larger sample or population.
telluride	a mineral compound containing tellurium and another metal, such as hessite, Ag_2Te
Tertiary	the first period of the Cenozoic era, covering the span of time between 2-3 million and 65 million years ago.
travertine	a carbonate mineral formed by rapid precipitation, usually when groundwater super-saturated with calcium and carbonate contacts a flowing stream.
travertine cones	conical solid deposits of travertine that form in stream beds.
Triassic	the first period of the Mesozoic era (after the Permian period of the Palaeo and before the Jurassic) ranging from 190 to 225 million years ago.
tuff	a general term for consolidated pyroclastic or volcanic rocks.
tuffaceous	containing tuff.
uplift	a structurally high area in the crust, produced by movements that raise or upthrust the rock.
US Standard Mesh	a defined standard for mesh screens used to size solid particles.
vermiculite	a group of platey or micaceous clay minerals closely related to chlorite and montmorillonite, also the weathering products of micas. Has a general formula: $(Mg,Fe,Al)_3(Al,SI)_4O_{10}(OH)_2 \cdot 4H_2O$
volcanism	the processes by which magma rises to the surface of the earth's crust and is extruded.
weathering	the process whereby one mineral is converted to another.
XRD	X-ray diffraction.
XRF	X-ray fluorescence.
zeolite	a large group of white or colorless aluminosilicate minerals similar to feldspars, usually associated with volcanic tuffs. Zeolites also possess ion exchange capacity.

Chemistry Terms

AA	atomic absorption.
AAS	atomic absorption spectrophotometer.
adsorbed	analytes chemically bound or otherwise attached to the surface of a particle.
alkalinity	the acid neutralizing capacity of a water or soil, usually associated with the amount of carbonate, bicarbonate, or hydroxide in a sample. In geology, a rock that contains Na or K or other alkali metals.

analyte	the chemical compound or element being analyzed in a sample.
anions	negatively charged ions, usually the major anions: HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-.
atm	atmosphere, SI unit, equal to the atmospheric pressure at mean sea level.
carboxylic acid	an organic acid containing -COOH functional groups, such as acetic acid (CH_3-COOH).
carboxylate	a charged, deprotonated carboxylic acid group, -COO^-
cations	positively charged ions, usually Ca, Mg, Na, and K
centrifugate	the denser liquid or solid separated from a liquid during centrifugation.
colloid	very small particles suspended in water that do not settle.
colorimetric	a spectrophotometric analysis technique where the intensity of a colored compound is related to the analyte concentration.
complex	a compound formed between a metal and a ligand, usually called a “trace metal complex.”
CVAA	cold vapor atomic absorption.
CVAFS	cold vapor atomic fluorescence spectrophotometry.
dissolved	an operationally defined term applied to water analysis results, usually meaning that the sample is filtered through a 0.45-µm pore-size membrane filter before analysis.
EC	electron capture detector, on a GC instrument (also electrical conductivity).
electrometric	analysis using measurement of electrical potential (voltage), as with an electrode that measures pH.
equilibrium	the state in a chemical reaction when the forward and reverse reaction rates are equal.
FIA	flow injection analyzer, an automated colorimetric instrument.
FID	flame ionization detector, on a GC instrument.
filtrate	the liquid passed through a filter.
fluorescence	the emission of light caused by incident light, a spectrophotometric analysis method based on fluorescence.
fulvic acid	a class of natural organic matter produced by the chemical breakdown of plant and animal matter, usually dissolved and having a distribution of molecular weights between 600 and 2000 amu.
functional group	a reactive site on a molecule
GFAA	graphite furnace atomic absorption.
grab sample	a randomly selected single sample.
humic acid	a class of natural organic matter produced by the chemical breakdown of plant and animal matter, usually particulate or adsorbed and having a distribution of molecular weights between 2000 and 20,000 amu.
IC	ion chromatograph.
ICP-ES	inductively-coupled plasma - emission spectrograph.
ICP-MS	inductively-coupled plasma - mass spectrometer.
ion, ionic	an element or compound having a positive or negative charge.
ion exchange	the chemical reaction process where one ion will replace another in a reaction with a mineral, such as a clay, or a medium containing ionic binding sites.
ligand	a compound or functional group on a molecule, usually negatively charged, that forms a chemical bond with a positively charged trace element.

major ions	higher concentration elements dissolved in water, usually: Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-
media	the type of material associated with a sample: water, wastewater, groundwater, soil, sediments, rock, tissue, etc.
methylation	the chemical process of adding a methyl group(-CH3) to an inorganic or organic compound.
nutrients	a term referring to all nitrogen and phosphorus species, usually includes total-P, ortho-P, TKN, NH_3, NO_2, and NO_3
oversaturated	the temporary condition in a two-phase (solid-solution) system when the reactants in solution that form a chemical compound exceed concentrations required to form the solid compound at equilibrium. Oversaturated solutions tend to form the solid product and precipitate out of solution.
oxidation	chemical combination or reaction with oxygen, or removal of electrons to increase oxidation state.
partial pressure	the proportional pressure exerted by a gas in the presence of other gases, usually expressed in atm.
particulate	analytes bound to, or strongly associated with suspended particles in water.
pH	the degree of acidity or alkalinity of a solution.
precipitate	v. to change phase from solution (liquid) to solid or to form an insoluble compound that settles out of solution. n. a solid compound that settles out of solution.
Q	flow.
raw sample	a sample that is untreated, unpreserved, or otherwise processed.
reduction	the chemical removal of oxygen from a compound, or the addition of electrons to lower the oxidation state.
redox	oxidation-reduction.
saturated	the condition when a chemical compound is in equilibrium with its solid and solution forms.
saturation index	a measure of undersaturation or oversaturation for a mineral or solid compound in aqueous solution.
slurry	a mixture of solid materials in a liquid.
solute	the chemical that is dissolved into the solvent.
solvent	the chemical that dissolves the solute.
speciation	the description of the different compounds formed by an element in a natural water.
species	chemically, the term applied to different compounds that are formed with elements in natural water.
spectrophotometric	an analytical technique that determines analyte concentration by measuring light transmission, emission, or adsorption, at given wavelength.
stoichiometry	the set of coefficients for reactants and products in a chemical reaction that produce a balanced algebraic equation and condition of mass balance between reactants and products.
supernate	the liquid separated from a slurry during centrifugation.
suspended	an operationally defined term applied to water analysis results. Analytes associated with suspended particles larger than 0.45-µm, usually calculated by subtracting dissolved from total.

thermodynamic	pertaining to the study of heat transfer and the formation and breaking down of chemical compounds.
titration	the process of adding a standardized reactant chemical solution to a liquid sample, and monitoring completion of a reaction that forms a detectable product.
total	an operationally defined term applied water analysis results, usually meaning an unfiltered sample that is digested or extracted without filtration prior to analysis
trace	low concentrations, generally from mg/L to many µg/L.
trace element	in water chemistry, the general term for transition metals and other elements present in low concentrations.
trace metals	a general term for low concentration trace elements.
turbidity	suspended particles that scatter light in a water sample.
ultra-clean	special precautions taken to minimize sample contamination.
ultra-trace	extremely low concentrations, generally µg/L or lower.
undersaturated	the condition in a two-phase (solid-solution) system when the reactants in solution that form a chemical compound are below concentrations required to form the solid compound. Undersaturated solutions tend to dissolve the solid reaction product.
volatile	a solid or liquid with a tendency to evaporate or sublimate into the gas phase.

Elements and Analytes

Ag	silver
Al	aluminum
As	arsenic
AsO_4^{2-}	arsenate ion
Cl^-	chloride, or chloride ion
B	boron
Ba	barium
BOD	biological oxygen demand
Ca, Ca^{2+}	calcium, or calcium ion
Cd	cadmium
Cl^-	chloride, or chloride ion
Co	cobalt
CO_3^{2-}	carbonate, or carbonate ion
COD	chemical oxygen demand
Cr	chromium
Cu	copper
DO	dissolved oxygen, mg/L
DOC	dissolved organic carbon
EC	electrical conductivity, µS/cm
Eh	redox potential, mV
F^-	fluoride, or fluoride ion
FA	fulvic acid

Fe	iron
HA	humic acid
HCO_3^-	bicarbonate, or bicarbonate ion
Hg	mercury
K, K^+	potassium, or potassium ion
Me-Hg	methylmercury, also CH_3Hg^+, methylmecuric ion
Mg, Mg^{2+}	magnesium, or magnesium ion
Mn	manganese
Mo	molybdenum
N	nitrogen
NH_3	ammonia
NH_4^+	ammonium ion
NO_3^-	nitrate, or nitrate ion
NO_2^-	nitrite, or nitrite ion
NO_3+NO_2	nitrate plus nitrite
Na, Na^+	sodium, sodium ion
Ni	nickel
OH^-	hydroxide, or hydroxide ion
ON	organic nitrogen
o-P, ortho-P	orthophosphate
P	phosphorus
Pb	lead
PO_4^{3-}	orthophosphate, phosphate, or phosphate ion
Sb	antimony
Se	selenium
SeO_4^{2-}	selenate ion
Si	silicon (element)
SiO_2	silica (mineral)
SiO_4, SiO_3^{2-}	silicate, silicate ion
Sn	tin
SO_4^{2-}	sulfate, or sulfate ion
T	temperature, ˚C
TDS	total dissolved solids, mg/L, also called “filterable residue”
Tl	thallium
Ti	titanium
TKN	total Kjeldahl nitrogen
TM	trace metals
TOC	total organic carbon
TON	total organic nitrogen
TSS	total suspended solids, mg/L, also called “non-filterable residue”
t-P, total-P	total phosphorus
U	uranium
UO_2^{2+}	uranate ion
V	vanadium
VO_2^+	vanadate ion
Zn	zinc

Measurement Units

amu	atomic mass units.
acre	English unit for land area, (1 acre = 2.471 ha).
acre-ft	acre-foot.
cfs	cubic feet per second, English and engineering unit for flow discharge.
equivalent	a chemical concentration unit based on reactivity, equal to the molar weight divided by the valence of the compound or ion .
eq/L	equivalents per liter.
g	gram, SI mass unit.
ha	hectare, SI area unit (1 ha = 1.00 X 10^4 m^2).
Hz	Hertz, SI unit for frequency in cycles per second.
kg	kilogram, SI mass unit, 1 kg = 1000 g.
kV	kilovolt, (1,000 volts)
kW	kilowatt (1,000 watts).
L	liter, SI volume unit.
lat/long	latitude/longitude.
M	molarity, moles per liter.
m	meter, SI length unit.
meq/L	milliequivalents per liter, 10^{-3} equivalents per liter
mesh	a size standard unit based on the diameter of space between the wire mesh in a screen, used to separate and quantify size fractions of solid materials.
-80 mesh	minus-80 mesh, material passing through a U.S. Standard No. 80 Screen sieve.
+80 mesh	plus-80 mesh, material retained on a U.S. Standard No. 80 Screen sieve.
-10 mesh	minus-10 mesh, materials passing through a U.S. Standard No. 10 Screen sieve.
+10 mesh	plus-10 mesh, materials retained on a U.S. Standard No. 10 Screen sieve.
mg	milligram, SI mass unit, (1 mg = 10^{-3} g).
mg/kg	milligrams per kilogram (1,000 g), SI concentration unit applied to solid samples and liquid samples with high salinity.
mg/L	milligrams per liter, SI concentration unit.
mi^2	square mile.
mL	milliliter, SI volume unit, (1,000 mL = 1.000 L).
mm	millimeter (10^{-3} m), SI length unit.
molal	moles per 1,000 g of solution.
mole	a chemical concentration unit based on the empirical formula of a chemical compound, equal to the mass of Avogadro's number (6.023 X 10^{23}) of molecules of a chemical compound, or atoms of an element.
mol/L, M/L	moles per liter.
mM/L, mmol/L	millimoles per liter, 10^{-3} moles per liter.
mV	millivolt, (10^{-3} volts) SI voltage unit.
µM/L, µmol/L	micromoles per liter, 10^{-6} moles per liter.
µeq/L	microequivalents per liter, 10^{-6} equivalents per liter.
µg	microgram, SI mass unit, (1 µg = 10^{-6} g).
µg/kg	micrograms per kilogram (1,000 g), SI concentration unit applied to solid samples and liquid samples with high salinity.

µg/L	micrograms per liter, SI concentration unit.
µm	micrometer, or micron (10^{-6} m), SI length unit.
µS/cm	microsiemens per square centimeter, SI unit for electrical conductivity.
nm	nanometers, (10^{-9} m), usually applied to spectral wavelengths.
N	normality, expressed in equivalents/liter.
NTU	nephelometric turbidity units.
ng	nanogram, SI mass unit, ($1 \text{ ng} = 10^{-9}$ g).
ng/kg	nanograms per kilogram (1000 g), SI concentration unit applied to solid samples and liquid samples with high salinity.
ng/L	nanograms per liter, SI concentration unit.
ppb	parts per *billion*, equivalent to µg/kg and properly applied to solid sample concentrations.
ppm	parts per *million*, equivalent to mg/kg and properly applied to solid sample concentrations.
ppt	parts per *trillion*, equivalent to ng/kg and properly applied to solid sample concentrations.
percent H_2O	weight percent water.
SI	Système Internationale d'Unités, the international standard system for metric measurement units.
su or s.u.	standard units, usually applied to pH.
V	volt, SI voltage unit.

Quality Control and Statistics Terms

accuracy	a measurement of closeness to the true or actual value.
α	Greek letter alpha. In statistics, the probability of rejecting the hypothesis being tested (the null hypothesis) when it is true. Also called the Type I error and the level of significance.
alternative hypothesis	H_1 - the statistical testing hypothesis accepted if the null hypothesis, H_0 , is rejected.
ANOVA	analysis of variance, a statistical test used to compare means.
blank	a clean check sample used to test for contamination during an instrument run.
blind	a check sample or standard submitted to a lab disguised as a normal sample.
calibration verification	a known concentration certified standard, different from the standards used to calibrate an instrument, that is analyzed after calibration and during the period the instrument is analyzing samples. Used to independently verify initial (ICV) and continuing calibration (CCV).
check sample	a sample analyzed during an instrument run having known concentrations, not necessarily certified or traceable.
certified	as applied to a standard, having documentation attesting to the precision, accuracy, and traceability of a reported concentration.
confidence interval	the interval bounded by confidence limits. An estimate of variability about a mean using the standard deviation adjusted for sample size.
df	degrees of freedom.
distribution	the overall shape of the data set with respect to data values and frequency of occurrence.
DL	detection limit.
estimated	in the data validation process, a term used to indicate that a data value has been qualified because of some degree of QC non-conformance (for example, "J" by EPA protocols). A way of saying that the number may have less certainty.

F	F-statistic, the ratio of two estimates of variance, or the distribution of this ratio.
H_0	null hypothesis.
H_1	alternative hypothesis.
IB	instrument blank - usually pure water or solvent run to check for contamination associated with actual analysis.
ICB	initial calibration blank.
ICV	initial calibration verification.
IDL	instrument detection limit.
interquartile range	a rank based statistic defined as the range of values from the 25th to the 75th percentile value.
Ion Balance	a percentage calculation used to check major ions data that compares cations to anions.
J	EPA data validation code for "estimated."
LCS	laboratory control sample, a check sample with known, but not necessarily certified, concentration.
linear regression	a statistical method for fitting data to a linear model.
LOD	limit of detection, statistically based. 3 times the standard deviation calculated from repeated same-sample results.
LOQ	limit of quantitation, statistically based. 10 times the standard deviation calculated from repeated same-sample results.
MB	method blank, a clean deionized water sample that is digested or extracted following a given method.
MDL	method detection limit.
mean	arithmetic average, denoted as x-bar, or $\bar{X}$.
median	the middle value of a data set that has been sorted from low value to high, also called the 50th percentile.
MSD	matrix spike duplicate.
matrix	the sum of all chemical components in the sample *besides the analyte* being tested.
matrix spike	a real sample to which a known amount of an analyte is added, sometime denoted MS.
μ	Greek letter mu. In statistics, the population mean.
n	number of data points.
ND	not detected, also U, undetected, or <(number), meaning less than the detection limit.
null hypothesis	H_0 - the hypothesis to be tested by statistical analysis, usually that means are equal or unequal.
%R	percent recovery, in general, (observed value)÷(true value) X 100.
parameter	a coefficient for a random variable derived from a statistical analysis.
percentile	a rank based statistic, a data value corresponding to the percentage of the data set below the value associated with the percentage. Examples: the 50th percentile, called the *median*, is the boundary value below which 50% of the data values will fall, or 50 percent of the data will be less than the value of the 50th percentile; a test score in the 97th percentile means that the score is higher than 97 percent of the scores, and less than only 3 percent of the scores.
percent RSD	percent relative standard deviation, the ratio of the standard deviation to the mean, expressed as a percentage.
precision	a measure of the variability of repeated measurements.
PQL	practical quantitation limit.
QA	quality assurance, overall efforts, audits, and tests performed to make sure that sample collectors and the analysis lab are following the QC requirements. These could include lab and field sampling audits, or submission of known concentration samples as blind check samples.

QC	quality control, efforts and tests undertaken *in the lab* to check or document analysis data quality.
qualification	a code or commentary describing QA/QC non-conformance and its effect on data usability.
qualitative	detected, but not at a high level of precision and/or accuracy.
quantitative	detected with a higher degree of precision and accuracy.
RPD	relative percent difference, a way to calculate precision from duplicate analysis data.
Recovery	observed concentration divided by theoretical or true concentration, usually expressed as a percentage.
residual	the difference between the statistically predicted value and the actual value, for a mean, $\bar{X} - x_i$.
R-squared, R^2	adjusted correlation coefficient, a measure of linear correlation.
s	sample standard deviation.
SDG	sample delivery group.
σ	Greek letter sigma. In statistics, the population standard deviation.
spike	a known amount of an analyte added to a real sample or blank.
SRM	standard reference material, a known-concentration standard, usually manufactured and tested by a national standards organization (such as NIST.)
standard deviation	an statistical estimate of variability about a mean.
t	t-statistic, used to compare sample means or the distribution of the statistic.
traceable	usually refers to a check sample or verification sample with known values and a certificate indicating comparison to a standard reference material.
TV	true value.
validation	the process of checking and documenting the quality of analysis data.
variable	a measured property that varies.
$\bar{X}$, x-bar	arithmetic average or mean.

Agency, Organizational, and Location Abbreviations

ACS	American Chemical Society.
ANSI	American National Standards Institute.
APHA	American Public Health Association.
ASQC	American Society for Quality Control.
ASTM	American Society for Testing and Materials.
AWWA	American Water Works Association.
BLM	U.S. Department of the Interior, Bureau of Land Management.
DOI	U.S. Department of the Interior.
EPA	U.S. Environmental Protection Agency.
FGS	Frontier Geosciences, Inc., Seattle, Washington.
IEC	International Electrotechnical Committee.
ISO	International Organization for Standardization.
NIST	National Institute for Standards and Technology, formerly NBS, National Bureau of Standards.
NOAA	National Oceanic and Atmospheric Agency.
SPSS	Statistical Package for the Social Sciences, SPSS, Inc.
TSC	Technical Service Center, Bureau of Reclamation, Denver, Colorado.
UC	Upper Colorado Region, Bureau of Reclamation
USBR	U.S. Department of the Interior, Bureau of Reclamation.
USGS	U.S. Department of the Interior, Geological Survey.
WEF	Water Environment Federation.