NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Identification of Water-Quality Trends Using Sediment Cores from Dillon Reservoir, Summit County, Colorado

Water-Resources Investigations Report 01–4022

U.S. Department of the Interior
U.S. Geological Survey

Upper cover photograph: Dillon Reservoir, August 1997.

Lower left cover photograph: Pontoon boat used
for the sediment-core sampling on Dillon Reservoir.

Lower right cover photograph: Two sediment-core samples
from Dillon Reservoir held in acrylic liners prior to processing.

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By Adrienne I. Greve, Norman E. Spahr, Peter C. Van Metre, and Jennifer T. Wilson

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. (http://www.usgs.gov/). Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. (http://water.usgs.gov/nawqa). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. (http://water.usgs.gov/nawqa/nawqamap.html). Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings. (http://water.usgs.gov/nawqa/natsyn.html).

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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APPENDIX TABLES

CONVERSION FACTORS, VERTICAL DATUM, and ABBREVIATIONS

Multiply	By	To obtain
gram	0.002205	pound
centimeter	0.3937	inch
millimeter	0.03937	inch
acre	4,047	square meter
mile	1.609	kilometer
square mile	259	hectare
square mile	2.590	square kilometer
acre-foot	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.003785	cubic meter per minute

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8 (°C + 32)$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Elevation, as used in this report, refers to distance above or below sea level.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of chemical constituents in bed sediment are given either in milligrams per kilogram (mg/kg), also referred to as parts per million (ppm); micrograms per kilogram (µg/kg); or as a percentage based on weight.

Water year is a 12-month period beginning October 1 of one year and ending September 30 of the following year. A water year is identified by the year in which it ends.

Identification of Water-Quality Trends Using Sediment Cores from Dillon Reservoir, Summit County, Colorado

By Adrienne I. Greve, Norman E. Spahr, Peter C. Van Metre, *and* Jennifer T. Wilson

Abstract

Since the construction of Dillon Reservoir, in Summit County, Colorado, in 1963, its drainage area has been the site of rapid urban development and the continued influence of historical mining. In an effort to assess changes in water quality within the drainage area, sediment cores were collected from Dillon Reservoir in 1997. The sediment cores were analyzed for pesticides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and trace elements. Pesticides, PCBs, and PAHs were used to determine the effects of urban development, and trace elements were used to identify mining contributions. Water-quality and streambed-sediment samples, collected at the mouth of three streams that drain into Dillon Reservoir, were analyzed for trace elements.

Of the 14 pesticides and 3 PCBs for which the sediment samples were analyzed, only 2 pesticides were detected. Low amounts of dichloro-diphenyldichloroethylene (DDE) and dichloro-diphenyldichloroethane (DDD), metabolites of dichlorodiphenyltrichloroethane (DDT), were found at core depths of 5 centimeters and below 15 centimeters in a core collected near the dam.

The longest core, which was collected near the dam, spanned the entire sedimentation history of the reservoir. Concentrations of total combustion PAH and the ratio of fluoranthene to pyrene in the core sample decreased with core depth and increased over time. This relation is likely due to growth in residential and tourist populations in the region. Comparisons between core samples gathered in each arm of the reservoir showed the highest PAH concentrations were found in the Tenmile Creek arm, the only arm that has an urban area on its shores, the town of Frisco. All PAH concentrations, except the pyrene concentration in one segment in the core near the dam and acenaphthylene concentrations in the tops of three cores taken in the reservoir arms, were below Canadian interim freshwater sediment-quality guidelines.

Concentrations of arsenic, cadmium, chromium, copper, lead, and zinc in sediment samples from Dillon Reservoir exceeded the Canadian interim freshwater sediment-quality guidelines. Copper, iron, lithium, nickel, scandium, titanium, and vanadium concentrations in sediment samples decreased over time. Other elements, while no trend was evident, displayed concentration spikes in the down-core profiles, indicating loads entering the reservoir may have been larger than they were in 1997. The highest concentrations of copper, lead, manganese, mercury, and zinc were detected during the late 1970's and early 1980's.

Elevated concentrations of trace elements in sediment in Dillon Reservoir likely resulted from historical mining in the drainage area. The downward trend identified for copper, iron, lithium, nickel, scandium, titanium, and vanadium may be due in part to restoration efforts in mining-affected areas and a decrease in active mining in the Dillon Reservoir watershed.

Although many trace-element core-sediment concentrations exceeded the Canadian probable effect level for freshwater lakes, under current limnological conditions, the high core-sediment concentrations do not adversely affect water quality in Dillon Reservoir. The trace-element concentrations in the reservoir water column meet the standards established by the Colorado Water Quality Control Commission.

INTRODUCTION

Dillon Reservoir is located in the Upper Colorado River study unit (UCOL) of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program. The UCOL was one 59 study units selected for assessment of current water-quality conditions, the change in water-quality over time, and the primary natural and human factors that affect water quality. Investigation began on the UCOL in 1994.

As well as providing drinking-water storage for the city of Denver, Dillon Reservoir is of recreational and esthetic value to both residents and visitors. The reservoir's drainage area occupies the southern part of Summit County. Since the reservoir was constructed in 1963, the drainage area has undergone significant changes. The region has had a large increase in both permanent and tourist populations and continues to be affected by a long history of mining activity.

A common goal of water-quality monitoring is the identification of trends. In many cases, however, the data record is inadequate to effectively identify a change over time. The usefulness of a data record for trend detection may be limited by low sampling frequencies, a short period of data collection, and small numbers of variables analyzed. The use of sediment cores is one manner in which a missing historical data record may be partly reconstructed (Van Metre and Callender, 1996, 1997). In an effort to assess changes in water quality, sediment cores were collected at seven locations in Dillon Reservoir.

Purpose and Scope

This report describes long-term trends in water quality for the Dillon Reservoir watershed by analyzing concentrations of pesticides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and trace elements in sediment cores taken from Dillon Reservoir. Loads of trace elements entering and leaving Dillon Reservoir were determined for 1997 and 1998 and are related to results from the sediment cores. Differences in trace-element loading among the three primary tributaries to Dillon Reservoir also are investigated.

Acknowledgments

Description of Study Area

The 335-square-mile area that drains to Dillon Reservoir (the study area, fig. 1) ranges in elevation from 14,270 feet above sea level to the reservoir water level of about 9,015 feet. Construction of the dam was completed and the storage pool filled in 1963. During water year 1998, average surface area of the reservoir was 3,140 acres, average capacity was 246,777 acre-feet, and the residence time of water was about 1 year. Dillon Reservoir is fed primarily by three streams—Tenmile Creek, the Snake River, and the Blue River. The smallest of the three main streams draining into Dillon Reservoir, the Snake River, contributes approximately one-fourth of the flow into the reservoir. The remaining flow is divided almost equally between Tenmile Creek and the Blue River. Runoff and discharge from the incorporated towns of Blue River, Breckenridge, Dillon, Frisco, and Montezuma drain to Dillon Reservoir. Only one major center of population within Summit County, Silverthorne, is downstream from the reservoir. Four ski resorts also lie within the reservoir drainage area: Arapahoe Basin, Breckenridge, Copper Mountain, and Keystone.

Between 1970 and 1980, Summit County reported the largest growth rate of any county in the United States, a 232-percent population increase
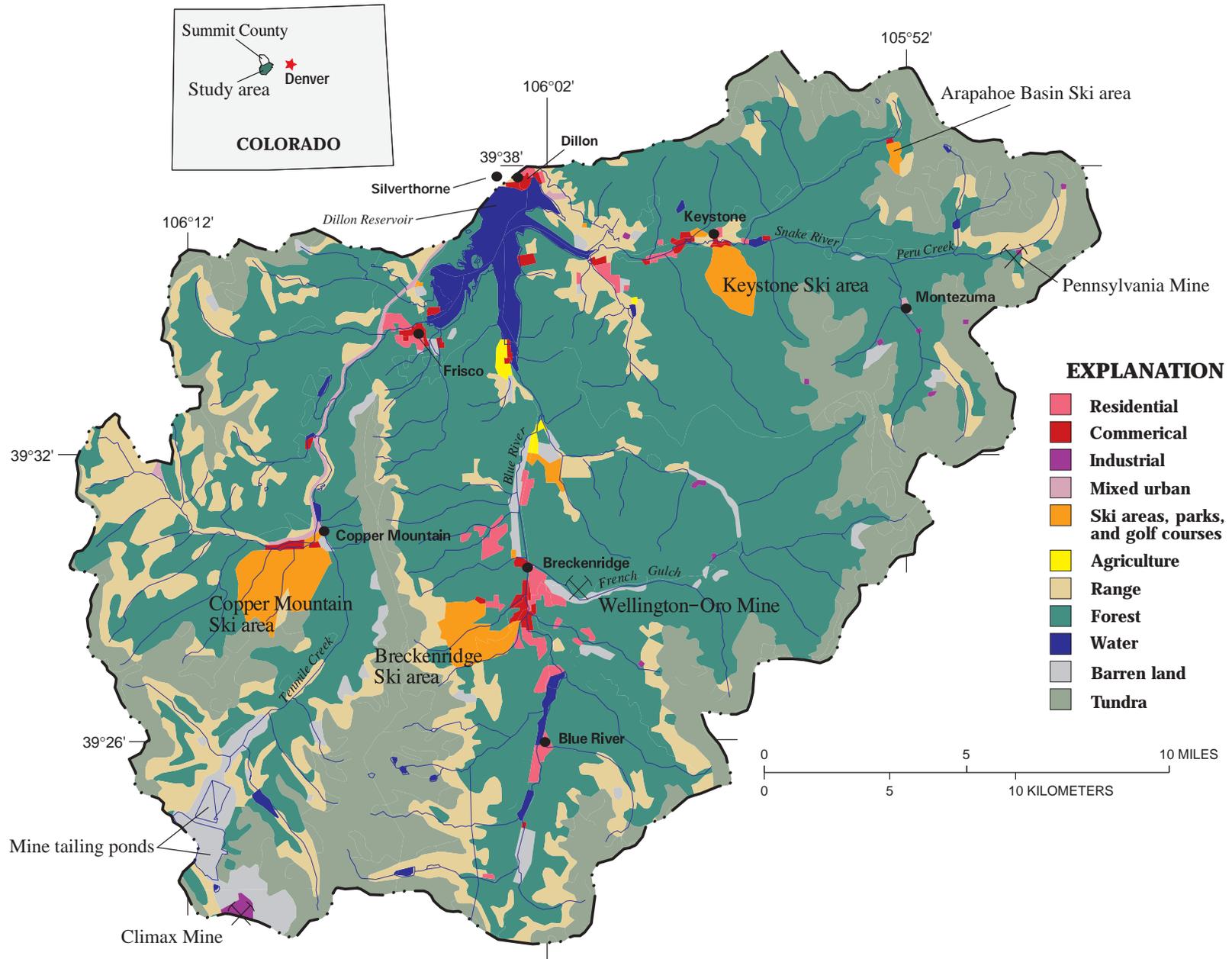
Figure 1. Dillon Reservoir drainage area and associated land use/land cover. [Based on GIRAS (Geographic Information Retrieval and Analysis System) land-use data from the 1970's (Fegeas and others, 1983) and refined with 1990 population data (Hitt, 1995).

(Summit County Government, 1999). Over that same period, the number of housing units in the county grew from 2,198 to 8,364, a 281-percent increase. By 1998, the area had a permanent population of more than 19,000 that increased to more than 100,000 during the peak tourist season from December to mid-March. Similarly, the total number of housing units in the county reached more than 23,000 by 1998 (Summit County Government, 1999). This type of growth in population typically generates increased construction, numbers of automobiles, sewage waste, stormwater runoff, and energy demands.

The study area also has a long history of mining activity, which continues to affect water quality in Dillon Reservoir. The sources of some of the largest trace-element loads to reach Dillon Reservoir are more easily described on a subwatershed basis.

Tenmile Creek

The Climax Mine occupies the southernmost part of Tenmile Creek's 93.3-square-mile drainage area. The history of this molybdenum mine, changes in land use, and mine drainage as described by Voynick (1996) follow. The mine was operated, with few breaks, from 1917 to 1980 and intermittently between 1980 and 1992. Through most of its history, Climax was primarily an underground mining operation, with only limited open-pit mining. Development of a large-scale open-pit mine began in 1972. In 5 years, the pit mine produced an average of 17,000 tons of ore per day. In addition to the Climax Mine, the Tenmile Creek drainage area contains hundreds of prospect holes, shafts, and tunnels from mining operations as early as the 1860's. The metal-laden runoff from active and abandoned mines destroyed all aquatic life in Tenmile Creek to its confluence with the Blue River until the 1970's.

The first steps to reduce the effects of Climax Mine on water quality in Tenmile Creek were taken in 1936. In that year, a new tailings pond, Robinson Pond, was built as a closed system to replace previous free-draining ponds. In 1957, the filling of Robinson Pond necessitated construction of a second closed-system pond, the Tenmile Tailings Pond. Between 1972 and 1978, the Mayflower Tailings Pond System was completed. This pond system was built down-stream from the mill, smelter wastes, and mine. Water from the mine was diverted into the pond system, and unaffected water was diverted in channels around

the mine for release directly into Tenmile Creek. By 1978, an ionic-exchange treatment plant (Bryce Romig, Climax Mine, oral commun., 1999) was treating 2,000 gallons per hour of discharge from the Mayflower Tailings Pond System. As a result of the Mayflower Tailings Pond System, water quality in Tenmile Creek improved to the point that trout returned for the first time in the century. The treatment method at the Mayflower plant was changed in 1984 to a two-stage pH adjustment method to treat all flow, including spring runoff (Bryce Romig, Climax Mine, oral commun., 1999). The mine currently employs a small staff whose responsibilities include mine and mill maintenance, environmental quality and reclamation, and development of water resources.

Snake River

The remnants of a silver mining industry that peaked in the late 1800's and early 1900's are evident in Peru Creek, a tributary of the Snake River (drainage area approximately 115 square miles). Of the mines draining to Peru Creek, the Pennsylvania Mine contributes the largest metal loads, particularly zinc (Sullivan and others, 1998). Conditions in Peru Creek have been severe enough that, as recently as 1998, no fish were found in the reach nearest the mine (Sullivan and others, 1998). In the 1990's, there have been several efforts to improve the environmental quality in Peru Creek. In 1990, a passive treatment system was installed to reduce metal concentrations in the drainage from the Pennsylvania Mine. The system was run as a pilot study from 1990 to 1993 (Northwest Colorado Council of Governments, written commun., 1999).

The Snake River upstream from Dillon Reservoir.

Blue River

French Gulch is a small tributary of the Blue River. It drains more than 10 square miles of the 121-square-mile Blue River drainage area upstream from Dillon Reservoir. There have been several mining operations along French Gulch. In total, more than 600,000 tons of gold, silver, lead, and zinc were removed along French Gulch (Miller, 1995). The largest metal loads to reach the stream originate from the Wellington-Oro Mine (Kimball and others, 1999), located 2 miles upstream from the confluence with the Blue River, near Breckenridge. The mine was operated from 1882 to 1930 and again from 1940 to 1970. In 1972, in an attempt to reopen the mine, the flooded underground mine shafts were pumped for more than a year at a rate of 600 to 1,000 gallons per minute (American Geological Services, written commun., 1999).

In the late 1980's, the Colorado Department of Public Health and Environment began monitoring in the French Gulch drainage area to investigate increased fish mortality rates (Bails, 1998). This monitoring began to identify the sources of the most contaminated discharge. The Colorado Division of Minerals and Geology has since identified four likely sources of metal loading to French Gulch: mill tailings, discarded waste-rock piles, roaster fines, and flooded portions of the Wellington-Oro Mine (Science Applications International Corporation, written commun., 1995). The largest loads originate in the flooded mine. It was estimated that six levels, 80 percent of the mine workings, were currently below the water table in 1995 (Science Applications International Corporation, written commun., 1995). A considerable amount of reclamation has been done to improve water quality within French Gulch, including the sealing of a mine shaft in 1992, streambed clearing and revegetation in 1993, and the removal of roaster fines and tailings piles in 1998 (Science Applications International Corporation, written commun., 1995).

STUDY METHODS

Seven sediment-core samples were collected from Dillon Reservoir. Streambed-sediment and water-quality samples were gathered from the three main streams draining into the reservoir and the Blue River exiting the reservoir. Water-quality samples also were gathered at four sites on the reservoir.

The water-quality samples and streambed-sediment samples were gathered to complement the sediment-core data.

Reservoir Bottom-Sediment Core Samples

Sediment-core samples were collected at seven locations within Dillon Reservoir, two in each of the three arms of the reservoir and one near the dam (fig. 2), in August 1997. Samples were analyzed for pesticides, PCBs, PAHs, and major and trace elements (Appendix 1–3). Samples were collected from a pontoon boat. The sediment cores from each arm of the reservoir were collected using a 15- by 15- by 20-cm-deep box corer. A 50-cm-deep box corer was used to collect the core near the dam. The corers were fitted with an acrylic liner, used to hold the sample after collection. The samples were divided into discrete segments 1 or 2 cm in thickness. Each segment was further divided: one-half for organic compound analysis and one-half for analysis for inorganic compounds. All samples were stored and shipped on ice until received by USGS laboratories in Arvada, Colorado, or Reston, Virginia.

Collecting sediment-core sample from Dillon Reservoir.
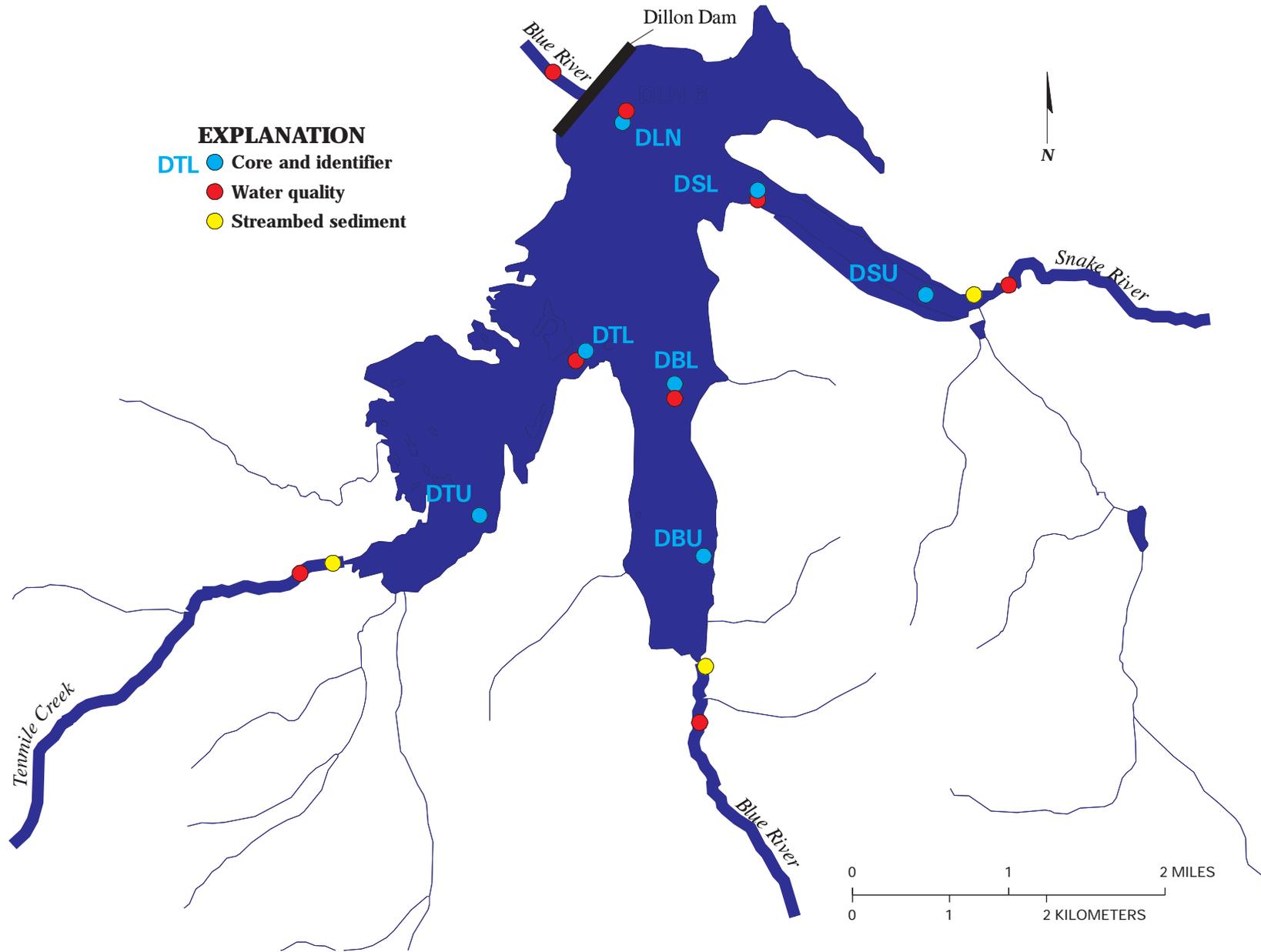
Figure 2. Dillon Reservoir and tributary sampling sites.

Pesticides were identified through solvent extraction followed by gel permeation chromatography, followed by additional alumina-over-silica column chromatography with quantification through dual capillary-column gas chromatography with electron-capture detection (Furlong and others, 1996). PCBs in bottom sediment were identified through dual capillary-column gas chromatography with electron capture detection (Foreman and others, 1995). Pesticide and PCB analysis was done at the USGS National Water Quality Laboratory.

PAHs were identified through solvent extraction followed by gel permeation chromatography. The concentration of each compound was determined by capillary-column gas chromatography/mass spectrometry (Furlong and others, 1996) at the USGS National Water Quality Laboratory in Arvada, Colorado.

Trace elements were analyzed at the USGS National Research Program Laboratory in Reston, Virginia. All trace-element concentrations, except chromium, lead, zinc, and mercury, were determined through inductively coupled plasma-atomic emission spectrometry. Chromium, lead, and zinc were analyzed by graphite furnace atomic absorption and mercury by cold vapor atomic absorption (Lickte and others, 1987; Fishman, 1993).

Only core DLN (fig. 2) was representative of sediment deposited throughout the existence of the reservoir. Determination of the approximate age of each core segment was based on measured porosity (volume of the voids divided by the volume of the solids) and the assumption of a constant sedimentation rate from the pre-reservoir (1963) surface near the bottom of the core to the top of the core (representing 1997). The mass of each segment was determined using measured porosity for that segment, thus adjusting for the effects of compaction over time. The length of time to deposit each segment was determined by dividing the segment mass by the average sedimentation rate (mass per time). Calculation of the age of each segment was done by subtracting the cumulative deposition time of all segments above the segment of interest from the sampling date. Due to compaction, a segment from the bottom of the core had a lower porosity than the sediment deposited at the top of the core. Therefore, a 1-centimeter segment from the bottom of the core spanned a longer time period a than 1-centimeter segment from the top of the core.

Streambed-Sediment Samples

Streambed-sediment samples were collected near the reservoir on each of the main three tributaries (fig. 2) and analyzed for trace elements as part of other studies within the UCOL. Samples on the Snake River and Tenmile Creek were collected in 1996. Protocols and methods used for these samples are described by Deacon and Driver (1999). The sample from the Blue River was collected in 1995, and protocols and methods are described by Apodaca and others (2000).

Water Samples

Stream-water samples were collected monthly at the three tributary sites and downstream from the dam on the Blue River (fig. 2) over a 13-month period beginning in May 1997. Samples were collected using protocols described by Shelton (1994). Equal-width-increment samples were processed onsite and shipped to the USGS National Water Quality Laboratory in Arvada, Colorado. Samples were analyzed for trace-element concentrations using methods described by Faires (1993) and Hoffman and others (1996). Stream-water analysis data are available in the USGS National Water Information System (NWIS) data base.

Reservoir-water samples were collected at discrete depths at four locations in June, August, and November of 1997. Water from a particular depth was pumped to a boat and processed for shipment to the USGS National Water Quality Laboratory. The same laboratory methods used for the stream-water samples

Collecting water-quality samples on the Blue River upstream from Dillon Reservoir.

Collecting water-quality samples from a cableway downstream from Dillon Reservoir on the Blue River.

were used for the reservoir samples. Concentrations of dissolved aluminum, barium, copper, iron, manganese, molybdenum, and zinc were determined both for the stream- and the reservoir-water samples. Total concentrations were determined for copper, iron, manganese, molybdenum, and zinc. "Dissolved" indicates that the water was passed through a 0.45-micrometer filter in the field prior to laboratory analysis; "total" indicates that the water was not filtered. Reservoir-water analysis data are available in the USGS NWIS data base.

Data Analysis

Trend analysis was performed on the data from the sediment core collected near the dam by using Kendall's tau (Helsel and Hirsch, 1993). This analysis measures the monotonic relation between two variables, x and y. Because the analysis is rank-based, it is resistant to the effects of small sample sizes, censored data, and non-normal population distributions. A positive correlation is identified if the y variable increases more often than it decreases as x increases. In this study, a trend was determined to be present when the p-value of the statistical test was less

than 0.05. A p-value expresses the probability of detecting a trend when no trend is present. A detailed discussion of Kendall's tau and its application is included in Helsel and Hirsch (1993). Because Kendall's tau depends upon the rank of data rather than a numerical value, an analysis using the core depth or the estimated year of deposition would yield the same results. In most cases, core depth (x variable) was paired with constituent concentration (y variable); the results were used to make inferences about trends in water quality within the reservoir over time.

Mass loads of trace elements were determined for water entering and leaving the reservoir during water years 1997 and 1998. The loads were calculated as a sum of daily loads, using daily mean flow from gaging stations located near the sampling sites in a regression based on the log of the instantaneous concentration relative to the log of instantaneous flow. The smearing estimator (Duan, 1983) was used to correct for retransformation bias for log-transformed data. In cases where there was no relationship between the log of streamflow and the log of concentration, the mean concentration was used to estimate daily loads. This case was most often observed in the data obtained from the Blue River downstream from Dillon Reservoir. Censored data were replaced with one-half the detection limit. Robertson and Roerish (1999) estimated for small streams, where load estimates are less accurate than those of larger streams, that errors are commonly about 30 percent, assuming 2 years of data and small sample sizes.

Quality-Control Samples

Quality-control samples were collected with the sediment-core and water-quality samples. Quality-control samples allow the bias and variability associated with sample collection, processing, and analysis to be evaluated.

Sediment Cores

Field-blank quality-control samples were not run as part of the pesticide or PCB analysis. However, as part of the standard laboratory methods for pesticide analysis, a replicate sample, surrogate recoveries, and spike recoveries were determined and deemed to be within acceptable limits by the laboratory with each batch of 12 environmental samples. These methods are described by Foreman and others (1995). A method

blank was run as part of the PAH analysis. A method blank is a laboratory blank containing 125 grams of sodium sulfate that undergoes extract filtration, gel permeation chromatography, fraction concentration and solvent exchange, and instrumental analysis (Furlong and others, 1996). All PAH concentrations were below the laboratory reporting limits for the method blank, indicating contamination of samples due to laboratory procedures was negligible.

Field replicate quality-control samples were not run as part of the pesticide, PCB, or PAH analysis. However, seven replicate samples from Dillon Reservoir were analyzed for trace elements—four from the longest core taken near the dam and three from core samples taken in the arms of the reservoir. Among the trace-element results for the seven replicate samples, only four trace-element concentrations, out of 169 possible comparisons, had a relative percent difference (RPD) higher than 10 percent. RPD is calculated using:

$$RPD = \left| \frac{(concentration1 - concentration2)}{(concentration1 + concentration2)/2} \times 100 \right|$$

The concentration of sodium in the replicate samples taken at the 3- to 4-cm depth in core DLN differed by 0.08 µg/g (microgram per gram), an RPD of 10.81 percent; and the concentration of the chromium replicate samples taken from the top 2 cm in the upper Snake River arm differed by 9 µg/g, an RPD of 14 percent. Samples from the core taken in the upper part of the arm of the reservoir receiving water from the Blue River at the 2- to 3-cm depth had chromium and cobalt RPDs of 10.65 and 19.24 percent, respectively, and differences in concentration of 9 µg/g and 3.3 µg/g. Of the 129 possible trace-element concentration comparisons between replicate samples, 103 had a RPD below 5 percent, and 22 had RPDs between 5 and 10 percent.

No field replicate samples were analyzed for the pesticides, PCBs, or PAHs. The variability of the sampling and analysis methods can be estimated on the basis of field and laboratory replicates from cores collected from several other studies in different locations. These cores were collected and analyzed using the same methods as those used to collect the cores from Dillon Reservoir. Field replicates were from a single core. The sample segment was split in the field. Laboratory replicates were single samples which were sent to the USGS National Water Quality Laboratory,

where they were split and analyzed in duplicate. Five field replicates from other studies were available for pesticides. The average RPD was equal to or less than 20 percent for all compounds except chlordane (24 percent) and DDD (25 percent). Among the 27 lab replicates available for pesticides, 5 compounds had an average RPD above 20 percent: chlordane (26 percent), dieldrin (23 percent), DDD (33 percent), DDT (58 percent), and mirex (40 percent).

PAH data from other cores included 21 laboratory replicates and 4 field replicates. The laboratory replicates had 15 compounds with an average RPD above 20 percent; 9 between 30 percent and 20 percent, 4 between 40 percent and 30 percent, and 2 above 40 percent. The two compounds with the highest average RPD were C4–128 isomers (42 percent) and C2–166 isomers (61 percent). The field replicates had 14 compounds with an average RPD above 20 percent; 8 between 30 percent and 20 percent, 4 between 40 percent and 30 percent, and 2 above 40 percent. The two compounds with the highest average RPD were 1,6-dimethylnaphthalene (44 percent) and 2,3,6-trimethylnaphthalene (41 percent).

The results of the trace-element replicates and the laboratory quality-control checks used in the PAH and pesticide analysis indicate that any variability or bias due to sampling, processing, and analysis did not substantially affect the results of this study.

Stream-Water Sampling

One replicate and one field-blank quality-control sample were collected during stream-water sampling. Differences in the concentrations for trace elements in the replicate samples were within 1 µg/L (microgram per liter) with the exception of dissolved aluminum, 2 µg/L (28 µg/L and 26 µg/L); total copper, 3 µg/L (17 µg/L and 20 µg/L); and total iron, 10 µg/L (230 µg/L and 220 µg/L). Total iron is reported to the nearest 10 µg/L. Relative percent differences are not presented because they do not realistically reflect variability in data sets that span orders of magnitude and are reported with different numbers of significant figures. No concentrations above the minimum laboratory reporting level for the trace elements were found in the field-blank sample. Based on these results, variability and bias as a result of stream-water sample collection, processing, and analysis did not substantially affect results presented for this study.

Reservoir-Water Sampling

Quality-control samples (one replicate and one field blank) were collected during the reservoir-water sampling. Differences in the concentrations for trace elements in the replicate samples were generally within 1 µg/L with the exception of dissolved barium, 3 µg/L (28 µg/L compared to 31 µg/L); dissolved zinc, 4 µg/L (29 µg/L compared to 33 µg/L); total zinc, 10 µg/L (40 µg/L compared to 30 µg/L); and total iron, 20 µg/L (50 µg/L compared to 30 µg/L). Total zinc and total iron are reported to the nearest 10 µg/L. RPDs are not presented as they do not realistically reflect variability in data sets that span orders of magnitude and are reported with different numbers of significant figures. No detections of trace elements greater than the minimum laboratory reporting limit were found in the blank sample. Variability and bias as a result of reservoir-water sample collection, processing, and analysis did not substantially affect results presented for this study.

IDENTIFICATION OF WATER-QUALITY TRENDS

Pesticides and Polychlorinated Biphenyls in Reservoir-Sediment Cores

Of the 14 pesticides and 3 PCBs for which the reservoir-core samples were analyzed, only 2 pesticides were detected. Low concentrations of DDE and DDD, metabolites of DDT, were found at core depths of 5 cm and below 15 cm in core DLN (table 1). These findings are reasonable, especially for the sediment below 15 cm, which corresponds to the time period of 1963 through 1977. Use of DDT in the United States peaked in the 1960's and was banned in 1972. Sediment cores taken in a number of other lakes and reservoirs had elevated DDE, DDD, and DDT concentrations in the pre-1970 sediment, followed by a slow decline in younger sediment (Van Metre and Callender, 1996; Van Metre and others, 1997; Kalkhoff and Van Metre, 1997). No trend analysis was conducted for DDE and DDD due to the large number of censored values.

Table 1. Presence of dichlorodiphenyldichloroethylene (DDE) and dichlorodiphenyldichloroethane (DDD) in core DLN collected in August 1997

[cm, centimeter; E, estimated value; <, less than; µg/kg, micrograms per kilogram dry weight]

Depth (cm)	Estimated date of deposition*	DDE (µg/kg)	DDD (µg/kg)
0–2	1995.8	<1	<1
2–4	1992.9	<1	<1
4–6	1989.8	1.2	E1.9
6–8	1986.8	<1	<1
8–10	1984.4	<1	<1
10–12	1982.1	<1	<1
12–14	1979.0	<1	<1
14–16	1974.5	1.1	E1.7
16–18	1968.9	1.2	E1.9
18–19	1964.0	1.4	E2

*See explanation in text on page 7.

Polycyclic Aromatic Hydrocarbons in Reservoir-Sediment Cores

PAHs, some of which have carcinogenic and mutagenic properties, are a group of petroleum-related compounds that sorb strongly to sediment. They are produced by the burning of coal, oil, gas, wood, and refuse or from uncombusted sources such as oil and petroleum products. Combustion-derived PAHs (in comparison to noncombustion-derived PAHs) tend to have greater proportions of 4- or 5-ringed compounds than 2- or 3-ringed compounds, greater amounts of fluoranthene than pyrene, and more phenanthrene than anthracene than noncombustion-derived PAHs (Heit and others, 1988). In an effort to detect changes due to urban development, the three ratios described above, total PAHs, and total combustion PAHs were analyzed.

Total PAHs is the sum all PAH compounds including parent compounds and isomers except perylene. Perylene is excluded from the sum of total PAHs because it is believed to form in situ and not be a petroleum-related compound (LaFlamme and Hites, 1978). Total combustion PAHs refers to the sum of nine compounds that are most commonly found in combustion emissions regardless of the type of fuel being burned. The compounds summed to produce total combustion PAH concentration are fluoranthene, pyrene, benz(a)anthracene, chrysene, benzofluoranthenes, benzo(a)pyrene, benzo(e)pyrene,

indeno(1,2,3-c,d)pyrene, and benzo(g,h,i)perylene (Prahl and Carpenter, 1983).

Using Kendall's tau, the statistically significant ($\alpha = 0.05$) correlations between core depth and some components of the PAH data were determined for core DLN. The ratio of fluoranthene to pyrene concentrations and total combustion PAH decreased with depth, or increased over time (table 2, figure 3). Total combustion PAH concentrations also increased with population (p-value = 0.044). Housing units and skier days increased substantially since construction of the reservoir, but direct relations to components of the PAH data were not identified.

Because sites located near the mouth of rivers can be affected by flooding or scouring, only the top 2 cm of each of the cores from the arms of the reservoir were analyzed for PAHs. The upper core values for two of the three arms had higher concentrations of total and combustion PAH than concentrations from the core collected at the dam site, with the largest values at Tenmile Creek. This may be because the Tenmile arm of the reservoir has the most development near its shores, which includes the town of Frisco. The PAH components expressed as ratios were similar to those for the core taken near the dam.

Residential, commercial, and industrial energy use has been linked to combustion-derived PAH concentrations (Heit and others, 1988). It is likely that the increased concentrations of total combustion PAH and the increased ratios of fluoranthene to pyrene is due to the rapid growth in the area over the last 30 years. However, even though the concentrations of PAHs have increased in Dillon Reservoir, all core concentrations are well below concentrations detected in major urban areas and are within the range typical of remote freshwater lakes in the Western United States (Heit, 1985). To evaluate the ecological significance of the concentrations of PAHs in sediments, values were compared to the Canadian Sediment Quality Guidelines for freshwater lakes (Canadian Council of Ministers of the Environment, 1999); both the interim sediment-quality guidelines (ISQGs) and probable effect levels (PELs) were used. Canadian standards were used as a basis of comparison because similar standards in the United States were in review at the time of writing and subject to revision. Only two PAH constituent concentrations exceeded the ISQG: acenaphthylene concentrations from the top of three cores taken in the reservoir arms and pyrene concentration at the 2–4 cm depth in the core taken near the dam. In all cases, the concentrations were slightly above the ISQG and well below the PEL.

Trace Elements in Reservoir-Sediment Cores, Stream-Sediment, and Water Samples

Trace-element sediment-core concentrations also were compared to the Canadian interim sediment-quality guidelines. Guidelines have been set for arsenic, cadmium, chromium, copper, lead, mercury, and zinc. In all cases except mercury, each core, at all depths, contained concentrations that exceeded the ISQG. Zinc and lead concentrations in all seven cores were well above the PELs, and cadmium concentrations, in all cores except DLN, exceeded the PELs (fig. 4, table 3). Although concentrations of many trace elements in sediment samples exceeded the PEL for freshwater lakes established by the Canadian Council of Ministers of the Environment, limnological conditions (based on data from 1997 and 1998) do not appear to allow the elevated core-sediment concentrations to affect water quality in Dillon Reservoir. The concentrations of trace elements in the reservoir water column did not exceed the water-quality standards established by the Colorado Water Quality Control Commission (Colorado Department of Public Health and Environment Water Quality Control Commission, 1998).

Copper, iron, lithium, nickel, scandium, titanium, and vanadium concentrations were identified,

Table 2. Kendall's tau results for five polycyclic aromatic hydrocarbon components paired with core depth for core DLN, collected near the dam in Dillon Reservoir, August 1997

[--, not applicable]

Parameter or ratio	Tau	p-Value	Trend	Direction
2- and 3-ringed compounds : 4- and 5-ringed compounds	−0.067	0.862	no	--
Fluoranthene : pyrene	−0.511	0.046	yes	Upward over time
Phenanthrene : anthracene	−0.111	0.728	no	--
Total PAH	−0.200	0.484	no	--
Total combustion PAH	−0.644	0.009	yes	Upward over time
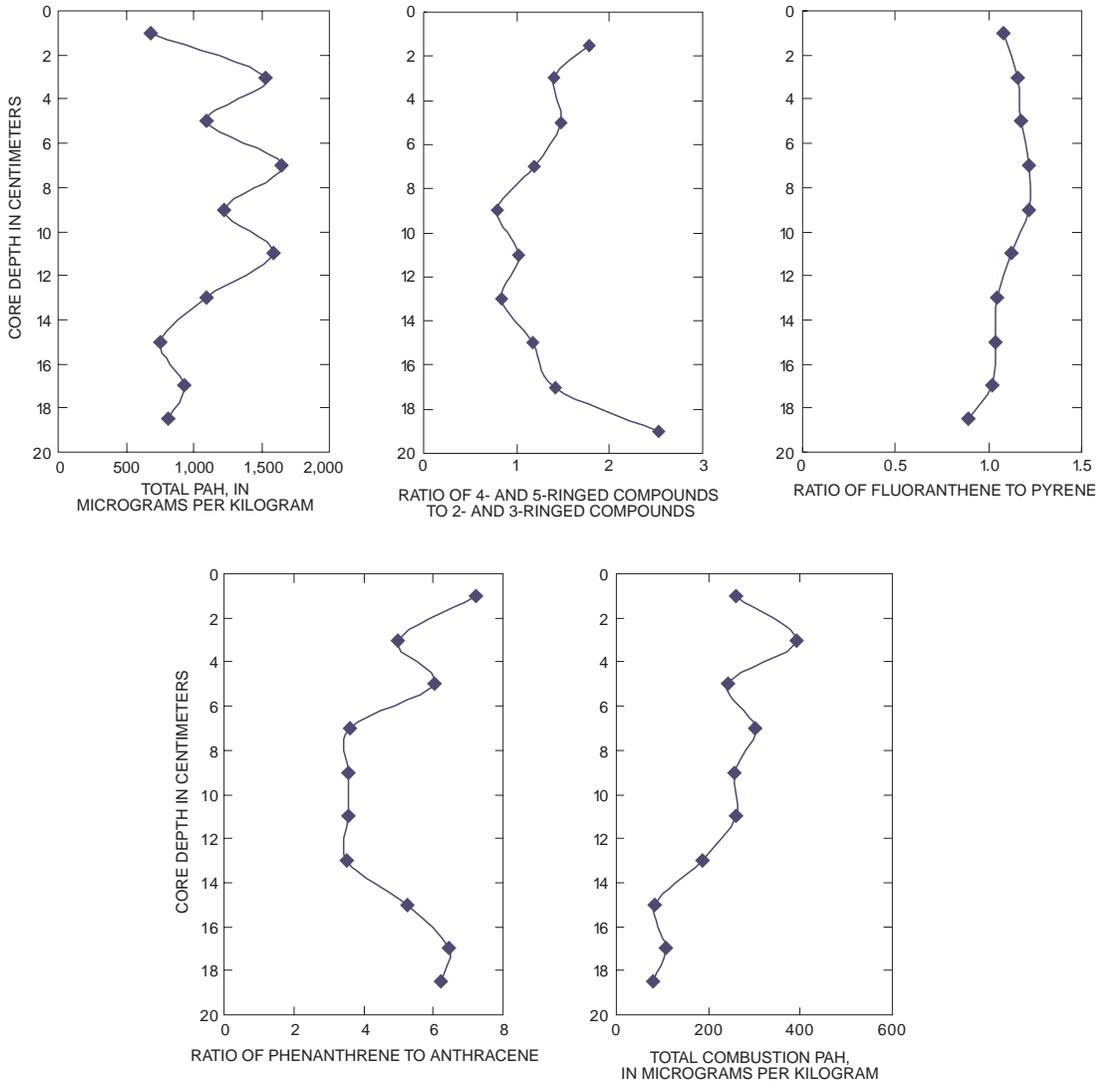
Figure 3. Five polycyclic aromatic hydrocarbon components plotted against depth in core DLN. (The ratio of 4- and 5-ringed compounds is commonly reported as 2- and 3-ringed compounds to 4- and 5-ringed compounds. The ratio was reversed in this figure in order to show all three ratios that relate combustion- and noncombustion-derived compounds to be comparable.)

using Kendall's tau, as increasing with core depth, indicating that concentrations in the sediment column have decreased over time (table 4). The decrease in trace-element concentrations over time may be due in part to the decrease in active mining in the drainage area and efforts to reclaim old mine sites.

Elements shown to increase over time were cadmium and mercury. Cadmium can be associated with mining but is typically found in zinc-ore minerals (Hem, 1992). Zinc concentrations in the sediment core did not show a trend, which indicates that there may be a source of cadmium that is not mining

related. Cadmium is used in paint, plastics, ink, and batteries. It also can enter the environment through the combustion of fossil fuels (Hem, 1992). The increase of cadmium concentrations in reservoir sediment may be associated with the population increase and urban development in the Dillon Reservoir watershed.

Mercury is a trace element commonly associated with coal-fired powerplant emissions and waste incinerators. It can be regionally transported and enter a watershed through atmospheric deposition (U.S. Environmental Protection Agency, 1997). Low concentrations of mercury were identified in snow-
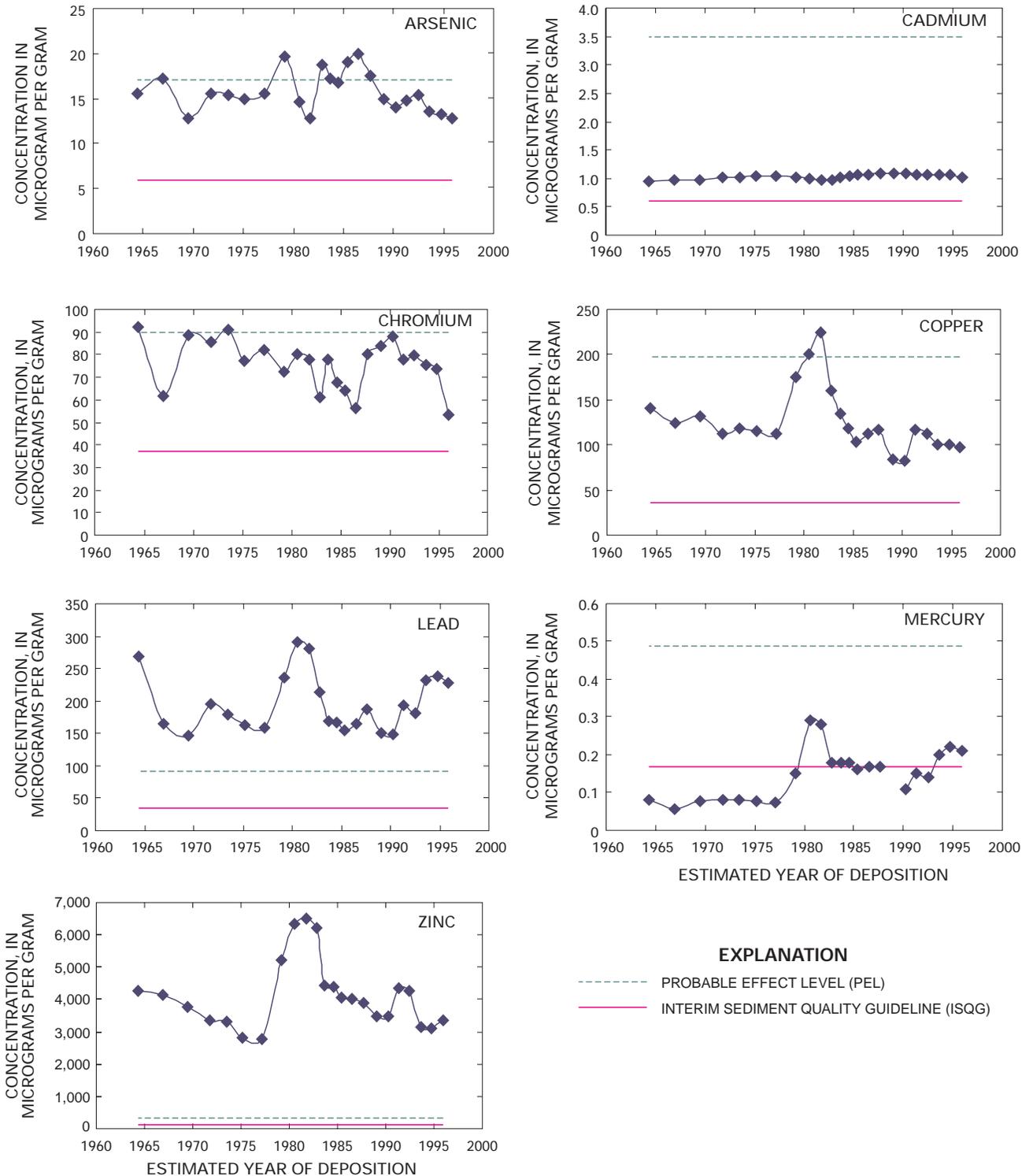
Figure 4. Concentrations of selected trace elements in Dillon Reservoir core DLN (taken near dam August 1997) compared to the Canadian Sediment Quality Guidelines. [Concentrations below the ISQG are not expected to be associated with any adverse biological effects. Concentrations between the ISQG and the PEL represent a range in which adverse biological effects are occasionally observed; concentrations above the PEL are expected to be frequently associated with adverse biological effects (Canadian Council of Ministers of the Environment, 1999).]

Table 3. Trace-element concentrations from cores taken in the arms of Dillon Reservoir, and the top 4 centimeters of the core taken near the dam, August 1997, compared to Canadian Sediment Quality Guidelines

[Mercury data were not collected in arms of reservoir; shaded values exceed probable effect level (PEL); **bold** values exceed interim sediment-quality guideline (ISQG), but not PEL; cm, centimeter; --, not available; all concentrations are in micrograms per gram]

Guideline or reservoir arm	Depth (cm)	Arsenic	Cadmium	Chromium	Copper	Lead	Mercury	Zinc
ISQG[1]		5.9	0.6	37.3	35.7	35.0	0.170	123
PEL[2]		17.0	3.5	90.0	197.0	91.3	0.486	315
Blue River upper arm	0–1	**10.0**	5.8	**70**	**58.1**	220	--	1,870
Core DBU	1–2	**9.6**	4.6	**86**	**59.6**	218	--	2,000
	2–3	**11.9**	5.0	**89**	**70.6**	237	--	2,100
Blue River lower arm	0–2	**11.0**	5.6	**70**	**63.1**	219	--	1,960
Core DBL	2–4	**13.4**	5.7	**66**	**66.5**	265	--	1,850
Snake River upper arm	0–2	**11.2**	5.0	**69**	**128**	516	--	2,870
Core DSU	2–4	**14.9**	3.6	**66**	**140**	510	--	2,860
Snake River lower arm	0–2	**15.4**	4.8	**75**	**113**	390	--	3,170
Core DSL	2–4	**13.7**	5.1	**69**	**112**	331	--	3,150
Tenmile Creek upper arm	0–2	**16.5**	4.8	**88**	**74.9**	413	--	2,280
Core DTU	2–4	20.7	4.4	94	**70.9**	468	--	2,330
Tenmile Creek lower arm	0–2	**12.4**	4.6	90	**75.4**	231	--	2,610
Core DTL	2–4	**12.7**	**3.3**	84	**77.7**	232	--	2,640
Dillon Reservoir near dam	0–1	**12.8**	**1.02**	53	**97.5**	227	**0.21**	3,370
Core DLN	1–2	**13.2**	**1.07**	74	**101**	238	**0.22**	3,120
	2–3	**13.6**	**1.06**	75	**101**	232	**0.20**	3,150
	3–4	**15.4**	**1.06**	80	**112**	181	**0.14**	4,260

[1]Concentrations below the ISQG are not expected to be associated with any adverse biological effects. Concentrations between the ISQG and the PEL represent a range in which adverse biological effects are occasionally observed (Canadian Council of Ministers of the Environment, 1999).

[2]Concentrations above the PEL are expected to be frequently associated with adverse biological effects (Canadian Council of Ministers of the Environment, 1999).

pack samples collected in the region during 1999 (Don Campbell, U.S. Geological Survey, written commun., 2000). This finding indicates that there is likely some atmospheric deposition in the drainage area. Mercury also is commonly found in gold deposits and therefore is a by-product of gold mining operations (U.S. Environmental Protection Agency, 1994).

In addition to the gradual (monotonic) trends observed for some trace elements, several had more complex temporal variations including high concentrations or spikes, indicating that loads into the reservoir in the past may have been much higher over certain periods (fig. 5). The most prominent of these spikes was observed in the distribution of copper, lead, manganese, mercury, and zinc and was estimated to have occurred in the late 1970's and early 1980's. Because of the importance of mining in the Dillon Reservoir watershed, it was hypothesized that spikes in trace-element concentrations could be caused by changes in mining activities in the watershed. No single change in mining operation or land use occurred in the early 1980's that could explain the temporal patterns in the cores. The number of mining claims increased over this period due to an increase in the price of gold; however, these claims were not actively mined (Delbert Tolen, St. John Mine, oral commun., 2001).

Dissolved and total trace-element data from streams emptying into the reservoir were used in conjunction with streamflow data to determine incoming and outgoing loads of trace elements to and from Dillon Reservoir for water years 1997 and 1998. The loads entering the reservoir in most cases were much larger than those exiting through the Blue River. This indicates that the reservoir acts as a sink for

major and trace elements (table 5). Generally, copper, iron, and manganese had the largest percentages of the incoming total load left in the reservoir. Copper, iron, manganese, molybdenum, and zinc were analyzed for total (unfiltered) concentration, which allowed the percentage of the overall load occurring in the dissolved phase to be determined (table 6). In the case of copper, iron, and zinc, the entering load had a smaller dissolved percentage than the exiting load. It is likely much of the incoming copper and iron was in the suspended phase and was deposited on the reservoir bottom by settling. Manganese showed a decrease and zinc did not show a large increase in dissolved-percentage exiting the reservoir, implying that geochemical processes in addition to sedimentation are acting to contribute loads to Dillon Reservoir.

From the load calculations, the stream contributing the largest amount of a given element was identified. Tenmile Creek, which accounts for about 37 percent of the total water inflow, delivered the largest loads of aluminum, barium, and, as one would expect, molybdenum. The Blue River contributed no more than one-third of any trace-element load entering the reservoir, less than the portion of the flow contributed (35 percent of inflow) to the reservoir. The Snake River, generating 28 percent of the total inflow, contributed most of the copper, manganese, and zinc loads.

Those streams delivering the largest loads of trace elements to the reservoir also had higher streambed-sediment concentrations, with the exception of barium. The barium load delivered by the Snake River was smaller than the barium loads carried by the Blue River and Tenmile Creek; however, the

Table 4. Results of Kendall's tau calculations relating trace-element concentrations to core depth in core DNL, collected August 1997

[μg/g, micrograms per gram; %, percentage; --, not applicable; value is based on the large sample size approximation described in Helsel and Hirsch (1993)]

Element	Units	Tau	p-value	Trend	Direction
Aluminum	%	0.099	0.576	No	--
Arsenic	μg/g	0.111	0.529	No	--
Barium	μg/g	−0.006	1.000	No	--
Cadmium	μg/g	−0.637	0.000	Yes	Upward over time
Calcium	%	−0.158	0.363	No	--
Chromium	μg/g	0.333	0.050	No	--
Cobalt	μg/g	0.287	0.093	No	--
Copper	μg/g	0.509	0.003	Yes	Downward over time
Iron	%	0.345	0.042	Yes	Downward over time
Lead	μg/g	−0.053	0.780	No	--
Lithium	μg/g	0.439	0.010	Yes	Downward over time
Magnesium	%	−0.018	0.944	No	--
Manganese	μg/g	0.228	0.184	No	--
Mercury	μg/g	−0.380	0.025	Yes	Upward over time
Nickel	μg/g	0.544	0.001	Yes	Downward over time
Potassium	%	0.170	0.327	No	--
Scandium	μg/g	0.357	0.036	Yes	Downward over time
Silicon	%	0.135	0.442	No	--
Sodium	%	0.123	0.484	No	--
Strontium	μg/g	0.006	1.000	No	--
Titanium	%	0.673	0.000	Yes	Downward over time
Vanadium	μg/g	0.626	0.000	Yes	Downward over time
Zinc	μg/g	0.298	0.080	No	--
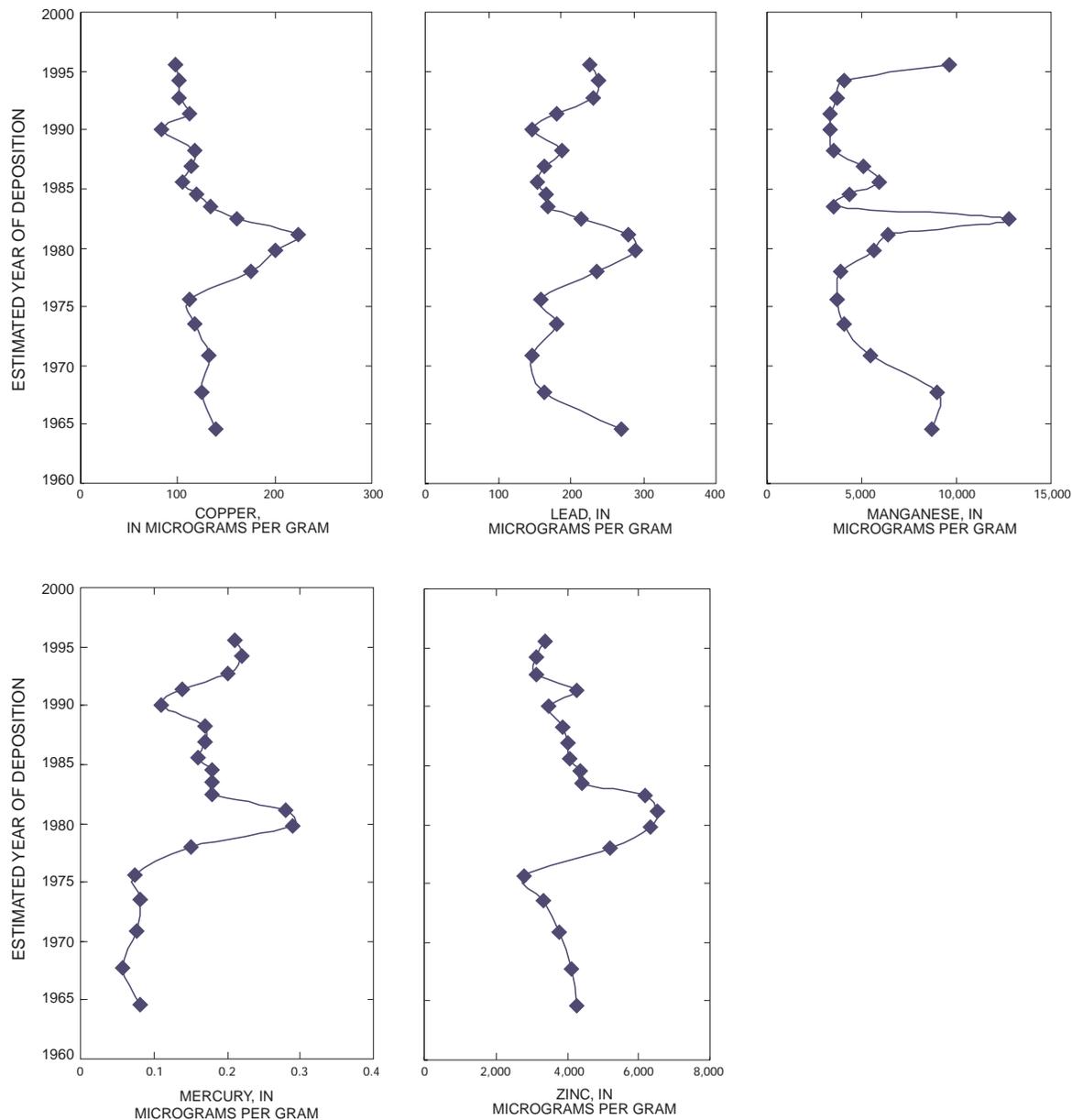
Figure 5. Concentration plotted against estimated year of deposition for trace elements that displayed a concentration spike in the late 1970's and early 1980's. (All concentrations are in micrograms per gram.)

streambed-sediment concentration of barium was highest in the Snake River.

The streambed-sediment samples also provided data on trace elements that were not detected in the water samples (Deacon and Driver, 1999; Apodaca and others, 2000). Tenmile Creek streambed sediments had the greatest concentrations of arsenic, beryllium, chromium, and selenium of the three main streams flowing into Dillon Reservoir, and the Snake River sediments had the most antimony, cadmium,

copper, lead, silver, vanadium, and zinc. In the Blue River, uranium concentrations in sediment were highest.

Streambed-sediment concentrations were compared to the concentrations in the sediment cores taken in Dillon Reservoir. Streambed-sediment samples were wet-sieved in the field, and the silt and clay fraction (finer than 0.063 mm) was analyzed for metals. The wet sieving was done to facilitate comparisons among samples because trace elements tend

Table 5. Load calculations for trace elements entering and leaving Dillon Reservoir for 1997 and 1998 based on regression analysis of the log of instantaneous flow relative to the log of concentration

[kg/yr, kilograms per year; %, percent; total and dissolved loads for lead and cadmium are not included due to most of the data being censored. Dissolved molybdenum concentrations in some cases were reported as greater than the total molybdenum concentrations, which resulted in higher calculated loads of dissolved molybdenum in Tenmile Creek and in the Blue River below the dam. All concentrations were deemed accurate within laboratory method precision]

Element	Incoming loads						Total (kg/yr)	Outgoing load		
	Tenmile Creek		Blue River		Snake River			Blue River	%	%
	(kg/yr)	(% of total)	(kg/yr)	(% of total)	(kg/yr)	(% of total)		(kg/yr)	exiting	remaining
Water Year 1997										
Aluminum, dissolved	6,190	60	490	5	3,680	35	10,360	3,840		
Barium, dissolved	8,690	55	5,120	33	1,860	12	15,670	11,600		
Copper, dissolved	160	20	180	23	450	57	790	500		
Copper, total	260	11	300	12	1,880	77	2,440	570	23	77
Iron, dissolved	1,660	45	910	24	1,150	31	3,720	1,460		
Iron, total	56,620	33	49,960	29	65,750	38	172,330	10,150	6	94
Manganese, dissolved	11,890	40	580	2	17,550	58	30,020	2,940		
Manganese, total	20,520	42	2,080	4	25,780	54	48,380	5,330	11	89
Molybdenum, dissolved	22,000	100	100	0	50	0	22,150	19,370		
Molybdenum, total	20,770	99	210	1	100	0	21,080	11,660	55	45
Zinc, dissolved	3,100	9	9,690	29	21,240	62	34,030	11,300		
Zinc, total	5,540	12	12,760	28	28,000	60	46,300	13,960	30	70
Water Year 1998										
Aluminum, dissolved	3,010	67	150	3	1,330	30	4,490	2,260		
Barium, dissolved	8,690	68	2,910	23	1,140	9	12,740	6,350		
Copper, dissolved	90	23	70	18	240	59	400	2,970		
Copper, total	90	10	80	9	730	81	900	340	38	62
Iron, dissolved	800	45	330	19	630	36	1,760	860		
Iron, total	15,670	37	7,820	18	19,150	45	42,640	5,970	14	86
Manganese, dissolved	6,800	39	120	1	10,340	60	17,260	1,730		
Manganese, total	7,390	36	440	2	12,820	62	20,650	3,130	15	85
Molybdenum, dissolved	17,950	100	50	0	30	0	18,030	9,080		
Molybdenum, total	17,170	99	100	1	50	0	17,320	6,850	40	60
Zinc, dissolved	2,120	11	3,960	20	13,640	69	19,720	6,650		
Zinc, total	1,850	8	4,400	20	15,720	72	21,970	8,210	37	63

Table 6. Percentage of copper, iron, manganese, molybdenum, and zinc loads in the dissolved phase entering and leaving Dillon Reservoir, water year 1997

[All values in percent; Dissolved molybdenum concentrations in some cases were greater than the total molybdenum concentrations. In this case, the dissolved percentage was listed as 100 percent. All concentrations were deemed accurate within laboratory method precision]

Element	Tenmile Creek	Blue River	Snake River	Total incoming	Blue River outgoing
Copper	62	60	24	32	88
Iron	2.9	1.8	1.7	2.2	14.4
Manganese	58	28	68	62	55
Molybdenum	100	48	50	100	100
Zinc	56	76	76	73	81

to be concentrated in the finer grain-size materials (Horowitz and Elrick, 1988). Reservoir bottom-sediment samples were not sieved, however, because larger grain-size materials settle out quickly as streams enter the reservoir; as a result, all of these samples were predominantly silt and clay. Samples from the three upper arm sites ranged from 77 to 92 percent silt and clay; lower arm sites ranged from 93 to 97 percent; and the main lake site was 98 percent silt and clay. Although the wet sieving and the sorting in the reservoir help to minimize the effects of grain size on trace-element concentrations, concentrations were normalized against the percent content of clay-sized particles prior to comparisons among sites to further reduce possible variability caused by differences in particle-size distributions.

Clay-normalized concentrations of trace elements in streamed sediments and surficial reservoir sediments are shown in figure 6. Differences between each stream and arm of the reservoir and longitudinal differences in the downstream direction are evident on these plots. The heavy metal concentrations that were higher in the Snake River streambed-sediment sample (barium, copper, lead, nickel, and zinc) also were higher in sediment samples from the Snake River arm of Dillon Reservoir than in sediment samples from the other arms. In most cases, concentrations in the Blue River and Tenmile Creek were less than those from the Snake River streambed sediment.

Among the seven elements shown in figure 6, a common longitudinal pattern is found. Concentrations of barium, cadmium, copper, iron, lead, nickel, and zinc display a longitudinal decrease in normalized concentration. The largest decrease in clay-normalized concentration occurs between the streambed sediment and the upper arm of the reservoir. Little change in sediment-core concentration is seen from the upper arm to the dam for the arm with the lowest concentration, typically the Blue River or Tenmile Creek.

If there were no additional sources of sediment between the streambed-sampling sites and near the dam in the lower part of the reservoir, and if there were no geochemical alterations of the sediment chemistry within the reservoir, normalized concentrations near the dam would be expected to be the mass-weighted average of concentrations in sediments from the arms. In this situation, the normalized concentration near the dam would be expected to be between those levels observed in the arms. The elements in figure 6 exhibit slightly lower concentrations at the site near the dam than would be expected if the above scenario were the only influence on the sedimentation of trace elements. The decrease in many of the metals in the downstream direction suggests the influence of dilution of the stream sediments by sediment with trace-element concentrations similar to or lower than that of the Blue River, the stream with typically the lowest trace-element sediment concentrations. One logical source of sediment that would act to dilute concentrations of some metals is erosion of bank material in the reservoir. When a reservoir is built, a new shoreline is formed. It can take years or even decades for this new shoreline to stabilize, and erosion can be a major source of sediment to the reservoir. The shoreline has yet to stabilize around parts of Dillon Reservoir (fig. 7) and, because sedimentation rates in the reservoir are relatively low (about 0.5 cm/yr at site
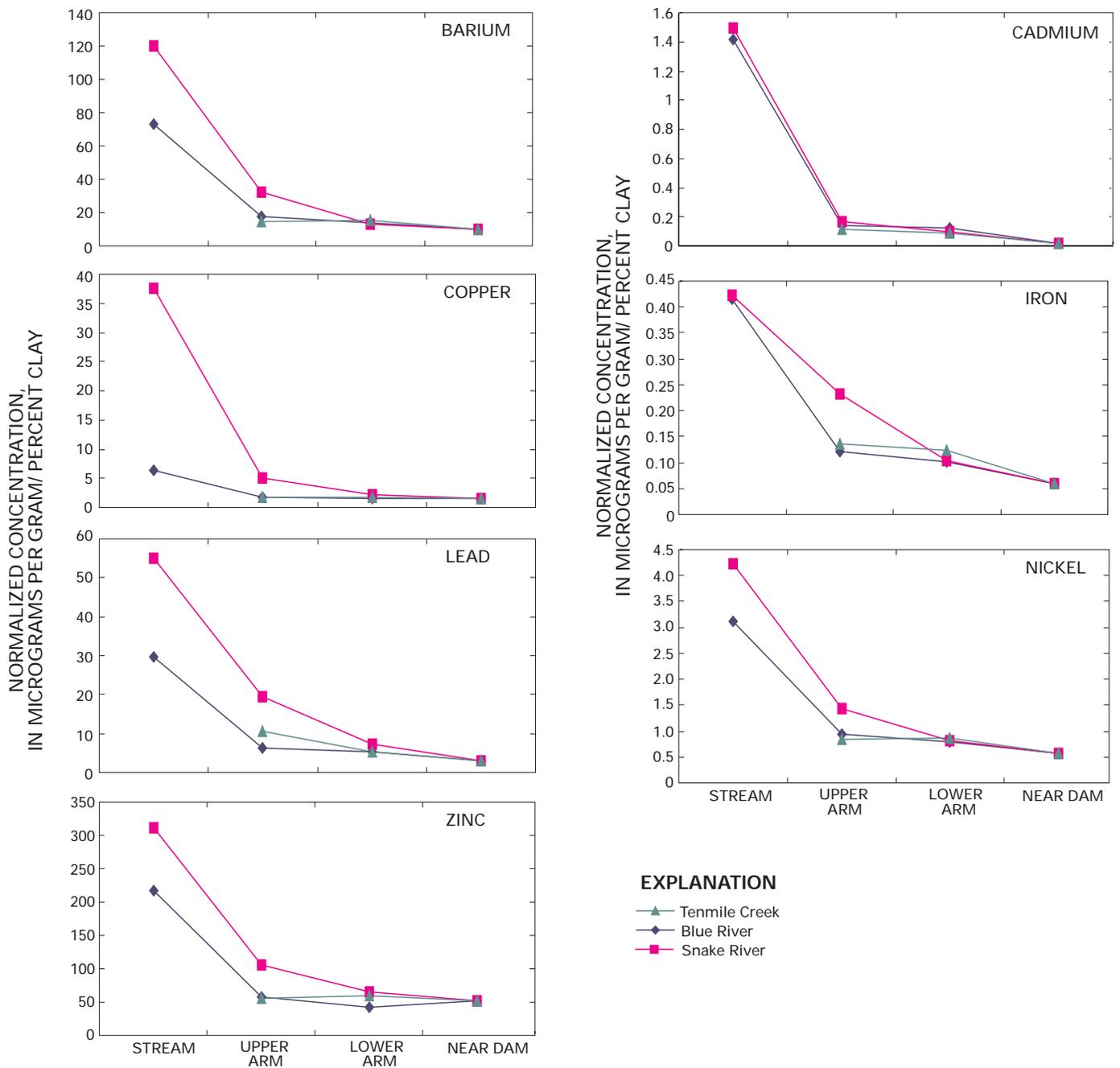
Figure 6. Concentrations of trace elements in clay-normalized sediment cores from the mouth of the streams to the dam at Dillon Reservoir, 1997. [Clay content data were not available for the stream-sediment sample gathered near the mouth of Tenmile Creek. Streambed-sediment concentrations from Deacon and Driver (1999) and Apodaca and others (2000).]

Figure 7. Evidence of bank erosion on Dillon Reservoir, Colorado.

DLN), bank erosion could be an important contributor of sediment.

SUMMARY AND CONCLUSIONS

The drainage area of Dillon Reservoir, in Summit County, Colorado, has been the site of rapid urban development and the continued influence of historical mining. Sediment cores were collected at seven locations in Dillon Reservoir in an effort to assess changes in the water quality. The sediment cores were analyzed for pesticides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and trace elements. Pesticides, PCBs, and PAHs were used to determine the effects of urban development, and trace elements were used to identify mining contributions. Water-quality and streambed-sediment samples also were collected at the mouth of three streams that drain into the reservoir.

The use of pesticides and PCBs can increase with urban growth. Of the 14 pesticides and 3 PCBs for which the sediment samples were analyzed, only 2 pesticides were detected. Low amounts of dichlorodiphenyldichloroethylene (DDE) and dichlorodiphenyldichloroethane (DDD), metabolites of dichlorodiphenyltrichloroethane (DDT), were found

at core depths of 5 cm and below 15 cm in a core collected near the dam.

Historical mining and urban development within the Dillon Reservoir watershed have affected water quality. Combustion-derived PAH concentrations and the ratio of fluoranthene to pyrene have increased over time within the sediments of Dillon Reservoir. A relation also was established between resident population and total combustion PAH. These upward trends and the relation between population and total combustion PAH is likely due to the growth in both the resident and tourist populations in the region. Comparisons between core samples gathered in each arm of the reservoir showed the highest PAH concentrations were from the Tenmile Creek arm, the only arm that has an urban area on its shores, the town of Frisco. The levels of PAHs, however, are low by comparison with lakes and reservoirs in urban areas and are typical of remote freshwater lakes. All PAH concentrations, except pyrene concentration in one segment in the core near the dam and acenaphthylene concentrations in the tops of three cores taken in the reservoir arms, were below Canadian interim freshwater sediment-quality guidelines.

Trace-element concentrations of arsenic, cadmium, chromium, copper, lead, and zinc in Dillon Reservoir sediment exceeded freshwater sediment-quality guidelines established by the Canadian

Council of Ministers of the Environment and likely resulted from historical mining in the watershed. The core data establish the presence of trace-element deposition throughout the history of the reservoir. The analysis of stream data indicate that metals loads are delivered through the system of tributaries draining into the reservoir. The data gathered, however, are not detailed enough to firmly establish a specific source for individual trace elements within a specific subwatershed. The downward trends identified for copper, iron, lithium, nickel, scandium, titanium, and vanadium may be due in part to the mine-restoration efforts and the decrease in active mining in the watershed. In addition to the monotonic trend in trace elements, several elements had a number of high concentrations or spikes, which indicate that loads entering the reservoir may have been higher in the past. These spikes occurred in concentrations of copper, lead, manganese, mercury, and zinc during the late 1970's and early 1980's.

Although concentrations of many trace elements in sediment samples exceeded the probable effects levels for freshwater lakes established by the Canadian Council of Ministers of the Environment, under current (1997) limnological conditions, elevated sediment concentrations do not appear to significantly affect water quality in Dillon Reservoir. The concentrations of trace elements in the reservoir water column did not exceed the water-quality standards established by the Colorado Water Quality Control Commission.

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APPENDIX

Table A1. Concentration of pesticides and polychlorinated biphenyls in seven bottom-sediment core samples from Dillon Reservoir, 1997

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	Lindane	Heptachlor	Aldrin	Heptachlor epoxide	Chlordane	Endosulfan	Dieldrin	Endrin
Minimum laboratory reporting level		**1**	**1**	**1**	**1**	**10**	**1**	**1**	**1**
DLN	0–2	<1	<1	<1	<1	<10	<1	<1	<1
DLN	2–4	<1	<1	<1	<1	<10	<1	<1	<1
DLN	4–6	<1	<1	<1	<1	<10	<1.1	<1	<1
DLN	6–8	<1	<1	<1	<1	<10	<1	<1	<1
DLN	8–10	<1	<1	<1	<1	<10	<1	<1	<1
DLN	10–12	<1	<1	<1	<1	<10	<1	<1	<1
DLN	12–14	<1	<1	<1	<1	<10	<1	<1	<1
DLN	14–16	<1	<1	<1	<1	<10	<1	<1	<1
DLN	16–18	<1	<1	<1	<1	<10	<1	<1	<1
DLN	18–19	<1	<1	<1	<1	<10	<1	<1	<1
Minimum laboratory reporting level		**0.5**	**0.5**	**0.5**	**0.5**	**5**	**0.5**	**0.5**	**0.5**
DSU	0–2	<0.5	<0.5	<0.5	<0.5	<5	<0.5	<0.5	<0.5
DSL	0–2	<0.5	<0.5	<0.5	<0.5	<5	<0.5	<0.5	<0.5
DBU	0–2	<0.5	<0.5	<0.5	<0.5	<5	<0.5	<0.5	<0.5
DBL	0–2	<0.5	<0.5	<0.5	<0.5	<5	<0.5	<0.5	<0.5
DTU	0–2	<0.5	<0.5	<0.5	<0.5	<5	<0.5	<0.5	<0.5
DTL	0–2	<0.5	<0.5	<0.5	<0.5	<5	<0.5	<0.5	<0.5

Table A1. Concentration of pesticides and polychlorinated biphenyls in seven bottom-sediment core samples from Dillon Reservoir, 1997—Continued

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	DDE	DDD	DDT	Methoxychlor	Mirex	Toxaphene	PCB Aroclor 1242	PCB Aroclor 1254	PCB Aroclor 1260
Minimum laboratory reporting level		**1**	**1**	**1**	**4**	**1**	**100**	**10**	**10**	**10**
DLN	0–2	<1	<1	<1	<4	<1	<100	<10	<10	<10
DLN	2–4	<1	<1	<1	<4	<1	<100	<10	<10	<10
DLN	4–6	1.2	E1.9	<1	<4	<1	<100	<10	<10	<10
DLN	6–8	<1	<1	<1	<4	<1	<100	<10	<10	<10
DLN	8–10	<1	<1	<1	<4	<1	<100	<10	<10	<10
DLN	10–12	<1	<1	<1	<4	<1	<100	<10	<10	<10
DLN	12–14	<1	<1	<1	<4	<1	<100	<10	<10	<10
DLN	14–16	1.1	E1.7	<1	<4	<1	<100	<10	<10	<10
DLN	16–18	1.2	E1.9	<1	<4	<1	<100	<10	<10	<10
DLN	18–19	1.4	E2	<1	<4	<1	<100	<10	<10	<10
Minimum laboratory reporting level		**0.5**	**0.5**	**0.5**	**2**	**0.5**	**50**	**5**	**5**	**5**
DSU	0–2	<0.5	<0.5	<0.5	<2	<0.5	<50	<5	<5	<5
DSL	0–2	<0.5	<0.5	<0.5	<2	<0.5	<50	<5	<5	<5
DBU	0–2	<0.5	<0.5	<0.5	<2	<0.5	<50	<5	<5	<5
DBL	0–2	<0.5	<0.5	<0.5	<2	<0.5	<50	<5	<5	<5
DTU	0–2	<0.5	<0.5	<0.5	<2	<0.5	<50	<5	<5	<5
DTL	0–2	<0.5	<0.5	<0.5	<2	<0.5	<50	<5	<5	<5

Table A2. Concentration of polycyclic aromatic hydrocarbons in seven bottom-sediment core samples from Dillon Reservoir, 1997

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	Naphtha-lene	C1–128 isomers	2-ethylnaph-thalene	2,6-dimethyl-naphthalene	1,6-dimethyl-naphthalene	C2–128 isomers	Acenaph-thylene	1,2-dimethyl-naphthalene	Acenaph-thene	C3–128 isomers	2,3,6-trimethyl-naphthalene
Minimum laboratory reporting level		10	10	10	10	10	10	10	10	10	10	10
DLN	0–2	E4.5	19.6	<10	32.6	E3.8	57.8	E3.8	<10	<10	33	<10
DLN	2–4	E6.5	32.5	E1.8	154	13.5	204	E5.1	<10	E1.5	78.1	E3.6
DLN	4–6	E5.1	37.2	<10	138	11.4	200	E3.4	E4.3	<10	57.5	E2.7
DLN	6–8	E5.4	20	<10	350	24.8	427	<10	<10	<10	66.8	E5.6
DLN	8–10	E5.1	19.8	<10	220	16	279	E4.7	<10	<10	40.6	E5.3
DLN	10–12	E5.8	29	<10	338	24.7	414	E5.3	E3.3	<10	65.4	E6.2
DLN	12–14	E5.2	30.2	<10	178	15.7	232	E5.0	E0.92	<10	52.7	E4.8
DLN	14–16	E4.4	40.5	E1.8	116	11.1	156	E3.3	<10	<10	48.8	E2.8
DLN	16–18	E3.8	32.9	E1.4	123	10.4	163	E3.3	88.2	E1.1	64.6	E3.3
DLN	18–19	E4.3	36.2	E1.1	106	E9.5	156	<10	<10	<10	82.6	E3.2
Minimum laboratory reporting level		5	5	5	5	5	5	5	5	5	5	5
DBL	0–2	E2.8	10.6	<5	25.4	E5.0	50.1	7.1	<5	<5	23.6	E2.3
DBU	0–2	<5	11.5	<5	29.7	5.4	52.8	5.2	E0.48	<5	29.8	E1.9
DTL	0–2	E3.5	11.4	E0.74	15.6	E3.2	44	6.3	<5	E0.84	21.3	E1.8
DTU	0–2	E4.4	15.2	E0.94	27.8	5.1	52.8	5.2	E1.1	E0.95	30.8	E2.4
DSL	0–2	E3.7	13.9	<5	30.9	E3.9	52.4	5.8	<5	E0.62	17.3	E2.3
DSU	0–2	E4.0	16.4	E1.3	35.9	E3.6	61.1	6.5	E0.50	<5	24.2	E2.6

Table A2. Concentration of polycyclic aromatic hydrocarbons in seven bottom-sediment core samples from Dillon Reservoir, 1997—Continued

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	9H-Fluorene	C4–128 isomers	1-methyl-9H-Fluorene	Phenan-threne	Anthra-cene	C5–128 isomers	2-methyl-anthracene	4,5-methylene-phenanthrene	C1–178 isomers	1-methyl-phenanthrene	C2–178 isomers	Fluoran-thene
Minimum laboratory reporting level		10	10	10	10	10	Varied	10	10	10	10	10	10
DLN	0–2	E2.6	<10	<10	33.3	E4.6	<10	<10	E4.3	36.7	10.5	25.5	47.4
DLN	2–4	E3.8	<10	<10	60.5	12.1	<30	<10	E7.5	147	27	66.6	75
DLN	4–6	E2.8	<10	E2.6	40.5	E6.7	<10	<10	E5.0	71	26.9	43.9	46.4
DLN	6–8	E4.1	<10	E6.5	39.2	10.9	<40	E8.6	E5.6	53.6	E7.4	62.6	48.4
DLN	8–10	E3.8	<10	E5.8	39.6	11.1	<20	E7.9	E5.8	54.8	E6.5	58.1	44.1
DLN	10–12	E3.9	<10	E6.0	32.8	E9.2	<50	E7.6	E4.9	51.5	E6.4	66.8	32.5
DLN	12–14	E3.3	<10	5.1	26.9	E7.6	<40	E6.2	E3.8	47.5	E7.1	55.2	24.3
DLN	14–16	E2.6	<10	E4.1	20.5	E3.9	<20	<10	E3.8	43.5	E9.6	43.6	15.5
DLN	16–18	<10	14.7	E3.2	19.4	E3.0	23.8	<10	E3.9	40.9	10.3	41.6	15.8
DLN	18–19	E2.0	30.9	E3.0	17.4	E2.8	21.8	<10	E3.7	45.5	11.1	46.3	10.3
Minimum laboratory reporting level		5	5	5	5	5	5	5	5	5	5	5	5
DBL	0–2	E2.1	<5	E2.6	30.6	5.2	<5	E3.6	E3.5	52.1	5.6	52.1	38.1
DBU	0–2	E1.9	9.2	E2.3	19.9	E4.5	<5	E3.1	E3.1	33.9	10.1	37.7	29.5
DTL	0–2	E2.6	<5	E2.6	29.9	6.2	<20	E3.6	E4.5	37.9	E4.7	39	50.8
DTU	0–2	E3.8	<5	E4.2	30.1	7.1	<5	E3.8	5.4	97.4	6.2	50	53.7
DSL	0–2	E2.6	<5	E2.5	29.3	E4.9	E4.0	E3.4	E3.9	36.9	9.9	35.3	44.9
DSU	0–2	E2.6	9.7	<5	28.5	7.6	<5	E4.1	E4.2	22.6	5.7	38	47.4

Table A2. Concentration of polycyclic aromatic hydrocarbons in seven bottom-sediment core samples from Dillon Reservoir, 1997—Continued

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	Pyrene	C3–178 isomers	C4–178 isomers	1-methyl-pyrene	C1–202 isomers	C2–202 isomers	C5–178 isomers	Benz(a) anthracene	Chry-sene	C3–202 isomers	C1–228 isomers	C4–202 isomers	C5–202 isomers	C2–228 isomers
Minimum Laboratory Reporting Level		10	10	10	10	10	10	10	10	10	10	10	10	10	10
DLN	0–2	43.8	15.7	<10	E3.0	28	38.8	<10	13.5	35.8	11.5	15.2	E7.4	<10	8
DLN	2–4	64.7	25.1	E8.1	E4.2	48.5	67.3	<10	23	56.1	29.9	32.3	16.2	<10	18.3
DLN	4–6	39.5	18.8	E5.3	E3.0	30.4	44.1	<10	13.6	35.7	19.3	17	10.2	<10	17.7
DLN	6–8	39.9	33.6	10.7	E7.3	41.4	50.1	<10	E19.2	39.3	<10	37.8	<10	E7.8	24.6
DLN	8–10	36.3	17.1	E9.3	E7.7	36.9	37.5	<10	E16.9	34.9	E8.5	31.1	<10	<10	18.9
DLN	10–12	29	44.5	10.4	E7.3	40.6	43.2	<10	E14.6	36.4	E8.3	34.4	<10	E8.4	22
DLN	12–14	23.3	33.9	E8.4	E6.3	32.2	35.7	<10	E12.1	28.4	E6.3	30.8	<10	<10	23.2
DLN	14–16	14.9	21.2	E6.2	E2.3	21.8	26.1	<10	E4.5	19.3	16.1	15.4	<10	<10	14.3
DLN	16–18	15.5	22.2	E6.5	E1.8	20.2	33.9	<10	E6.2	20.2	16.8	17.8	<10	<10	15.3
DLN	18–19	11.6	24.9	E7.6	E2.3	19.6	27.1	<10	E3.4	17.1	13.5	14.1	E7.8	E2.7	12.3
Minimum laboratory reporting level		5	5	5	5	5	5	5	5	5	5	5	5	5	5
DBL	0–2	33.2	30.2	6.4	E4.3	30.7	32.5	<5	E14.9	32.8	16.2	21.9	19.3	5.6	16
DBU	0–2	25.9	25.3	7.1	E3.8	27.4	27.5	<5	E12.7	23.6	10.6	21.7	11.5	6.8	16
DTL	0–2	42.9	33.4	8	E4.0	31.4	22.5	<5	E18.6	34	13.3	19.9	12.6	7.2	10.9
DTU	0–2	47.7	34.4	10.7	E4.5	39.1	33.9	<5	E22.3	37.2	E4.0	24.5	14.2	9.5	15.4
DSL	0–2	38.4	8.9	10.2	E4.0	22.1	22.7	<5	E16.1	31.2	12.3	18.5	12.1	<5	11.6
DSU	0–2	42.1	15.1	15.5	E4.6	38.8	28	<5	E21.3	36.8	14	32.6	11.6	<5	19.6

Table A2. Concentration of polycyclic aromatic hydrocarbons in seven bottom-sediment core samples from Dillon Reservoir, 1997—Continued

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	Benzo(b) fluoranthene	Benzo(k) fluoranthene	Benzo(e) pyrene	Benzo(a) pyrene	Perylene	C1–252 isomers	C3–228 isomers	C2–252 isomers	C4–228 isomers	Benzo(g,h,i) perylene
Minimum laboratory reporting level		**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**
DLN	0–2	22.3	19.4	19.4	17.5	15.9	12.9	<10	E5.5	<10	21.4
DLN	2–4	39	33.1	31.7	28.6	29.3	E8.4	<100	<10	<10	18.4
DLN	4–6	24.4	21.4	19	16.8	24.8	17.2	<50	<10	<10	11.6
DLN	6–8	33	22.6	16.4	20.7	52.6	18.8	<10	<10	<10	20.7
DLN	8–10	28.9	21.1	14.6	14.8	44.4	16.5	<10	<10	<10	15.3
DLN	10–12	27	17.4	14.3	12.3	83.9	14.4	<10	<10	<10	35
DLN	12–14	20	12.8	11.2	10.8	123	18.8	<10	11.5	<10	19.3
DLN	14–16	E9.4	E5.5	<10	E4.6	204	E9.5	19.4	<10	<10	E5.4
DLN	16–18	11.5	E7.9	E9.6	E6.3	254	13.5	10	E5.0	<10	E6.6
DLN	18–19	E9.2	E4.6	E8.4	E3.4	368	10.1	<10	E5.5	<10	E6.4
Minimum laboratory reporting level		**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
DBL	0–2	23.3	19.8	14.8	16.4	26.3	12.7	<5	6	<5	13.5
DBU	0–2	18	13.5	11.7	13.8	46.6	13.6	E3.0	8.2	<5	11.2
DTL	0–2	27.6	23.2	15.7	21	44.3	14.9	<5	6.7	<5	14.3
DTU	0–2	25.4	25.8	17.6	25.8	150	15.7	<5	<10	<5	16.2
DSL	0–2	23.2	18.8	13.8	16.5	47.9	10.9	<5	7.7	E2.8	14
DSU	0–2	28.1	23.9	19.5	24	120	24.6	<5	14.6	<5	18.1

Table A2. Concentration of polycyclic aromatic hydrocarbons in seven bottom-sediment core samples from Dillon Reservoir, 1997—Continued

[<, less than; E, estimated value; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm. All concentrations are in micrograms per kilogram. The minimum laboratory reporting level is determined in part by the amount of material available for analysis; less material was analyzed from the core gathered near the dam (DLN)]

Core identifier	Depth (centimeters)	Indeno(1,2,3-c,d) pyrene	Dibenzo(a,h) anthracene	C3–252 isomers	C4–252 isomers	C5–228 isomers	C5–252 isomers	Coronene
Minimum laboratory reporting level		10	10	10	10	10	10	10
DLN	0–2	19.1	E3.9	<10	<10	<10	<10	E4.4
DLN	2–4	21.2	E6.3	<10	<10	39.1	<10	E4.4
DLN	4–6	13.7	E3.4	<10	<10	<10	<10	E2.0
DLN	6–8	40.4	E4.3	<10	<10	<10	<10	E12.0
DLN	8–10	31.1	<10	<10	<10	<10	<10	<10
DLN	10–12	42.7	E3.6	<10	<10	<10	<10	E12.4
DLN	12–14	24	<10	<10	<10	<10	<10	E9.0
DLN	14–16	E5.1	E1.7	<10	<10	<25	<10	E2.1
DLN	16–18	E6.4	E2.4	<10	<10	<10	<10	E2.4
DLN	18–19	E5.0	E1.7	<10	<10	<10	<10	E2.1
Minimum laboratory reporting level		5	5	5	5	5	5	5
DBL	0–2	22.1	E2.7	E2.1	<5	11.5	<5	E7.1
DBU	0–2	17.3	E2.6	<5	<5	<30	<5	E5.8
DTL	0–2	24	E3.3	<5	<5	<30	<5	E6.2
DTU	0–2	27	E3.8	<5	<5	<30	<5	E7.0
DSL	0–2	22.1	<5	<5	<5	8.8	<5	E6.9
DSU	0–2	28.6	4.5	<5	<5	<40	<5	<5

Table A3. Concentrations of selected major and trace elements in seven bottom-sediment core samples from Dillon Reservoir, 1997

[µg/g, micrograms per gram; <, less than; E, estimated value; --, not available; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm]

Core identifier	Depth (centimeters)	Silica (percent)	Aluminum (percent)	Calcium (percent)	Iron (percent)	Potassium (percent)	Magnesium (percent)	Sodium (percent)	Phosphorus (percent)	Titanium (percent)	Arsenic (µg/g)	Barium (µg/g)	Beryllium (µg/g)
Minimum laboratory reporting level			0.10	0.01	0.10	0.10	0.01	0.04				100	2.0
DLN	0–1	22.0	8.10	1.02	4.34	1.71	0.62	0.54	0.12	0.32	12.8	698	<2.0
DLN	1–2	24.6	8.60	0.94	3.98	1.95	0.56	0.79	0.12	0.33	13.2	678	<2.0
DLN	2–3	25.4	7.85	0.99	3.80	2.08	0.55	0.74	0.13	0.30	13.6	662	<2.0
DLN	3–4	25.7	8.05	1.07	4.06	1.47	0.86	0.78	0.12	0.30	15.4	695	<2.0
DLN	4–5	25.4	7.9	0.96	3.60	1.51	0.73	0.58	0.090	0.28	14.0	690	<2.0
DLN	5–6	26.4	8.53	1.22	4.20	1.62	0.94	0.79	0.098	0.37	17.6	672	<2.0
DLN	6–7	25.9	7.90	1.22	4.30	1.44	0.84	0.72	0.094	0.34	20.0	675	<2.0
DLN	7–8	30.4	7.55	1.19	4.28	1.39	0.84	0.72	0.090	0.31	19.0	659	<2.0
DLN	8–9	28.3	7.03	1.18	3.84	1.33	0.65	0.55	0.093	0.32	16.8	609	<2.0
DLN	9–10	27.2	6.45	1.10	3.78	1.27	0.68	0.50	0.093	0.35	17.2	613	<2.0
DLN	10–11	23.4	9.30	1.29	4.98	1.81	0.94	0.83	0.10	0.35	18.8	849	<2.0
DLN	11–12	24.1	10.18	1.05	4.96	1.89	0.86	0.78	0.13	0.39	12.8	849	<2.0
DLN	12–13	23.3	9.75	1.11	4.85	1.82	0.88	0.80	0.12	0.40	14.7	839	<2.0
DLN	13–14	27.9	9.50	1.17	4.70	1.71	0.92	0.83	0.12	0.41	19.6	828	<2.0
DLN	14–15	24.7	8.57	0.98	4.60	1.74	0.59	0.83	0.079	0.40	15.6	731	<2.0
DLN	15–16	26.2	9.13	1.06	4.50	1.89	0.86	0.83	0.092	0.44	15.4	750	<2.0
DLN	16–17	26.1	7.32	0.91	4.30	1.81	0.56	0.50	0.10	0.45	12.8	583	<2.0
DLN	17–18	28.3	8.89	1.01	5.44	2.12	0.76	0.70	0.12	0.44	17.2	645	<2.0
DLN	18–19	23.5	8.13	0.91	4.40	1.84	0.53	0.80	0.10	0.43	15.5	746	<2.0
DBL	0–2	--	8.05	0.71	4.60	1.98	0.74	0.62	0.10	0.34	11.0	649	<4.0
DBL	2–4	--	8.07	0.64	4.43	2.14	0.73	0.61	0.11	0.35	13.4	624	<4.0
DBU	0–1	--	6.92	0.73	4.00	2.02	0.65	0.68	0.10	0.36	10.0	515	<4.0
DBU	1–2	--	7.30	0.74	4.08	2.06	0.68	0.71	0.13	0.37	9.6	555	<4.0
DBU	2–3	--	9.06	0.80	4.48	2.10	0.90	0.72	0.12	0.41	11.9	741	<4.0
DSL	0–2	--	6.19	0.72	5.02	1.72	0.45	0.59	0.12	0.34	15.4	558	<4.0
DSL	2–4	--	7.93	0.67	5.14	1.88	0.62	0.59	0.10	0.33	13.7	733	<4.0
DSU	0–2	--	7.58	0.80	6.11	1.38	0.68	0.65	0.12	0.35	11.2	884	<4.0
DSU	2–4	--	8.54	0.84	6.36	1.61	0.76	0.72	0.12	0.37	14.9	881	<4.0
DTL	0–2	--	8.02	0.84	5.64	1.72	0.85	0.72	0.12	0.37	12.4	714	<4.0
DTL	2–4	--	7.83	0.81	5.21	1.81	0.81	0.75	0.12	0.37	12.7	640	<4.0
DTU	0–2	--	7.51	0.76	5.84	1.96	0.86	0.94	0.11	0.38	16.5	599	<4.0
DTU	2–4	--	7.62	0.76	5.62	2.12	0.89	0.99	0.099	0.37	20.7	633	<4.0

Table A3. Concentration of selected major and trace elements in seven bottom-sediment core samples from Dillon Reservoir, 1997—Continued

[μg/g, micrograms per gram; <, less than; E, estimated value; --, not available; DLN, Dillon Reservoir near the dam; DSU and DSL, upper and lower part of the Snake River arm; DBU and DBL, upper and lower part of Blue River arm; DTU and DTL, upper and lower part of Tenmile Creek arm]

Core Indentifier	Depth (centimeters)	Cadmium (μg/g)	Cobalt (μg/g)	Chromium (μg/g)	Copper (μg/g)	Lithium (μg/g)	Manganese (μg/g)	Nickel (μg/g)	Lead (μg/g)	Scandium (μg/g)	Strontium (μg/g)	Vanadium (μg/g)	Zinc (μg/g)	Mercury (μg/g)
Minimum laboratory reporting level		0.04	2.0	2.0	2.0	10	100	2.0	100	2.0	20	2.0	2.0	0.04
DLN	0–1	1.02	28.6	53	97.5	40.4	9,660	38.3	227	7.6	101	114	3,370	0.21
DLN	1–2	1.07	30.0	74	101	41.4	4,090	36.8	238	6.7	80	132	3,120	0.22
DLN	2–3	1.06	29.7	75	101	39.4	3,720	37.4	232	7.8	82	125	3,150	0.20
DLN	3–4	1.06	34.9	80	112	42.4	3,370	40.7	181	12.1	247	135	4,260	0.14
DLN	4–5	1.09	30.8	88	82.6	39.5	3,300	37.2	148	6.4	216	119	3,480	0.11
DLN	5–6	1.09	27.4	80	117	46.0	3,500	42.6	187	16.4	267	147	3,890	0.17
DLN	6–7	1.07	28.9	56	113	43.9	5,130	40.7	165	15.1	236	127	4,020	0.17
DLN	7–8	1.06	29.4	64	104	39.4	5,890	39.1	155	13.4	233	106	4,050	0.16
DLN	8–9	1.04	26.9	68	119	39.8	4,330	39.6	167	12.5	200	132	4,380	0.18
DLN	9–10	1.02	33.4	78	134	38.4	3,520	45.5	169	11.1	217	137	4,420	0.18
DLN	10–11	0.98	76.3	61	160	46.2	12,760	59.8	214	17.1	254	145	6,200	0.18
DLN	11–12	0.98	57.4	78	224	50.9	6,430	57.1	280	18.1	292	160	6,520	0.28
DLN	12–13	0.99	54.5	80	200	50.1	5,690	55.2	290	16.9	263	159	6,320	0.29
DLN	13–14	1.01	49.7	72	175	49.7	3,870	51.8	237	15.8	240	157	5,200	0.15
DLN	14–15	1.03	31.2	82	112	43.3	3,670	48.0	158	16.0	186	141	2,780	0.075
DLN	15–16	1.02	30.3	91	118	47.4	4,030	48.4	180	16.3	219	185	3,320	0.081
DLN	16–17	0.98	30.8	89	132	48.8	5,460	52.1	146	11.4	154	191	3,770	0.077
DLN	17–18	0.96	34.1	62	124	52.4	8,970	55.2	165	15.2	177	181	4,140	0.057
DLN	18–19	0.95	35.0	92	140	46.5	8,690	50.0	269	15.4	137	166	4,250	0.082
DBL	0–2	5.6	19.4	70	63.1	38.8	8,760	35.8	219	10.9	157	110	1,960	--
DBL	2–4	5.7	17.9	66	66.5	38.2	3,730	36.2	265	10.0	157	124	1,850	--
DBU	0–1	5.8	14.0	70	58.1	35.3	1,310	30.6	220	10.6	157	107	1,870	--
DBU	1–2	4.6	14.6	86	59.6	36.8	980	32.0	218	15.0	160	114	2,000	--
DBU	2–3	5.0	18.8	89	70.6	40.0	1,000	36.4	237	19.3	197	126	2,100	--
DSL	0–2	4.8	27.1	75	113	41.2	7,160	38.9	390	12.7	101	122	3,170	--
DSL	2–4	5.1	28.5	69	112	41.4	4,540	40.9	331	17.3	136	122	3,150	--
DSU	0–2	5.0	21.8	69	128	30.6	1,990	37.5	516	18.5	186	91.7	2,870	--
DSU	2–4	3.6	20.1	66	140	33.8	1,290	38.8	510	19.0	187	105	2,860	--
DTL	0–2	4.6	21.8	90	75.4	41.0	5,520	36.9	231	16.1	148	100	2,610	--
DTL	2–4	3.3	22.4	84	77.7	40.8	3,070	38.8	232	16.0	141	98.8	2,640	--
DTU	0–2	4.8	16.8	88	74.9	41.6	751	35.6	413	14.5	139	72.9	2,280	--
DTU	2–4	4.4	15.6	94	70.9	42.0	636	34.4	468	19.0	138	70.5	2,330	--