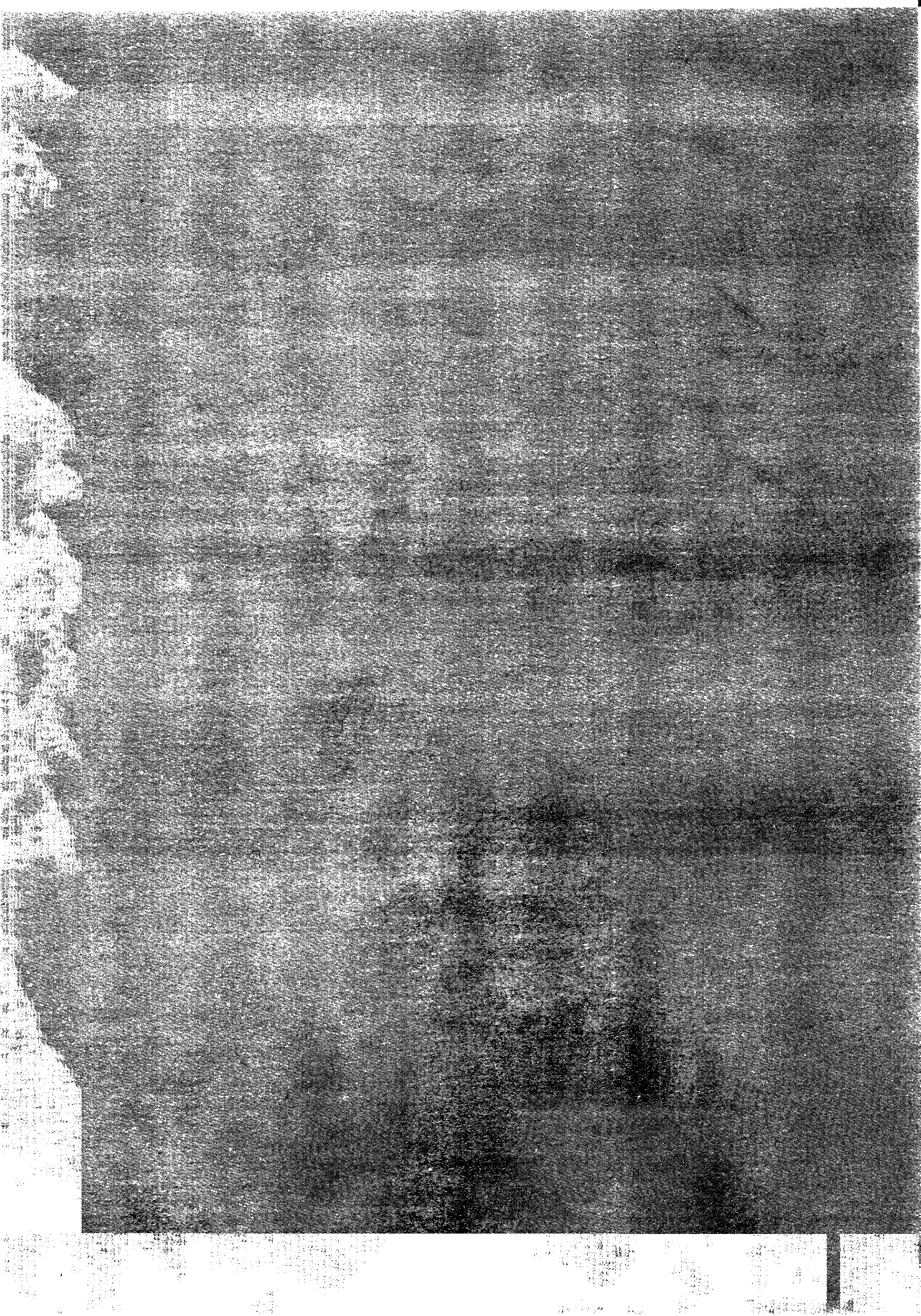
Streamflow Transport of Radio-nuclides and Other Chemical Constituents in the Puerco and the Little Colorado River Basins, Arizona and New Mexico



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Prepared in cooperation with the Office of Navajo and Hopi Indian Relocation, the Bureau of Indian Affairs, the Arizona Department of Environmental Quality, the Arizona Department of Water Resources, The Navajo Nation, and the New Mexico Environment Department

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Streamflow Transport of Radionuclides and Other Chemical Constituents in the Puerco and the Little Colorado River Basins, Arizona and New Mexico

By JULIA B. GRAF, LAURIE WIRT, EDWIN K. SWANSON, GREGORY G. FISK, and JOHN R. GRAY

Prepared in cooperation with the Office of Navajo and Hopi Indian Relocation, the Bureau of Indian Affairs, the Arizona Department of Environmental Quality, the Arizona Department of Water Resources, the Navajo Nation, and the New Mexico Environment Department

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
millimeter (mm)	25.4	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square meter (m^2)	2.471×10^{-4}	acre
square kilometer (km^2)	0.3861	square mile
cubic meter per second (m^3/s)	35.31	cubic foot per second
gram (g)	0.002205	pound
kilogram (kg)	2.205	pound
megagram (Mg)	1.102	ton, short

In this report, temperatures are reported in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8\,(°C) + 32$$

VERTICAL DATUM

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

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (μg/L). Milligrams per liter is a unit expressing the solute mass per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 mg/L. For concentrations less than 7,000 mg/L, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter (μS/cm) at 25°C. Radioactivity is expressed in picocuries per liter (pCi/L) or picocuries per gram (pCi/g), which is the amount of radioactive decay that would produce 2.2 disintegrations per minute in a unit volume (liter) of water or unit mass (gram) of sediment, respectively. Chemical concentration in material from core samples is given in grams per kilogram (g/kg) or micrograms per gram (μg/g). Micrograms per gram is equivalent to parts per million.

Streamflow Transport of Radionuclides and Other Chemical Constituents in the Puerco and the Little Colorado River Basins, Arizona and New Mexico

By Julia B. Graf, Laurie Wirt, Edwin K. Swanson, Gregory G. Fisk, *and* John R. Gray

Abstract

Samples of water and sediment were collected from 1988 to 1991 at nine streamflow-gaging stations in the Little Colorado River Basin to determine the occurrence and transport of selected radionuclides and other chemical constituents. More than two decades of uranium mining and a single spill of uranium-mine tailings due to the failure of a tailings-pond dike released high levels of radionuclides and other chemical constituents to the Puerco River, a tributary of the Little Colorado River. The releases caused public concern that streams downstream from mining areas were contaminated. Concentration and radioactivity of selected radionuclides and other chemical constituents were compared with applicable water-quality standards, and quality of streamflow was found to depend primarily on the concentration of suspended sediment. Typically, streamflow samples met drinking-water standards for the dissolved fraction, but unfiltered samples exceeded the drinking-water standards for a large suite of constituents. The combination of high suspended-sediment concentration, large particle-surface area, and the abundance of clay-sized particles with high cation-exchange capacity provides nearly optimal conditions for transport of radionuclides and other chemical constituents on sediment in streams in the study area. More than 99 percent (by mass) of analyzed constituents in a given sample were transported on suspended sediment.

Radioactivity of suspended sediment collected during the study period is related to location in the basin rather than to proximity of the sampling site to past uranium mining. Suspended-sediment radioactivity from uranium–238, uranium–234, radium–226, thorium–230, and thorium–232 was higher at sample sites on the Puerco and Zuni Rivers and Black Creek, which drain the northeastern part of the Little Colorado River Basin, than on the Little Colorado River. Suspended-sediment radioactivity for those isotopes was about 1.3 to 2.1 picocuries per gram for samples from those three streams and about 0.9 to 1.5 picocuries per gram for samples from the Little Colorado River. Radioactivity of suspended sediment measured in this study, therefore, probably represents natural conditions for the sampled streams rather than an effect of mining. During the study period, radionuclide load increased downstream because suspended-sediment load increased downstream. For water year 1991, suspended-sediment load was estimated to be 0.31×10^6 megagrams on the Puerco River near Church Rock, New Mexico, and 6.6×10^6 megagrams on the Little Colorado River near Cameron, Arizona. Radioactivity load from uranium was estimated to be 0.83 and 14 curies at the two streamflow-gaging stations, respectively. Radioactivity of sediment and water transported downstream from the mines by the Puerco River has decreased significantly since the cessation of mining. Comparison of chemical analyses of samples collected during the present study with analyses of samples of mine-dewatering effluent

collected during mining indicates that the uranium load of the Puerco River near Church Rock in 1991 was about 4 percent of that during an average year of mine dewatering.

INTRODUCTION

The Colorado Plateau region has substantial amounts of naturally occurring radioactivity in rock, sediment, and water. In addition, more than two decades of uranium mining and the failure of a uranium tailings-pond dike released high levels of radionuclides and other chemical constituents to the headwaters of the Puerco River, a major tributary of the Little Colorado River. The tailings-pond dike failure in 1979 resulted in a spill that raised public concern that the Puerco River was contaminated with radionuclides that posed a possible health risk to local residents. Concern was heightened by a projected population growth near the Puerco River in Arizona, which was a result of the planned relocation of the Navajo Indians into the study area (Office of Navajo and Hopi Indian Relocation, 1990). This report focuses on the transport of selected radionuclides and other chemical constituents in the Little Colorado River Basin of the Colorado Plateau (fig. 1) and the relation of those radionuclides and chemical constituents to uranium mining.

Although radionuclides, such as uranium (U), radium (Ra), and thorium (Th), are common in the Colorado Plateau region, these elements vary in concentration because of natural processes and can be redistributed by human activities. About 65 percent of all the U produced in the United States through 1982 was mined in the Colorado Plateau and more than 40 percent of that production was from northwestern New Mexico (Chenoweth and McLemore, 1989). Beginning in 1960, U was mined near Pipeline Arroyo (Perkins and Goad, 1980), a small tributary to the Puerco River about 35 km northeast of Gallup, New Mexico (fig. 1). The area is known locally as the Church Rock Mining District.

Because ore bodies in the Church Rock Mining District were mined below the water table, water seeping into shafts was pumped to prevent flooding. The dewatering effluent had higher concentrations of dissolved U, molybdenum (Mo), and selenium (Se) and higher gross-alpha radioactivity in the dissolved phase than in runoff (Gallaher and Cary, 1986; Van Metre and Gray, 1992). Before the mid-1970's, untreated effluent from dewatering operations discharged directly to Pipeline Arroyo (Gallaher and Cary, 1986). In the mid-1970's, measures were taken to improve the quality of dewatering effluent released to watercourses to comply with the Federal National Pollution Discharge Elimination System (NPDES). Treatment of effluent at each of the three mines near Pipeline Arroyo was implemented over several years during the mid-1970's. Treatment reduced concentrations of U and radioactivity of Ra by about 85 percent between 1975 and 1982. Milling of U ceased in 1985, and mine dewatering ceased in February 1986.

On July 16, 1979, a uranium mill tailings-pond dike near the United Nuclear Church Rock mill failed, resulting in the single largest release of uranium mill-tailings liquid in the history of the United States. An estimated 360,000 m^3 of water from uranium processing and 1,000 Mg of tailings were discharged to the Puerco River through Pipeline Arroyo (Weimer and others, 1981). Water and tailings from the spill flowed about 130 km downstream to a point near Navajo, Arizona, before the last water infiltrated the alluvium (Hussein Aldis, Ecology and Environment, Inc., written commun., 1979).

Findings of this investigation indicate that radioactivity from U, Ra, and Th—the principal radioactive constituents in streamflow in the study area—is primarily on the suspended sediment. The radioactivity of these elements on suspended sediment is related mainly to variations in geographical factors, such as distribution of the various rock types. No significant correlation was found between the radioactivity of suspended sediment from U, Ra, and Th and the occurrence of uranium mining upstream from the point where the sample was collected. This study was done by the U.S. Geological Survey (USGS) in cooperation with the Office of Navajo and Hopi Indian Relocation (ONHIR), the Bureau of Indian Affairs (BIA), the Arizona Department of Environmental Quality (ADEQ), the Arizona Department of Water Resources (ADWR), The Navajo Nation, and the New Mexico Environment Department (NMED).

Purpose and Scope

This report presents the results of the surface-water phase of a study designed to expand on previous water-quality investigations in the Little Colorado River Basin and to provide a detailed evaluation of water quality and hydrology in relation to possible

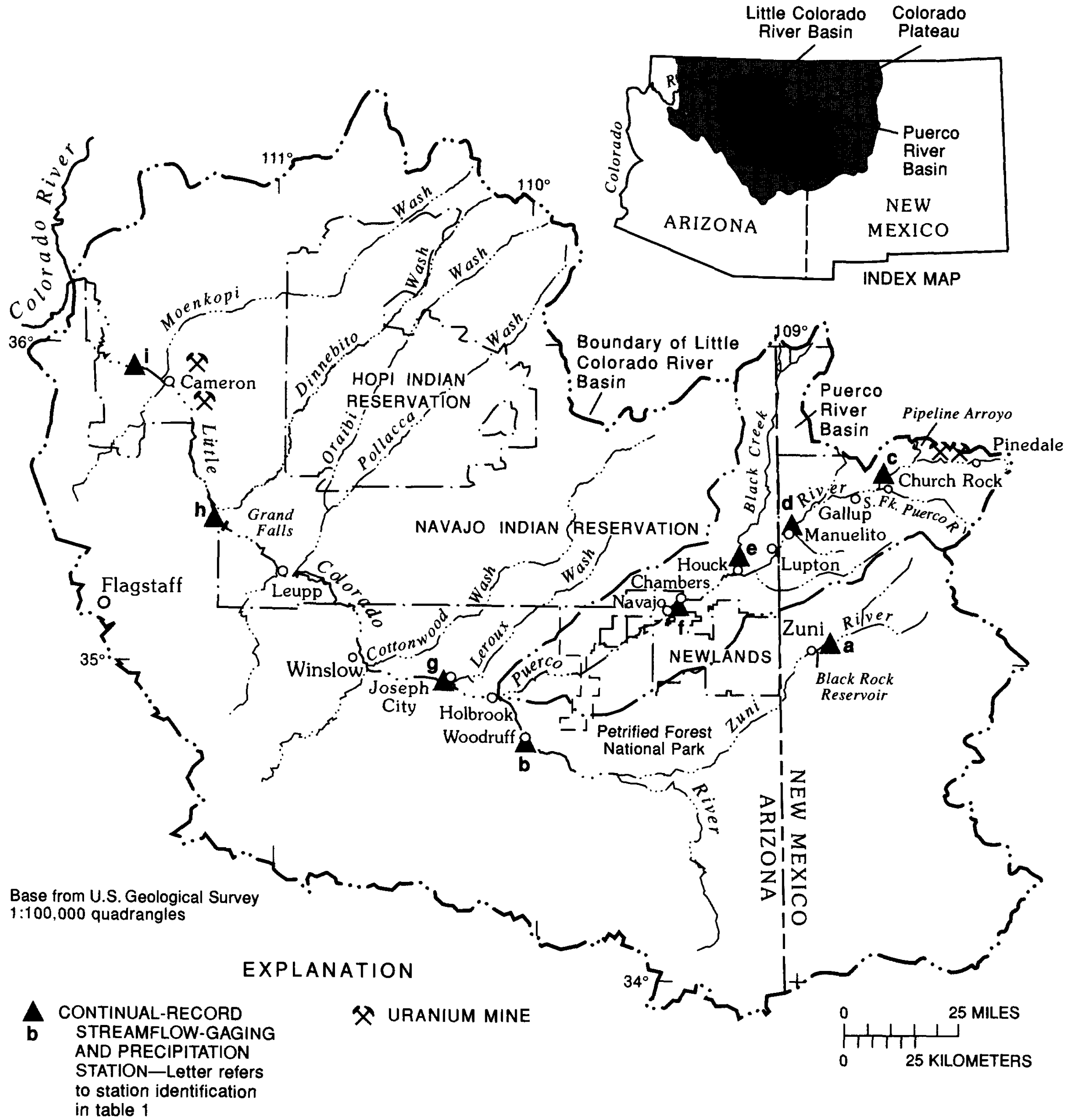

Figure 1. Study area in the Puerco and the Little Colorado River Basins, Arizona and New Mexico.

violations of water-quality standards resulting from uranium-mine releases. The objectives of the surface-water phase of the study were to determine (1) streamflow compliance with applicable water-quality standards at selected sites, (2) radioactivity and concentration of radionuclides and other chemical constituents in surface water and fluvial sediment, (3) distribution of these constituents in the Puerco River and in the Little Colorado River, and (4) the effects of mining on transport of radionuclides and other chemical constituents in streamflow. The streamflow-compliance evaluation for the study differs substantially from previous work because the present study is the only multiyear data-collection effort to date to evaluate suspended-sediment transport in periods of storm runoff. For the study, the USGS monitored the presence and movement of radionuclides, other chemical constituents, and suspended sediment in selected streams in the Little Colorado River Basin from July 1988 through September 1991 (fig. 1).

This report summarizes methods used for data collection and analysis and describes the presence of radionuclides and other chemical constituents in surface water and suspended sediment, the characteristics of streamflow and suspended-sediment transport, and the processes controlling the transport of radionuclides and other chemical constituents. Suspended-phase loads of radionuclides for the period of study are presented, and the role of mining in producing those loads is discussed. Methods of data collection are described in more detail by Gray and Fisk (1992) and by Fisk and others (1994). Fisk and others (1994) have compiled all data collected during the present study. The presence and movement of radionuclides in ground water and between surface water and ground water was studied by Peter Van Metre (hydrologist, U.S. Geological Survey, written commun., 1994). As a part of the study, historical data were compiled (Wirt and others, 1991) and interpreted (Gray and Webb, 1991; Van Metre and Gray, 1992).

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Bruce M. Gallaher and David Baker of the New Mexico Environment Department, Christopher Shuey of the Southwest Research and Information Center, and David Shaw-Serdar and Tim Varner of the Office of Navajo and Hopi Indian Relocation provided support and cooperation during the study. Loren Berge of the New Mexico Environment Department performed analyses of radionuclides in suspended sediment and well-core material. Kent A. Elrick, Mark R. Colberg, and Arthur J. Horowitz of the Sediment Partitioning Research Project of the U.S. Geological Survey in Atlanta, Georgia, analyzed trace-metal concentration and determined surface area for some samples. The Navajo Nation operated the streamflow-gaging station on Black Creek and provided the data. The Atchison Topeka and Santa Fe Railroad gave permission to attach equipment to their trestle at the streamflow-gaging station near Manuelito, New Mexico.

BACKGROUND

Basic Concepts of Radioactivity Applicable to This Study

Radionuclides of natural origin are derived largely from the radioactive decay of uranium and thorium. Uranium ores mined in the western United States typically contain little thorium–232 (^{232}Th; Haywood and others, 1977). Thus, the bulk of the radioactivity in the ore is associated with uranium–238 (^{238}U) and its daughter products (fig. 2).

Radionuclides undergo spontaneous transformations of their nuclei that cause the emission of alpha and beta particles and, to a lesser extent, gamma rays (Faure, 1977). The radioactivity of a radionuclide is a measure of the number of nuclear transformations in a given time. Gross-alpha activity and gross-beta activity are commonly used as indicators of alpha-emitting and beta-emitting radionuclides in water, respectively. The total radioactivity of a sample depends on the sum of the concentration of each radionuclide in the sample and its atomic weight and half-life (fig. 2). Concentration can be computed from the measured radioactivity by the relation,

$$C = k(WTD),$$

where

C = concentration, in milligrams per liter;
W = atomic weight;
T = half-life, in seconds;
D = radioactivity, in picocuries per liter; and
k = conversion constant that accounts for the number of atoms in a gram-molecular weight, the conversion from curies to picocuries, and the conversion from grams to micrograms.

In the absence of isotopic fractionation, each atom is transformed according to a series of reactions known as a radioactive-decay series (fig. 2). The flux, or activity, of atoms passing through each step in the series is the same. In this state, the isotopes are said to be in secular equilibrium. For example, if uranium–234 (^{234}U) is in secular equilibrium with its parent, ^{238}U, the activity ratio of ^{234}U to ^{238}U would be 1:1. The relations given above show that although different isotopes may be in secular equilibrium, concentrations will be different because atomic weights and half-lives are different. Isotopic disequilibrium—an activity ratio other than 1—implies that one or both isotopes have accumulated or become depleted by some physical or chemical process. Differences in activity ratios are used in this study to indicate the types of physical and chemical processes that are occurring.

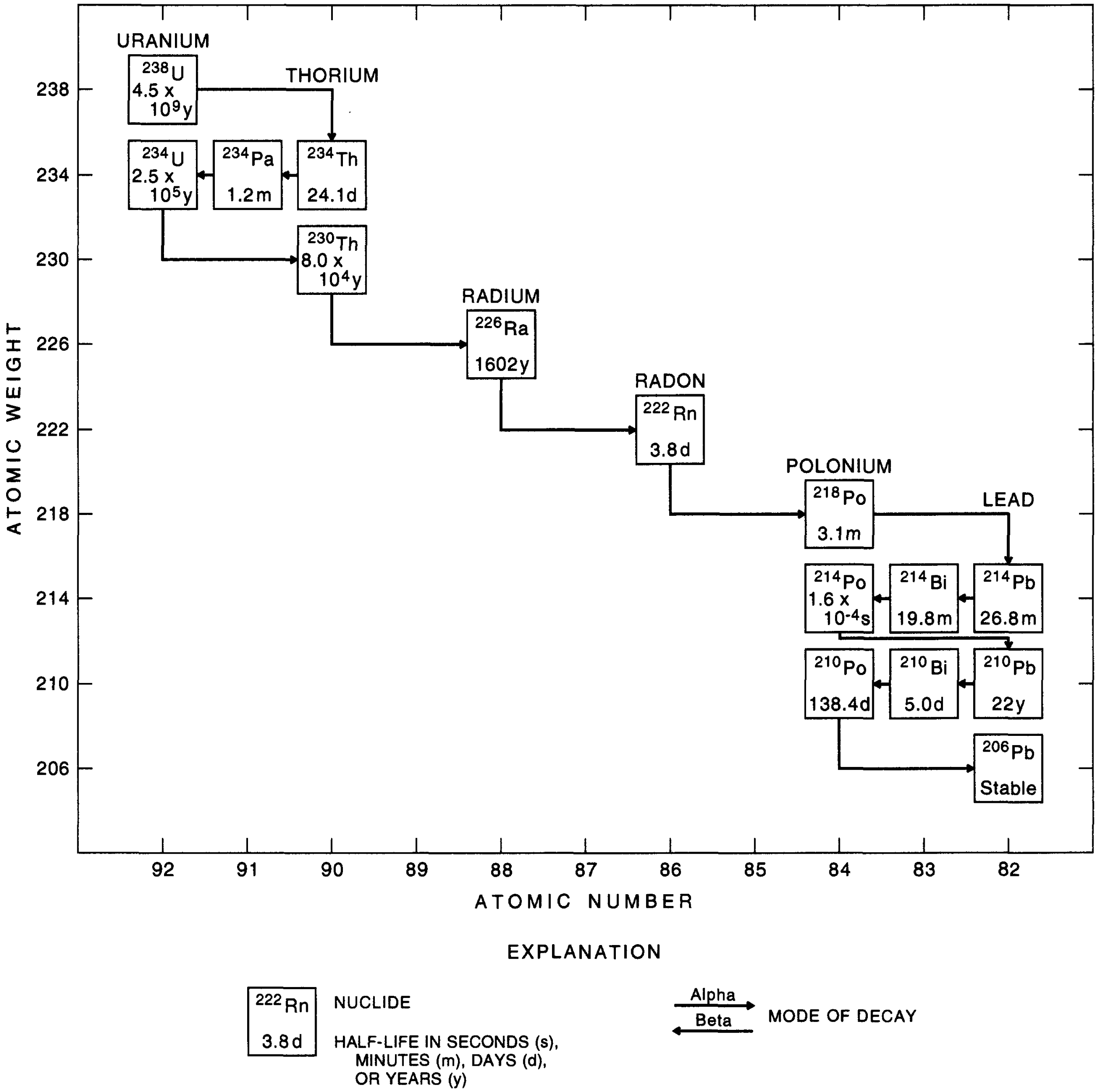

Figure 2. Radioactive-decay series of uranium–238.

Previous Investigations

From 1979 through 1985, several State and Federal agencies and the Southwest Research and Information Center (SRIC), a nonprofit public-information group, collected samples from streams in the Little Colorado River Basin for analysis in connection with mine dewatering and the tailings-pond spill on July 16, 1979. Samples of streamflow and of sediment from the channel bottom and banks and the flood-plain terraces were collected from the Puerco River upstream and downstream from the spill site, from the Little Colorado River downstream from the mouth of the Puerco River, and from the Colorado River downstream from the mouth of the Little Colorado River in Grand Canyon National Park. The USGS, in conjunction with the Arizona Department of Health Services (ADHS), Division of Environmental Health (the predecessor agency to ADEQ), operated water-quality monitoring sites on the Puerco River near Chambers for water years 1982–84 and on the

Little Colorado River near Cameron for water years 1980–82. Streamflow samples were collected at those sites whenever runoff occurred during a scheduled site visit by the USGS. Gross-alpha radioactivity measured in some samples at those sites during mine dewatering exceeded State of Arizona standards for any use by more than two orders of magnitude (Gray and Webb, 1991). A study by ADHS in 1985 consisted of sampling streamflow on three occasions in winter, spring, and summer when flow was relatively low—daily mean discharge was less than about 14 m^3/s (Arizona Department of Health Services, 1986). In 1987, SRIC collected discrete samples of runoff from a single storm (Shuey, 1992). Findings of these studies differ because of differences in flows sampled, sample locations, field and laboratory methods, and the timing and location of sampling related to the tailings-pond dike failure.

The results of the ADHS sampling, done during dewatering, suggested that unfiltered Puerco River water had higher concentrations of some trace elements and radionuclides than water from Black Creek (Arizona Department of Health Services, 1986). The lithology of the watershed of Black Creek is similar to that of the Puerco River, but no uranium mining is known to have occurred in the Black Creek watershed. The one sample collected from Black Creek had lower gross-alpha and thorium–230 (^{230}Th) radioactivity and lower concentrations of U, Mo, and Se than samples collected at the five sites on the Puerco River (Arizona Department of Health Services, 1986, table 5, p. 25–27). Water-quality standards were exceeded at the five sites. Standards for radium–226 (^{226}Ra) were exceeded in 73 percent of the ADHS samples. Concentrations of arsenic (As), copper (Cu), manganese (Mn), lead (Pb), and Se also exceeded water-quality standards of the State of Arizona. Concentrations of U and sulfate (SO_4) exceeded recommended drinking-water standards (Arizona Department of Health Services, 1986, tables 4–6).

Concentrations of all chemical constituents measured except Se were found to be closely associated with the amount of suspended sediment in the sample in the ADHS study. Gallaher and Cary (1986) also found a strong association of many constituents with the sediment concentration. They concluded that mine dewatering had a major effect on water quality in the Puerco River and that ^{226}Ra, lead–210 (^{210}Pb), U, Mo, and Se were the constituents that most frequently caused mining-related water-quality concerns in the Puerco River in New Mexico.

Conflicting results about the effects of mining operations on water quality (Western Technologies, Inc., 1985; Arizona Department of Health Services, 1986; Shuey, 1986) were the impetus for a reconnaissance-level study by the USGS of water quality in the alluvial aquifer, grasses, and surficial sediments in the Puerco River Basin (Webb and others, 1986; Webb and others, 1987). Webb and others (1986, 1987) determined that gross-alpha radioactivity in 5 of 14 wells was at or above the maximum contaminant level (MCL) for the State of Arizona (McClennan, 1986) and the U.S. Environmental Protection Agency (USEPA; U.S. Environmental Protection Agency, 1991c). Before the present study, natural levels of radionuclides and other chemical constituents in the Puerco and Little Colorado Rivers were undefined, and the effect of cessation of mine dewatering was unknown. Little information is available on the water quality, including radionuclides, before uranium mining began. Most historical water-chemistry data for radionuclides (Wirt and others, 1991) was collected after 1975.

Physical Setting

The Little Colorado River originates in the White Mountains of east-central Arizona and flows 573 km to the Colorado River (fig. 1). The river drains 68,529 km^2 upstream from the streamflow-gaging station near Cameron, which is 72 km upstream from the confluence with the Colorado River. The Puerco River, which is a major tributary to the Little Colorado River, heads in the uranium-mining area of northwestern New Mexico, drains 7,800 km^2, and joins the Little Colorado River at Holbrook. The confluence of the Puerco River and the Little Colorado River is about 288 km upstream from the confluence of the Little Colorado River and the Colorado River in Grand Canyon.

Much of the Little Colorado River Basin is sparsely vegetated plains interrupted in places by arroyos, deep canyons, and high volcanic mountains (U.S. Soil Conservation Service, 1981). Although rocks of Precambrian through recent ages are exposed in the basin, Mesozoic and Cenozoic rocks cover most of the basin area. The major types of sedimentary rocks of the south-central Colorado Plateau province, in decreasing order of abundance, are mudstone, siltstone, silty sandstone, limestone, and conglomerate (Cooley and others, 1969, p. 11). Bedrock formations have been deformed into a series of northwest- to southeast-trending folds (Cooley and others, 1969, figs. 6, 7), and bedrock structure influences the hydraulics of the Puerco River (Graf, 1990).

Uranium-ore bodies are present in rocks of Jurassic and Cretaceous age. Although ore bodies typically are subsurface, rocks containing high concentrations of U and other radioactive elements crop out in the Little Colorado River Basin. Erosion of surficial rocks that contain uranium-ore bodies can produce high levels of radioactivity in surface water and surficial sediments (Weimer and others, 1981, p. 41). In fact, one of the highest values of gross-alpha radioactivity measured in the present study was measured on a sample from the South Fork of the Puerco River, which is a basin in which uranium mining is not known to have occurred.

Many of the exposed rock formations are highly erodible because of fine grain size, thin bedding, and (or) poor cementing. Erosion rates estimated by the U.S. Soil Conservation Service (1981, appendix III, table 1-1) range from 180 to 820 Mg/km^2/yr in different drainage basins within the Little Colorado River Basin. Estimated rates in the Little Colorado River Basin were highest for the upper part of the Puerco River Basin, which is upstream from Houck (fig. 1). Erosion rates in the lower part of the Puerco River Basin are less than in the upper part but are above the average for the entire Little Colorado River Basin (U.S. Soil Conservation Service, 1981, appendix III, table 1-1).

The climate in the Little Colorado River Basin is arid in the lower elevations and semiarid to subhumid in the uplands. Annual precipitation for 1941–70 ranged from 200 mm or less in the lower elevations in much of the central part of the basin to more than 800 mm in the highest elevations along the south boundary of the basin (U.S. Soil Conservation Service, 1981). Most precipitation occurs in two periods—the late summer and early fall months and the winter and early spring months (fig. 3). Summer precipitation generally occurs during convective thunderstorms that produce locally intense rainfall that often results in runoff and flash flooding. Winter precipitation results from frontal systems that generally are more widespread and of lower intensity than summer convective storms. Winter precipitation typically produces less runoff than summer precipitation

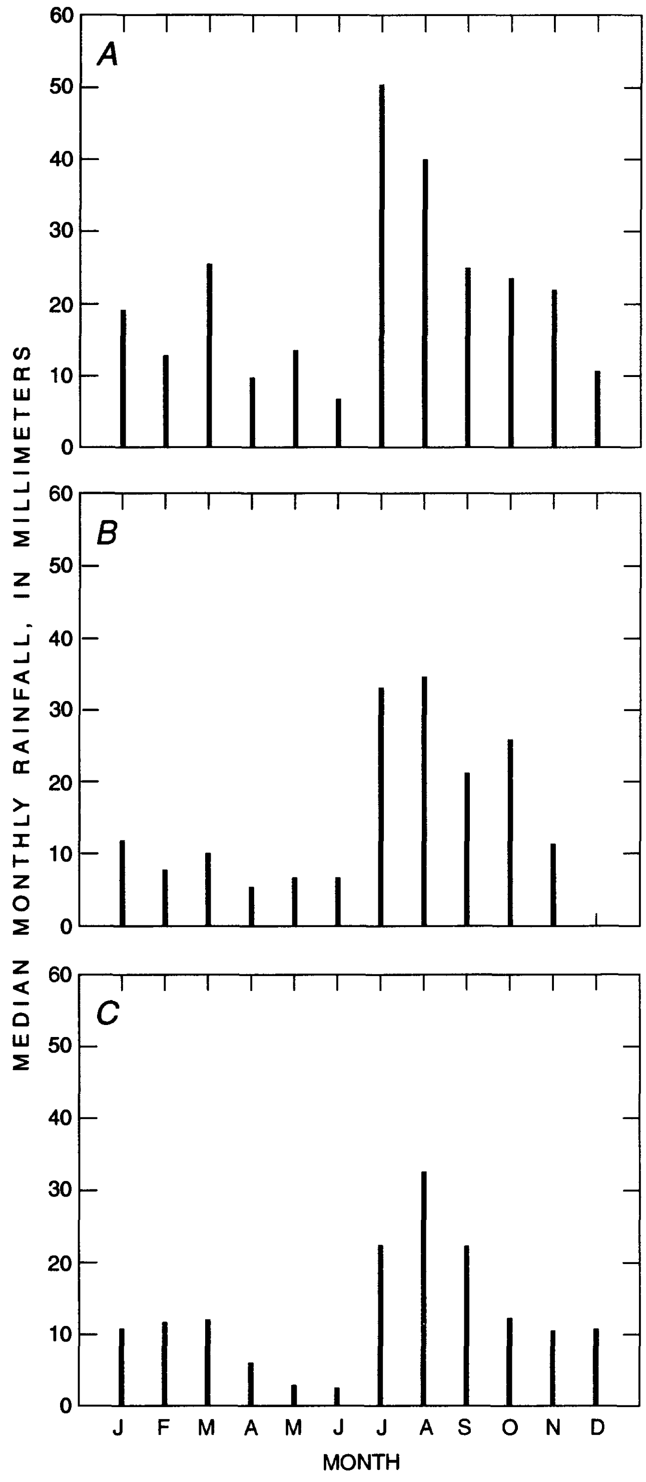

Figure 3. Median monthly rainfall for indicated period for three National Weather Service rainfall-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico. *A,* Gallup, New Mexico, at Gallup Municipal Airport, water years 1974–90; *B,* Gallup, water years 1949–80; *C,* Holbrook, Arizona, water years 1932–91. (Data from the National Oceanic and Atmospheric Administration, National Climatic Data Center.)

and probably contributes substantially to ground-water recharge (Cooley and others, 1969). The total annual rainfall generally ranges from about 100 to 400 mm in the Puerco River Basin (fig. 4).

The Little Colorado and the Puerco Rivers are ephemeral over most of their length, and the channels are dry for long periods. Flow in some reaches of the Puerco River changed from ephemeral to perennial in the early 1950's as a result of effluent discharged from uranium mines and from the sewage-treatment plant at Gallup (Perkins and Goad, 1980; Gallaher and Cary, 1986).

Vegetation type and density, like precipitation, vary with elevation. Great Basin desert scrub covers about 16 percent of the basin area at lower elevations along drainages. At intermediate elevations, plains and desert grassland cover 43 percent of the basin and juniper-pine woodlands cover 31 percent. Forest vegetation grows at the highest elevations, primarily near the margins of the basin. Vegetation density ranges from thick forests to nearly barren land (U.S. Soil Conservation Service, 1981, appendix I).

Erodible surficial material, intense rainstorms, and sparse vegetation combine to produce very high suspended-sediment concentrations during runoff in the Little Colorado River Basin. Analysis of samples collected during the study period indicated that suspended-sediment concentrations of more than 100,000 mg/L were typical during runoff in the Puerco River. Concentrations in the Little Colorado River near Cameron were slightly lower than those in the Puerco River but still commonly exceeded 100,000 mg/L. Estimated annual sediment yield from subbasins ranges from 150 to 660 Mg/km^2. Basins draining the forested highlands to the south of the Little Colorado River have lower yields, and basins draining semiarid plains to the north and east of the river have higher yields (U.S. Soil Conservation Service, 1981, appendix III). The Puerco River Basin and other Little Colorado River tributaries—the Dinnebito, the Leroux, the Moenkopi, the Polacca, and the Oraibi Washes (fig. 1)—all have mean annual sediment yields that exceed 400 Mg/km^2 (U.S. Soil Conservation Service, 1981, appendix III).

Radionuclides and some other chemical constituents have a strong tendency to sorb to fine-grained sediment under most natural surface-water conditions (Ames and Rai, 1978; Langmuir, 1978; Horowitz, 1985; Hsi and Langmuir, 1985; Horowitz and Elrick, 1987). The high percentage of silt- and clay-sized sediment with large particle surface area in the Puerco and Little Colorado Rivers yields a high potential for sorption of chemical constituents. Gross-alpha radioactivity of unfiltered samples of runoff from the Puerco River is two to three orders of magnitude higher than that of filtered water samples (Gallaher and Cary, 1986, p. 45–51; Gray and Webb, 1991).

Study of the recent alluvial history reveals that most Colorado Plateau streams have undergone three phases in the development of the present channel configuration—channel entrenchment and arroyo development beginning about 1880, channel aggradation by flood-plain building beginning in the early 1940's, and incision of flood plains beginning about 1980 (Hereford, 1987). Flood-plain building apparently was initiated by a sequence of years in the 1940's and 1950's that had lower annual discharge and lower frequency of floods than the previous period (Hereford, 1987). In some streams, flood-plain building came to an end about 1980 when the flood plain had built to a height at which it was no longer inundated by floods (Hereford, 1984, 1987; Graf and others, 1991). The Puerco River underwent an episode of channel entrenchment, although the major part of the entrenchment may have taken place later than that of the Little Colorado River (Leopold and Snyder, 1951; Hereford, 1984; Graf, 1990).

The present channels of the Little Colorado and Puerco Rivers are cut into older alluvium that fills valleys eroded in the Quaternary Period (Leopold and Snyder, 1951; Mann and Nemecek, 1983). The valley-fill material ranges in thickness from 0 to more than 45 m and in width from about 100 m to more than 6 km (Mann and Nemecek, 1983). Graf (1990) found that the most upstream 48 km of the Puerco River channel could be divided into segments characterized by thick alluvial-fill material separated by bedrock that constrains the channel laterally or vertically.

Miller and Wells (1986) identified areas that were short-term (less than 50 years) sediment-storage sites in the Puerco River channel from its headwaters to a short distance downstream from Gallup. Using repeated surveys of selected cross sections, scour chains, and analysis of historical photographs, Miller and Wells (1986) concluded that sediment is being deposited in the Puerco River channel downstream from the confluence with Pipeline Arroyo and that deposition increases downstream to near Gallup. If sediment containing contaminants derived from mining is stored in these short-term storage sites, that

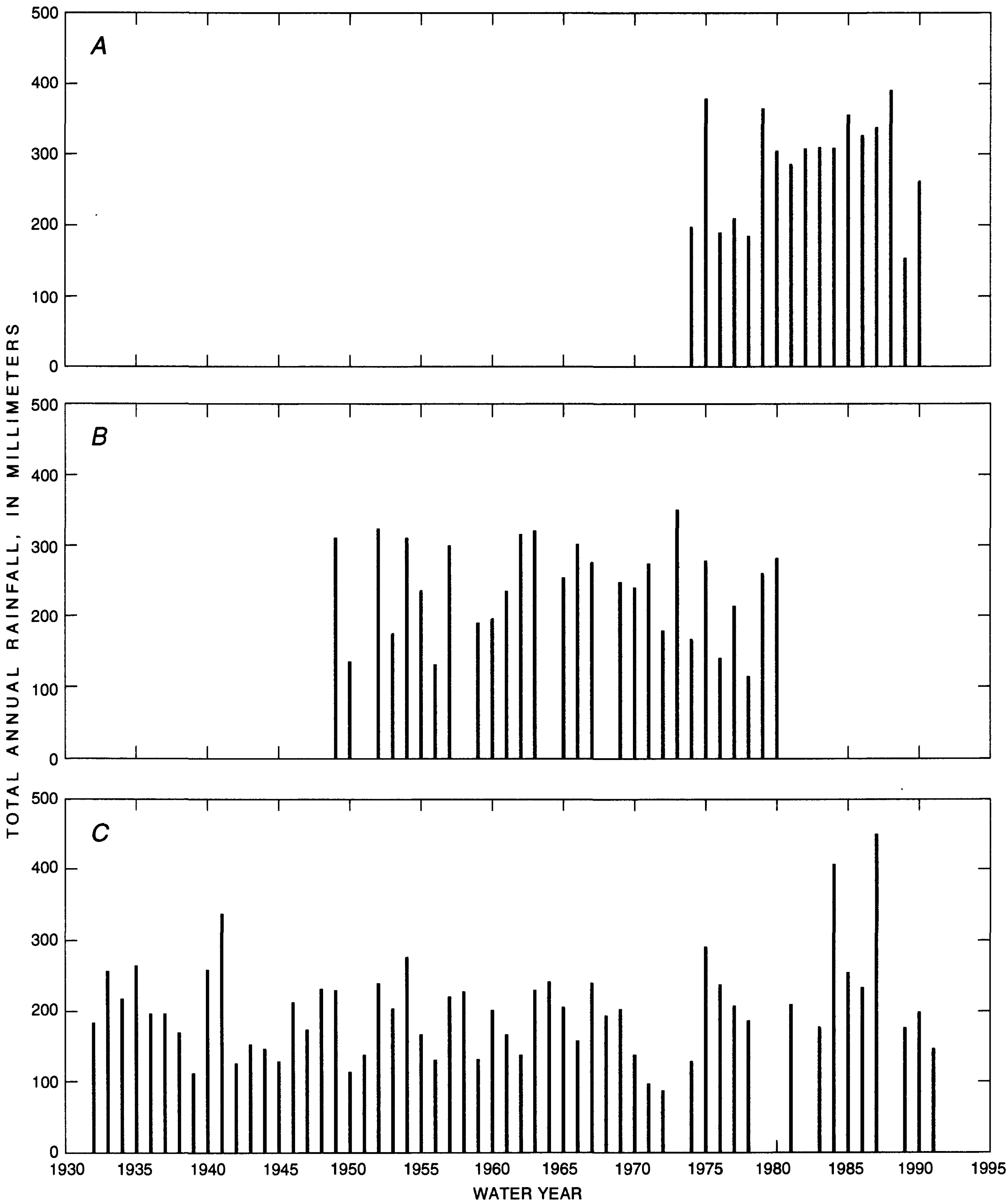

Figure 4. Total annual rainfall for the indicated period for three National Weather Service rainfall-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico. *A,* Gallup, New Mexico, at Gallup Municipal Airport, water year 1991 incomplete; *B,* Gallup, water years 1951, 1958, 1964, and 1968 incomplete; *C,* Holbrook, Arizona, water years 1973, 1979, 1980, 1982, and 1988 incomplete. (Data from the National Oceanic and Atmospheric Administration, National Climatic Data Center.)

sediment could be a source of radionuclides and other chemical constituents to streamflow.

APPROACH

Design of Sampling Network

Because of the importance of sediment in transporting radionuclides and other constituents of concern in the Puerco and Little Colorado Rivers, the sampling-site network was designed for collection of data for computation of suspended-sediment loads and loads of chemical constituents carried with the sediment. Because most sediment in the basin is transported during brief periods of runoff and sample sites are in remote locations, automatic water- and suspended-sediment-sampling systems were used as the primary mechanism for sample collection.

Data were collected at nine continuous-record streamflow-gaging stations (fig.1; table 1). Streamflow-gaging stations were established at sites where discharge and constituent and suspended-sediment loads were to be computed for all runoff periods. Three gaging stations—on Black Creek, Zuni River, and Little Colorado River at Woodruff—were installed at sites in drainage basins that have not been affected by mining. Those sites were sampled to compare constituent concentrations with those from sites downstream from uranium-mining operations. In this report, the term "background" is applied to samples collected where uranium mining has not occurred upstream. The other six sites are downstream from the Church Rock Mining District and may have been affected by mining. These gaging stations are on the Puerco River near Church Rock, Manuelito, and Chambers and on the Little Colorado River near Joseph City, at Grand Falls, and near Cameron.

Two sites—the Puerco River near Manuelito and Black Creek near Houck—had not been previously gaged (table 2). The gaging station near Manuelito is about 14.5 km upstream from the Arizona–New Mexico State line and was established to allow estimation of constituent loads transported from New Mexico into Arizona. The gaging station near Chambers was used because the location approximately coincides with the end of the reach of perennial flow caused by mine dewatering. Also, some historical discharge and water-chemistry information was available at that site. The gaging stations on the Little Colorado River at Woodruff, near Joseph City, and near Cameron are continual-record stations for which historical information on discharge and sediment transport is available (table 2). The gaging station near Cameron also provides information on transport of sediment and chemical constituents in the Little Colorado River at a point 72.4 km upstream from its confluence with the Colorado River. The gaging station on the Little Colorado River near Joseph City provides flow and sediment-transport information for the Little Colorado River about 15.6 km downstream from the confluence with the Puerco River. The gaging stations on Black Creek and the Zuni River were used to establish transport of constituents from natural sources.

Methods of Data Collection and Sample Analysis

Data Collection

Instrumentation at the streamflow-gaging stations consisted of a stage sensor, a water-sampling system, a rain gage, and a data-collection platform (DCP). The DCP received input from the stage sensor and the rain gage, activated the water-sampling system, and transmitted data by a satellite to a USGS computer. The stage sensor was either a balance-beam manometer or a float gage. The rain gage was a tipping-bucket gage that measured rainfall in 0.25-mm increments (Gray and Fisk, 1992).

The water-sampling system had two compo nents, a Manning Environmental Corporation Model S–4050 automatic water sampler and an auxiliary pump. The DCP activated the automatic sampler when stage, monitored at 10-minute intervals, first exceeded a predetermined minimum threshold. Thereafter, the water-sampling system could be activated by the DCP as many as 23 times on the basis of time, stage, and rate-of-stage-change criteria determined for each site (Gray and Fisk, 1992). During water years 1989–91, samples were collected during 6 to 19 runoff periods, and 22 to 90 samples were collected at streamflow-gaging stations (table 2).

Streamflow-gaging stations were visited during runoff whenever possible. During a site visit, a flow-integrated streamflow sample was collected by methods described by Edwards and Glysson (1988), and field measurements of water temperature, pH, specific conductance, dissolved-oxygen concentration, and alkalinity were made. Water discharge was measured

Table 1. Streamflow-gaging stations used to monitor chemical constituents and suspended-sediment transport, Puerco and Little Colorado River Basins, Arizona and New Mexico

Station number	Letter identifying station as shown in figure 1	Station name	Drainage area, in square kilometers	Approximate distsnce downstream from Church Rock Mining District, in kilometers
09386950	a	Zuni River above Black Rock Reservoir, New Mexico	2,196	([1])
09394500	b	Little Colorado River at Woodruff, Arizona	20,906	([1])
09395350	c	Puerco River near Church Rock, New Mexico	500	13
09395630	d	Puerco River near Manuelito, New Mexico	2,176	62
09395990	e	Black Creek below West Fork Black Creek, near Houck, Arizona	[2]1,680	([1])
09396100	f	Puerco River near Chambers, Arizona	5,584	119
09397300	g	Little Colorado River near Joseph City, Arizona	32,075	215
09401000	h	Little Colorado River at Grand Falls, Arizona	54,908	355
09402000	i	Little Colorado River near Cameron, Arizona	68,529	415

[1]Not downstream from Church Rock Mining District. [2]Approximate.

Table 2. Period of record and number of runoff periods sampled and samples collected from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico

Station number	Station name	Period of record for daily mean discharges	Period of record for daily suspended-sediment load	Number of runoff periods sampled (1988–91)	Number of samples collected (1988–91)
09386950	Zuni River above Black Rock Reservoir, New Mexico	1969–91	[1]1989–91	13	27
09394500	Little Colorado River at Woodruff, Arizona	1905–07, 1917–19, 1929–33, 1935–91	1951–57 [2]1989–91	13	79
09395350	Puerco River near Church Rock, New Mexico	1977–82, 1989–91	[2]1989–91	11	32
09395630	Puerco River near Manuelito, New Mexico	1989–91	[3]1989–91	14	35
09395990	Black Creek below West Fork Black Creek, near Houck, Arizona.	1989–91	[1]1989–91	6	22
09396100	Puerco River near Chambers, Arizona	[4]1973–89, [5]1989–91	[5]1989–91	15	37
09397300	Little Colorado River near Joseph City, Arizona	[4]1973–89, [3]1989–91	[4]1979–89, [3]1989–91	16	78
09401000	Little Colorado River at Grand Falls, Arizona	1925–51, 1953–60, 1989–91	[5]1989–91	14	90
09402000	Little Colorado River near Cameron, Arizona	1947–89	[4]1957–70, [5]1989–91	19	33

Computations were for days on which the daily mean discharge exceeded:

[1]0.14 cubic meter per second (m^3/s). [2]0.28 m^3/s. [3]1.4 m^3/s. [4]14.0 m^3/s. [5]0.57 m^3/s.

using methods described by Rantz and others (1982). Specific conductance and pH were measured on samples collected both manually and automatically.

Sample Analysis

Analyses included determination of concentration and grain-size distribution of suspended sediment, and the radioactivity and concentration of other selected chemical constituents in the dissolved and suspended phases. Water-sediment samples from Arizona were processed at the USGS field office in Flagstaff, Arizona, and those from New Mexico were processed at the USGS field office in Albuquerque, New Mexico, in preparation for further analysis.

Early in the study, quality-assurance checks on radiochemical analyses of sample splits showed that analyses of dried sediment (reported in picocuries per gram) were more reproducible than values determined for sample splits for whole samples (reported in picocuries per liter). Differences in the analytical values for replicate analyses on unfiltered split samples probably are caused by nonrepresentative wet-sample splitting techniques. After this finding, all analyses for total radioactivity were made on dried suspended sediment rather than on whole samples. Values of total or suspended-phase radionuclides reported in this study were converted from picocuries per gram to picocuries per liter using the suspended-sediment concentration as described in footnotes to the data tables. In earlier studies, analyses commonly were performed on whole samples, therefore comparisons of data from this study with historical data are limited to those for which the methods have been determined to be comparable and the suspended-sediment concentration is known.

An aliquot of the whole sample was sent to USGS Sediment Laboratories in Iowa City, Iowa, or Vancouver, Washington, for determination of suspended-sediment concentration by the evaporation method and grain-size distribution by sieving or by visual accumulation tube (Guy, 1969). The remainder of the sample was centrifuged and filtered through a 0.45-micrometer cellulose nitrate paper filter. Filtered water was split into several subsamples for analysis of concentration or radioactivity of chemical constituents. Analytical results were reported in micrograms per gram or weight percent for uranium and nonradioactive constituents and in picocuries per gram for other radioactive constituents. The results were multiplied by the sediment concentration in milligrams per liter and converted to units of milligrams per liter and picocuries per liter for comparison with water-quality standards to determine the compliance status.

The residual sediment from the centrifuge was weighed, oven dried, reweighed, and separated representatively into three parts. One aliquot was used for analysis of radionuclide concentration or radioactivity, a second aliquot was used for analysis of concentration of nonradioactive chemical constituents, and the third aliquot was archived in a plastic container for possible future use.

Individual subsamples for chemical analysis were submitted to one of several laboratories, including the USGS National Water-Quality Laboratory (NWQL) in Arvada, Colorado, the State of New Mexico's radiochemical laboratory, several USGS National Research Program (NRP) laboratories, and several USGS-approved contract laboratories. Detection limits and analytical errors vary, depending on the element being analyzed, the method used, and the laboratory performing the analysis. Samples were analyzed for constituent concentrations in the dissolved phase at the NWQL by methods described by Fishman and Friedman (1989). Analyses of isotopes of oxygen and hydrogen were made at an NRP laboratory in Reston, Virginia. Concentrations of nonradioactive chemical constituents on suspended sediment were measured by the USGS Branch of Mineral Resources Laboratory, Denver, Colorado, by complete digestion of dried sediment in mixed acids before analysis by induction-coupled plasma–atomic emission spectrometry (ICP-AES) (Fishman and Friedman, 1989).

Three laboratories analyzed samples for radionuclide activity during the 4–year data-collection period. The State of New Mexico, Health and Environment Department, Scientific Laboratory Division (NMSLD) in Albuquerque, New Mexico, analyzed suspended sediment and bed material collected from July 1988 to September 1990. Water samples and sediment samples analyzed after September 1990 were sent to laboratories subcontracted to the NWQL; U.S. Testing, Richland, Washington, in 1988, International Technology Corporation (IT), Oak Ridge, Tennessee, in 1989, and IT Labs, Richland, Washington (formerly U.S. Testing of Richland), in 1990 and 1991. Analytical methods and quality-assurance procedures differed among the three subcontract laboratories. Measurements of uranium-series radionuclides followed standard methods described by the U.S. Environmental Protection Agency (1980), USGS (Thatcher and others, 1977), and American Society for Testing and

Materials (1992). At all three laboratories, radioactivity of isotopes in the suspended phase was reported in picocuries per gram.

Particle-surface area was estimated for 19 suspended-sediment samples by the USGS Sediment Partitioning Project laboratory in Doraville, Georgia, using methods described by Horowitz and Elrick (1987). Mineralogy of 15 well-core samples was determined using X-ray diffraction by David M. Hendricks of the University of Arizona Department of Soil and Water Science.

COMPONENTS OF STREAMFLOW IN THE PUERCO AND THE LITTLE COLORADO RIVERS DOWNSTREAM FROM THE MOUTH OF THE PUERCO RIVER

Before the late 1950's, the Puerco River was ephemeral, and streamflow was derived from runoff and a few small springs in the river channel. Since the late 1950's, a significant component of Puerco River streamflow has been from human activities. Continuous releases from the sewage-treatment plant at Gallup since the late 1950's and mine-dewatering effluent from the Church Rock Mining District from 1960 to 1986 created perennial flow in some reaches of the Puerco River. In addition, the tailings-pond spill of 1979 was a one-time release of water, mill tailings, and associated chemical constituents to the Puerco River. Each of these natural and artificial streamflow components has distinct chemical characteristics, and the relative proportions of the components have varied with distance from the source and with time.

Volume of Streamflow Components

Runoff causes periods of flow in the Puerco River that last from several hours to more than a week, depending on storm type, duration, frequency, and time of year. Spring runoff from snowmelt typically lasts from 4 to 8 weeks, depending on snowpack and temperature. The quantity of runoff varies considerably from year to year in streams in this area. For the 1990–91 water years, the annual volume of runoff averaged about 1.3×10^6 m^3 at the streamflow-gaging station near Church Rock and 6.0×10^6 m^3 near Manuelito. An estimated total of 1.4×10^8 m^3 of mine-dewatering effluent was discharged from uranium mines from 1960 to 1961 and 1967 to 1986 (Van Metre and Gray, 1992). Most of that discharge occurred from 1967 to 1986. The discharge of mine-dewatering effluent for those years averaged about 0.2 m^3/s, or about 6.4×10^6 m^3/yr. Van Metre and Gray (1992) estimated that more than half the water released by mining entered the alluvial aquifer before reaching Gallup. The remaining mine-dewatering effluent mixed with sewage effluent at Gallup and flowed as far as several kilometers downstream from Chambers (Chris Shuey, SRIC, Albuquerque, New Mexico, oral commun., 1992). The discharge of sewage effluent is typically about 0.15 m^3/s, or about 4.7×10^6 m^3/yr, and decreases by evaporation and infiltration to about 0.05 m^3/s—about 1.6×10^6 m^3/yr—about 13 km downstream at the streamflow-gaging station near Manuelito. The volume of treated effluent varies considerably on a daily basis (Albert Jackson, Wastewater System Superintendent, Water Maintenance and Repair, City of Gallup, New Mexico, written commun., 1990). An unknown amount of treated and untreated sewage also is discharged intermittently into the Puerco River channel at trailer courts and truck stops near the river in New Mexico (Shuey, 1986, 1992).

Three small springs, each estimated to discharge less than 0.01 m^3/s, contribute flow to the Puerco River. The springs are associated with bedrock exposures in the channel and are caused by abrupt drops in streambed elevation that result in interception of the water table by the streambed. At two of the springs—near streamflow-gaging stations near Church Rock and Chambers—bedrock drops almost vertically 2 to 3 m in elevation. The third spring is in New Mexico near the Arizona-New Mexico State line, where several small discharge points are in and near the channel of the Puerco River and its tributaries. Spring water typically infiltrates or evaporates within a short distance downstream at all three sites and does not constitute a significant part of the annual surface-water flow.

The tailings-pond spill contributed an estimated 360,000 m^3 of liquid and 1,000 Mg of suspended sediment to the Puerco River (Weimer and others, 1981). The spill flowed from the pond to Pipeline Arroyo into the Puerco River and in the river to a point about 30 to 40 km downstream from the Arizona-New Mexico State line, which is 110 to120 km downstream from the tailings pond.

In comparison, the volume of the spill was about 6 percent of the volume released in a typical year by mine dewatering and about 28 percent of the average annual runoff in 1990 and 1991 at the Church Rock gaging station. The average annual volume of dewatering effluent from 1967 to 1986 was about five times the average runoff per year at the Church Rock streamflow-gaging station for 1990–91. The average annual volume of sewage effluent released at Gallup is almost as large—about three-fourths—as the average annual runoff at the Manuelito streamflow-gaging station for 1990–91. Use of data for water years 1990–91 for these estimates may overestimate the dewatering effluent and spill percentages because water year 1990–91 runoff was less than the mean of the long-term record for other streams in the basin. Because annual flow volume increases downstream in the drainage basin and because of the discharge of sewage effluent in Gallup, mining releases were a smaller percentage of the total flow with increasing distance from the mines.

Chemistry of Streamflow Components

Major ions and trace constituents in snowmelt and storm runoff are derived largely by dissolution of surficial materials in the drainage basin. Differences in proportions of major ions in streamflow at sampling sites on the Puerco River, Black Creek, and the Little Colorado River below Holbrook are shown by the trilinear method of Piper (1944; fig. 5, this report). Samples of runoff from Pipeline Arroyo and the Church Rock streamflow-gaging station have a calcium- and sulfate-dominated chemistry that reflects the abundance of gypsum ($CaSO_4$) and lime (CaOH) in soils and rock units at or near the land surface in the headwaters near Pinedale, New Mexico (Gallaher and Cary, 1986). Within the Puerco River Basin, the

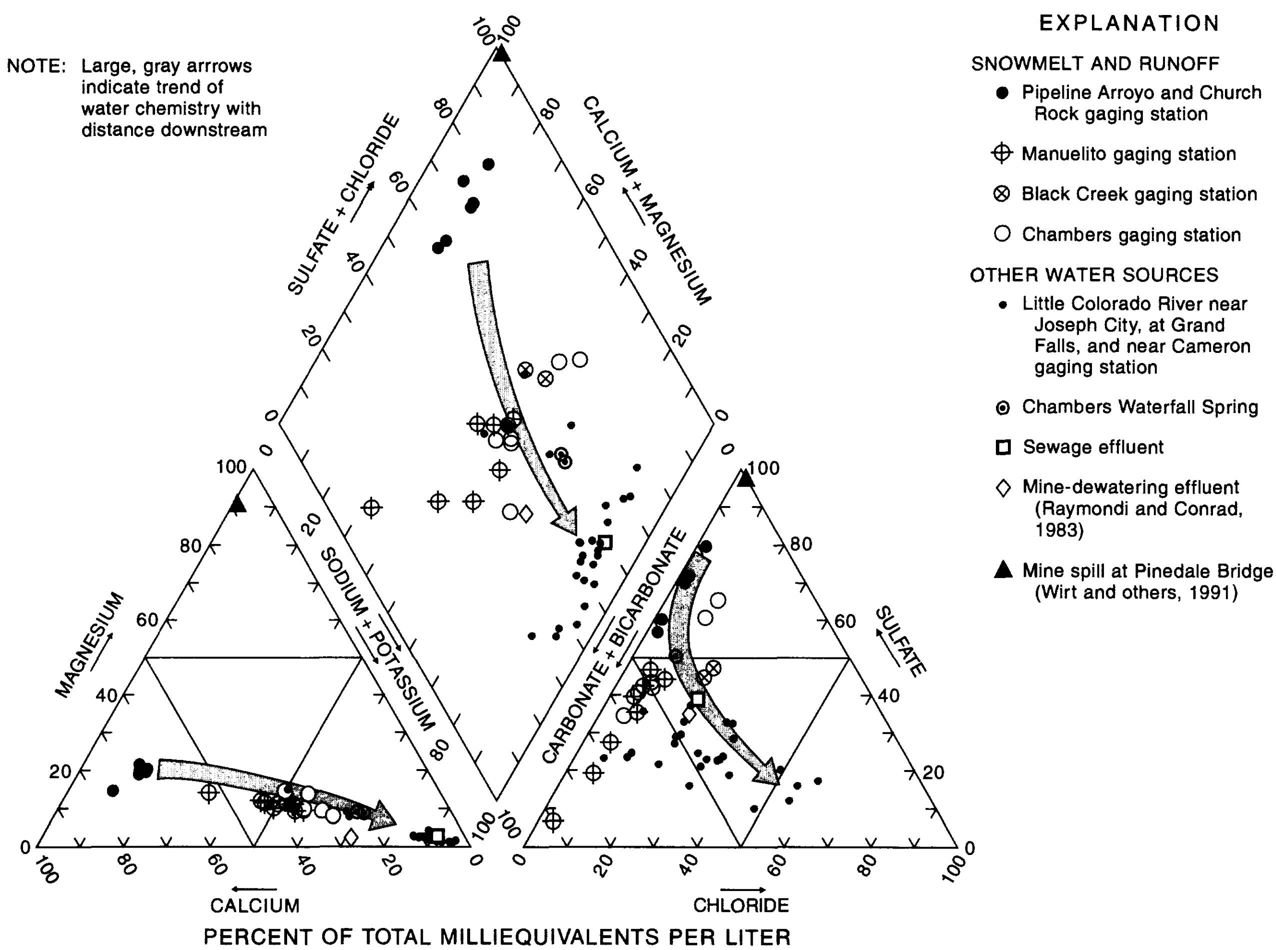

Figure 5. Relative compositions of snowmelt and runoff, sewage effluent, and mine-dewatering effluent in the Puerco River and the Little Colorado River below Holbrook, Arizona.

proportion of sodium in runoff increases downstream as soils derived from sandstones of Jurassic age and sedimentary rocks of Triassic age are encountered (Cooley and others, 1969). The sandstones are exposed east of Gallup and near the Arizona–New Mexico State line, and the younger sedimentary rocks are extensively exposed as the Chinle Formation in the Arizona part of the basin. Streamflow samples from gaging stations on the Puerco River near Chambers and the Little Colorado River near Joseph City and at Grand Falls are enriched in sodium and bicarbonate compared with those from upstream stations. Samples of water collected at the Little Colorado River gaging station near Cameron when streamflow originated primarily from Moenkopi Wash had a unique chemistry and did not reflect the downstream trend, whereas samples collected at that station when flow from Moenkopi Wash was not a significant part of the total flow did show the downstream increase in sodium concentration. The downstream trend reflects a gradual change in response to variations in the lithology and soils in the drainage basin.

Specific conductance of runoff in the Puerco River varied considerably with time and location during the study period (table 3) and ranged from about 456 to 1,980 μS/cm. Specific conductance typically varied with season, the amount of time between runoff periods, and the duration of runoff. For example, concentrations of dissolved evaporative salts that accumulate in the streambed during the first runoff of the late summer thunderstorm season would be expected to be relatively high compared with the last runoff of spring snowmelt. Large spatial and temporal variations in water chemistry at different locations during a single runoff period are attributed to irregular inputs from tributaries and gradual geochemical changes as the water flows downstream. Specific conductance of runoff typically increased downstream between Manuelito and Chambers, probably as a function of several factors, including lithology, the length of time that water is in contact with sediments, and evaporation during low flows. Measurements made during a single high flow on September 6, 1989, had values of 644, 1,340, and 1,630 μS/cm near Church Rock, Manuelito, and Chambers, respectively.

Concentrations of dissolved elements from Waterfall Spring near Chambers are similar to those found in local runoff and also to nearby ground-water samples (Peter Van Metre, hydrologist, U.S. Geological Survey, written commun., 1994). Specific conductance for Waterfall Spring was 1,150 μS/cm on May 8, 1990 (table 3).

Treated sewage effluent collected downstream from the sewage-plant outfall in Gallup on March 31, 1989, was a sodium bicarbonate water with a specific conductance of 1,960 μS/cm. During the study period, concentrations of major ions and specific conductance in discharged sewage effluent were observed to increase gradually downstream from Gallup. For example, at low flow on October 16, 1990, specific conductance increased from 1,760 μS/cm at the sewage-plant outlet to 1,940 μS/cm near Lupton, and dissolved chloride increased from 120 to 160 mg/L in the same reach. The water in sewage effluent originates as ground water from deep municipal wells that is withdrawn mainly from the Gallup Sandstone of Cretaceous age. Many wells also are screened in other sandstone units of Cretaceous and Jurassic ages, including the Westwater Canyon Sandstone Member of the Morrison Formation. Sewage effluent typically contains higher concentrations of sodium, chloride, and silica than runoff (table 3). Concentrations of other constituents are similar for both water types. Concentrations of uranium in sewage effluent are negligible, as indicated by a value of 1.3 pCi/L for dissolved-phase gross-alpha radioactivity. Suspended-sediment concentration in sewage effluent is insignificant compared with that in runoff.

The tailings-pond spill had a unique chemistry (fig. 5) because of its extreme acidity, as indicated by a pH of 1.4 (table 3; Weimer and others, 1981). In contrast, mine-dewatering effluent and sewage effluent are similar in proportions of major ions to streamflow in the Puerco River downstream from Manuelito and the Little Colorado River downstream from Holbrook. Mine water in the Church Rock Mining District was pumped primarily from the Westwater Canyon Sandstone Member of the Morrison Formation. Although sewage effluent and mine-dewatering effluent are both derived from sandstone aquifers and cannot be distinguished from runoff solely on the basis of major chemical constituents, differences are evident in stable-isotope ratios between the components. Stable-isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/H$ or D/H) are often used as hydrologic tracers to indicate the origin and history of water. Variations in stable-isotope values can indicate hydrologic conditions such as the temperature and elevation of precipitation or the amount of evaporation that occurs as water flows downstream. Isotope values are

Table 3. Chemistry of snowmelt and storm runoff in the Puerco River, spring flow, sewage effluent, mine-dewatering effluent, and the tailings-pond spill of July 16, 1979

[m^3/s, cubic meters per second; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter; μg/L, micrograms per liter; pCi/L, picocuries per liter. ---, sample was not analyzed for constituent. All samples were dissolved analyses from filtered samples unless noted otherwise]

Constituent	Puerco River		Waterfall Spring near Chambers[2]	Treated sewage effluent[3]	Mine-dewatering effluent					Mine tailings-pond spill (July 16, 1979)	
					Untreated		Treated				
	Snowmelt and storm runoff[1]	Number of samples			Median, (1980–82)[4]	Number of samples	Median, (1977–82)[4]	Number of samples	Streamflow sample (3–23–82)[5]	Tailings-pond liquid[6]	Spill liquid at Pinedale bridge[7]
Discharge (m^3/s)	1.9–220	27	[8]<0.1	[8]1.4	---	---	---	---	---	---	---
Suspended sediment (mg/L)	55,600–229,000	20	---	---	---	---	---	---	---	---	---
pH (standard units)	7.4–8.1	27	7.8	7.6	---	---	---	---	---	1.9	1.4
Alkalinity as HCO_3 (mg/L)	---	---	---	---	---	---	---	---	240	---	---
Alkalinity as $CaCO_3$ (mg/L)	82–317	20	---	430	---	---	---	---	---	---	---
Specific conductance (μS/cm)	456–1,980	27	1,150	1,960	---	---	---	---	---	---	---
Calcium (mg/L)	19–130	23	54	23	---	---	---	---	28	---	150
Magnesium (mg/L)	4.1–25	23	12	6.2	---	---	---	---	10	50	1,000
Sodium (mg/L)	13–280	23	180	380	---	---	---	---	130	520	7,700
Potassium (mg/L)	3.5–9.2	23	8.4	12	---	---	---	---	1.2	---	96
Chloride (mg/L)	3.0–96	27	45	150	---	---	---	---	15	50	5,500
Fluoride (mg/L)	.30–1.0	27	.50	1.7	---	---	---	---	---	2.5	27
Silica (mg/L)	6.6–18	23	11	22	---	---	---	---	---	---	---
Sulfate (mg/L)	55–710	27	280	400	[9]156	9	[9]140	17	200	4,800	27,000
Arsenic (μg/L)	<1–8	22	---	5	[9]8	6	[9]<5	16	10	70	8
Barium (μg/L)	35–170	23	41	---	---	---	[9]400	15	300	<.1	880
Chromium (μg/L)	<5	22	<5	<1.0	---	---	---	---	---	.15	1,600
Lithium (μg/L)	7–24	22	65	---	---	---	---	---	---	---	---

Table 3. Chemistry of snowmelt and storm runoff in the Puerco River, spring flow, sewage effluent, mine-dewatering effluent, and the tailings-pond spill of July 16, 1979—Continued

Constituent	Puerco River		Water-fall Spring near Chambers[2]	Treated sewage effluent[3]	Mine-dewatering effluent					Mine tailings-pond spill (July 16, 1979)	
					Untreated		Treated				
	Snowmelt and storm runoff[1]	Number of samples			Median, (1980–82)[4]	Number of samples	Median, (1977–82)[4]	Number of samples	Streamflow sample (3–23–82)[5]	Tailings-pond liquid[6]	Spill liquid at Pinedale bridge[7]
Molybdenum (μg/L)	≤10	23	<10	---	[9]30	6	[9]10	15	270	0.04	560
Selenium (μg/L)	<2–3	22	---	<1	[9]11–70	2	[9]40	15	40	---	81
Strontium (μg/L)	310–1,600	23	1,300	320	---	---	---	---	---	---	---
Gross alpha (pCi/L)	4.4–21	14	12	1.3	[9]3,200	10	[9]440	11	[9]250	---	120
Uranium (μg/L)	1.9–13	5	[8]16	---	[9]4,300	6	[9]1,100	14	---	[9]4,100	[9]6,500
Gross beta as cesium–137 (pCi/L)	5.4–29	14	16	20	[9]1,300	6	[9]460	6	---	---	---
Gross beta as strontium–90 (pCi/L)	4.9–23	14	12	12	---	---	---	---	---	---	---
Radium–226 (pCi/L)	---	---	---	---	[9]295	10	[9]2	13	---	[9]210	100
Radium–228 (pCi/L)	---	---	[10]<.1	[11]<.5	---	---	[9]<.2	1	---	---	---
Thorium–230 (pCi/L)	---	---	[10].1	---	[9].1–210	2	[9]<.2–3.9	2	---	[9]10,200	8,100
Lead–210 (pCi/L)	---	---	---	---	[9]44–1,200	2	[9]4.5–10	2	---	---	---

[1]Surface runoff collected by U.S. Geological Survey (USGS) a s composite cross-section samples or point samples collected at streamflow-gaging stations near Church Rock and Manuelito, New Mexico, and Chambers, Arizona, between August 31, 1988, and October 20, 1990.
[2]Filtered spring sample collected by USGS on May 8, 1990.
[3]Filtered samples collected by USGS at city of Gallup sewage-treatment plant on March 31, 1989.
[4]Samples collected by New Mexico Environmental Department (NMED; Gallaher and Cary, 1986; tables 7.1, 7.3).
[5]Streamflow sample collected by NMED on March 23, 1982, near Church Rock streamflow-gaging station (Wirt and others, 1991).
[6]Samples collected by United Nuclear Mining Company on February 5, 1979, from tailings pond, near Church Rock, New Mexico (Weimer and others, 1981).
[7]Samples collected by United Nuclear Mining Company on July 16, 1979, at Pinedale Bridge, New Mexico (Wirt and others, 1991).
[8]Estimated.
[9]Total analysis from unfiltered sample.
[10]Estimated value based on sample collected by USGS on December 3, 1986.
[11]Estimated value based on sample collected by USGS on October 4, 1985.

expressed in δ (delta) notation. Delta values are expressed as per mil (‰). The delta notation for the stable isotopes of oxygen and hydrogen is defined as follows:

$$\delta^{18}O = 1,000\left[\frac{\left(\frac{^{18}O}{^{16}O}\right)\text{sample}}{\left(\frac{^{18}O}{^{16}O}\right)\text{reference}} - 1\right]$$

and

$$\delta D = 1,000\left[\frac{\left(\frac{^{2}H}{^{2}H}\right)\text{sample}}{\left(\frac{^{2}H}{^{2}H}\right)\text{reference}} - 1\right]$$

Per mil values included in this report are presented relative to reference compounds. Vienna standard mean ocean water (V-SMOW) is the reference compound for $\delta^{18}O$ and δD analyses. Values of δD and $\delta^{18}O$ for runoff samples from the Puerco and Little Colorado Rivers plot along the meteoric water line of $\delta D = 8\delta^{18}O + 10‰$ (fig. 6; Craig, 1961), indicating that evaporation is insignificant for these large flows of relatively short duration. Sewage effluent sampled at the outfall pipe near Gallup also plots near the meteoric water line, but samples of sewage effluent collected from several downstream locations between Gallup and Sanders show a departure from the meteoric water line. The deviation from the meteoric water line (fig. 6) indicates that extensive evaporation occurs as effluent flows downstream under low-flow conditions. The shift is an indication that, in proportion to their volume, low flows have a larger surface area and longer time over which evaporation can occur than high flows. By analogy, mine-dewatering effluent was pumped from the Westwater Canyon Sandstone Member of the Morrison Formation and probably underwent extensive evaporation as it moved downstream. Mine effluent probably had a δD and $\delta^{18}O$ signature and an evaporative shift similar to sewage effluent.

Mine-dewatering effluent is clearly distinguished from sewage effluent on the basis of radioactivity. The gross-alpha radioactivity of sewage effluent is barely above detection limits (1.3 pCi/L; table 3), whereas the median value of gross-alpha radioactivity for untreated mine-dewatering effluent was 3,200 pCi/L. Mine dewatering released nearly six times more radioactivity during the cumulative 22 years than was released by the tailings-pond spill (Van Metre and Gray, 1992). Untreated dewatering effluent contained higher gross-alpha and gross-beta radioactivity and concentrations of ^{226}Ra, ^{210}Pb, U, Mo, and Se than runoff (Gallaher and Cary, 1986, p. 80–93). Concentrations of dissolved solids, barium (Ba), As, and vanadium (V) also were higher in untreated dewatering effluent than in runoff (Gallaher and Cary, 1986). More than 85 percent of gross-alpha radioactivity, natural U, Mo, and Se, and 30 percent of ^{226}Ra present in mine-dewatering effluent typically was in the dissolved fraction. Treating dewatering effluent reduced concentrations of ^{226}Ra, ^{210}Pb, polonium–210 (^{210}Po), natural U, and gross-alpha radioactivity (table 3). Only U, Mo, and Se concentrations were consistently higher in treated dewatering effluent than in runoff. Isotopes of Th did not exceed the detection limit in available analyses for dewatering effluent (Gallaher and Cary, 1986; Wirt and others, 1991). The suspended-sediment concentration of dewatering effluent was low compared with that of runoff; typically, suspended-sediment concentration was about 100 mg/L in untreated dewatering effluent and about 10 mg/L in treated dewatering effluent (Gallaher and Cary, 1986). The cumulative 22 years of mine dewatering released an estimated 508 Mg of uranium and 260 Ci of gross-alpha radioactivity to the Puerco River (Van Metre and Gray, 1992).

Improved treatment of dewatering effluent during the mid-1970's reduced ^{226}Ra concentration in the effluent but increased ^{226}Ra concentration in the tailings-pond liquid and sediment (Gallaher and Cary, 1986). Unfiltered tailings-pond liquid had higher concentrations of ^{226}Ra, ^{230}Th, and U than treated mine-dewatering effluent (table 3). Samples of liquid from the spill collected at the bridge in Pinedale (fig. 1) contained high concentrations of magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), fluoride (F), SO_4, Ba, chromium (Cr), and Mo (table 3). Samples of liquid from the spill also contained high concentrations of dissolved iron (Fe), Mn, and aluminum (Al) (Wirt and others, 1991) because these elements were leached from tailings sediments by the low pH. The spill had concentrations of total U and total ^{226}Ra similar to concentrations in untreated dewatering effluent (table 3).

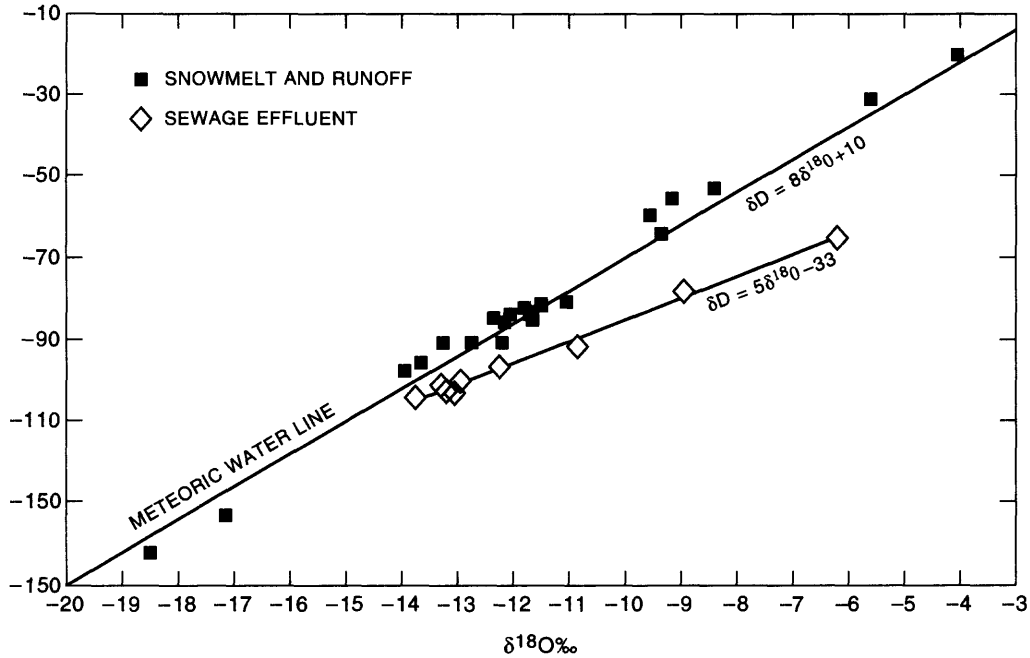

Figure 6. Relation between deuterium (δD) and oxygen–18 ($\delta^{18}O$) compositions in runoff and sewage effluent, Puerco River, Arizona and New Mexico.

RELATION OF CHEMICAL CONCENTRATIONS AND RADIOACTIVITIES TO WATER-QUALITY STANDARDS

Regulatory Background

Regulatory programs to manage radionuclides and other chemical constituents in water have been established by Federal laws. These laws, that include the Federal Clean Water, Safe Drinking Water, and Atomic Energy Acts, provide a nationwide framework for programs that can be implemented by States. State agencies use research findings about the public health, safety, and welfare risks of toxic and other deleterious substances to set standards and implement controls. Quality of water in the Puerco and Little Colorado Rivers was evaluated by comparison of data from analysis of samples collected in the present study with the water-quality standards that apply to the study area.

In the study area, water-quality programs are administered on Indian Reservations by Federal agencies—USEPA, U.S. Department of Energy, and the Public Health Service. In nonreservation areas, programs are administered by agencies of the States of Arizona and New Mexico—ADEQ, Arizona Radiation Regulatory Agency, and NMED.

The Federal Safe Drinking Water Act (SDWA)[1] focuses on water delivered by public drinking-water distribution systems. USEPA Maximum Contaminant Levels (MCL's) are the standards for the quality of water delivered to domestic users to protect human health. Source water for a drinking-water distribution system may require treatment to achieve MCL's. Although MCL's are not specifically applicable to the regulation of stream water quality, they are useful for reference and are summarized for constituents considered in this study (table 4).

The Federal Clean Water Act (CWA)[2] delegates stream water-quality regulation to State and Tribal water-pollution control agencies. Under section 303(c) of the CWA, USEPA is responsible for approval and oversight of adopted water-quality standards. Approval of standards by USEPA is based on conformance with the purposes of the CWA and consistency between jurisdictions. USEPA must resolve inconsistencies in any CWA water-quality standard across jurisdictional boundaries to ensure that the

[1]The Federal Safe Drinking Water Act, as amended (P.L. 93–523; 88 Stat. 1660; 95–190; 91 Stat. 1393; 42 United States Code §§ 300f through 300j–26).

[2]The Federal Water Pollution Control Act Amendment of 1972, as amended (P.L. 92–500; 86 Stat. 816; 33 United States Code §§ 1251 through 1387).

Table 4. Federal and State regulatory standards that apply to selected constituents in public drinking-water supplies and streamflow, Puerco and Little Colorado River Basins, Arizona and New Mexico

[pCi/L, picocuries per liter; D, value for dissolved fraction; ---, no established limit. Values, in milligrams per liter, as total recoverable fraction unless noted otherwise]

Constituent	U.S. Environmental Protection Agency[1]	State of New Mexico[2]	State of Arizona						
			Drinking water[3]		Surface water[4]				
		Public water-supply system	Community water system	Non-community water system	Domestic water source	Full body contact	Aquatic and wildlife (warm water fishery)	Agricultural livestock watering	Agricultural irrigation
Arsenic	0.05	0.05	0.05	0.10	0.05	0.50	0.360 D	0.2	2.0
Barium	2	1	1	2	1.0 D	1.0	---	---	---
Beryllium	.001	---	---	---	.000006	.00033	.0065	---	---
Boron	---	---	---	---	---	---	---	---	1.0
Cadmium	.005	.010	.010	.020	.005	.07	([5])	.050	.050
Chloride	(250)	---	([6])	([6])	250	---	---	---	---
Chromium	.1	.05	.05	.5	.1	---	([5])	1.0	1.0
Copper	(1.0)	---	([6])	([6])	---	---	([5])	.50	5.0
Fluoride	(2)	4.0	4.0	6.0	4.0	---	---	---	---
Gross alpha, in pCi/L. Includes radium–226 but excludes radon and uranium.	[7]15	[7]15	[7]15	[7]15	[7]15	---	---	---	---
Gross beta, in pCi/L. Manmade sources only.	---	---	[8]50	[8]50	---	---	---	---	---
Iron	(.3)	---	([6])	([6])	---	---	---	---	---
Lead	.005	.05	.05	.1	.050	---	([5])	.10	10
Manganese	(.05)	---	([6])	([6])	---	---	---	10	---
Mercury	.002	.002	.002	.004	.0021	.0006	.0024D	.01	---
Nickel	---	---	---	---	.14	2.8	([5])	---	---
Radium–226, in pCi/L	[9]20	---	---	---	---	---	---	---	---
Radium–228, in pCi/L	[9]20	---	---	---	---	---	---	---	---
Radium–226 plus radium–228, in pCi/L.	5	5	5	5	5	---	---	---	---

Table 4. Federal and State regulatory standards that apply to selected constituents in public drinking-water supplies and streamflow, Puerco and Little Colorado River Basins, Arizona and New Mexico—Continued

Constituent	U.S. Environmental Protection Agency[1]	State of New Mexico[2] Public water-supply system	State of Arizona: Drinking water[3] Community water system	Non-community water system	Surface water[4] Domestic water source	Full body contact	Aquatic and wildlife (warm water fishery)	Agricultural livestock watering	Agricultural irrigation
Radon, in pCi/L	[9]300	---	---	---	---	---	---	---	---
Selenium	.05	0.01	0.01	0.02	0.050	0.420	0.02	0.05	0.02
Silver	(.10)	.05	.05	.10	---	---	([5])	---	---
Sulfate	(250)	---	([6])	([6])	250	---	---	---	---
Total dissolved solids	(500)	---	([6])	([6])	500	---	---	---	[10]1,000 [11]2,000
Uranium	[9].020	---	---	---	.035 D	---	---	---	---
Zinc	(5)	---	([6])	([6])	5.0	28	([5])	25	10

[1]U.S. Environmental Protection Agency (1992). Values in this column are primary maximum contaminant levels, except those enclosed by parentheses, which are secondary maximum contaminant levels. The primary maximum contaminant levels are maximum limits for water delivered for public drinking-water consumption. The secondary maximum contaminant levels are nonenforceable guidelines that indicate an upper aesthetic limit. These Federal regulations are not applicable to surface water.

[2]State of New Mexico Environment Department (1991). Regulations governing water supplies, as amended through April 16, 1991, effective May 16, 1991.

[3]State of Arizona (1992). Designated for domestic water use according to Rule A.A.C.R18–11–10.4. These values are maximum limits for public drinking-water consumption and are not applicable to streamflow.

[4]State of Arizona (1992). Designated for protection of "aquatic and wildlife (warm water fishery)" use according to Rule A.A.C.R18–11–104 for the Puerco and Little Colorado Rivers.

[5]State of Arizona (1992). Regulations designated for protection of "aquatic and wildlife (warm water fishery)" use per Rule A.A.C.R18–11–104 for the Puerco and Little Colorado Rivers. The most restrictive dissolved-metal constituent levels for cadmium, copper, lead, nickel, and zinc are based on chronic toxicity criteria. The most restrictive regulation for silver is based on an acute toxicity criterion because no chronic standard has been established. The standard for the dissolved fraction for each constituent is related to hardness (H, as $CaCO_3$) in milligrams per liter according to the relations:

Cadmium: $e^{0.7852 \ln H - 3.490}$ Lead: $e^{1.2730 \ln H - 4.705}$ Silver: $e^{1.72 \ln H - 6.52}$

Copper: $e^{0.8545 \ln H - 1.465}$ Nickel: $e^{0.8460 \ln H + 1.1644}$ Zinc: $e^{0.8473 \ln H + 0.761}$

Hardness ranged from 110 to 400 milligrams per liter (mg/L) with an average of 273 mg/L for nine samples in the Puerco River near Chambers and ranged from 11 to 100 mg/L with an average of 37 mg/L for six samples in the Little Colorado River near Joseph City. Compliance levels for data in this study were calculated for an assumed hardness of 150 mg/L.

[6]No maximum contaminant level established. Constituent to be monitored and reported to regulatory agency.

[7]In cases where no data are available for individual radionuclides (radium–226, radon, and uranium), if value is less than or equal to 15 picocuries per liter (pCi/L), compliance is presumed.

[8]If the average annual concentration of manmade beta activity released from a regulated facility exceeds 50 pCi/L, additional analysis is required according to State of Arizona, Department of Environmental Quality, Public and semipublic water-supply system rules: August 8, 1991, Section R18–4–245, p. 33–35.

[9]Maximum contaminant levels for radium–226, radium–228, and uranium are proposed standards under consideration (U.S. Environmental Protection Agency, 1991a, b).

[10]Streams or lakes with agricultural irrigation as a designated use were assessed as partially supporting if the average total dissolved-solids concentration was more than 1,000 mg/L (Arizona Department of Environmental Quality, 1994, p. 61).

[11]Streams or lakes with agricultural irrigation as a designated use were assessed as nonsupporting if the average total dissolved-solids concentration was greater than 2,000 mg/L (Arizona Department of Environmental Quality, 1994, p. 61).

more restrictive standards are achieved. Although State and Tribal agencies are authorized by the CWA to adopt water-quality standards, in the study area only the States of Arizona and New Mexico have adopted standards.

Water-quality standards under CWA are applicable to "waters of the United States" and consist of designated uses and water-quality criteria for the designated uses. Unlike quality standards for drinking water, quality standards for stream water protect both public health and welfare and, therefore, include uses for recreation, wildlife, commercial fisheries, agriculture, and aquatic ecosystems. The broad definition of the terms "pollutant" and "waters of the United States" in the CWA necessitates consideration of pollutant transport and fate under ephemeral, and intermittent streamflow that occurs in arid regions such as the study area. Water-quality standards for the Arizona reach of the Puerco River and for the Little Colorado River are based on the designated uses listed on the following table (State of Arizona, 1992). The selection of criteria for evaluation is described later in this section.

Designated use	Puerco River	Little Colorado River	Criteria selected for evaluation
Domestic water source	No	Yes	Yes
Fish consumption[1]	No	Yes	No
Full body contact recreation	No	Yes	No
Partial body contact recreation	Yes	No	Yes
Aquatic and wildlife	Yes	Yes	Yes
Agricultural livestock watering	Yes	Yes	Yes
Agricultural irrigation	Yes	Yes	Yes

[1]Standard was adopted in 1992 after data were collected.

Radionuclides present a health risk to humans and animals because of radiotoxicity and chemical toxicity. Water-quality standards have been developed for both types of toxicity. Radiotoxicity causes physical damage to living tissue through spontaneous release of atomic particles and energy, and chemical toxicity impairs tissue health through chemical and biological reactions. Different radionuclides exhibit different degrees of radiotoxicity and chemical toxicity. Although U is a radioactive chemical element, its radiotoxicity is less than its chemical toxicity (Wrenn and others, 1987) because all three isotopes of U have long half-lives (fig. 2) and therefore emit low radioactivity. In contrast, ^{226}Ra is highly radiotoxic because it and its daughter progeny are predominantly alpha-particle emitters with short half-lives (fig. 2). On the basis of chemical toxicity, the USEPA has proposed a MCL for U of 0.020 mg/L, which converts to about 14 pCi/L, assuming secular equilibrium (U.S. Environmental Protection Agency, 1991a, b). The State of Arizona has a standard for dissolved U of 0.035 mg/L (equivalent to about 24 pCi/L) for domestic water sources. The MCL for ^{226}Ra plus ^{228}Ra is lower—5.0 pCi/L—because of the higher radioactivity of Ra. A proposed USEPA MCL of 20 pCi/L is under consideration for total ^{226}Ra and for total ^{228}Ra. The MCL for gross-alpha radioactivity minus the sum of U and radon (Rn) radioactivities is 15 pCi/L (U.S. Environmental Protection Agency, 1991c). At present, a USEPA MCL has not been adopted for radon, but the proposed MCL is 300 pCi/L (U.S. Environmental Protection Agency, 1991a, b).

Approach to Evaluation of Water Quality

Water-chemistry data collected in the study (tables 14–17 at the end of the report) were compared with the selected water-quality standards to evaluate water quality (table 5). Determination of compliance with standards was made for each constituent for each reported value.

Water-quality standards selected for the evaluation focused on the Puerco River and its uses as defined by the CWA. Designated uses for aquatic and wildlife, agricultural livestock watering, and agricultural irrigation are recognized and protected by State of Arizona standards on the Puerco and the Little Colorado Rivers. The standard for partial body contact recreation was selected for the evaluation (a Puerco River designated use) rather than that for full body contact recreation (a Little Colorado River designated use). Although the use of the partial body contact criterion relaxes the levels for As and beryllium (Be) for recreation use, the domestic water-source criterion for these constituents is more restrictive and, therefore, controls the overall levels. Although domestic water-source use is not listed as a designated use for the Puerco River in the current regulations (State of Arizona, 1992), the standards for domestic water use are used for water-quality evaluation in this report.

Domestic water source, however, is a designated use for the Little Colorado River. Direct streamflow withdrawal from the Puerco River near Lupton and Sanders for private domestic use was observed before July 1979 (McClennan, 1986), and uses existing on or before November 28, 1975, must be protected (Title 40, Code of Federal Regulations, Part 131). In addition, the alluvial aquifer underlying the Puerco River is vulnerable to contamination from streamflow because the water table is typically less than 1 m beneath the streambed (Peter Van Metre, hydrologist, USGS, written commun., 1994). Wells used for drinking water tap the Puerco River alluvium in this area, and the connection has been established between streamflow and the shallow alluvial aquifer along the Puerco River from Lupton to Chambers (Peter Van Metre, USGS, written commun., 1994). The ADEQ is reviewing the domestic water-source use for the Puerco River. The criteria for fish consumption for the Little Colorado River were not used for evaluation of water quality in this study because fish are not known to inhabit the Puerco River.

The standards for chemical concentration and radioactivity for each constituent of interest for the study are given by agency and by use (table 4). Evaluation of surface-water quality was based on the most restrictive standards for each constituent in the surface-water group. For example, the limit for total recoverable cadmium (Cd) is 0.005 mg/L and the limit for dissolved cadmium is 0.00016 mg/L. Domestic water-source and aquatic and wildlife use criteria are the most restrictive for all constituents except boron (B) and Cu. Standards for B and Cu are determined by criteria for agriculture use. The limits for U are based on the chemical and radiological toxicity on human health.

Each value that was less than or equal to the standard was considered to be in compliance with standards. A value higher than the standard was considered an exceedance. Chemical data reported as "less than" values were considered to be indeterminant when the detection limit was greater than the standard.

Compliance With Water-Quality Standards

Analytical results for both dissolved- and suspended-phase samples (tables 14–17 at the end of the report) were compared with regulatory standards to determine the extent to which Puerco and Little Colorado River streamflow was in compliance (table 5). For some constituents, the standards selected for comparison are different for the dissolved-phase fraction than the standards that were selected for the suspended-phase fraction (table 4). To evaluate compliance of the suspended phase, comparisons were made to standards that apply to either the total recoverable fraction or the insoluble residue fraction because the dissolved fraction of the total sample was not considered significant.

As shown below, nearly all analyses for dissolved-phase As, Ba, Cr, nickel (Ni), and U were in compliance with selected standards and, for most other constituents, 90 percent or more analyses resulted in values that were in compliance. Cu and mercury (Hg) showed 14 and 23 percent compliance, respectively. Excluding indeterminant evaluations, the overall compliance rate for dissolved constituents was 94 percent. Mn is not included because a standard has not been established. ^{226}Ra and ^{228}Ra were not analyzed in the dissolved phase because of the strong adsorption to the suspended phase for those constituents.

Rates of exceedance of standards showed little variation from site to site. Exceedance rate was lowest—3 percent—on the Puerco River near Manuelito and on the Little Colorado River at Grand Falls. Exceedance rate was highest—6 percent—on the Puerco River near Church Rock and the Little Colorado River at Woodruff (table 5).

In contrast, most or all suspended-phase samples at all sites exceeded standards for the total recoverable fraction (table 5 and the unnumbered table on p. 24). For most constituents, more than 80 percent of the sample analyses resulted in values that exceeded standards. No standard has been established for concentrations of Ba in the total recoverable or insoluble fraction (table 4). Overall rates of exceedance at each site ranged from a low of 54 percent on the Zuni River to a high of 84 percent on the Puerco River near Church Rock and near Chambers. All other sampling sites had exceedance rates from 72 to 79 percent. The overall rate of exceedance of standards for the total recoverable fraction for all sites in the basin was 75 percent.

Analyses made during this study, which began several years after mine dewatering ended, indicated that filtered samples of streamflow generally were in compliance with the provisions of the SDWA for the constituents analyzed in this study. Suspended sediment throughout the study area contains high

Compliance, in percent	Exceedance, in percent		
99–100	Less than or equal to 10	Greater than 10 to 80	Greater than 80
	Dissolved phase		
Arsenic, barium, chromium, nickel, zinc, uranium	Beryllium, cadmium, lead, selenium, gross alpha, and gross alpha plus gross beta	Mercury, copper	None
	Suspended phase		
None	None	Arsenic, mercury, zinc	Beryllium, chromium, copper, manganese, selenium, uranium, lead, nickel, radium–226 plus radium–228, and gross alpha

concentrations of radioactive and other chemical constituents. Streamflow containing sediment at concentrations typically occurring in Puerco River runoff therefore is unfit for human consumption as defined by current water-quality standards. For example, water is likely to exceed the standard of 5 pCi/L for ^{226}Ra plus ^{228}Ra when it contains only about 2,000 mg/L of sediment, but suspended-sediment concentration commonly exceeded 100,000 mg/L in samples collected on the Puerco and Little Colorado Rivers during this study. A relation of exceedance rate to mining cannot be identified when all the constituents potentially related to mining are considered (table 5).

DISTRIBUTION OF RADIONUCLIDES AND OTHER CHEMICAL CONSTITUENTS IN STREAMFLOW

Factors that can influence the large-scale spatial distribution of radionuclides and other chemical constituents include surficial lithology, geochemical processes and fluvial transport (including the weathering and erosion of soil and rock), grain size and availability of sediment, and human activities. This section first examines the sources of chemical constituents and their distribution between the suspended and dissolved phases, and then evaluates the occurrence of certain radionuclides and selected other constituents on the basis of sediment characteristics, geographical location, and proximity to mining.

Sources of Radionuclides

Radionuclides in streamflow of the Little Colorado River are derived from rocks bearing U within the Little Colorado River Basin. Deposits of U are present naturally throughout the Colorado Plateau (Chenoweth and McLemore, 1989). In the Puerco River headwaters, uranium ore was mined extensively from the Dakota Sandstone of Cretaceous age and the Westwater Canyon Member of the Morrison Formation of Jurassic age (Hilpert, 1969; New Mexico Water Quality Control Commission, 1988; Chenoweth and McLemore, 1989). Other major rock units containing U that are extensively exposed in the Puerco and Little Colorado River Basins are the Petrified Forest and Shinarump Members of the Chinle Formation and the Kayenta Formation. The Chinle Formation is the major exposed rock unit in the Puerco and Little Colorado River Basins in Arizona and consists of fine- to medium-grained sandstone and mudstone. Uranium was mined as U_3O_8 from large open pits in the Chinle Formation near Cameron. Fossil logs bearing U are common in this area. Significant deposits of U also are found in solution-collapse breccia pipes throughout the Grand Canyon region, including the South Rim area near Cameron. Other small ore bodies are known to be present in sandstone lenses in the lower Petrified Forest Member near Holbrook (Chenoweth and McLemore, 1989; Wenrich and others, 1989).

Concentrations of U in dissolved and suspended phases of streamflow are controlled by many factors, including the pH and oxidation state of water, concentration of complexing species, and the presence of highly sorptive materials such as organic matter, Fe and Mn oxyhydroxides, and clays (Langmuir, 1978; Dongerra and Langmuir, 1980; Posey-Dowty and others, 1987). Sorption generally is a more important control on concentration of U in the suspended phase than is mineral precipitation of U (Hsi and Langmuir, 1985). In pH-neutral oxidized waters, such as runoff

Table 5. Compliance status of inorganic chemical constituents and radionuclides from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[NS, no standard; ---, no data. All values represent number of samples. Data in tables 14–16 were used with table 4 to evaluate compliance]

Constituent	Dissolved observations				Total recoverable observations[1]			
	Total number	Indeterminant[2]	Compliance	Exceeded standard	Total number	Indeterminant[2]	Compliance	Exceeded standard
Zuni River above Black Rock Reservoir, near Zuni, New Mexico (09386950)								
Arsenic	13	0	13	0	9	4	0	5
Barium	8	0	8	0	NS	NS	NS	NS
Beryllium	8	8	0	0	7	0	0	7
Cadmium	18	0	16	2	9	9	0	0
Chromium	18	0	18	0	9	0	0	9
Copper	18	0	18	0	9	0	9	0
Lead	18	8	8	2	9	0	0	9
Manganese	NS	NS	NS	NS	9	0	9	0
Mercury	10	8	0	2	3	0	3	0
Nickel	8	0	8	0	9	0	9	7
Selenium	13	0	13	0	3	0	0	3
Zinc	18	0	18	0	9	0	9	0
Uranium	1	0	1	0	8	0	3	5
Radium–226 plus radium–228	---	---	---	---	5	0	0	5
Gross alpha	10	0	10	0	10	0	1	9
Gross beta	10	0	10	0	12	0	2	10
Total	171	24	141	6	120	13	36	71
Little Colorado River at Woodruff, Arizona (09394500)								
Arsenic	4	0	4	0	13	8	0	5
Barium	8	0	8	0	NS	NS	NS	NS
Beryllium	7	6	0	1	11	0	0	11
Cadmium	8	0	8	0	13	13	0	0
Chromium	7	0	7	0	13	0	0	13
Copper	8	0	4	4	13	0	0	13
Lead	8	7	1	0	13	0	0	13
Manganese	NS	NS	NS	NS	13	0	0	13
Mercury	1	0	0	1	5	0	4	1
Nickel	8	0	8	0	13	0	0	13
Selenium	6	0	6	0	5	0	0	5
Zinc	8	0	8	0	13	0	13	0
Uranium	1	0	1	0	8	0	0	8
Radium–226 plus radium–228	1	0	1	0	8	0	0	8
Gross alpha	15	2	13	0	18	0	1	17
Gross beta	15	0	15	0	20	0	2	18
Total	105	15	84	6	178	21	20	137
Puerco River near Church Rock, New Mexico (09395350)								
Arsenic	6	0	6	0	12	4	0	8
Barium	5	0	5	0	NS	NS	NS	NS
Beryllium	5	4	0	1	5	0	0	5
Cadmium	5	0	4	1	7	7	0	0

Table 5. Compliance status of inorganic chemical constituents and radionuclides from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Constituent	Dissolved observations				Total recoverable observations[1]			
	Total number	Indeterminant[2]	Compliance	Exceeded standard	Total number	Indeterminant[2]	Compliance	Exceeded standard
Puerco River near Church Rock, New Mexico (09395350)—Continued								
Chromium	5	0	5	0	7	0	0	7
Copper	5	0	5	0	7	0	0	7
Lead	5	5	0	0	7	0	0	7
Manganese	NS	NS	NS	NS	7	0	0	7
Mercury	---	---	---	---	8	0	0	8
Nickel	5	0	5	0	7	0	0	7
Selenium	6	1	4	1	8	0	0	8
Zinc	5	0	4	1	7	0	1	6
Uranium	1	0	1	0	6	0	0	6
Radium–226 plus radium–228	---	---	---	---	2	0	0	2
Gross alpha	6	0	6	0	6	0	0	6
Gross beta	6	0	6	0	7	0	0	7
Total	75	12	59	4	103	11	1	91
Puerco River near Manuelito, New Mexico (09395630)								
Arsenic	11	0	11	0	12	4	1	7
Barium	9	0	9	0	NS	NS	NS	NS
Beryllium	8	7	0	1	5	0	0	5
Cadmium	10	0	9	1	12	11	1	0
Chromium	8	0	8	0	12	0	1	11
Copper	10	0	10	0	12	0	1	11
Lead	10	8	1	1	12	0	1	11
Manganese	NS	NS	NS	NS	12	0	1	11
Mercury	2	2	0	0	8	0	0	8
Nickel	10	0	10	0	12	0	1	11
Selenium	11	0	11	0	8	0	1	7
Zinc	10	0	10	0	12	0	1	11
Uranium	4	0	4	0	15	0	0	15
Radium–226 plus radium–228	0	---	---	---	8	0	0	8
Gross alpha	9	1	8	0	10	0	4	6
Gross beta	9	0	9	0	10	0	4	6
Total	121	18	100	3	160	15	17	128
Black Creek below West Fork Black Creek, near Houck, Arizona (09395990)								
Arsenic	2	0	2	0	7	3	0	4
Barium	6	0	6	0	NS	NS	NS	NS
Beryllium	6	6	0	0	5	0	0	5
Cadmium	6	0	6	0	7	7	0	0
Chromium	6	0	6	0	7	0	0	7
Copper	6	0	4	2	7	0	0	7
Lead	6	5	0	1	7	0	0	7

Table 5. Compliance status of inorganic chemical constituents and radionuclides from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Constituent	Dissolved observations				Total recoverable observations[1]			
	Total number	Indeterminant[2]	Compliance	Exceeded standard	Total number	Indeterminant[2]	Compliance	Exceeded standard
Black Creek below West Fork Black Creek, near Houck, Arizona (09395990)—Continued								
Manganese	NS	NS	NS	NS	7	0	0	7
Mercury	---	---	---	---	4	0	1	3
Nickel	6	0	6	0	7	0	0	7
Selenium	2	0	2	0	4	0	0	4
Zinc	6	0	6	0	7	0	3	4
Uranium	---	---	---	---	4	0	0	4
Radium–226 plus radium–228	---	---	---	---	4	0	0	4
Gross alpha	6	0	6	0	9	0	0	9
Gross beta	6	0	6	0	10	0	0	10
Total	64	11	50	3	104	10	12	82
Puerco River near Chambers, Arizona (09396100)								
Arsenic	6	0	6	0	14	4	0	10
Barium	9	0	9	0	NS	NS	NS	NS
Beryllium	9	9	0	0	13	9	0	9
Cadmium	9	0	8	1	13	13	0	0
Chromium	9	0	9	0	13	13	0	13
Copper	9	0	9	0	13	0	0	13
Lead	9	8	0	1	13	0	0	13
Manganese	NS	NS	NS	NS	13	0	0	13
Mercury	---	---	---	---	10	0	0	10
Nickel	9	0	9	0	13	0	0	13
Selenium	6	0	6	0	7	0	0	7
Zinc	9	0	9	0	10	0	0	10
Uranium	2	0	2	0	6	0	0	6
Radium–226 plus radium–228	---	---	---	---	5	0	0	5
Gross alpha	13	1	11	1	16	0	1	15
Gross beta	13	0	11	2	16	0	1	15
Total	112	18	89	5	177	17	2	158
Little Colorado River near Joseph City, Arizona (09397300)								
Arsenic	6	0	6	0	10	3	0	7
Barium	6	0	6	0	NS	NS	NS	NS
Beryllium	6	5	0	1	8	0	0	8
Cadmium	6	0	6	0	8	8	0	0
Chromium	6	0	6	0	8	0	0	8
Copper	6	0	4	2	8	0	1	7
Lead	6	6	0	0	8	0	0	8
Manganese	NS	NS	NS	NS	8	0	1	7
Mercury	---	---	---	---	7	0	2	5
Nickel	6	0	6	0	8	0	0	8
Selenium	6	0	6	0	7	0	1	6
Zinc	6	0	6	0	8	0	7	1
Uranium	1	0	1	0	4	0	0	4

Table 5. Compliance status of inorganic chemical constituents and radionuclides from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Constituent	Dissolved observations				Total recoverable observations[1]			
	Total number	Indeterminant[2]	Compliance	Exceeded standard	Total number	Indeterminant[2]	Compliance	Exceeded standard
Little Colorado River near Joseph City, Arizona (09397300)—Continued								
Radium–226 plus radium–228	---	---	---	---	4	0	0	4
Gross alpha	16	3	12	1	14	0	2	12
Gross beta	16	1	14	1	15	0	13	12
Total	93	15	73	5	125	11	17	97
Little Colorado River at Grand Falls, Arizona (09401000)								
Arsenic	13	0	13	0	11	9	0	2
Barium	14	0	14	0	NS	NS	NS	NS
Beryllium	14	14	0	0	11	0	0	11
Cadmium	14	0	13	1	11	11	0	0
Chromium	14	0	14	0	11	0	0	11
Copper	14	0	11	3	11	0	1	10
Lead	14	13	0	1	11	0	0	11
Manganese	NS	NS	NS	NS	11	0	0	11
Mercury	---	---	---	---	2	0	1	1
Nickel	14	0	14	0	11	0	0	11
Selenium	13	1	12	0	2	0	1	1
Zinc	14	0	14	0	11	0	6	5
Uranium	2	0	2	0	6	0	0	6
Radium–226 plus radium–228	---	---	---	---	4	0	0	4
Gross alpha	8	0	8	0	7	0	0	7
Gross beta	8	0	8	0	7	0	0	7
Total	156	28	123	5	127	20	9	98
Little Colorado River near Cameron, Arizona (09402000)								
Arsenic	8	0	8	0	6	1	0	5
Barium	8	0	8	0	NS	NS	NS	NS
Beryllium	7	7	0	0	6	0	0	6
Cadmium	8	0	6	2	6	6	0	0
Chromium	8	0	8	0	6	0	0	6
Copper	8	0	7	1	6	0	0	6
Lead	8	5	3	0	6	0	0	6
Manganese	NS	NS	NS	NS	6	0	0	6
Mercury	---	---	---	---	5	0	3	2
Nickel	7	0	7	0	6	0	0	6
Selenium	8	1	6	1	5	0	0	5
Zinc	8	0	8	0	6	0	4	2
Uranium	2	0	2	0	3	0	0	3
Radium–226 plus radium–228	---	---	---	---	1	0	0	1
Gross alpha	4	1	3	0	3	0	0	3
Gross beta	4	0	4	0	3	0	0	3
Total	88	14	70	4	74	7	7	60

[1]For the radioactive constituents, uranium through thorium (total fraction), compliance evaluation was based on the insoluble or suspended fraction.

[2]Compliance status was indeterminant because calculated or reported detection limit is greater than the water-quality standard limit, or within the range of analytical precision.

in the Little Colorado River Basin, U can be present in both the dissolved and solid phases. Ra generally is insoluble because it is strongly sorbed on solid-phase constituents and substitutes for other divalent cations during replacement or precipitation reactions (Ames and Rai, 1978; Langmuir and Riese, 1985). Th forms insoluble compounds at near-neutral pH and is strongly adsorbed by clay (Ames and Rai, 1978; Langmuir and Herman, 1980). In general, adsorption of U, Ra, and Th tends to increase with decreasing particle size. ^{222}Rn does not occur in significant quantities in ephemeral surface water or surficial sediment because it is a gas and has a half-life of only 3.8 days.

Variations in ratios of individual isotopes can provide an indication of the different processes that enrich one isotope species relative to another. A less-than-unity (<1) value of ^{234}U/^{238}U indicates that ^{234}U has been depleted by leaching or incongruent dissolution. Alpha recoil, the primary fractionation mechanism for isotopes of U, causes destruction of the mineral lattice and positioning of ^{234}U in an unstable lattice configuration where it is more vulnerable to leaching than its neighboring atoms (Osmond and Cowart, 1976, 1982). Studies indicate that suspended sediment from rivers typically is depleted in ^{234}U, with an average activity ratio of 0.94, whereas the activity ratio for the dissolved phase of river water typically is 1.2 to 1.3 (Osmond and Cowart, 1976; Scott, 1968; 1982, p. 191–195; Sarin and others, 1990). Preferential leaching of radiogenic ^{234}U from silicates has been suggested as a cause for the observed ^{234}U depletion in sediments in areas of abundant siltstones and sandstones (Osmond and Cowart, 1976; Rosholt, 1982, p. 171; Hussain and Lal, 1986). Suspended sediment from the Puerco River, Black Creek, and the Zuni River is depleted in ^{234}U (table 6), indicating that some U has been leached from the solid phase to the dissolved phase.

Sorption of Th increases with increasing pH and generally is complete at a pH greater than 6.5 (Langmuir and Herman, 1980). The range of pH in runoff in the Puerco River generally is from 7.0 to 8.5; therefore, loss of Th due to leaching is unlikely. Excess ^{230}Th relative to ^{238}U results from either preferential leaching or dissolution of U, preferential sorption of Th on the solid phase, or both (Sarin and others, 1990). Excess ^{238}U relative to ^{230}Th may result from sorption or precipitation of U on sediment, whereas depletion of ^{238}U relative to ^{230}Th occurs when U is soluble. In most near-surface environments, U is partitioned between the dissolved phase and the solid phase until it encounters a reducing environment where it becomes insoluble (Ames and Rai, 1978). Weathering and dissolution of U is suggested by the predominantly greater-than-unity values of ^{230}Th/^{238}U in suspended sediments in the Little Colorado River at Woodruff (table 6). Less-than-unity values in the Zuni River indicate dissolved U may have precipitated or sorbed to suspended sediments. No trend in values of ^{230}Th/^{238} U is apparent for suspended-sediment samples from any of the Puerco River sites, the sampling site on Black Creek, or the sampling site on the Little Colorado River below Holbrook (table 6). Although ^{230}Th/^{238}U values range from 0.68 to 1.88 for these 58 samples, the mean (± standard error) and median values (1.07±0.26 and 1.02, respectively) approach unity, suggesting that although variations in U solubility may occur on a local scale, on a larger scale, the net loss of U from the basin is probably not significant.

Distribution of Radioactivity and Chemical Constituents Between Dissolved and Suspended Phases

The occurrence of many chemical constituents in streamflow in the Little Colorado River Basin is controlled largely by the concentration of fine-grained suspended sediment because most chemical constituents in runoff are in the suspended phase. For example, a whole-water sample of Puerco River streamflow collected on August 31, 1988, near Manuelito (fig. 1) had 2,700 pCi/L gross-alpha radioactivity and 2,900 pCi/L gross-beta radioactivity. A filtered subsample had 4.0 pCi/L gross-alpha radioactivity and 7.1 pCi/L gross-beta radioactivity—three orders of magnitude less than the radioactivity of the unfiltered water sample, or less than 0.5 percent of the total radioactivity.

In general, the higher the concentration of suspended sediment, the greater the total radioactivity and the concentration of chemical constituents in a water sample. Gallaher and Cary (1986) found a linear, first-order, positive relation between concentrations of selected chemical constituents and concentration of suspended sediment. The relation was different for each constituent and for each drainage basin. Gallaher and Cary (1986) postulated that the difference in the relation of constituent concentration to sediment concentration between basins was caused

Table 6. Radioactivity and activity ratios for suspended sediment from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[pCi/g, picocuries per gram; ---, no data. Methods: M, automated sample collected from a point location; C, composited from several automated point samples representing different phases of the hydrograph; B, bottom material; G, grab or dip sample; D, manually collected sample at equal distance intervals]

Record Number[1]	Date	Time	Method	Uranium–238 (pCi/g)	Uranium–234 (pCi/g)	$^{234}U/^{238}U$	Radium–226 (pCi/g)	Radium–228 (pCi/g)	Thorium–232 (pCi/g)	Thorium–230 (pCi/g)	$^{230}Th/^{238}U$	Lead–210 (pCi/g)
Zuni River above Black Rock Reservoir, New Mexico (09386950)												
RC-89-0297	07–26–89	0320	M	1.86±0.14	1.66±0.14	0.89	1.70±0.15	1.40±0.25	1.47±0.12	1.41±0.12	0.76	2.60±0.40
RC-89-0295	07–26–89	0210	M	1.59±.12	1.42±.12	.89	1.71±.15	1.90±.30	1.44±.18	1.40±.15	.88	2.60±.30
RC-89-0299	07–26–89	1200	C	2.2±.16	2.11±.16	.95	1.83±.15	1.60±.25	1.86±.16	1.39±.12	.62	2.70±.40
RC-89-0296	07–26–89	0240	M	1.7±.14	1.49±.14	.88	1.61±.15	1.80±.20	1.69±.14	1.38±.12	.82	2.90±.20
RC-89-0298	07–26–89	0500	M	3.63±.24	3.48±.22	.96	3.70±.30	1.70±.30	3.40±.30	1.56±.16	.43	4.50±.50
Little Colorado River at Woodruff, Arizona (09394500)												
RC-89-0316	08–18–89	1200	C	.91±.12	.91±.12	1.00	.96±.09	1.13±.11	1.14±.12	1.13±.18	1.24	1.30±.30
RC-89-0315	08–18–89	1740	M	1.01±.10	.93±.10	.92	.99±.09	1.16±.10	1.22±.12	1.30±.20	1.29	1.81±.40
RC-89-0312	07–23–89	1230	M	.96±.12	.73±.10	.76	1.04±.09	1.32±.12	1.22±.13	.89±.16	.93	2.10±.30
RC-89-0313	07–23–89	1010	M	.92±.11	.90±.11	.98	1.01±.09	1.15±.11	1.14±.12	1.18±.24	1.28	1.60±.30
RC-89-0317	07–23–89	1200	C	.97±.12	1.18±.13	1.22	1.08±.09	1.17±.11	1.07±.12	1.20±.21	1.24	1.48±.24
RC-89-0314	07–23–89	1510	M	1.02±.11	.87±.10	.85	2.40±.20	1.47±.13	1.46±.14	1.48±.21	1.45	1.50±.30
903610106	08–16–90	(2)	---	.99±.23	1.17±.25	1.18	1.13±.1	---	.99±.26	1.27±.39	1.28	---
910170158	01–06–91	1840	M	1.03±.14	.96±.13	.93	---	---	.92±.13	.91±.1	.88	---
RC-88-0777	---	(2)	B	1.15±.09	1.06±.08	.92	1.27±.08	2.60±.30	1.40±.10	1.50±.10	1.30	1.30±.50
Puerco River near Church Rock, New Mexico (09395350)												
RC-88-0778	---	(2)	B	2.10±.10	2.0±.10	.95	1.89±.11	3.0±.30	1.90±.10	1.80±.10	.86	1.60±.50
RC-89-0332	09–05–89	2110	M	1.48±.14	1.39±.14	.94	1.32±.12	1.60±.14	1.59±.16	1.40±.50	.95	2.11±.50
903530071	07–09–90	2020	M	1.12±.30	1.47±.33	1.31	---	---	1.52±.18	1.43±.18	1.28	---
903530075	07–09–90	2120	M	.63±.17	.80±.20	1.27	---	---	.79±.23	.70±.2	1.11	---
903530070	07–12–90	0100	M	1.24±.30	1.32±.31	1.06	---	---	.92±.21	1.07±.2	.86	---
903530062	08–15–90	1030	---	1.41±.34	1.26±.32	.89	1.49±.2	---	1.50±.19	1.35±.18	.96	---

Table 6. Radioactivity and activity ratios for suspended sediment from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record Number[1]	Date	Time	Method	Uranium–238 (pCi/g)	Uranium–234 (pCi/g)	$^{234}U/^{238}U$	Radium–226 (pCi/g)	Radium–228 (pCi/g)	Thorium–232 (pCi/g)	Thorium–230 (pCi/g)	$^{230}Th/^{23}U$	Lead–210 (pCi/g)
Puerco River near Manuelito, New Mexico (09395630)												
903530055	08–14–90	2035	---	0.87±.13	1.46±.19	1.68	---	---	---	---	---	---
RC-89-0331	09–06–89	0110	M	1.31±.14	1.28±.14	.98	1.40±.12	1.26±.12	1.39±.15	1.10±.30	0.84	1.09±.23
RC-89-0329	09–06–89	0130	M	1.53±.15	1.54±.15	1.01	1.43±.12	1.54±.15	1.72±.18	1.90±.20	1.24	1.80±.40
RC-89-0330	09–06–89	0120	M	1.42±.15	1.58±.16	1.11	1.27±.14	1.41±.14	1.42±.16	1.10±.30	.77	1.80±.40
903530072	10–20–90	0330	M	1.36±.27	1.0±.22	.74	---	---	1.23±.16	1.30±.17	.96	---
903530074	10–20–90	0030	M	1.24±.26	1.29±.27	1.04	---	---	1.60±.55	1.73±.5	1.40	---
903530073	10–20–90	0200	M	1.26±.28	1.13±.27	.90	---	---	1.47±.31	1.59±.3	1.26	---
903530065	07–13–90	1900	M	1.40±.25	1.27±.23	.91	---	---	---	---	---	---
903530064	07–13–90	1950	M	1.21±.23	1.29±.24	1.07	---	---	---	---	---	---
903530069	07–13–90	2010	---	1.02±.25	1.27±.29	1.25	1.19±.2	---	1.04±.15	1.18±.10	1.16	---
903530068	07–13–90	1850	---	1.3±.3	1.2±.3	.96	1.3±.2	---	1.12±.16	1.02±.11	.80	---
903530067	07–13–90	1920	---	1.49±.31	1.20±.27	.81	1.35±.2	---	1.39±.18	1.33±.13	.89	---
903530063	08–15–90	0800	---	---	1.27±.40	---	1.32±.2	---	1.23±.16	1.28±.12	---	---
Black Creek below West Fork Black Creek, near Houck, Arizona (09395990)												
RC-89-0322	09–05–89	2050	M	1.45±.14	1.48±.14	1.02	1.73±.15	1.64±.14	1.71±.16	1.60±.20	1.10	2.0±.30
RC-89-0320	09–05–89	2020	M	1.30±.12	1.06±.11	.82	1.31±.11	1.52±.12	1.39±.13	1.30±.20	1.00	1.70±.25
RC-89-0323	09–05–89	2200	M	1.38±.12	1.33±.12	.96	1.30±.11	1.54±.13	1.67±.15	1.30±.40	.94	2.40±.30
RC-89-0324	09–05–89	2320	M	1.40±.13	1.34±.13	.96	1.42±.12	1.50±.12	1.44±.13	1.40±.20	1.00	2.70±.30
Puerco River near Chambers, Arizona (09396100)												
RC-88-0776	---	(2)	B	1.35±0.10	1.34±0.09	0.99	.95±0.06	2.20±0.30	1.32±0.10	1.30±0.10	0.96	3.0±0.60
RC-89-0321	09–06–89	1515	G	1.42±.13	1.36±.13	.96	1.37±.12	1.38±.12	1.50±.14	1.60±.30	1.13	1.40±.30
RC-89-0319	09–06–89	1440	M	1.32±.13	1.21±.13	.92	1.46±.12	1.43±.12	1.54±.14	1.10±.20	.83	1.90±.30
RC-89-0318	09–06–89	1510	M	1.47±.12	1.40±.12	.95	1.30±.12	1.45±.12	1.50±.14	1.50±.30	1.02	2.40±.30

Table 6. Radioactivity and activity ratios for suspended sediment from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record Number[1]	Date	Time	Method	Uranium–238 (pCi/g)	Uranium–234 (pCi/g)	$^{234}U/^{238}U$	Radium–226 (pCi/g)	Radium–228 (pCi/g)	Thorium–232 (pCi/g)	Thorium–230 (pCi/g)	$^{230}Th/^{23}U$	Lead–210 (pCi/g)
Puerco River near Chambers, Arizona (09396100)												
903510192	10–20–90	0800	---	1.06±.28	0.90±.25	0.85	---	---	0.87±.21	0.90±.21	0.85	---
903610105	08–15–90	0250	---	1.41±.29	1.19±.27	.84	1.27±.2	---	1.40±.36	1.54±.31	1.09	---
Little Colorado River near Joseph City, Arizona (09397300)												
910310032	08–15–90	1820	D	1.38±.17	1.36±.17	.99	1.68±.3	---	1.74±.21	1.88±.22	1.36	---
910170163	10–20–90	0800	---	1.29±.16	1.10±.14	.85	---	---	1.37±.18	1.26±.1	.98	---
903610099	08–16–90	1645	---	1.12±.24	1.37±.27	1.22	---	---	1.33±.32	1.59.36	1.42	---
903610102	08–16–90	1750	---	1.0±.23	1.21±.25	1.21	1.27±.2	---	1.20±.34	1.41±.32	1.41	---
910170159	01–07–91	1620	D	1.0±.14	1.01±.14	1.01	---	---	.85±.18	.96±.1	.96	---
910310033	07–14–90	(2)	M	.96±.13	.13±.04	.14	.90±.1	---	1.0±.14	.89±.14	.93	---
Little Colorado River at Grand Falls, Arizona (09401000)												
903610101	07–17–90	1800	C	1.31±.26	1.16±.24	.89	---	---	1.18±.31	1.37±.34	1.05	---
903610104	07–17–90	1840	C	1.03±.22	1.10±.23	1.07	1.26±.2	---	1.62±.35	1.58±.35	1.53	---
910730033	03–05–91	(2)	M	1.7±.20	2.46±.27	1.44	---	---	1.14±.15	1.17±.1	.68	---
910730028	03–05–91	1300	C	1.1±.16	1.07±.16	1.01	---	---	1.26±.17	1.04±.1	.98	---
910170157	01–07–91	(2)	M	1.05±.14	1.03±.14	.98	---	---	1.01±.15	1.25±.1	1.19	---
903610103	08–17–90	1230	---	1.46±.29	1.34±.27	.92	1.34±.2	---	1.48±.34	1.50±.32	1.03	---
Little Colorado River near Cameron, Arizona (09402000)												
RC-88-0782	---	(2)	B	1.3±0.1	1.32±0.09	1.03	1.14±0.07	2.40±0.30	1.30±0.10	1.40±0.10	1.09	2.70±0.70
903610100	08–19–90	1245	---	1.1±.2	1.03±.22	.93	1.28±.2	---	1.17±.32	1.65±.41	1.49	---
910170155	01–08–91	1530	---	.97±.01	1.01±.15	1.04	---	---	1.71±.24	1.82±.2	1.88	---
910730027	03–07–91	1400	C	.92±.12	.82±.11	.89	---	---	.94±.13	1.01±.1	1.10	---

[1]Record number is an arbitrary number assigned to each sample by the USGS National Water-Quality Laboratory when the sample is received. The record number uniquely identifies each sample in the USGS water-quality data base. Record numbers beginning with the letters "RC" were analyzed by the New Mexico Scientific Laboratory. All other samples were analyzed by USGS laboratories or by contract laboratories approved by the USGS.

[2]Composite from different sampling times.

by differences in character of the sediment-source material. In this report, the radioactivity in the dissolved phase is considered insignificant relative to the radioactivity of the sediment phase for statistical analysis of samples containing high concentrations of suspended sediment. Although the dissolved phase was considered an insignificant fraction of the total chemical transport during the study, the presence of certain dissolved constituents may still be important from a health standpoint.

Concentration of constituents in both dissolved and suspended phases was determined for 57 streamflow samples from nine gages and Pipeline Arroyo under a range of runoff conditions. Discharge at the time of sample collection ranged from 0.4 to 125 m^3/s, and suspended-sediment concentration ranged from 11,800 to 312,000 mg/L. Constituent concentration in the dissolved phase was determined as mass per volume (milligrams per liter), and concentration in the suspended phase was determined as mass per mass (as milligrams per gram, micrograms per gram, or as percentage of total sample weight, depending on the constituent). Suspended-phase concentration was converted to the dissolved-phase units using the suspended-sediment concentration of the sample to compute the percentage of constituent in the suspended phase of a sample. After unit conversion, the percentage of a constituent in the suspended phase was calculated as follows:

$$\text{Suspended fraction} = \frac{C_s}{(C_s + C_d)},$$

where

Suspended fraction = percentage of the total amount of the constituent in the sample in the suspended phase,

C_s = concentration of the constituent in the suspended phase, and

C_d = concentration of the constituent in the dissolved phase.

The percentage of constituent in the suspended phase was calculated for Ca, Na, K, Ba, Fe, Mn, strontium (Sr), zinc (Zn), lithium (Li), V, and U (table 7). Variability of that percentage among samples and constituents was small, and results show that typically 99 percent or more of the measured chemical constituents occurs in the suspended phase of a streamflow sample.

Concentrations of dissolved and suspended As and Cd and dissolved Be, cobalt (Co), Cr, Pb, Hg, Mo, Ni, silver (Ag), and Se generally were below the detection limit of the analytical method, and thus the percentage of the total constituent in the suspended phase could not be determined. The relation between the dissolved and suspended phases for these constituents is expected to be similar to that of the constituents in table 7.

Relation of Constituent Concentration to Suspended-Sediment Properties

Previous studies have shown that materials with large surface areas are the main sites for sorption of trace inorganic constituents (Horowitz, 1985). Studies of suspended-sediment chemistry and physical properties have shown that metal concentration has a strong inverse correlation with grain size (higher concentration for smaller grain size) and a strong positive correlation with surface area, surface charge, cation-exchange capacity, concentration of Fe and Mn oxides, organic matter, and clay minerals (Horowitz, 1985; Horowitz and Elrick, 1987). For the same mass, clay-sized sediments (less than 0.002–0.004 mm) have surface areas that are

Table 7. Percentage, by mass, of chemical constituents in the suspended phase of streamflow samples, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[Percentage based on median of 57 samples except for uranium, which was based on median of 6 samples]

Constituent	Percentage of constituent in suspended phase, standard deviation
Calcium	99.96±0.06
Sodium	99.72±.01
Potassium	99.99±.00
Barium	99.24±.02
Iron	99.00±.01
Manganese	99.41±.32
Strontium	99.06±.08
Zinc	99.41±.30
Lithium	99.09±.09
Vanadium	99.42±.28
Uranium	99.95±.07

typically an order of magnitude larger than sand-sized particles (Grim, 1968; Jones and Bowser, 1978).

Measurement of surface area and concentration of 14 constituents on suspended sediment in seven water-sediment samples from the Puerco River and 1 each from the Little Colorado River at Woodruff, Black Creek, and Zuni River shows that sediments have large surface areas. The surface area of sediment in samples from the Puerco River ranged from 13.99 to 47.74 m^2/g and averaged 35.9 m^2/g, which was comparable to measured values reported by Horowitz (1985, p. 26) for various clay minerals. Surface areas of sediment in samples from the Little Colorado and Zuni Rivers and Black Creek were 44.81, 53.72, and 37.18 m^2/g, respectively. For all samples, surface area was significantly correlated with concentrations of Fe, Al, and titanium (Ti); correlations were 0.97, 0.85, and 0.76, respectively. The correlation between surface area and these metals indicates that metals form oxide coatings on grain surfaces that then serve as sorption sites for other constituents (Horowitz, 1985). For sediments analyzed, Mn was not significantly correlated with surface area, suggesting that Mn oxide coatings on suspended sediments are not prevalent in the study area. Concentration of Fe on measured sediments is significantly correlated with concentrations of Cu, Ni, Co, and Cr; Al with Cu, Pb, Zn, Co, Cr, and Se; and Ti with Cu, Pb, Zn, Co, Cr, As, and Se. Concentrations of Hg, As, and antimony (Sb) on sediments also were measured, but those concentrations had no significant correlation with either surface area or concentrations of Fe, Al, and Ti.

According to Haywood and others (1977, p. 5–6), radioactivity in uranium-mill tailings is found in both the sand and fine fractions but is concentrated in the fine fraction. In the terminology used in mining, the fine fraction is called slime and is typically material equal to or less than 0.074 mm in size. Slime generally makes up about 20 percent of the total volume and about 80 percent of the natural radioactivity of tailings (Haywood and others, 1977). The radioactivity of ^{226}Ra in slimes resulting from the processing of western ores may reach 3,000 pCi/g, whereas radioactivity in the sand fraction generally is an order of magnitude less. In addition, radionuclides in liquid processing wastes and mine-dewatering effluent were probably adsorbed on suspended and bed sediments. Sorption on sediments is the most likely fate for radionuclides and other chemical constituents of concern in the study area.

Streamflow in the Little Colorado River Basin has the capacity to transport large loads of chemical constituents in the suspended phase not only because suspended-sediment concentrations are among the highest measured in the United States but also because of the physical and chemical properties of the suspended sediment. Grain size and mineralogy of selected samples were measured to characterize the chemical-carrying capacity of suspended sediment. Suspended-sediment samples collected during the study period commonly contained more than 90 percent (by weight) silt- and clay-sized material (fig. 7). Suspended-sediment samples from the Puerco River contained a higher percentage of sand than those from other streams studied, and the percentage of sand tended to decrease with distance downstream in the Puerco River (fig. 7).

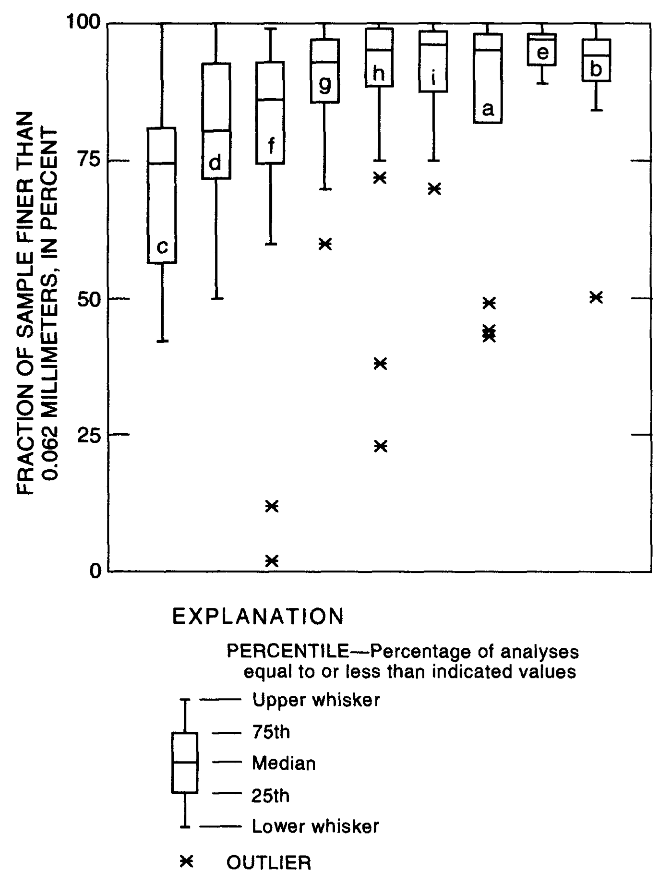

Figure 7. Percentage of total sample weight finer than 0.062 millimeter for suspended-sediment samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico. The letters inside the boxes correspond to gaging stations listed in table 1.

The fine fraction—less than 0.062 mm—of suspended sediments in the Puerco, Little Colorado, and Zuni Rivers was predominantly smectite (table 8). Smectite is a "shrink-swell" clay known for its high cation-exchange capacity. Bed material, however, contained only trace amounts of clay minerals (table 8). Bed material from the Puerco River, collected approximately 0.5 m below the surface of the dry streambed, was a medium-grained sand with a small amount of material finer than sand. Because suspended-sediment samples generally were fine sediment, both suspended-sediment and bed-material analyses are assumed to represent the mineralogy of the whole sample.

Table 8. Mineralogy of suspended sediment and bed material, Puerco and Little Colorado River Basins, Arizona and New Mexico

[All numbers are in percent of total sample, by weight. The fine fraction is the fraction less than 0.062 mm in diameter. ---, no fraction for indicated mineral]

Mineral	Suspended sediment (fine fraction)[1]	Bed material (all sizes)[2]
Kaolinite	0–20	Trace.
Illite	0–20	Do.
Smectite	60–100	Do.
Quartz	---	60–73
Potassium feldspar	---	15–25
Plagioclase	---	5–10
Calcite	---	2–5

[1]Analysis of five suspended-sediment samples from streamflow-gaging stations at Puerco River near Church Rock, New Mexico, Puerco River near Manuelito, New Mexico, Puerco River near Chambers, Arizona, Little Colorado River at Woodruff, Arizona, and at Zuni River above Black Rock Reservoir, New Mexico.

[2]Bed-material samples were collected about 0.5 meter below the streambed at Puerco River near Church Rock, New Mexico, Puerco River near Lupton, Arizona, and at Black Creek below West Fork Black Creek, near Houck, Arizona.

Spatial Variation in Chemistry of Suspended Sediment

Sixty-five suspended-sediment samples from the nine streamflow-gaging stations and Pipeline Arroyo were analyzed for ^{238}U, ^{234}U, ^{228}Ra, ^{230}Th, and ^{232}Th. Seventy-one samples were analyzed for 40 other chemical constituents. Nonradioactive constituents were analyzed to determine the concentration of constituents known to be related to mining and to characterize the chemical properties of the sediment. Variations in sediment chemistry were examined in relation to several factors, including location of sample collection sites relative to mining, overall location within the basin, and grain size of sediment. In addition, suspended-phase chemistry was compared with chemistry of near-stream alluvium from well cuttings near Chambers.

If the Puerco River was significantly affected by releases of radionuclides by mining, the highest sediment radioactivity would be expected at sites on the Puerco River downstream from Pipeline Arroyo. Laboratory analyses of radionuclides, reported in picocuries per gram, enable comparisons between analytical results that are independent of variations caused by differences in sediment concentration (fig. 8 and table 9). Paired *t*-tests (Iman and Conover, 1983, p. 246) were used to determine whether the mean radioactivity of samples collected from streamflow-gaging stations on the Puerco River downstream from mining is significantly higher than the mean of samples from background sampling sites—Black Creek, Zuni River, and Little Colorado River at Woodruff (table 9). All samples included in this analysis are a subset from the eastern Little Colorado River Basin. Low two-sided probability values ($p \leq 0.2$) indicate that group means are different at a confidence level of at least 90 percent. The *t*-test results indicate that means of ^{238}U, ^{234}U, and ^{228}Ra radioactivity for samples downstream from mining are significantly different from those for samples collected from background sites. The mean radioactivity for each of these constituents, however, is lower for samples downstream from mining than for background sites (table 9). Radioactivity of ^{230}Th and ^{232}Th for sites potentially affected by mining and background sites are not significantly different (table 9).

To test for the influence of factors related to location in the basin, such as lithology, samples were grouped into those collected at gaging stations in the eastern part of the Little Colorado River Basin (fig. 8)—Puerco River and its tributaries, Zuni River, and Black Creek—and samples collected at gaging stations on the lower main stem of the Little Colorado River—at Woodruff, near Joseph City, at Grand Falls, and near Cameron. The *t*-tests were used to determine whether the difference between the mean radioactivity of samples from the eastern tributaries and the mean of samples from the main stem Little Colorado River is statistically significant (table 10). For these tests, the

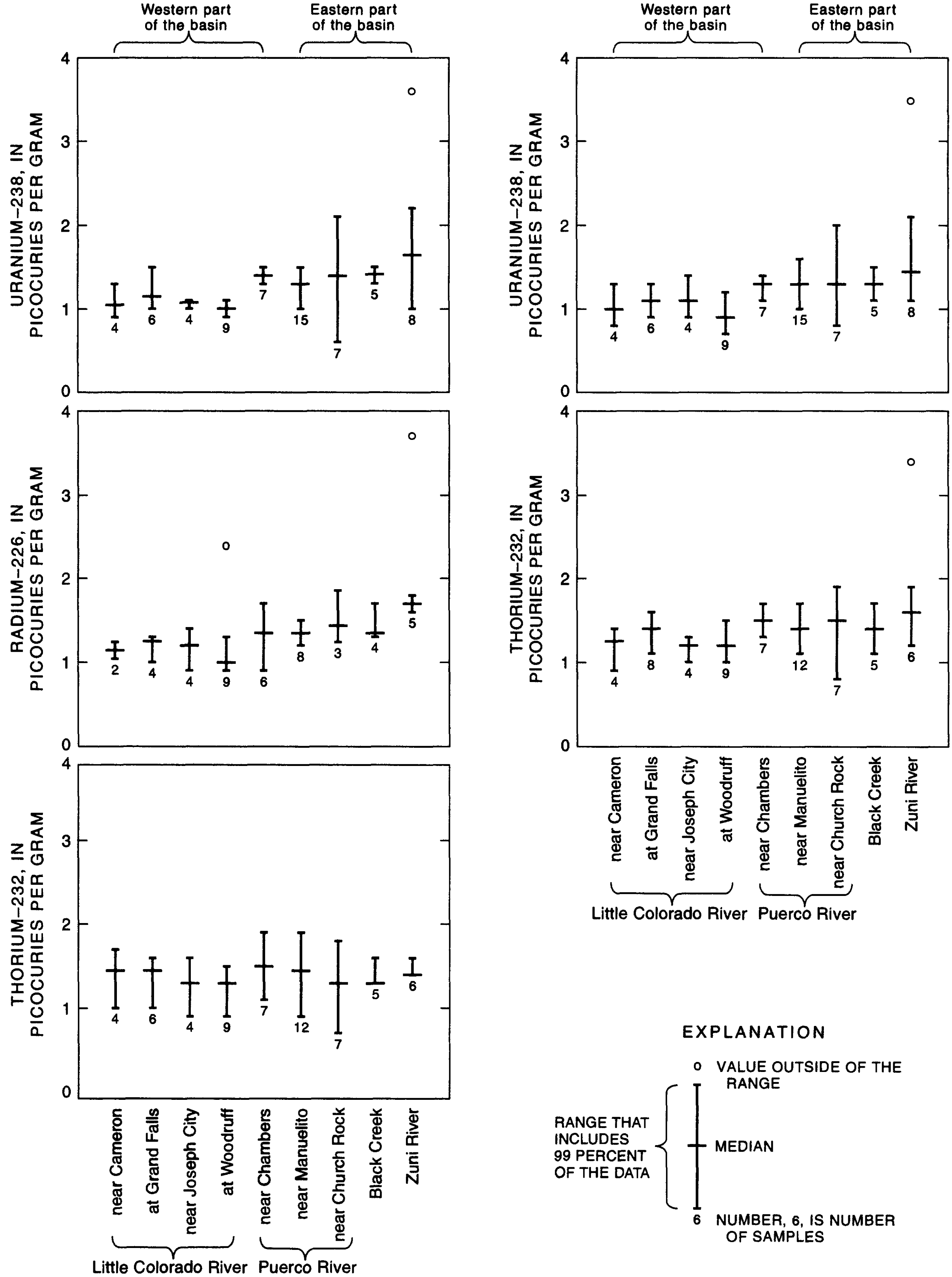

Figure 8. Radioactivity of radionuclides at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico.

Table 9. Results of *t*-tests for suspended-sediment samples collected from sites potentially affected by mining and from background sites, Puerco and Little Colorado River Basins, Arizona and New Mexico

[Sites potentially affected by mining are Puerco River at Pipeline Arroyo and below Pipeline Arroyo and streamflow-gaging stations Puerco River near Church Rock, New Mexico; Puerco River near Manuelito, New Mexico; and Puerco River near Chambers, Arizona. Background sites are Zuni River, Little Colorado River at Woodruff, South Fork Puerco River, Manuelito Wash of the Puerco River, and Black Creek. Data from one sample from Zuni River was omitted from the analysis because it was a very high outlier that had a strong influence on the mean]

		Sites potentially affected by mining		Background sites	
Constituent	Two-sided p value	Sample mean plus or minus standard error	Number of samples	Sample mean plus or minus standard error	Number of samples
Radionuclides, in picocuries per gram					
Uranium–238	[1]0.0564	1.31±0.04	17	1.48±0.09	12
Uranium–234	[1].1280	1.28±.04	17	1.40±.08	12
Radium–228	[1].0577	1.39±.03	17	1.56±.07	8
Thorium–230	.5504	1.45±.05	17	1.50±.08	10
Thorium–232	.9810	1.39±.06	17	1.39±.03	10
Other chemical constituents, in micrograms per gram except as noted					
Aluminum, in percent	.2597	8.5±.3	20	9.0±.3	26
Barium	.9409	578±16	20	579±15	26
Beryllium	.2393	2.00±.07	20	2.12±.06	26
Calcium, in percent	[1].0051	1.47±.09	20	2.41±.29	26
Cerium	.5699	78±2	20	76±3	26
Chromium	[1].0110	45±2	20	52±2	26
Cobalt	[1].0008	11.7±.3	20	13.3±.3	26
Copper	[1].0081	22.0±.5	20	24.7±.8	26
Gallium	[1].1724	19.7±.7	20	21.1±.7	26
Iron, in percent	[1].0350	2.99±.12	20	3.30±.09	26
Lanthanum	.4911	43±1	20	41±1	26
Lead	[1].1248	21.4±.5	20	23.0±.9	26
Lithium	[1].1136	36±2	20	39±1	26
Magnesium, in percent	[1].0010	.86±.05	20	1.30±.11	26
Manganese	[1].0004	365±13	20	494±28	26
Neodymium	.9442	35±1	20	35±1	26
Nickel	[1].0001	16.5±.8	20	21.9±.9	26
Niobium	.2783	11.0±.7	20	12.2±.8	26
Phosphorus, in percent	.2022	.051±.002	20	.054±.002	26
Potassium, in percent	.5549	1.97±.02	20	1.94±.06	26
Scandium	.2269	12.0±.5	20	12.8±.4	26
Sodium, in percent	[1].0208	.51±.03	20	.38±.04	26
Strontium	.2022	165±5	20	186±16	26
Thorium	.6616	14.2±.5	20	13.9±.5	25
Titanium, in percent	.2452	.40±.01	20	.38±.02	26
Vanadium	.8211	89±4	20	90±3	26
Yttrium	.8069	24.2±.8	20	24.5±.7	26
Ytterbium	[1].1029	3.10±.28	20	2.65±.10	26
Zinc	.6510	80±3	20	78±3	26

[1]Difference between sample means is significant at a 0.2 level.

Table 10. Results of *t*-tests for suspended-sediment samples collected from the eastern and western parts of the Little Colorado River Basin, Arizona and New Mexico

[Samples from the eastern basin include those from the Zuni River, Black Creek, and Puerco River. Samples from the western basin are from Little Colorado River at Woodruff, Little Colorado River near Joseph City, Little Colorado River at Grand Falls, and Little Colorado River near Cameron, Arizona. Data from one sample from Zuni River was omitted from the analysis because it was a very high outlier that had a strong influence on the mean]

Constituent	Two-sided p value	Eastern Little Colorado River Basin above confluence of Puerco River		Western Little Colorado River Basin below confluence of Puerco River	
		Sample mean plus or minus standard error	Number of samples	Sample mean plus or minus standard error	Number of samples
Radionuclides, in picocuries per gram					
Uranium–238	[1]0.0002	1.44±0.07	42	1.06±0.03	23
Uranium–234	[1].0003	1.39±.06	42	1.04±.04	23
Radium–228	[1].0134	1.53±.10	26	1.19±.08	19
Thorium–230	[1].0026	1.52±.07	37	1.24±.04	23
Thorium–232	[1].1683	1.41±.04	37	1.31±.05	23
Other chemical constituents, in micrograms per gram except as noted					
Aluminum, in percent	[1].1368	8.94±.26	35	8.45±.19	36
Barium	[1].1566	573±10	35	547±15	36
Beryllium	[1].1573	2.09±.06	35	1.97±.05	36
Calcium, in percent	[1].0000	1.45±.09	35	3.10±.16	36
Cerium	[1].0000	81±2	35	65±1	36
Chromium	.7275	48±1	35	49±1	36
Cobalt	[1].0004	12.2±.3	35	13.6±.3	36
Copper	[1].1162	23±.5	35	24±.7	36
Gallium	[1].0417	20.9±.6	35	19.3±.4	36
Iron, in percent	[1].1624	3.12±.09	35	3.29±.08	36
Lanthanum	[1].0000	44±1	35	36±1	36
Lead	.4798	22.7±.6	35	21.6±1.4	36
Lithium	[1].1599	37±1	35	40±1	36
Magnesium, in percent	[1].0000	.87±.04	35	1.64±.05	36
Manganese	[1].0000	372±9	35	563±13	36
Neodymium	[1].0000	36±.3	35	30±.5	36
Nickel	[1].0000	17.8±.6	35	22.2±.7	36
Niobium	[1].0000	12.8±.6	35	8.7±.3	36
Phosphorus, in percent	[1].0020	.051±.001	35	.058±.0017	36
Potassium, in percent	[1].1556	1.95±.02	35	1.88±.04	36
Scandium	.4710	12.6±.4	35	12.2±.3	36
Sodium, in percent	.3608	.45±.03	35	.49±.03	36
Strontium	[1].0000	153±5	35	276±10	36
Thorium	[1].0000	14.7±.4	35	12.1±.41	36
Titanium, in percent	[1].0000	.41±.01	35	.34±.01	36
Vanadium	[1].0100	92±3	35	83±2	36
Yttrium	[1].0000	25.3±.6	35	22.3±.3	36
Ytterbium	[1].0037	2.97±.17	35	2.42±.08	36
Zinc	[1].0000	82±1	35	67±2	36

[1]Difference between sample means is significant at a 0.2 level.

null hypothesis was that the two groups of samples are from the same population, and the significance level for rejection was $p \leq 0.2$. The *t*-test results indicate that, for ^{238}U, ^{234}U, ^{228}Ra, ^{230}Th, and ^{232}Th radioactivity, the group means are significantly different and that mean values are higher in the eastern tributaries than on the main stem Little Colorado River. The two sets of *t*-tests suggest that variations in radioactivity of suspended sediment are more closely related to basin-wide differences in the lithology and hydrology than to the influence of uranium mining.

The 71 samples analyzed for 40 nonradioactive chemical constituents consisted solely of the fraction of the sample finer than 0.062 mm, whereas radionuclide analyses were done on the whole sample. In most cases, the fine fraction represents 90 percent or more of the sample (fig. 7). Because of the high proportion of fines in samples and the greater adsorption potential of the fine fraction, analyses probably represent the entire sample with little error. For samples in which the sand fraction of the sample is greater than about 10 percent, the error in assuming that the fine fraction represents the entire sample may be unacceptably high. Ten constituents—As, bismuth (Bi), Cd, europium (Eu), gold (Au), holmium (Ho), Mo, Ag, tantalum (Ta), and tin (Sn)—typically were below the respective detection limit for the analytic method.

Tests of the difference between means of samples grouped into those potentially influenced by mining and background sites show that differences between the group means was significant for ten chemical constituents (table 9). The group means for Ca, Cr, Co, Cu, gallium (Ga), Fe, Pb, Li, Mg, Mn, Se, and Ni were significantly lower for samples downstream from mining. The group means for Na and ytterbium (Yb) were significantly higher for samples downstream from mining. Neither constituent is recognized as a possible mining-associated contaminant.

The *t*-tests also were applied to samples of nonradioactive constituents grouped on the basis of location within the basin. Test results show a significant difference between the group means of samples from the eastern tributaries and the group means of samples from the main stem of the Little Colorado River for all chemical constituents except Cr, Pb, scandium (Sc) and Na (table 10). The group means of Al, Ba, Be, cerium (Ce), Ga, lanthanum (La), neodymium (Nd), niobium (Nb), K, Th, Ti, V, yttrium (Yt), Yb, and Zn (table 10) were significantly higher in the eastern basin than in the western basin. Conversely, the group means of Ca, Co, Cu, Fe, Li, Mg, Mn, Ni, phosphorus (P), and Sr were significantly lower for samples from the eastern basin. The group means of 25 chemical constituents were different on the basis of geographic position, whereas the group means of 13 constituents were determined to be different on the basis of whether mining had occurred.

To summarize the results of the *t*-tests, measured radioactivity from ^{234}U, ^{238}U, ^{228}Ra, ^{230}Th, and ^{232}Th on suspended sediment was higher in the eastern part of the Little Colorado River Basin than in the western part. Measured radioactivity in the eastern basin represents background, or natural, suspended-sediment radioactivity in the study area. Sediment radioactivity for the isotopes was about 1.3–2.1 pCi/g for samples from the eastern gaging stations and about 0.9–1.5 pCi/g for samples from the western gaging stations. Variation in radioactivity of sediment probably is related to factors that naturally vary geographically, such as lithology of sediment source areas, rather than to the occurrence of mining. Background concentrations of most measured chemical constituents on suspended sediment collected at streamflow-gaging stations in the eastern part of the basin tended to be significantly different than those of samples from the western part of the basin. Evidence was not found during this study of residual effects on streamflow chemistry from uranium mining in the Church Rock Mining District.

SUSPENDED-PHASE LOADS OF RADIONUCLIDES

Characteristics of Streamflow and Sediment Transport

Runoff in the Puerco and Little Colorado Rivers is produced by intense local thunderstorms in summer, widespread, low-intensity rainfall in winter, and snowmelt in spring. The proportion of the annual flow contributed by these components is different at different locations in the basin and varies considerably from year to year. In the eastern part of the Little Colorado River Basin, represented by the streamflow-gaging station at Woodruff, the highest average monthly flow volumes are produced by thunderstorms that typically occur in July, August, and September. Winter storms also produce significant monthly flow volume in January, February, and March (fig. 9).

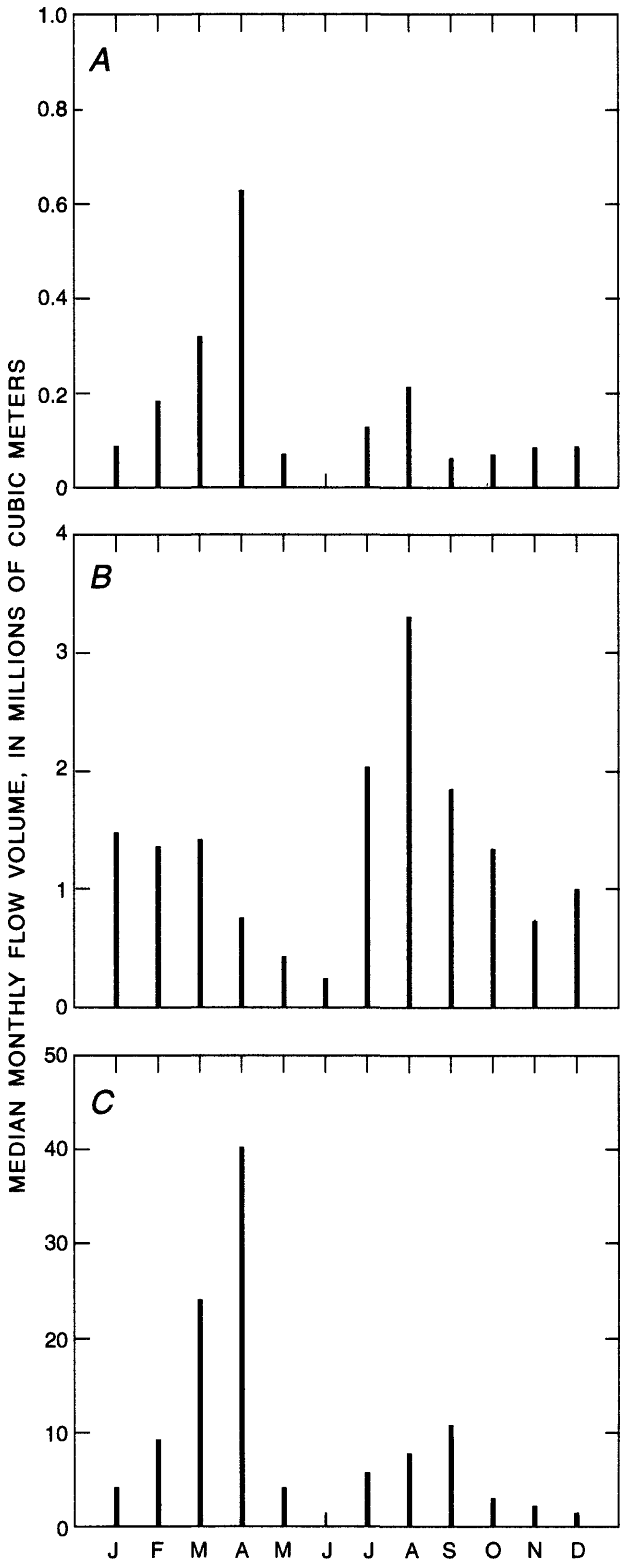

Figure 9. Median monthly flow volume, Zuni and Little Colorado Rivers, Arizona, and New Mexico water years 1972–91. *A,* Zuni River above Black Rock Reservoir, New Mexico; *B,* Little Colorado River at Woodruff, Arizona; C, Little Colorado River near Cameron, Arizona.

In the western part of the basin, represented by the streamflow-gaging station near Cameron, snowmelt from the streams that drain the higher areas along the west and south boundaries of the basin produces high average monthly flow volume in March and April (fig. 9). Snowmelt is a significant component of streamflow in the upper part of the Zuni River, which drains the Zuni Mountains (fig. 9). Flow in all streams is low in May and June.

Total monthly flow volume could not be computed for the streamflow-gaging station on the Puerco River near Chambers because, before this study, daily mean discharge was determined only for days on which the instantaneous discharge exceeded 14 m^3/s. An indication of the seasonal distribution of flow, however, is given by the number of days per month on which that discharge was exceeded (fig. 10). Although figure 10 shows a significant number of days with runoff in the spring, spring runoff is not typical at that site—more than half the total number of days in March and April and almost all the days in May were in one year of the 19-year period of record. That year—1973—had an exceptionally large number of days of runoff (fig. 10) most of which were in the spring. For the Puerco River Basin, runoff typically occurs in response to thunderstorms in July and August.

Although large volumes of runoff occur in winter and spring at some sites in the Little Colorado River Basin, sediment concentration of winter runoff is low compared with that of summer runoff. Most of the annual suspended-sediment load is transported in the summer during runoff produced by thunderstorms (fig. 11).

The study period was one of lower-than-average runoff at most streamflow-gaging stations in the study area. The interannual variability in precipitation (fig. 4), runoff (figs. 12–15), and suspended-sediment load (fig. 16) is high in the Little Colorado River Basin. Both the annual peak discharge (figs. 12, 13) and the number of peaks higher than a base discharge (figs. 14, 15) vary greatly from year to year. Most of the gaged sites in the study area had fewer periods of runoff (fig. 14), lower annual peak discharge (figs. 12, 13), and (or) fewer peaks higher than the base discharge (figs. 14, 15) than the average of the previous years. No trend is apparent, however, in either annual peak discharge or number of peaks higher than base discharge over the period of record. The peak of July 14, 1990, on the Puerco River near

Chambers was caused by runoff from a thunderstorm that was intensified by the breaching of an earthen roadway that crossed the river about 23 km upstream from the gaging station. The floodwave that was generated when the roadway failed caused a peak discharge at the gaging station near Chambers that is among the highest peak discharges recorded at the site (fig. 13).

Because most runoff in the Puerco River Basin results from local thunderstorms, the spatial and temporal distribution of runoff in the river is complex. July 24 to August 3, 1989, is typical of summer-runoff periods (fig. 17). Few tributaries contribute to flow at the gaging station near Church Rock; consequently, thunderstorms produce simple, discrete runoff hydrographs (fig. 17). About eight tributaries, including the South Fork of the Puerco River, enter the Puerco River between the gaging stations near Church Rock and Manuelito. Because of these additional sources of inflow, flow occurs more frequently at the Manuelito gaging station and flow periods have greater variability than those at the gaging station near Church Rock (fig. 17). Black Creek and about six other tributaries join the Puerco River between the gaging stations near Manuelito and Chambers. These additional sources of inflow can produce higher and more variable runoff. Some periods of flow at the Church Rock and (or) Manuelito gaging stations, however, produce no flow at the gaging station near Chambers because of water losses by evaporation and infiltration in the reach between the stations near Manuelito and Chambers (fig. 17).

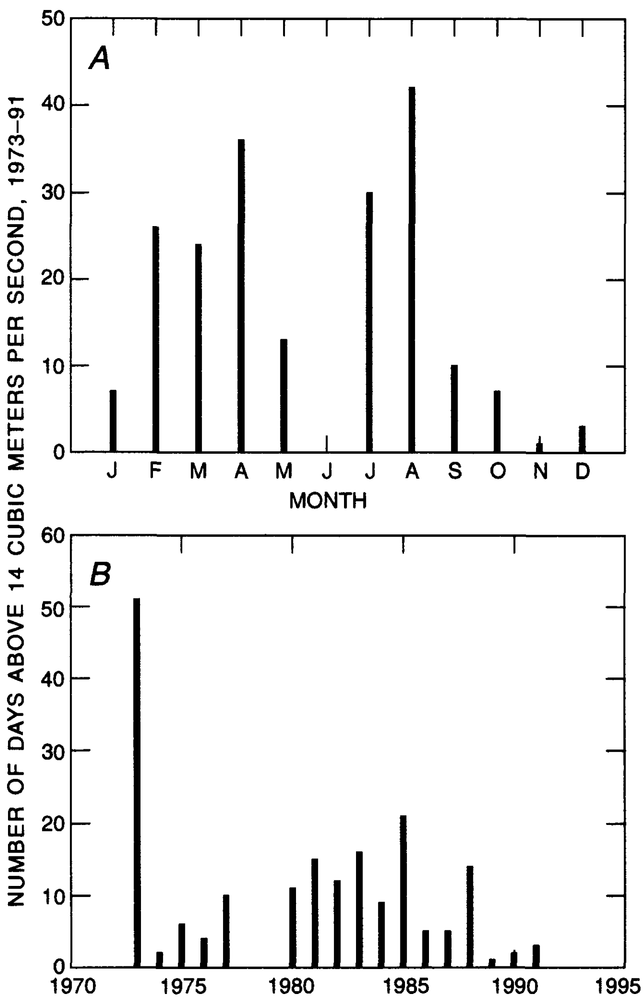

Figure 10. Number of days daily mean discharge exceeded 14 cubic meters per second, Puerco River near Chambers, Arizona, water years 1973–91. *A*, Number of days per month. *B*, Number of days per year.

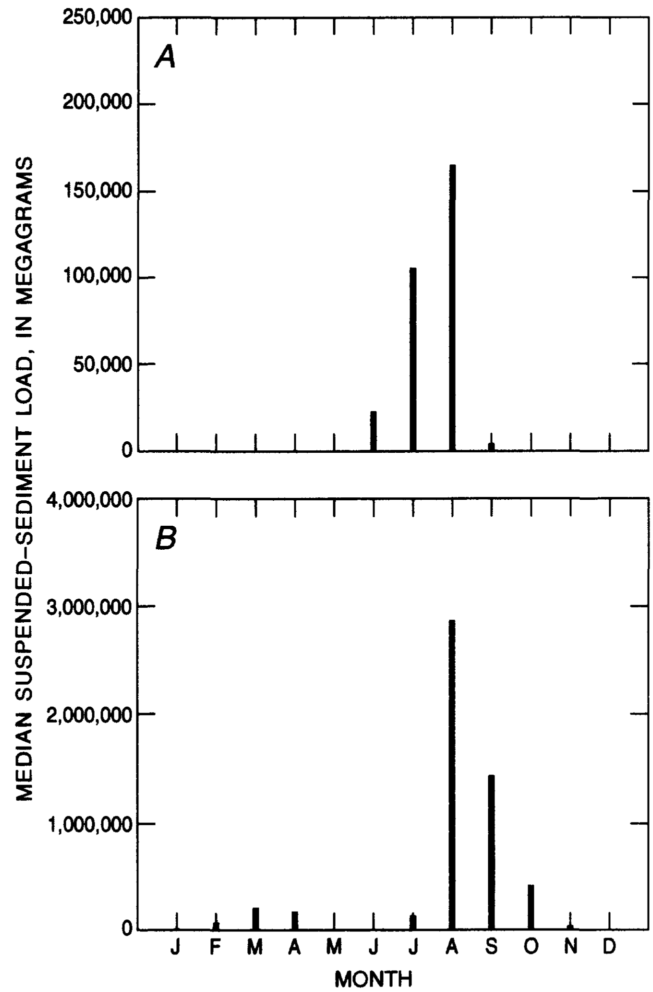

Figure 11. Median suspended-sediment load, by month, Little Colorado River, Arizona. *A*, Little Colorado River at Woodruff, Arizona, water years 1951–56. *B*, Little Colorado River near Cameron, Arizona, water years 1957–70.

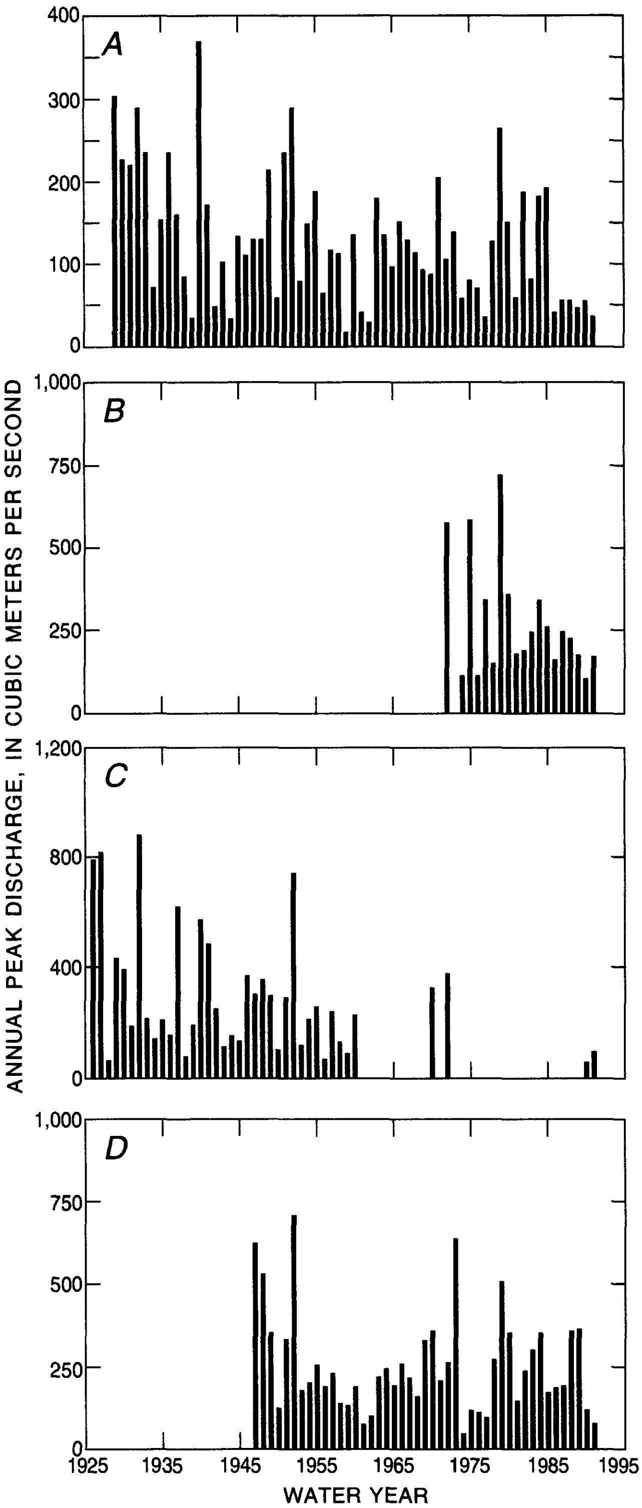

Figure 12. Annual peak discharge at streamflow-gaging stations, Little Colorado River, Arizona. *A,* Little Colorado River at Woodruff, Arizona, water years 1929–91; *B,* Little Colorado River near Joseph City, Arizona, water years 1972–91; *C,* Little Colorado River at Grand Falls, Arizona, water years 1926–60, 1970, 1972, and 1990–91; *D,* Little Colorado River near Cameron, Arizona, water years 1947–91.

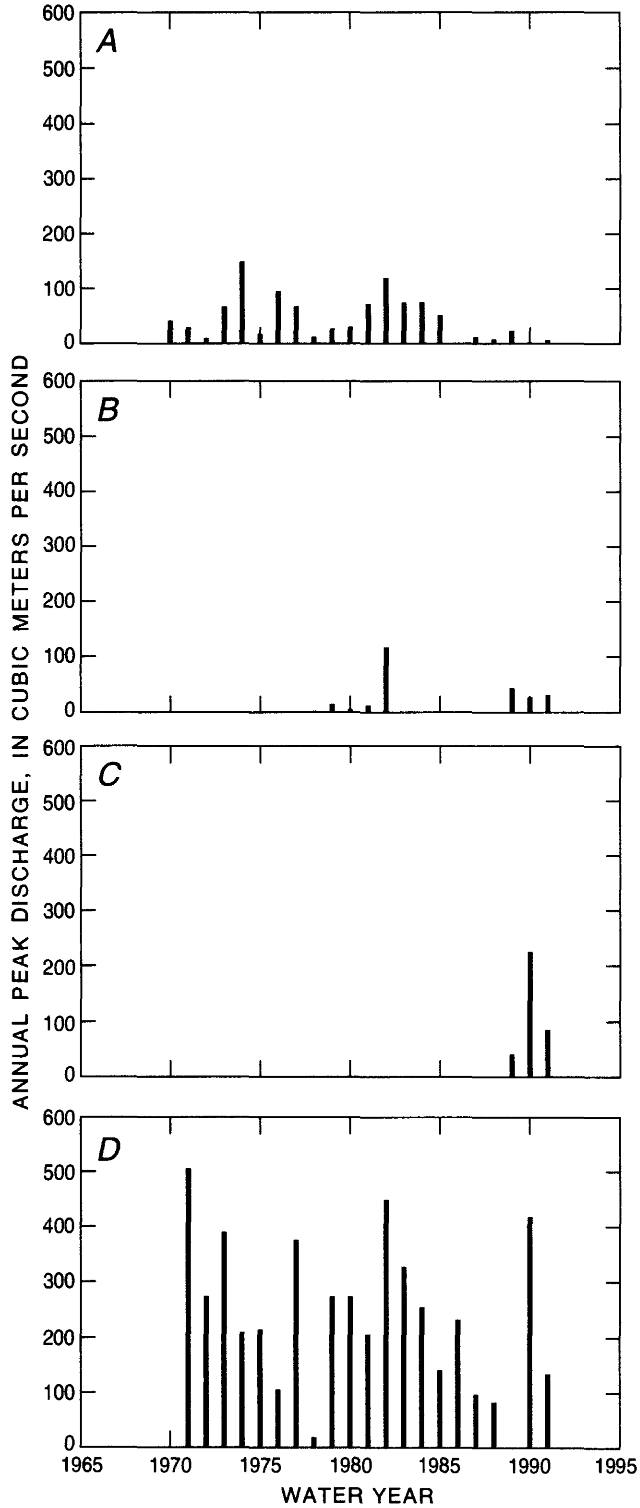

Figure 13. Annual peak discharge at streamflow-gaging stations, Zuni and Puerco Rivers, Arizona and New Mexico. *A,* Zuni River above Black Rock Reservoir, New Mexico, water years 1970–91; *B,* Puerco River near Church Rock, New Mexico, water years 1978–82 and 1989–91; *C,* Puerco River near Manuelito, New Mexico, water years 1989–91; *D,* Puerco River near Chambers, Arizona, water years 1971–91.

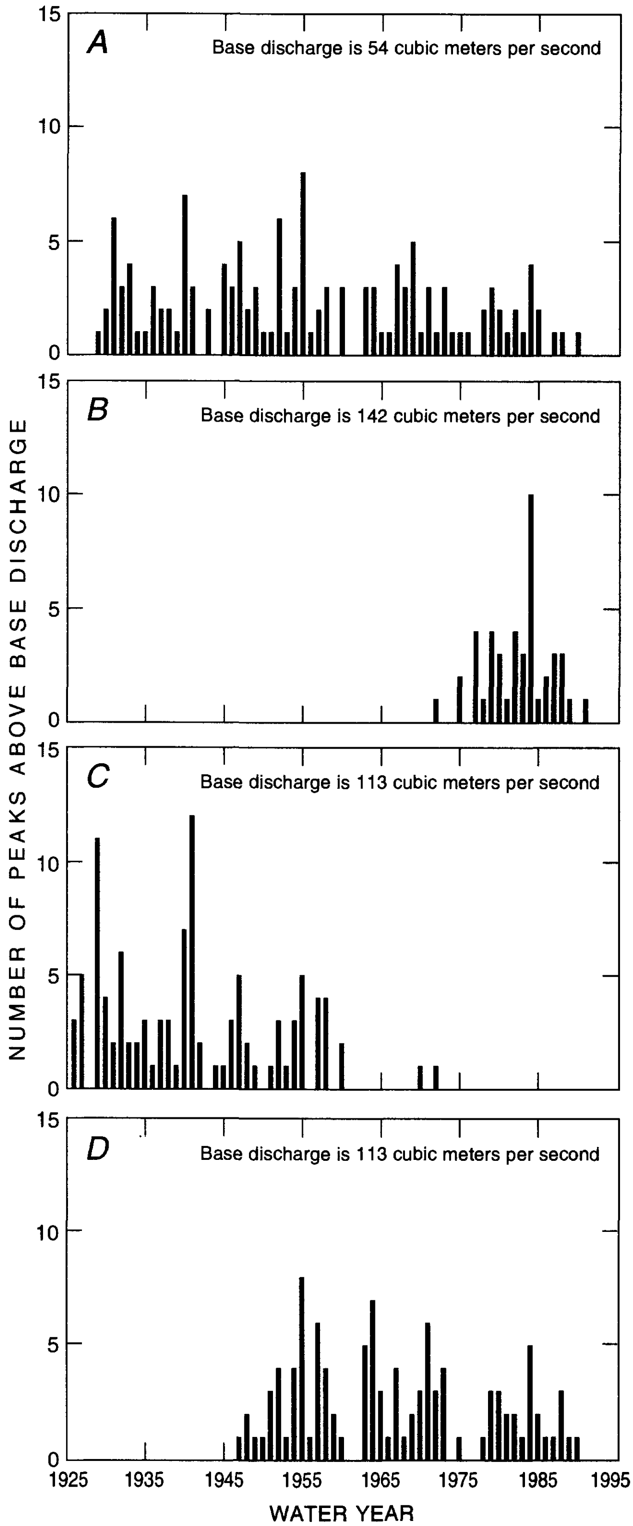

Figure 14. Number of peaks above base discharge at streamflow-gaging stations, Little Colorado River, Arizona. *A,* Little Colorado River at Woodruff, Arizona, water years 1929–91; *B,* Little Colorado River near Joseph City, Arizona, water years 1972–91; *C,* Little Colorado River at Grand Falls, Arizona, water years 1926–60, 1970, 1972, and 1990–91; *D,* Little Colorado River near Cameron, Arizona, water years 1947–91.

Computation of Suspended-Sediment Load

Computation of chemical-constituent load in the suspended phase requires data on concentration of suspended sediment, concentration of chemical constituents in the suspended phase, and corresponding discharge. Instantaneous discharge was computed at 10-minute intervals from stage data recorded at that interval and a stage-discharge relation that was developed for each site from recent current-meter measurements (Rantz and others, 1982). For most of the study period, suspended-sediment loads were computed using the instantaneous discharge and measured and estimated instantaneous values of suspended-sediment concentration using methods described by Porterfield (1972). Relations between instantaneous suspended-sediment concentration and discharge—sediment rating curves—were developed from measured concentration and corresponding discharge. The rating curves were used to compute concentration for each 10-minute interval for periods in

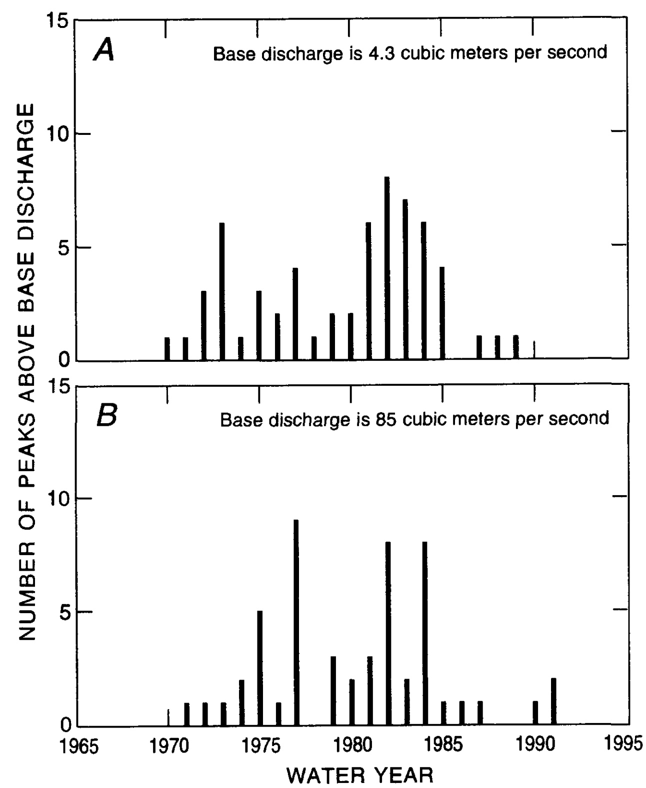

Figure 15. Number of peaks above base discharge at streamflow-gaging stations, Zuni and Puerco Rivers, Arizona and New Mexico. *A,* Zuni River above Black Rock Reservoir, New Mexico, water years 1970–91; *B,* Puerco River near Chambers, Arizona, water years 1971–91.

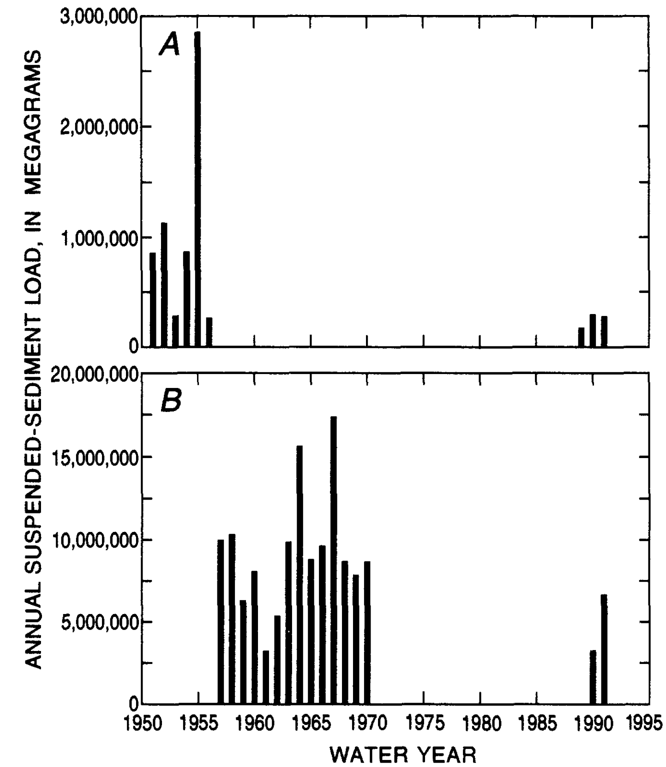

Figure 16. Annual suspended-sediment load for the indicated period of record, Little Colorado River, Arizona. *A*, Little Colorado River at Woodruff, Arizona, water years 1951–56 and 1989–91; *B*, Little Colorado River near Cameron, Arizona, water years 1957–70 and 1990–91.

which the temporal distribution of samples was considered insufficient to define the variability of suspended-sediment concentration with time. Sediment-rating curves were used for the gaging station on Black Creek for the entire study period and for gaging stations on the Puerco River near Chambers and the Little Colorado River at Woodruff and near Joseph City for October 1988 to March 1989 before initiation of suspended-sediment sampling at those sites.

Daily mean discharge (figs. 18–20) and daily suspended-sediment load (figs. 21–23) were computed for each day of the study period on which significant flow occurred. Daily sediment load was computed for all days on which the daily mean discharge exceeded 0.28 m^3/s at the gaging stations on the Puerco River near Church Rock, on the Zuni River, and on Black Creek. Daily suspended-sediment load was computed for days on which the daily mean discharge exceeded 0.57 m^3/s at the gaging stations on the Little Colorado River at Woodruff, at Grand Falls, and near Cameron and on the Puerco River near Chambers. Daily suspended-sediment load was computed for days on which the daily mean discharge exceeded 1.4 m^3/s at the gaging stations on the Puerco River near Manuelito and on the Little Colorado River near Joseph City.

Cumulative suspended-sediment loads for runoff periods were computed for each gaging station by totaling the daily suspended-sediment loads for periods defined by consecutive days of significant flow (table 11). Suspended-sediment loads for water years in the study period were computed by totaling the runoff-period loads (table 12). These loads were used to compute loads of radionuclides, as described in the following section.

Relations between daily mean discharge and daily suspended-sediment load were developed to allow estimation of constituent loads for days outside the study period for which daily sediment load was not computed. Linear regression on natural logarithms of suspended-sediment load and daily mean discharge was used to develop the relations. The Duan smearing estimator (Duan, 1983) was used to correct for the bias incurred in using the resulting relations in their untransformed form. The smearing estimator is computed as the mean of the retransformed residuals and is independent of the distribution of the residuals. The relations are

$$L = 1.18(10.400Q^{1.49}),$$

$$L = 1.14(5,170Q^{1.30}),$$

and

$$L = 1.06(2,370Q^{1.51}),$$

where the equations are for the gaging stations on the Puerco River near Church Rock, Manuelito, and Chambers, respectively, and where L is estimated daily suspended-sediment load in megagrams and Q is daily mean discharge, in cubic meters per second. The number outside the parentheses is the smearing estimator. For each gaging station, the data are linearly related when transformed, and the estimating equation is a good fit to the data (fig. 24). The relations explain 94, 84, and 88 percent of the variation in the data, respectively.

Radionuclide Loads

Suspended-phase loads of radionuclides for runoff periods (table 11) and for water years in

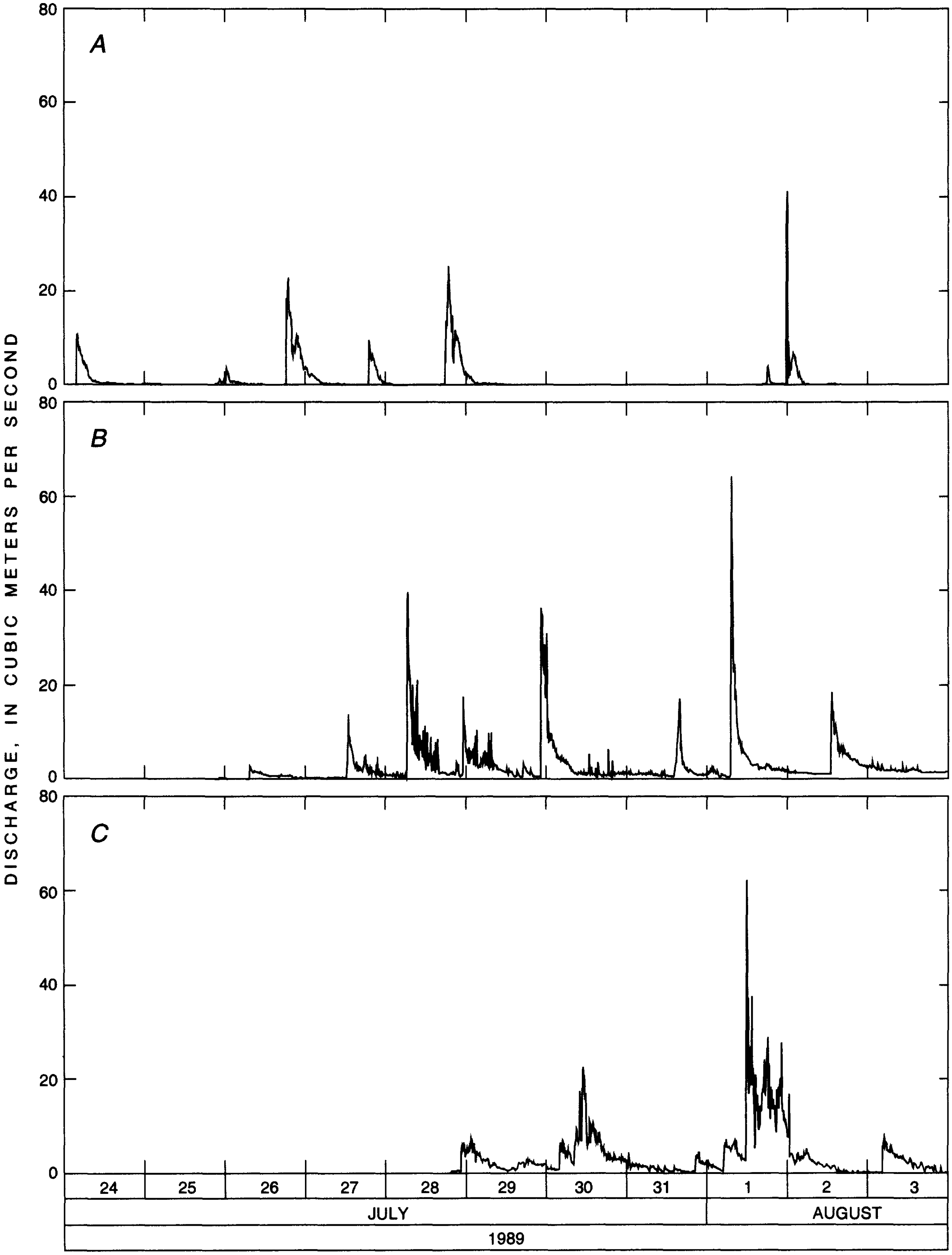

Figure 17. Instantaneous discharge at streamflow-gaging stations, Puerco River, Arizona and New Mexico, July 24 to August 3, 1989. *A,* Puerco River near Church Rock, New Mexico; *B,* Puerco River near Manuelito, New Mexico; *C,* Puerco River near Chambers, Arizona.

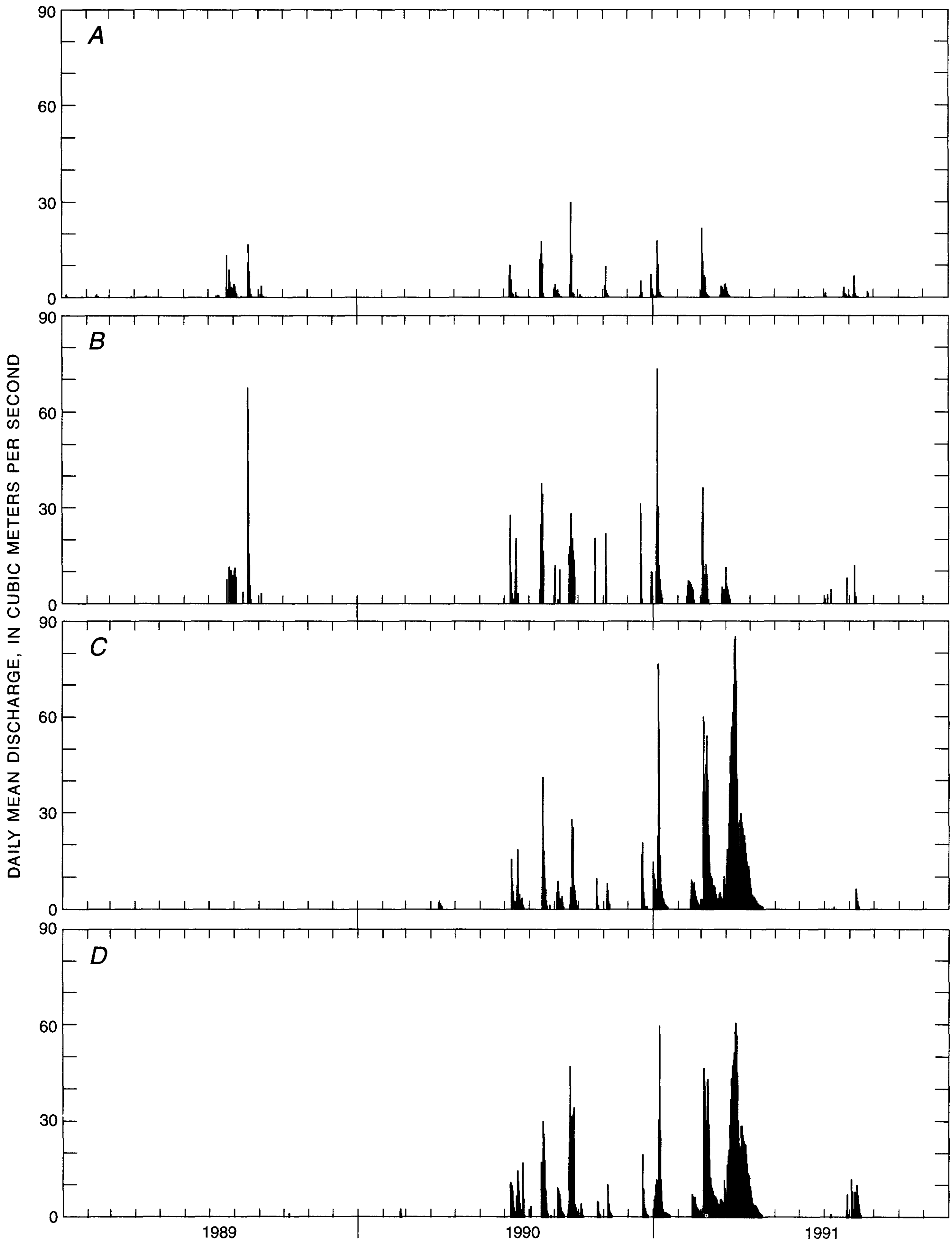

Figure 18. Daily mean discharge at streamflow-gaging stations, Little Colorado River, Arizona, water years 1989–91. *A,* Little Colorado River at Woodruff, Arizona; *B,* Little Colorado River near Joseph City, Arizona; *C,* Little Colorado River at Grand Falls, Arizona; *D,* Little Colorado River near Cameron, Arizona.

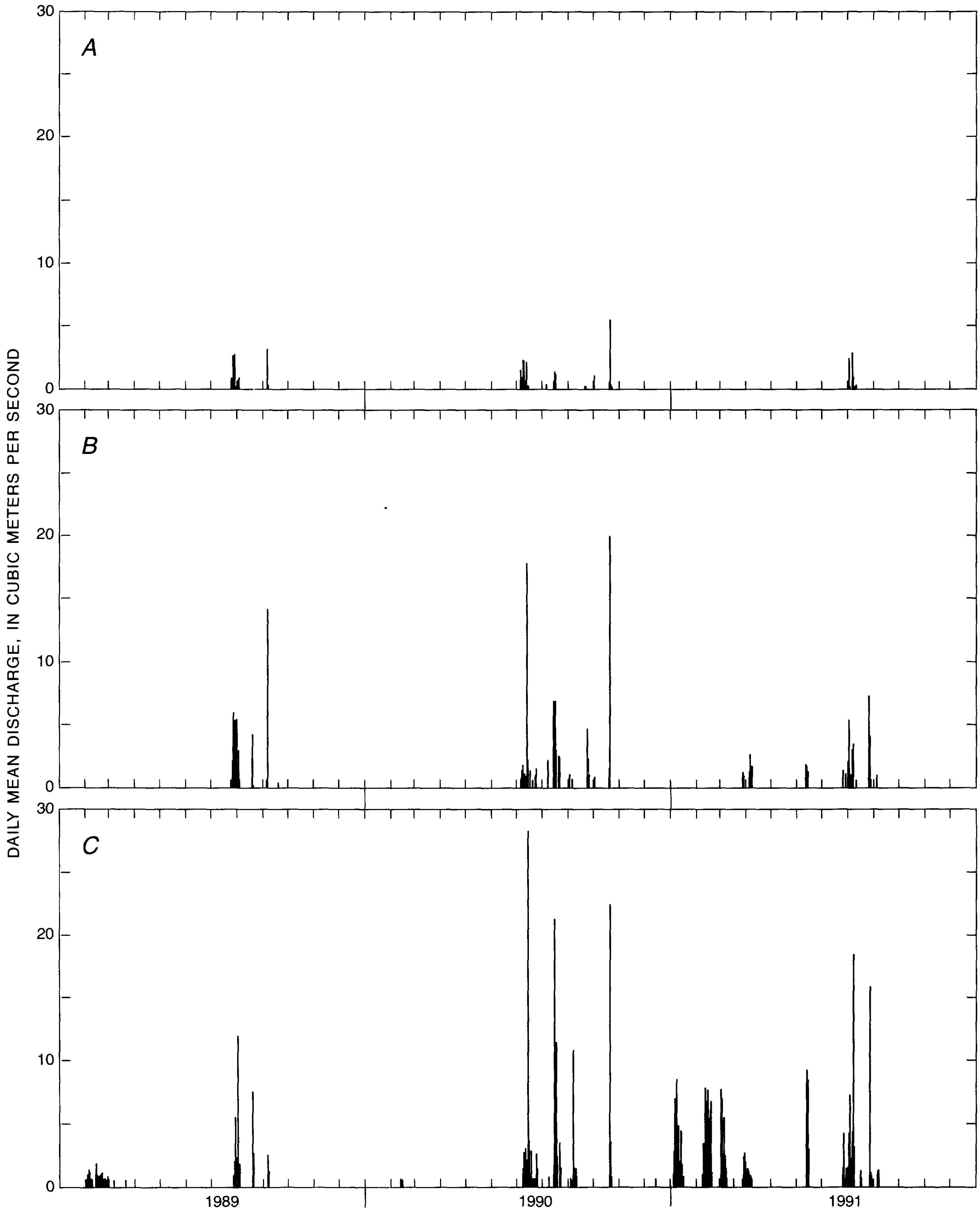

Figure 19. Daily mean discharge at streamflow-gaging stations, Puerco River, Arizona and New Mexico, water years 1989–91. *A*, Puerco River near Church Rock, New Mexico; *B*, Puerco River near Manuelito, New Mexico; *C*, Puerco River near Chambers, Arizona.

the study period (table 12) were computed from suspended-sediment loads and median radioactivity of sediment for each of five radionuclides for each streamflow-gaging station (table 13). Loads of radionuclides, in curies, were computed by multiplying the suspended-sediment load, in megagrams, by the median radio-activity, in picocuries per gram, and by 10^{-6} to convert from picocuries to curies and megagrams to grams.

Radionuclide loads vary closely with suspended-sediment loads because variability in radioactivity per gram of sediment among the sample sites and among radionuclides is small (table 13). Radioactivity of U and Ra on sediment is highest at the gaging station on the Zuni River; however, loads on the Zuni River are smallest because of the low volume of runoff and the low suspended-sediment concentrations (tables 12 and 13). Radioactivity of U and Ra on suspended sediment at stations on the Puerco River are about the same as those at the station on Black Creek and slightly lower than those at the station on the Zuni River (table 13). Radioactivity of ^{238}U, ^{234}U, ^{228}Ra, and ^{230}Th on sediment from Little Colorado River stations is lower than the radioactivity from the eastern basin stations (tables 10 and 13). Mean radioactivity of ^{232}Th on sediment is not significantly different at stations in the eastern and western basins.

Radionuclide load increases downstream on the Puerco and Little Colorado Rivers (fig. 25) because suspended-sediment loads tend to be higher for larger drainage areas. The amount of ^{226}Ra transported during water years 1989–91 ranged from 1.0 to 4.8 Ci on the Puerco River and from 0.72 to 12 Ci on the Little Colorado River (obtained by summing the values in table 12 for each streamflow-gaging station). The amount of suspended sediment transported per unit volume of flow varies from station to station. More sediment is tranported per unit volume of flow at the Puerco River stations than at other stations in the study. The total suspended-sediment load for the study period divided by the total flow volume for the same period ranges from 0.26 Mg/m^3 on the Puerco River near Church Rock to 0.08 Mg/m^3 on the Puerco River near Chambers. No similar downstream trend

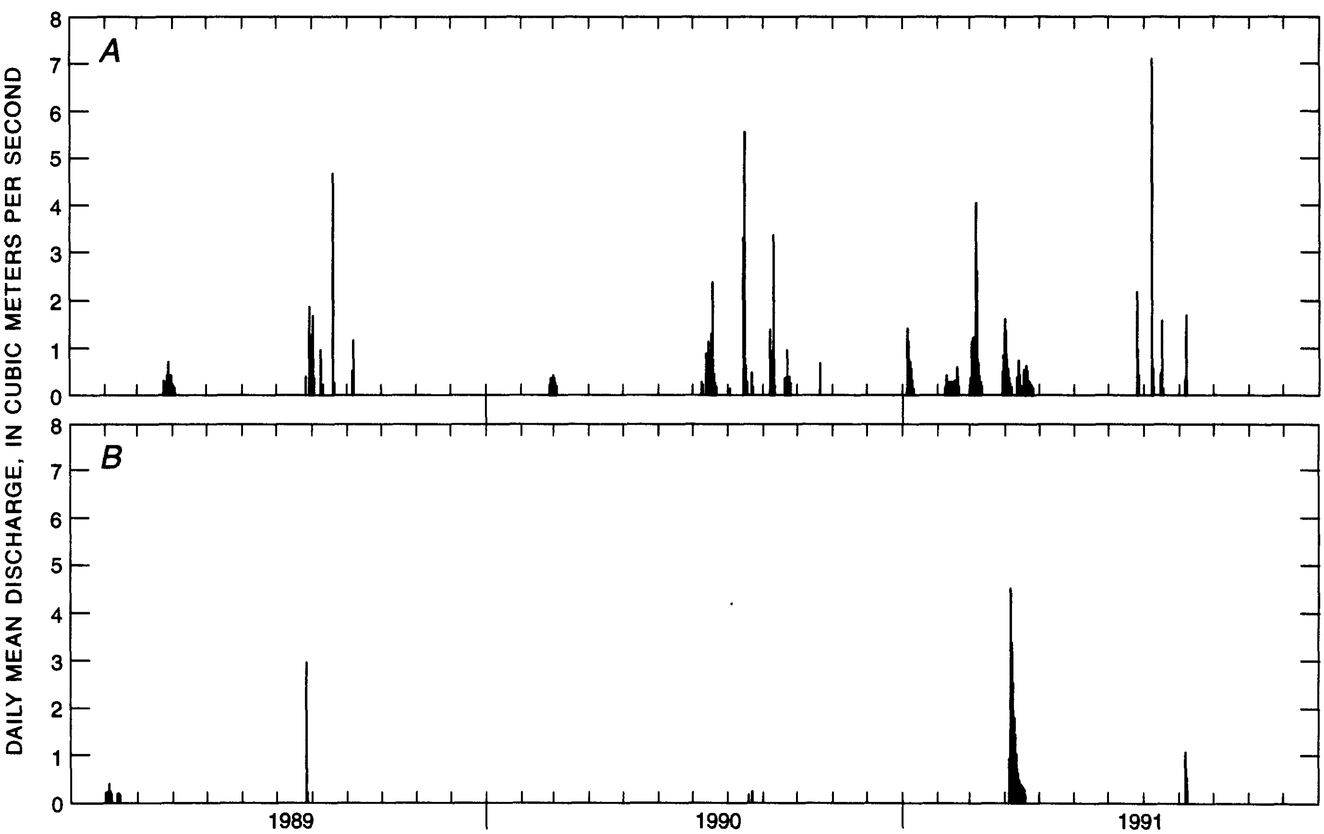

Figure 20. Daily mean discharge at streamflow-gaging stations, Black Creek, Arizona, and Zuni River, New Mexico, water years 1989–91. *A*, Black Creek below West Fork Black Creek, near Houck, Arizona; *B*, Zuni River above Black Rock Reservoir, New Mexico.

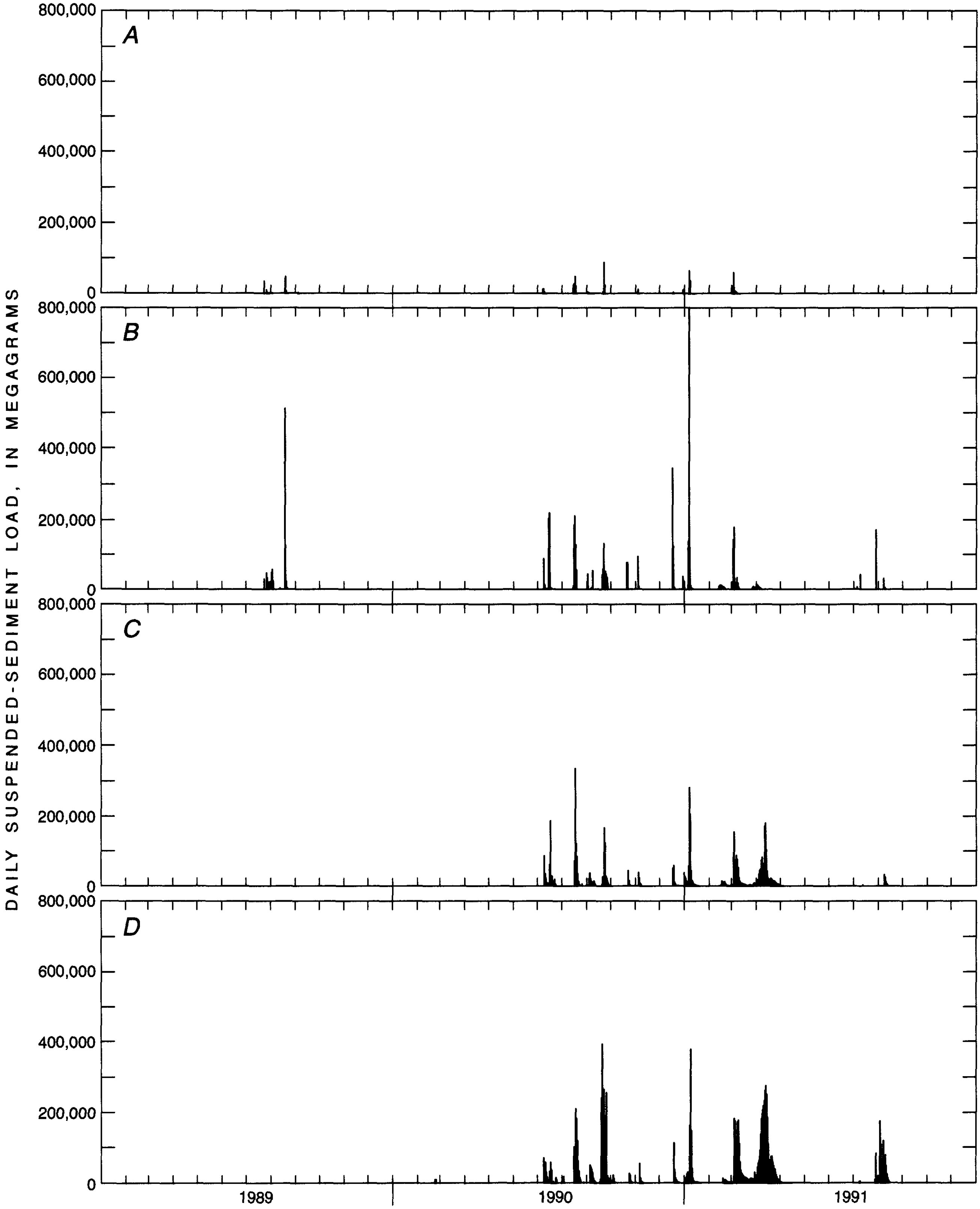

Figure 21. Daily suspended-sediment load at streamflow-gaging stations for days on which the daily mean discharge equaled or exceeded a lower limit, Little Colorado River, Arizona, water years 1989–91. *A,* Little Colorado River at Woodruff, Arizona, lower limit 0.28 cubic meter per second; *B,* Little Colorado River near Joseph City, Arizona, lower limit 1.4 cubic meters per second; *C,* Little Colorado River at Grand Falls, Arizona, lower limit 0.57 cubic meter per second; *D,* Little Colorado River near Cameron, Arizona, lower limit 0.57 cubic meter per second.

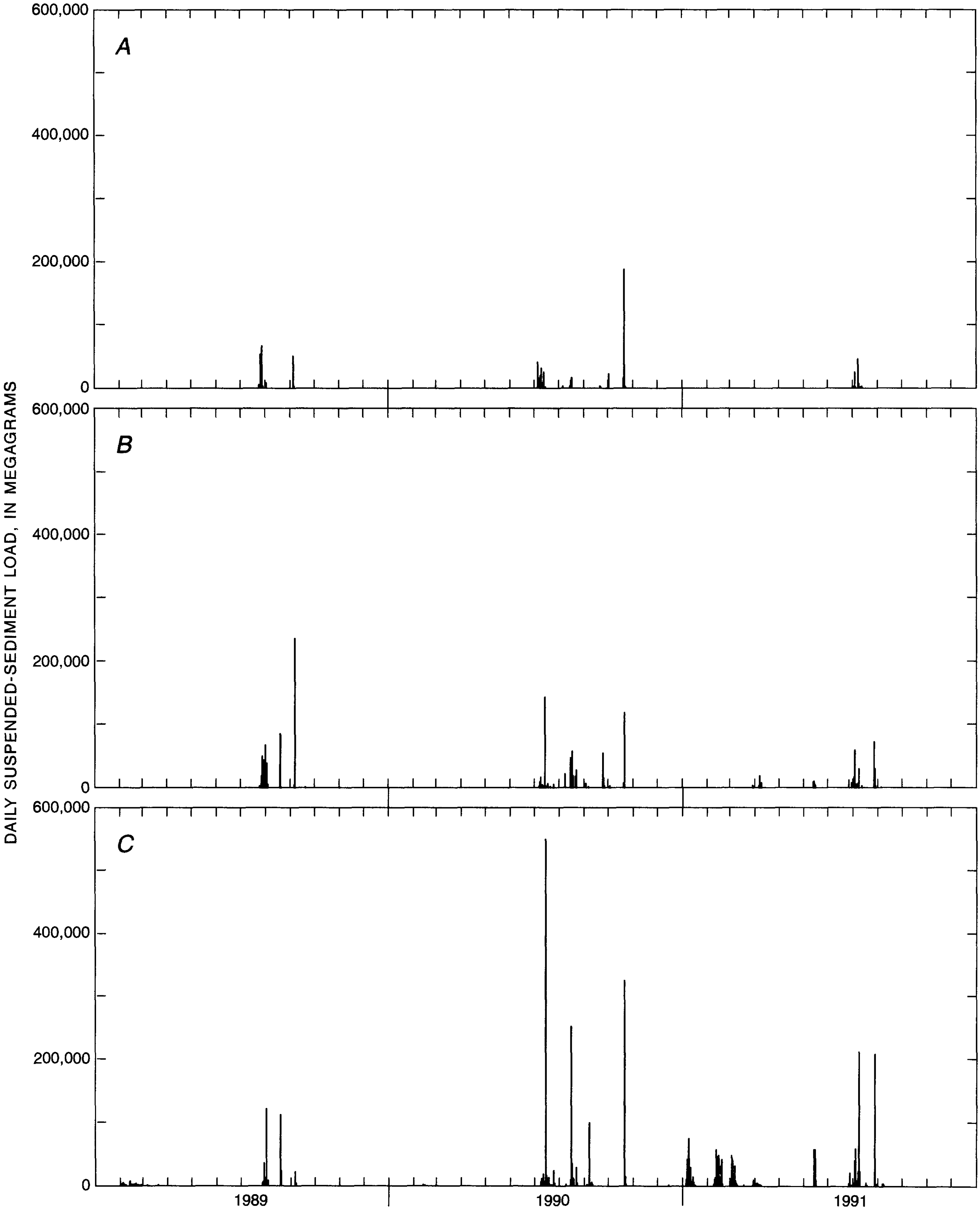

Figure 22. Daily suspended-sediment load at streamflow-gaging stations for days on which the daily mean discharge equaled or exceeded a lower limit, Puerco River, Arizona and New Mexico, water years 1989–91. *A*, Puerco River near Church Rock, New Mexico, lower limit 0.28 cubic meter per second; *B*, Puerco River near Manuelito, New Mexico, lower limit 1.4 cubic meters per second; *C*, Puerco River near Chambers, Arizona, lower limit 0.57 cubic meter per second.

is apparent in the Little Colorado River, but the average value for all stations on the Little Colorado River—0.035 Mg/m^3—is lower than the lowest Puerco River value. Black Creek has about the same value—0.03 Mg/m^3—as the Little Colorado River, and the Zuni River has the lowest value of all stations—0.0007 Mg/m^3. Runoff volume increases downstream in both the Puerco and Little Colorado Rivers, and the change in runoff volume is greater than the change in suspended-sediment concentration (table 13). The basinwide trend in radionuclide loads, therefore, is related to the increase in runoff volume with increasing drainage area rather than to a trend in radioactivity of suspended sediment or in the suspended-sediment concentration during the study period.

Because the study period was below average in number and size of discharge peaks at gaging stations for which some historical record exists, it is possible that some sediment with radioactivity higher than background levels was stored in the channel and not transported during the study period. The discharge peak in July 1990 at the gaging station near Chambers, however, was high enough to rework much of the sediment deposited during mining if any remained in the channel (fig. 13).

DISCUSSION

Comparison of the radioactivity of suspended sediment sampled in the present study (table 13) with radioactivity of sediment sampled during mine dewatering (Arizona Department of Health Services, 1986) indicates that sediment radioactivity has decreased since cessation of mine dewatering. The radioactivity of ^{226}Ra in 10 suspended-sediment samples collected from 5 sites on the Puerco River in 1985 during dewatering ranged from 1.1 to 2.8 pCi/g and averaged 1.9 pCi/g. A slight downstream increase in ^{226}Ra concentration is suggested by the data—the three sites at Chambers and upstream averaged 1.7 pCi/g and the two sites downstream from Chambers averaged 2.3 pCi/g. The radioactivity of

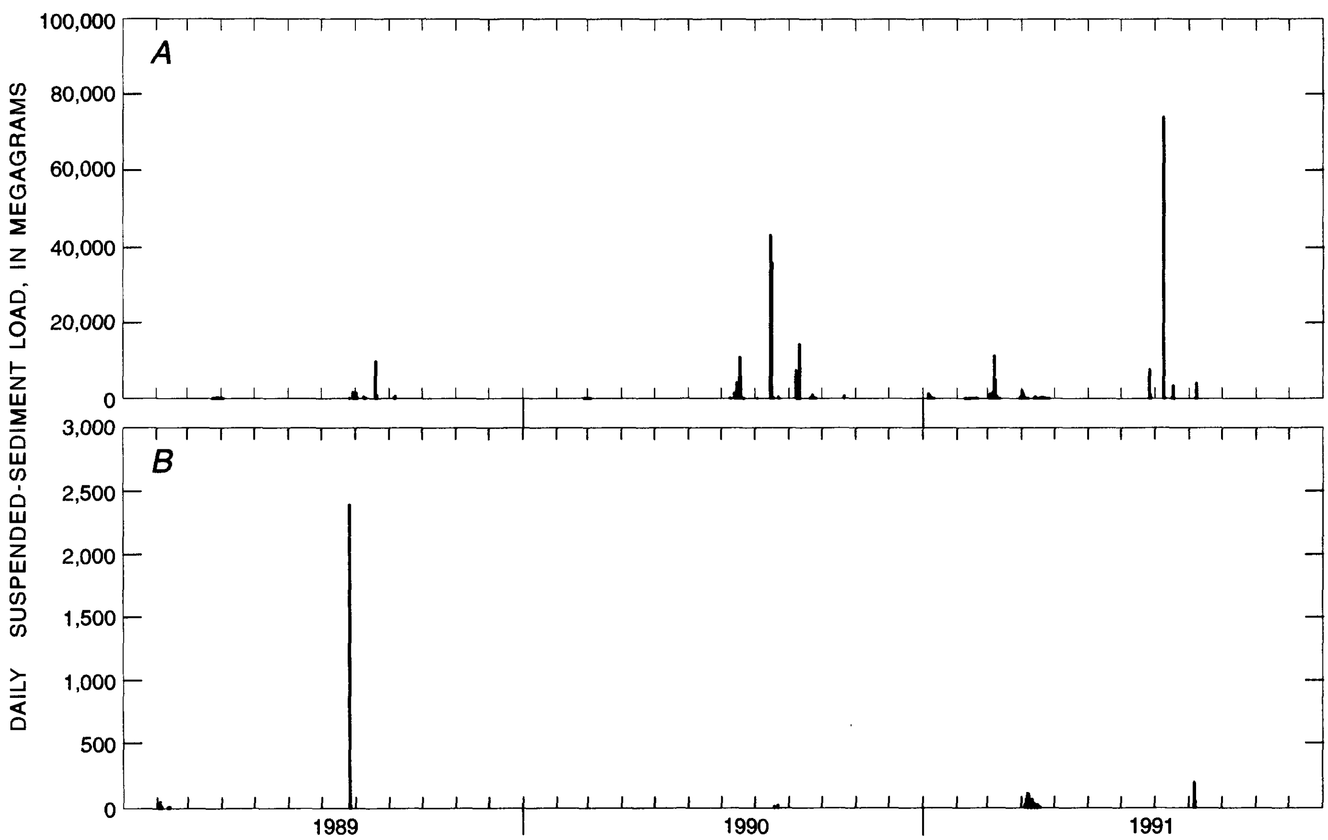

Figure 23. Daily suspended-sediment load at streamflow-gaging stations for days on which the daily mean discharge equaled or exceeded 0.14 cubic meter per second, Black Creek, Arizona, and Zuni River, New Mexico, water years 1989–91. *A,* Black Creek below West Fork Black Creek, near Houck, Arizona; *B,* Zuni River above Black Rock Reservoir, New Mexico.

Table 11. Suspended-sediment loads and suspended-phase loads of radionuclides for runoff periods at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

Date	Suspended-sediment loads, in megagrams	Suspended-phase loads, in curies				
		Uranium–238	Uranium–234	Radium–226	Thorium–230	Thorium–232
Zuni River above Black Rock Reservoir, New Mexico (09386950)						
February 2–5, 1989	90	0.00015	0.00013	0.00015	0.00014	0.00013
February 10–12, 1989	26	.000043	.000038	.000043	.000041	.000036
July 26–27, 1989	2,420	.0041	.0036	.0041	.0039	.0034
August 18, 1990	12	.000021	.000019	.000021	.000020	.000017
August 21, 1990	21	.000035	.000031	.000035	.000033	.000029
April 4–18, 1991	645	.0011	.00097	.0011	.0010	.00090
September 5–7, 1991	239	.00041	.00036	.00041	.00038	.00033
Little Colorado River at Woodruff, Arizona (09394500)						
October 11–12, 1988	37	0.000037	0.000033	0.000037	0.000045	0.000048
October 14–17, 1988	579	.00058	.00052	.00058	.00069	.00075
January 6–7, 1989	181	.00018	.00016	.00018	.00022	.00024
January 25, 1989	25	.000025	.000022	.000025	.000030	.000032
February 11–14, 1989	352	.00035	.00032	.00035	.00042	.00046
March 27, 1989	52	.000052	.000047	.000052	.000062	.000067
April 14–15, 1989	95	.000095	.000085	.000095	.00011	.00012
July 10, 1989	110	.00011	.000099	.00011	.00013	.00014
July 12–13, 1989	217	.00022	.00020	.00022	.00026	.00028
July 23–August 6, 1989	59,500	.060	.054	.060	.071	.077
August 10, 1989	36	.000036	.000033	.000036	.000044	.000047
August 18–23, 1989	100,400	.10	.090	.10	.12	.13
September 3–6, 1989	3,970	.0040	.0036	.0040	.0048	.0052
July 7–12, 1990	31,600	.032	.028	.032	.038	.041
July 15–16, 1990	605	.00061	.00054	.00061	.00073	.00079
July 18, 1990	45	.000045	.000041	.000045	.000054	.000059
August 1, 1990	68	.000068	.000061	.000068	.000081	.000088
August 14–19, 1990	123,000	.12	.11	.12	.15	.16
September 1–9, 1990	10,700	.011	.0096	.011	.013	.014
September 20–26, 1990	119,000	.12	.11	.12	.14	.15
October 3–4, 1990	152	.00015	.00014	.00015	.00018	.00020
October 21–22, 1990	36	.000036	.000033	.000036	.000044	.000047
November 2–7, 1990	16,200	.016	.015	.016	.020	.021
December 16–18, 1990	4,640	.0046	.0042	.0046	.0056	.0060
December 29, 1990–January 2, 1991	11,900	.012	.011	.012	.014	.016
January 4–13, 1991	104,000	.10	.093	.10	.12	.13
March 1–11, 1991	100,000	.10	.090	.10	.12	.13
March 25–April 6, 1991	14,700	.015	.013	.015	.018	.019
July 7, 1991	629	.00063	.00057	.00063	.00075	.00082
August 1–3, 1991	725	.00073	.00065	.00073	.00087	.00094
August 24–September 11, 1991	14,000	.014	.013	.014	.017	.018
September 23–25, 1991	1,270	.0013	.0011	.0013	.0015	.0016

Table 11. Suspended-sediment loads and suspended-phase loads of radionuclides for runoff periods at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Date	Suspended-sediment loads, in megagrams	Suspended-phase loads, in curies				
		Uranium–238	Uranium–234	Radium–226	Thorium–230	Thorium–232
Puerco River near Church Rock, New Mexico (09395350)						
July 24–29, 1989	139,000	0.19	0.18	0.21	0.21	0.18
August 1–2, 1989	9,960	.014	.013	.015	.015	.013
September 5–6, 1989	51,000	.071	.066	.077	.077	.066
July 5–10, 1990	118,000	.16	.15	.18	.18	.15
July 12, 1990	24,300	.034	.032	.036	.036	.032
July 14, 1990	996	.0014	.0013	.0015	.0015	.0013
August 5, 1990	2,220	.0031	.0029	.0033	.0033	.0029
August 14–16, 1990	29,100	.041	.038	.044	.044	.038
September 20–21, 1990	3,060	.0043	.0040	.0046	.0046	.0040
October 1, 1990	21,900	.031	.028	.033	.033	.028
October 19–22, 1990	205,000	.29	.27	.31	.31	.27
August 1–3, 1991	26,800	.038	.035	.040	.040	.035
August 6–8, 1991	51,700	.072	.067	.078	.078	.067
August 10–11, 1991	2,990	.0042	.0039	.0045	.0045	.0039
Puerco River near Manuelito, New Mexico (09395630)						
July 24, 1989	3,150	.0041	.0041	.0044	.0044	.0044
July 26–August 3, 1989	267,000	.35	.35	.37	.37	.37
August 18–20, 1989	124,000	.16	.16	.17	.17	.17
September 5–6, 1989	241,000	.31	.31	.34	.34	.34
September 19, 1989	1,560	.0020	.0020	.0022	.0022	.0022
October 31, 1989	1,630	.0021	.0021	.0023	.0023	.0023
July 6–8, 1989	28,600	.037	.037	.040	.040	.040
July 10, 1989	4,960	.0065	.0065	.0069	.0069	.0069
July 12–14, 1989	150,000	.19	.19	.21	.21	.21
July 17, 1990	6,870	.0089	.0089	.0096	.0096	.0096
July 20, 1990	2,430	.0032	.0032	.0034	.0034	.0034
July 23–24, 1990	7,010	.0091	.0091	.0098	.0098	.0098
August 7, 1990	21,700	.028	.028	.030	.030	.030
August 14–17, 1990	156,000	.20	.20	.22	.22	.22
August 20–21, 1990	46,200	.060	.060	.065	.065	.065
September 2, 1990	6,750	.0088	.0088	.0095	.0095	.0095
September 5, 1990	2,220	.0029	.0029	.0031	.0031	.0031
September 23–25, 1990	74,500	.097	.097	.10	.10	.10
October 1–2, 1990	3,830	.0050	.0050	.0054	.0054	.0054
October 19–20, 1990	128,000	.17	.17	.18	.18	.18
March 28–29, 1991	6,780	.0088	.0088	.0095	.0095	.0095
April 5–6, 1991	23,100	.030	.030	.032	.032	.032
April 8, 1991	8,310	.011	.011	.012	.012	.012
June 11–14, 1991	32,700	.042	.042	.046	.046	.046
July 26–27, 1991	26,600	.035	.035	.037	.037	.037

Table 11. Suspended-sediment loads and suspended-phase loads of radionuclides for runoff periods at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Date	Suspended-sediment loads, in megagrams	Suspended-phase loads, in curies				
		Uranium–238	Uranium–234	Radium–226	Thorium–230	Thorium–232
Puerco River near Manuelito, New Mexico (09395630)—Continued						
July 29, 1991	8,080	0.010	0.010	0.011	0.011	0.011
August 1–4, 1991	89,700	.12	.12	.13	.13	.13
August 6–7, 1991	38,000	.049	.049	.053	.053	.053
August 11, 1991	3,700	.0048	.0048	.0052	.0052	.0052
August 26–28, 1991	108,000	.14	.14	.15	.15	.15
September 4, 1991	1,840	.0024	.0024	.0026	.0026	.0026
Black Creek below West Fork Black Creek, near Houck, Arizona (09395990)						
March 23–April 2, 1989	1,090	.0015	.0014	.0015	.0015	.0016
July 26–August 2, 1989	4,910	.0069	.0064	.0069	.0069	.0074
August 8–10, 1989	499	.00070	.00065	.00070	.00070	.00075
August 19–20, 1989	10,700	.015	.014	.015	.015	.016
September 5–6, 1989	789	.0011	.0010	.0011	.0011	.0012
February 25–March 3, 1990	570	.00080	.00074	.00080	.00080	.00085
July 8–9, 1990	142	.00020	.00019	.00020	.00020	.00021
July 12–21, 1990	23,500	.033	.031	.033	.033	.035
August 2, 1990	26	.000036	.000033	.000036	.000036	.000038
August 14–17, 1990	79,900	.11	.10	.11	.11	.12
August 21–22, 1990	413	.00058	.00054	.00058	.00058	.00062
September 6–10, 1990	22,900	.032	.030	.032	.032	.034
September 19–24, 1990	1,810	.0025	.0024	.0025	.0025	.0027
October 20, 1990	702	.00098	.00091	.00098	.00098	.0011
January 4–10, 1991	2,740	.0038	.0036	.0038	.0038	.0041
February 7–19, 1991	1,030	.0014	.0013	.0014	.0014	.0015
March 1–11, 1991	21,800	.031	.028	.031	.031	.033
March 29–April 6, 1991	5,450	.0076	.0071	.0076	.0076	.0082
April 11–25, 1991	2,082	.0029	.0027	.0029	.0029	.0031
July 25–27, 1991	9,060	.013	.012	.013	.013	.014
August 7–9, 1991	74,500	.10	.097	.10	.10	.11
August 15–16, 1991	3,800	.0053	.0049	.0053	.0053	.0057
September 5–7, 1991	4,370	.0061	.0057	.0061	.0061	.0066
Puerco River near Chambers, Arizona (09396100)						
February 2–8, 1989	16,800	.024	.022	.024	.024	.025
February 12–28, 1989	37,200	.052	.048	.052	.052	.056
March 6, 1989	881	.0012	.0011	.0012	.0012	.0013
March 20, 1989	881	.0012	.0011	.0012	.0012	.0013
July 27–August 3, 1989	195,000	.27	.25	.27	.27	.29
August 19–20, 1989	136,000	.19	.18	.19	.19	.20
September 6–7, 1989	26,000	.036	.034	.036	.036	.039
February 12, 1990	1,350	.0019	.0018	.0019	.0019	.0020

Table 11. Suspended-sediment loads and suspended-phase loads of radionuclides for runoff periods at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Date	Suspended-sediment loads, in megagrams	Suspended-phase loads, in curies				
		Uranium–238	Uranium–234	Radium–226	Thorium–230	Thorium–232
Puerco River near Chambers, Arizona (09396100)—Continued						
February 14, 1990	1,050	0.0015	0.0014	0.0015	0.0015	0.0016
July 8–25, 1990	667,000	.93	.87	.93	.93	1.00
August 8, 1990	1,990	.0028	.0026	.0028	.0028	.0030
August 14–18, 1990	318,000	.44	.41	.44	.44	.48
August 21–22, 1990	32,500	.046	.042	.046	.046	.049
September 3–10, 1990	116,000	.16	.15	.16	.16	.17
October 20–22, 1990	342,000	.48	.44	.48	.48	.51
December 14, 1990	1,170	.0016	.0015	.0016	.0016	.0018
January 4–16, 1991	212,000	.30	.28	.30	.30	.32
February 8–19, 1991	333,000	.47	.43	.47	.47	.50
March 2–9, 1991	153,000	.21	.20	.21	.21	.23
March 17, 1991	1,260	.0018	.0016	.0018	.0018	.0019
March 28–April 8, 1991	41,700	.058	.054	.058	.058	.063
June 12–15, 1991	149,000	.21	.19	.21	.21	.22
July 26–August 8, 1991	402,000	.56	.52	.56	.56	.60
August 16–17, 1991	6,190	.0087	.0080	.0087	.0087	.0092
August 27–31, 1991	216,000	.30	.28	.30	.30	.32
September 5–8, 1991	9,300	.013	.012	.013	.013	.014
Little Colorado River near Joseph City, Arizona (09397300)						
November 26, 1988	1,620	.0016	.0018	.0019	.0019	.0021
February 5, 1989	4,930	.0049	.0054	.0059	.0059	.0064
March 27, 1989	2,460	.0025	.0027	.0030	.0030	.0032
July 23, 1989	28,700	.029	.032	.034	.034	.037
July 26–August 3, 1989	265,000	.27	.29	.32	.32	.34
August 12, 1989	2,350	.0023	.0036	.0028	.0028	.0031
August 18–22, 1989	664,000	.66	.73	.80	.80	.86
September 4, 1989	3,830	.0038	.0042	.0046	.0046	.0050
July 8–10, 1990	103,000	.10	.11	.12	.12	.13
July 12, 1990	1,160	.0012	.0013	.0014	.0014	.0015
July 14–18, 1990	473,000	.47	.52	.57	.57	.61
August 14–18, 1990	586,000	.59	.64	.70	.70	.76
September 1, 1990	43,300	.043	.048	.052	.052	.056
September 5, 1990	2,960	.0030	.0033	.0035	.0035	.0038
September 7, 1990	53,100	.053	.058	.064	.064	.069
September 19–26, 1990	430,000	.43	.47	.52	.52	.56
October 20–21, 1990	151,000	.15	.17	.18	.18	.20
November 3–4, 1990	100,000	.10	.11	.12	.12	.13
December 16–18, 1990	47,100	.47	.52	.57	.57	.61
December 29–30. 1990	59,400	.059	.065	.071	.071	.077
January 4–12, 1991	1,090,000	1.1	1.2	1.3	1.3	1.4

Table 11. Suspended-sediment loads and suspended-phase loads of radionuclides for runoff periods at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Date	Suspended-sediment loads, in megagrams	Suspended-phase loads, in curies				
		Uranium–238	Uranium–234	Radium–226	Thorium–230	Thorium–232
Little Colorado River near Joseph City, Arizona (09397300)—Continued						
February 11–20, 1991	62,900	0.063	0.069	0.075	0.075	0.082
March 2–10, 1991	440,000	.44	.48	.53	.53	.57
March 26–April 6, 1991	74,700	.075	.082	.090	.090	.097
August 1, 1991	1,430	.0014	.0016	.0017	.0017	.0019
August 4, 1991	5,610	.0056	.0062	.0067	.0067	.0073
August 8, 1991	4,200	.0042	.0046	.0050	.0050	.0055
August 28, 1991	170,000	.17	.19	.20	.20	.22
September 6–8, 1991	41,500	.041	.046	.050	.050	.054
Little Colorado River at Grand Falls, Arizona (09401000)						
April 10–14, 1990	1,140	.0014	.0013	.0015	.0016	.0017
July 9–24, 1990	520,000	.62	.57	.67	.73	.78
August 16–22, 1990	662,000	.79	.73	.86	.93	.99
August 25, 1990	5,050	.0061	.0056	.0066	.0071	.0076
September 3–11, 1990	127,000	.15	.14	.16	.18	.19
September 19–29, 1990	412,000	.49	.45	.54	.58	.62
October 22–24, 1990	61,700	.074	.068	.080	.86	.093
November 4–7, 1990	73,300	.088	.081	.095	.10	.11
December 17–24, 1990	129,000	.16	.14	.17	.18	.19
December 31, 1990–January 18, 1991	755,000	.91	.83	.98	1.1	1.1
February 15–May 16, 1991	1,930,000	2.3	2.1	2.5	2.7	2.9
August 12, 1991	2,700	.0032	.0030	.0035	.00038	.0041
September 8–12, 1991	77,300	.093	.085	.10	.11	.12
Little Colorado River near Cameron, Arizona (09402000)						
October 7, 1989	569	.00063	.00057	.00068	.00074	.00085
February 21–23, 1990	28,600	.032	.029	.034	.037	.043
July 8–25, 1990	394,000	.43	.39	.47	.51	.59
August 2, 1990	18,100	.020	.018	.022	.024	.027
August 15–23, 1990	785,000	.86	.78	.94	1.0	1.2
August 26–27, 1990	2,770	.0031	.0028	.0033	.0036	.0042
September 4–12, 1990	190,000	.21	.19	.23	.25	.29
September 16–October 5, 1990	1, 830,000	2.0	1.8	2.2	2.4	2.7
October 23–27, 1990	62,600	.069	.063	.075	.081	.094
November 5–10, 1990	82,300	.091	.082	.099	.11	.12
December 18–25, 1990	180,000	.20	.18	.22	.23	.27
January 1–21, 1991	897,000	.99	.90	1.1	1.2	1.3
February 17–May 15, 1991	4,460,000	4.9	4.5	5.4	5.8	6.7
August 7–8, 1991	8,810	.0097	.0088	.011	.011	.013
August 27–29, 1991	103,000	.11	.10	.12	.13	.15
September 2–14, 1991	759,000	.83	.76	.91	.99	1.1

Table 12. Suspended-sediment load, flow volume, and suspended-phase loads of radionuclides at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[Period of sediment sampling, water years 1989–91 for 09394500, 09397300, and 09396100, water years 1990–91 for 09401000 and 09402000, April 1989 to September 30, 1991, for all other gaging stations. Uranium is ^{234}U + ^{238}U, radium is ^{226}Ra + ^{228}Ra, and Thorium is ^{230}Th + ^{232}Th. Because insufficient analyses were made to determine the concentration of ^{228}Ra on sediment, the ^{228}Ra concentration was assumed to equal the ^{226}Ra concentration. ---, no data]

Station number	Station name	Suspended-sediment load, in megagrams	Flow volume, in cubic meters	Suspended-phase loads of radionuclides, in curies		
				Uranium	Radium	Thorium
	Water year 1989					
09386950	Zuni River above Black Rock Reservoir, New Mexico	0.00253x10^6	1.61x10^6	0.0081	0.0086	0.0075
09394500	Little Colorado River at Woodruff, Arizona	.165x10^6	12.5x10^6	.32	.34	.41
09395350	Puerco River near Church Rock, New Mexico	.200x10^6	1.08x10^6	.54	.60	.56
09395630	Puerco River near Manuelito, New Mexico	.636x10^6	4.31x10^6	1.7	1.8	1.8
09395990	Black Creek below West Fork Black Creek, near Houck, Arizona.	.0180x10^6	1.64x10^6	.048	.050	.048
09396100	Puerco River near Chambers, Arizona	.412x10^6	5.45x10^6	1.1	1.2	1.2
09397300	Little Colorado River near Joseph City, Arizona	.974x10^6	[1]9.8x10^6	2.0	2.3	2.4
09401000	Little Colorado River at Grand Falls, Arizona	---	---	---	---	---
09402000	Little Colorado River near Cameron, Arizona	---	45.0x10^6	---	---	---
	Water year 1990					
09386950	Zuni River above Black Rock Reservoir, New Mexico	.000034x10^6	.442x10^6	.00011	.00012	.00010
09394500	Little Colorado River at Woodruff, Arizona	.285x10^6	15.5x10^6	.55	.58	.71
09395350	Puerco River near Church Rock, New Mexico	.177x10^6	1.24x10^6	.48	.52	.49
09395630	Puerco River near Manuelito, New Mexico	.509x10^6	5.95x10^6	1.3	1.4	1.5
09395990	Black Creek below West Fork Black Creek, near Houck, Arizona.	.129x10^6	2.84x10^6	.35	.36	.35
09396100	Puerco River near Chambers, Arizona	1.14x10^6	10.8x10^6	3.1	3.2	3.4
09397300	Little Colorado River near Joseph City, Arizona	1.69x10^6	32.3x10^6	3.6	4.0	5.0
09401000	Little Colorado River at Grand Falls, Arizona	1.73x10^6	26.9x10^6	4.0	4.5	5.0
09402000	Little Colorado River near Cameron, Arizona	3.20x10^6	44.5x10^6	6.7	7.7	9.0
	Water year 1991					
09386950	Zuni River above Black Rock Reservoir, New Mexico	.000884x10^6	3.13x10^6	.0028	.0030	.0026
09394500	Little Colorado River at Woodruff, Arizona	.268x10^6	19.9x10^6	.51	.54	.67
09395350	Puerco River near Church Rock, New Mexico	.309x10^6	1.28x10^6	.83	.92	.86
09395630	Puerco River near Manuelito, New Mexico	.476x10^6	5.96x10^6	1.2	1.3	1.4
09395990	Black Creek below West Fork Black Creek, near Houck, Arizona.	.126x10^6	4.75x10^6	.34	.36	.34
09396100	Puerco River near Chambers, Arizona	1.86x10^6	24.2x10^6	5.0	5.2	5.6
09397300	Little Colorado River near Joseph City, Arizona	2.71x10^6	49.1x10^6	5.7	6.5	6.8
09401000	Little Colorado River at Grand Falls, Arizona	3.03x10^6	168x10^6	7.0	7.9	8.8
09402000	Little Colorado River near Cameron, Arizona	6.60x10^6	154x10^6	14	16	18

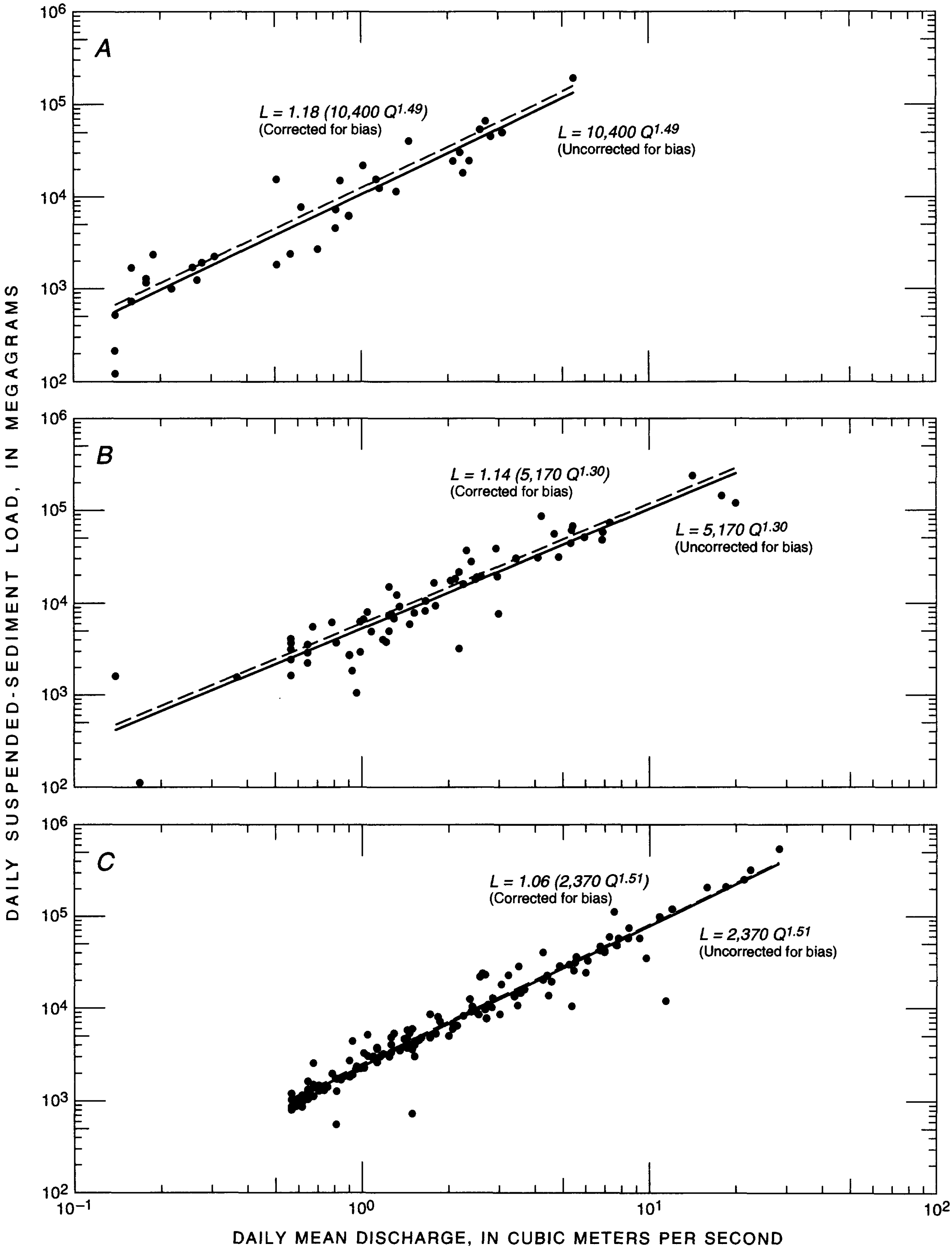

Figure 24. Relation of daily suspended-sediment load to daily mean discharge at streamflow-gaging stations, Puerco River, Arizona and New Mexico. *A*, Puerco River near Church Rock, New Mexico; *B*, Puerco River near Manuelito, New Mexico; *C*, Puerco River near Chambers, Arizona.

Table 13. Mean and median radioactivity of suspended-sediment samples collected at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[All values are in picocuries per gram of dry sediment. ±, plus or minus]

Station number	Station name	Uranium–238			Uranium–234			Radium–226			Thorium–230			Thorium–232		
		Number of samples	Median	Mean± standard deviation	Number of samples	Median	Mean± standard deviation	Number of samples	Median	Mean± standard deviation	Number of samples	Median	Mean± standard deviation	Number of samples	Median	Mean± standard deviation
09386950	Zuni River above Black Rock Reservoir, New Mexico.	8	1.7	1.8±0.8	8	1.5	1.7±0.8	5	1.7	2.1±0.9	6	1.6	1.9±0.8	6	1.4	1.4±0.1
09394500	Little Colorado River at Woodruff, Arizona.	9	1.0	1.0±.1	9	.9	1.0±.2	9	1.0	1.2±.5	9	1.2	1.2±.2	9	1.3	1.3±.2
09395350	Puerco River near Church Rock, New Mexico.	7	1.4	1.4±.5	7	1.3	1.3±.4	3	1.5	1.6±.3	7	1.5	1.5±.4	7	1.3	1.3±.4
09395630	Puerco River near Manuelito, New Mexico.	15	1.3	1.3±.1	15	1.3	1.3±.2	8	1.4	1.4±.1	12	1.4	1.4±.2	12	1.5	1.4±.3
09395990	Black Creek below West Fork Black Creek, near Houck, Arizona.	5	1.4	1.4±.1	5	1.3	1.3±.1	4	1.4	1.4±.5	5	1.4	1.5±.3	5	1.3	1.4±.1
09396100	Puerco River near Chambers, Arizona.	7	1.4	1.4±.1	7	1.3	1.3±.1	6	1.4	1.4±.3	7	1.5	1.5±.1	7	1.5	1.5±.3
09397300	Little Colorado River near Joseph City, Arizona.	4	1.0	1.0±.1	4	1.1	1.1±.2	4	1.2	1.2±.2	4	1.2	1.2±.1	4	1.3	1.3±.3
09401000	Little Colorado River at Grand Falls, Arizona.	6	1.2	1.2±.2	6	1.1	1.1±.1	4	1.3	1.2±.5	6	1.4	1.4±.2	6	1.5	1.4±.2
09402000	Little Colorado River near Cameron, Arizona.	4	1.1	1.1±.2	4	1.0	1.0±.2	2	1.2	1.2±.1	4	1.3	1.2±.2	4	1.5	1.4±.3

^{230}Th in the same samples ranged from 1.3 to 9.7 pCi/g and averaged 2.9 pCi/g. The downstream increase of ^{230}Th was greater than that of ^{226}Ra—the three upstream sites averaged 1.9 pCi/g and the two downstream sites averaged 4.3 pCi/g. In the present study, ^{226}Ra averaged about 1.4 pCi/g and ^{230}Th averaged about 1.5 pCi/g at the Puerco River gaging stations (table 13). All stations on the Puerco River were at or upstream from Chambers in the present study, and the results presented in this report cannot be used to determine if a decrease with time in concentration of these two isotopes has occurred in the reach downstream from Chambers.

The tailings-pond spill of 1979 probably was the most significant source of ^{230}Th to sediment in the Puerco River (Weimer and others, 1981; Graf, 1990), and radioactivity of sediment in the Puerco River from ^{230}Th has decreased to levels at or near background. Radioactivity of ^{230}Th in a tailings-pond sample collected before the spill was 10,225 pCi/L, and soon after the spill, radioactivity of ^{230}Th on bed material was greater than 30 pCi/g as far as about 65 km downstream from the mines (Weimer and others, 1981). Millard and others (1984) measured radioactivity of samples of alluvium from high terraces unaffected by mining from Pipeline Arroyo

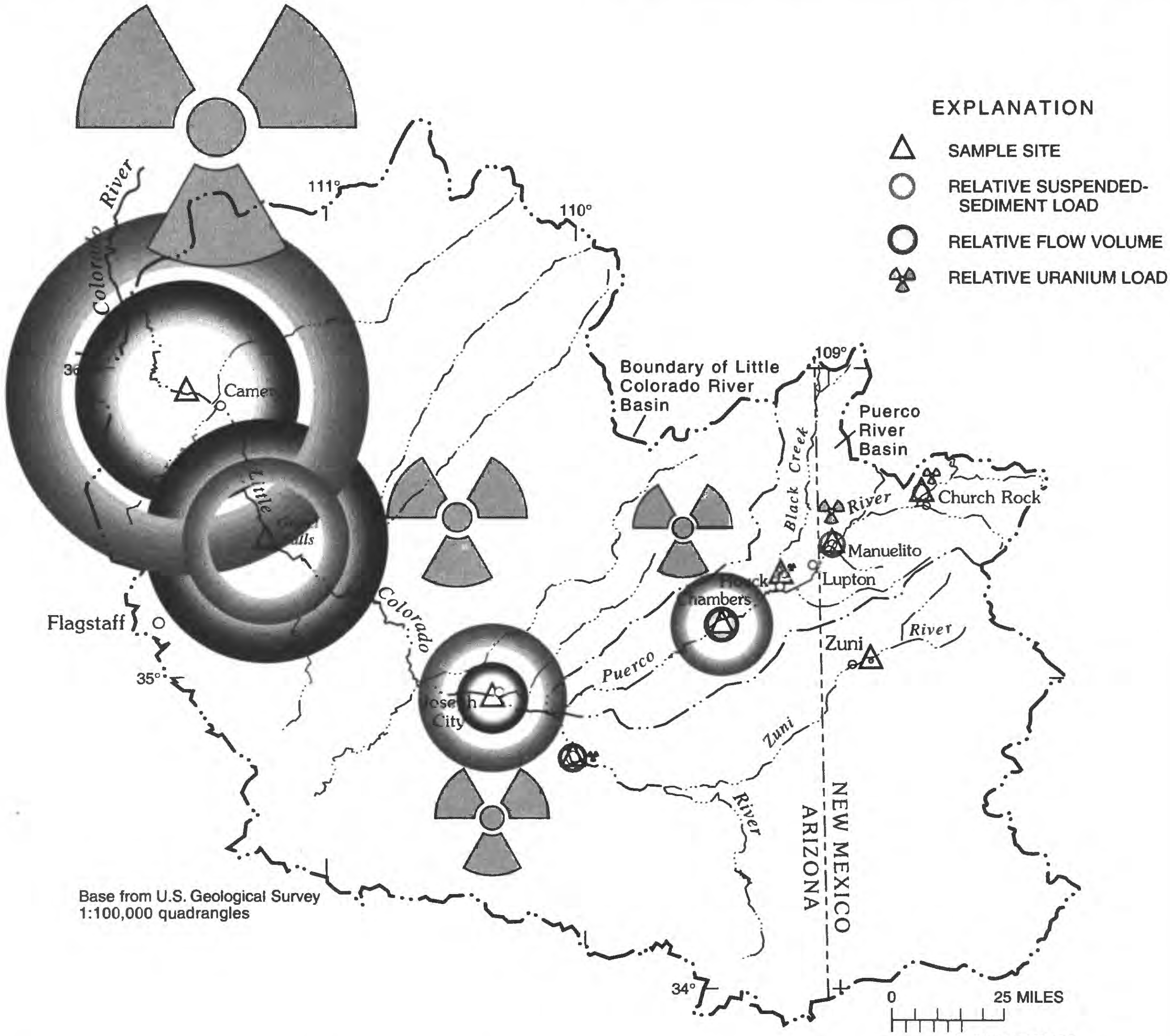

Figure 25. Relative magnitude of annual flow volume, suspended-sediment load, and uranium load at streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico.

upstream from the spill and from the Puerco River downstream from the spill in 1979 and 1980. Thorium-230 radioactivity was 0.75±1.28 pCi/g in high-terrace samples and 4.70±1.65 pCi/g in Pipeline Arroyo samples affected by dewatering but not by the spill. In the main channel downstream from the spill, ^{230}Th radioactivity averaged 27±1 pCi/g in 1979 and 8.4±0.5 pCi/g in 1980. Mean values of ^{230}Th in suspended sediment during this study ranged from 1.2 to 1.9 pCi/g and standard deviations were 0.1– 0.8 pCi/g (table 13).

The results of the ADHS study in 1985 and the present study indicate that although the effects of the spill were no longer detectable in New Mexico by the mid-1980's (Weimer and others, 1981; Millard and others, 1983, 1984; Gallaher and Cary, 1986; Miller and Wells, 1986), the effects of the spill were still detectable in 1985 in the Arizona reach of the Puerco River, especially downstream from Chambers. The small decrease in ^{230}Th concentration from 1985 to the present study period in the reach just upstream from Chambers indicates that some Th originating from the spill may have been present at Chambers and in the reach upstream in 1985. The sample numbers are small in both studies, and small numbers of samples and large ranges in values precludes definitive conclusions. The difference in radioactivity of ^{230}Th on sediment, however, may be significant. In the ADHS study of 1985, radioactivity of the total suspended-solids fraction of the sample was analyzed, rather than the less-than 0.062-mm fraction as was done in the present study. Because radioactive isotopes tend to concentrate in the fine fraction, the difference between the values obtained in 1985 and those of the present study probably would be greater if only the fine fraction had been analyzed in the study in 1985.

A decrease in dissolved-phase concentrations of Mo, Se, Ra, U, and gross-alpha and gross-beta radioactivity in the 100 km downstream from the uranium mines was found by Van Metre and Gray (1992) for data collected during 1975–84, which was during dewatering. A decrease in dissolved-phase concentrations of Mo and Se at Gallup from the period of dewatering to the post-dewatering period also was found by Van Metre and Gray (1992). In the present study, dissolved-phase concentrations of both Mo and Se were found to be below detection, suggesting a further decrease in dissolved-phase concentration in the period following cessation of mine dewatering.

Suspended gross-alpha and gross-beta radioactivity, in picocuries per liter, showed no trend with either time or downstream distance from 1975 to 1984 but did have a significant positive correlation with discharge as would be expected because of the increase in suspended-sediment concentration with increasing discharge (Van Metre and Gray, 1992). Much of the radioactivity data collected in previous studies cannot be compared with sediment radioactivity measured in the present study because suspended-sediment concentration commonly was not determined in previous studies.

An estimate of ^{226}Ra load contributed by mine dewatering was made to compare with radionuclide loads carried on suspended sediment during the study. The median radioactivity of ^{226}Ra in untreated effluent (295 pCi/L, table 3) and the average annual volume of dewatering effluent (6.4×10^6 m^3 or 6.4×10^9 L; Van Metre and Gray, 1992) were used to estimate that 1.9 Ci of ^{226}Ra were released to the Puerco River through Pipeline Arroyo each year by dewatering before treatment of effluent was implemented. In comparison, about 0.5 Ci of ^{226}Ra is estimated to have been transported on sediment past the Puerco River gaging station near Church Rock in water year 1991 (table 12). A ^{226}Ra radioactivity of about 6 pCi/g for suspended sediment was estimated at the gaging station at Church Rock during release of untreated dewatering effluent. The estimate was made by assuming that all the ^{226}Ra released by mine dewatering in a single year was sorbed onto sediment and transported in suspension past the gaging station near Church Rock and that the suspended-sediment load equaled the load that passed the Church Rock station in 1991. Sediment radioactivity caused by ^{226}Ra during the study period—1.5 pCi/g at Puerco River near Church Rock—therefore, is estimated to be about 25 percent of that during release of untreated dewatering effluent.

Although U is less radioactive than Ra, U was present in much higher concentrations than Ra and was the primary source of radioactivity in mine-dewatering effluent (table 3). Van Metre and Gray (1992) estimated that 508 Mg of U were released in the 22 years of dewatering. Using a specific radioactivity of 0.695 Ci/Mg for natural U, an estimate was made that 353 curies of natural U were released during dewatering—an average of 16 Ci/yr. In comparison, the radioactivity of ^{238}U plus ^{234}U transported past the gaging station on the Puerco River near Church Rock during the 3-year study was estimated to be 1.9 Ci (table 12). The amount of U transported past the gaging station near Church Rock during an average study year—0.63 Ci—therefore, is approximately 4 percent of the amount released in an average year during dewatering. During mine dewatering, radionuclide loads in streamflow probably decreased downstream because of dilution by sediment not affected by mining.

If mining had influenced surface-water chemistry in the study area, secular disequilibrium probably would have resulted from an excess of one or more ^{238}U series radionuclides (^{238}U, ^{234}U, ^{226}Ra, and ^{230}Th). Mean and median radioactivities of ^{238}U series radionuclides (table 13) are in secular equilibrium within measurement error. That observation supports the conclusion that past mining no longer significantly influences sediment chemistry in the Puerco River.

Data from samples collected by the SRIC in 1987 during runoff indicate that the radioactivity of suspended sediment was greater in the North Fork than in the unmined South Fork of the Puerco River (Shuey, 1992). The difference between the SRIC study results and those of the present study could be caused by the timing of the two studies—the SRIC samples were collected less than 1 year after mine dewatering had ceased. Differences also could be attributed to the laboratory error inherent in measurements of total gross-alpha and gross-beta radioactivity for samples having high suspended-sediment concentrations. Differences in methods among studies prevent definitive comparisons of study results.

CONCLUSIONS

Measurement of flow and suspended-sediment transport and analysis of sediment and water chemistry at nine streamflow-gaging stations in the Little Colorado River basin from 1988 to 1991 supports the following major conclusions:

- Surface water from which suspended sediment has been removed typically met water-quality standards for drinking water for radionuclides and other chemical constituents that were measured. Water containing large amounts of sediment typically exceeded water-quality standards.
- Measured radioactivity from ^{234}U, ^{238}U, and ^{228}Ra on suspended-sediment samples collected downstream from uranium mines was significantly lower than that of samples collected at sites where no uranium mining had occurred.
- Variation in radioactivity of suspended sediment probably is related to lithology of sediment-source areas rather than to mining. Suspended sediment collected at streamflow-gaging stations in the eastern part of the Little Colorado River Basin—on the Puerco and Zuni Rivers and on Black Creek—had higher ^{234}U, ^{238}U, ^{228}Ra, ^{230}Th, and ^{232}Th radioactivities than samples from gaging stations in the western part of the basin—on the main stem of the Little Colorado River. Sediment radioactivity for those isotopes was about 1.3–2.1 pCi/g for samples from the eastern part of the Little Colorado River Basin and about 0.9–1.5 pCi/g for samples from the western part.
- More than 99 percent (by mass) of the total chemical load of studied constituents was transported on suspended sediment. Large particle-surface area, abundant clay-sized particles, and clay minerals with high cation-exchange capacity make suspended sediment in the Little Colorado River Basin ideal for sorption and transport of chemical constituents.
- Streams in this study area carry large loads of suspended sediment, and those large loads probably mixed with sediment that had high radioactivity from mining to produce sediment that has radioactivity at background levels. Annual suspended-sediment loads transported past the gaging stations on the Puerco River near Church Rock and Chambers, averaged about 230,000 and 1,300,000 Mg, respectively. Suspended sediment transported per unit volume of flow is highest on the Puerco River near Church Rock (0.26 Mg/m^3) and lowest on the Zuni River above Black Rock Reservoir (0.0007 Mg/m^3).
- The chemical load becomes larger downstream in the Puerco and Little Colorado Rivers because the suspended-sediment load is larger for larger drainage areas and not because of downstream trends in radioactivity of sediment or the amount of suspended sediment carried by a given volume of flow. For water year 1991, suspended-sediment load was estimated to be 0.31×10^6 Mg on the Puerco River near Church Rock and 6.6×10^6 Mg on the Little Colorado River near Cameron.
- Comparison of chemical analyses of samples collected during the present study with those

collected during mine dewatering indicates that radioactivity transported by the Puerco River downstream from mining has decreased significantly. The sum of ^{234}U and ^{238}U transported annually past the gaging station on the Puerco River near Church Rock during the study period was about 4 percent of that produced in an average year by release of untreated dewatering effluent. Sediment radioactivity from ^{226}Ra during the study period was estimated to be reduced to about one-fifth of that estimated for the period of active mining.

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DATA TABLES 14—17

Table 14. Concentrations of selected chemical constituents in the dissolved phase of samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[m^3/s, cubic meters per second; μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; <, less than; >, greater than. Sampling method: M, automated sample collected from a point location; D, manually collected sample at equal distance intervals; C, composited from several automated point samples representing different phases of the hydrograph; G, grab or dip sample. All samples were passed through a 0.45-micrometer cellulose nitrate paper filter. ---, no data]

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (μS/cm)	pH, field	Hardness as $CaCO_3$ (mg/L)	Concentration, in micrograms per liter: Arsenic (As)	Barium (Be)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Zuni River above Black Rock Reservoir, New Mexico (09386950)																		
98800024	07–15–88	1030	--	0.27	590	8.4	210	2	--	--	2	<1	1	<5	<0.1	--	<1	12
98800025	08–17–88	1400	--	1.6	370	8.3	140	1	--	--	<1	<1	3	<5	<.1	--	<1	8
98900034	11–06–88	1510	--	2.1	650	8.4	240	1	--	--	2	<1	<1	<5	<.1	--	<1	8
98900231	07–26–89	0110	M	266	472	--	130	--	190	<0.5	<1	<5	<10	10	--	<10	--	10
98900236	07–26–89	0110	M	322	--	--	100	--	140	<.5	<1	<5	10	<10	--	<10	--	4
98900232	07–26–89	0140	M	757	419	--	110	--	160	<.5	<1	<5	<10	20	--	<10	--	5
98900233	07–26–89	0400	M	263	242	--	85	--	120	<.5	<1	<5	<10	<10	--	<10	--	5
98900213	07–26–89	1600	D	15	220	7.6	90	--	95	<.5	<1	<5	<10	<10	--	<10	--	13
99000693	11–14–89	1450	--	.15	900	8.4	260	1	--	--	<1	<1	3	<1	<.1	--	<1	6
99000694	01–04–90	1300	--	.39	--	8.1	380	<1	--	--	<1	1	<10	<10	<.1	--	1	5
99000695	03–19–90	1530	--	1.3	730	8.2	280	<1	--	--	<1	<5	<10	<10	<.1	--	<1	5
99000696	09–25–90	1315	--	.29	365	8.1	100	<1	--	--	<1	<1	5	<1	<.1	--	<1	6
99100733	12–05–90	1030	--	.21	810	8.3	300	1	--	--	<1	<1	3	<1	.1	--	<1	4
99100734	02–26–91	1500	--	1.3	710	8.6	240	<1	--	--	<1	<1	1	1	<.1	--	<1	3
99100105	04–05–91	1403	M	142	490	8.3	170	1	77	<.5	<1	<5	<10	<10	--	<10	<1	<3
99100106	04–05–91	1430	D	146	491	8.0	170	1	76	<.5	<1	<5	<10	<10	--	<10	<1	<3
99100735	05–14–91	1030	--	.53	710	8.0	200	<1	--	--	<1	<1	<1	1	.1	--	<1	5
99100678	09–06–91	0915	D	14	340	7.9	120	<1	70	<.5	<1	<5	<10	<10	--	<10	<1	8
Little Colorado River at Woodruff, Arizona (09394500)																		
98800012	08–30–88	1445	D	249	325	9.0	--	7	23	--	<1	--	<1	<5	.1	<1	<1	<3
98900151	08–18–89	([2])	C	945	--	[3]7.9	--	--	33	<.5	<1	<5	<10	<10	--	<10	--	12
98900150	08–18–89	1740	M	885	--	[3]6.8	10	--	63	<.5	<1	<5	10	<10	--	<10	--	26
99000531	07–07–90	2020	C	888	490	7.3	130	4	330	<.5	<1	<5	<10	<10	--	<10	<1	<3
99000556	08–16–90	([2])	C	--	--	[3]8.8	7	--	6	<.5	<1	<5	50	<10	--	<10	1	7
99000555	08–16–90	1235	D	530	--	[3]8.9	12	--	32	<.5	<1	<5	50	<10	--	<10	<1	17
99000542	09–21–90	([2])	C	888	500	8.3	21	6	31	.6	<1	<5	20	<10	--	<10	<1	4
99100052	01–06–91	1840	M	1,290	574	9.3	12	5	45	<.5	<1	<5	20	<10	--	<10	<1	26
99000529	07–07–90	2350	M	578	--	[3]7.1	430	1	92	<.5	<1	<5	<10	<10	--	<10	1	6
99000534	07–08–90	0800	G	33	720	7.8	320	<1	58	<.5	<1	<5	<10	<10	--	<10	2	6

Table 14. Concentrations of selected chemical constituents in the dissolved phase of samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Hardness as $CaCO_3$ (mg/L)	Concentration, in micrograms per liter: Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Puerco River near Church Rock, New Mexico (09395350)																		
99000535	07–09–90	2020	M	671	--	[3]7.4	350	<1	60	0.5	<1	<5	<10	<10	--	<10	<3	<3
99000537	07–09–90	2120	M	598	690	[3]7.4	--	<1	--	--	--	--	--	--	--	--	<2	--
99000536	07–12–90	0100	M	650	--	[3]7.4	390	<1	61	<.5	1	<5	<10	<10	--	<10	3	<3
99000560	08–15–90	1030	D	66	530	8.6	330	1	72	<.5	5	<5	<10	<10	--	<10	<1	1900
Puerco River near Manuelito, New Mexico (09395630)																		
98800032	08–31–88	1400	--	97	510	8.0	120	1	42	--	2	--	10	<10	<.1	4	1	18
98900082	04–05–89	1315	--	5.0	2,020	8.7	83	9	--	--	<1	--	12	<5	<.1	10	<1	10
99000538	07–13–90	1850	M	3,650	--	[5]7.1	190	3	91	.5	<1	<5	<10	<10	--	<10	<2	<3
99000619	07–13–90	1920	M	7,900	490	7.5	180	3	120	<.5	<1	<5	<10	<10	--	<10	<2	<3
99000622	07–13–90	1950	M	4,930	--	[3]7.3	140	2	89	<.5	<1	<5	<10	10	--	<10	<2	6
99000522	08–03–90	([2])	C	--	--	[3]7.9	--	5	--	--	--	--	--	--	--	--	1	--
99000562	08–14–90	2035	G	80	--	[3]7.3	190	8	68	<.5	<1	<5	<10	<10	--	<10	<1	<3
99000561	08–15–90	0800	D	370	415	8.8	110	1	59	<.5	<1	<5	<10	<10	--	<10	<1	4
99100049	10–20–90	0030	M	1,190	--	[3]7.6	98	1	50	<.5	<1	<5	<10	<10	--	<10	<1	12
99100070	10–20–90	0200	M	2,800	341	[3]7.7	77	<1	35	<.5	1	<5	<10	<10	--	<10	<1	<3
99100067	10–20–90	0330	M	1,770	--	[3]7.7	120	1	54	<.5	<1	<5	<10	<10	--	<10	<1	4
Black Creek above West Fork Black Creek, near Houck, Arizona (09395990)																		
98900147	09–05–89	2020	M	619	--	[3]7.7	--	--	160	<.5	<1	<5	<10	<10	--	<10	--	24
98900148	09–05–89	2050	M	199	--	[3]7.7	--	--	120	<.5	<1	<5	<10	20	--	<10	--	14
98900146	09–05–89	2200	M	157	--	[3]7.7	--	--	130	<.5	<1	<5	<10	<10	--	<10	--	20
98900145	09–06–89	2320	M	130	--	[3]7.7	--	--	120	<.5	<1	<5	<10	<10	--	<10	--	17
99100118	07–26–91	1400	D	41	772	8.1	38	2	80	<.5	<1	<5	20	<10	--	<10	1	19
99100662	08–07–91	1215	D	145	585	[5]7.6	41	4	61	<.5	<1	<5	20	<10	--	<10	1	8
Puerco River near Chambers, Arizona (09396100)																		
98900149	09–06–89	1440	M	[4]108	--	[3]8.1	370	--	150	<.5	<1	<5	<10	<10	--	<10	--	5
98900152	09–06–89	1510	M	188	--	[3]7.9	370	--	160	<.5	<1	<5	<10	<10	--	<10	--	17
98900153	09–06–89	1515	G	[4]150	1,200	[3]7.9	370	--	150	<.5	<1	<5	<10	<10	--	<10	--	11
99000530	07–11–90	1320	D	90	2,090	7.1	400	1	170	<.5	1	<5	<10	<10	--	<10	<1	39
99000552	08–15–90	0250	M	2,350	950	7.8	210	2	160	<.5	<1	<5	<10	<10	--	<10	<1	11
99000554	08–15–90	1135	G	941	980	8.1	180	1	110	<.5	<1	<5	<10	<10	--	<10	<1	8

Table 14. Concentrations of selected chemical constituents in the dissolved phase of samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Hardness as $CaCO_3$ (mg/L)	Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
								Concentration, in micrograms per liter										
Puerco River near Chambers, Arizona (09396100)—Continued																		
99000551	08–15–90	1820	G	280	860	7.8	190	1	120	<0.5	<1	<5	<10	<10	--	<10	<1	8
99000553	08–16–90	0930	G	167	720	7.6	110	1	99	<.5	<1	<5	<10	20	--	<10	<1	6
99100047	10–20–90	0800	M	4,400	--	[3]7.5	260	2	110	<.5	3	<5	<10	<10	--	<10	<1	7
Little Colorado River near Joseph City, Arizona (09397300)																		
99000548	08–16–90	1645	D	961	--	[3]8.1	23	6	31	<.5	<1	<5	10	<10	--	<10	2	<3
99000545	08–16–90	1750	M	790	--	[3]8.1	25	5	25	<.5	1	<5	40	<10	--	<10	1	14
99000547	09–01–90	([2])	C	--	--	[3]7.8	100	2	80	<.5	<1	<5	<10	<10	--	<10	<1	<3
99000543	09–21–90	([2])	C	1,010	592	8.3	26	6	46	.5	<1	<5	<10	<10	--	<10	<1	<3
99100053	01–07–91	1620	G	790	518	9.3	11	8	49	<.5	<1	<5	20	<10	--	<10	<1	6
99100119	08–01–91	1145	D	82	408	[3]7.8	100	2	100	<.5	<1	<5	10	<10	--	<10	<1	11
Little Colorado River at Grand Falls, Arizona (09401000)																		
99000532	07–09–90	1210	M	1,500	--	[3]8.1	46	10	170	<.5	<1	<5	<10	<10	--	<10	1	8
99000533	07–09–90	1810	M	1,020	--	[3]7.8	61	6	200	<.5	<1	<5	<10	<10	--	<10	<1	7
99000525	07–10–90	1405	D	278	--	[3]8.1	39	8	120	<.5	1	<5	<10	<10	--	<10	<1	31
99000519	07–17–90	1600	M	404	--	[3]7.8	51	3	160	<.5	2	<5	<10	<10	--	<10	1	12
99000539	07–17–90	1800	D	341	--	[3]7.8	62	3	150	<.5	1	<5	<10	<10	--	<10	1	8
99000517	07–17–90	1840	M	333	--	[3]8.1	29	5	11	<.5	<1	<5	50	10	--	<10	1	18
99000549	08–17–90	1230	D	1,590	--	[3]7.7	76	3	130	<.5	<1	<5	<10	<10	--	<10	2	6
99000550	08–17–90	1240	--	1,600	--	[3]7.8	73	2	30	<.5	<1	<5	70	<10	--	<10	2	13
99000544	09–22–90	([2])	C	--	760	8.0	45	4	120	<.5	<1	<5	<10	<10	--	<10	2	9
99100051	01–07–91	([2])	C	--	605	8.7	16	7	30	<.5	<1	<5	10	<10	--	<10	<10	34
99100072	03–05–91	([2])	C	1,060	511	8.6	23	3	13	<.5	<1	<5	10	<10	--	<10	<1	6
99100071	03–05–91	1300	D	1,110	511	8.5	28	3	19	<.5	<1	<5	40	<10	--	<10	1	25
99100098	05–01–91	1245	G	241	343	8.0	51	--	33	<.5	<1	<5	10	<10	--	<10	--	25
99100096	05–01–91	1255	D	241	343	8.0	49	--	--	--	--	--	--	--	--	--	--	--
99100445	09–09–91	1445	D	138	762	8.1	31	6	32	<.5	<1	<5	10	<10	--	<10	1	<3
Little Colorado River near Cameron, Arizona (09402000)																		
99000524	07–12–90	1230	D	100	1,210	8.1	57	5	240	<.5	2	2	7	3	--	<10	1	72
99000515	07–23–90	1840	M	2,680	--	[3]7.8	71	3	170	<.5	2	<5	<10	<10	--	<10	1	15
99000557	08–19–90	1245	D	720	--	[3]8.0	47	4	130	<.5	<1	<5	<10	<10	--	<10	2	8

Table 14. Concentrations of selected chemical constituents in the dissolved phase of samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Hardness as $CaCO_3$ (mg/L)	Concentration, in micrograms per liter: Arsenic (As)	Barium (Ba)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Little Colorado River near Cameron, Arizona (09402000)—Continued																		
99000540	09–19–90	([2])	C	--	1,340	7.8	430	<1	160	<0.5	<1	<5	<10	<10	--	<10	3	<3
99100050	01–08–91	1530	D	2,230	709	8.6	19	5	16	<.5	<1	<5	20	<10	--	<10	<3	3
99100073	03–07–91	1400	D	1,270	520	8.5	21	2	25	<.5	<1	<5	10	<10	--	<10	<1	<3
99100097	05–02–91	1315	D	213	354	8.0	55	1	77	--	<1	<1	2	<1	--	--	<1	<3
99100446	09–05–91	1300	D	18	1,250	7.5	490	2	160	<.5	<1	<1	11	<1	--	<10	2	3
Little Colorado River near Holbrook, Arizona (345351110094402)																		
99000491	05–15–90	0900	--	--	1450	8.6	310	--	140	<.5	<1	<5	<10	<10	--	<10	--	6
Puerco River near Querino Road upstream from Sanders, Arizona (351527109161902)																		
98900080	04–04–89	1700	G	5.0	845	8.2	240	5	53	--	<1	--	3	<5	<.1	2	1	9
Puerco River near Lupton, Arizona (351942109041401)																		
99000421	11–17–89	1700	G	--	2,530	7.0	790	--	83	<1	<2	<10	<20	<20	--	30	--	420
99100040	10–16–90	1220	G	--	1,890	6.8	260	3	87	<.5	<1	<5	<10	<10	--	<10	<1	4
99100108	06–11–91	1500	G	--	3,920	6.9	870	2	110	<2	<3	<20	<30	<30	--	<30	<1	72
Puerco River at Route 83 Bridge, Gallup, New Mexico (353056108504402)																		
98900138	03–31–89	1630	G	--	2,020	--	83	5	--	--	<1	--	10	<5	.1	5	<1	10
99000521	08–03–90	0725	G	--	--	[3]7.8	--	3	--	--	--	--	--	--	--	--	<1	--
99100048	10–16–90	0800	G	--	1,710	8.0	--	2	--	--	--	--	--	--	--	--	<1	--
Puerco River at Sewage-Treatment Plant, Gallup, New Mexico (353104108490201)																		
98900067	03–27–89	1700	G	[4]50	1,950	7.6	78	3	--	--	<1	--	11	<5	.2	<1	<1	19
99000528	08–03–90	0920	G	--	--	[3]7.4	--	2	--	--	--	--	--	--	--	--	<1	--
Arroyo Chico near San Luis, New Mexico (353535107112701)																		
99000513	05–18–90	1400	G	--	--	[3]8.4	220	--	88	<2	<3	<20	<30	<30	--	<30	--	11
Pipeline Arroyo near Church Rock, New Mexico (353730108312001)																		
99000546	08–15–90	1330	D	--	--	[3]7.8	370	4	120	<.5	1	<5	<10	<10	--	<10	2	5
99000546	08–15–90	[5]1330	D	--	--	[3]7.8	--	4	--	<.5	1	<5	<10	<10	--	<10	2	5
Rio Puerco near San Luis, New Mexico (354020107043302)																		
99000510	05–18–90	1200	G	--	7,660	8.1	230	--	83	<.5	<1	<5	<10	<10	--	<10	--	50

[1]Record number is an arbitrary number assigned to each sample by the U.S. Geological Survey National Water-Quality Laboratory when the sample is received.
[2]Composite from different sampling times. [3]Laboratory measurement. [4]Estimated. [5]Duplicate sample.

Table 15. Concentrations of selected chemical constituents in the less than 0.062-millimeter fraction of the suspended phase in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[m^3/s, cubic meters per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; <, less than; >, greater than. Sampling method: M, automated sample collected from a point location; C, composited from several automated point samples representing different phases of the hydrograph; D, manually collected sample at equal distance intervals; G, grab or dip sample. ---, no data]

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Percent sediment <0.062 mm	Arsenic (As)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
							Concentration, in milligrams per liter[2]										
Zuni River above Black Rock Reservoir, New Mexico (09386950)																	
98900231	07–26–89	[3]0110	M	7.5	15,600	[4]100	[5]0.14	--	[5]<0.078	[5]0.81	[5]0.37	[5]0.37	[5]4.7	[5]0.0011	[5]0.27	[5]0.011	[5]1.6
98900231	07–26–89	[3]0110	M	7.5	15,600	[4]100	<.16	0.03	<.03	.78	.42	.44	5.9	--	.31	--	1.7
98900236	07–26–89	([3,6])	C	9.1	15,500	67	<.16	.03	<.03	.84	.40	.43	5.6	--	.31	--	1.5
98900236	07–26–89	([3,6])	C	9.1	15,500	67	[5].14	--	[5]<.078	[5].81	[5].39	[5].40	[5]4.7	[5].0011	[5].26	.011	[5]1.6
98900232	07–26–89	0140	M	21	17,600	--	.35	.04	<.03	.97	.48	.60	6.8	--	.32	--	1.6
98900234	07–26–89	0220	M	15.2	17,400	94	<.17	.03	<.03	.96	.47	.47	6.4	--	.31	--	1.6
98900233	07–26–89	0400	M	7.5	16,700	--	.33	.05	<.05	.87	.43	.48	6.0	--	.32	--	1.6
98900235	07–26–89	0840	M	2.4	13,400	96	<.13	.04	<.03	.75	.34	.38	4.6	--	.27	--	1.3
98900213	07–26–89	1600	D	.42	11,800	100	[5].07	.04	<.02	.67	.31	.32	4.0	[5].0002	.26	[5].005	1.1
Little Colorado River at Woodruff, Arizona (09394500)																	
98900151	08–18–89	([3,6])	C	27	49,300	85	<.49	.10	<.10	2.2	1.1	.89	32	--	1.0	--	2.4
98900151	08–18–89	([3,6])	C	27	49,300	85	[5].18	--	[5]<.025	[5]2.4	[5].99	[5].59	[5]30	[5].0010	[5].94	[5].005	[5]2.9
98900151	08–18–89	([3,6])	C	27	49,300	85	[5].17	--	[5]<.025	[5]1.8	[5].99	[5].59	[5]30	[5].0010	[5].94	[5].005	[5]2.9
98900183	07–23–89	1010	M	40	41,100	98	<.41	.08	<.08	2.5	1.3	.99	28	--	1.3	--	3.5
98900184	07–23–89	1230	M	42	36,200	85	<.36	.07	<.07	2.3	1.1	.87	24	--	1.1	--	3.0
98900185	07–23–89	1510	M	15	22,400	99	<.22	.04	<.04	1.4	.67	.54	15	--	.67	--	1.9
98900182	07–23–89	([6])	C	44	35,400	--	<.35	.07	<.07	2.3	1.1	.85	23	--	1.1	--	2.9
98900150	08–18–89	1740	M	25	46,500	84	[5].14	.09	<.09	1.9	.98	.84	32	[5].0030	.88	[5].005	2.1
99000531	07–07–90	2020	C	25	27,000	94	[5].17	.05	<.05	1.3	.78	.76	21	[5].0003	.59	[5].003	2.1
99000555	08–16–90	1235	D	15	34,800	98	<.35	.07	<.07	1.4	.63	.59	17	--	.84	--	1.7
99000556	08–16–90	([6])	C	--	40,400	--	<.40	.08	<.08	1.5	.65	.65	21	--	.77	--	1.9
99000542	09–21–90	([6])	C	--	42,700	--	[5].22	.09	<.09	2.3	1.0	.90	28	[5]<.0004	1.0	[5].004	3.5
99100052	01–06–91	1840	M	37	43,000	86	<.43	.09	<.09	2.2	.86	.73	27	--	.99	--	2.2
Pipeline Arroyo near Church Rock, New Mexico (353730108312001)																	
99000792	08–15–90	([3,6])	C	--	116,300	--	[5].81	.23	<.23	5.3	2.6	2.7	32	[5].0093	2.0	[5].070	9.0
99000792	08–15–90	([3,6])	C	--	116,300	--	[5]1.1	--	--	--	--	--	--	[5].0105	--	[5].070	--
98900217	07–27–89	1025	D	.24	55,000	--	<.55	.11	<.11	3.9	1.3	1.3	17	--	1.4	--	5.4

Table 15. Concentrations of selected chemical constituents in the less than 0.062-millimeter fraction of the suspended phase in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Percent sediment <0.062 mm	Concentration, in milligrams per liter[2] Arsenic (As)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Puerco River near Church Rock, New Mexico (09395350)[5]																	
99000630	07–07–90	2350	M	16.4	119,000	55	<1.19	0.24	<0.24	5.5	2.4	2.4	38	--	2.0	--	8.7
98900215	07–24–89	0515	M	1.4	115,000	--	[5]1.0	--	--	--	--	--	--	[5]0.0058	--	[5]0.069	--
98900216	07–24–89	[3]1435	D	15	80,000	63	[5].72	--	[5]<.040	[5]4.2	[5]1.7	[5]2.1	[5]24	[5].0056	[5]1.28	[5].056	[5]7.9
98900216	07–24–89	[3]1435	D	15	80,000	63	[5].77	--	[5]<.040	3.9	[5]1.6	[5]1.7	[5]24	[5].0072	[5]1.3	[5].056	[5]7.8
98900217	07–27–89	1025	D	.24	54,500	--	[5].49	--	--	--	--	--	--	[5].0038	--	[5].033	--
99000630	07–07–90	2350	M	16.5	119,000	--	[5].77	--	--	--	--	--	--	[5].011	--	[5].048	--
99000534	07–08–90	0800	G	.93	56,900	[4]94	[5].51	.17	<.11	3.1	1.4	1.3	19	[5].0051	1.0	[5].034	5.3
99000537	07–09–90	2120	M	17	238,000	[4]77	<2.4	.48	<.48	9.0	5.2	4.8	69	--	3.1	--	16
99000560	08–15–90	1030	D	1.9	55,600	--	<.56	.11	<.11	2.3	1.1	1.0	15	--	.78	--	4.1
99100677	08–06–91	[3]2110	M	29	258,000	--	[5]1.8	--	--	--	--	--	--	[5].015	--	[5].10	--
99100677	08–06–91	[3]2110	M	29	258,000	--	[5]1.8	--	--	--	--	--	--	[5].0260	--	[5].10	--
South Branch Puerco River, New Mexico (353151108361301)																	
99100828	10–19–90	([6])	M	--	107,500		[5].74	.21	<.21	4.6	2.1	2.1	38	[5].0043	1.5	[5].04	7.2
Manuelito Wash of the Puerco River, New Mexico (352450108592401)																	
99100827	10–19–90	([6])	M	--	170,000		[5]1.1	.34	<.34	7.1	3.2	3.2	56	[5]<.0017	2.7	[5].05	11
Puerco River near Manuelito, New Mexico (09395630)																	
98900222	07–13–89	1400	G	21	1,990	66	[5].017	--	[5]<.001	[5].034	[5].038	[5].026	[5]40	[5].0022	[5].022	[5].001	[5].16
98900223	07–27–89	[3]1400	G	71	79,800	60	[5].73	--	[5]<.040	[5]4.1	[5]1.7	[5]1.6	[5]24	[5].0048	[5]1.2	[5].05	[5]7.8
98900223	07–27–89	[3]1400	G	71	79,800	60	[5].54	--	[5]<.040	[5]4.0	[5]1.8	[5]1.6	[5]32	[5].0056	[5]1.1	[5].02	[5]6.6
98900224	07–27–89	[3]1410	G	73	81,200	60	[5].63	--	[5]<.041	[5]4.2	[5]1.7	[5]1.6	[5]24	[5].0041	[5]1.1	[5].04	[5]7.6
98900224	07–27–89	[3]1410	G	73	81,200	60	[5].63	--	[5]<.041	[5]4.1	[5]1.9	[5]1.7	[5]24	[5].0065	[5]1.1	[5].03	[5]7.8
98900226	09–06–89	0110	M	32.3	77,200	31	[5].46	--	[5]<.039	[5]2.5	[5]1.2	[5]1.2	[5]23	[5].0046	[5].77	[5].02	[5]5.2
98900228	09–06–89	0130	M	32.3	116,000	41	[5].72	--	[5]<.058	[5]3.2	[5]1.6	[5]1.7	[5]35	[5].0046	[5].93	[5].04	[5]7.3
99000562	08–14–90	2035	G	2.2	111,000	--	<1.1	.22	<.22	4.6	2.6	2.4	38	--	1.6	--	8.8
99000561	08–15–90	0800	D	1.5	68,200	--	<.68	.14	<.14	3.0	1.6	1.6	27	--	1.1	--	6.3
99100049	10–20–90	0030	M	34	102,000	55	<1.0	.20	<.20	3.3	1.9	2.2	35	--	1.2	--	7.3
99100070	10–20–90	0200	M	79	92,500	--	<.93	.19	<.19	2.8	1.7	1.6	31	--	1.1	--	6.4
99100067	10–20–90	0330	M	50	77,200	66	[5].52	.15	<.15	2.7	1.5	1.5	27	[5].0062	1.0	[5].031	5.9

Table 15. Concentrations of selected chemical constituents in the less than 0.062-millimeter fraction of the suspended phase in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Percent sediment <0.062 mm	Concentration, in milligrams per liter[2] Arsenic (As)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
Black Creek below West Fork of Black Creek, near Houck, Arizona (09395990)																	
98900190	08–01–89	1300	G	73	37,000	--	<0.40	0.07	<0.07	1.9	0.89	0.6	16	--	0.8	--	2.5
98900147	09–05–89	[3]2020	M	17.5	71,800	97	[5].52	--	[5]<.036	[5]3.1	[5]1.7	[5]1.6	[5]29	[5]0.0050	[5]1.1	[5]0.029	[5]5.7
98900147	09–05–89	[3]2020	M	17.5	71,800	97	<.72	.14	<.14	3.6	1.7	1.5	29	--	1.4	--	5.6
98900148	09–05–89	[3]2050	M	5.6	73,300	96	[5].54	--	[5]<.037	[5]3.2	[5]1.7	[5]1.5	[5]29	[5].0044	[5]1.2	[5].029	[5]6.1
98900148	09–05–89	[3]2050	M	5.6	73,300	96	<.73	.15	<.15	3.6	1.8	1.6	29	--	1.5	--	5.6
98900146	09–05–89	2200	M	4.4	62,100	97	[5].44	.12	<.12	2.9	1.4	1.4	24	[5].0019	1.2	[5].031	4.6
98900145	09–06–89	2320	M	3.7	47,100	97	[5].29	.09	<.09	2.4	1.2	1.0	19	[5].0024	.94	[5].019	4.0
Puerco River near Chambers, Arizona (09396100)																	
98900199	08–18–89	[3]2400	M	5.7	177,000	84	[5]1.1	--	[5]<.089	[5]8.0	[5]3.5	[5]3.0	[5]71	[5].011	[5]2.5	[5].035	[5]13
98900199	08–18–89	[3]2400	M	5.7	177,000	84	[5]1.2	--	[5]<.089	[5]6.7	[5]3.4	[5]3.2	[5]71	[5].016	[5]2.5	[5].089	[5]13
98900149	09–06–89	[3]1440	M	3.1	147,000	91	[5]1.2	--	[5]<.074	[5]6.3	[5]3.5	[5]3.2	[5]59	[5].0088	[5]2.2	[5].088	[5]13
98900149	09–06–89	[3]1440	M	3.1	147,000	91	<1.5	.29	<.29	6.6	3.7	3.2	57	--	2.5	--	12
98900152	09–06–89	[3]1510	M	5.3	165,000	45	[5]1.5	--	[5]<.083	[5]6.8	[5]3.5	[5]3.8	[5]66	[5].0099	[5]2.8	[5].12	16
98900152	09–06–89	[3]1510	M	5.3	165,000	[4]84	[5]1.0	.33	<.33	7.4	3.8	3.6	63	[5].012	3.0	[5].08	13
98900153	09–06–89	1515	G	4.3	180,000	[4]80	<1.8	.36	<.36	8.5	4.0	4.1	68	--	3.2	--	14
99000530	07–11–90	1320	D	2.5	143,000	[4]86	<1.4	.29	<.29	7.2	3.6	3.9	64	--	2.9	--	13
99000552	08–15–90	0250	M	67	172,000	77	[5]1.2	.34	<.34	7.7	3.8	3.4	77	[5].0086	3.3	[5].052	12
99000554	08–15–90	1135	G	26.6	139,000	73	<1.4	.28	<.28	7.0	3.3	3.2	60	--	2.4	--	13
99000551	08–15–90	1820	G	7.9	95,300	93	[5].59	.19	<.19	4.8	2.2	2.1	40	[5].0076	1.7	[5].038	8.6
99000553	08–16–90	0930	G	4.7	67,500	93	[5].51	.14	<.14	3.5	1.6	1.4	32	[5].0074	1.4	[5].030	6.1
99100047	10–20–90	[3]0800	M	125	229,000	60	[5].97	.23	<.46	8.2	3.9	4.1	80	[5].0203	2.5	[5].045	11
99100047	10–20–90	[3]0800	M	125	229,000	60	[5].98	--	--	--	--	--	--	[5].0206	--	--	--
Little Colorado River near Joseph City, Arizona (09397300)																	
98900209	08–18–89	2140	M	11.4	84,700	--	[5].38	.17	<.20	4.6	2.1	1.2	53	[5].0211	2.0	[5].008	4.3
99000516	07–08–90	0440	M	67.4	45,600	90	[5].21	.09	<.09	1.9	1.0	.91	26	[5].0023	1.0	[5].005	2.6
99000520	07–14–90	1730	M	101	178,000	93	<1.8	.36	<.36	6.4	3.2	3.0	78	--	2.8	--	9.8
99000760	07–14–90	2340	M	28.6	226,000	71.4	[5]1.3	--	--	--	--	--	--	[5].016	--	[5].09	--
99000759	07–14–90	2150	M	35.1	238,000	71.4	[5]1.5	--	--	--	--	--	--	[5].024	--	[5].10	--
99000548	08–16–90	1645	D	27	51,300	97	[5].31	.10	<.10	2.8	1.2	1.0	27	[5].0051	1.0	[5].015	4.0

Table 15. Concentrations of selected chemical constituents in the less than 0.062-millimeter fraction of the suspended phase in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Percent sediment <0.062 mm	Concentration, in milligrams per liter[2] Arsenic (As)	Beryllium (Be)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lead (Pb)	Manganese (Mn)	Mercury (Hg)	Nickel (Ni)	Selenium (Se)	Zinc (Zn)
							Little Colorado River near Joseph City, Arizona (09397300)—Continued										
99000545	08–16–90	1750	M	22	64,500	86	<0.65	0.13	<0.13	3.3	1.5	1.4	34	--	1.6	--	5.0
99000547	09–01–90	([6])	C	--	44,800	84	[5].36	.09	<.09	2.2	1.0	.9	25	[5]0.0019	.81	[5]0.019	3.2
99000543	09–21–90	([6])	C	--	46,800	--	<.47	.09	<.09	2.4	1.1	.8	27	--	1.1	--	3.1
99100053	01–07–91	1620	G	22	17,100	89	[5].06	.03	<.03	1.1	.36	.31	9.6	[5].0010	.44	[5].002	1.0
							Little Colorado River at Grand Falls, Arizona (09401000)										
99000532	07–09–90	1210	M	42	79,500	88	<.80	.16	<.16	3.8	1.8	1.7	38	--	1.7	--	4.5
99000533	07–09–90	1810	M	29	60,000	93	<.60	.12	<.12	2.8	1.4	1.3	32	--	1.4	--	3.6
99000525	07–10–90	1405	D	7.9	51,900	99	<.52	.10	<.10	2.6	1.2	3.5	28	--	1.3	--	4.5
99000519	07–17–90	1600	M	11	77,100	99	<.77	.15	<.15	3.7	1.9	1.8	41	--	1.9	--	5.7
99000539	07–17–90	1800	D	9.7	85,100	99	<.85	.17	<.17	4.4	2.2	2.0	45	--	2.0	--	6.6
99000517	07–17–90	1840	M	9.4	87,400	99	<.87	.17	<.17	4.3	2.2	1.9	45	--	1.9	--	6.9
99000549	08–17–90	1230	D	45	92,300	100	[5].58	.18	<.18	4.6	2.9	1.9	50	[5].011	1.8	[5].03	7.0
99000550	08–17–90	1240	C	45.3	92,300	100	<.92	.18	<.18	4.6	2.3	1.8	51	--	1.6	--	6.9
99000544	09–22–90	([6])	C	--	69,100	--	<.69	.14	<.14	3.5	1.7	1.6	37	--	1.6	--	4.8
99100051	01–07–91	([6])	C	--	21,700	--	[5].08	.04	<.04	1.1	.50	.43	11.3	[5].0017	.54	[5].002	1.3
99100072	03–05–91	1300	D	31	22,500	--	<.23	.02	<.05	.83	.56	.36	14.0	--	.36	--	1.0
							Little Colorado River near Cameron, Arizona (09402000)										
99000524	07–12–90	1230	D	2.8	67,000	--	[5].32	.20	<.13	2.9	1.5	1.5	34	[5].0020	1.5	[5].007	4.4
99000515	07–23–90	1840	M	76	25,000	88	[5].14	.05	<.05	.75	.75	.60	11.5	[5].0017	.40	[5].005	1.7
99000557	08–19–90	1245	D	20	78,000	98	[5].46	.16	<.16	3.9	2.1	1.6	41	[5].0070	1.5	[5].023	5.9
99000540	09–19–90	([6])	C	--	98,900	--	[5].65	.20	<.2	5.1	2.7	2.1	43	[5].0020	2.2	[5].040	9.0
99100050	01–08–91	([6])	D	63	85,500	70	[5].65	.17	<.17	3.6	1.9	1.6	42	[5].0070	1.8	[5].040	4.9
99100073	03–07–91	1400	D	36	46,100	77	<.46	.05	<.09	1.3	.83	.69	24	--	.51	--	1.7

[1]Record number is an arbitrary number assigned to each sample by the U.S. Geological Survey National Water-Quality Laboratory when the sample is received.

[2]All concentrations were computed from analytical results (reported in units of micrograms per gram or parts per million of sediment) by multiplying by suspended-sediment concentration in milligrams per liter and dividing by 10^6 to obtain milligrams per liter. Values for manganese from the Sediment Partitioning Laboratory, Doraville, Georgia, were reported in weight percent and converted to milligrams per liter by multiplying by the suspended-sediment concentration in milligrams per liter and dividing by 10^2. The dissolved fraction is assumed negligible in all cases.

[3]Duplicate sample. [4]Fall diameter. [5]Constituent analyzed at Sediment Partitioning Laboratory. [6]Composite from different sampling times.

Table 16. Concentrations of selected dissolved radiochemical constituents in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[m³/s, cubic meters per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; pCi/L, picocuries per liter; µg/L, micrograms per liter; <, less than; >, greater than. Sampling method: G, grab or dip sample; M, automated sample collected from a point location; C, composited from several automated point samples representing different phases of the hydrograph; D, manually collected sample at equal distance intervals; V, manually collected sample at a single vertical. All samples were passed through a 0.45-micrometer cellulose nitrate paper filter. ---, no data]

Record number[1]	Date	Time	Sampling method	Discharge (m³/s)	Specific conductance, field (µS/cm)	pH, field	Sediment concentration (mg/L)	Gross alpha[2] (pCi/L)	Gross beta (pCi/L as Sr–90)	Gross alpha plus gross beta (pCi/L)[3]	Uranium natural (µg/L)	Uranium (µg/L)[4]	Uranium (pCi/L)[5]	^{226}Radium (pCi/L)	^{228}Radium (pCi/L)	^{226}Radium plus ^{228}Radium (pCi/L)[6]
Zuni River above Black Rock Reservoir, New Mexico (09386950)																
98900166	03–08–89	1545	G	0.11	680	8.0	846	2.5±0.9	4.7±1.2	7.2	--	--	--	--	--	--
98900167	03–22–89	1145	G	.09	--	--	--	2.9±1.0	4.0±1.1	6.9	--	--	--	--	--	--
98900231	07–26–89	0110	M	6.4	472	--	15,600	[7].3	[7]10±	10.3	--	--	--	--	--	--
98900236	07–26–89	([8])	C	9.1	--	--	15,500	1.0±.3	6.8±1.0	7.8	--	--	--	--	--	--
98900232	07–26–89	0140	M	21	419	--	17,600	1.8±.4	5.2±.80	7.0	--	--	--	--	--	--
98900233	07–26–89	0400	M	7.5	242	--	16,700	1.0±.3	6.3±.90	7.3	--	--	--	--	--	--
98900213	07–26–89	1600	D	.42	220	7.6	11,800	.5±.3	5.8±.90	6.3	--	--	--	--	--	--
99100105	04–05–91	1403	M	4.0	490	8.3	210	2.6±.8	7.0±1.3	9.6	--	--	--	--	--	--
99100106	04–05–91	1430	D	4.1	491	8.0	186	1.9±.7	6.2±1.1	8.1	--	--	--	--	--	--
99100678	09–06–91	0915	D	.39	340	7.9	1,210	1.1±.7	7.0±1.6	8.1	--	0.77	0.52	--	--	--
Little Colorado River at Woodruff, Arizona (09394500)																
98800009	08–10–88	1705	--	.42	--	--	--	[7]2.0	[7]4.6	6.6	--	--	--	--	--	--
98800012	08–30–88	1445	D	7.1	325	9.0	18,400	[7]9.0	[7]2.2	11.2	--	2.3	1.6	<0.02	<1.0	<1.0
98900083	03–14–89	1520	G	.05	--	--	--	2.0±.4	4.3±.70	6.3	--	--	--	--	--	--
98900182	07–23–89	([8])	C	23	--	--	35,400	8.2±1.5	2.0±.90	10.2	--	--	--	--	--	--
98900179	07–23–89	0910	M	28	--	--	30,400	2.2±.5	9.9±1.7	12.1	--	--	--	--	--	--
98900180	07–23–89	1130	M	46	--	--	35,900	1.0±.6	.6±1.3	1.6	--	--	--	--	--	--
98900181	07–23–89	1330	M	32	--	--	28,400	2.2±1.3	1.5±1.3	3.7	--	--	--	--	--	--
98900151	08–18–89	([8])	C	--	[9]489	[9]7.9	49,300	15.6±2.9	2.8±.90	18	--	--	--	--	--	--
98900150	08–18–89	1740	M	25	[9]355	[9]6.8	46,500	8.2±2.2	3.4±1.2	11.6	--	--	--	--	--	--

Table 16. Concentrations of selected dissolved radiochemical constituents in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Sediment concentration (mg/L)	Gross alpha[2] (pCi/L)	Gross beta (pCi/L as Sr–90)	Gross alpha plus gross beta (pCi/L)[3]	Uranium, natural (µg/L)	Uranium (µg/L)[4]	Uranium (pCi/L)[5]	^{226}Radium (pCi/L)	^{228}Radium (pCi/L)	^{226}Radium plus ^{228}Radium (pCi/L)[6]
Little Colorado River at Woodruff, Arizona (09394500)—Continued																
98900186	08–18–89	2030	M	31	--	--	56,100	15.0±3.2	5.4±1.2	20	--	--	--	--	--	--
98900187	08–18–89	2230	M	26	--	--	48,800	4.8±1.2	4.3±1.0	9.1	--	--	--	--	--	--
98900188	08–19–89	1500	V	21	--	--	35,900	2.7±9	1.2±.70	3.9	--	--	--	--	--	--
98900189	08–19–89	1505	M	21	--	--	36,000	.4±.3	3.8±1.0	4.2	--	--	--	--	--	--
99000531	07–07–90	2020	C	25	490	7.3	27,000	2.7±1.0	5.5±1.2	8.2	--	--	--	--	--	--
99100052	01–06–91	1840	M	37	574	9.3	43,000	7.5±2.0	2.2±.86	9.7	--	--	--	--	--	--
Puerco River near Church Rock, New Mexico (09395350)																
98900221	09–05–89	2110	M	11	[9]661	[9]7.8	66,800	8.2±1.5	10±1.8	18	--	--	--	--	--	--
99000529	07–07–90	2350	M	16	[9]1,000	[9]7.1	--	4.3±1.6	16±3.2	20	--	--	--	--	--	--
99000534	07–08–90	0800	G	.93	720	7.8	56,900	7.5±1.8	10±2.2	18	--	--	--	--	--	--
99000535	07–09–90	2020	M	19	[9]814	[9]7.4	--	9.5±2.2	14±2.8	24	--	--	--	--	--	--
99000537	07–09–90	2120	M	17	690	7.4	238,000	8.2±2.0	13±2.6	21	--	--	--	--	--	--
99000536	07–12–90	0100	M	18	[9]883	[9]7.4	--	6.8±1.8	13±2.7	20	--	--	--	--	--	--
99000560	08–15–90	1030	D	1.9	530	8.6	55,600	--	--	--	3.1	2.7	1.8	--	--	--
Puerco River near Manuelito, New Mexico (09395630)																
98800033	09–01–88	1635	--	--	--	--	--	8.8±1.7	7.7±1.6	17	--	--	--	--	--	--
98800034	09–02–88	1000	--	--	--	--	--	6.5±1.5	6.1±1.4	13	--	--	--	--	--	--
98900104	03–09–89	0815	G	.42	[9]1,850	--	1,140	6.2±1.4	11±2.3	17	--	--	--	--	--	--
98900082	04–05–89	1315	--	.14	2,020	8.7	--	2.7±1.3	13±2.8	16	--	4.1	2.8	--	--	--
98900319	04–11–89	1419	G	.19	1,980	7.8	37	3.4±.8	18±5.2	21	--	--	--	--	--	--
98900222	07–13–89	1400	G	.59	2,090	8.4	1,990	5.2±.7	24±6.1	29	--	--	--	--	--	--
98900226	09–06–89	0110	M	32	1,340	[9]7.8	77,200	16±2.7	23±3.2	39	--	21.5	14.6	--	--	--

Table 16. Concentrations of selected dissolved radiochemical constituents in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Sediment concentration (mg/L)	Gross alpha[2] (pCi/L)	Gross beta (pCi/L as Sr–90)	Gross alpha plus gross beta (pCi/L)[3]	Uranium natural (µg/L)	Uranium (µg/L)[4]	Uranium (pCi/L)[5]	^{226}Radium (pCi/L)	^{228}Radium (pCi/L)	^{226}Radium plus ^{228}Radium (pCi/L)[6]
Puerco River near Manuelito, New Mexico (09395630)—Continued																
99000538	07–13–90	1850	M	103	[9]935	[9]7.1	--	3.1±.9	8.2±2.0	11.3	4.4	--	--	--	--	--
99000622	07–13–90	1950	M	170	[9]524	[9]7.3	--	3.0±.9	6.2±1.4	9.2	--	--	--	--	--	--
99000562	08–14–90	2035	G	2.2	[9]486	[9]7.3	111,000	--	--	--	1.9	2.1	1.4	--	--	--
99000561	08–15–90	0800	D	10.5	415	8.8	68,200	--	--		2.2	2.1	1.4	--	--	--
Black Creek below West Fork of Black Creek, near Houck, Arizona (09395990)																
98900069	03–09–89	1030	G	.39	--	--	--	8.2±1.6	9.1±1.8	17	--	--	--	--	--	--
98900190	08–01–89	1300	G	2.1	--	--	37,100	2.4±.7	18±2.3	20	--	--	--	--	--	--
98900147	09–05–89	2020	M	17.5	[9]819	--	71,800	5.1±1.0	6.4±1.3	11.5	--	--	--	--	--	--
98900148	09–05–89	2050	M	5.6	[9]690	[9]7.7	73,300	.8±2.6	6.4±1.4	7.2	--	--	--	--	--	--
98900146	09–05–89	2200	M	4.4	[9]530	[9]7.7	62,100	4.4±1.0	4.9±1.1	9.3	--	--	--	--	--	--
98900145	09–06–89	2320	M	3.7	[9]454	[9]7.7	47,100	3.0±.8	4.0±1.3	7.0	--	--	--	--	--	--
Puerco River near Chambers, Arizona (09396100)																
98800010	08–10–88	1705	D	.14	--	--	42,600	[7]16	[7]30	46	--	13.9	9.5	--	--	--
98900103	02–15–89	1400	G	.71	--	--	--	5.3±1.4	11±2.1	16	--	--	--	--	--	--
98900198	08–01–89	0130	M	37	--	--	181,000	5.4±1.0	8.4±2.0	13.8	--	--	--	--	--	--
98900194	08–01–89	0710	M	24	--	--	73,500	4.7±.7	8.0±1.4	12.7	--	--	--	--	--	--
98900238	08–01–89	0810	M	27	--	--	70,200	4.8±.9	6.1±1.1	10.9	--	--	--	--	--	--
98900237	08–01–89	1030	M	13	--	--	--	7.5±1.2	6.0±1.4	13.5	--	--	--	--	--	--
98900196	08–01–89	1320	M	28	--	--	103,000	7.5±1.2	7.5±1.5	15.0	--	--	--	--	--	--
98900197	08–01–89	1630	M	4.0	--	--	95,800	2.6±.5	7.3±1.4	9.9	--	--	--	--	--	--
98900199	08–18–89	2400	M	5.7	--	--	177,000	8.8±1.6	11±2.1	20	--	--	--	--	--	--
98900149	09–06–89	1440	M	3.1	[9]1,590	[9]8.1	147,000	4.6±1.0	4.9±1.9	9.5	--	--	--	--	--	--

Table 16. Concentrations of selected dissolved radiochemical constituents in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Sediment concentration (mg/L)	Gross alpha[2] (pCi/L)	Gross beta (pCi/L as Sr–90)	Gross alpha plus gross beta (pCi/L)[3]	Uranium natural (µg/L)	Uranium (µg/L)[4]	Uranium (pCi/L)[5]	^{226}Radium (pCi/L)	^{228}Radium (pCi/L)	^{226}Radium plus ^{228}Radium (pCi/L)[6]
Puerco River near Chambers, Arizona (09396100)—Continued																
98900152	09–06–89	1510	M	5.3	[9]1,630	[9]7.9	165,000	3.4±.7	5.3±2.0	8.7	--	--	--	--	--	--
98900153	09–06–89	1515	G	4.3	1,200	7.9	180,000	4.5	6.1±1.3	10.6	--	--	--	--	--	--
99000530	07–11–90	1320	D	2.5	2,090	7.1	143,000	23±3.4	22±4.4	45	13	17.6	12.0	--	--	--
Little Colorado River near Joseph City, Arizona (09397300)																
98800003	08–02–88	1725	D	34	1,480	8.1	244,000	[7]25	[7]9.0	34	--	23.5	16.0	--	--	--
98900101	02–17–89	1300	G	.93	--	--	--	[7]15.0	6.6±1.4	22	--	--	--	--	--	--
98900091	03–15–89	1145	G	.18	--	--	44	2.9±.5	6.5±1.8	9.4	--	--	--	--	--	--
98900102	03–27–89	1300	G	3.5	--	--	--	13.6±2.2	6.9±1.5	21	--	--	--	--	--	--
98900200	07–23–89	1550	M	70	--	--	53,700	6.8±1.0	10±1.9	17	--	--	--	--	--	--
98900201	07–23–89	1630	M	70	--	--	61,000	6.5±1.0	2,400±360	2,400	--	--	--	--	--	--
98900202	07–24–89	1045	G	8.9	--	--	4,800	.9±.3	7.1±1.4	8.0	--	--	--	--	--	--
98900203	07–26–89	0630	M	71	--	--	22,500	2.4±.5	6.5±1.2	8.9	--	--	--	--	--	--
98900204	07–26–89	0730	M	71	--	--	58,600	4.8±.8	8.2±1.5	13.0	--	--	--	--	--	--
98900205	07–26–89	0950	M	60	--	--	73,000	5.6±1.0	7.2±2.0	12.8	--	--	--	--	--	--
98900206	07–26–89	1010	M	47	--	--	71,200	8.2±1.1	7.8±1.7	16	--	--	--	--	--	--
98900207	07–26–89	1820	M	43	--	--	44,500	5.6±1.0	6.8±1.3	12.4	--	--	--	--	--	--
98900208	08–18–89	1630	M	185	--	--	93,500	9.5±1.8	6.5±1.3	16	--	--	--	--	--	--
98900209	08–18–89	2140	M	110	--	--	84,700	5.4±1.6	2.7±.70	8.1	--	--	--	--	--	--
98900210	08–19–89	0440	M	86	--	--	55,300	8.2±1.7	3.4±.90	11.6	--	--	--	--	--	--
99100053	01–07–91	1620	G	22	518	9.3	17,100	12.9±2.9	5.0±1.4	18	--	--	--	--	--	--
Little Colorado River at Grand Falls, Arizona (09401000)																
98900192	08–20–89	1300	G	28	--	--	--	4.7±1.3	6.1±1.2	10.8	--	--	--	--	--	--

Table 16. Concentrations of selected dissolved radiochemical constituents in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Sediment concentration (mg/L)	Gross alpha[2] (pCi/L)	Gross beta (pCi/L as Sr–90)	Gross alpha plus gross beta (pCi/L)[3]	Uranium natural (µg/L)	Uranium (µg/L)[4]	Uranium (pCi/L)[5]	^{226}Radium (pCi/L)	^{228}Radium (pCi/L)	^{226}Radium plus ^{228}Radium (pCi/L)[6]
Little Colorado River at Grand Falls, Arizona (09401000)—Continued																
99000533	07–09–90	1810	M	29	[9]1,490	[9]7.8	60,000	5.5±1.2	8.5±2.2	14.0	--	--	--	--	--	--
99000525	07–10–90	1405	D	7.9	[9]870	[9]8.1	51900	5.2±1.2	5.0±1.3	10.2	9.2	--	--	--	--	--
99000519	07–17–90	1600	M	11	[9]1,070	[9]7.8	77,100	7.5±1.5	6.0±1.7	13.5	--	--	--	--	--	--
99000539	07–17–90	1800	D	9.7	[9]1,240	[9]7.8	85,100	7.5±1.5	7.7±2.0	15	--	--	--	--	--	--
99000517	07–17–90	1840	M	9.4	[9]629	[9]8.1	87,400	5.5±1.2	5.6±1.2	11.1	--	--	--	--	--	--
99100051	01–07–91	([8])	C	--	605	8.7	21,700	9.5±2.1	5.6±1.3	15	--	--	--	--	--	--
99100072	03–05–91	([8])	C	30	511	8.6	21,100	--	--	--	--	4.2	2.9	--	--	--
99100071	03–05–91	1300	D	31	511	8.5	22,500	--	--	--	--	3.6	2.5	--	--	--
Little Colorado River near Cameron, Arizona (09402000)																
98800002	08–04–88	1200	G	.04	495	8.1	8,270	[7]3.9	[7]8.4	12.3	--	1.2	.82	--	--	--
98800027	09–01–88	1350	D	33	--	--	67,600	[7]10.2	[7]6.4	17	--	--	--	--	--	--
99000515	07–23–90	1840	M	76	[9]1,150	[9]7.8	25,000	10.2±1.9	9.4±2.2	20	--	--	--	--	--	--
99100050	01–08–91	1530	D	63	709	8.6	85,500	12.2±8.3	6.9±1.5	19	--	--	--	--	--	--
99100073	03–07–91	1400	D	36	520	8.5	46,100	--	--	--	--	3.8	2.6	--	--	--
Little Colorado River near Holbrook, Arizona (345351110094402)																
99000491	05–15–90	0900	G	--	1,450	8.6	--	2.9±.8	6.1±2.0	9.0	<1.0	1.7	1.2	--	--	--
Puerco River near Querino Road upstream from Sanders, Arizona (351527109161902)																
98900080	04–04–89	1700	G	.14	845	8.2	--	9.0±1.9	7.5±1.6	17	--	5.7	3.8	--	--	--
99000448	03–08–90	1510	G	--	[9]1,750	--	--	--	--	--	--	13.8	9.4	--	--	--
Puerco River near Lupton, Arizona (351933109041901)																
99000450	03–08–90	1200	G	--	[9]1,830	--	--	---	--	--	--	5.8	3.9	--	--	--

Table 16. Concentrations of selected dissolved radiochemical constituents in samples from streamflow-gaging stations and miscellaneous sampling sites, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Specific conductance, field (µS/cm)	pH, field	Sediment concentration (mg/L)	Gross alpha[2] (pCi/L)	Gross beta (pCi/L as Sr–90)	Gross alpha plus gross beta (pCi/L)[3]	Uranium natural (µg/L)	Uranium (µg/L)[4]	Uranium (pCi/L)[5]	^{226}Radium (pCi/L)	^{228}Radium (pCi/L)	^{226}Radium plus ^{228}Radium (pCi/L)[6]
Puerco River near Lupton, Arizona (351933109041901)																
99000421	11–17–89	1700	G	--	2,530	7.0	--	14.5±2.3	15±3.0	30	11	21.3	14.5	--	--	--
99100040	10–16–90	1220	G	--	1,890	6.8	--	6.1±1.7	4.5±2.4	10.6	7.8	4.8	3.3	<1.0	--	--
99100108	06–11–91	1500	G	--	3,920	6.9	--	9.9±2.2	10±4.5	20	7.6	16.2	11.0	--	--	--
Puerco River at Route 83 Bridge, Gallup, New Mexico (353056108504402)																
98900138	03–31–89	1630	G	--	2,020	--	--	[7].9	[7]12	12.9	--	--	--	--	--	--
Puerco River at Sewage-Treatment Plant, Gallup, New Mexico (353104108490201)																
98900067	03–27–89	1700	G	1.4	1,950	7.6	--	[7].9	[7]12	12.9	--	--	--	--	--	--
99000446	03–08–90	0815	G	--	--	--	--	--	--	--	--	.88	.60	--	--	--
South Fork of the Puerco River near Gallup, New Mexico (353156108362301)																
98800085	06–29–88	1958	G	--	--	--	--	[7]7.5	[7]5.4	12.9	--	--	--	--	--	--
Arroyo Chico near San Luis, New Mexico 9353535107112701)																
99000513	05–18–90	1400	G	--	2,900	--	--	581±93	160±20	741	--	465	316	--	--	--
Rio Puerco near San Luis, New Mexico (354020107043302)																
99000510	05–18–90	1200	G	--	7,660	8.1	--	7.5±2.0	5.1±1.2	12.6	--	4.0	2.7	--	--	--

[1] Record number is an arbitrary number assigned to each sample by the U.S. Geological Survey National Water-Quality Laboratory when the sample is received.

[2]Gross alpha and gross alpha precision error was reported in micrograms per liter, and values were converted to picocuries per liter by assuming that uranium–238 (^{238}U), uranium–235 (^{235}U), and uranium–234 (^{234}U) are in secular equilibrium and multiplying total uranium by 0.68, except in cases where data for ^{238}U, ^{235}U, and ^{234}U are available. Because secular disequilibrium was known for those cases, total uranium concentration was multiplied by 0.68 and $^{234}U/^{238}U$.

[3]Calculated by adding the two columns to the left.

[4]Uranium was calculated by adding the activity of ^{238}U, ^{235}U, and ^{234}U, in picocuries per liter, divided by 0.68 times the activity of $^{234}U/^{238}U$.

[5]Calculated by assuming secular equilibrium and multiplying column to the left by 0.68.

[6]Calculated by adding the two columns to the left where both analyses are available.

[7]Value for range of error is not available. [8]Composite from different sampling times. [9]Laboratory measurement.

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91

[Total fraction is in picocuries per liter or micrograms per liter; m^3/s, cubic meters per second, mg/L, milligrams per liter; mm, millimeters; pCi/L, picocuries per liter; μg/L, micrograms per liter; <, less than; >, greater than. Sampling method: G, grab or dip sample; M, automated sample collected from a point location; C, composited from several automated point samples representing different phases of the hydrograph; D, manually collected sample at equal distance intervals; V, manually collected sample at a single vertical. ---, no data]

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (μg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Zuni River above Black Rock Reservoir, New Mexico (09386950)															
98900166	03–08–89	1545	G	0.11	850	86	0.68	1.1±0.7	1.8	--	--	--	--	--	--
98900167	03–22–89	1145	G	.09	--	--	--	.9±.6	--	--	--	--	--	--	--
98900231	07–26–89	0110	M	6.4	15,600	[11]100	600	[12]1,200	1,800	--	--	--	--	--	--
98900236	07–26–89	([13])	C	9.1	15,500	[11]100	630	480±61	1,110	--	--	--	--	--	--
98900232	07–26–89	0140	M	21	17,600	--	820	840±110	1,660	--	--	--	--	--	--
RC-89-0295	07–26–89	0210	M	17	16,500	94	360±70	380±70	740	65	50	28	31	24	43
RC-89-0296	07–26–89	0240	M	14	14,100	--	370±60	380±60	750	58	45	23	25	24	41
RC-89-0297	07–26–89	0320	M	9.5	15,400	--	310±50	480±50	790	71	54	26	22	23	40
98900233	07–26–89	0400	M	7.5	16,700	--	820	410±45	1,230	--	--	--	--	--	--
RC-89-0298	07–26–89	0500	--	5.4	15,600	--	660±80	550±60	1,200	156	111	58	28	53	70
98900213	07–26–89	1600	D	.42	11,800	100	610	160±23	770	--	--	--	--	--	--
RC-89-0299	07–26–89	([13])	C	[14]1.4	12,600	[14]98	320±50	365±50	685	76	55	23	20	23	34
99100105	04–05–91	1403	M	4.0	210	98	--	--	--	.80	.55	--	--	--	--
99100106	04–05–91	1430	D	4.1	186	98	--	--	--	.58	.43	--	--	--	--
99100678	09–06–91	0915	D	.39	1,210	99	--	--	--	5.3	2.8	--	--	1.8	--
Little Colorado River at Woodruff, Arizona (09394500)															
98800009	08–10–88	1705	--	.42	--	--	30	[12]26	56	--	--	--	--	--	--
98800012	08–30–88	1445	D	7.1	18,400	96	1,160	[12]1,400	2,560	--	--	--	--	--	--
98900083	03–14–89	1520	G	.05	--	--	5.8	5.2±.8	11.0	--	--	--	--	--	--
98900182	07–23–89	([13])	C	23	35,400	--	350	980±130	1,330	--	--	--	--	--	--

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (μg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Little Colorado River at Woodruff, Arizona (09394500)—Continued															
98900179	07–23–89	0910	M	28	30,400	[11]93	540	1,100±160	1,640	--	--	--	--	--	--
RC-89-0313	07–23–89	1010	M	40	41,100	98	820±120	1,290±120	2,110	108	75	42	47	47	66
98900180	07–23–89	1130	M	46	35,900	[11]94	490	1,100±150	1,590	--	--	--	--	--	--
RC-89-0317	07–23–89	([13])	C	44	33,100	--	830±100	1,090±100	1,920	127	71	36	39	35	49
RC-89-0312	07–23–89	1230	M	42	36,200	85	650±110	1,120±110	1,770	68	61	38	48	44	76
98900181	07–23–89	1330	M	32	28,400	[11]94	300	970±140	1,270	--	--	--	--	--	--
RC-89-0314	07–23–89	1510	M	15	22,400	99	560±70	720±70	1,280	53	42	54	33	33	34
RC-89-0315	08–18–89	[15]1740	M	25	46,500	84	840±140	900±90	1,740	122	90	46	54	57	84
98900150	08–18–89	[15]1740	M	25	46,500	84	370	1,500±240	1,870	--	--	--	--	--	--
RC-89-0316	08–18–89	([13,15])	C	27	49,300	85	690±100	930±100	1,620	132	90	47	56	56	64
98900151	08–18–89	([13,15])	C	27	49,300	85	420	1,000±150	1,420	--	--	--	--	--	--
98900186	08–18–89	2030	M	31	56,100	85	140	1,300±190	1,440	--	--	--	--	--	--
98900187	08–18–89	2230	M	26	48,800	89	350	1,000±140	1,350	--	--	--	--	--	--
98900188	08–19–89	1500	V	21	35,900	86	260	650±90	910	--	--	--	--	--	--
98900189	08–19–89	1505	M	21	36,000	--	310	690±110	1,000	--	--	--	--	--	--
99000531	07–07–90	2020	C	25	27,000	94	260	280±75	540	--	--	--	--	--	--
99000555	08–16–90	1235	D	15	34,800	98	--	--	--	135	77	38	--	35	--
99100052	01–06–91	1840	M	37	43,000	86	--	--	--	96	73	39	--	52	--
Puerco River near Church Rock, New Mexico (09395350)															
RC-89-0332	09–05–89	[15]2110	M	11	66,800	78	1,300±200	2,000±200	3,300	265	192	88	107	106	141
98900221	09–05–89	[15]2110	M	11	66,800	[11]78	1,200	1,900±270	3,100	--	--	--	--	--	--
99000529	07–07–90	2350	M	16	--	--	8,200	4,100±1,100	12,300	--	--	--	--	--	--
99000534	07–08–90	0800	G	.93	56,900	[11]94	1,800	1,900±560	3,700	--	--	--	--	--	--

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (µg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Puerco River near Church Rock, New Mexico (09395350)—Continued															
99000535	07–09–90	2020	M	19	--	--	2,000	3,900±1,000	5,900	--	--	--	--	--	--
99000537	07–09–90	2120	M	17	238,000	[11]77	3,700	3,700±1,000	7,400	653	333	--	--	190	--
99000536	07–12–90	0100	M	18	--	--	5,500	3,900±1,100	9,400	--	--	--	--	--	--
99000560	08–15–90	1030	D	1.9	55,600	[11]75	--	--	--	205	150	83	--	106	--
99100676	08–01–91	1900	M	8.3	73,300	[11]83	--	--	--	345	235	--	--	132	--
99100675	08–02–91	0310	M	14	144,000	[11]80	--	--	--	489	360	--	--	216	--
99100677	08–06–91	2110	M	29	258,000	[11]64	--	--	--	759	516	--	--	439	--
Puerco River near Manuelito, New Mexico (09395630)															
98800033	09–01–88	1635	--	--	--	--	6.0	6.1±1.6	12	--	--	--	--	--	--
98800034	09–02–88	1000	--	--	--	--	3.6	4.0±1.2	7.6	--	--	--	--	--	--
98900104	03–09–89	0815	G	.42	1,140	[11]99	.61	1.1±1.0	1.7	--	--	--	--	--	--
98900319	04–11–89	1419	G	.19	37	--	2.8	3.4±.8	6.2	--	--	--	--	--	--
98900222	07–13–89	1400	G	.59	1,990.	[11]97	57	52±7.3	109	--	--	--	--	--	--
RC-89-0331	09–06–89	[15]0110	M	32	77,200	[11]71	1,390±190	2,160±230	3,550	287	200	108	97	107	84
98900226	09–06–89	[15]0110	M	32	77,200	[11]71	1,360	1,600±220	2,960	--	--	--	--	--	--
RC-89-0330	09–06–89	0120	M	32	142,000	84	3,980±570	4,830±570	8,800	697	426	180	200	202	256
RC-89-0329	09–06–89	0130	M	32	116,000	89	2,320±350	3,250±350	5,570	527	356	166	179	200	208
99000620	07–13–90	1850	M	53	133,000	[11]81	--	--	--	451	333	173	--	186	--
99000538	07–13–90	9999	C	103	--	--	1,700	920±280	2,620	--	--	--	--	--	--
99000611	07–13–90	1900	M	153	--	79	--	--	--	523	383	--	--	--	--
99000619	07–13–90	[15]1920	M	224	145,000	[11]80	--	--	--	461	392	203	--	247	--
99000610	07–13–90	[15]1950	M	170	146,000	60	--	--	--	581	365	--	--	--	--
99000622	07–13–90	[15]1950	M	139	--	--	2,400	1,800±490	4,200	--	--	--	--	--	--

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (μg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Puerco River near Manuelito, New Mexico (09395630)—Continued															
99000621	07–13–90	2010	M	124	130,000	[11]67	--	--	--	572	299	156	--	169	--
99000612	07–13–90	2030	M	96	97,900	60	--	--	--	537	274	--	--	--	--
99000561	08–15–90	0800	D	10.5	68,200	[11]90	--	--	--	251	184	87	--	102	--
99100049	10–20–90	0030	M	34	102,000	--	--	--	--	406	255	--	--	143	--
99100070	10–20–90	0200	M	79	92,500	--	--	--	--	276	222	--	--	139	--
99100067	10–20–90	0330	M	50	77,200	--	--	--	--	195	185	--	--	116	--
99100674	06–13–91	2120	M	36	96,600	[11]81	--	--	--	341	232	--	--	135	--
99100681	08–26–91	2240	M	57	102,000	[11]78	--	--	--	406	296	153	--	143	--
Black Creek below West Fork of Black Creek, near Houck, Arizona (09395990)															
98900069	03–09–89	1030	G	.39	--	--	--	.70±.60	--	--	--	--	--	--	--
98900190	08–01–89	1300	G	2.1	37,100	--	350	830±120	1,180	--	--	--	--	--	--
RC-89-0320	09–05–89	[15]2020	M	17.5	71,800	97	1650±215	1,870±215	3,520	203	169	94	109	100	122
98900147	09–05–89	[15]2020	M	17.5	71,800	97	400	2,300±300	2,700	--	--	--	--	--	--
RC-89-0322	09–05–89	[15]2050	M	5.6	73,300	96	1,610±220	2,050±220	3,670	322	215	127	120	125	147
98900148	09–05–89	[15]2050	M	5.6	73,300	96	381	2,700±400	3,081	--	--	--	--	--	--
98900146	09–05–89	[15]2200	M	4.4	62,100	97	632	1,500±230	2,132	--	--	--	--	--	--
RC-89-0323	09–05–89	[15]2200	M	4.4	62,100	97	1,490±190	1,990±190	3,480	239	168	81	96	104	150
98900145	09–06–89	[15]2320	M	3.7	47,000	97	750	1,400±200	2,150	--		--	--	--	--
RC-89-0324	09–05–89	[15]2320	M	3.7	47,000	--	920±140	1,430±190	2,350	178	126	65	69	66	124
Puerco River near Chambers, Arizona (09396100)															
98800010	08–10–88	1705	D	.14	42,600	[11]91	100	90±190	190	--	--	--	--	--	--
98900103	02–15–89	1400	G	.71	--	--	1.2	2.5±.9	3.7	--	--	--	--	--	--
98900198	08–01–89	0130	M	37	181,000	85	250	450±70	700	--	--	--	--	--	--

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (μg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Puerco River near Chambers, Arizona (09396100)—Continued															
98900194	08–01–89	0710	M	24	73,500	90	1,500	2,100±300	3,600	--	--	--	--	--	--
98900238	08–01–89	0810	M	27	70,200	98	570	1,700±240	2,270	--	--	--	--	--	--
98900237	08–01–89	1030	M	13	--	--	370	290±50	660	--	--	--	--	--	--
98900196	08–01–89	1320	M	28	103,000	93	1,500	2,700±370	4,200	--	--	--	--	--	--
98900197	08–01–89	1630	M	4.0	95,800	95	470	1,100±150	1,570	--	--	--	--	--	--
98900199	08–18–89	2400	M	5.7	177,000	84	1,220	3,900±580	5,120	--	--	--	--	--	--
RC-89-0319	09–06–89	[15]1440	M	3.1	147,000	91	3,820±590	4,400±340	8,220	501	372	215	210	226	279
98900149	09–06–89	[15]1440	M	3.1	147,000	91	1,290	3,100±530	4,390	--	--	--	--	--	--
98900152	09–06–89	[15]1510	M	5.3	165,000	[11]84	680	4,500±670	5,180	--	--	--	--	--	--
RC-89-0318	09–06–89	[15]1510	M	5.3	165,000	84	5,280±660	5,120±500	10,400	663	474	215	239	248	396
RC-89-0321	09–06–89	[15]1515	G	4.3	180,000	80	4,320±540	5,330±410	9,650	705	500	247	248	270	252
98900153	09–06–89	[15]1515	G	4.3	180,000	[11]80	160	6,000±960	6,160	--	--	--	--	--	--
99000530	07–11–90	1320	D	2.5	143,000	[11]86	1,630	1,500±530	3,130	--	--	--	--	--	--
99000552	08–15–90	0250	M	67	172,000	77	--	--	--	564	447	224	--	241	--
99000551	08–15–90	1820	G	7.9	95,300	93	--	--	--	392	267	162	--	210	--
99100047	10–20–90	0800	M	125	229,000	60	--	--	--	684	550	--	--	389	--
Little Colorado River near Joseph City, Arizona (09397300)															
98800003	08–02–88	1725	D	34	244,000	[11]70	160	[12]140	300	--	--	--	--	--	--
98900101	02–17–89	1300	G	.93	--	--	--	1.3±.6	--	--	--	--	--	--	--
98900091	03–15–89	1145	G	.18	44	--	1.9	1.6±.4	3.5	--	--	--	--	--	--
98900102	03–27–89	1300	G	3.5	--	--	.88	1.6±.7	2.5	--	--	--	--	--	--
98900200	07–23–89	1550	M	70	53,700	99	230	1,800±240	2,030	--	--	--	--	--	--
98900201	07–23–89	1630	M	70	61,000	98	590	1,800±240	2,390	--	--	--	--	--	--
98900202	07–24–89	1045	G	8.9	4,800	99	88	130±18	220	--	--	--	--	--	--
98900203	07–26–89	0630	M	71	22,500	97	290	680±90	970	--	--	--	--	--	--

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (µg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Little Colorado River near Joseph City, Arizona (09397300)—Continued															
98900204	07–26–89	0730	M	71	58,600	95	750	2,800±310	3,550	--	--	--	--	--	--
98900205	07–26–89	0950	M	60	73,000	98	585	1,800±250	2,385	--	--	--	--	--	--
98900206	07–26–89	1010	M	47	71,200	98	880	1,300±200	2,180	--	--	--	--	--	--
98900207	07–26–89	1820	M	43	44,500	--	590	940±130	1,530	--	--	--	--	--	--
98900208	08–18–89	1630	M	185	93,500	77	600	2,300±330	2,900	--	--	--	--	--	--
98900209	08–18–89	2140	M	110	84,700	--	400	1,200±160	1,600	--	--	--	--	--	--
98900210	08–19–89	0440	M	86	55,300	85	670	1,900±280	2,570	--	--	--	--	--	--
99000520	07–14–90	1730	M	101	178,000	93	--	--	--	524	356	160	--	214	--
99000548	08–16–90	1645	M	27	51,300	97	--	--	--	240	128	72	--	67	--
99000545	08–16–90	1750	M	22	64,500	86	--	--	--	250	142	84	--	77	--
99100053	01–07–91	1620	G	22	17,100	89	--	--	--	43	32	19	--	21	--
Little Colorado River at Grand Falls, Arizona (09401000)															
98900192	08–20–89	1300	G	28	--	--	350	1,200±180	1,550	--	--	--	--	--	--
99000532	07–09–90	1210	M	42	79,500	88	750	730±230	1,480	--	--	--	--	--	--
99000533	07–09–90	1810	M	29	60,000	93	950	950±250	1,900	--	--	--	--	--	--
99000525	07–10–90	1405	D	7.9	51,900	99	80	86±29	170	--	--	--	--	--	--
99000519	07–17–90	1600	M	11	77,100	99	1,100	980±270	2,080	--	--	--	--	--	--
99000539	07–17–90	1800	D	9.7	85,100	99	3,300	2,100±520	5,400	289	213	102	--	102	--
99000517	07–17–90	1840	M	9.4	87,400	99	640	440±190	1,080	297	184	114	--	140	--
99000549	08–17–90	1230	D	45	92,300	100	--	--	--	329	258	120	--	138	--
99100051	01–07–91	([13])	C	--	21,700	[11]75	--	--	--	52	43	22	--	33	--
99100072	03–05–91	([13])	C	30	21,100	[11]96	--	--	--	65	49	--	--	30	--

Table 17. Concentrations of selected radiochemical constituents in the suspended phase in samples from streamflow-gaging stations, Puerco and Little Colorado River Basins, Arizona and New Mexico, water years 1989–91—Continued

Record number[1]	Date	Time	Sampling method	Discharge (m^3/s)	Sediment concentration (mg/L)	Sediment grain size <0.062 (mm)	Suspended gross alpha[2] (pCi/L)	Suspended gross beta[3] (pCi/L as Sr–90)	Suspended gross alpha plus gross beta (pCi/L)[4]	Suspended uranium (μg/L)[5]	Suspended uranium (pCi/L)[6]	Suspended ^{226}radium (pCi/L)[7]	Suspended ^{228}radium (pCi/L)[8]	Suspended ^{230}thorium (pCi/L)[9]	Suspended ^{210}lead (pCi/L)[10]
Little Colorado River at Grand Falls, Arizona (09401000)—Continued															
98900204	07–26–89	0730	M	71	58,600	95	750	2,800±310	3,550	--	--	--	--	--	--
Little Colorado River near Cameron, Arizona (09402000)															
99100071	03–05–91	1300	D	31	22,500	91	--	--	--	73	50	--	--	34	--
98800002	08–04–88	1200	G	.04	8,270	[11]100	300	[12]370	670	--	--	--	--	--	--
98800027	09–01–88	1350	D	33	67,600	--	1,300	[12]1,400	2,700	--	--	--	--	--	--
99000515	07–23–90	1840	M	76	25,000	88	1,400	750±240	2,150	--	--	--	--	--	--
99000557	08–19–90	1245	D	20	78,000	98	--	--	--	219	164	101	--	94	--
99100050	01–08–91	1530	D	63	85,500	70	--	--	--	251	171	--	--	120	--
99100073	03–07–91	1400	D	36	46,100	77	--	--	--	102	78	--	--	55	--
Querino Road upstream from Sanders, Arizona (351527109161902)															
98900080	04–04–89	1700	--	.14	--	--	5.0	5.0±1.7	10.0	--	--	--	--	--	--
South Fork of the Puerco River, near Gallup, New Mexico (353156108362301)															
98800085	06–29–88	1958	—	--	--	--	2,450	[12]1,600	4,050	--	--	--	--	--	--

[1]Record number is an arbitrary number assigned to each sample by the U.S. Geological Survey National Water-Quality Laboratory when the sample is received. Record numbers beginning with the letters "RC" were analyzed by the New Mexico Scientific Laboratory.

[2]Gross alpha was calculated by dividing suspended gross alpha, in micrograms per liter (parameter code 80040), by 0.68 if measured by a contract laboratory; and by multiplying suspended gross alpha, in picocuries per gram, by the sediment concentration and dividing by 1,000 if measured by the New Mexico Scientific Laboratory.

[3]Gross beta is reported as suspended gross beta, in picocuries per liter, by the contract laboratories (parameter code 80060) and was calculated by multiplying suspended gross beta, in picocuries per gram, by the sediment concentration, in milligrams per liter, and dividing by 1,000 milligrams per gram (mg/g) if measured by the New Mexico Scientific Laboratory.

[4]Gross alpha plus gross beta was calculated by adding the two previous columns.

[5]Suspended uranium, in micrograms per liter, was calculated by adding the activity of suspended uranium–238 (^{238}U) and uranium–234 (^{234}U), in picocuries per gram, multiplying the sum of the sediment concentration, in milligrams per liter, and dividing by 1,000 mg/g, and then dividing the product by $^{234}U/^{238}U$ times 0.68.

[6]Suspended uranium, in picocuries per liter, was calculated by adding the activity of suspended ^{238}U and ^{234}U, in picocuries per gram, multiplying the sum by the sediment concentration, in milligrams per liter, and dividing by 1,000 milligrams per gram.

[7]Suspended radium–226 (^{226}Ra), in picocuries per liter, was calculated by multiplying suspended ^{226}Ra, in picocuries per gram, by the sediment concentration, in milligrams per liter, and dividing by 1,000 mg/g.

[8]Suspended radium–228 (^{228}Ra), in picocuries per liter, was calculated by multiplying suspended ^{228}Ra, in picocuries per gram, by the sediment concentration, in milligrams per liter, and dividing by 1,000 mg/g.

[9]Suspended thorium–230 (^{230}Th), in picocuries per liter, was calculated by multiplying suspended ^{230}Th, in picocuries per gram, by the sediment concentration, in milligrams per liter, and dividing by 1,000 mg/g.

[10]Suspended lead–210 (^{210}Pb), in picocuries per liter, was calculated by multiplying suspended ^{210}Pb, in picocuries per gram, by the sediment concentration, in milligrams per liter, and dividing by 1,000 mg/g.

[11]Fall diameter. [12]Value for range of error is not available. [13]Composite from different sampling times. [14]Calculated. [15]Duplicated samples.

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