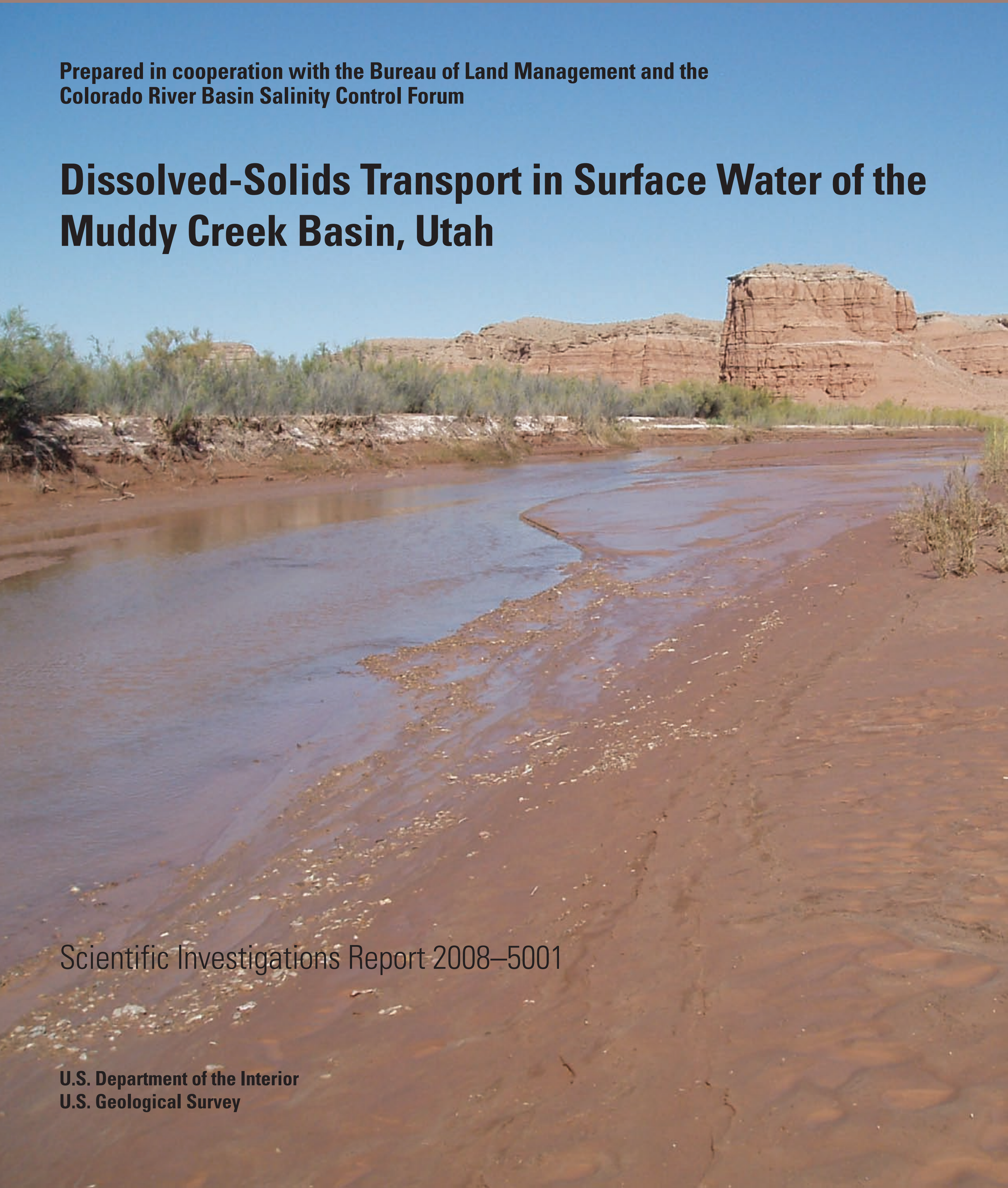

Prepared in cooperation with the Bureau of Land Management and the Colorado River Basin Salinity Control Forum

Dissolved-Solids Transport in Surface Water of the Muddy Creek Basin, Utah

Scientific Investigations Report 2008–5001

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

Cover photo: Muddy Creek near U.S. Geological Survey streamgage 09332800 .
(Photo credit: Steven Gerner, USGS, Salt Lake City, Utah.)

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Abbreviations and Acronyms

(Clarification or additional information given in parentheses)

EWI	equal-width-increment
ICP-MS	inductively coupled plasma mass spectrometry
MRL	Minimum Reporting Level
NCEP	National Centers for Environmental Prediction
NWIS	National Water Information System (USGS)
PRISM	Parameter-elevation Regressions on Independent Slopes Model (Oregon State University)
QC	quality control
SWReGAP	Southwest Regional Gap Analysis Program
ROE	residue on evaporation
RSD	relative standard deviation
SC	specific conductance
TDS	total dissolved solids
WY	water year

Organizations

BLM	Bureau of Land Management (U.S. Dept. of the Interior)
BOR	Bureau of Reclamation (U.S. Dept. of the Interior)
EWCD	Emery Water Conservancy District
FWS	U.S. Fish and Wildlife Service (U.S. Dept. of the Interior)
NRCS	Natural Resources Conservation Service (U.S. Dept. of Agriculture)
NWQL	National Water Quality Laboratory (USGS)
SUFCO	Southern Utah Fuel Company
USFS	U.S. Forest Service (U.S. Dept. of Agriculture)
USGS	U.S. Geological Survey (U.S. Dept. of the Interior)

Units of measurement

ft	foot (feet)
gal	gallon
in.	inch
kg	kilogram (10^3 grams)
km^2	square kilometer
L	liter
mg	milligram (10^{-3} gram)
mg/L	milligram per liter (10^{-3} grams per liter)
mi^2	square mile
min	minute
mL	milliliter (10^{-3} liter)
s	second
WY	water year
yr	year(s)

Notes

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32)/1.8.$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Specific conductance is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are reported in milligrams per liter (mg/L).

Dissolved-Solids Transport in Surface Water of the Muddy Creek Basin, Utah

By Steven J. Gerner

Abstract

Muddy Creek is located in the southeastern part of central Utah and is a tributary of the Dirty Devil River, which, in turn, is a tributary of the Colorado River. Dissolved solids transported from the Muddy Creek Basin may be stored in the lower Dirty Devil River Basin, but are eventually discharged to the Colorado River and impact downstream water users. This study used selected dissolved-solids measurements made by various local, State, and Federal agencies from the 1970s through 2006, and additional dissolved-solids data that were collected by the U.S. Geological Survey during April 2004 through November 2006, to compute dissolved-solids loads, determine the distribution of dissolved-solids concentrations, and identify trends in dissolved-solids concentration in surface water of the Muddy Creek Basin.

The dissolved-solids concentration values measured in water samples collected from Muddy Creek during April 2004 through October 2006 ranged from 385 milligrams per liter (mg/L) to 5,950 mg/L. The highest dissolved-solids concentration values measured in the study area were in water samples collected at sites in South Salt Wash (27,000 mg/L) and Salt Wash (4,940 to 6,780 mg/L).

The mean annual dissolved-solids load in Muddy Creek for the periods October 1976 to September 1980 and October 2005 to September 2006 was smallest at a site near the headwaters (9,670 tons per year [tons/yr]) and largest at a site at the mouth (68,700 tons/yr). For this period, the mean annual yield of dissolved solids from the Muddy Creek Basin was 44 tons per square mile. During October 2005 to September 2006, direct runoff transported as much as 45 percent of the annual dissolved-solids load at the mouth of Muddy Creek.

A storm that occurred during October 5–7, 2006 resulted in a peak streamflow at the mouth of Muddy Creek of 7,150 cubic feet per second (ft^3/s) and the transport of an estimated 35,000 tons of dissolved solids, which is about 51 percent of the average annual dissolved-solids load at the mouth of Muddy Creek.

A significant downward trend in dissolved-solids concentrations from 1973 to 2006 was determined for Muddy Creek at a site just downstream of that portion of the basin containing agricultural land. Dissolved-solids concentrations decreased about 2.1 percent per year; however, the rate of change was a decrease of 1.8 percent per year when dissolved-solids concentrations were adjusted for flow.

Introduction

The Muddy Creek Basin in central Utah is drained by Muddy Creek, which is a tributary of the Dirty Devil River, and the Colorado River. Hence, dissolved solids transported from the basin are likely to be discharged eventually to the Colorado River. These dissolved solids impact downstream water users by affecting the suitability of water for municipal, industrial, and agricultural use. Dissolved-solids concentrations are increased in the Upper Colorado River Basin, including the Muddy Creek Basin, through depletion of dilute inflow or accretion of dissolved solids in ground-water discharge or surface runoff. Concentrations are further increased through evaporation in streams and reservoirs, and transpiration by phreatophyte and riparian vegetation.

On average, since 1980, approximately 8.7 million tons of dissolved solids have been transported annually past Hoover Dam by the Colorado River (U.S. Department of the Interior, 2005). Even though the Muddy Creek Basin contributes less than 1 percent of this annual amount, salinity[1] control within the basin is an important consideration for land managers. In 1974, Congress enacted the Colorado River Basin Salinity Control Act, which authorizes the construction, operation, and maintenance of salinity control works in the Colorado River Basin to manage dissolved-solids concentrations. The Bureau of Land Management (BLM) of the U.S. Department of the Interior implements a comprehensive salinity-control program on the public land that it administers and coordinates its activities with the U.S. Bureau of Reclamation (BOR), the Natural Resources Conservation Service (NRCS), the U.S. Fish and Wildlife Service (FWS), and the U.S. Environmental Protection Agency. The U.S. Geological Survey (USGS), in cooperation with the BLM and the Colorado River Basin Salinity Control Forum, studied dissolved-solids transport in surface water of the Muddy Creek Basin during April 2004 through November 2006.

[1]The term “salinity,” as used in this report, is synonymous with dissolved solids.

Purpose and Scope

This report presents the results of a study of dissolved-solids in the Muddy Creek Basin. These results include (1) estimates of the dissolved-solids loads in Muddy Creek at various sites and at various time scales, (2) measures of dissolved-solids concentrations at various sites within the Muddy Creek Basin, and (3) measures of precipitation in the basin from October 2004 to September 2005 and the impacts of that precipitation on dissolved-solids loads in Muddy Creek.

Intensive field-data collection for this study began in April 2004 and continued through September 2006. Data collection specific to this study ended with an indirect measurement of the peak streamflow of October 6, 2006, made in November 2006, at the mouth of Muddy Creek. Results presented in tables, figures, and discussions in this report rely most heavily on the data collected between December 2003 and November 2006; however, additional analyses and results were derived from data collected prior to 2003 by the USGS and data collected from 1976 to 2006 by the Emery Water Conservancy District (EWCD).

Environmental Setting

The Muddy Creek Basin is an area of approximately 1,560 mi^2 located in the southeastern part of central Utah in parts of Sanpete, Sevier, Emery, and Wayne Counties (fig. 1). Encompassed within the study area are parts of the Wasatch Montane Zone, Semiarid Benchlands and Canyonlands, and Shale Desert ecoregions; hence, it contains a range of geographic features that include alpine forests, desert canyons, and non-vegetated badlands (Woods and others, 2001). Elevations range from about 4,500 ft at the mouth of Muddy Creek to 11,533 ft at the summit of Hilgard Mountain on the western edge of the basin. Settlement in the Muddy Creek Basin is concentrated in the area near Emery, Utah, in a community of about 300 people. There are no permanent habitations downstream of the confluence of Ivie and Muddy Creeks; an area of about 1,140 mi^2.

Geology and Associated Hydrologic Characteristics

The headwaters of Muddy Creek, in the northwest part of the study area, are in the Tertiary-age Flagstaff Limestone and North Horn Formations (fig. 2). These carbonate aquifers underlie a generally high elevation alpine to sub-alpine area where ground and surface water have relatively low dissolved-solids concentrations. The headwater areas of tributaries farther to the south are underlain by Cretaceous-age Price River Formation and the Castlegate Sandstone, which yield fresh to slightly saline water.

Southeast of the high-elevation area of the Wasatch Plateau is a wide band of Mancos Shale that trends from the southwest to the northeast through the farming community of Emery, Utah. The Cretaceous-age Mancos Shale has low permeability. Ground water discharging from Mancos Shale and Mancos Shale derived soils is saline because of the dissolution of mainly gypsum and some carbonate minerals, and cation exchange with sodium-rich clays (Rittmaster and Mueller, 1986). Projects that improve irrigation methods have been implemented in the upper Muddy Creek Basin with the intent of reducing deep percolation of excess irrigation water and dissolution of salts from Mancos Shale (Natural Resources Conservation Service, 2004).

A prominent structure partially contained in the Muddy Creek Basin is the San Rafael Swell: a large asymmetrical anticline in the eastern half of the central part of the Muddy Creek Basin. The San Rafael Reef with its steeply dipping formations is the eastern edge of this anticline (photo 1). Formations on the western edge of the San Rafael Swell dip more gradually. The uplift of the San Rafael Swell resulted in the exposure of formations with aquifers that contain slightly saline[2] water to brines. Of these formations, the Carmel Formation, which is widely exposed in the Muddy Creek Basin, is notable for discharging saline water. The Carmel Formation contains substantial quantities of evaporites—mainly gypsum and sodium salts, which dissolve in ground water. As a result, springs discharging from the Carmel Formation are generally slightly-to-very saline (Hood and Danielson, 1981). Most of these springs discharge from less than 1 to 20 gal/min; however, some can yield as much as 3 ft^3/s. Caine Springs, in Salt Wash, discharges about 2 ft^3/s of moderately saline water from the Carmel Formation.

Muddy Creek and many of its tributaries have formed deep canyons in outcrops of Navajo Sandstone that are located around the periphery of the San Rafael Swell. Navajo Sandstone is a major aquifer in the Muddy Creek Basin because of its thickness and potential for locally large yields of ground water. Ground water discharged from the Navajo Sandstone in the Muddy Creek Basin is generally slightly-to-moderately saline, sometimes becoming degraded as a result of inter-formational leakage.

Muddy Creek flows through Quaternary alluvium just downstream from Salt Wash to its confluence with the Fremont River. Much of this alluvium is debris from the surrounding older formations (Rittmaster and Mueller, 1986). The salinity of this alluvium is such that surface deposits of efflorescent salts are present throughout much of the flood plain.

[2]The terms used in this report to classify water according to the concentration of dissolved solids are defined in Fretwell and others (1996). These terms include slightly saline (1,000–3,000 mg/L), moderately saline (3,000–10,000 mg/L), and very saline (10,000–35,000 mg/L).

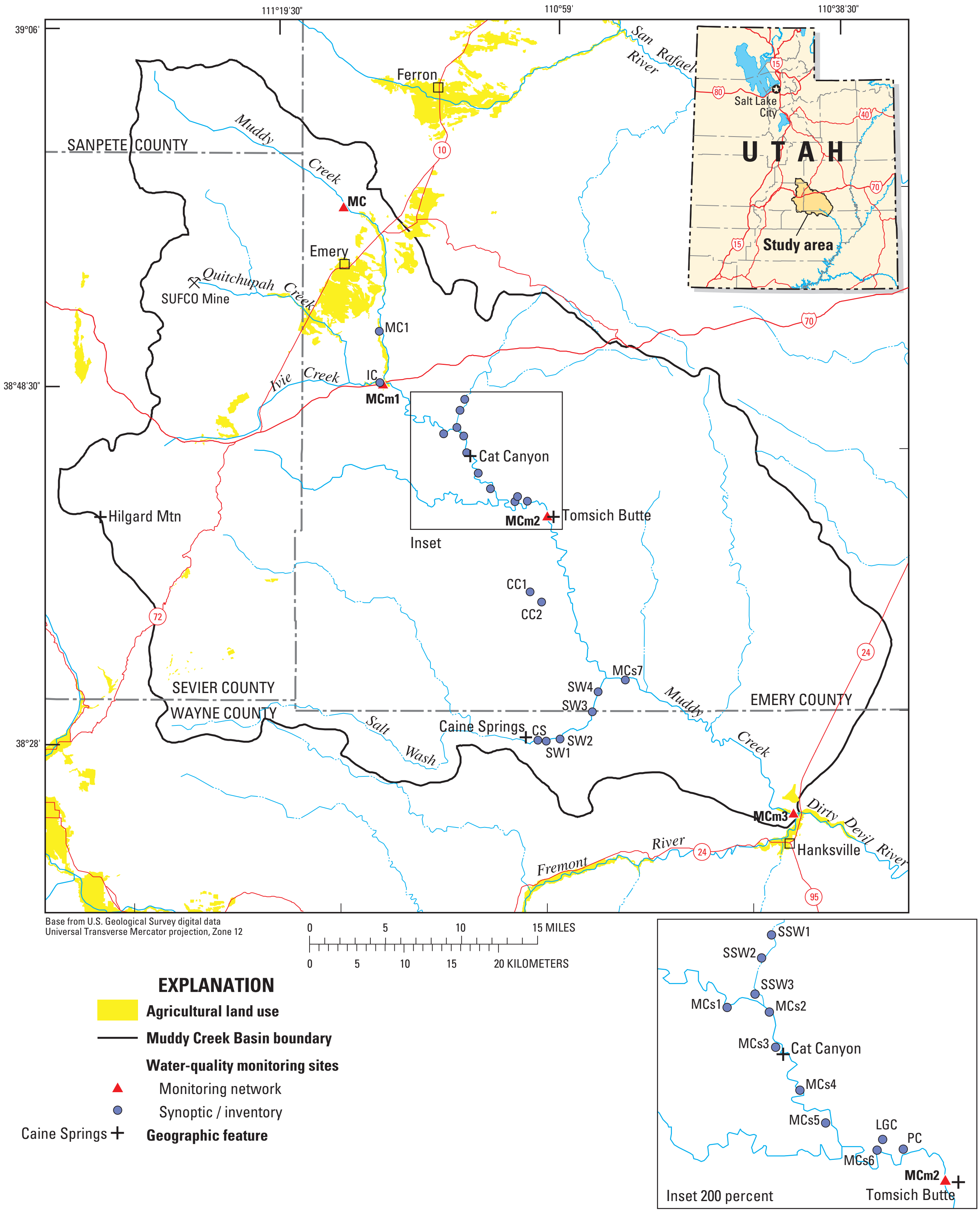

Figure 1. Geographic features and water-quality monitoring sites in the Muddy Creek Basin, Utah.

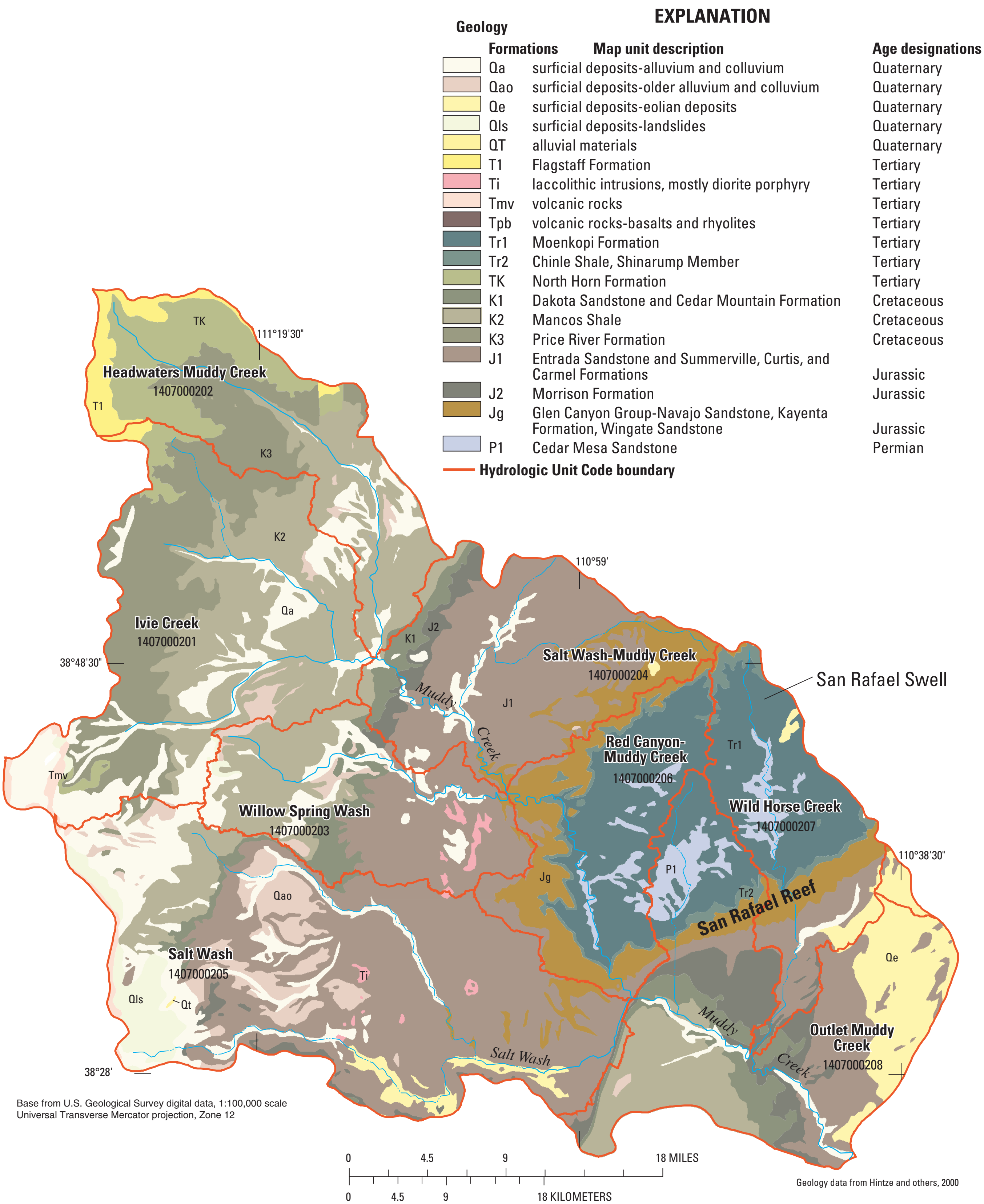

Figure 2. Geology and 10-digit hydrologic units in Muddy Creek Basin, Utah.

Photo 1. Mancos shale badlands (foreground) adjacent to the San Rafael Reef in the Muddy Creek Basin, Utah. The center of the photograph shows the confluence of Muddy Creek and Salt Wash. (Photo credit: Steven Gerner, USGS, Salt Lake City, Utah).

The stream gage at the mouth of Muddy Creek (USGS station number 09332800, Muddy Creek at mouth, near Hanksville, Utah [referred to as site MCm3 (fig. 1, table 1) in this report]), was constructed on an outcrop of Entrada Sandstone that is exposed when large flow events scour the stream channel down to this bedrock feature. This feature provides a barrier that probably forces much of the ground water flowing in the alluvium to the surface and into the channel.

Land Cover and Use

Much of the Muddy Creek Basin has a harsh climate with little rainfall and large temperature extremes. Consequently, forests within the basin are primarily located at higher elevations along the western margin of the area and agricultural land is generally located in the adjacent bench lands where growing conditions are the most favorable. Crops, particularly alfalfa and pasture grasses, are grown to support the livestock industry on about 6,000 acres of agricultural land near Emery (Natural Resources Conservation Service, 2004) (fig. 3). Domestic cattle, sheep, and horses; and small bands of wild horses, burros, and Desert bighorn sheep, graze on the grasslands and shrubs located throughout much of the basin.

Natural vegetation, shown as forest, grassland, and shrubland on figure 3, varies substantially within the study area. In the mountainous headwaters, the vegetative growth is lush and dominated by forests whose plant communities include aspen, spruce, and fir. In the semi-arid and arid middle- and lower-elevation parts of the basin, the vegetation is sparse. Iorns and others (1964) noted that “important plant communities in these areas include pinion-juniper, shadscale, blackbrush, greasewood, and big sagebrush.” Runoff and aquifer recharge are limited, in part, by the presence of these plant communities.

The federal government owns the largest portion of the land within the Muddy Creek Basin, and most of this portion is administered by the BLM (fig. 4). Federal lands on the western and southwestern margin of the basin are within the Fish Lake National Forest and Capitol Reef National Park and are administered by the U.S. Forest Service (USFS) and the National Park Service (NPS), respectively. Scattered throughout the basin are State of Utah Trust Lands. There is extensive land held in private ownership near Emery, Utah. Land management objectives may vary widely among these public and private land-ownership groups, and the management decisions of each affect the transport of dissolved solids within the basin.

Table 1. Location of water-quality monitoring sites in the Muddy Creek Basin, Utah.

[Site types: I, inventory; M, water-quality monitoring; S, synoptic; —, not calculated]

Site identifier (see fig. 1 for site location)	U.S. Geological Survey station number	Site name	Latitude	Longitude	Site type	Drainage area, square miles
MC	09330500	Muddy Creek, near Emery	38.982	–111.249	M	107
MC1	385145111121701	Muddy Creek below Miller Canyon, near Emery	38.862	–111.205	I	—
IC	384849111121301	Ivie Creek at mouth, near Emery	38.814	–111.204	I	—
MCm1	09332100	Muddy Creek below I-70, near Emery	38.813	–111.200	M	418
MCs1	384553111073301	Muddy Creek at Lone Tree Crossing	38.765	–111.126	S	—
SSW1	384752111060301	South Salt Wash at first road crossing, near Emery	38.798	–111.101	S	—
SSW2	384714111062201	South Salt Wash at second road crossing, near Emery	38.787	–111.106	S	—
SSW3	384615111063801	South Salt Wash at mouth, at Muddy Creek	38.771	–111.110	S	—
MCs2	384545111060801	Muddy Creek below South Salt Wash, near Emery	38.763	–111.102	S	—
MCs3	384448111055101	Muddy Creek above Cat Canyon, near Emery	38.747	–111.098	S	—
MCs4	384338111050101	Muddy Creek below Cat Canyon, near Emery	38.727	–111.084	S	—
MCs5	384245111040701	Muddy Creek above Willow Springs Wash, near Emery	38.712	–111.069	S	—
MCs6	384200111022001	Muddy Creek below Willow Springs Wash, near Emery	38.700	–111.039	S	—
LGC	384217111020801	Little Gem Canyon, near Hanksville	38.705	–111.036	I	—
PC	384202111012701	Poor Canyon, near Hanksville	38.701	–111.024	I	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	38.687	–111.000	M	730
CS	382820111004001	Caine Springs, near Hanksville	38.472	–111.011	I	—
SW1	382816111000501	Salt Wash below Caine Springs, near Hanksville	38.471	–111.001	I	—
SW2	382824110590201	Salt Wash at Bedrock Falls, near Hanksville	38.473	–110.984	I	—
SW3	382958110564201	Salt Wash at County Line, near Hanksville	38.499	–110.945	I	—
SW4	383108110561001	Salt Wash at mouth, at Muddy Creek	38.519	–110.938	I	—
MCs7	383147110541201	Muddy Creek 2 miles below Salt Wash	38.530	–110.905	I	—
CC2	383615111002401	Chimney Canyon, near Hanksville	38.604	–111.007	I	—
CC1	383649111011601	North Fork of Chimney Canyon, near Hanksville	38.614	–111.021	I	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	38.403	–110.701	M	1,555

General Climatic Characteristics

Climate in the study area varies from mild summers and cold winters in the higher elevations to hot summers and mild winters in the lower elevations. Precipitation estimates for the Muddy Creek Basin for water years[3] (WYs) 1976–2006 were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (PRISM Group, Oregon State University, 2007). The average annual precipitation in the study area during this period ranged from 2.2 in./yr near the mouth of Muddy Creek to 57 in./yr in the mountains of the Wasatch Plateau, and the basin-wide average was 10.3 in./yr. The average estimated annual volume of precipitation falling in the Muddy Creek Basin during WYs 1976–2006 was 858,000 acre-ft. During WY 2005, the estimated annual volume of precipitation was 1,170,000 acre-ft or about 136 percent of the WY 1976–2006 average. The estimated annual volume of precipitation in WY 2006 was 733,000 acre-ft or about 85 percent of the WY 1976–2006 average.

Most of the precipitation in the lower elevations results from rainfall produced by convective thunderstorms or longer periods of rainfall associated with moisture-laden air masses crossing the basin from the south or west during August–October. Some of these storms are downpours of high intensity and produce flash flooding. The largest portion of precipitation in the mountainous headwaters falls as snow during November–April. Much of the precipitation that falls in the Muddy Creek Basin is lost to evapotranspiration or sublimation; the remainder becomes runoff in streams or recharge to aquifers. In the eastern part of the study area, the pan evaporation rate is as high as 60 in./yr (Farnsworth and others, 1982), substantially exceeding precipitation and contributing to periods of no flow in portions of Muddy Creek.

[3]A water year starts October 1 and ends September 30. It is denoted by the year in which this period ends. For example, October 1, 2005–September 30, 2006 is the 2006 water year.

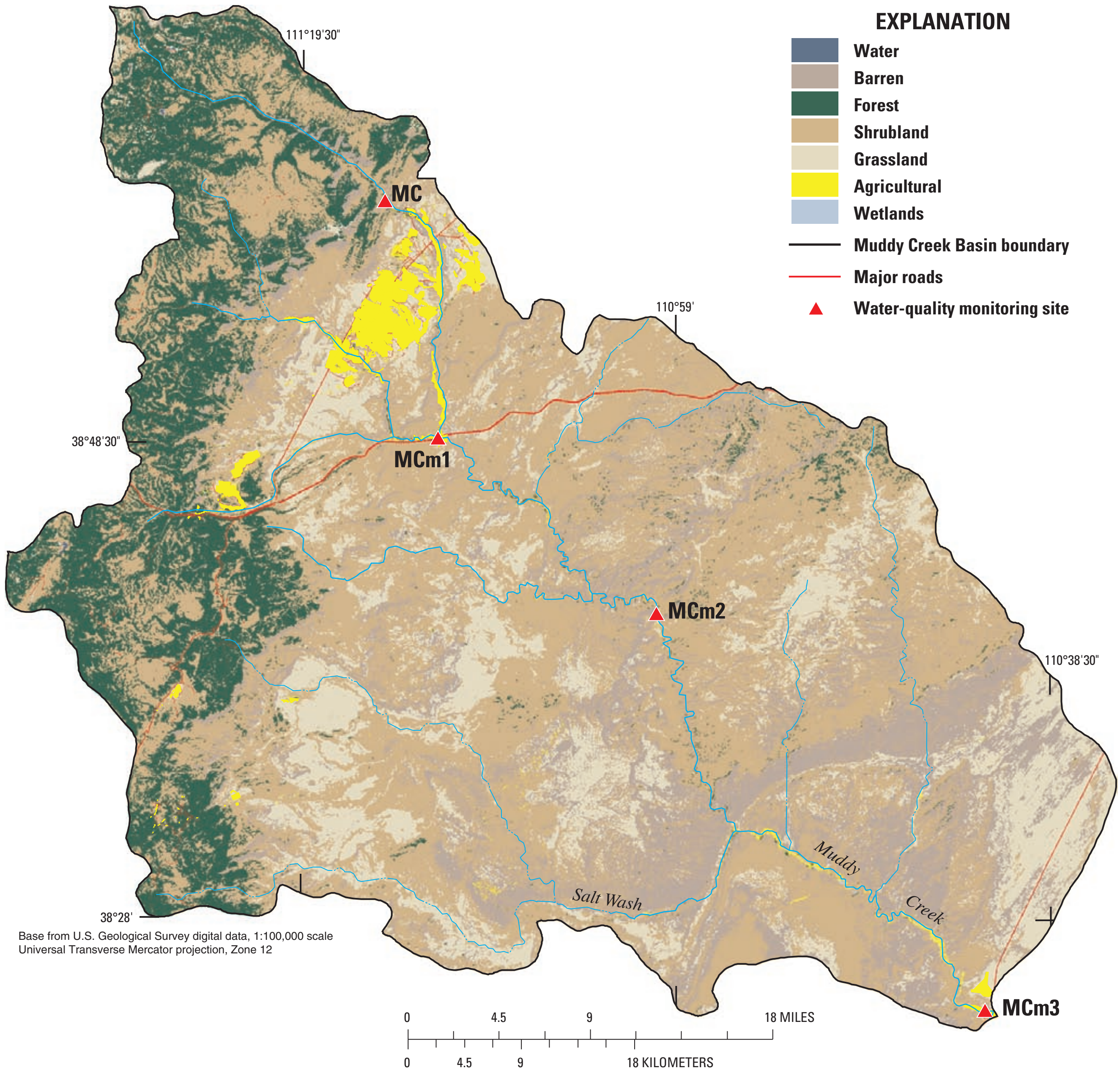

Figure 3. Land cover and use in Muddy Creek Basin, Utah.

Hydrology

The concentration and load of dissolved solids in Muddy Creek are dependent on the hydrologic processes that occur in the basin. For example, the amount of streamflow diverted for irrigation in the upper basin and the timing of those diversions have a large impact on the concentration of dissolved-solids at the mouth of Muddy Creek. In the following paragraphs, streamflow is described for selected sites on Muddy Creek including site MC near the headwaters, site MCm1 downstream of Emery, Utah, and site MCm3 at the mouth of Muddy Creek (fig. 1). The average daily streamflow and average annual runoff in Muddy Creek at these sites were calculated from data for WYs 1976–80 and WYs 2005–06—periods in which data were collected at all of the sites.

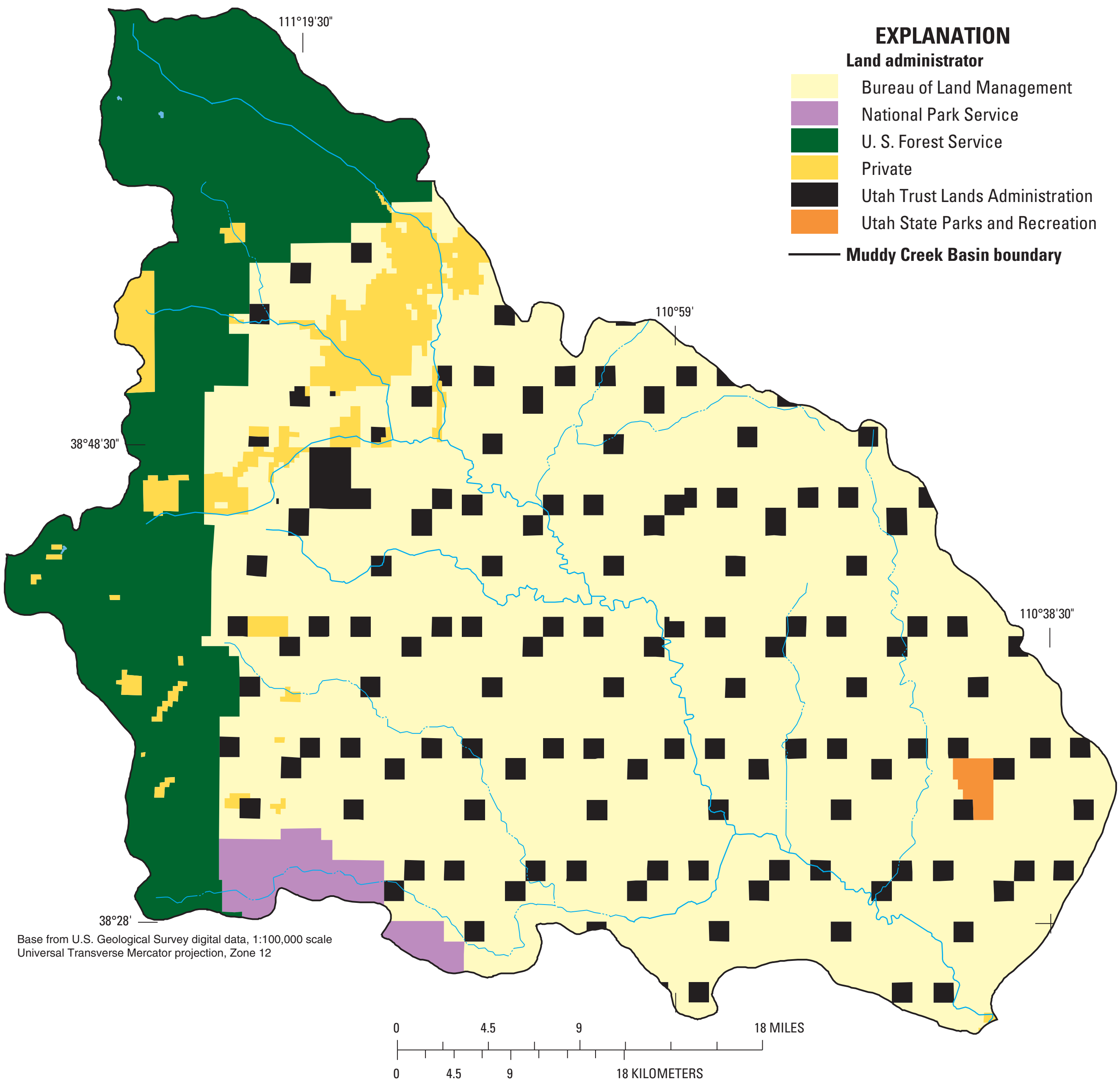

Figure 4. Land ownership in Muddy Creek Basin, Utah.

The average annual runoff from the headwater areas of Muddy Creek upstream from site MC was 30,900 acre-ft. The annual runoff ranged from 6,800 to 62,400 acre-ft during the entire period of record (fig. 5). The average daily streamflow was 41 ft^3/s. Annual runoff data from the headwater areas of Quitchupah and Ivie Creeks are sparse; however, the average annual runoff for Quitchupah Creek during WYs 1979–81 was 6,110 acre-ft, and the average annual runoff from the headwater areas of Ivie Creek during WYs 1951–61 was 2,830 acre-ft (U.S. Geological Survey, 2007). Runoff from the headwater areas is mainly attributed to snowmelt during May–July. From April to October, most of the runoff from headwater areas is diverted from Muddy, Quitchupah, and Ivie Creeks for irrigation of the crop lands near Emery, so that during mid- to late summer, there is often no flow in some reaches of Muddy Creek between sites MC and MCm1.

The average annual runoff at site MCm1 was 16,300 acre-ft: a decrease of about 47 percent compared with the annual runoff from headwater areas upstream of site MC. The average daily streamflow at site MCm1 was 23 ft^3/s. Most of the runoff at this site occurred during snowmelt when runoff in the headwater areas exceeded the capacity of irrigation diversions. During some years, such as WYs 1983–84 when there was an exceptionally large snow pack in the headwater

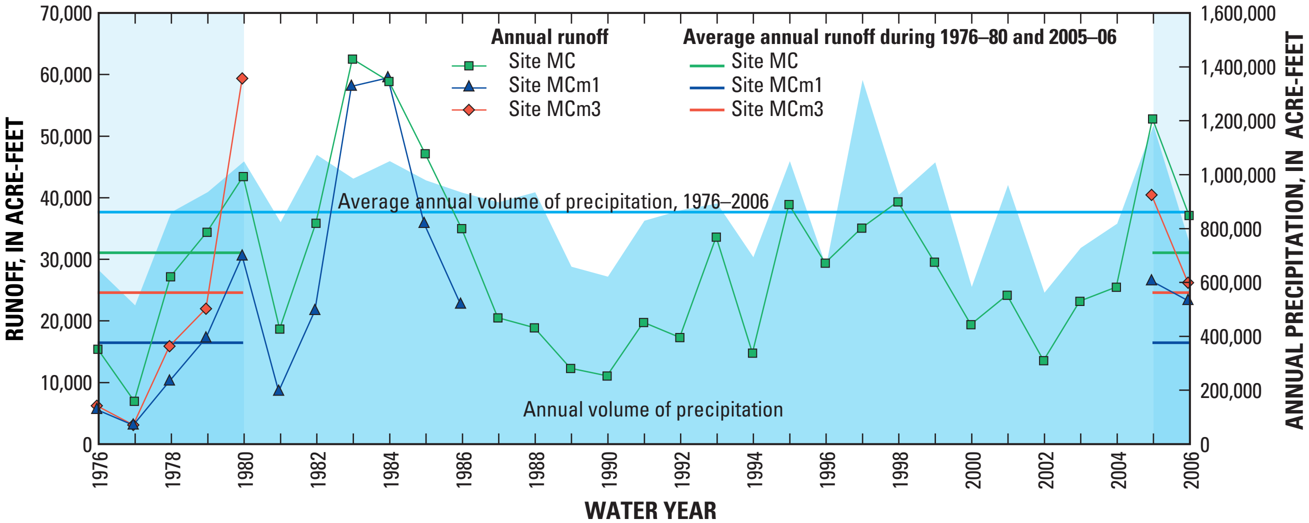

Figure 5. Annual runoff and average annual runoff at selected water-quality monitoring sites and annual volume of precipitation, Muddy Creek Basin, Utah, 1976 to 2006. Average annual runoff is shown for that period with data available for all sites.

areas that melted rapidly, the runoff at site MCm1 was 90 percent or more of the runoff from the headwater areas. Even though portions of Muddy Creek between sites MC and MCm1 are dewatered from irrigation diversion, there is generally flow at site MCm1 from ground-water discharge, discharge from mines in the Quitchupah Creek drainage, irrigation return flow, and intermittent flow from ephemeral washes.

Average annual runoff at site MCm3 for WYs 1976–80 and WYs 2005–06 was 24,400 acre-ft—a 50 percent increase compared with runoff at site MCm1. Much of the increase in runoff is due to inflow from the perennial stream discharging from Salt Wash and inflow of direct storm runoff from the basin between these sites. The average daily streamflow at site MCm3 during this period was 34 ft^3/s.

Conceptual Model of Dissolved-Solids Sources and Transport

Water in the Muddy Creek Basin naturally contains dissolved solids (principally sodium, calcium, magnesium, potassium, sulfate, chloride, bicarbonate, fluoride, and silica) that are derived from the weathering and dissolution of minerals in rocks near the land surface (Hem, 1992). There are two main processes by which dissolved-solids concentrations increase in Muddy Creek. Dissolved solids are concentrated as a result of the consumptive use of water, such as the diversion of low-saline water out of Muddy Creek for irrigation of agricultural lands in the upper basin, by direct evaporation of water from surface water, and by transpiration of water through plants. In these examples, dissolved solids are not added to the water or removed, but the dissolved-solids concentration increases because less stream water is available for dilution. Dissolved solids are added to Muddy Creek when solids are dissolved from the surface (soil) and subsurface (basin bedrock) and then transported to the stream. The concentration of dissolved solids in water samples from water-quality monitoring sites in the Muddy Creek Basin, and the daily mean dissolved-solids concentrations calculated for select monitoring sites, varied spatially and seasonally because of the factors that affect the dilution at, and transport to, these sites.

Natural factors that affect the chemical composition and dissolved-solids concentrations in Muddy Creek Basin streams include geology and eroded materials (soils and alluvium), precipitation and evapotranspiration rates, diffuse ground-water discharge, and mineral spring discharge. The major sources of dissolved solids in the Muddy Creek Basin are the sedimentary formations that underlie the basin, and the principal dissolved-solids transport mechanisms in the basin are ground-water flow and direct runoff of precipitation. Muddy Creek crosses geologic formations that contain minerals of varying solubility, acquiring more dissolved solids from those rocks that are less resistant, such as the Mancos Shale. Likewise, ground-water flow paths within the basin transit these same geologic formations. As a result, ground water acquires dissolved solids from soluble minerals in the rocks, then transports those dissolved solids to Muddy Creek Basin streams in the form of ground-water discharge.

Direct runoff of precipitation falling in the Muddy Creek Basin acquires dissolved solids from surface deposits of efflorescent salts, surficial bedrock, soils and alluvium, then transports those dissolved solids to basin streams. Dissolved solids from interstitial pore space near the surface are also available for transport through direct runoff. The annual volume of flow and dissolved-solids loads associated with direct runoff from rain in the Muddy Creek Basin is the most variable, particularly at the mouth of Muddy Creek. The number and intensity of storms producing runoff in the basin varies annually depending on the occurrence of certain regional weather patterns. Periods of moist southwesterly air flow especially can produce large daily volumes of direct runoff. For example, this type of weather pattern produced rainfall that resulted in 1,530 acre-ft of runoff that transported 6,140 tons of dissolved solids at site MCm3 on October 19, 2005. This was about 6 percent of the annual runoff and about 8 percent of the annual dissolved-solids load for WY 2006.

Agricultural activities, primarily irrigation of agricultural lands, are responsible for additional dissolution and transport of dissolved solids in the basin (Natural Resources Conservation Service, 2004). Irrigation water applied in excess of crop needs may percolate through the root zone and acquire additional solids dissolved from soil and bedrock that can then be discharged in ground water to Muddy Creek Basin streams.

Previous Studies

There have been many studies investigating dissolved solids in the Upper Colorado River Basin: some that include data, and analyses of data, from the Dirty Devil River Basin or the Muddy Creek Basin. Biennial reports produced by BOR (U.S. Department of the Interior, 2005) provide updates on the quality of water in the Colorado River Basin and on projects intended to reduce dissolved solids in the Colorado River. These reports include an extensive list of references related to dissolved solids in the Colorado River Basin. There have been several notable studies that emphasize water quality in the Muddy Creek Basin. Among these is a reconnaissance of surface-water quality in the Dirty Devil River Basin by Mundorff (1979). This reconnaissance was conducted during 1975–76, and data values reflect the dry conditions that existed during that period. Hood and Danielson (1981) conducted a study of bedrock aquifers in an area that included much of the Muddy Creek Basin. Aquifer properties as well as the quality of water discharged from these aquifers were reported. A study by Rittmaster and Mueller (1986) identified sources of dissolved-solids loading to the Dirty Devil River and its major tributaries. The Bureau of Reclamation (1987) published a report containing the results of an extensive data collection and analysis effort. This report details hydrology and salinity in the Dirty Devil River Basin and the Muddy Creek Basin in particular. The primary controllable sources of dissolved solids to Muddy Creek are identified and quantified in this report. A plan and associated environmental assessment for salinity control in the Muddy Creek, Utah, Unit has been published by the Natural Resources Conservation Service (2004). This report provides details on the occurrence of dissolved solids in and near the agricultural lands in the Muddy Creek Basin and provides a plan for reducing the amount of dissolved solids contributed to Muddy Creek through agricultural activities on those lands.

Acknowledgments

The author gratefully acknowledges the cooperation and assistance of EWCD personnel who provided stream stage and water-quality data for the stream gage operated by them at site MCm1 (fig. 1). Thanks to Tim McKinney (USGS) and Shane Wright (USGS) for their assistance with obtaining and analyzing historical precipitation data and GIS analysis; James Tibbetts (USGS) for assisting with stream gage operations; and Terry Kenney (USGS) for conducting slope-area discharge measurements.

Methods

Because the dissolved-solids loads transported by Muddy Creek are a function of the dissolved-solids concentration and flow in the stream, measurements of specific conductance, dissolved-solids concentration, and flow were made in Muddy Creek and the tributaries to Muddy Creek. The average daily flow and specific conductance in Muddy Creek were computed from measurements made at 15-min intervals at sites MCm1 and MCm3 from October 2004 through September 2006, and at site MCm2 (photo 2) from May 2005 through September 2006. Water-quality samples were collected from these sites (referred to in the report as monitoring sites) between April 2004 and October 2006 and analyzed for a variety of constituents (table 2).

Water samples were collected from streams and springs in the Muddy Creek Basin using a depth-integrated, isokinetic sampler and the equal-width-increment (EWI) method when appropriate (U.S. Geological Survey, variously dated); however, samples from shallow and (or) slow-moving streams were collected from the center of flow into an open-mouth, 1-L polyethylene bottle. Water samples collected for analysis of dissolved constituents were filtered through a disposable 0.45-micron capsule filter by using a peristaltic pump. Sample filtering was completed in the field.

Water samples were analyzed for the concentration of major ions and (or) residue on evaporation (ROE) at 180°C at the USGS's National Water Quality Laboratory (NWQL) in Lakewood, Colorado, with the standard analytical techniques described in Fishman and Friedman (1989). All data are stored in the USGS's National Water Information System (NWIS) database and are available via the internet (http://waterdata.usgs.gov/ut/nwis/qw). Analytical methods and minimum reporting limits for the analyzed properties and constituents are listed in table 3.

Photo 2. Water-quality monitoring site MCm2, Muddy Creek at Tomsich Butte, near Hanksville, Utah. (Photo credit: Steven Gerner, USGS, Salt Lake City, Utah)

Dissolved-Solids Concentration Determinations

Dissolved-solids concentrations were determined for this study using a number of methods. Residue on evaporation, a method of determination that involves weighing the dry residue remaining after evaporation of the volatile portion of an aliquot of the water sample, was analyzed for most samples. Additionally, selected samples were analyzed for major constituents, and the dissolved-solids concentrations of these samples were calculated by summing these constituents. For these calculations, lab alkalinity values, reported as mg/L $CaCO_3$, were converted to carbonate concentration by multiplying the alkalinity value by 0.60 (Fishman and Friedman, 1989).

Water Samples

In general, the dissolved-solids concentrations of water samples collected by USGS personnel in the Muddy Creek Basin prior to 1986 had been calculated from the sum of constituents. Because of the economy of ROE analysis, and the widespread use of this analysis for samples collected in the Upper Colorado River Basin, ROE was the preferred dissolved-solids concentration analysis for this study. However, it is not uncommon for water that has a high sulfate concentration, like most of that found in the Muddy Creek Basin, to yield an ROE value that exceeds the computed dissolved-solids value (Hem, 1992). For samples collected during this study, the ratio of dissolved solids from sum of constituents to dissolved solids from ROE varied from 0.90 to 1.0, but, on average, the dissolved-solids concentration calculated by the sum of constituents was 94 percent of the ROE (table 2).

Estimates from Specific-Conductance Values

During the study period, specific conductance was measured each time a site in the study area was visited and these values were often used as a surrogate for determining dissolved-solids concentration when that parameter was not measured. In addition, in situ specific conductance sensors provided a continuous (15 min interval) record of specific conductance in Muddy Creek at sites MCm1 and MCm3 (October 1, 2004–September 30, 2006) and site MCm2 (April 6, 2005–September 30, 2006) from which daily mean specific conductance was calculated and daily mean dissolved-solids concentration was determined.

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, Utah, 2004–06.

[°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identifier	U.S. Geological Survey site number	Site name	Sample date (m/d/y)	Sample time (MT)	Dominant flow component	Streamflow, instantaneous (ft³/s)	pH, water, unfiltered, laboratory (standard units)	Specific conductance, water, unfiltered, laboratory (µS/cm at 25°C)	Specific conductance, water, field, unfiltered (µS/cm at 25°C)	Temperature, water (°C)	Hardness, water (mg/L as $CaCO_3$)	Calcium, water, filtered (mg/L)
Muddy Creek water-quality monitoring sites												
MCm1	09332100	Muddy Creek below I-70, near Emery	04/22/04	11:45	baseflow	35	8	1,590	1,670	4.5	520	100
MCm1	09332100	Muddy Creek below I-70, near Emery	07/15/04	12:20	baseflow	7.7	7.5	1,370	1,370	22.2	560	104
MCm1	09332100	Muddy Creek below I-70, near Emery	09/07/04	10:10	baseflow	7.2	—	—	1,160	12.4	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	10/13/04	13:00	baseflow	9.6	7.9	1,620	1,660	12.5	540	92
MCm1	09332100	Muddy Creek below I-70, near Emery	11/10/04	11:45	direct runoff	23	8	2,120	2,200	5.2	630	119
MCm1	09332100	Muddy Creek below I-70, near Emery	12/15/04	09:40	baseflow	16	—	—	1,590	1	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	01/31/05	10:30	baseflow	19	8.2	1,830	—	0	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	03/07/05	10:10	baseflow	23	—	—	1,810	—	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	03/15/05	15:20	baseflow	20	8.1	1,600	1,590	7.6	650	116
MCm1	09332100	Muddy Creek below I-70, near Emery	04/04/05	10:15	baseflow	35	—	—	1,340	—	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	04/27/05	08:55	baseflow	27	—	—	2,170	8.8	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	05/17/05	13:50	snowmelt	125	7.9	566	596	11.6	240	55
MCm1	09332100	Muddy Creek below I-70, near Emery	05/25/05	14:00	snowmelt	239	—	—	614	15.1	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	06/28/05	11:30	snowmelt	138	—	—	718	13.9	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	08/03/05	13:20	baseflow	9.9	—	—	2,500	23.6	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	08/04/05	16:25	baseflow	4.4	—	—	1,840	25.4	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	09/06/05	10:15	baseflow	2.7	—	—	2,970	15.5	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	09/13/05	15:15	baseflow	4.9	7.9	2,770	2,870	20.4	770	114
MCm1	09332100	Muddy Creek below I-70, near Emery	10/11/05	11:25	baseflow	8.5	—	—	2,230	7.6	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	10/24/05	16:15	baseflow	12	8.2	1,740	1,820	12.7	630	107
MCm1	09332100	Muddy Creek below I-70, near Emery	11/29/05	13:00	baseflow	8.8	8	1,990	2,100	0	730	128
MCm1	09332100	Muddy Creek below I-70, near Emery	01/04/06	11:50	baseflow	17	8.1	1,910	1,970	0.6	640	112
MCm1	09332100	Muddy Creek below I-70, near Emery	03/10/06	09:05	baseflow	20	8.1	1,580	1,600	0	560	100
MCm1	09332100	Muddy Creek below I-70, near Emery	04/14/06	10:40	snowmelt	68	7.6	1,160	1,100	9.5	380	80
MCm1	09332100	Muddy Creek below I-70, near Emery	05/11/06	14:20	snowmelt	84	—	—	792	11.9	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	05/31/06	11:20	snowmelt	88	—	—	790	11.3	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	06/22/06	17:30	baseflow	25	—	—	1,250	24.2	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	08/04/06	10:00	baseflow	7	—	—	2,070	17.4	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	08/16/06	21:00	direct runoff	308	—	—	2,350	—	—	—
MCm1	09332100	Muddy Creek below I-70, near Emery	08/25/06	13:30	baseflow	16	—	—	1,640	20.5	—	—

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

[°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identifier	U.S. Geological Survey site number	Site name	Sample date (m/d/y)	Sample time (MT)	Dominant flow component	Streamflow, instantaneous (ft³/s)	pH, water, unfiltered, laboratory (standard units)	Specific conductance, water, unfiltered, laboratory (µS/cm at 25°C)	Specific conductance, water, field, unfiltered (µS/cm at 25°C)	Temperature, water (°C)	Hardness, water (mg/L as $CaCO_3$)	Calcium, water, filtered (mg/L)
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	03/16/05	15:30	baseflow	25	8	2,450	2,390	9.4	700	136
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	04/08/05	11:30	baseflow	32	8	1,640	1,750	9.2	550	105
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	05/04/05	16:25	baseflow	19	8.1	2,800	2,930	19.8	770	135
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	07/08/05	11:30	direct runoff	39	8.1	1,530	1,580	18.4	470	98
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	08/04/05	15:05	direct runoff	7.6	7.8	4,330	4,460	25.8	1,000	218
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	09/14/05	11:00	baseflow	4.1	7.8	4,000	4,150	12.6	1,300	395
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	10/25/05	10:20	baseflow	13	8.1	2,760	2,860	9.8	830	184
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	01/04/06	16:00	baseflow	31	8	2,030	2,080	0	650	125
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	03/09/06	15:50	baseflow	19	8	2,250	2,310	7	720	136
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	04/13/06	16:00	baseflow	28	—	—	1,740	18.5	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	05/30/06	15:20	snowmelt	111	—	—	820	16.4	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	06/23/06	09:30	snowmelt	23	—	—	2,210	17.5	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	08/03/06	17:50	baseflow	8	—	—	3,440	25.5	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	08/17/06	05:40	direct runoff	209	—	—	3,230	—	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	08/24/06	19:15	direct runoff	10	—	—	3,280	22.7	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	04/21/04	13:15	baseflow	13	8	3,650	3,820	15.9	890	210
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:10	direct runoff	—	—	—	—	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:15	direct runoff	—	—	—	—	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:20	direct runoff	E730	—	—	—	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:25	direct runoff	—	—	—	—	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:30	direct runoff	—	7.2	6,260	5,640	—	2,000	619
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:40	direct runoff	—	—	—	—	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	11:50	direct runoff	—	—	—	4,720	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	12:20	direct runoff	—	—	—	4,180	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	12:55	direct runoff	—	—	—	3,690	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	14:00	direct runoff	E416	—	—	3,140	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	15:00	direct runoff	—	7.3	3,180	3,010	—	1,300	446

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identifier	U.S. Geological Survey site number	Site name	Sample date (m/d/y)	Sample time (MT)	Dominant flow component	Streamflow, instantaneous (ft³/s)	pH, water, unfiltered, laboratory (standard units)	Specific conductance, water, unfiltered, laboratory (µS/cm at 25°C)	Specific conductance, water, field, unfiltered (µS/cm at 25°C)	Temperature, water (°C)	Hardness, water (mg/L as $CaCO_3$)	Calcium, water, filtered (mg/L)
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	16:00	direct runoff	E365	—	—	2,950	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	17:30	direct runoff	E268	—	—	2,890	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/04	20:00	direct runoff	E190	—	—	2,900	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/19/04	08:55	direct runoff	E36	—	—	3,220	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	10/15/04	11:15	baseflow	5.1	7.9	4,850	5,040	14	1,000	252
MCm3	09332800	Muddy Creek at mouth, near Hanksville	11/10/04	09:25	direct runoff	E700	—	—	2,110	5.2	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	11/17/04	14:35	baseflow	23	7.8	3,800	3,890	9.7	1,000	297
MCm3	09332800	Muddy Creek at mouth, near Hanksville	02/01/05	13:00	baseflow	59	8.2	2,780	2,860	4	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	03/17/05	15:00	baseflow	29	7.9	3,510	3,490	13.6	870	210
MCm3	09332800	Muddy Creek at mouth, near Hanksville	04/07/05	10:20	baseflow	26	7.9	3,090	3,180	9.5	790	172
MCm3	09332800	Muddy Creek at mouth, near Hanksville	04/28/05	10:30	baseflow	23	—	—	3,130	11	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	05/12/05	10:00	snowmelt	43	7.9	2,140	2,220	11.2	560	121
MCm3	09332800	Muddy Creek at mouth, near Hanksville	05/19/05	08:35	snowmelt	102	—	—	1,220	15.1	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	05/25/05	07:30	snowmelt	178	7.9	962	980	—	380	100
MCm3	09332800	Muddy Creek at mouth, near Hanksville	06/16/05	08:30	snowmelt	136	8	1,140	1,250	18.9	420	99
MCm3	09332800	Muddy Creek at mouth, near Hanksville	07/18/05	09:00	baseflow	6.3	7.8	4,270	4,400	19.5	1,200	301
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/03/05	17:20	direct runoff	78	—	—	3,360	26.3	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/12/05	10:05	direct runoff	88	7.3	2,870	2,840	20.9	1,600	586
MCm3	09332800	Muddy Creek at mouth, near Hanksville	09/12/05	10:00	baseflow	16	7.3	4,200	4,320	16	1,500	537
MCm3	09332800	Muddy Creek at mouth, near Hanksville	10/17/05	10:00	baseflow	7.5	6.9	5,240	5,380	10.5	1,300	361
MCm3	09332800	Muddy Creek at mouth, near Hanksville	10/19/05	10:00	direct runoff	E1,080	7.2	2,940	2,860	11	1,500	525
MCm3	09332800	Muddy Creek at mouth, near Hanksville	10/19/05	11:00	direct runoff	E973	—	—	2,930	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	11/17/05	10:00	baseflow	20	7.7	3,810	3,830	2.5	980	256
MCm3	09332800	Muddy Creek at mouth, near Hanksville	01/05/06	11:20	baseflow	20	7.9	3,070	3,170	0	820	196
MCm3	09332800	Muddy Creek at mouth, near Hanksville	03/09/06	11:15	baseflow	20	8	3,340	3,380	7	840	190
MCm3	09332800	Muddy Creek at mouth, near Hanksville	03/14/06	11:45	baseflow	16	—	—	3,660	7.3	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	04/13/06	11:40	baseflow	37	—	—	2,510	14	—	—

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft^3/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identi-fier	U.S. Geological Survey site number	Site name	Sample date (m/d/y)	Sample time (MT)	Dominant flow com-ponent	Stream-flow, instant-aneous (ft^3/s)	pH, water, unfiltered, laboratory (standard units)	Specific conduct-ance, water, unfiltered, labora-tory (µS/cm at 25°C)	Specific conduct-ance, water, field, unfiltered (µS/cm at 25°C)	Temper-ature, water (°C)	Hard-ness, water (mg/L as $CaCO_3$)	Calcium, water, filtered (mg/L)
MCm3	09332800	Muddy Creek at mouth, near Hanksville	05/04/06	09:30	snowmelt	106	—	—	1,780	14	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	05/29/06	16:10	snowmelt	120	—	—	1,050	20.3	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	06/27/06	10:45	baseflow	11	—	—	3,000	20.5	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	07/13/06	08:50	baseflow	20	—	—	4,490	17.9	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/01/06	17:00	direct runoff	462	—	—	4,400	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/03/06	11:50	baseflow	17	—	—	4,150	22.3	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	19:00	direct runoff	—	—	—	3,740	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	19:30	direct runoff	—	—	—	3,280	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	21:00	direct runoff	—	—	—	4,330	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	21:30	direct runoff	—	—	—	3,960	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	22:00	direct runoff	—	—	—	3,940	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	22:30	direct runoff	—	—	—	4,090	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/16/06	23:00	direct runoff	—	—	—	4,240	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/18/06	08:45	direct runoff	56	—	—	3,400	19.5	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/24/06	14:25	direct runoff	15	7.2	3,160	3,110	26.4	1,400	491
MCm3	09332800	Muddy Creek at mouth, near Hanksville	09/06/06	09:45	baseflow	1.5	—	—	6,370	20.5	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	10/18/06	12:30	direct runoff	—	—	—	3,020	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	10/23/06	14:40	baseflow	—	—	—	5,600	—	—	—
		Quality-assurance samples										
MCm1	09332100	Muddy Creek below I-70, near Emery	04/14/06	10:30	NA	—	6.2	8	—	—	—	<.02
MCm1	09332100	Muddy Creek below I-70, near Emery	08/25/06	13:20	NA	—	—	<3	—	—	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	09/14/05	11:01	NA	—	9	3	—	—	—	<.02
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	03/09/06	15:55	baseflow	—	—	—	—	—	—	—
MCm2	09332600	Muddy Creek at Tomsich Butte, near Hanksville	08/03/06	17:51	baseflow	8	—	—	3,470	—	—	—
MCm3	09332800	Muddy Creek at mouth, near Hanksville	08/24/06	14:10	NA	—	7.5	3	—	—	—	<.02
		Miscellaneous water-quality sites										
MC1	385145111121701	Muddy Creek below Miller Canyon, near Emery	07/12/06	13:00	baseflow	E2.5	—	—	2,770	—	—	—
MC1	385145111121701	Muddy Creek below Miller Canyon, near Emery	08/04/06	11:40	baseflow	—	—	—	3,714	—	—	—
IC	384849111121301	Ivie Creek at mouth, near Emery	07/12/06	13:20	baseflow	E6	—	—	1,650	—	—	—
IC	384849111121301	Ivie Creek at mouth, near Emery	08/04/06	11:30	baseflow	—	—	—	1,820	—	—	—
MCs1	384553111073301	Muddy Creek at Lone Tree Crossing	03/16/05	09:50	baseflow	19	—	—	1,620	2.6	—	—

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft^3/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identifier	U.S. Geological Survey site number	Site name	Sample date (m/d/y)	Sample time (MT)	Dominant flow component	Streamflow, instantaneous (ft^3/s)	pH, water, unfiltered, laboratory (standard units)	Specific conductance, water, unfiltered, laboratory (µS/cm at 25°C)	Specific conductance, water, field, unfiltered (µS/cm at 25°C)	Temperature, water (°C)	Hardness, water (mg/L as $CaCO_3$)	Calcium, water, filtered (mg/L)
MCs1	384553111073301	Muddy Creek at Lone Tree Crossing	04/06/05	11:15	baseflow	19	8.1	1,440	1,540	6.1	530	100
SSW1	384752111060301	South Salt Wash at first road crossing, near Emery	03/15/05	17:50	baseflow	E.2	—	—	15,900	—	—	—
SSW2	384714111062201	South Salt Wash at second road crossing, near Emery	03/15/05	12:55	baseflow	E.2	—	—	30,100	—	—	—
SSW3	384615111063801	South Salt Wash at mouth, at Muddy Creek	03/16/05	12:00	baseflow	0.11	7.9	E37,800	37,600	16.5	3,600	958
SSW3	384615111063801	South Salt Wash at mouth, at Muddy Creek	05/11/06	17:35	baseflow	0.04	—	—	44,600	—	—	—
MCs2	384545111060801	Muddy Creek below South Salt Wash, near Emery	04/06/05	13:30	baseflow	18	8.1	1,510	1,600	9.4	540	103
MCs2	384545111060801	Muddy Creek below South Salt Wash, near Emery	05/11/06	17:30	snowmelt	—	—	—	804	—	—	—
MCs3	384448111055101	Muddy Creek above Cat Canyon, near Emery	04/06/05	15:00	baseflow	17	8.1	1,830	1,950	12.8	580	114
MCs4	384338111050101	Muddy Creek below Cat Canyon, near Emery	04/07/05	10:50	baseflow	21	8	1,660	1,800	8.2	540	104
MCs5	384245111040701	Muddy Creek above Willow Springs Wash, near Emery	04/07/05	12:55	baseflow	23	8	1,740	1,870	10.9	550	107
MCs6	384200111022001	Muddy Creek below Willow Springs Wash, near Emery	04/08/05	11:45	baseflow	30	8	1,600	1,700	9.9	510	101
LGC	384217111020801	Little Gem Canyon, near Hanksville	10/08/05	11:30	baseflow	<.01	—	—	1,130	—	—	—
PC	384202111012701	Poor Canyon, near Hanksville	10/08/05	10:00	baseflow	<.01	—	—	1,910	—	—	—
CS	382820111004001	Caine Springs, near Hanksville	01/24/06	11:40	baseflow	E.50	8	9,490	9,210	7	1,200	339
SW1	382816111000501	Salt Wash below Caine Springs, near Hanksville	01/24/06	10:40	baseflow	2	7.8	9,710	9,390	10	1,300	370
SW2	382824110590201	Salt Wash at Bedrock Falls, near Hanksville	01/23/06	16:00	baseflow	E1.5	—	—	9,060	—	—	—
SW3	382958110564201	Salt Wash at County Line, near Hanksville	05/18/05	15:15	baseflow	2.1	—	—	10,600	30	—	—
SW3	382958110564201	Salt Wash at County Line, near Hanksville	07/07/05	12:05	baseflow	1.9	—	—	10,300	30	—	—
SW3	382958110564201	Salt Wash at County Line, near Hanksville	08/04/05	07:50	baseflow	2.9	—	—	7,160	17.7	—	—
SW3	382958110564201	Salt Wash at County Line, near Hanksville	09/14/05	16:00	baseflow	2.5	8.2	10,100	10,300	28.5	1,500	424
SW3	382958110564201	Salt Wash at County Line, near Hanksville	10/25/05	15:20	baseflow	2.2	—	—	10,100	21.8	—	—
SW4	383108110561001	Salt Wash at mouth, at Muddy Creek	03/17/05	11:00	baseflow	2.6	7.7	10,200	9,800	11.5	1,600	457
MCs7	383147110541201	Muddy Creek 2 miles below Salt Wash	03/17/05	12:45	baseflow	29	7.9	3,360	3,260	11.2	780	165
CC2	383615111002401	Chimney Canyon, near Hanksville	10/10/05	09:50	baseflow	E.01	—	—	4,620	—	—	—
CC1	383649111011601	North Fork of Chimney Canyon, near Hanksville	10/10/05	07:16	baseflow	<.01	—	—	3,910	—	—	—

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identifier	Sample date	Magnesium, water, filtered (mg/L)	Potassium, water, filtered (mg/L)	Sodium, water, filtered (mg/L)	Alkalinity, water, filtered, incremental titration, lab (mg/L)	Chloride, water, filtered (mg/L)	Fluoride, water, filtered (mg/L)	Silica, water, filtered (mg/L)	Sulfate, water, filtered (mg/L)	Solids, dissolved, sum of constituents, water, filtered, (mg/L)	Ratio of solids, dissolved, sum of constituents and solids, dissolved, ROE	Solids, dissolved, ROE, water, filtered (mg/L)	Ratio of solids, dissolved, ROE and specific conductance, field
Muddy Creek water-quality monitoring sites													
MCm1	04/22/04	67	4.9	193	211	34	—	5.4	620	1,150	0.93	1,240	0.74
MCm1	07/15/04	72	7.5	117	—	27	—	6.0	497	—	—	1,050	0.77
MCm1	09/07/04	—	—	—	—	—	—	—	—	—	—	787	0.68
MCm1	10/13/04	75	6.0	187	269	32	0.5	8.4	572	1,130	0.97	1,170	0.70
MCm1	11/10/04	82	6.7	291	254	40	0.4	7.8	897	1,600	0.95	1,680	0.76
MCm1	12/15/04	—	—	—	—	—	—	—	—	—	—	1,160	0.73
MCm1	01/31/05	—	—	—	—	33	0.5	—	723	—	—	1,420	—
MCm1	03/07/05	—	—	—	—	—	—	—	—	—	—	1,350	0.75
MCm1	03/15/05	88	4.1	169	286	37	0.4	8.8	582	—	—	1,230	0.77
MCm1	04/04/05	—	—	—	—	—	—	—	—	—	—	872	0.65
MCm1	04/27/05	—	—	—	—	—	—	—	—	—	—	1,650	0.76
MCm1	05/17/05	25	3.0	38	156	9.1	0.3	11	134	—	—	385	0.65
MCm1	05/25/05	—	—	—	—	—	—	—	—	—	—	405	0.66
MCm1	06/28/05	—	—	—	—	—	—	—	—	—	—	465	0.65
MCm1	08/03/05	—	—	—	—	46	—	—	1,150	—	—	2,040	0.82
MCm1	08/04/05	—	—	—	—	—	—	—	—	—	—	1,490	0.81
MCm1	09/06/05	—	—	—	—	—	—	—	—	—	—	2,360	0.79
MCm1	09/13/05	118	6.5	365	286	53	0.5	7.9	1,240	2,080	1.0	2,270	0.79
MCm1	10/11/05	—	—	—	—	—	—	—	—	—	—	1,690	0.76
MCm1	10/24/05	89	4.8	193	248	34	0.4	8.1	674	1,260	0.93	1,360	0.75
MCm1	11/29/05	99	5.0	224	267	36	0.4	9.4	796	1,460	0.91	1,610	0.77
MCm1	01/04/06	87	3.8	215	293	33	0.4	8.6	742	1,380	0.92	1,500	0.76
MCm1	03/10/06	76	3.7	165	253	30	0.4	7.0	576	1,110	0.92	1,200	0.75
MCm1	04/14/06	45	3.7	106	222	17	0.4	5.6	330	719	0.94	765	0.70
MCm1	05/11/06	—	—	—	—	—	—	—	—	—	—	530	0.67
MCm1	05/31/06	—	—	—	—	9	—	—	190	—	—	535	0.68
MCm1	06/22/06	—	—	—	—	17	—	—	392	—	—	870	0.70
MCm1	08/04/06	—	—	—	—	40	—	—	781	—	—	1,540	0.74
MCm1	08/16/06	—	—	—	—	—	—	—	—	—	—	2,250	0.96
MCm1	08/25/06	—	—	—	—	31	—	—	618	—	—	1,260	0.77

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identi-fier	Sample date	Magne-sium, water, filtered (mg/L)	Potas-sium, water, filtered (mg/L)	Sodium, water, filtered (mg/L)	Alkalinity, water, filtered, incremental titration, lab (mg/L)	Chloride, water, filtered (mg/L)	Fluoride, water, filtered (mg/L)	Silica, water, filtered (mg/L)	Sulfate, water, filtered (mg/L)	Solids, dissolved, sum of consti-tuents, water, filtered, (mg/L)	Ratio of solids, dissolved, sum of consti-tuents and solids, dissolved, ROE	Solids, dissolved, ROE, water, filtered (mg/L)	Ratio of solids, dissolved, ROE and specific conduct-ance, field
MCm2	03/16/05	87.7	4.79	308	261	252	0.4	8.82	689	1,640	0.94	1,750	0.73
MCm2	04/08/05	69	4.5	202	242	92	0.4	8.2	542	1,170	0.95	1,230	0.70
MCm2	05/04/05	104	6.3	417	243	283	0.5	8.6	909	2,010	0.96	2,100	0.72
MCm2	07/08/05	56	3.2	171	193	124	0.3	7.1	434	1,010	0.94	1,070	0.68
MCm2	08/04/05	112	8.1	640	178	696	0.4	8.1	1,210	3,000	0.92	3,260	0.73
MCm2	09/14/05	84	11	502	169	404	0.4	11	1,660	3,170	0.93	3,400	0.82
MCm2	10/25/05	91	5.9	334	220	228	0.4	9.6	1,010	1,990	0.91	2,190	0.76
MCm2	01/04/06	82	4.5	227	249	132	0.4	8.6	677	1,410	0.91	1,550	0.75
MCm2	03/09/06	92	5.3	283	245	166	0.5	8.2	748	1,590	0.93	1,710	0.74
MCm2	04/13/06	—	—	—	—	115	—	—	518	—	—	1,230	0.71
MCm2	05/12/06	—	—	—	—	—	—	—	—	—	—	652	0.66
MCm2	05/30/06	—	—	—	—	33	—	—	171	—	—	525	0.64
MCm2	06/23/06	—	—	—	—	199	—	—	635	—	—	1,560	0.71
MCm2	08/03/06	—	—	—	—	246	—	—	1,490	—	—	2,910	0.85
MCm2	08/17/06	—	—	—	—	91	—	—	1,680	—	—	3,070	0.95
MCm2	08/24/06	—	—	—	—	199	—	—	1,330	—	—	2,630	0.80
MCm3	04/21/04	89	7.1	518	163	615	—	9.6	961	2,510	0.94	2,670	0.70
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	5,950	—
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	5,690	—
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	5,450	—
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	5,260	—
MCm3	08/18/04	99	20	871	170	1,090	0.4	14	2,070	4,890	0.96	5,090	0.90
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	4,700	—
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	4,390	0.93
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	3,960	0.95
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	3,440	0.93
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	3,050	0.97
MCm3	08/18/04	51	13	320	90	146	0.4	12	1,680	2,720	0.97	2,810	0.93
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	2,820	0.96
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	2,640	0.91
MCm3	08/18/04	—	—	—	—	—	—	—	—	—	—	2,600	0.90

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft^3/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identifier	Sample date	Magnesium, water, filtered (mg/L)	Potassium, water, filtered (mg/L)	Sodium, water, filtered (mg/L)	Alkalinity, water, filtered, incremental titration, lab (mg/L)	Chloride, water, filtered (mg/L)	Fluoride, water, filtered (mg/L)	Silica, water, filtered (mg/L)	Sulfate, water, filtered (mg/L)	Solids, dissolved, sum of constituents, water, filtered, (mg/L)	Ratio of solids, dissolved, sum of constituents and solids, dissolved, ROE	Solids, dissolved, ROE, water, filtered (mg/L)	Ratio of solids, dissolved, ROE and specific conductance, field
MCm3	08/19/04	—	—	—	—	—	—	—	—	—	—	2,800	0.87
MCm3	10/15/04	93	10	729	141	930	0.4	10	1,140	3,250	0.94	3,440	0.68
MCm3	11/10/04	—	—	—	—	—	—	—	—	—	—	1,660	0.79
MCm3	11/17/04	63	6.7	540	172	556	0.5	10	1,140	2,720	0.97	2,810	0.72
MCm3	02/01/05	—	—	—	—	363	0.5	—	773	—	—	2,000	0.70
MCm3	03/17/05	85	6.2	482	194	572	0.4	9.6	863	2,340	0.96	2,430	0.70
MCm3	04/07/05	88	6.1	446	174	457	0.4	8.7	813	2,100	0.94	2,220	0.70
MCm3	04/28/05	—	—	—	—	—	—	—	—	—	—	2,160	0.69
MCm3	05/12/05	62	5.6	277	195	260	0.4	8.2	568	1,420	0.92	1,540	0.69
MCm3	05/19/05	—	—	—	—	100	—	—	327	—	—	832	0.68
MCm3	05/25/05	31	3.4	70.2	174	60	0.3	9.5	236	614	0.93	661	0.67
MCm3	06/16/05	43	3.1	110	186	100	0.3	8.1	304	778	0.94	831	0.66
MCm3	07/18/05	103	8.5	566	—	701	0.3	11	1,230	—	—	3,220	0.73
MCm3	08/03/05	—	—	—	—	215	—	—	1,890	—	—	3,320	0.99
MCm3	08/12/05	38	13	160	83	76	0.3	12	1,640	2,580	0.94	2,750	0.97
MCm3	09/12/05	50	12	454	68	383	0.4	9.7	1,970	3,460	0.93	3,730	0.86
MCm3	10/17/05	105	9.3	704	129	922	0.4	11	1,540	3,730	0.93	3,990	0.74
MCm3	10/19/05	37	12	174	61	111	0.3	6.0	1,580	2,480	1.0	2,430	0.85
MCm3	10/19/05	—	—	—	—	137	—	—	1,560	—	—	2,460	0.84
MCm3	11/17/05	83	6.7	448	176	564	0.4	9.0	1,100	2,570	0.91	2,820	0.74
MCm3	01/05/06	81	5.0	373	200	436	0.4	8.7	854	2,070	0.93	2,230	0.70
MCm3	03/09/06	89	6.0	459	182	486	0.5	8.6	902	2,250	1.0	2,230	0.66
MCm3	03/14/06	—	—	—	—	498	—	—	1,000	—	—	2,570	0.70
MCm3	04/13/06	—	—	—	—	331	—	—	636	—	—	1,730	0.69
MCm3	05/04/06	—	—	—	—	—	—	—	—	—	—	1,160	0.65
MCm3	05/29/06	—	—	—	—	87	—	—	231	—	—	697	0.66
MCm3	06/27/06	—	—	—	—	—	—	—	—	—	—	2,440	0.81
MCm3	07/13/06	—	—	—	—	—	—	—	—	—	—	3,830	0.85
MCm3	08/01/06	—	—	—	—	367	—	—	2,080	—	—	3,950	0.90
MCm3	08/03/06	—	—	—	—	373	—	—	1,920	—	—	3,730	0.90
MCm3	08/16/06	—	—	—	—	154	—	—	1,990	—	—	3,420	0.91

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identi-fier	Sample date	Magne-sium, water, filtered (mg/L)	Potas-sium, water, filtered (mg/L)	Sodium, water, filtered (mg/L)	Alkalinity, water, filtered, incremental titration, lab (mg/L)	Chloride, water, filtered (mg/L)	Fluoride, water, filtered (mg/L)	Silica, water, filtered (mg/L)	Sulfate, water, filtered (mg/L)	Solids, dissolved, sum of consti-tuents, water, filtered, (mg/L)	Ratio of solids, dissolved, sum of consti-tuents and solids, dissolved, ROE	Solids, dissolved, ROE, water, filtered (mg/L)	Ratio of solids, dissolved, ROE and specific conduct-ance, field
MCm3	08/16/06	—	—	—	—	—	—	—	—	—	—	2,980	0.91
MCm3	08/16/06	—	—	—	—	332	—	—	1,950	—	—	3,680	0.85
MCm3	08/16/06	—	—	—	—	—	—	—	—	—	—	3,450	0.87
MCm3	08/16/06	—	—	—	—	—	—	—	—	—	—	3,480	0.88
MCm3	08/16/06	—	—	—	—	—	—	—	—	—	—	3,560	0.87
MCm3	08/16/06	—	—	—	—	235	—	—	2,050	—	—	3,640	0.86
MCm3	08/18/06	—	—	—	—	—	—	—	—	—	—	3,470	1.00
MCm3	08/24/06	51	13.2	194	100.2	189	0.3	7.7	1,530	2,540	0.90	2,810	0.90
MCm3	09/06/06	—	—	—	—	1,040	—	—	1,970	—	—	4,920	0.77
MCm3	10/18/06	—	—	—	—	121	—	—	1,470	—	—	2,590	0.86
MCm3	10/23/06	—	—	—	—	764	—	—	1,840	—	—	4,280	0.76
Quality-assurance samples													
MCm1	04/14/06	<.008	<.16	<.20	<1	<.20	<.1	<.04	<.2	—	—	<10	—
MCm1	08/25/06	—	—	—	—	<.20	—	—	<.2	—	—	<10	—
MCm2	09/14/05	<.008	<.16	<.20	3	<.20	<.1	<.04	<.2	—	—	<10	—
MCm2	03/09/06	—	—	—	—	—	—	—	—	—	—	1,690	—
MCm2	08/03/06	—	—	—	—	250	—	—	1,500	—	—	2,920	0.84
MCm3	08/24/06	<.008	<.16	<.20	<1	<.20	<.1	<.04	<.2	—	—	<10	—
Miscellaneous water-quality sites													
MC1	07/12/06	—	—	—	—	—	—	—	—	—	—	—	—
MC1	08/04/06	—	—	—	—	—	—	—	—	—	—	—	—
IC	07/12/06	—	—	—	—	—	—	—	—	—	—	—	—
IC	08/04/06	—	—	—	—	—	—	—	—	—	—	—	—
MCs1	03/16/05	—	—	—	—	—	—	—	—	—	—	—	—
MCs1	04/06/05	68	3.9	160	274	33	0.4	8.3	505	1,040	0.96	1,090	0.71
SSW3	03/15/05	—	—	—	—	—	—	—	—	—	—	—	—
SSW2	03/15/05	—	—	—	—	—	—	—	—	—	—	—	—
SSW1	03/16/05	291	27	8,350	146	12,100	0.6	12	4,020	25,800	0.96	27,000	0.72
SSW1	05/11/06	—	—	—	—	—	—	—	—	—	—	—	—
MCs2	04/06/05	69	4.1	173	268	51	0.5	8.3	518	1,090	0.97	1,120	0.70

Table 2. Discharge, properties, major-ion concentration, and residue on evaporation of water samples collected from select water-quality monitoring sites in the Muddy Creek Basin, 2004–06—Continued.

°C, degrees Celsius; E, estimated; ft³/s, cubic feet per second; m/d/y, month/day/year; mg/L, milligrams per liter; MT, mountain time; NA, not applicable; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter; —, no data; <, less than]

Site identi-fier	Sample date	Magne-sium, water, filtered (mg/L)	Potas-sium, water, filtered (mg/L)	Sodium, water, filtered (mg/L)	Alkalinity, water, filtered, incremental titration, lab (mg/L)	Chloride, water, filtered (mg/L)	Fluoride, water, filtered (mg/L)	Silica, water, filtered (mg/L)	Sulfate, water, filtered (mg/L)	Solids, dissolved, sum of consti-tuents, water, filtered, (mg/L)	Ratio of solids, dissolved, sum of consti-tuents and solids, dissolved, ROE	Solids, dissolved, ROE, water, filtered (mg/L)	Ratio of solids, dissolved, ROE and specific conduct-ance, field
MCs2	05/11/06	—	—	—	—	—	—	—	—	—	—	—	—
MCs3	04/06/05	72	4.3	233	270	140	0.4	8.3	549	1,280	0.96	1,340	0.69
MCs4	04/07/05	69	3.9	206	249	126	0.4	8.1	517	1,180	0.95	1,250	0.69
MCs5	04/07/05	70	4.1	219	248	132	0.4	8.2	544	1,230	0.93	1,320	0.71
MCs6	04/08/05	62	4.2	195	230	97	0.4	7.4	512	1,120	0.96	1,160	0.68
LGC	10/08/05	—	—	—	—	—	—	—	—	—	—	—	—
PC	10/08/05	—	—	—	—	—	—	—	—	—	—	—	—
CS	01/24/06	82	9.2	1,560	164	2,420	0.5	12	1,000	5,520	0.96	5,740	0.62
SW1	01/24/06	87	9.2	1,540	166	2,450	0.5	12	1,150	5,720	0.95	6,000	0.64
SW2	01/23/06	—	—	—	—	—	—	—	—	—	—	—	—
SW3	05/18/05	—	—	—	—	—	—	—	—	—	—	—	—
SW3	07/07/05	—	—	—	—	—	—	—	—	—	—	—	—
SW3	08/04/05	—	—	—	—	1,620	—	—	1,390	—	—	4,940	—
SW3	09/14/05	103	12	1,690	—	2,790	0.4	13	1,370	—	—	6,780	0.66
SW3	10/25/05	—	—	—	—	2,680	—	—	1,360	—	—	6,550	—
SW4	03/17/05	110	11	1,710	153	2,630	0.5	13	1,290	6,310	0.98	6,470	0.66
MCs7	03/17/05	90	5.5	457	216	523	0.4	9.1	773	2,150	0.93	2,310	0.71
CC2	10/10/05	—	—	—	—	—	—	—	—	—	—	—	—
CC1	10/10/05	—	—	—	—	—	—	—	—	—	—	—	—

Table 3. Field and analytical methods and minimum reporting levels for water-quality field measurements and constituent concentrations in samples collected from water-quality monitoring sites in the Muddy Creek Basin, Utah.

[°C, degrees Celsius; ft^3/s, cubic feet per second; IC, ion chromatography; ICP, inductively coupled plasma; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; —, not applicable]

Measurement or constituent	Unit	Field method	Analytical method	Minimum reporting level
Physical Properties				
Discharge, instantaneous	ft^3/s	Mid-interval	—	Variable
Specific conductance	µS/cm at 25°C	Point	—	1
Water temperature	°C	Point	—	.1
Alkalinity	mg/L	—	Titration	1
Chemical Properties				
pH	standard units	—	Electrometric Electrode	0.1
Calcium, dissolved, as Ca	mg/L	—	ICP	.1
Chloride, dissolved, as Cl	mg/L	—	IC	.1
Fluoride, dissolved, as F	mg/L	—	Ion-selective electrode	.1
Hardness, total, as $CaCO_3$	mg/L	—	Calculated	1
Magnesium, dissolved, as Mg	mg/L	—	ICP	.1
Potassium, dissolved, as K	mg/L	—	ICP	.1
Silica, dissolved, as Si	mg/L	—	ICP	.1
Sodium, dissolved, as Na	mg/L	—	ICP	.1
Sulfate, dissolved, as SO_4	mg/L	—	IC	.1
Solids, dissolved, sum of constituents	mg/L	—	Calculated	1
Solids, dissolved, residue on evaporation (ROE) at 180°C	mg/L	—	Gravimetric	10

There was a significant linear relation among dissolved-solids concentration (from ROE) and specific conductance for most water samples collected from sites MCm1, MCm2, and MCm3. However, samples collected from sites MCm2 and MCm3, when direct runoff from storms was a very large component of flow, did not fit this linear relationship. Consequently, to obtain an estimate of the daily mean dissolved-solids concentration at these sites on the first day of a storm, days of peak storm flow, and the day following the peak if discharge was at least 75 percent of the peak, daily mean specific conductance was multiplied by 0.91. This multiplier was the average ROE/specific conductance ratio from water samples collected when storm flow was the principal component.

At site MCm1, and at sites MCm2 and MCm3 when storm flow was not a principal component, daily mean dissolved-solids concentrations were estimated from daily mean specific conductance using a linear least-squares regression equation determined on the analytical values for dissolved-solids concentration (from ROE, in mg/L) as a function of associated field-measured specific conductance (microsiemens per centimeter) for nonstorm water samples collected between April 2004 and April 2006 (fig. 6). Coefficient of determination (R^2) values for these linear regressions were larger than 0.98 with better than 99 percent confidence. The residuals from predicted values had a fairly constant variance from the regression line for sites MCm1 and MCm3. The residuals from predicted values for site MCm2 had increasing variance with increasing specific conductance, probably because of a lack of data rather than a lack of fit. The residual standard error was 48 mg/L for site MCm1, 115 mg/L for site MCm2, and 80 mg/L for site MCm3.

Dissolved-Solids Load Estimates

The S-PLUS LOAD ESTimator (S-LOADEST) computer program (Dave Lorenz, USGS, written commun., 2005) was used for estimating dissolved-solids loads in Muddy Creek at monitoring sites during periods that had daily mean streamflow values and infrequent measurements of dissolved-solids concentrations with associated values of instantaneous streamflow. The S-LOADEST program is a menu-driven version of the LOADEST FORTRAN program of Runkel and others (2004) and uses measures of constituent concentration and streamflow to develop a regression model for estimating dissolved-solids loads from a time series of streamflow. The formulated regression model (table 4) then is used to estimate daily and annual loads. The calibration and estimation procedure used within S-LOADEST to determine estimated dissolved-solids loads in Muddy Creek is based on the Adjusted Maximum Likelihood Estimation (AMLE) method. Regression methods used to estimate dissolved-solids loads use the natural logarithm (ln) transformed relation between streamflow and concentration (load) to estimate the daily load of the constituent. There are nine predefined models within S-LOADEST, one of which can be selected automatically by the software as the best fit given the calibration data. These nine models contain one or all of the explanatory variables on the right side of the following general equation from Runkel and others (2004):

$$\ln(L) = b_0 + b_1 \ln Q + b_2 \ln Q^2 + b_3\ dtime + b_4\ dtime^2 + b_5 \sin(2\pi dtime) + b_6 \cos(2\pi dtime) \quad (1)$$

Where

L represents the daily constituent load,

b_0 represents the regression constant,

b_1, b_2, b_3, b_4, b_5, and b_6 represent regression coefficients,

Q represents daily streamflow, and

$dtime$ represents decimal time and is used in determinations of annual and seasonal ($2\pi dtime$) variability.

Annual dissolved-solids loads at monitoring sites MC, MCm1, and MCm3 were determined for the period prior to this study in which daily streamflow and intermittent water-quality samples were collected at those sites (part or all of WYs 1976–92). The S-LOADEST program generated regression models (table 4) that were used for these determinations (table 5). Additionally, an S-LOADEST model presented in table 4 was used to determine the annual dissolved-solids loads at site MC for WYs 2005–06.

Daily mean dissolved-solids concentrations were computed from daily mean specific-conductance values for most of WYs 2005–06 for sites MCm1 and MCm3 and for most of WY 2006 for site MCm2, as previously described. These daily mean concentrations were then used to determine a daily dissolved-solids load using the following equation:

$$DS_{load} = DS_{conc} \times Q \times 0.002697 \quad (2)$$

Where

DS_{load} is the daily dissolved-solids load in tons,

DS_{conc} is the daily-mean dissolved-solids concentration in mg/L, and

Q is the daily-mean discharge in ft^3/s.

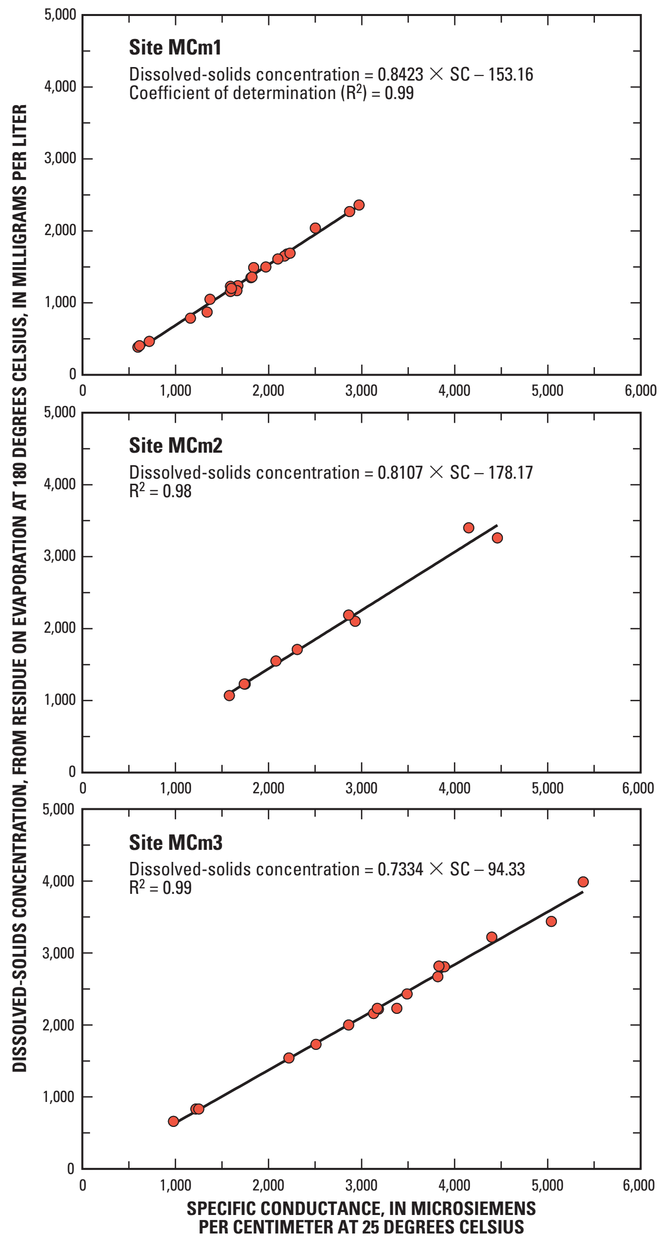

Figure 6. Relation of dissolved-solids concentration from residue on evaporation (ROE) at 180°C to specific conductance (SC) in water samples from water-quality monitoring sites MCm1, MCm2, and MCm3 in the Muddy Creek Basin, Utah.

Table 4. Regression models for estimating dissolved-solids loads at water-quality-monitoring stations in the Muddy Creek Basin, Utah.

[ln, natural logarithm; L, daily load in tons per day; no., number; obs., observations; Q, mean daily streamflow in cubic feet per second; R^2, coefficient of determination; SS, seasonality parameter (2πdectime); T, dectime, time parameter in decimal years; *, asterisk represents the multiplication symbol]

Site identifier	Station name (number)	Dates (water years)	No. of obs.	Regression model	Estimated residual variance[1]	R^2 (percent)
MC	Muddy Creek, near Emery (09330500)	1976–92	165	$\ln(L) = 2.85 + 0.987*\ln Q + 0.0027*T + 0.048*\sin SS + 0.087*\cos SS$	0.011	99
MC	Muddy Creek, near Emery (09330500)	2005–06	24	$\ln(L) = 3.26 + 0.922*\ln Q + 0.0534*\ln Q^2$	0.031	98
MCm1	Muddy Creek below I-70, near Emery (09332100)	1976–85	116	$\ln(L) = 3.75 + 0.618*\ln Q - 0.051*\ln Q^2 + 0.002*T + 0.007*T^2 - 0.031*\sin SS + 0.173*\cos SS$	0.077	93
MCm1	Muddy Creek below I-70, near Emery (09332100)	2005–06	29	$\ln(L) = 4.28 + 0.594*\ln Q + 0.097*\sin SS + 0.165*\cos SS$	0.064	89
MCm2	Muddy Creek at Tomsich Butte, near Hanksville (09332600)	2005	310	$\ln(L) = 3.75 + 0.728*\ln Q -0.071*\ln Q^2 + 0.019*T - 0.212*T^2 + 0.022*\sin SS - 0.056*\cos SS$	0.022	90
MCm3	Muddy Creek at mouth, near Hanksville (09332800)	1976–80	39	$\ln(L) = 4.02 + 0.889*\ln Q - 0.106*T - 0.016*\sin SS + 0.168*\cos SS$	0.114	98
MCm3	Muddy Creek at mouth, near Hanksville (09332800)	2005	248	$\ln(L) = 5.11 + 0.736*\ln Q - 0.012*\ln Q^2 + 0.402*T - 2.28*T^2 - 0.244*\sin SS + 0.129*\cos SS$	0.038	94
MCm3	Muddy Creek at mouth, near Hanksville (09332800)	2006	242	$\ln(L) = 4.77 + 0.853*\ln Q -0.063*\ln Q^2 - 0.122*T - 2.25*T^2 - 0.265*\sin SS - 0.005*\cos SS$	0.035	89

[1]Estimated residual variance is the maximum likelihood estimation variance corrected for the number of observations and number of parameters in the regression model.

Table 5. Estimated annual dissolved-solids loads determined for water-quality monitoring sites MC, MCm1, MCm2, and MCm3, Muddy Creek, Utah.

Year	Estimated annual dissolved-solids load, in tons per year	Lower confidence bound of estimated annual dissolved-solids load, in tons per year	Upper confidence bound of estimated annual dissolved-solids load, in tons per year
Site MC			
1976	4,610	4,450	4,760
1977	2,100	2,020	2,180
1978	7,870	7,600	8,160
1979	10,100	9,800	10,400
1980	12,800	12,400	13,300
1981	5,610	5,480	5,750
1982	10,600	10,200	10,900
1983	18,200	17,400	18,900
1984	17,400	16,700	18,000
1985	14,300	13,900	14,800
1986	10,600	10,300	10,900
1987	6,370	6,200	6,550
1988	5,790	5,600	5,960
1989	3,860	3,740	3,990
1990	3,440	3,310	3,570
1991	6,010	5,770	6,250
1992	5,400	5,170	5,610
2005	17,700	14,300	21,500
2006	12,600	10,300	15,200
Site MCm1			
1976	15,400	14,100	16,900
1977	8,730	8,050	9,450
1978	16,700	15,200	18,300
1979	19,200	17,300	21,200
1980	25,700	22,800	28,700
1981	17,000	15,500	18,500
1982	27,200	25,100	29,500
1983	42,200	38,200	46,500
1984	47,000	42,100	52,200
1985	43,500	37,600	50,000
2005	24,600	17,100	32,600
2006	26,000	18,100	34,500
Site MCm2			
2006	38,200	28,900	48,900
Site MCm3			
1976	32,000	26,200	38,700
1977	11,200	8,700	14,200
1978	58,800	50,900	67,600
1979	69,000	57,600	82,000
1980	142,000	112,000	179,000
2005	93,400	72,700	120,000
2006	72,900	50,300	102,000

At sites MCm1, MCm2, and MCm3, there were 109, 82, and 145 days, respectively, that daily mean specific-conductance values were not computed for WYs 2005–06, and so, for those days, the estimated daily dissolved-solids loads were derived using the S-LOADEST program. For site MCm1, the variables used to calibrate the S-LOADEST model shown in table 4 consisted of dissolved-solids concentrations and streamflow associated with water samples collected from April 2004 to August 2005. For sites MCm2 and MCm3, the variables used to calibrate the S-LOADEST model shown in table 4 consisted of the daily mean dissolved-solids concentrations (determined from specific conductance) and the associated daily mean streamflow. Daily dissolved-solids loads were determined from the S-LOADEST models for all of WYs 2005 and 2006 for sites MCm1 and MCm3 and all of WY 2006 for site MCm2; however, the results from the S-LOADEST models were only considered for those days in which daily dissolved-solids loads had not been previously determined from specific conductance values. The daily dissolved-solids loads were aggregated to determine the annual dissolved-solids load at these sites (table 5).

The total error associated with dissolved-solids loads reported as upper and lower confidence bounds was either (1) the aggregate error associated with the determination of streamflow and specific conductance for those days when dissolved-solids loads were calculated from daily mean specific conductance or (2) the upper and lower 95th percentile confidence bounds determined by the S-LOADEST model (table 5).

Annual yields also were computed from estimated annual loads at sites MC, MCm1, MCm2, and MCm3. These yields (reported as tons/mi^2) were calculated by dividing the annual load (tons) by the drainage area (mi^2) that contributed flow at the location of the monitoring site.

Baseflow Dissolved-Solids Load

The dissolved-solids load in baseflow at monitoring sites MCm1, MCm2, and MCm3 was estimated for WYs 2005 and 2006. Hydrograph separation, which is the process of separating baseflow from other flow components, was done on a time-series plot of Muddy Creek streamflow and then used to quantify the dissolved-solids load in baseflow. The program PART was used to determine baseflow. This automated method of hydrograph separation uses streamflow partitioning to estimate a daily record of baseflow. PART designates baseflow to be equal to streamflow on days that fit a requirement of antecedent recession and then linearly interpolates baseflow for other days (Rutledge, 1998). Results from the PART program were not applicable during periods of snowmelt runoff because antecedent recession conditions were falsely recognized during these periods. For this study, baseflow during snowmelt runoff was determined by linear interpolation from the onset of snowmelt runoff to the approximate cessation of that runoff.

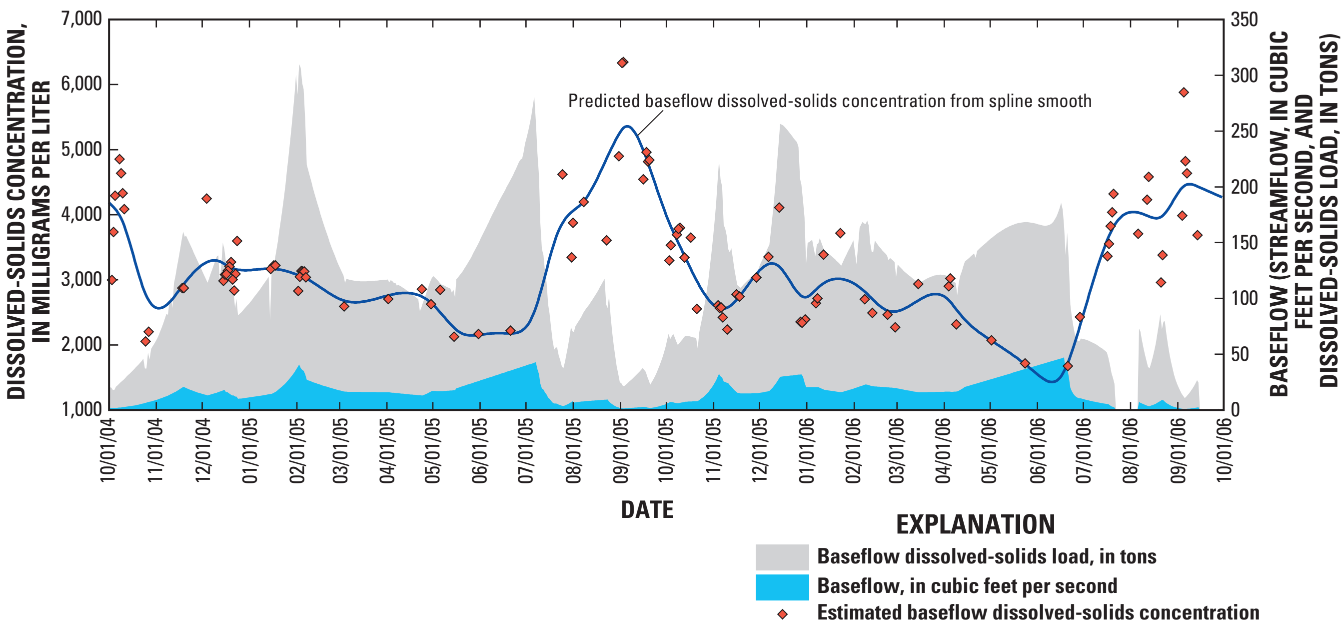

Figure 7. Relation of estimated baseflow dissolved-solids concentration to baseflow and baseflow dissolved-solids load at site MCm3, Muddy Creek, Utah, water years 2005–06.

The concentration of dissolved solids in baseflow was determined using a multiple-step process. A spline smooth was applied to a time series of daily mean dissolved-solids concentrations developed for days when baseflow was within 0.5 ft^3/s of total flow. A predicted dissolved-solids concentration for each day of WYs 2005 and 2006 was determined from that smooth (fig. 7). Baseflow dissolved-solids concentrations for the period of snowmelt runoff were determined by linear interpolation of those values immediately preceding and following this period. Baseflow dissolved-solids loads were determined using equation (2).

Relationship of Precipitation in the Basin to Flow and Dissolved Solids in Muddy Creek

Because a substantial amount of the dissolved solids transported by Muddy Creek are moved to the stream by overland flow and interstitial flow resulting from direct runoff of rainfall, this transport process was examined by documenting the characteristics of storms in the Muddy Creek Basin during WY 2005 and the different responses that were elicited in streamflow and dissolved-solids concentration and load at the mouth of Muddy Creek.

Spatially referenced precipitation data were used to determine the location and estimated magnitude of precipitation that occurred in the Muddy Creek Basin. These data were obtained from the National Centers for Environmental Prediction (NCEP) (National Centers for Environmental Prediction, 2007) and are termed “NCEP Stage IV precipitation analysis.” These estimates of precipitation are a mosaic of estimates from regional analysis that use algorithms that contain precipitation values determined from radar estimates and rain-gage measurements (Lin and Mitchell, 2005). NCEP Stage IV precipitation analyses provide hourly estimates of rainfall on a national 4-km grid, but also 6- and 24-hour aggregates of these estimates. The 24-hour estimates of rainfall were obtained from the NCEP website, then processed and stored. The processed data were imported to a Geographic Information System (GIS) and subsequently analyzed to determine rainfall distribution and total rainfall volume (acre-ft) in the Muddy Creek Basin for each storm. Additional data layers were imported to the GIS to determine the relation of rainfall to the physical and geographic attributes of the basin.

Relations between rainfall and basin attributes were determined for individual storms occurring during October–November or April–September of WY 2005. A storm, as defined for this study, includes consecutive days that each had an area-weighted average precipitation of 0.02 in. or more, provided one of those days had an area-weighted average precipitation of 0.05 in. or more. By using these criteria, 28 events were determined for WY 2005 (table 6). Data from the NCEP stage IV precipitation analysis are total precipitation for a 24-hour period beginning at 6:00 a.m. Mountain Standard Time.

Table 6. Characteristics of runoff resulting from 28 rain events and the basin characteristics associated with the occurrence of precipitation during those events, Muddy Creek Basin, Utah, water year 2005.

[CPMBCT, Colorado Plateau Mixed Bedrock Canyon and Tableland; NLCD, National Land-cover Dataset; SWReGAP, Southwest Regional Gap Analysis Project; °C, degrees Celsius; mg/L, milligrams per liter; nd, no data; µS/cm, microsiemens per centimeter; —, not computed; %, percent; <, less than]

Storm characteristics										
Storm dates	Season	Dominant age of geologic formation where precipitation occurred, Cretaceous or Jurassic	Dominant hydrologic unit where precipitation occurred	Dominant elevation range, in feet, in which precipitation occurred	Amount of precipitation falling on impermeable soils	Amount of precipitation falling on barren land NLCD land cover	Amount of precipitation falling on CPMBCT SWReGAP cover type	Amount of precipitation falling on slopes from 0 to 3 degrees	Estimated total precipitation, acre-feet	Estimated maximum 1 day precipitation, inches
October 1–5	Fall	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	4% or more	25% or more	10,100	0.35
October 18–24	Fall	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	4% or more	<25%	94,600	1.66
October 27–28	Fall	Mixed	Salt Wash	5,950–7,639	45% or more	<19%	4% or more	25% or more	17,800	.47
November 7–9	Fall	Jurassic	Mouth	4,250–5,949	<45%	19% or more	4% or more	25% or more	83,000	.98
November 11–13	Fall	Cretaceous	Headwaters	4,250–5,949	45 % or more	19% or more	<4%	25% or more	16,900	.48
November 20–21	Fall	Jurassic	Salt Wash	4,250–5,949	<45%	19% or more	4% or more	25% or more	26,900	.88
November 25–28	Fall	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	<4%	<25%	47,400	2.08
March 19–21	Spring	Mixed	Mouth	4,250–5,949	<45%	19% or more	<4%	25% or more	19,100	.66
March 23–25	Spring	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	<4%	<25%	16,200	.79
March 28–30	Spring	Mixed	Headwaters	7,640–11,500	45% or more	<19%	<4%	<25%	9,110	.65
April 9–10	Spring	Mixed	Salt Wash	7,640–11,500	<45%	<19%	<4%	<25%	15,100	.75
April 23–24	Spring	Mixed	Salt Wash	7,640–11,500	<45%	19% or more	4% or more	25% or more	23,900	.78
April 30–May 2	Spring	Mixed	Salt Wash	5,950–7,639	45% or more	<19%	4% or more	25% or more	28,900	.63
May 6–7	Spring	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	<4%	<25%	10,200	.57
May 10–11	Spring	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	<4%	<25%	7,370	.53
June 2–3	snowmelt	Cretaceous	Headwaters	5,950–7,639	45% or more	<19%	4% or more	25% or more	122,000	4.37
June11–12	snowmelt	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	4% or more	<25%	19,400	.88
June 22–23	snowmelt	Jurassic	Salt Wash	4,250–5,949	<45%	19% or more	4% or more	25% or more	11,600	.31
July 24–26	Summer	Jurassic	Salt Wash	5,950–7,639	<45%	19% or more	4% or more	25% or more	17,100	.41
August 2–3	Summer	Cretaceous	Salt Wash	5,950–7,639	45% or more	<19%	4% or more	25% or more	16,000	.45
August 5	Summer	Cretaceous	Headwaters	7,640–11,500	45% or more	<19%	4% or more	<25%	5,340	.28
August 7–13	Summer	Mixed	Salt Wash	5,950–7,639	45% or more	<19%	4% or more	25% or more	24,800	.62
August 19	Summer	Jurassic	Salt Wash	4,250–5,949	<45%	19% or more	4% or more	25% or more	6,080	.26
August 23	Summer	Cretaceous	Salt Wash	5,950–7,639	45% or more	<19%	4% or more	25% or more	4,210	.22
September 3–4	Summer	Jurassic	Mouth	4,250–5,949	<45%	19% or more	4% or more	25% or more	12,600	.46
September 8–9	Summer	Jurassic	Mouth	4,250–5,949	<45%	19% or more	4% or more	25% or more	18,200	.52
September 21	Fall	Mixed	Salt Wash	5,950–7,639	45% or more	<19%	4% or more	<25%	6,480	.25
September 27–28	Fall	Mixed	Mouth	4,250–5,949	<45%	19% or more	4% or more	25% or more	33,200	.65

Table 6. Characteristics of runoff resulting from 28 rain events and the basin characteristics associated with the occurrence of precipitation during those events, Muddy Creek Basin, Utah, water year 2005—Continued.

[CPMBCT, Colorado Plateau Mixed Bedrock Canyon and Tableland; NLCD, National Land-cover Dataset; SWReGAP, Southwest Regional Gap Analysis Project; °C, degrees Celsius; mg/L, milligrams per liter; nd, no data; µS/cm, microsiemens per centimeter; —, not computed; %, percent; <, less than]

Storm dates	Characteristics of runoff at site MCm3														
	Total runoff, acre-feet	Total baseflow, acre-feet	Total direct runoff, acre-feet	Ratio of baseflow to stormflow	Runoff efficiency, in percent	Maximum instantaneous streamflow, in cubic feet per second	Total dissolved-solids load, tons	Total baseflow dissolved-solids load, tons	Total direct runoff dissolved-solids load, tons	Ratio of baseflow to direct runoff dissolved-solids load	Dissolved solids in direct runoff per acre-foot of precipitation, tons	Maximum specific conductance, µS/cm at 25°C	Minimum specific conductance, µS/cm at 25°C	Maximum daily mean dissolved-solids concentration, mg/L	Mean daily dissolved-solids concentration, mg/L
October 1–5	71	36	35	1.01	0.70	100	323	193	130	1.49	0.013	—	—	4,840	3,700
October 18–24	632	100	532	.19	0.67	578	2,060	377	1,690	.22	.018	4,880	1,790	3,360	2,540
October 27–28	132	99	33	2.95	0.74	20	439	342	98	3.50	.005	4,270	2,760	2,780	2,420
November 7–9	2,210	105	2,110	.05	2.67	1,310	5,490	369	5,120	.07	.062	3,690	1,770	2,470	2,090
November 11–13	1,560	239	1,320	.18	9.25	786	3,790	884	2,910	.30	.172	4,150	1,560	2,760	1,850
November 20–21	577	184	393	.47	2.14	150	1,690	750	942	.80	.035	4,120	1,840	3,050	2,320
November 25–28	497	243	254	.95	1.05	208	1,790	1,040	746	1.40	.016	6,130	2,150	4,120	2,780
March 19–21	224	127	97	1.32	1.18	54	764	462	302	1.53	.016	3,730	3,350	2,550	2,510
March 23–25	215	158	57	2.80	1.33	50	762	580	182	3.18	.011	4,000	3,440	2,680	2,610
March 28–30	250	220	30	7.25	2.74	37	906	814	92	8.86	.010	4,100	3,530	2,770	2,670
April 9–10	277	173	104	1.67	1.84	48	815	654	161	4.06	.011	3,710	2,530	2,560	2,200
April 23–24	225	168	57	2.92	0.94	50	789	611	178	3.44	.007	4,760	2,630	3,140	2,600
April 30 – May 2	392	202	190	1.06	1.35	106	1,430	704	724	.97	.025	4,270	2,290	3,360	2,630
May 6–7	242	134	108	1.25	2.37	68	836	447	389	1.15	.038	4,100	2,630	2,830	2,580
May 10–11	362	208	154	1.35	4.91	62	1,070	643	426	1.51	.058	3,410	2,160	2,690	2,090
June 2–3	4,680	336	1,510	.22	3.82	1,260	8,010	983	5,000	.20	.041	3,170	960	1,910	1,130
June11–12	2,130	384	—	—	11.0	239	2,360	1,130	—	—	—	1,360	1,110	—	—
June 22–23	1,640	442	—	—	14.1	245	1,390	1,310	—	—	—	nd	nd	—	—
July 24–26	224	68	156	.44	1.31	114	1,220	364	852	.43	.050	9,080	3,280	5,560	3,860
August 2–3	308	42	266	.16	1.92	282	1,330	232	1,090	.21	.068	7,740	3,200	3,550	3,280
August 5	58	30	29	1.03	1.09	43	238	166	72	2.31	.013	5,380	3,540	3,470	3,080
August 7–13	741	180	561	.32	2.99	285	2,860	1,070	1,790	.60	.072	6,960	1,700	4,260	3,140
August 19	122	72	49	1.46	2.01	56	517	440	77	5.74	.013	nd	nd	3,540	3,180
August 23	134	65	69	.94	3.19	68	588	404	183	2.21	.044	nd	nd	3,630	3,320
September 3–4	90	17	73	.23	0.71	72	449	120	329	.36	.026	7,340	3,830	6,330	4,520
September 8–9	1,470	26	1,440	.02	8.05	1,510	7,010	186	6,830	.03	.374	6,780	3,040	4,120	3,500
September 21	505	25	480	.05	7.80	716	2,090	152	1,940	.08	.299	6,910	3,060	4,850	3,400
September 27–28	181	36	146	.24	0.55	249	875	200	675	.30	.020	6,570	3,220	5,340	3,550
Statistical summary															
Minimum	58	17	29	.02	0.55	20	238	120	72	0.03	.005	1,360	960	1,910	1,130
Maximum	4,680	442	2,110	7.25	14.12	1,510	8,010	1,310	6,830	8.86	.374	9,080	3,830	6,330	4,520
Average	720	147	395	1.17	3.30	313	1,850	558	1,270	1.73	.058	5,030	2,560	3,560	2,830
Median	292	131	150	.95	1.96	110	1,140	455	550	1.06	.026	4,270	2,630	3,360	2,650
Standard deviation	996	111	558	1.52	3.51	421	1,970	336	1,780	2.07	.089	1,790	817	1,090	720
Total	20,200	4,120	10,300	—	—	—	51,900	15,600	32,900	—	—	—	—	—	—

Quality Assurance and Control

Streamflow measurements were made using the standard USGS methods described in Rantz (1982) and the Office of Surface Water Technical Memorandum 2004.04 (U.S. Geological Survey, 2004). Standard USGS methods, as described in the National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated) were used for measuring water temperature and specific conductance, and for water sample collection and processing.

Quality-control samples were collected at selected sites to determine if data quality associated with water samples collected for this study is sufficient for water-quality assessments (table 2). Two types of quality-control samples were collected and analyzed: (1) field blanks to determine sample bias and (2) replicates to determine sample variability.

Four field-blank samples were collected at selected water-quality monitoring sites during this study and analyzed for major ions. No constituents were detected above the laboratory method reporting limits, indicating that there probably was no bias associated with sample collection or processing.

Two replicate samples were collected at site MCm2 during this study. These samples were analyzed for ROE only, or for ROE, chloride, and sulfate. The average relative standard deviation for these constituents was less than 2 percent, which indicates that variability that was due to sample collection and processing or to lab analytical procedures was small.

Overall, the data from quality-control samples collected during this study show that bias from sample contamination is minimal or nonexistent, and the sampling and analytical procedures yield reproducible results.

Transport of Dissolved Solids

The annual dissolved solids load discharged from the Muddy Creek Basin to the Dirty Devil River is essential information for land managers monitoring, planning, or implementing salinity control in the Muddy Creek Basin. Included in this section are estimates of the annual dissolved-solids loads at select sites on Muddy Creek for periods during WYs 1976–2006 that had complete data. The concentration of dissolved solids in Muddy Creek, its tributaries, and in springs in the Muddy Creek Basin are important measures used to assess the adequacy of water in the Muddy Creek Basin for various uses and the impacts of the quality of that water on downstream users. The range of dissolved-solids concentrations, and where and when they occurred, were examined. Streamflow affects the concentration and transport of dissolved solids in Muddy Creek; hence, daily, seasonal, and annual streamflow in Muddy Creek were also examined. Dissolved-solids transport and its relation to individual components of streamflow (baseflow, snowmelt runoff, and direct runoff) may be a consideration when land managers are planning or assessing dissolved-solids mitigation projects; hence, these relations were also examined.

Annual Dissolved-Solids Loads and Yields, WYs 1976–2006

Annual dissolved-solids loads at any particular site on Muddy Creek varied substantially from year to year. For example, the estimated dissolved-solids load discharged at site MCm3 was 11,200 tons during WY 1977 and 142,000 tons during WY 1980 (fig. 8, table 5). This variation is due to primarily climatic variability. Precipitation was 70 percent of the 1976–2006 average during WY 1977 when loads were small and 123 percent of the 1976–2006 average during WY 1980 when loads were large. In addition, the WY 1980 annual dissolved-solids load was substantially affected by a single storm event that resulted in the second largest streamflow peak measured at this site (5,000 ft^3/s, September 10, 1980) and the transport of an estimated 28,000 tons from September 7 to September 14. The difference in annual dissolved-solids loads among individual sites on Muddy Creek also varied from year to year. For example, in WY 2005, the annual dissolved-solids load discharged at site MCm1 was 24,600 tons or 26 percent of the load discharged at site MCm3 (93,000 tons). However, in WY 1977, the annual dissolved-solids load discharged at site MCm1 was 8,730 tons or 78 percent of the load discharged at site MCm3 (11,200 tons).

During the seven years that streamflow and water quality were monitored at the mouth of Muddy Creek by the USGS (WYs 1976–80 and 2005–06), the average annual load of dissolved-solids discharged from Muddy Creek to the Dirty Devil River was 68,700 tons (table 7). The average annual loads of dissolved solids discharged from the upper Muddy Creek Basin at sites MC and MCm1 for the same period were 9,670 and 19,500 tons, respectively. For this period, there were, on average, 49,100 tons of dissolved solids discharged annually to Muddy Creek between sites MCm1 and MCm3 (the lower Muddy Creek Basin). The lower Muddy Creek Basin is 1,140 mi^2 of mostly undeveloped public land. During WYs 1976–80 and 2005–06, the annual yield of dissolved solids from these natural lands in the lower Muddy Creek Basin ranged from 2 tons/mi^2 to 102 tons/mi^2 and averaged 43 tons/mi^2. This average value is 39 percent larger than the 33 tons/mi^2 reported by Iorns and others (1965) for the quantity of dissolved solids discharged by natural sources in the Dirty Devil River Basin, which includes the Muddy Creek Basin. This may be an indication that, on average, there are more dissolved solids derived from natural lands in the Muddy Creek Basin than in either or both of the Fremont River Basin and the lower Dirty Devil River Basin. However, additional studies are necessary to determine if this is a correct assumption.

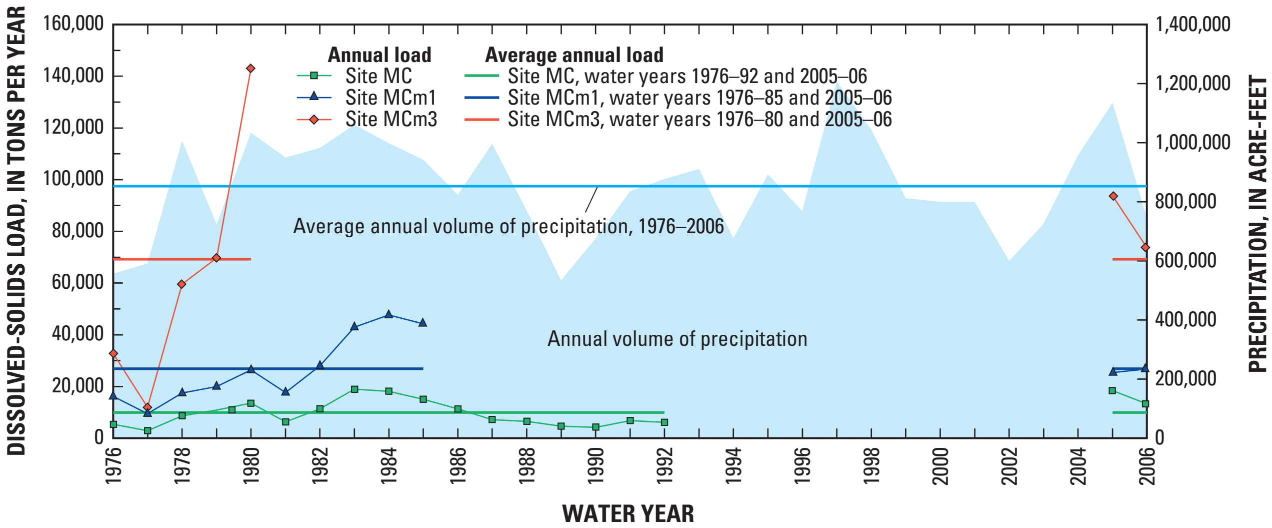

Figure 8. Estimated annual dissolved-solids loads at sites MC, MCm1, and MCm3 on Muddy Creek, Utah, and annual precipitation in the Muddy Creek Basin.

Table 7. Summary of annual dissolved-solids loads and yield at select sites on Muddy Creek, Utah, water years 1976–2006.

[nd, no data; tons/mi², tons per square mile; —, not computed]

Period	Annual dissolved-solids load, in tons					Annual dissolved-solids yield, in tons/mi²					
	Site MC	Site MCm1	Site MCm2	Lower basin[1]	Site MCm3	Site MC	Site MCm1	Site MCm2	Lower basin[1]	Site MCm3	Precipitation, percent of 1976–2006 average[2]
1976	4,610	15,400	nd	17,600	33,000	44	37	nd	15	21	74
1977	2,100	8,730	nd	2,470	11,200	20	21	nd	2	7	59
1978	7,870	16,700	nd	42,100	58,800	75	40	nd	37	38	99
1979	10,100	19,200	nd	49,800	69,000	96	46	nd	44	44	108
1980	12,800	25,700	nd	116,300	142,000	122	61	nd	102	91	121
1981	5,610	17,000	nd	—	nd	53	41	nd	—	nd	95
1982	10,600	27,200	nd	—	nd	101	65	nd	—	nd	124
1983	18,200	42,200	nd	—	nd	173	101	nd	—	nd	114
1984	17,400	47,000	nd	—	nd	166	112	nd	—	nd	121
1985	14,300	43,500	nd	—	nd	136	104	nd	—	nd	113
1986–2004	[3]5,920	nd	nd	—	nd	56	nd	nd	—	nd	97
2005	17,700	24,600	nd	68,800	93,400	169	59	nd	60	60	137
2006	12,600	26,000	38,200	46,900	72,900	120	62	52	41	47	85
Average, 1976–80, 2005–06	9,670	19,500	—	49,100	68,700	92	47	—	43	44	98
Average, period of record	9,220	26,100	38,200	49,100	68,700	102	62	52	—	44	—

[1]The lower basin is the portion that drains to the stream between sites MCm1 and MCm3.

[2]The water year 1976–2006 average annual precipitation in the Muddy Creek Basin is 858,000 acre-feet.

[3]Value is the average of estimated annual dissolved-solids loads from 1986 to 1992.

Streamflow, Specific Conductance, and Dissolved Solids, WYs 2005–06

Most of the dissolved-solids data from the Muddy Creek Basin prior to this study had been collected in the 1970s and 1980s. For this study, it was desirable to be able to describe more recent conditions in the basin, and so, additional streamflow, specific conductance, and dissolved-solids data were collected (table 2). Relations between streamflow, specific conductance, and dissolved-solids concentration were used in this study for estimating daily dissolved-solids loads in Muddy Creek and Salt Wash in WYs 2005–06.

Streamflow

Streamflow in Muddy Creek was measured at selected sites during WYs 2005 and 2006 to determine variability in streamflow at daily and seasonal time scales, to determine the volume of flow associated with various flow components (baseflow, snowmelt runoff, and storm runoff), and to provide input to the dissolved-solids load equations.

The streamflow in Muddy Creek in WYs 2005 and 2006 exhibited large spatial and temporal variability. For example, on November 10, 2004, the daily mean streamflow at site MCm1 was 23 ft^3/s whereas the daily mean streamflow downstream at site MCm3 was 495 ft^3/s. The streamflow at site MCm3 was 11 ft^3/s at *8:00 p.m.* Mountain Standard Time on October 18, 2005, and 1,170 ft^3/s four hours later. These large differences in streamflow among sites and over time occurred most often when direct runoff generated by convective thunderstorms or moist southerly air masses was a large component of streamflow. Smaller differences in streamflow resulted from the effects of evapotranspiration and perhaps some loss of flow to the underlying aquifer. During the summer, the streamflow in Muddy Creek diminished in the downstream direction, sometimes to the point where there was no streamflow at the mouth of Muddy Creek (photo 3). Peak streamflows generally occurred during late summer and fall as a result of rain storms. However, as occurred on June 4, 2005, annual peak streamflows can occur with large volumes of rain in the basin during the snowmelt period (fig. 9).

Snowmelt was the largest component of streamflow (46 percent of total flow) in Muddy Creek at site MCm1 in WY 2005 (table 8); baseflow was the second largest streamflow component; and direct runoff from storms was the least. A number of storms in the basin downstream of site MCm1 produced substantial direct runoff. As a result, direct runoff from storms at site MCm3 exceeded snowmelt runoff during WY 2005. Baseflow at site MCm3 during WY 2005 was about 25 percent more than that calculated for site MCm1.

At sites MCm1, MCm2, and MCm3, baseflow was the largest component of streamflow in Muddy Creek during WY 2006. The accumulation of snow in the Muddy Creek Basin headwaters was much less during the winter of the 2006 WY than during the previous winter; consequently, there was much less snowmelt runoff. Direct runoff from storms was the smallest streamflow component.

During WY 2005, annual runoff in Muddy Creek was greater than the average annual runoff for the period of record at site MCm1 and much greater than the average at site MCm3 (table 8). During WY 2006, annual runoff in Muddy Creek was less than the average annual runoff for the period of record at site MCm1 and slightly greater than the average at site MCm3.

Streamflow Partitioning into Baseflow, Snowmelt Runoff, and Direct Runoff

The volume and temporal distribution of individual components of streamflow (baseflow, snowmelt, and direct runoff) in Muddy Creek is important when analyzing the effects of these components on dissolved-solids transport and possible mitigation of dissolved solids. Baseflow during WYs 2005–06 was determined as previously described in the Methods section on Baseflow Dissolved Solids Load. Snowmelt runoff and direct runoff were determined to be the remaining streamflow after baseflow was subtracted from the total daily streamflow.

Baseflow

The baseflow component of streamflow in Muddy Creek was a substantial portion of the annual streamflow during WYs 2005–06 and was the component that varied the least annually. On average, during WYs 2005–06, baseflow at site MCm1 accounted for 40 percent of the annual streamflow; however, the amount of baseflow at site MCm1 is largely a function of upstream diversions, return flow from irrigation, and discharge from the SUFCO coal mine of about 8 ft^3/s (Jay Humphries, Emery Water Conservancy District, oral commun., 2005). Baseflow at site MCm3 accounted for 38 percent of the annual streamflow (table 8). The Bureau of Reclamation (1987) estimated that about 2,200 acre-ft/yr discharges to Muddy Creek from springs in South Salt Wash and Salt Wash—a volume about equal to the increase in annual Muddy Creek baseflow between sites MCm1 and MCm3 during WYs 2005–06. There is additional ground water discharged to Muddy Creek between these sites from diffuse seeps and minor springs; however, much of the baseflow in the stream between sites MCm1 and MCm3 is lost to evapotranspiration during the summer months. As a result there is an increase in dissolved-solids concentration in the remaining streamflow.

Snowmelt Runoff

The largest volume of precipitation occurring in the Muddy Creek Basin generally falls as snow during late fall and winter at the higher elevations of the Muddy Creek Basin. Some snow accumulates in the middle elevations, but is generally not persistent through the winter. Snow falling in the middle and lower elevations generally melts or sublimates in late winter and early spring, replenishing soil moisture, but not providing much direct runoff to Muddy Creek.

Photo 3. No streamflow at water-quality monitoring site MCm3, Muddy Creek at mouth, near Hanksville, Utah, September 2005. (Photo credit: Steven Gerner, USGS, Salt Lake City, Utah)

The snowmelt component of streamflow in Muddy Creek, shown in table 8, was quite variable from year to year, but accounted for at least 27 percent of the annual streamflow. On average, during WYs 2005–06, snowmelt runoff was 42 percent of the annual streamflow at site MCm1 and 31 percent of the annual streamflow at site MCm3.

Direct Runoff

The direct-runoff component of streamflow in Muddy Creek is generally a substantial portion of the annual streamflow, but its volume is quite variable from year to year. During WYs 2005–06, direct runoff was, on average, 18 percent of the annual streamflow at site MCm1 and 31 percent at site MCm3. There were fewer storms in late fall and summer during WY 2006, than during WY 2005, and the storms that did occur usually resulted in less runoff (fig. 9). Consequently, the volume of direct runoff in streamflow at site MCm3 was much larger in WY 2005 than in WY 2006 (table 8). The maximum instantaneous streamflow associated with direct runoff during WYs 2005–06 occurred on October 19, 2005, and was 1,740 ft^3/s. A recurrence interval of less than 2 yr was determined for this event (Terry Kenney, U.S. Geological Survey, written commun., 2007) using computation methods described in U.S. Interagency Advisory Committee on Water Data (1982).

Specific Conductance and Relation to Dissolved-Solids Concentration and Flow

Specific-conductance values measured in Muddy Creek during site visits ranged from 596 µS/cm at site MCm1 to 6,370 µS/cm at site MCm3 (table 2). At monitoring sites, the specific conductance in Muddy Creek was lowest during the spring, especially when snowmelt was the largest component of flow. It was highest during the summer and fall, especially when direct runoff, generated by convective storms, was the largest component of flow. The specific conductance of Muddy Creek generally increased in the downstream direction. In fact, the median value for daily mean specific conductance measured during WYs 2005–06 was 133 percent larger at site MCm3 than it was upstream at site MCm1.

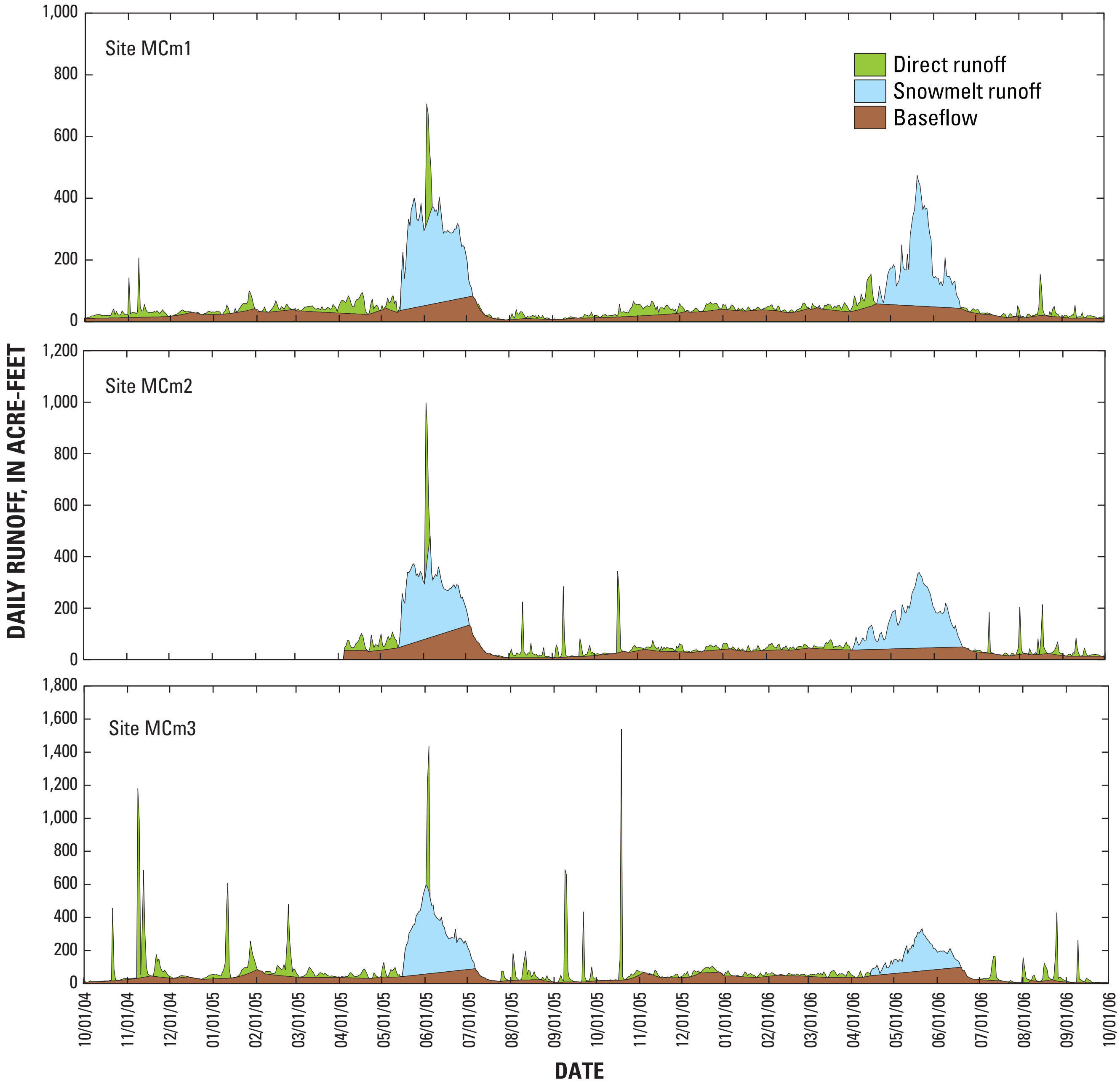

Figure 9. Daily baseflow, snowmelt runoff, and direct runoff at water-quality monitoring sites MCm1, MCm2, and MCm3, Muddy Creek, Utah, water years 2005–06.

The ratio of dissolved-solids concentration (from ROE) to specific conductance in water samples from the Muddy Creek Basin ranged from 0.62 to 1.00 (table 2, table 9). Land managers or scientists can apply an average of these ratios for estimating dissolved-solids concentration from specific-conductance measured in the field during visits to the Muddy Creek Basin. These average ratios are less site specific than the regression equations shown in figure 6, but should be adequate for reconnaissance level evaluations. In general, specific-conductance values measured in Muddy Creek can be multiplied by 0.74 to obtain an estimate of the dissolved-solids concentration. However, specific-conductance values from flow in the lower basin that is largely from direct runoff should be multiplied by 0.91 and specific-conductance values from snowmelt runoff should be multiplied by 0.66 to determine an estimate of dissolved-solids concentration. Because these multiplication factors were determined on sulfate-type waters using dissolved-solids concentrations from ROE, estimates of dissolved-solids concentrations using these coefficients will be slightly higher (up to 10 percent) than salinity concentrations determined from an analysis of sum of constituents.

Table 8. Summary of flow at select sites on Muddy Creek, Utah, water years 2005–06.

[ac-ft, acre-feet; ft³/s, cubic feet per second; —, no data or not computed]

Flow component	Period of record[1]				Water year 2005				Water year 2006			
	Average annual runoff, in ac-ft	Minimum daily mean flow, in ft³/s	Average daily mean flow, in ft³/s	Maximum daily mean flow, in ft³/s	Total runoff, in ac-ft	Minimum daily flow, in ft³/s	Average daily flow, in ft³/s	Maximum daily flow, in ft³/s	Total runoff, in ac-ft	Minimum daily flow, in ft³/s	Average daily flow, in ft³/s	Maximum daily flow, in ft³/s
Site MC, Muddy Creek near Emery												
Total flow	28,300	0	39.1	664	52,670	7	72.7	456	36,990	5.1	51.1	282
Site MCm1, Muddy Creek below I-70, near Emery												
Total flow	23,300	3.8	32.1	650	26,100	1.6	36.1	355	22,900	4.1	31.7	238
Baseflow	—	—	—	—	9,040	1.6	12.5	40.5	10,200	4.1	14.1	27.7
Snowmelt[2]	—	—	—	—	12,000	14.3	118	179	8,800	3	75.2	214
Direct runoff	—	—	—	—	5,120	0	7.1	196	3,900	0	5.4	67.8
Site MCm2, Muddy Creek at Tomsich Butte, near Hanksville												
Total flow	—	—	—	—	—	—	—	—	23,600	4.5	32.7	171
Baseflow	—	—	—	—	—	—	—	—	10,500	4.5	14.5	23.2
Snowmelt[2]	—	—	—	—	—	—	—	—	9,480	4.8	61.3	149
Direct runoff	—	—	—	—	—	—	—	—	3,640	0	5	160
Site MCm3, Muddy Creek at mouth, near Hanksville												
Total flow	24,400	0	33.7	5,000	40,100	1.5	55.4	722	25,900	0	35.7	774
Baseflow	—	—	—	—	11,300	1.5	15.7	42.8	12,500	0	17.3	47.1
Snowmelt[2]	—	—	—	—	13,800	19.8	136	271	6,910	4.5	54.4	128
Direct runoff	—	—	—	—	15,000	0	20.7	580	6,410	0	8.9	766

[1]The period of daily discharge record is 1911–13 and 1950–2006 for site MC; 1973–87 and 2005–06 for site MCm1; 2006 for site MCm2; and 1976–80 and 2005–06 for site MCm3.

[2]Statistical summaries for the snowmelt component are for the period of snowmelt only.

Table 9. Statistical summary of selected physical and chemical data associated with water samples collected from the Muddy Creek Basin, Utah, 2004–06.

[°C, degrees Celsius; ft^3/s, cubic feet per second; mg/L, milligrams per liter; ROE, residue on evaporation at 180°C; µS/cm, microsiemens per centimeter]

Statistic	Discharge, in ft^3/s	Specific conductance, in µS/cm at 25°C	ROE/Specific conductance ratio	Residue on evaporation at 180°C, in mg/L	Sum of constituents/ROE ratio	Calcium, in mg/L	Magnesium, in mg/L	Sodium, in mg/L	Potassium, in mg/L	Sulfate, in mg/L	Chloride, in mg/L	Alkalinity, as $CaCO_3$ in mg/L
Site MCm1, Muddy Creek below I-70, near Emery												
Number of values	29	29	29	30	9	12	12	12	12	18	18	11
Maximum	239	2,970	0.96	2,360	1.00	128	118	365	7	1,240	53	293
75th percentile	35	2,100	0.77	1,590	0.95	115	88	217	6	771	36	278
Mean	38	1,670	0.74	1,270	0.94	102	77	189	5	640	31	250
Median	19	1,660	0.75	1,250	0.93	106	79	190	5	619	33	254
25th percentile	9	1,250	0.70	871	0.92	98	71	153	4	516	28	235
Minimum	3	596	0.65	385	0.91	55	25	38	3	134	9	156
Standard deviation	52	636	0.06	548	0.03	20	24	85	1	287	12	40
Site MCm2, Muddy Creek at Tomsich Butte, near Emery												
Number of values	16	16	16	16	9	9	9	9	9	15	15	9
Maximum	209	4,460	0.95	3,400	0.96	395	112	640	11	1,680	696	261
75th percentile	34	3,240	0.77	2,700	0.94	184	92	417	6	1,270	249	245
Mean	41	2,510	0.75	1,927	0.93	170	86	343	6	914	217	222
Median	24	2,350	0.73	1,730	0.93	136	88	308	5	748	199	242
25th percentile	12	1,750	0.71	1,230	0.92	125	82	227	4	589	120	193
Minimum	4	820	0.64	525	0.91	98	56	171	3	171	33	169
Standard deviation	52	1,040	0.08	912	0.02	92	17	153	2	466	162	34
Site MCm3, Muddy Creek at mouth, near Hanksville												
Number of values	39	52	52	55	18	19	19	19	19	32	32	18
Maximum	1,080	6,370	1.00	5,950	1.00	619	105	871	20	2,080	1,090	200
75th percentile	157	4,160	0.90	3,700	0.96	469	89	529	12	1,900	558	180
Mean	167	3,460	0.81	3,060	0.95	314	70	416	9	1,270	403	148
Median	37	3,370	0.85	2,820	0.94	256	81	448	7	1,180	365	171
25th percentile	19	2,920	0.70	2,430	0.93	193	50	236	6	844	152	107
Minimum	2	980	0.65	661	0.90	99	31	70	3	231	60	61
Standard deviation	271	1,130	0.11	1,230	0.03	170	25	219	4	604	289	47
Miscellaneous sites in Muddy Creek Basin[1]												
Number of values	27	30	12	14	11	12	12	12	12	14	14	11
Maximum	30	44,600	0.72	27,000	0.98	958	291	8,350	27	4,020	12,100	274
75th percentile	18	10,000	0.71	6,350	0.96	384	93	1,590	10	1,340	2,580	258
Mean	8	8,400	0.68	5,220	0.96	279	98	1,370	8	1,110	1,980	217
Median	2	3,800	0.69	3,620	0.96	140	77	345	5	887	1,070	230
25th percentile	0	1,800	0.66	1,270	0.95	104	69	203	4	525	128	165
Minimum	<.01	804	0.62	1,090	0.93	100	62	160	4	505	33	146
Standard deviation	10	10,800	0.03	6,710	0.02	256	63	2,300	7	916	3,140	50

[1]These results include analyses from water samples collected at miscellaneous sites on Muddy Creek, in Salt Wash, and in South Salt Wash.

In most natural streams, there is an inverse relation between flow and specific conductance (Hem, 1992). Generally, an increase in streamflow resulted in dilution of dissolved solids and lower specific conductance in Muddy Creek. However, the initial increase in streamflow from the direct runoff generated by an event was often accompanied by an increase in specific conductance. This situation is often described as a "first flush" and it occurs when readily available or easily dissolved constituents are transported to the stream in the earliest direct runoff (Sansalone and Cristina, 2004). An inverse relation between flow and specific conductance generally applies at sites MCm1, MCm2, and MCm3; however, the relation between flow and specific conductance (and dissolved solids) is much less predictable at site MCm3 when streamflow values exceed 180 ft^3/s. The correlation coefficients for the relation of the natural logs of streamflow and specific conductance were –0.84, –0.96, and –0.84 at sites MCm1, MCm2, and MCm3 (at streamflows less than 180 ft^3/s), respectively (fig. 10). Because specific conductance and dissolved solids concentrations are much less correlated to higher flows in the lower reaches of Muddy Creek, estimates of dissolved-solids concentrations predicted from streamflows above 180 ft^3/s are less certain.

The variation in specific conductance of water at site MCm3 at the mouth of Muddy Creek depends on the mix of flow components in the stream as well as the processes by which those components were derived. For example, the specific conductance in Muddy Creek at site MCm3 increased and decreased in sync with flow as runoff from a storm was transported downstream November 11–13, 2004 (fig. 11). Precipitation from this storm fell evenly throughout the elevation range in the basin, but the largest percentage fell in areas with Cretaceous-age surface geology (table 6). These relations suggest that in some subbasins, and during some periods, there were sufficient sources of dissolved solids, whether dissolved from efflorescent salts or in interstitial soil moisture, to limit dilution from continued precipitation and runoff. Conversely, specific conductance generally decreased as flow increased when runoff from a storm was transported downstream August 16–18, 2006. There was a small 'first flush' from this storm, but then the dissolved solids concentration in the stream was rapidly diluted and specific-conductance values decreased.

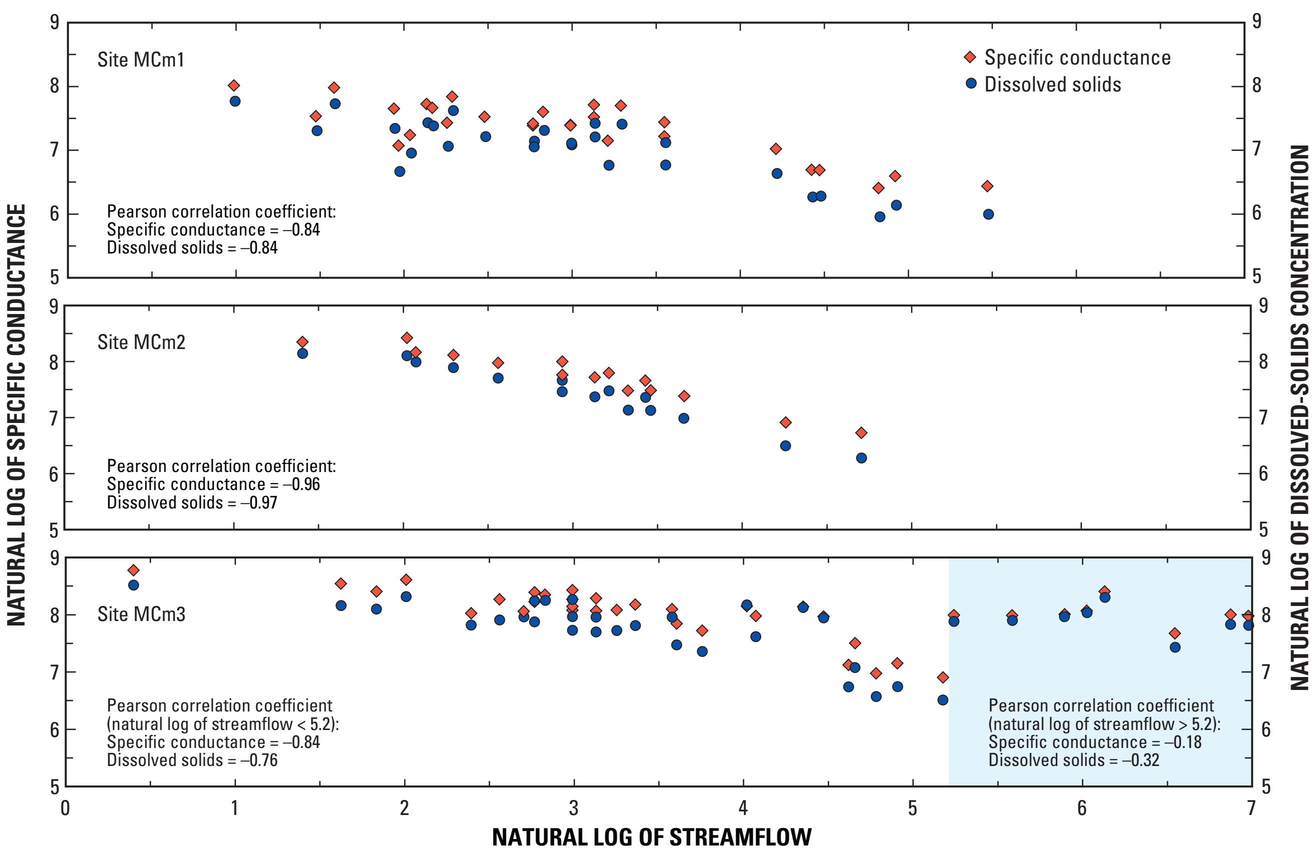

Figure 10. Relation of specific conductance and dissolved solids in water samples to streamflow at water-quality monitoring sites MCm1, MCm2, and MCm3, Muddy Creek, Utah.

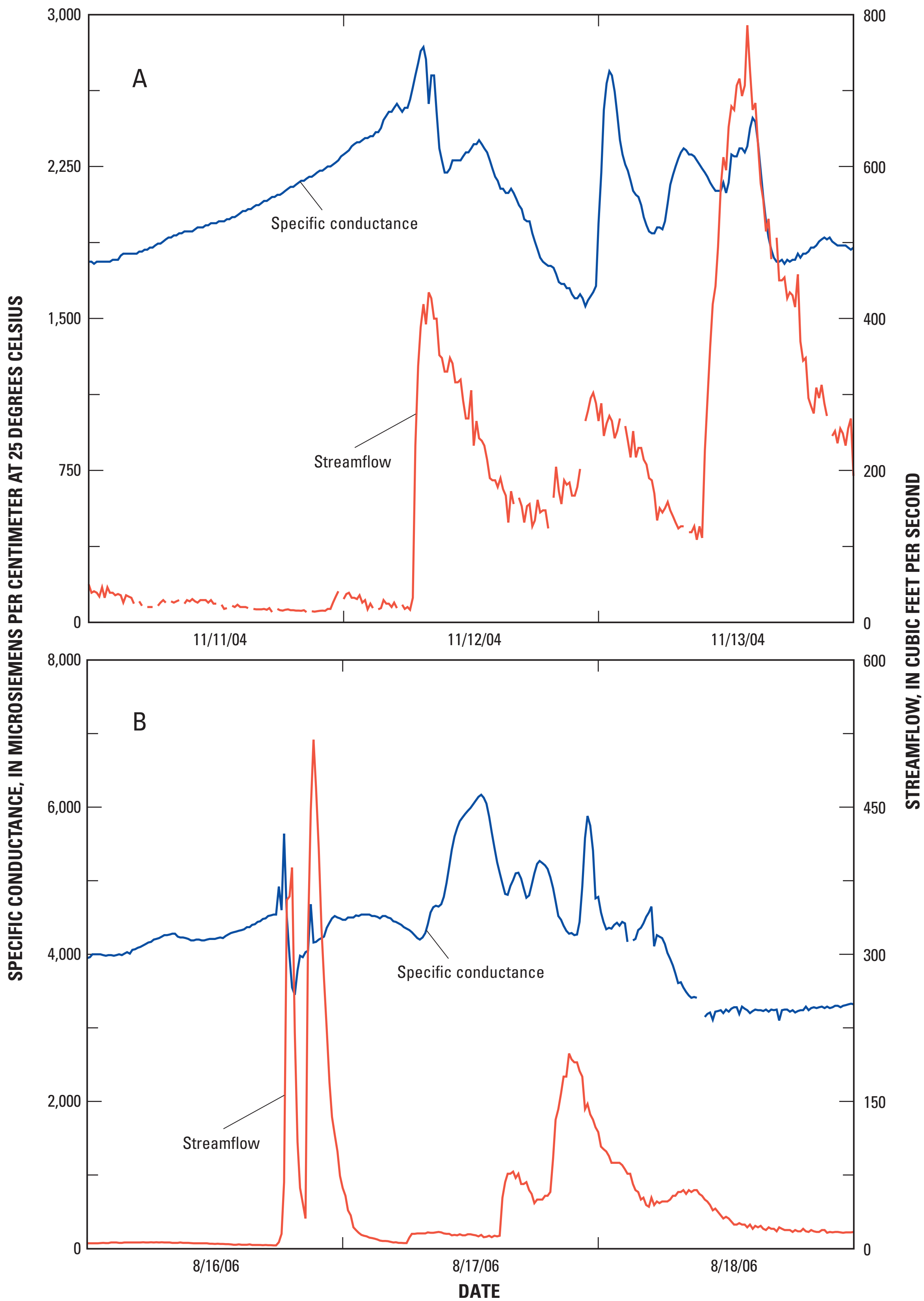

Figure 11. Relation of flow and specific conductance during the events of November 11–13, 2004, and August 16–18, 2006, water-quality monitoring site MCm3, Muddy Creek, Utah.

Dissolved-Solids Concentrations

The concentration of dissolved solids in Muddy Creek and its tributaries often limits the use of the water for irrigation, public supply, or industrial uses. For example, Muddy Creek is designated by the State of Utah as protected for agricultural uses (Utah Department of Environmental Quality, Division of Water Quality, 2004); however, the concentration of dissolved solids in many segments of Muddy Creek often exceeds the criteria of 1,200 mg/L for water intended for irrigation and 2,000 mg/L for water intended for stock watering (Utah Division of Administrative Rules, 2005). Because a large portion of the dissolved solids in Muddy Creek are derived from natural lands, and the stream is naturally high in dissolved solids, the criteria for some segments of the stream have been adjusted. The criteria for the concentration of dissolved solids in Muddy Creek and its tributaries between highway U10 and approximately I-70 is currently (2007) 2,600 mg/L (Utah Department of Environmental Quality, Division of Water Quality, 2004). Downstream from I-70 the criterion is currently 5,600 mg/L. The segment of Muddy Creek above highway U10 is designated by the State of Utah as protected for domestic purposes and is used for public supply in the Emery area. The concentration of dissolved solids in this segment rarely exceeds the EPA Secondary Drinking Water Standard (500 mg/L [U.S. Environmental Protection Agency, 2006]). Water in Muddy Creek downstream from highway U10 rarely has a concentration of dissolved solids less than 500 mg/L, except during snowmelt runoff.

Dissolved-solids concentrations measured in water samples from water-quality monitoring sites on Muddy Creek varied spatially, ranging from 385 mg/L at site MCm1 to 5,950 mg/L at site MCm3 (table 2, table 9). The highest dissolved-solids concentration values measured in the study area were in water samples collected at sites in South Salt Wash (27,000 mg/L) and Salt Wash (4,940 to 6,780 mg/L). These samples were taken from surface flow, most of which was discharge from saline springs. There were also large temporal variations in dissolved-solids concentrations at individual sites. For example, the dissolved-solids concentration in a water sample from site MCm3 on August 18, 2004, was 5,950 mg/L, and the concentration in water collected on May 25, 2005, was 661 mg/L. The first sample contained water from the initial flood wave generated by direct runoff from a thunderstorm, and the second sample contained water from snowmelt runoff. Dissolved-solids concentrations in Muddy Creek generally increased in the downstream direction, as shown by the daily mean concentrations for WYs 2005–06 at monitoring sites MCm1, MCm2, and MCm3 in figure 12. During the spring, when runoff from snowmelt is the principal component of flow, the dissolved-solids concentrations in Muddy Creek are lowest. Dissolved-solids concentrations are generally much higher during the summer, particularly when flow in Muddy Creek is reduced by extensive evapotranspiration.

Daily mean dissolved-solids concentrations at site MC during WYs 2005–06 were uniformly low—always less than 300 mg/L. However, at site MCm1, the daily mean dissolved-solids concentrations were much more variable and ranged from 267 to 3,260 mg/L (fig. 13). The flow-weighted[4] mean dissolved-solids concentrations in Muddy Creek at site MCm1 were 693 mg/L for WY 2005 and 835 mg/L for WY 2006. The median dissolved-solids concentrations during the spring of WYs 2005–06 (439 and 657 mg/L, respectively) were significantly less than for all other seasons. Median dissolved-solids concentrations during summer, fall, and winter ranged from 1,140 to 1,390 mg/L.

The dominant anion in water samples from site MCm1 was sulfate, and the dominant cation was sodium; however, when snowmelt was a large component, bicarbonate and calcium were the dominant anion and cation, respectively (fig. 14). The process of cation exchange—calcium for sodium in Mancos shale—is principally responsible for the composition of cations in water from site MCm1.

Daily mean dissolved-solids concentrations at site MCm2 ranged from 381 to 3,380 mg/L during WY 2006. The flow-weighted mean dissolved-solids concentration in Muddy Creek at site MCm2 was 1,190 mg/L for WY 2006. The dominant anion in water samples from site MCm2 was sulfate, and the dominant cation was sodium. Relative to samples from site MCm1, the samples from site MCm2 were enriched in chloride, most likely derived from ground water discharged from the Carmel formation in, and downstream from, South Salt Wash (Bureau of Reclamation, 1987).

Daily mean dissolved-solids concentrations at site MCm3 ranged from 587 to 9,240 mg/L during WYs 2005–06. The flow-weighted mean dissolved-solids concentration in Muddy Creek at site MCm3 was 1,710 mg/L for WY 2005 and 2,070 mg/L for WY 2006. The median dissolved-solids concentrations during the spring (2,090 mg/L and 1,320 mg/L during WY 2005 and 2006, respectively) were significantly less than for other seasons (fig. 13). Median dissolved-solids concentrations during other seasons were higher, as much as 3,310 mg/L during the summer of WY 2005. Generally, the dominant anion in water samples from site MCm3 was sulfate and the dominant cation was sodium. When direct runoff from rain storms was the principal component, the dominant cation in water samples collected from site MCm3 was calcium. When snowmelt was the principal component, the relative quantity of bicarbonate was larger. Samples from site MCm3 generally had a larger relative quantity of chloride than samples from sites MCm1 and MCm2, probably because of ground water discharged from the Carmel Formation to

[4]The flow-weighted mean dissolved-solids concentration is the average concentration of all of the water flowing past a site and is a general measure of the overall quality of the water at the site. Annual flow-weighted mean dissolved-solids concentration (mg/L) at a particular site was calculated by dividing the annual load of dissolved solids (tons) by the annual runoff (acre-ft), then dividing the result by 0.00136.

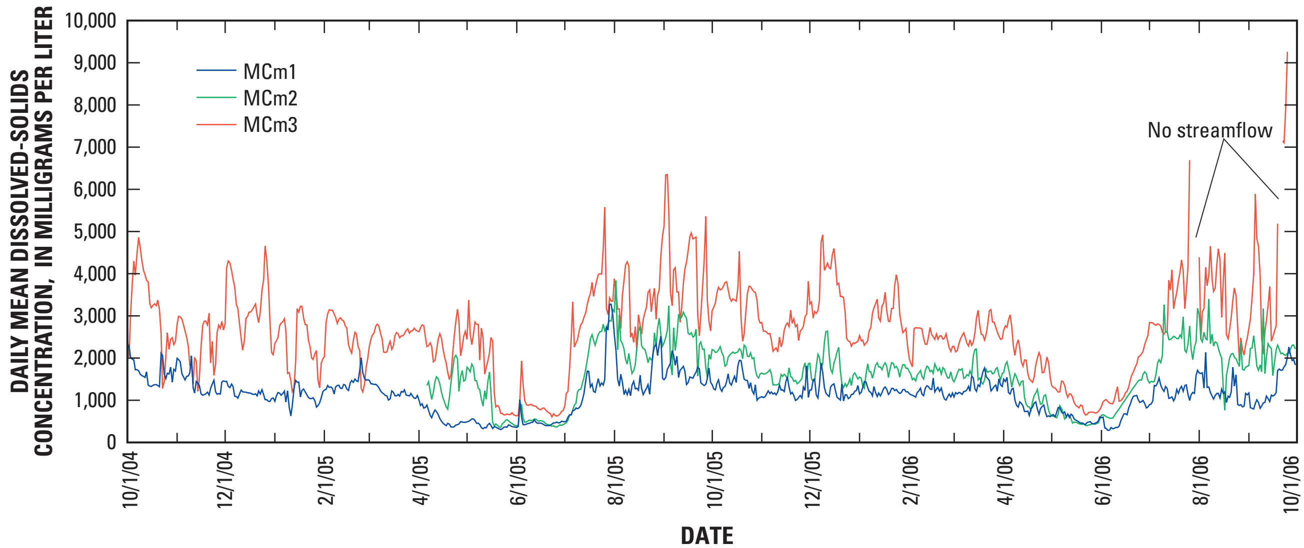

Figure 12. Daily mean dissolved-solids concentration at water-quality monitoring sites MCm1, MCm2, and MCm3, Muddy Creek, Utah.

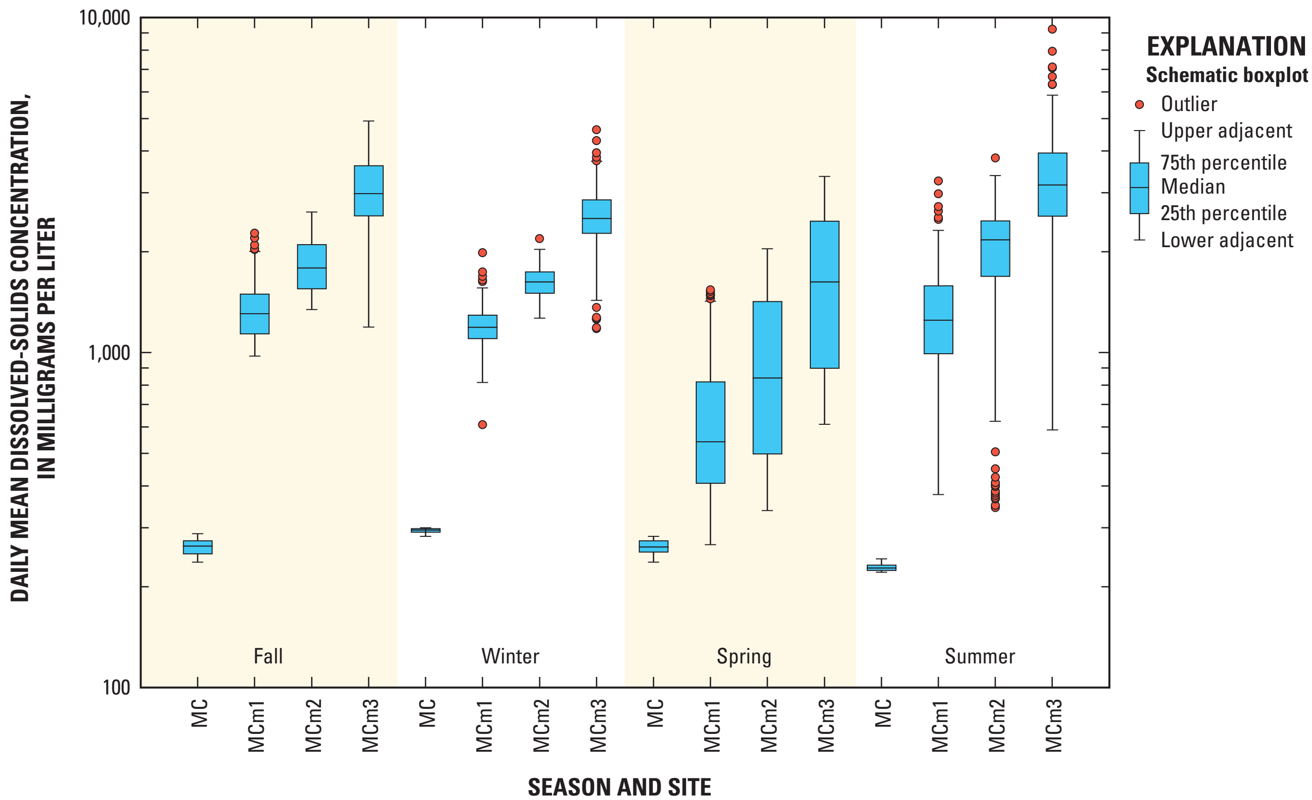

Figure 13. Distribution of daily mean dissolved-solids concentrations at monitoring sites on Muddy Creek, Utah, water years 2005–06.

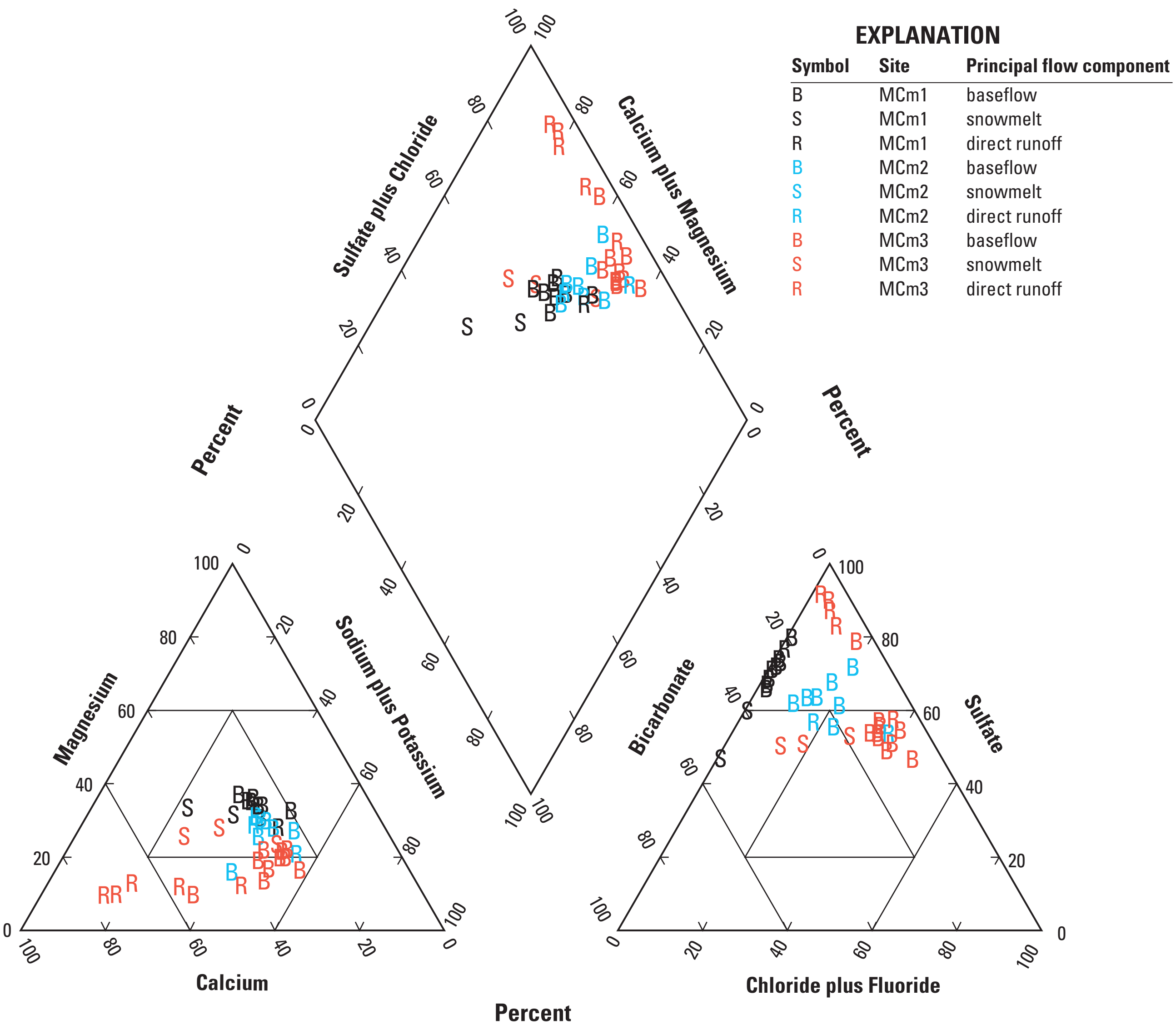

Figure 14. Relation of major constituents in water samples from water-quality monitoring sites MCm1, MCm2, and MCm3, Muddy Creek Basin, Utah.

Muddy Creek downstream from sites MCm1 and MCm2, particularly in Salt Wash.

During WYs 2005–06, there were 8 days, mostly during September, when the mean daily dissolved-solids concentration at site MCm3 exceeded 5,600 mg/L—the State of Utah dissolved solids criteria for that reach of Muddy Creek. These occurrences were rare and only when streamflow was less than 2 ft^3/s.

Dissolved-Solids Loads

The concentration of dissolved solids in Muddy Creek Basin surface waters is of primary importance to water managers within the basin, but water managers downstream from the basin are most affected by the dissolved-solids load transported out of the basin by Muddy Creek. Salinity models for the Colorado River Basin, and land-management decisions within that basin relative to salinity, are often predicated on knowing the average or range of annual dissolved-solids loads expected from individual subbasins. Dissolved-solids loads in Muddy Creek Basin streams were previously calculated by the Bureau of Reclamation (1987), and land managers have used these values to assist in making salinity-related plans and decisions in the basin. Estimates of the Muddy Creek dissolved-solids load from this study provide an expanded basis for making future plans as well as an expanded foundation for determining changes in dissolved-solids loads in the Muddy Creek Basin.

There were 17,700 and 12,500 tons of dissolved solids in Muddy Creek streamflow at site MC during WYs 2005 and 2006, respectively (table 10). The basin upstream from site MC mainly consists of natural lands administered by the USFS. About 40 percent of this part of the basin is underlain by Cretaceous-age rocks, such as the Price River Formation, which are easily eroded and discharge fresh to slightly saline ground water. (The ground-water salinity scale is described in the section on Geology and Associated Hydrologic Characteristics.) Most of the water and dissolved solids discharged at site MC are diverted from Muddy Creek into irrigation canals and then applied to agricultural lands in the Emery area (Natural Resources Conservation Service, 2004).

At site MCm1, downstream of the Emery agricultural areas, there were 24,600 and 26,000 tons of dissolved solids in Muddy Creek streamflow during WYs 2005 and 2006, respectively. Because most of the flow in Muddy Creek between sites MC and MCm1 is diverted for irrigation of the agricultural land near Emery (fig. 1), a substantial portion of the dissolved solids at site MCm1 were probably discharged to Muddy, Ivie, and Quitchupah Creeks in runoff and ground-water discharge from agricultural lands. Additionally, about half of the baseflow, and consequently a substantial portion of the annual dissolved-solids load at site MCm1, originates in discharge from the SUFCO coal mine.

There were 38,200 tons of dissolved solids in Muddy Creek streamflow at site MCm2 in WY 2006. This load represents an addition of 12,200 tons of dissolved solids between sites MCm1 and MCm2. The Jurassic-age Carmel Formation is prominent here and discharges slightly saline and moderately saline ground water, particularly in the South Salt Wash subbasin (Bureau of Reclamation, 1987).

There were 93,400 and 72,900 tons of dissolved solids in Muddy Creek streamflow at site MCm3 during WYs 2005 and 2006, respectively. The amount of dissolved solids acquired in Muddy Creek between sites MCm1 and MCm3 was 68,800 tons during WY 2005 and 46,900 tons during WY 2006. Of this latter quantity, 34,700 tons were acquired between sites MCm2 and MCm3.

Dissolved-Solids Load Partitioned by Transport Flow Component

Estimates of the dissolved-solids loads transported in baseflow, snowmelt runoff, or direct runoff could be used to evaluate the application of salinity-control measures that may reduce salt loading associated with one of these streamflow components. Consequently, the dissolved-solids loads in Muddy Creek at sites MCm1, MCm2, and MCm3 during WYs

Table 10. Summary of annual dissolved-solids loads at select sites on Muddy Creek, Utah, water years 2005–06.

[—, no data or not computed]

Flow component	Water year 2005					Water year 2006				
	Total load, in tons	Yield, in tons per square mile	Minimum daily load, in tons	Average daily load, in tons	Maximum daily load, in tons	Total load, in tons	Yield, in tons per square mile	Minimum daily load, in tons	Average daily load, in tons	Maximum daily load, in tons
Site MC, Muddy Creek, near Emery										
Total flow	17,700	169	5	48	310	12,500	119	4	34	197
Site MCm1, Muddy Creek below I-70, near Emery										
Total flow	24,600	59	9	67	952	26,000	62	11	71	285
Baseflow	11,600	—	9	32	77	16,400	—	11	45	78
Snowmelt[1]	6,260	—	18	123	251	4,920	—	0	83	235
Direct runoff	6,790	—	0	19	793	4,660	—	0	13	203
Site MCm2, Muddy Creek at Tomsich Butte, near Hanksville										
Total flow	—	—	—	—	—	38,200	52	24	105	1,020
Baseflow	—	—	—	—	—	24,500	—	24	67	97
Snowmelt[1]	—	—	—	—	—	4,380	—	19	83	126
Direct runoff	—	—	—	—	—	9,370	—	0	26	951
Site MCm3, Muddy Creek at mouth, near Hanksville										
Total flow	93,400	60	18	256	3,720	72,900	47	0	200	6,150
Baseflow	42,600	—	18	117	310	41,100	—	0	113	256
Snowmelt[1]	8,660	—	0	144	347	5,640	—	0	90	193
Direct runoff	42,100	—	0	115	3,270	26,100	—	0	72	6,080

[1]Statistical summaries for the snowmelt component are for the period of snowmelt only.

2005–06 were partitioned by the streamflow component in which they were transported.

Dissolved-solids transport by the various flow components varied from WY 2005 to WY 2006 (fig. 15), particularly at site MCm3 at the mouth of Muddy Creek. Because of the frequency and magnitude of storms, the amount of dissolved solids transported in direct runoff was much larger in WY 2005 than in WY 2006. Less than normal snowfall in the headwaters resulted in a smaller amount of dissolved solids being transported in WY 2006 than in WY 2005. There was little change in the amount of dissolved solids transported in baseflow at site MCm3; however, the amount of dissolved solids transported in baseflow was 40 percent larger in WY 2006 than in WY 2005 at site MCm1.

The estimates of dissolved-solids loads associated with baseflow were derived using the procedure discussed in the Methods section on Baseflow Dissolved-Solids Load. There is uncertainty in these estimates (and those subsequently derived for the dissolved-solids loads associated with snowmelt and direct runoff) that is associated with (1) the streamflow partitioning procedures, (2) the determination of baseflow dissolved-solids concentrations, and (3) the determination of daily dissolved-solids loads. These estimates are provided for general purposes of comparison among monitoring sites

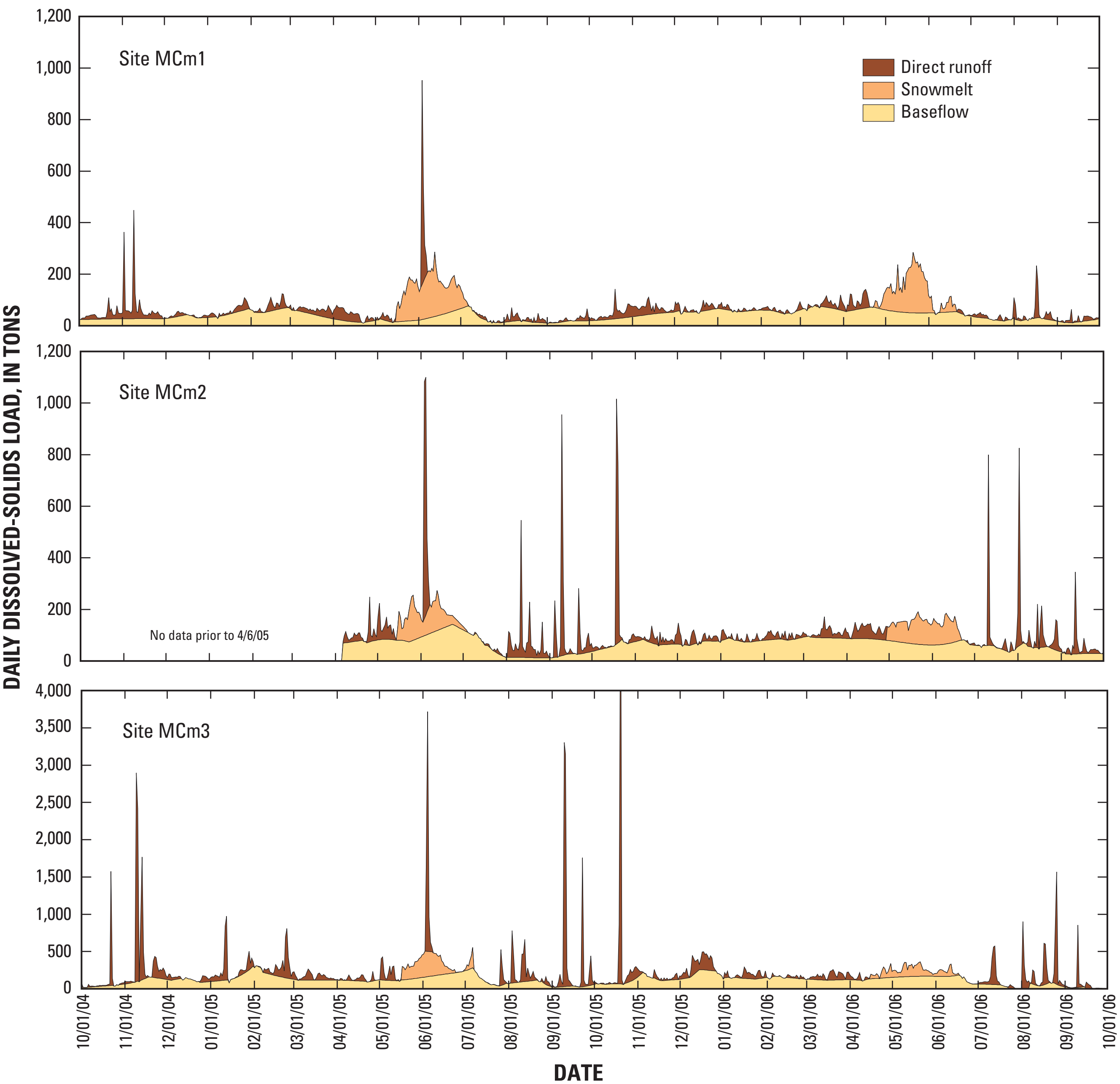

Figure 15. Relation of estimated daily dissolved-solids loads associated with baseflow, snowmelt runoff, and direct runoff at water-quality monitoring sites MCm1, MCm2, and MCm3, Muddy Creek, Utah, water years 2005–06.

within the Muddy Creek Basin and with values in the literature from other basins.

Baseflow

The baseflow component of streamflow at monitoring sites on Muddy Creek transported more dissolved solids during WYs 2005–06 than either snowmelt runoff or direct runoff. The annual dissolved-solids load in baseflow ranged from 11,600 tons at site MCm1 in WY 2005 to 42,600 tons at site MCm3 in WY 2005 (table 10). On average, 53 percent of the annual dissolved-solids loads estimated to be transported past the three monitoring sites on Muddy Creek during WYs 2005–06 were associated with baseflow. During WY 2005, there were 31,000 tons of dissolved solids added to Muddy Creek in baseflow discharged between sites MCm1 and MCm3. During WY 2006, there were 24,700 tons of dissolved solids added to Muddy Creek in baseflow discharged between sites MCm1 and MCm3. Of these, 8,100 tons of dissolved solids were added to Muddy Creek in baseflow between sites MCm1 and MCm2, and 16,600 tons were added in baseflow between sites MCm2 and MCm3.

Snowmelt

During WYs 2005–06, snowmelt runoff, on average, accounted for about 37 percent of the total flow at sites MCm1, MCm2, and MCm3. The dissolved-solids loads associated with snowmelt runoff, however, averaged about 12 percent of the total dissolved-solids loads at these sites. The annual dissolved-solids loads in snowmelt runoff ranged from 4,380 tons at site MCm2 to 8,660 tons at site MCm3. Because of a smaller-than-normal snow pack in the Muddy Creek headwaters during WY 2006, dissolved-solids loads in snowmelt runoff during that year were 21 percent smaller at site MCm1 and 35 percent smaller at the mouth of Muddy Creek compared with loads during WY 2005.

Direct Runoff

As much as 45 percent of the dissolved solids transported by Muddy Creek were associated with direct runoff from storms. While the baseflow component of the dissolved-solids load in Muddy Creek was relatively constant from day to day, the direct-runoff component was variable. For example, on October 17, 2005, there were 10 tons of dissolved solids transported in direct runoff in Muddy Creek at site MCm3, but on October 19, 2005, there were 6,080 tons of dissolved solids (8.3 percent of the annual total) transported past site MCm3 in direct runoff. There were many days when there was no direct runoff or associated dissolved-solids load in Muddy Creek. The annual dissolved-solids loads in direct runoff ranged from 4,660 tons at site MCm1 during WY 2006 to 42,100 tons at site MCm3 during WY 2005. During WY 2005, there were 35,310 tons of dissolved solids added to Muddy Creek in direct runoff between sites MCm1 and MCm3. During WY 2006, there were 21,440 tons of dissolved solids added to Muddy Creek in direct runoff between sites MCm1 and MCm3. Of these, 4,700 tons were acquired between sites MCm1 and MCm2, and 16,700 tons were acquired between sites MCm2 and MCm3.

Areas that contributed substantial dissolved-solids loads to Muddy Creek through direct runoff, such as the lower basin of Muddy Creek, might have reduced loading if salinity-control measures are maintained or additional salinity-control measures are applied. For example, construction of spreader dikes, which reduce down cutting in ephemeral stream channels, could reduce the dissolved-solids loads associated with direct runoff from storms.

Dissolved-Solids Yields

The average annual yield of dissolved solids, in tons of dissolved solids per square mile per year ([tons/mi^2]/yr), from the Muddy Creek Basin was determined so that land managers could compare the yield among subbasins in the study area as well as with values published for other basins. Dissolved-solids yields were determined for the aggregate area above each of the monitoring sites (tables 7 and 10) and for the area contributing dissolved solids to Muddy Creek between each of the monitoring sites (WY 2006 only) (fig. 16).

Upstream of site MC during WYs 2005 and 2006, the average yield of dissolved solids from the basin was 169 and 119 (tons/mi^2)/yr, respectively. The yields from this part of the basin are much higher than those from the rest of the basin, probably because of the much higher precipitation rates. The average yields from the entire basin upstream of site MCm1 during WY 2005 and WY 2006 were 59 and 62 (tons/mi^2)/yr, respectively. These yields represent the composite yield from agricultural, developed, and undeveloped (natural) lands in the upper Muddy Creek Basin as well as point discharges, such as the SUFCO mine. The average yield at site MCm1 is much less than at site MC mainly because runoff in the basin between these sites is much less than that upstream of site MC, but also because dissolved solids distributed through irrigation are possibly being stored in soil and alluvium, and some of the dissolved solids measured at site MC are exported to the San Rafael River Basin (Natural Resources Conservation Service, 2004). The average yield from the entire basin upstream from site MCm3 was 60 and 47 (tons/mi^2)/yr during WYs 2005 and 2006, respectively. The dissolved-solids yield between sites MCm1 and MCm3 during WYs 2005–06 was 60 and 41 (tons/mi^2)/yr, respectively. This portion of the Muddy Creek Basin is almost entirely undeveloped natural lands of which

Figure 16. Dissolved-solids yields, in tons per square mile, from selected subbasins of the Muddy Creek Basin, Utah, 2006.

approximately 80 percent are administered by BLM and most of the remainder is administered by the USFS, the NPS, and the School and Institutional Trust Lands Administration.

For WY 2006, dissolved-solids yields were calculated for the area contributing dissolved solids to the stream reach between monitoring sites (fig. 16). The average dissolved-solids yields from undeveloped lands upstream of site MC was 119 (tons/mi^2)/yr. The developed and undeveloped land contributing dissolved solids to Muddy Creek between sites MC and MCm1 yielded 43.4 (tons/mi^2)/yr of dissolved solids. The average dissolved-solids yields from the contributing subbasins between sites MCm1 and MCm2 was 39.1 (tons/mi^2)/yr; the smallest yield of those areas shown in figure 16. The smaller average yield may be due, in part, to the lower elevation and smaller amount of precipitation in the headwaters of this area relative to those found in the other areas on figure 16. The average dissolved-solids yields from the contributing subbasins between sites MCm2 and MCm3 was 42.1 (tons/mi^2)/yr.

Contribution of Dissolved Solids to Muddy Creek from Selected Areas

Salt Wash

Salt Wash discharges to Muddy Creek about 1 mi downstream from the eastern edge of the San Rafael Reef between sites MCm2 and MCm3 (fig. 1). It is the only perennial Muddy Creek tributary downstream from the confluence of Muddy and Ivie Creeks. Because of its perennial nature and the salinity of its water, Salt Wash (photo 4) is a significant contributor to the dissolved-solids load transported by Muddy Creek, particularly during periods when baseflow is the principal flow component at the mouth of Muddy Creek. Salt Wash has its headwaters in the Fish Lake Mountains at elevations that exceed 11,000 ft; however, snowmelt does not generally provide sustained flow in Salt Wash or its principal tributaries upstream of Caine Springs during the spring. Summertime convective storms or prolonged periods of moist southerly flow produce large flow events in Salt Wash that result in large amounts of water and dissolved solids discharging to Muddy Creek. During stream-stage monitoring in Salt Wash from June 2005 to May 2006, there were nine events where stage increased more than 1 ft. Bank cutting and subsequent dissolution of alluvial material and dissolution and transport of efflorescent salts are some of the processes occurring during these events that mobilize large quantities of dissolved solids into Muddy Creek. An event on September 21, 2005, produced a stage increase of 3.26 ft in Salt Wash, and dissolved-solids concentrations changed from 6,100 mg/L prior to the event to 3,400 mg/L at the peak of flow. When this flood reached the gage at the mouth of Muddy Creek, the flow at the gage increased from 1.7 ft^3/s to 300 ft^3/s in 15 min, then rose to an initial peak of 539 ft^3/s 30 min later. Assuming that the flood flow from Salt Wash was responsible for the initial rise in discharge at the mouth of Muddy Creek, the estimated initial discharge from Salt Wash was about 400 ft^3/s. Assuming a peak-flow discharge of 400 ft^3/s and a dissolved-solids concentration of 3,400 mg/L, the estimated dissolved-solids load being discharged at the peak of flow in Salt Wash on the afternoon of September 21 was 3,670 tons/d, contributing about 75 percent of the dissolved-solids load at the mouth of Muddy Creek during the initial flood peak on September 21.

The dissolved solids in baseflow discharged from Salt Wash to Muddy Creek were measured in the 1980s by the

Photo 4. Salt Wash, Muddy Creek Basin, Utah, May 2005. (Photo credit: Steven Gerner, USGS, Salt Lake City, Utah)

Bureau of Reclamation (1987) and identified as a controllable source of salinity. However, collection of dissolved solids in Salt Wash baseflow and subsequent disposal by deep-well injection was determined at the time to be uneconomical. Measurements of streamflow, specific conductance, and dissolved-solids concentration were made in Salt Wash during WYs 2005–06 to provide a basis for comparing the dissolved solids discharged from Salt Wash during the 1980s with those discharged during WYs 2005–06.

Baseflow in Salt Wash originates from ground water that is principally discharged from the Caine Springs complex (fig. 1). This complex of springs occupies about 30 acres located on the northern side of Salt Wash about 8 mi upstream from the confluence of Salt Wash and Muddy Creek. In Salt Wash above Caine Springs, flow is ephemeral. There are minor seeps and springs in Salt Wash between Caine Springs and the mouth, but their contribution to flow and dissolved solids in Salt Wash is relatively minor. Water from Caine Springs is a sodium–chloride type. The main constituents of this water—sodium, chloride, and sulfate—are from dissolution of halite and gypsum in the Carmel Formation (Hood and Danielson, 1981; Rittmaster and Mueller, 1986). The total discharge from the springs in January 2006 was about 2.0 ft^3/s. The specific conductance measured in January 2006 in the largest outflow from the spring complex was 9,490 µS/cm; however, the specific conductance measured in several other outflows ranged from 6,270 to 9,510 µS/cm. The temperature of water in Caine Springs outflow varied from 6.0 to 14.4°C. These variations in specific conductance and water temperature suggest mixing between water in the Carmel Formation and upward leaking water from the underlying Navajo Sandstone, as has been reported by Hood and Danielson (1981). The average discharge from Caine Springs in the early 1980s was reported to have been 2.1 ft^3/s and to have had an average dissolved-solids concentration of 5,750 mg/L (Bureau of Reclamation, 1987). These values are in close agreement with the measurements and sample results from the January 2006 visit to Caine Springs (table 2), indicating that Caine Springs discharged about 11,300 tons of dissolved solids annually for the past 25 yr and is likely to do so for the foreseeable future.

Periodically, flow and specific conductance were measured and dissolved-solids samples were collected in Salt Wash at the Emery–Wayne County Line during May 2005 to May 2006 (table 2). The average baseflow measured at this site (not including January 2006 measurements that were affected by upstream ice dams) was 2.3 ft^3/s, and the average dissolved-solids concentration (from ROE) was 6,440 mg/L. Extrapolating from those values, the estimated daily and annual baseflow dissolved-solids load at this site was 40 tons/d and 14,600 tons/yr, respectively. Average flow and dissolved-solids concentration in the early 1980s were reported to be 2.4 ft^3/s and 5,590 mg/L from sum of constituents, respectively, and the average annual dissolved-solids load was 13,400 tons/yr (Bureau of Reclamation, 1987). An additional 2,000 to 3,300 tons of dissolved solids were reported by BOR to be discharged annually directly to Muddy Creek from shallow ground water in Salt Wash alluvium.

Muddy Creek Between Sites MCm1 and MCm2

The potential for reducing salt loading to Muddy Creek from that part of the basin contributing dissolved solids to the Muddy Creek reach between sites MCm1 and MCm2 (fig. 1), particularly South Salt Wash, was studied in the 1980s by the Bureau of Reclamation (1987). Because salt loading from this area continues to be of interest to land managers, water samples were collected and streamflow measurements were made in Muddy Creek between sites MCm1 and MCm2 from April 6 to April 8, 2005, to identify specific areas contributing to the dissolved-solids load in Muddy Creek baseflow. During this period, the daily mean streamflow at site MCm1 increased from 30 to 40.5 ft^3/s; however, the daily mean dissolved-solids load varied less than 4 percent. During the period that samples were being collected, no surface runoff was observed discharging to Muddy Creek between sites MCm1 and MCm2; so the dissolved solids measured in the stream in this reach were being discharged to the stream in ground water. During April 6–8, 2005, the average increase in dissolved-solids load between sites MCm1 and MCm2 was 26 tons/d; much of the dissolved solids were discharged to Muddy Creek downstream of South Salt Wash (fig. 17, table 11). Data suggest that there were apparently 15 tons of dissolved solids stored between site MCm1 and site MCs2 just downstream of the mouth of South Salt Wash. These dissolved solids may have been stored in the alluvium, transported past synoptic sites in subsurface flow paths, or lost in recharge to the aquifer, but their actual fate is unknown. There were 7 tons of dissolved solids discharged to the stream in the reach from South Salt Wash to just above Cat Canyon. Most of these could have originated from South Salt Wash and been discharging in ground water from the fan of alluvial material that extends nearly a mile downstream from South Salt Wash. The largest increase in dissolved-solids concentration occurred in this reach and it is probably associated with the high concentration of dissolved solids in water from South Salt Wash (27,000 mg/L, table 2). Downstream from South Salt Wash, Muddy Creek bisects the Carmel Formation forming a deep canyon. Water samples were collected within this canyon in the vicinity of Cat Canyon and Willow Springs Wash. From above Cat Canyon (site MCs3) to below Willow Springs Wash (site MCs6), there were 32 tons of dissolved solids discharged to Muddy Creek. From below Willow Springs Wash (site MCs6) to Tomsich Butte (site MCm2), there were an additional 2 tons of dissolved solids discharged to the stream. From Tomsich Butte downstream to the mouth of Muddy Creek, there were,

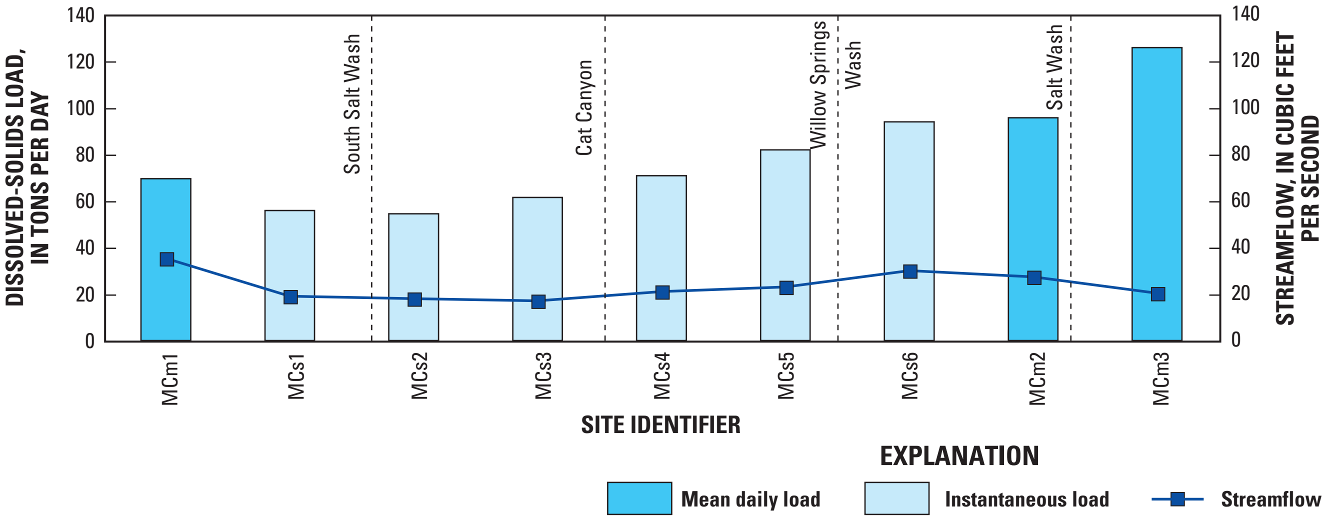

Figure 17. Distribution of streamflow and dissolved-solids loads at select sites on Muddy Creek, Utah, April 6–8, 2005.

Table 11. Dissolved-solids concentration and load at selected sites on Muddy Creek, Utah, April 6–8, 2005.

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; ROE, residue on evaporation at 180°C; tons/d, tons per day; —, not applicable]

Site identifier	Site name	Sample date	Stream flow (ft^3/s)	Dissolved solids, ROE, filtered (mg/L)	Dissolved-solids load (tons/d)	Apparent change in dissolved-solids load from upstream site (tons/d)	Net change in dissolved-solids load from site MCm1 (tons/d)
MCm1	Muddy Creek below I-70, near Emery	[1]—	35.2	743	69	—	—
MCs1	Muddy Creek at Lone Tree Crossing	04/06/2005	19	1,090	56	–14	–14
MCs2	Muddy Creek below South Salt Wash, near Emery	04/06/2005	18	1,120	54	–1	–15
MCs3	Muddy Creek above Cat Canyon, near Emery	04/06/2005	17	1,340	61	7	–8
MCs4	Muddy Creek below Cat Canyon, near Emery	04/07/2005	21	1,250	71	9	2
MCs5	Muddy Creek above Willow Springs Wash, near Emery	04/07/2005	23	1,320	82	11	13
MCs6	Muddy Creek below Willow Springs Wash, near Emery	04/08/2005	30	1,160	94	12	25
MCm2	Muddy Creek at Tomsich Butte, near Hanksville	[1]—	27.4	1,310	96	2	27
MCm3	Muddy Creek at mouth, near Hanksville	[1]—	20.3	2,290	126	30	57

[1]Streamflow, dissolved-solids concentration, and dissolved-solids load values are the average of daily mean values for 4/6/05–4/8/05.

on average, 30 additional tons of dissolved solids accumulated in the stream. Because there are, on average, about 40 tons/d of dissolved solids discharged to Muddy Creek in baseflow from Salt Wash, it appears that some dissolved solids are being stored in this reach or are not being measured in surface water at site MCm3.

Relation of Storms in Muddy Creek Basin and Dissolved-Solids Transport at Site MCm3

Once dissolved solids are actively being transported by direct runoff in Muddy Creek, they will likely move downstream into the Dirty Devil River with little or no opportunity for land managers to mitigate their movement. Twenty-eight storms that occurred in the Muddy Creek Basin (fig. 18) during WY 2005 were studied to identify relations between dissolved solids transported to the mouth of Muddy Creek (site MCm3) in direct runoff from these storms and the location and physical characteristics of the storms. Basin characteristics associated with the location of storms that resulted in higher dissolved-solids concentrations and larger dissolved-solids loads at site MCm3 and produced higher runoff efficiencies were identified.

The estimated total volume of precipitation in the Muddy Creek Basin from each of the storms ranged from 4,210 to 122,000 acre-ft and the dissolved-solids load in total direct runoff from these storms ranged from 72 to 6,830 tons (fig. 18,

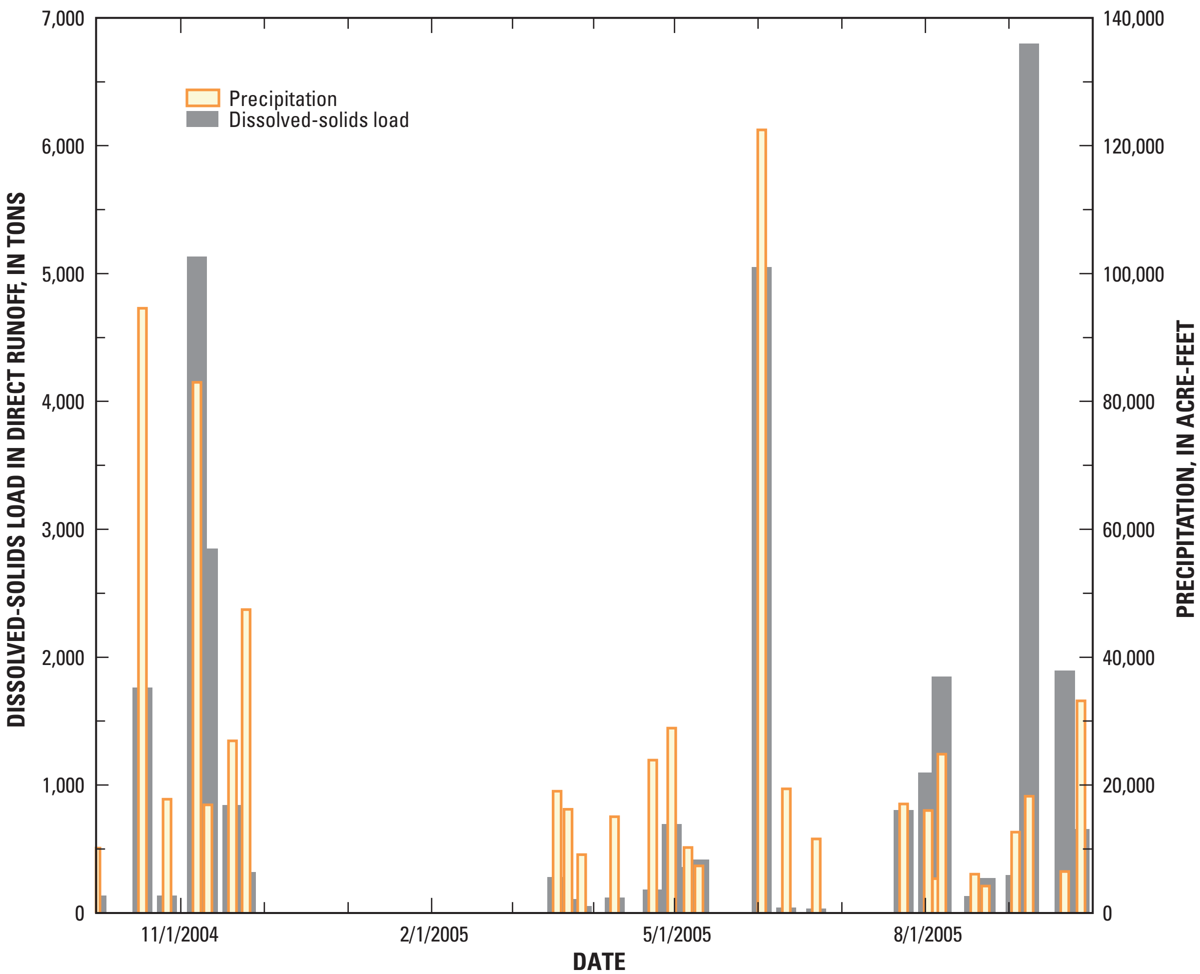

Figure 18. Precipitation from storms in the Muddy Creek Basin and the dissolved-solids loads in direct runoff associated with those storms at water-quality monitoring site MCm3, October 2004 to September 2005, Muddy Creek, Utah.

table 6). A storm in September coincided with the largest dissolved-solids load in storm-related runoff (6,830 tons), yet the estimated total volume of precipitation from this storm was near the median for all storms (17,000 acre-ft). Some of these storms were locally intense. A storm that occurred on June 2 and 3, 2005, had an estimated 24-hour precipitation rate as high as 4.37 in. in some portions of the Muddy Creek Basin.

The following characteristics were chosen to describe the storms that occurred in the Muddy Creek Basin during WY 2005 (table 6):

1. season in which the storm occurred
2. age classification of the dominant geologic formation in which precipitation fell
3. dominant hydrologic unit in which precipitation fell
4. dominant elevation range in which precipitation fell
5. percentage of precipitation that fell on impermeable soils
6. percentage of precipitation that fell on barren land
7. percentage of precipitation that fell on Colorado Plateau Mixed Bedrock Canyon and Tableland[5] SWReGAP land cover
8. percentage of precipitation that fell on slopes of 3 degrees or less

Metrics describing runoff at site MCm3 associated with rainfall events were computed for WY 2005 storms (table 6). The relations between storm location and these metrics were explored; however, because of small sample sizes and large sample variability, no significant differences were detected between storms that occurred in different areas of the basin. Some of the boxplots examined in this analysis do provide empirical evidence that the location of a storm in the Muddy Creek Basin does influence the resulting transport of dissolved solids at site MCm3. For example, graph A in figure 19 illustrates that at least half of the storms that

[5]The Colorado Plateau Mixed Bedrock Canyon and Tableland is a land cover defined in the Southwest Regional Gap Analysis Project that is comprised of barren and sparsely vegetated landscapes (USGS National Gap Analysis Program, 2005).

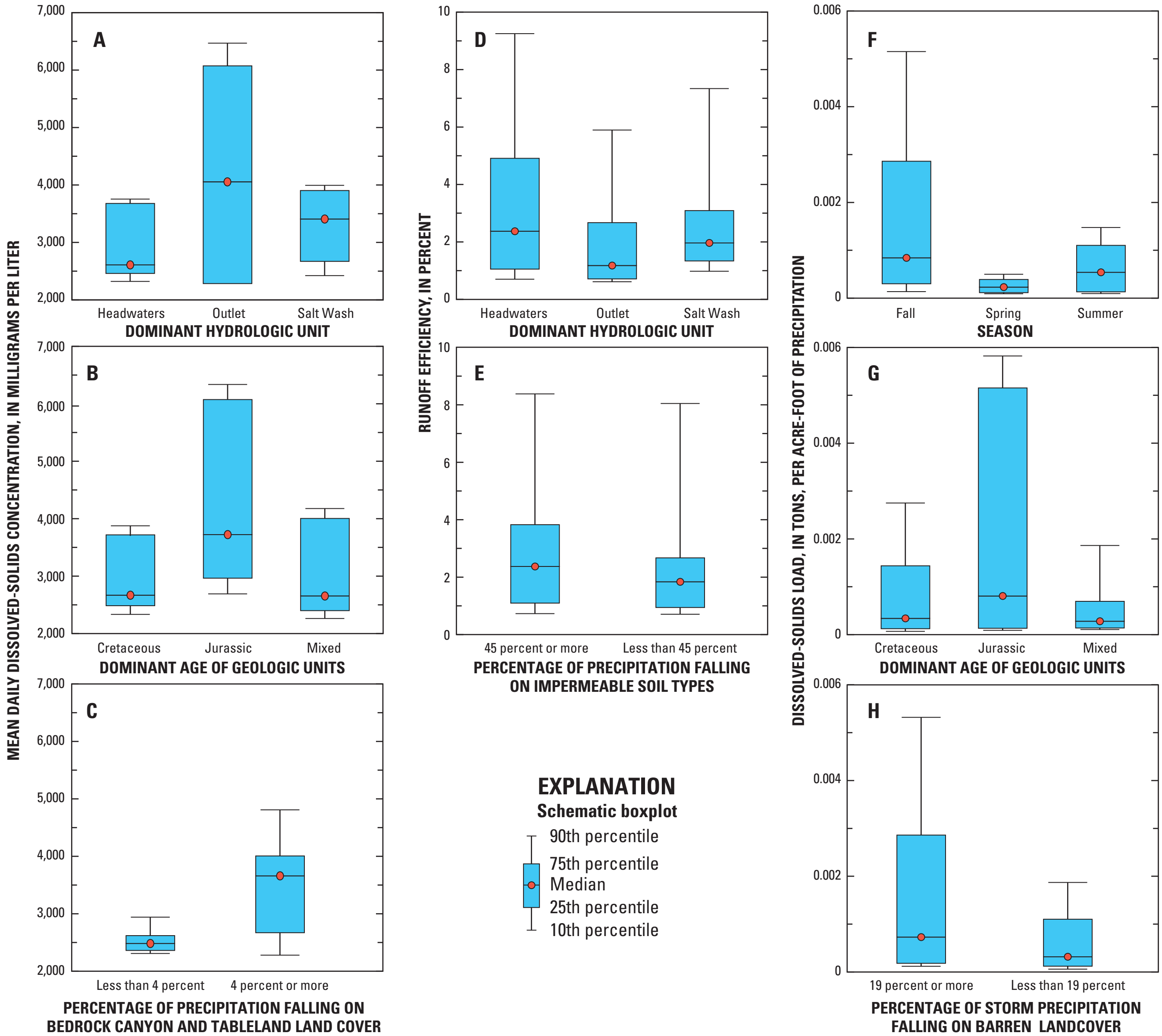

Figure 19. Relation of mean daily dissolved-solids concentrations, runoff efficiency, or dissolved-solids loads per acre-foot of precipitation in runoff at site MCm3 during rain events to select basin characteristics describing where the precipitation occurred in the Muddy Creek Basin, Utah.

occurred principally in the Outlet Muddy Creek hydrologic unit resulted in mean daily dissolved-solids concentrations at site MCm3 greater than 4,000 mg/L, whereas 90 percent of the storms that occurred principally in other hydrologic units resulted in dissolved-solids concentrations of less than 4,000 mg/L. Higher dissolved-solids concentrations also resulted from storms that occurred principally on Jurassic-age geologic formations and storms in which more precipitation fell on Colorado Plateau Mixed Bedrock Canyon and Tableland land cover. Higher runoff efficiencies were associated with more storms that occurred principally in the Headwaters Muddy Creek hydrologic unit or occurred on larger areas of impermeable soil types than other types of storms (fig. 19, graphs D and E). Storms that occurred on larger areas of Jurassic-age geologic formations, or on larger areas of barren land, more often resulted in the transport of at least 1 ton of dissolved solids at site MCm3 per 1,000 acre-ft of precipitation in the Muddy Creek Basin (fig. 19, graphs G and H).

Dissolved Solids Transported by a 10- to 25-Year Flood

Rain storms in the southwest desert can be spectacular events to witness. Meloy (2005) described one of these storms like this:

> And so it came: sky heavier than earth, migraine lightning, thunder you felt between your shoulder blades. The azure sky turned the color of granite. A sudden wall of wind preceded not showers but torrents. Sheets of rain drenched the desert, swelled the river to an astounding volume.

A storm that occurred in the Muddy Creek Basin during October 5–7, 2006, may have had some of the same characteristics. The October storm resulted from a moisture-laden air mass that moved across the basin from the south depositing an average of about 2.4 in. of rain (196,000 acre-ft) in the basin. From NCEP data, apparent rainfall during this storm ranged from 0.91 in. to 4.62 in. (fig. 20). The most intense rainfall occurred in the Wild Horse Creek and Outlet Muddy Creek hydrologic units. This storm produced a peak streamflow at the mouth of Muddy Creek of 7,150 ft^3/s. This was the largest recorded streamflow event in the Muddy Creek Basin. A recurrence interval for this storm of between 10 and 25 yr was determined using eight annual streamflow peaks and computation methods described in U.S. Interagency Advisory Committee on Water Data (1982). The stream channel was scoured more than a foot at site MCm3 at the mouth of Muddy Creek, exposing the underlying bedrock (photo 5).

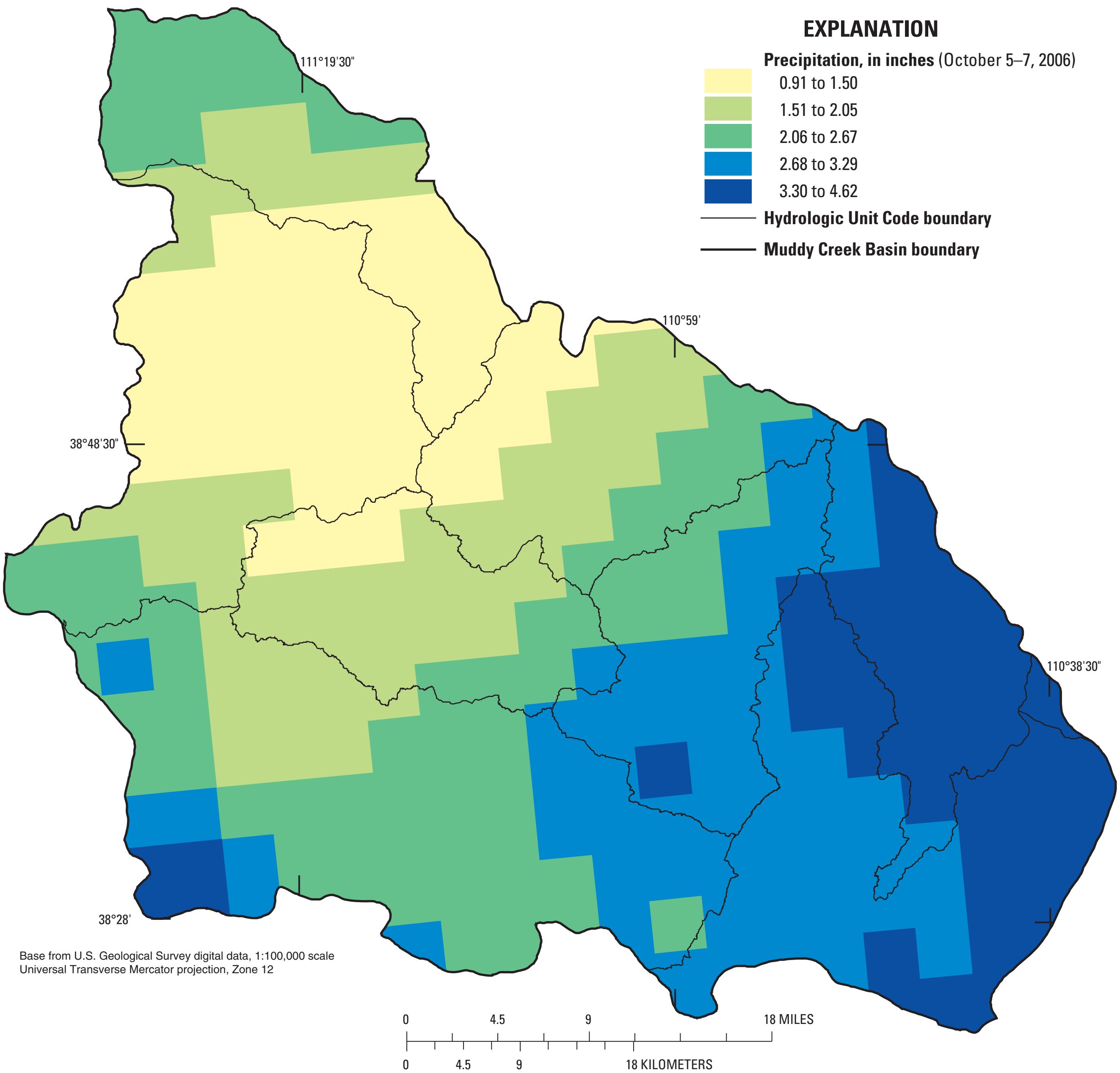

Figure 20. Distribution of rainfall in the Muddy Creek Basin, Utah, October 5–7, 2006.

Photo 5. Scoured stream channel at water-quality monitoring site MCm3, Muddy Creek at mouth, near Hanksville, Utah, July 12, 2007. The objects near the center of the photograph are a specific-conductance field meter and case. (Photo credit: Steven Gerner, USGS, Salt Lake City, Utah)

There were no measurements of specific conductance or dissolved-solids made during this event; however, linear regression of total dissolved-solids flux for a storm and the peak (maximum) streamflow for that storm was performed to provide a predictive tool for estimating dissolved-solids load transported by large rainfall events on Muddy Creek. The explanatory variable for this regression was the peak streamflow from 10 storms during WYs 2005–06, and the response variable for this regression was the dissolved-solids load in runoff from those storms. The best regression model was specified by limiting the explanatory dataset to storms with peak streamflows greater than 460 ft^3/s. The estimated linear relation between peak streamflow and total dissolved-solids flux is shown in figure 21 and described in the following equation:

$$TDS\_Flux = 5.0536 \times MaxQ - 1{,}134.5 \qquad (3)$$

Where

TDS_Flux is the total dissolved solids transported past site MCm3 in runoff from a storm, and

$MaxQ$ is the maximum streamflow at site MCm3 during the event.

By applying a maximum instantaneous streamflow of 7,150 ft^3/s in equation 3, the estimated total amount of dissolved solids transported in runoff from the storm of October 5–7 was 35,000 tons, which represents about 51 percent of the average annual dissolved-solids load for the period of record at site MCm3. However, the largest peak streamflow in the explanatory variable dataset used to develop the regression model shown in equation 3 was 1,740 ft^3/s, so the error associated with estimates derived from an extension of this linear relation beyond that streamflow may be large. The only other flood of similar magnitude recorded at this site occurred in September 1980. The maximum streamflow for this event was 5,000 ft^3/s (which has a recurrence interval of between 5 and 10 yr), and the estimated dissolved-solids load transported by runoff from this storm was 28,000 tons (from daily load estimates generated using the S-LOADEST software). The estimated annual dissolved-solids load at site MCm3 in 1980 was the largest during the period of record. Obviously, in a year in which this type of event happens, there is a much better chance that the dissolved-solids load transported from the Muddy Creek Basin will be greater-than-average, and the effect on dissolved-solids in the Colorado River will be larger.

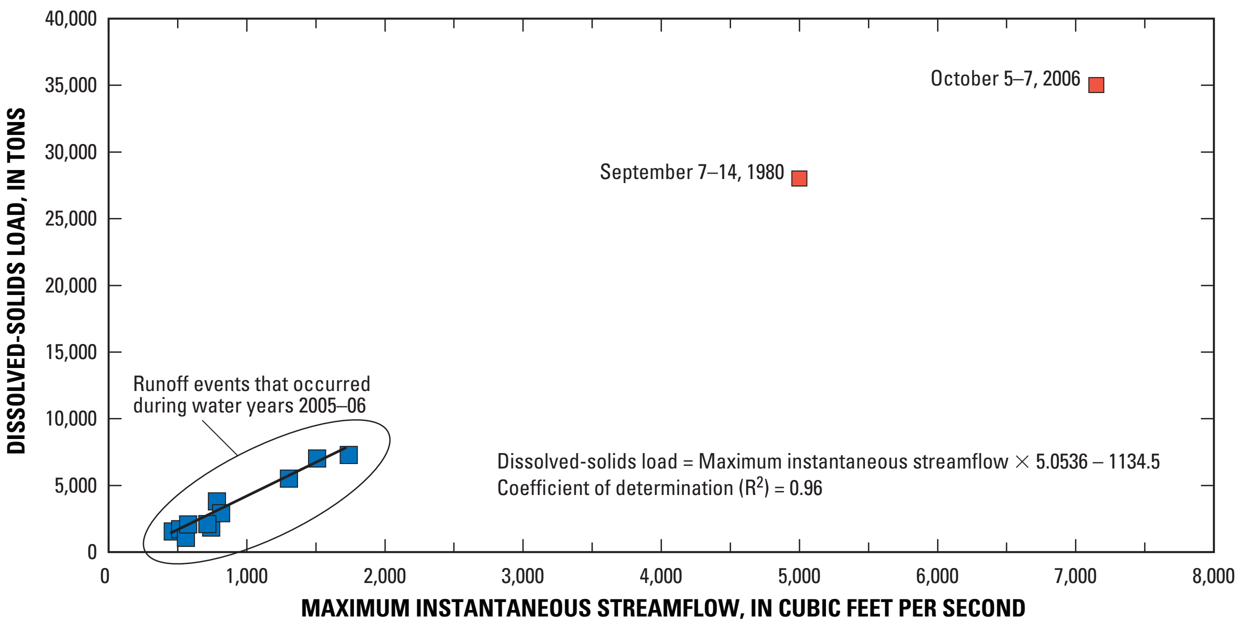

Figure 21. Relation of maximum instantaneous streamflow and total dissolved-solids loads associated with select runoff events at site MCm3.

Trends in Dissolved-Solids Concentrations in Muddy Creek

Dissolved solids in Muddy Creek vary in the short term, such as daily or seasonally, mostly because of changes in variables, such as precipitation, temperature, and solar radiation. These variables influence flow paths and surface runoff, soil erosion and chemical reactions. Short-term variations in Muddy Creek dissolved solids have been previously described in this report and can provide some guidance for land and water managers who are developing plans for utilizing Muddy Creek water or reducing dissolved solids in that water. Identification of long-term trends in dissolved solids in Muddy Creek can provide land and water managers a measure of how conditions, such as the drought from 1999 to 2003, or anthropogenic changes, such as salt-load reduction activities on agricultural lands, may have affected dissolved solids in Muddy Creek.

Trends in dissolved-solids concentration at site MCm1 were determined from a time series of dissolved-solids concentration values associated with water samples collected by USGS and EWCD personnel between August 1973 and October 2006 (fig. 22). These data were tested for monotonic trends using the Seasonal Kendall Test in the ESTIMATE TREND (ESTREND) computer program (Shertz and others, 1991). Dissolved-solids concentration values also were flow-adjusted within the ESTREND program and tested again for monotonic trends.

The locally weighted scatter plot smooth (LOWESS [Ott and Longnecker, 2001]) drawn through the unadjusted concentration values shown in figure 22 illustrates the general changes through time of these values. The LOWESS line appears to trend downward; however, there are some hills and valleys that coincide with periods of above- or below-average precipitation in the basin. Dissolved-solids concentrations are initially high, and annual precipitation is below the 1976–2006 water-year average of 858,000 acre-ft. Precipitation was mostly above average during WYs 1978 through 1988, and there is a corresponding decline in dissolved-solids concentrations. During WYs 1989 and 1990, precipitation was below average and dissolved-solids concentrations generally increased. From 1991 through 1999, annual precipitation was mostly above average and dissolved-solids concentrations once again declined; however, mostly below-average precipitation during WYs 2000 through 2004 corresponded to a general leveling of dissolved-solids concentrations. Above-average precipitation during WY 2005 corresponds to a decline in the dissolved-solids concentrations. There was a significant ($p < 0.001$) downward monotonic trend in unadjusted dissolved-solids concentrations from August 1973 to October 2006. The rate of change associated with this trend was –2.13 percent per year. This trend could be attributed to climatic variables that affect streamflow as well as anthropogenic changes in water and land use.

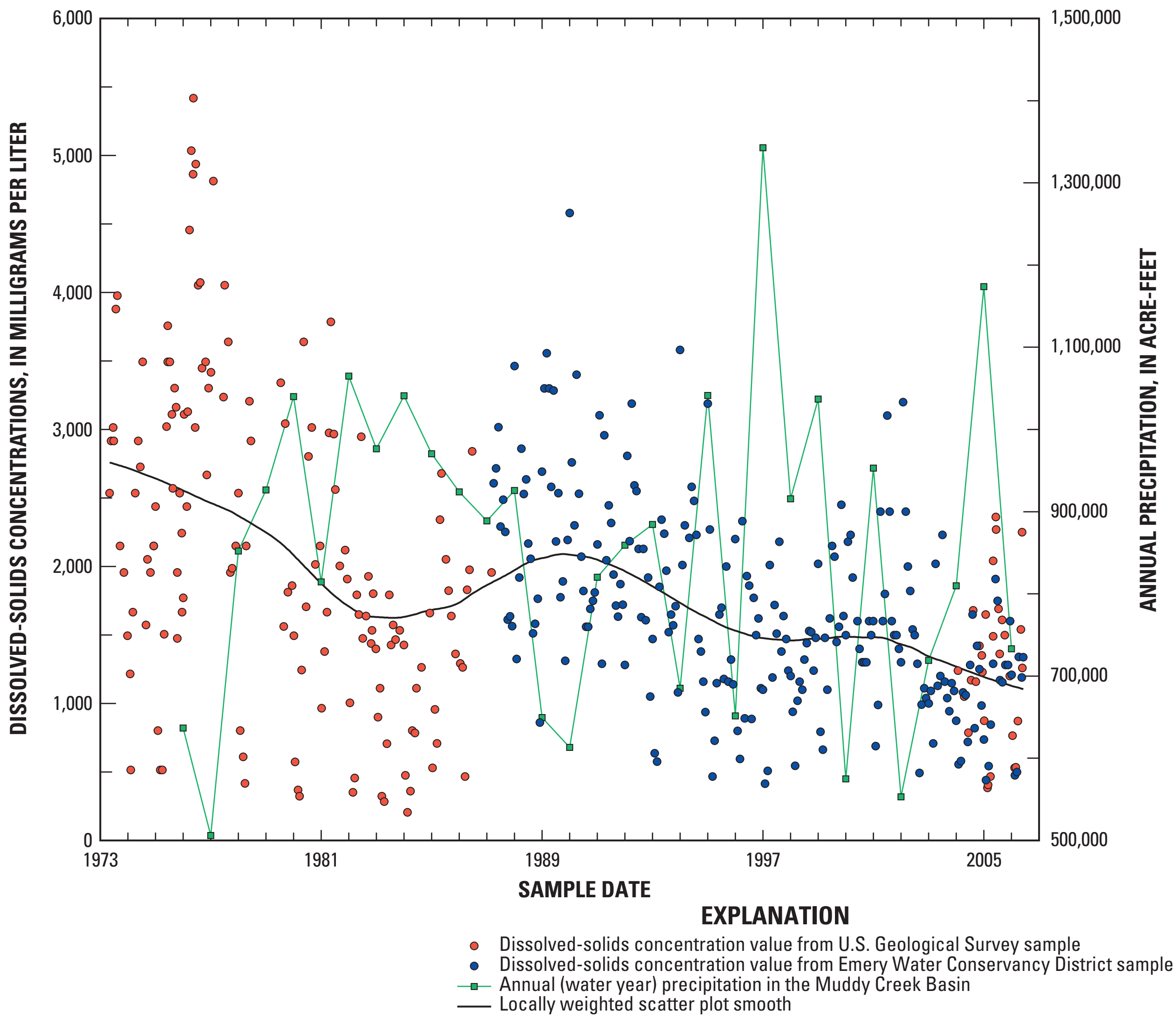

Figure 22. Dissolved-solids concentrations in water from site MCm1, Muddy Creek, Utah, August 1973 to October 2006, and annual precipitation in the Muddy Creek Basin, 1976–2006.

Dissolved-solids concentration data were adjusted for streamflow within the ESTREND program using a LOWESS smooth that was fit to log transformed concentration and log transformed flow data. The flow-adjusted, dissolved-solids concentrations (residuals) should have greatly reduced streamflow-related variability that increases the chance of detecting trends that are the result of some influence other than streamflow. There was a significant ($p < 0.001$) downward monotonic trend in adjusted dissolved-solids concentrations from August 1973 to October 2006. The rate of change was –1.80 percent per year. Because these data were flow-adjusted, the trend identified is less likely to be affected by climate conditions and more fully represents the affects of non-climatic factors that may include improved irrigation methods, water-quality protection measures, or changes in land use. Although variation in concentrations attributed to streamflow was minimized, not all of the effects of climate are accounted for. The climatic factors affecting discharge in a given year may also affect concentrations of dissolved solids in subsequent years. Consider for example, a wet year with above-average precipitation followed by one or more years of below-average precipitation. Variation in salinity concentration attributed to high streamflows was accounted for in the first year. However, during the wet year, there may be a flushing of salts during direct runoff. Such a flushing and diminishment of available salts could result in lower concentrations for a given discharge in subsequent years, which would be observed as a decrease in the adjusted concentrations. Thus, while variation in concentration resulting from variation in streamflow is minimized, climate can still contribute to trends in the adjusted concentration data.

It should be noted that trends in long-term water-quality data may occur because of changes in analytical methods or processing of the water samples. Dissolved solids concentration values reported by EWCD for the period 1988–2006 and the USGS for 2004–06, were determined from ROE. However, the dissolved-solids concentrations reported by the USGS for the period 1973–87 were determined from the sum of major constituents. Because this latter method has been shown to result in dissolved-solids concentration values consistently smaller than those determined from ROE, dissolved-solids concentrations determined from the sum of constituents and those estimated from specific conductance using the relation of sum of constituents to specific conductance, were normalized to ROE using the linear regression represented in equation 4. This equation was derived from the relation of ROE and the sum of major constituents for samples collected during WYs 2004–06:

$$DS_{\mathrm{ROE}} = (DS_{\mathrm{SUM}} \times 1.0974) - 30.559 \qquad (4)$$

Where

DS_{ROE} is the estimated concentration of dissolved solids from ROE in mg/L, and

DS_{SUM} is the concentration of dissolved solids from the sum of major constituents in mg/L.

Additionally, the affect on trends of filtering the samples using filters with different pore sizes is unknown. ROE samples collected by USGS personnel were generally filtered onsite using a 0.45-micron filter, and samples collected by EWCD personnel were filtered in the lab using a filter with a pore size smaller than 2 microns.

Even though there were discontinuities in processing and analytical methods, the trend results are most likely the result of environmental or anthropogenic changes in the basin given the persistent decrease in dissolved-solids concentrations whether the associated samples were collected by USGS or EWCD personnel. Downward trends in dissolved-solids concentrations have been recognized for many sites throughout the Upper Colorado River Basin for various periods from 1947 to 1996 (Vaill and Butler, 1999; Anning and others, 2007), so the identification of a downward trend in dissolved-solids concentrations at site MCm1 is not unexpected.

Hayes (1995) concluded that stream channels in the Upper Colorado River Basin have become more stable during the last 50 yr, and dissolved solids are being stored in channel alluvium, resulting in declines in dissolved-solids concentrations and loads. This may be the case throughout the Muddy Creek Basin; however, there is insufficient data from site MCm3 at the mouth of Muddy Creek to determine if a downward trend in dissolved solids exists there as well. If this is the case in the Muddy Creek Basin, the maintenance of existing stream-channel stabilizing structures, such as spreader dikes and the creation of new structures, may continue to stabilize or reduce the amount of dissolved-solids transported in Muddy Creek.

Trends, such as the downward trend in dissolved-solids concentrations in Muddy Creek at site MCm1, are important considerations for determining the effectiveness of existing salinity-control measures or the implementation of future salinity-control projects. Basin-wide trends in dissolved-solids concentration could be determined if periodic data (including instantaneous streamflow, specific conductance, and dissolved-solids concentration) were collected at the mouth of Muddy Creek.

Summary

The Muddy Creek Basin is drained by Muddy Creek, a tributary of the Dirty Devil River, which, in turn, is a tributary of the Colorado River. Hence, dissolved solids transported from the Muddy Creek Basin have the potential to be discharged to the Colorado River and impact downstream water users. This study used selected dissolved-solids measurements made by various local, State, and Federal agencies from the 1970s through 2006, and additional dissolved-solids data that were collected by the U.S. Geological Survey during April 2004 through November 2006 to compute dissolved-solids loads, determine the distribution of dissolved-solids concentrations, and identify trends in dissolved-solids concentration in surface water of the Muddy Creek Basin. Additionally, the study quantified the amount of dissolved solids transported by Muddy Creek in direct runoff from rain events and identified processes that contribute to that transport.

Because the dissolved-solids load transported by Muddy Creek is a function of the dissolved-solids concentration and streamflow, measurements of specific conductance, dissolved-solids concentration, and streamflow were made in Muddy Creek and tributaries to Muddy Creek between April 2004 and October 2006. Specific conductance was measured each time a site visit was made and these values were used as a surrogate for dissolved-solids concentration when that parameter was not measured. The ratio of dissolved-solids concentration to specific conductance values from water samples collected from Muddy Creek ranged from 0.62 to 1.00.

The dissolved-solids concentration values measured in water samples collected from Muddy Creek during site visits ranged from 385 to 5,950 mg/L; the larger values were generally from water samples collected at the mouth of Muddy Creek where the flow-weighted mean dissolved-solids concentrations were 1,710 mg/L for WY 2005 and 2,070 mg/L for WY 2006. The highest dissolved-solids concentration values measured in the study area were in water samples collected at sites in South Salt Wash (27,000 mg/L) and Salt Wash (4,940 to 6,780 mg/L). These samples were collected from surface flow of which the largest component was ground water discharged from saline springs.

The mean annual dissolved-solids load in Muddy Creek was determined for select water-quality-monitoring sites for WYs 1976–80 and 2005–06. These values were smallest at a site near the headwaters (9,670 tons/yr) and largest at a site at the mouth (68,700 tons/yr). The estimated annual dissolved-solids load discharged at the mouth of Muddy Creek ranged from 11,200 tons/yr (WY 1977) to 142,000 tons/yr (WY 1980). The mean annual yield of dissolved solids from the Muddy Creek Basin during WYs 1976–80 and 2005–06 was 44 tons/mi^2.

The dissolved-solids load transported by Muddy Creek during WYs 2005–06 was partitioned into those loads associated with baseflow, snowmelt runoff, and direct runoff from storms. The baseflow component of the annual dissolved-solids load transported by Muddy Creek averaged 53 percent. The portion of the annual dissolved-solids load transported in snowmelt runoff averaged 12 percent, and the portion of the annual dissolved-solids load transported in direct runoff averaged 35 percent.

The relations between rainfall location and amount and associated streamflow, dissolved-solids concentration, or dissolved-solids load at the mouth of Muddy Creek were studied for storms that occurred during WY 2005. It was determined that most storms with more precipitation occurring in the Outlet Muddy Creek hydrologic unit, on Jurassic-age geologic formations, or on larger areas of Colorado Plateau Mixed Bedrock Canyon and Tableland land cover, resulted in higher dissolved-solids concentrations at the mouth of Muddy Creek. The dissolved-solids load at the mouth of Muddy Creek resulting from direct runoff from a storm, relative to the total amount of precipitation from that storm, was largest when precipitation fell on larger areas of Jurassic-age geology or barren land cover.

For site MCm3 at the mouth of Muddy Creek, the relation of the dissolved-solids load transported in runoff from a storm to the maximum instantaneous streamflow resulting from that runoff was determined. Subsequently, this relation was used to determine the dissolved-solids load transported in runoff from a storm that occurred during October 5–7, 2006. The peak streamflow from this storm was 7,150 ft^3/s—a flow with a 10- to 25-yr recurrence interval. The dissolved-solids load transported in runoff from this storm was estimated to be 35,000 tons or about 51 percent of the average annual dissolved-solids load at the mouth of Muddy Creek.

A significant downward trend in dissolved-solids concentrations from 1973 to 2006 was determined for Muddy Creek at site MCm1. This location divides that portion of the basin containing agricultural land (upstream) from the portion of the drainage with no agricultural land (downstream). Dissolved-solids concentrations decreased about 2.1 percent per year; however, the rate of change was a decrease of 1.8 percent per year when dissolved-solids concentrations were adjusted for flow. This latter trend is less affected by climate conditions and more fully represents the affects of non-climatic factors that may include improved irrigation methods, water-quality protection measures, or changes in land and water use.

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