Prepared in cooperation with the Colorado River Basin Salinity Control Forum

Estimated Dissolved-Solids Loads and Trends for Selected Surface-Water Sites in and near the Uinta Basin, Utah, Water Years 1989–2013

Scientific Investigations Report 2017–5004

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

Cover photograph: View looking north-northwest up the Rock Creek drainage toward the Uinta Mountains (background). Photograph taken by Steve Butterweck, March 5, 2014.

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Conversion Factors, Datums, and Water-Quality Units

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 pounds)	0.9072	megagram (Mg)
ton per acre	224.17	megagram per square kilometer (Mg/km^2)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

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

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

Altitude, as used in this report, refers to distance above the vertical datum.

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

Concentrations of dissolved solids in water are given in milligrams per liter (mg/L).

Abbreviations and Acronyms

LOADEST	Load Estimator statistical package
LOWESS	LOcally WEighted Scatterplot Smoothing technique
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
RLOADEST	Load Estimator embedded into the statistical software package R
ROE	residue on evaporation
SCR	serial correlation of residuals
SOC	sum of constituents
USGS	U.S. Geological Survey
WY	water year

Estimated Dissolved-Solids Loads and Trends for Selected Surface-Water Sites in and near the Uinta Basin, Utah, Water Years 1989–2013

By Susan A. Thiros

Abstract

The U.S. Geological Survey (USGS), in cooperation with the Colorado River Basin Salinity Control Forum, studied trends in dissolved-solids loads at selected sites in and near the Uinta Basin, Utah. The Uinta Basin study area includes the Duchesne River Basin and the Middle Green River Basin in Utah from below Flaming Gorge Reservoir to the town of Green River.

Annual dissolved-solids loads for water years (WY) 1989 through 2013 were estimated for 16 gaging stations in the study area using streamflow and water-quality data from the USGS National Water Information System database. Eight gaging stations that monitored catchments with limited or no agricultural land use (natural subbasins) were used to assess loads from natural sources. Four gaging stations that monitored catchments with agricultural land in the Duchesne River Basin were used to assess loads from agricultural sources. Four other gaging stations were included in the dissolved-solids load and trend analysis to help assess the effects of agricultural areas that drain to the Green River in the Uinta Basin, but outside of the Duchesne River Basin.

Estimated mean annual dissolved-solids loads for WY 1989–2013 ranged from 1,520 tons at Lake Fork River above Moon Lake, near Mountain Home, Utah (UT), to 1,760,000 tons at Green River near Green River, UT. The flow-normalized loads at gaging stations upstream of agricultural activities showed no trend or a relatively small change. The largest net change in modeled flow-normalized load was -352,000 tons (a 17.8-percent decrease) at Green River near Green River, UT.

Annual streamflow and modeled dissolved-solids loads at the gaging stations were balanced between upstream and downstream sites to determine how much water and dissolved solids were transported to the Duchesne River and a section of the Green River, and how much was picked up in each drainage area. Mass-balance calculations of WY 1989–2013 mean annual dissolved-solids loads at the studied sites show that Green River near Jensen, UT, accounts for 64 percent of the load in the river at Green River, UT, while the Duchesne River and White River contribute 10 and 13 percent, respectively.

The flow-normalized dissolved-solids loads estimated at Duchesne River near Randlett, UT, and White River near Watson, UT, decreased by 68,000 and 55,300 tons, or 27.8 and 20.8 percent respectively, when comparing 1989 to 2013. The drainage basins for both rivers have undergone salinity-control projects since the early 1980s to reduce the dissolved-solids load entering the Colorado River. Approximately 19 percent of the net change in flow-normalized load at Green River at Green River, UT, is from changes in load modeled at Duchesne River near Randlett, UT, and 16 percent from changes in load modeled at White River near Watson, UT. The net change in flow-normalized load estimated at Green River near Greendale, UT, for WY 1989–2013 accounts for about 45 percent of the net change estimated at Green River at Green River, UT.

Mass-balance calculations of WY 1989–2013 mean annual dissolved-solids loads at the studied sites in the Duchesne River Basin show that 75,400 tons or 44 percent of the load at the Duchesne River near Randlett, UT, gaging station was not accounted for at any of the upstream gages. Most of this unmonitored load is derived from tributary inflow, groundwater discharge, unconsumed irrigation water, and irrigation tail water.

A mass balance of WY 1989–2013 flow-normalized loads estimated at sites in the Duchesne River Basin indicates that the flow-normalized load of unmonitored inflow to the Duchesne River between the Myton and Randlett gaging stations decreased by 38 percent. The total net decrease in flow-normalized load calculated for unmonitored inflow in the drainage basin accounts for 94 percent of the decrease in WY 1989–2013 flow-normalized load modeled at the Duchesne River near Randlett, UT, gaging station. Irrigation improvements in the drainage basin have likely contributed to the decrease in flow-normalized load.

Reductions in dissolved-solids load estimated by the Natural Resources Conservation Service (NRCS) and the Bureau of Reclamation (Reclamation) from on- and off-farm improvements in the Uinta Basin totaled about 135,000 tons in 2013 (81,900 tons from on-farm improvements and 53,300 tons from off-farm improvements). The reduction in dissolved-solids load resulting from on- and off-farm improvements facilitated by the NRCS and Reclamation in the Price River Basin from 1989 to 2013 was estimated to be 64,800 tons.

The amount of sprinkler-irrigated land mapped in the drainage area or subbasin area for a gaging station was used

to estimate the reduction in load resulting from the conversion from flood to sprinkler irrigation. Sprinkler-irrigated land mapped in the Uinta Basin totaled 109,630 acres in 2012. Assuming conversion to wheel-line sprinklers, a reduction in dissolved-solids load in the Uinta Basin of 95,800 tons in 2012 was calculated using the sprinkler-irrigation acreage and a pre-salinity-control project dissolved-solids yield of 1.04 tons per acre.

A reduction of 72,800 tons in dissolved-solids load from irrigation improvements was determined from sprinkler-irrigated lands in the Ashley Valley and Jensen, Pelican Lake, and Pleasant Valley areas (mapped in 2012); and in the Price River Basin (mapped in 2011). This decrease in dissolved-solids load is 8,800 tons more than the decrease in unmonitored flow-normalized dissolved-solids load (-64,000 tons) determined for the Green River between the Jensen and Green River gaging stations.

The net WY 1989–2013 change in flow-normalized dissolved-solids load at the Duchesne River near Randlett, UT, and the Green River between the Jensen and Green River, UT, gaging stations determined from mass-balance calculations was compared to reported reductions in dissolved-solids load from on- and off-farm improvements and estimated reductions in load determined from mapped sprinkler-irrigated areas in the Duchesne River Basin and the area draining to the Green River between the Jensen and Green River gaging stations. The combined NRCS and Reclamation estimates of reduction in dissolved-solids load from on- and off-farm improvements in the study area (200,000 tons) is more than the reduction in load estimated using the acreage with sprinkler improvements (136,000 tons) or the mass-balance of flow-normalized load (132,000 tons).

Introduction

Degradation of Colorado River water by the addition of dissolved solids from the Green River affects the suitability of the water for municipal, industrial, and agricultural use within the Lower Colorado River Basin. Annually, more than 6 million tons of dissolved solids are discharged from the Colorado River Basin upstream from Lees Ferry, Arizona (Upper Colorado River Basin) (Anning and others, 2007). It is estimated that agricultural activities contribute 40–45 percent of the load, while the remainder is attributed to natural sources (Kenney and others, 2009).

Public laws enacted in 1974 and 1984 established the Colorado River Basin Salinity Control Program, which authorized the planning and construction of numerous salinity-control projects to improve or prevent further degradation in the quality of Colorado River water used by the United States and Mexico (U.S. Department of Interior, 2013). Irrigated agriculture has been the focus of many salinity-control projects in the Colorado River Basin because changes to infrastructure and irrigation practices can yield substantial reductions in the transport of dissolved solids to streams (Natural Resources Conservation Service, 2015a). The goal of the Colorado River Basin Salinity Control Program and its participating federal agencies—the Bureau of Reclamation (Reclamation) and Bureau of Land Management of the U.S. Department of the Interior, and the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture—is the cost-effective reduction of dissolved-solids loads in the Colorado River.

The U.S. Department of Agriculture began implementation of on-farm control projects to reduce dissolved solids in parts of the Uinta Basin in 1980 and Reclamation began working on off-farm irrigation distribution system improvements in 1986. The infiltration of precipitation and irrigation water through mineral laden soils and the underlying rock mobilizes salts and can cause increases in dissolved-solids concentrations in rivers, streams, and drainages in and near the Uinta Basin in northeastern Utah. The study area includes the Uinta Basin, Duchesne River Basin, and the Middle Green River Basin, extending from Flaming Gorge Reservoir to the town of Green River, Utah (fig. 1). The Duchesne River, a major tributary to the Green River, drains the south slope of the Uinta Mountains and irrigated agricultural lands.

The U.S. Geological Survey (USGS), in cooperation with the Colorado River Basin Salinity Control Forum, began a study in 2014 to assess trends in dissolved-solids loads and quantify the effects of salinity-control projects on loads at selected sites in and near the Uinta Basin.

Purpose and Scope

This report presents annual dissolved-solids load data estimated for 16 gaging stations in the Uinta Basin and on the Green River just upstream and downstream of the Uinta Basin for water years (WY) 1989 through 2013 and estimated trends in flow-normalized loads during this period. Specific objectives of the study are to

1. Estimate the annual dissolved-solids load at selected sites in the study area that drain either undeveloped (natural) or agricultural land.

2. Estimate trends in dissolved-solids load at these selected sites.

3. Estimate proportions of the change in dissolved-solids load attributed to natural and agricultural sources.

4. Compare changes in dissolved-solids load attributed to agricultural sources determined from trend analysis to on-farm and off-farm salinity reduction estimates made by NRCS and Reclamation.

Annual dissolved-solids loads from WY 1989 through 2013 were estimated and trends in flow-normalized loads evaluated for selected gaging stations in the study area using streamflow and water-quality data from the USGS National Water Information System (NWIS) database. A water year

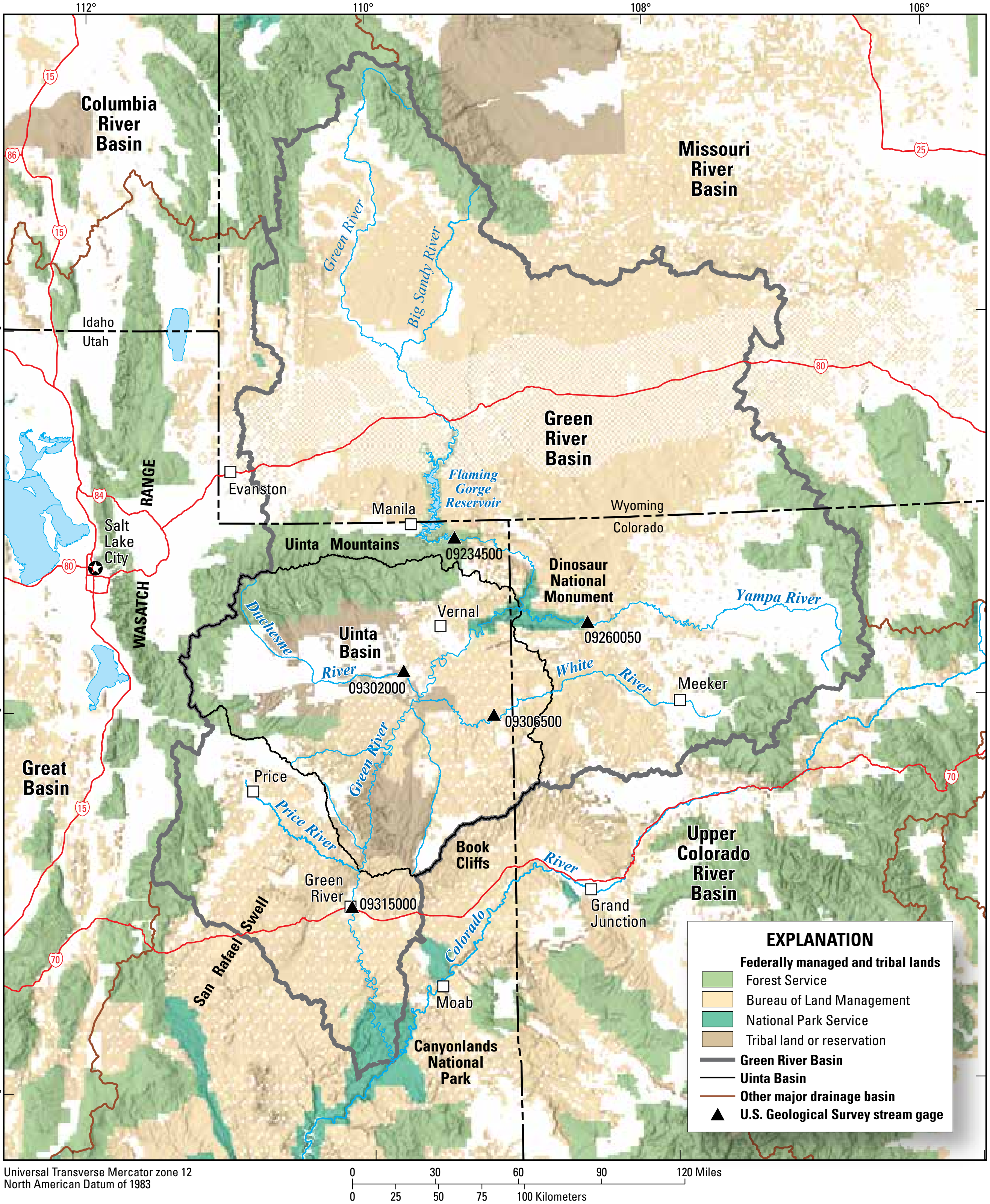

Figure 1. Overview of the Uinta Basin and the Green River Basin in Utah, Colorado, and Wyoming.

(WY) begins on October 1 of the previous year and ends the following September 30 and is designated by the year in which it ends. The gaging stations selected for analysis are listed in table 1 and the location of each site is shown on figure 2. A similar assessment of trends in dissolved-solids loads in the Gunnison River Basin in Colorado was conducted by the USGS in collaboration with the Colorado River Basin Salinity Control Forum (Schaffrath, 2012). For consistency and comparability of results, methods used in that study to calculate dissolved-solids loads and flow-normalized loads at selected sites were used in this study.

The gaging stations were selected on the basis of a review of available streamflow and water-quality data during WY 1989–2013. Eight gaging stations that monitor catchments with limited or no agricultural land use were used to assess dissolved-solids loading from natural sources. Four gaging stations that monitor catchments with agricultural land in the Duchesne River Basin were used to assess dissolved-solids loading from agricultural sources. Five gaging stations in Utah (UT)—Green River near Greendale, UT (09234500), Green River near Jensen, UT (09261000), White River near Watson, UT (09306500), Duchesne River near Randlett, UT (09302000), and Green River at Green River, UT (09315000)—were included in the dissolved-solids load and trend analysis to help assess dissolved-solids loading in the Green River, and the effects of agricultural areas that drain to the Green River in the Uinta Basin. The gaging station Duchesne River near Randlett, UT, is the most downstream site in the Duchesne River Basin and was used in the load and trend analysis to represent loading to the Green River from the basin. Secondarily, these sites were used to evaluate the effect of missing dissolved-solids concentration data on WY 1989–2013 annual load estimates for several sites.

Description of the Study Area

The study area includes the Duchesne River Basin and the Middle Green River Basin between the Green River near Greendale, UT, and Green River at Green River, UT, gaging stations (fig. 1). The drainage area of the Duchesne River Basin is 3,834 square miles (mi^2) with altitudes ranging from 13,528 feet (ft) at Kings Peak in the Uinta Mountains to 4,650 ft at the confluence with the Green River. Most of the irrigated agricultural land in Utah that drains to the Green River is in the Duchesne River Basin and in the Ashley Creek and Brush Creek drainages in the Vernal area (Buto and others, 2014) (fig. 2). These streams drain the south slope of the Uinta Mountains and the eastern part of the Wasatch Range and flow to the Green River downstream from the Green River near Jensen, UT, gaging station (fig. 2). The drainage area to the

Table 1. Gaging stations used for analysis of dissolved-solids loads and trends in the Uinta Basin study area.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; UT, Utah]

USGS gaging station number	USGS gaging station name	Altitude, in feet	Drainage area, in square miles	Streamflow period of record (water years)	Water year 1989–2013 mean annual streamflow, in ft^3/s	Source of dissolved solids in drainage area
	Middle Green River Basin					
09234500	Green River near Greendale, UT	5,589	19,350	1950–2014	1,670	Both [3]
09261000	Green River near Jensen, UT	4,758	29,660	[1] 1946–2014	3,690	Both [3]
09266500	Ashley Creek near Vernal, UT	6,231	101	[1] 1919–2014	83	Natural
09261700	Big Brush Creek above Red Fleet Reservoir, near Vernal, UT	5,625	77	1979–2014	39	Natural
09306500	White River near Watson, UT	4,947	4,020	[1] 1985–2014	637	Both [3]
09315000	Green River at Green River, UT	4,040	44,850	1905–2014	4,730	Both [3]
	Duchesne River Basin					
09277500	Duchesne River near Tabiona, UT	6,190	353	1918–2014	131	Both [3]
09279000	Rock Creek near Mountain Home, UT	7,250	147	1937–2014	88	Natural
09288180	Strawberry River near Duchesne, UT	5,722	917	1968–2014	132	Both [3]
09289500	Lake Fork River above Moon Lake, near Mountain Home, UT	8,180	78	[1] 1963–2014	110	Natural
09291000	Lake Fork River below Moon Lake, near Mountain Home, UT	7,970	112	[1] 1942–2014	117	Natural
09292500	Yellowstone River near Altonah, UT	7,430	132	1944–2014	129	Natural
09295000	Duchesne River at Myton, UT	5,061	2,643	[1] 1911–2014	237	Both [3]
09296800	Uinta River below powerplant diversion, near Neola, UT	7,330	157	1991–2014	[2] 145	Natural
09299500	Whiterocks River near Whiterocks, UT	7,200	109	[1] 1913–2014	106	Natural
09302000	Duchesne River near Randlett, UT	4,750	3,790	1956–2014	349	Both [3]

[1] Periods of intermittent streamflow records available prior to the period of record listed.

[2] Data from water years 1991–2013 were used to calculate mean annual streamflow at this gaging station.

[3] Both: natural and agricultural sources of dissolved solids.

Figure 2. Locations of gaging stations used to determine dissolved-solids loading in the Uinta Basin study area.

Green River between the Greendale and Green River gaging stations is about 25,500 mi^2.

The climate in much of the study area is semiarid. Average annual precipitation for 1981–2010 is 7.0 inches (in.) at Myton, 7.6 in. at Green River, 9.3 in. at Vernal, and 10.1 in. at Duchesne (Western Regional Climate Center, 2015). Potential evaporation exceeds precipitation at these sites with a 1928–2005 average annual pan evaporation of about 40 in. at the Vernal airport (Western Regional Climate Center, 2016). Typically, more precipitation occurs in the mountains in the form of snow during the winter. The 1981–2010 average precipitation at the Lakefork Basin NRCS SNOTEL site, in the headwaters area for the Lake Fork River at an altitude of 10,966 ft, was 37.0 in. (Natural Resources Conservation Service, 2015b).

Streamflow in the Green River and its tributaries within the study area are dominated by snowmelt runoff in the spring from mountains in Utah, Colorado, and Wyoming. Approximately half of the annual streamflow at the Green River near Jensen, UT, gaging station and more than 50 percent at most of the gaging stations on headwater streams occurs during snowmelt runoff, typically the 3-month period from May to July (fig. 3). Diversions for irrigation from the Duchesne River and its tributaries affect streamflow during the irrigation season, generally from May to October. Additionally, two of the gaging stations are influenced by large reservoirs in the study area. The Green River near Greendale, UT, gaging station is about 0.5 mile (mi) downstream from Flaming Gorge Reservoir, a large impoundment with a storage capacity of 4,002,700 acre-feet (acre-ft), completed in 1964. Streamflow measured at the Strawberry River near Duchesne, UT, gaging station (09288180) is controlled by releases from Strawberry Reservoir (storage capacity 1,106,500 acre-feet; U.S. Bureau of Reclamation, 2017), which is about 27 mi upstream from the gaging station.

Water resources in the Uinta Basin were previously studied by the USGS in the 1970s in cooperation with the Utah Department of Natural Resources, Division of Water Rights (Price and Miller, 1975; Hood and Fields, 1978). The boundaries of the Uinta Basin used in these studies were determined from surface-water drainage divides that surround the basin and extend from the Uinta Mountains in Utah into northwestern Colorado. The eastern boundary of the Uinta Basin used by this study extends into Colorado (figs. 1 and 2) to include topographically defined 5th level watersheds (10-digit hydrologic units). Hydrologic units are used to classify drainage areas in the United States by subdividing watershed boundaries into successively smaller units (Seaber and others, 1987).

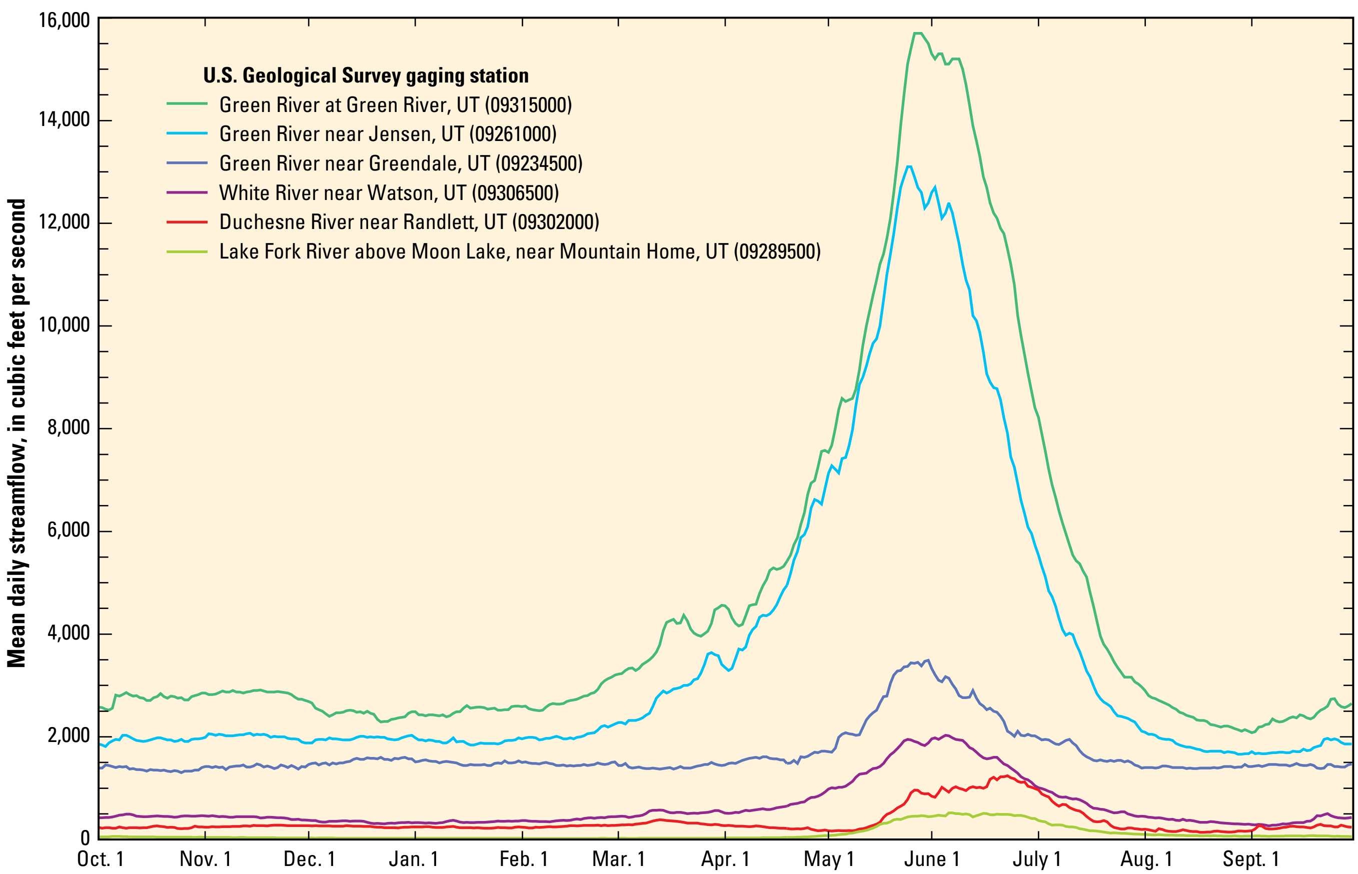

Figure 3. Mean daily streamflow for selected gaging stations in the Uinta Basin study area for water years 1989 through 2013.

The human-defined boundaries of the Uintah Basin are denoted by the letter h added to the word Uinta. Thus, the Uintah Basin as delineated by the Utah Division of Water Resources (2015) includes the Uinta Basin in Utah, but is bounded by the Utah-Wyoming state line on the north and the Utah-Colorado state line on the east. The Uintah Basin delineated by the Colorado River Basin Salinity Control Program is limited to a smaller area that includes about 225,000 irrigated agricultural acres in the Duchesne River Basin and areas in the vicinity of Vernal and Ouray that drain to the Green River (Natural Resources Conservation Service, 2015a). The term “Uinta Basin” is used in this report to represent both the watershed and human-defined areas.

Geology

The Duchesne River Basin and much of the Middle Green River Basin between the Green River near Greendale, UT, and Green River at Green River, UT, gaging stations are located within the Uinta Basin. The Uinta Basin is a structural and sedimentary basin that formed concurrently with the Uinta Mountains in the late Cretaceous Period and continued through the early Tertiary Period as a result of the Laramide orogeny (Johnson, 1985). Prior to the Laramide phase of mountain building, the Mancos Shale was deposited in the Upper Cretaceous seaway that extended from the Arctic Ocean to the Gulf of Mexico. The Mancos Shale is a source of dissolved solids to groundwater and surface-water systems in the Upper Colorado River Basin (Anning and others, 2007) and is exposed on both sides of Ashley Valley in Utah and eastward into Colorado (Sprinkel, 2007; fig. 4). A coastal plain advanced to the east during the late Cretaceous, depositing the Mesa Verde Group sandstones over the Mancos Shale.

The Uinta Mountains are an east-west trending anticline that borders the Uinta Basin on the north, along with other Laramide uplifts—the Wasatch Range to the west and the San Rafael Swell to the south (Johnson, 1985; fig. 1). The syncline that forms the Uinta Basin was filled with sediment eroded from the surrounding mountains during the Tertiary. The axis of the syncline is located just south of the Uinta Mountains and north of the Duchesne River through the Duchesne River Basin, and trends to the southeast about 4 mi west of Ashley Valley (Sprinkel, 2007; fig. 4). The strata deposited in the Uinta Basin dip steeply toward the axis (the deepest part of the basin) on its northern flank, whereas strata on the southern flank dip gently to the north. Sedimentary rock layers thin to the east, and the eastern boundary for the structural basin is near the level 5 watershed boundary for the hydrologic basin.

A series of lakes covered much of the area in the Uinta Basin beginning in the early Tertiary. Lake regressions accompanied transgressions and as a result, lacustrine deposits interfinger with fluvial deposits. As the lakes receded, the water became saline, and local deposition of evaporite minerals occurred (Holmes and Kimball, 1987). The mostly lacustrine Wasatch and Green River Formations are major sources of oil and gas in the Uinta Basin (Price and Miller, 1975).

The mostly fluvial deposits of the Tertiary-age Uinta Formation overlie and interfinger with deposits of the Green River Formation. Primarily thinly bedded shale, siltstone, and fine-grained sandstone, the Uinta Formation is exposed over a large area from near the town of Duchesne in the west and extending east and south along the Duchesne River and White River (fig. 4). Near the White River, the Uinta Formation weathers to a badlands topography and contains expandable clay (Lindskov and Kimball, 1984). The Uinta Formation is the main source of salt loading, both naturally and from agricultural activities, in the Duchesne River Basin and nearby areas that drain to the Green River. Downstream from Tabiona, the Uinta Formation adjacent to the Duchesne River valley contains water that has dissolved-solids concentrations from less than 1,000 to 10,000 milligrams per liter (mg/L) (Hood, 1977).

The Duchesne River Formation overlies the Uinta Formation and, while deposited in a similar fluvial environment, it was noted by Howells and others (1987) to have an overall coarser grained texture than the Uinta Formation. In some places, the Duchesne River Formation contains gypsum and other evaporite minerals that are relatively soluble. Fractures in both the Duchesne River Formation and Uinta Formation increase the permeability of the sedimentary rock. Areas with fractures can allow more groundwater to move vertically and laterally through the subsurface (Hood and Fields, 1978) and ultimately to streams.

Quaternary-age unconsolidated deposits in the study area were mainly deposited by streams and glaciers extending down from the Uinta Mountains. Runoff from the south slope of the Uinta Mountains flows over erosion-resistant rocks of Precambrian and Paleozoic age that contribute low concentrations of dissolved solids to the water. Unconsolidated deposits derived from these rocks contribute less dissolved solids than sediment weathered from rocks containing naturally occurring salts. Tertiary- and Upper Cretaceous-age sedimentary rocks in and underlying stream drainages in the study area have been found to be the largest natural sources of dissolved solids to area streams (Iorns and others, 1965; Anning and others, 2007; Kenney and others, 2009). Where irrigation water is added to areas with soils derived from saline-rich rocks, unconsumed water can percolate into the shallow subsurface and dissolve salts before eventually draining to a stream.

Land Use

Most of the land draining to the Green River between the gaging stations Green River near Greendale, UT, and Green River at Green River, UT, is natural rangeland. In the Uinta Basin, the Bureau of Land Management manages approximately 2,980 mi^2 of rangeland and the U.S. Forest Service manages 1,990 mi^2 of forest. Dinosaur National Monument covers 328 mi^2, of which 83 mi^2 lie in the Uinta Basin, and encompasses the Green River and Yampa River near their confluence. Approximately 1,800 mi^2 in the Uinta Basin are privately owned and 1,670 mi^2 are tribal lands. In 2010,

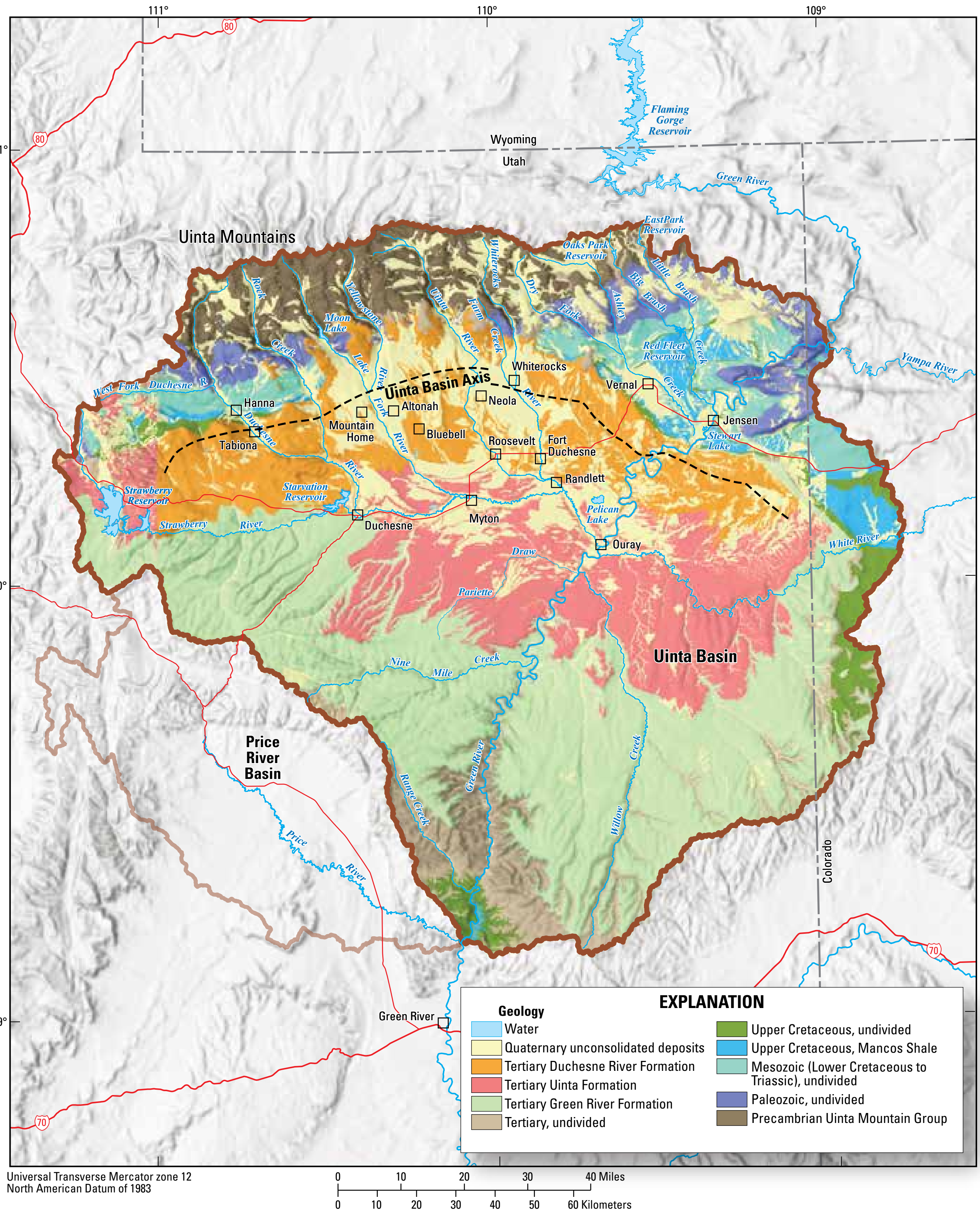

Figure 4. Geology of the Uinta Basin study area.

approximately 51,000 people lived in the study area, mostly in rural agricultural communities. The major cities and towns in the study area are Vernal (population 9,090), Roosevelt (population 6,050), Duchesne (population 1,690), and Green River (population 952) (U.S. Census Bureau, 2015).

Water-related land use in the Uinta Basin was inventoried by the Utah Division of Water Resources in 1992, 2000, 2006, and 2012 (Utah Department of Natural Resources, 2013). Refinements in the methods and tools have occurred with each successive land-use inventory. The Utah Division of Water Resources urges caution when comparing changes in the number of acres for particular land uses with time and in determining trends. Irrigated and subirrigated land mapped in the Uinta Basin totaled approximately 183,800 acres in 1992; 190,300 acres in 2000; 203,700 acres in 2006; and 192,600 acres in 2012, with an average of 192,600 acres. Irrigated and subirrigated land in the drainage area contributing streamflow to the Duchesne River near Randlett, UT, averaged about 143,200 acres over these snapshots in time. Areas in the Uinta Basin mapped as fallow and idle irrigated land increased from about 11,100 acres in 1992 to 71,800 acres in 2012 with much of the increase (83 percent) occurring in the Duchesne River near Randlett, UT, drainage area. Most of the irrigated land in the Uinta Basin in 2012 was pasture (48 percent) or alfalfa (30 percent) (Utah Department of Natural Resources, 2013). Areas mapped as sprinkler and flood irrigated in 2012 comprised approximately 109,600 acres and 77,200 acres, respectively, and are shown on figure 5.

Buto and others (2014) assessed the status and type of irrigation, sprinkler or flood, in the Uinta Basin during 2007–10 using satellite imagery (Landsat scenes during 2007–10 growing seasons), aerial imagery (National Agriculture Imagery Program images produced in 2009), and land-use data from Utah Division of Water Resources inventories done in 2000 and 2006. A total of 182,900 acres in the Uinta Basin were mapped as irrigated by this assessment and represent the period 2007–10. Of the 182,900 acres, 71,900 acres (39 percent) were categorized as sprinkler irrigated and 66,600 acres (36 percent) were categorized as flood irrigated in the Duchesne River Basin. The remainder of the Uinta Basin (outside of the Duchesne River Basin) had 39,000 acres of sprinkler-irrigated land and 5,420 acres of flood-irrigated land.

Data Compilation and Study Methods

Site Selection and Data

Twenty-three gaging stations in the Uinta Basin study area were active in WY 2013 and were considered for analysis as part of this study. Seven of these sites were not analyzed because of missing daily streamflow values during WY 1989–2013 (Current Creek near Fruitland, UT, USGS streamflow gaging station number 09288000; Strawberry River at Pinnacles near Fruitland, UT, 09285900; and Price River at Woodside, UT, 09314500) or because the streamflow period of record started in WY1998 or later and dissolved-solids concentration or specific-conductance data were not available before 2008 (Uinta River at Randlett, UT, 09301500; Duchesne River above Uinta River near Randlett, UT, 09295100; Yellowstone River at Bridge Campground near Altonah, UT, 09292000; and Green River at Ouray, UT, 09272400). The analyzed sites (table 1) have continuous streamflow data and periodic to sporadic specific-conductance measurements during WY 1989–2013, except for the Uinta River below powerplant diversion, near Neola, UT, (09296800) gaging station, where data from WY 1989–1990 were not collected. Data are accessible from the USGS NWIS database at http://waterdata.usgs.gov/nwis.

The 16 gaging stations included in this study are located in areas that are upstream from most agricultural or human development (natural landscape) or downstream from irrigated lands and have a combination of natural and agricultural sources of dissolved solids in the watershed (figs. 4 and 5; table 1). Natural sources of dissolved solids are typically nonpoint sources associated with the underlying geology and the concentration of dissolved minerals that occurs by evapotranspiration. The study sites representing “natural” conditions are located in the Uinta Mountains near the heads of the streams; therefore, these sites are not representative of all natural conditions that occur in the study area. Although impoundments and diversions upstream of natural landscapes affect streamflow at Rock Creek near Mountain Home, UT; Lake Fork River below Moon Lake, near Mountain Home, UT; Uinta River below powerplant diversion, near Neola, UT; Ashley Creek near Vernal, UT; and Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, these sites are presumed to represent natural dissolved-solids loads entering the study area.

Continuous Streamflow Estimates

Stream stage was monitored at 15-minute intervals at 15 gaging stations during WY 1989–2013 and one gaging station (Uinta River below powerplant diversion, near Neola, UT) during WY 1991–2013 (table 1). Streamflow at each site was determined from the stage-discharge relation method (Rantz and others, 1982), where area-velocity discharge (streamflow) measurements are associated with stage (height of

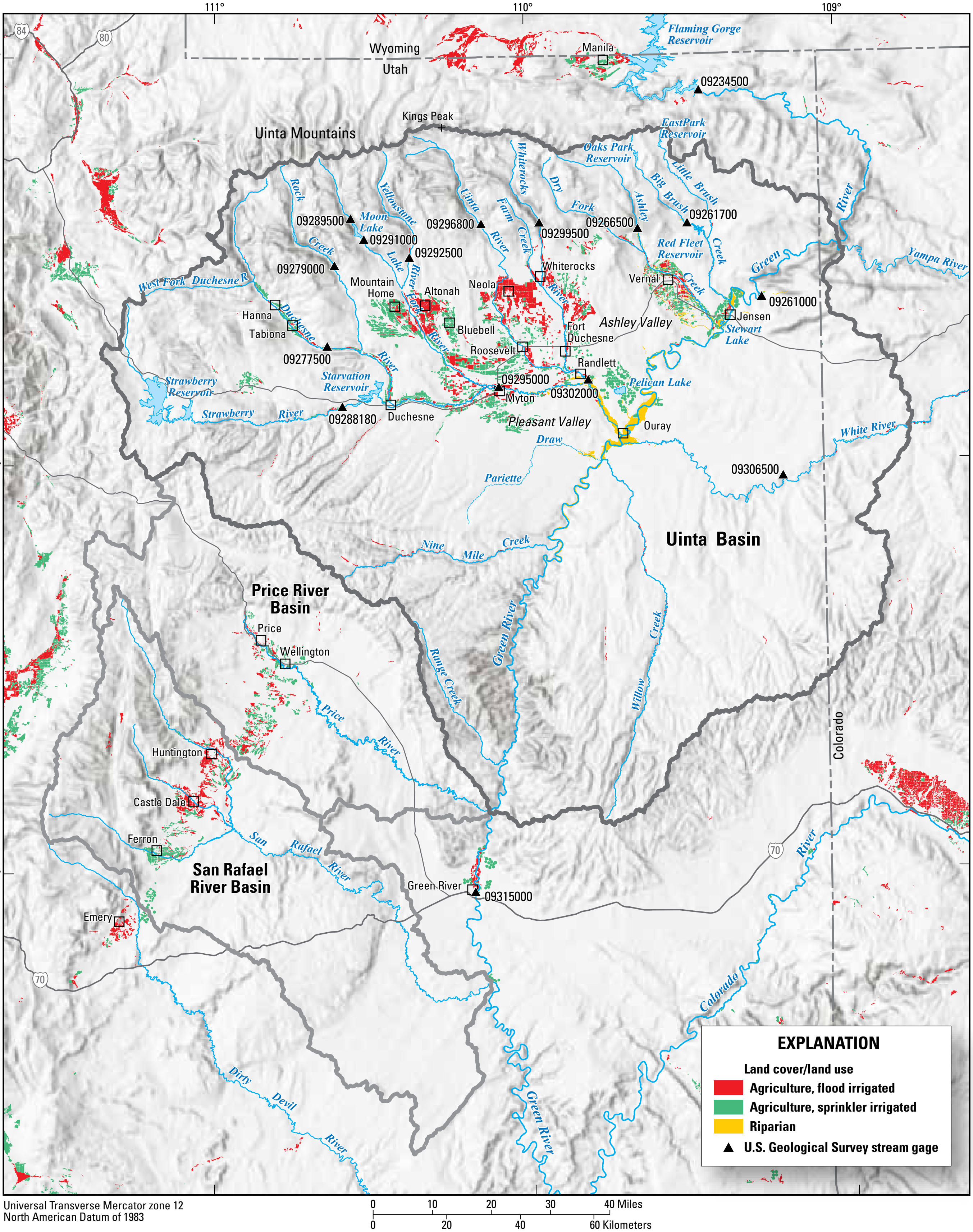

Figure 5. Irrigated land and irrigation type in the Uinta Basin study area in 2011 and 2012.

stream surface above a reference point) to calculate a time series of streamflow values based on a time series of stage measurements. These instantaneous streamflow values were aggregated to determine daily, monthly, and annual mean streamflow values. The mean annual streamflow for WY 1989–2013 ranged from 39 cubic feet per second (ft^3/s) at Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, to 4,730 ft^3/s at Green River at Green River, UT (table 1). Daily mean streamflow values were used to estimate dissolved-solids loads.

Mean daily streamflow was calculated from the average of daily mean streamflow values for each day of the year during WY 1989–2013, except for the Uinta River below powerplant diversion, near Neola, UT, gaging station, where the period of record from WY 1991–2013 was used. For example, the mean daily streamflow on May 5 is an average of all the daily mean streamflow values on May 5 from 1989 through 2013. The mean daily streamflow value determined for a period longer than 1 year includes a range in streamflow variability and represents the average streamflow condition for the period (Schaffrath, 2012). The mean annual streamflow is the sum of the 365 mean daily streamflow values for a period.

Mean daily streamflow values were used to estimate trends in flow-normalized dissolved-solids loads in the studied streams. Using mean daily streamflow for the study period to predict trends in dissolved-solids load removes the effects of streamflow variability at the selected sites. The effects of wet years and dry years are reduced and a significant trend in dissolved-solids load is attributable to something other than changes in streamflow.

Periodic Water-Quality Sampling

The term “dissolved solids” is synonymous with the terms “salinity” and “salt” in this report and refers to the mass of all cations and anions dissolved in the water. Dissolved-solids load (salinity load) is defined as the mass of dissolved solids flowing past a sampling site during a specific time interval and is expressed in units of mass/time. Dissolved-solids concentrations were determined as the sum of constituents (SOC) and (or) the residue on evaporation at 180 degrees Celsius (°C) (ROE). Sum of constituents is the sum of the constituent concentrations measured in a filtered water sample. The major ions calcium, magnesium, sodium, potassium, silica, chloride, sulfate, and alkalinity (carbonate/bicarbonate expressed as carbonate equivalent), typically make up the bulk of the dissolved constituents in a sample, but concentrations of any other constituents present are needed to obtain an accurate total dissolved-solids concentration (Hem, 1985).

Dissolved-solids concentrations determined as ROE involves weighing the dry residue remaining after evaporation of the volatile portion of an aliquot of the water sample. However, it is not uncommon for water that has high calcium and sulfate concentrations to be retained in the residue even after drying for an hour at 180 °C (Hem, 1985). This causes the ROE value to exceed the SOC value. High dissolved sulfate concentrations can occur in Uinta Basin streams flowing across rocks containing evaporite minerals, such as the gypsum-bearing Mancos Shale (Tuttle and others, 2014). The average ROE/SOC ratios for WY 1989–2013 samples from the Green River near Greendale and at Green River, UT; Duchesne River near Randlett, UT; and White River near Watson, UT, were all greater than 1.01, indicating that some water was likely retained in the ROE sample after drying. The SOC value was used in the dissolved-solids load analysis rather than the ROE value if both were available for a water sample.

Specific conductance was measured when collecting a water-quality sample for analysis of dissolved-solids concentration. Specific conductance is often used as a surrogate for estimating dissolved-solids concentration because it can be measured in the field and typically there is a strong relation between the two parameters. Specific conductance has been measured much more frequently than dissolved-solids concentration at the Green River near Greendale, UT; Green River near Jensen, UT; Duchesne River near Randlett, UT; White River near Watson, UT; and Green River at Green River, UT, gaging stations to provide information on dissolved-solids loads in the Upper Colorado River Basin. The remaining gaging stations, where the primary purpose of the site is to measure streamflow, have less specific-conductance and dissolved-solids concentration data. Specific conductance is typically measured at these sites when a discharge measurement is made, approximately every 6 to 8 weeks. Specific conductance was not measured during WY 1994–2008 at the majority of the gaging stations, resulting in a gap in specific-conductance data during the WY 1989–2013 study period. The number of dissolved-solids concentration values determined from water samples collected at the studied gaging stations and used in the dissolved-solids load analysis ranged from only one for Duchesne River near Tabiona, UT, to 205 values for Duchesne River near Randlett, UT (table 2).

Table 2. Relation between specific conductance and dissolved-solids concentration at gaging stations used for analysis of dissolved-solids loads and trends in the Uinta Basin study area.

[USGS, U.S. Geological Survey; DS, dissolved-solids concentration; SC, specific conductance; µS/cm, microsiemens per centimeter at 25 degrees Celsius; WY, water year; UT, Utah; ln, natural logarithm]

USGS gaging station number	USGS gaging station name	Number of pairs analyzed for DS to SC relation	Range of water years for DS-SC pairs	Mean SC of values used in DS to SC relation, in µS/cm	DS to SC ratio	Relation of DS to SC	Relation coefficient of determination (R^2)	Number of SC values used to calculate DS in WY 1989–2013
09234500	Green River near Greendale, UT	85	1989–2013	684	0.62	ln DS = ln SC(1.0366) − 0.7101	0.928	119
09261000	Green River near Jensen, UT	118	1985–2013	593	0.63	ln DS = ln SC(1.0099) − 0.5251	0.987	187
09266500	Ashley Creek near Vernal, UT	14	1955–2013	126	0.60	ln DS = ln SC(0.7851) + 0.5020	0.953	59
09261700	Big Brush Creek above Red Fleet Reservoir, near Vernal, UT	11	2010–2013	321	0.63	DS = SC(0.6289) + 0.6921	0.993	93
09306500	White River near Watson, UT	202	1986–2013	701	0.65	ln DS = ln SC(1.0585) − 0.8167	0.984	185
09315000	Green River at Green River, UT	202	1989–2013	692	0.63	ln DS = ln SC(1.0829) − 1.0060	0.991	202
09277500	Duchesne River near Tabiona, UT	1	2013	564	0.58	DS = SC(0.58)	1	91
09279000	Rock Creek near Mountain Home, UT	34	1958–1973	140	0.57	DS = SC(0.5702) − 0.4539	0.984	70
09288180	Strawberry River near Duchesne, UT	51	1949–2013	695	0.61	ln DS = ln SC(1.0577) − 0.8744	0.980	81
09289500	Lake Fork River above Moon Lake, near Mountain Home, UT	7	2010–2012	24	0.67	DS = SC(0.4338) + 5.3025	0.950	58
09291000	Lake Fork River below Moon Lake, near Mountain Home, UT	8	1958–1994	31	0.72	DS = SC(0.4495) + 7.9407	0.525	54
09292500	Yellowstone River near Altonah, UT	47	1958–2012	82	0.58	DS = SC(0.5908) − 1.2530	0.948	85
09295000	Duchesne River at Myton, UT	80	1941–2013	1,100	0.67	ln DS = ln SC(1.1137) − 1.1887	0.994	76
09296800	Uinta River below powerplant diversion, near Neola, UT	13	1994–2013	29	0.64	DS = SC(0.5899) + 1.5110	0.920	[1] 80
09299500	Whiterocks River near Whiterocks, UT	70	1941–1994	63	0.54	ln DS = ln SC(0.9522) − 0.4221	0.929	84
09302000	Duchesne River near Randlett, UT	205	1989–2013	1,390	0.67	ln DS = ln SC(1.0918) − 1.0555	0.992	410

[1] Number of specific-conductance values used to calculate dissolved-solids concentration in water years 1991–2013.

Dissolved-Solids Concentration and Load Estimation

Dissolved-solids concentration and streamflow were used to calculate dissolved-solids loads. Dissolved-solids loads were computed using the following equation:

$$Load = (Conc)\ (Flow)\ (CF) \tag{1}$$

where

Load is the estimated dissolved-solids load, in tons per unit time,

Conc is dissolved-solids concentration in milligrams per liter,

Flow is streamflow in cubic feet per second, and

CF is a conversion factor used to convert to a specific time interval.

The conversion factor used to calculate daily dissolved-solids loads in tons per day was 0.002697.

Daily mean streamflow and periodic dissolved-solids concentrations regressed from specific-conductance measurements were used in regression models to estimate daily dissolved-solids loads. Daily mean streamflow values were available for each site during WY 1989–2013 (9,131 days), except for Uinta River below powerplant diversion, near Neola, UT, where values were available during WY 1991–2013 (8,401 days). The coefficient of determination (R^2) is a statistical measure of how much the variance in the dependent variable is explained by the independent variable. R-squared varies between 0 and 1. A linear relation ($R^2 = 0.94$) was developed with measured streamflow at the Whiterocks River near Whiterocks, UT, gaging station for WY 1991–2013 to estimate annual mean streamflow at the site in WY 1989–90 (Uinta River below powerplant diversion, near Neola, UT, streamflow = [Whiterocks River near Whiterocks, UT, streamflow * 1.5286] – 22.088). A linear relation ($R^2 = 0.89$) between annual dissolved-solids load in WY 1991–2013 at Uinta River below powerplant diversion, near Neola, UT, and Whiterocks River near Whiterocks, UT, was used to estimate the missing values (Uinta River below powerplant diversion, near Neola, UT, dissolved-solids load = [Whiterocks River near Whiterocks, UT, load * 0.4984] + 692.16).

Surrogate Data for Estimating Dissolved-Solids Concentrations

Specific-conductance measurements (field and laboratory values), dissolved-solids concentrations (SOC and ROE values), and daily mean streamflow for each sample were retrieved from the NWIS database. Consistency in the data set was checked by comparing ratios of field specific conductance to laboratory specific conductance, SOC to specific conductance, ROE to specific conductance, and SOC to ROE. Specific conductance measured in the field was the first choice to pair with the dissolved-solids concentration of a sample, but specific conductance measured in the laboratory could be substituted to better fit the overall linear relation between specific conductance and dissolved-solids concentration for the site. Sum of constituents was the first choice to represent dissolved-solids concentration, but ROE could be used if SOC was not available. Residue on evaporation also could be used if SOC/ROE was significantly different from 1 and the ROE value better fit the overall linear relation between specific conductance and dissolved-solids concentration for the site.

Linear and logarithmic regression were used to determine the relation between paired specific conductance and dissolved-solids concentrations. Specific-conductance values were regressed against dissolved-solids concentrations measured in samples collected at the same time at a site, and the resulting regression equation for the site (table 2) was used to calculate dissolved-solids concentrations where only measurements of specific conductance were available during WY 1989–2013. This relation was used to estimate dissolved-solids concentrations from other measured specific-conductance values in order to increase the number of dissolved-solids concentration values in the input data set used to estimate dissolved-solids loads. An exception is site Duchesne River near Tabiona, UT, which only had one dissolved-solids concentration value paired to a specific-conductance value. The ratio between the two values (0.58) was used to estimate dissolved-solids concentrations for the remaining 90 specific-conductance measurements. Although using this ratio to estimate dissolved-solids concentrations causes more uncertainty in the modeling of dissolved-solids loads over time, it is in the range of ratios determined for other headwater streams in the area with multiple data pairs of dissolved-solids concentration and specific conductance (Rock Creek near Mountain Home, UT [0.57], and Strawberry River near Duchesne, UT [0.61]).

A line of best fit was applied to the data sets, and the resulting equation was used to predict dissolved-solids concentrations. Variables were logarithmically transformed if there was visual indication of a non-linear relation. Residuals from the regression models were plotted against predicted values and time, to check for curvature and changing variance (Helsel and Hirsch, 2002), which would violate the assumption of the linear relation between dissolved-solids concentration and specific conductance.

The relation between specific conductance and dissolved-solids concentration generally was consistent among the studied gaging stations. The ratio of specific conductance to dissolved-solids concentration mostly was in the range of 0.54 (Whiterocks River near Whiterocks, UT) to 0.67 (three sites) (table 2). The exception was a ratio of 0.72 determined for Lake Fork River below Moon Lake, near Mountain Home, UT, which may be affected by the upstream impoundment. Hem (1985) states that the ratio of dissolved-solids concentration to specific conductance in natural waters is mostly between 0.55 and 0.75.

Daily specific-conductance data were available for Green River near Greendale, UT, from WY 1989 to 2000 and from August 2012 through WY 2013; Duchesne River near Randlett, UT, from August 2008 through WY 2013; and Green River at Green River, UT, from WY 1989 to 2013. These daily specific-conductance values were not used to develop the relation between specific conductance and dissolved-solids concentration, but were used to check daily dissolved-solids loads estimated from calculated dissolved-solids concentrations and daily streamflow.

Regression Models Used for Estimating Dissolved-Solids Loads

The Load Estimator (LOADEST) statistical program (Runkel and others, 2004) was used to develop regression models using daily mean streamflow and discrete dissolved-solids concentration data to estimate dissolved-solids loads. The RLOADEST version of LOADEST (David Lorenz, U.S. Geological Survey, written commun., 2014) was used for this study. RLOADEST is LOADEST embedded into the statistical software package “R” (Hornik, 2015). A dissolved-solids load model for each gaging station was developed in RLOADEST by using a calibration data set consisting of calculated dissolved-solids concentrations and the associated daily mean streamflow values for the period WY 1989–2013. The calculated dissolved-solids concentrations and streamflow values were logarithmically transformed to help meet the assumptions of normality and constant variance (Hirsch and others, 1991). This report follows methodology presented in Schaffrath (2012).

The RLOADEST regression equation that relates dissolved-solids load to the explanatory variables takes the following general form:

$$\ln L = a + b_1(\ln Q - \ln Q^*) + b_2(\ln Q - \ln Q^*)^2 + b_3\,(t - t^*) + b_4\,(t - t^*)^2 + b_5\,[\sin(k2\pi T)] + b_6\,[\cos(k2\pi T)] + e \qquad (2)$$

where

- ln is the natural log function,
- L is the estimated dissolved-solids load, in tons per day,
- a is the regression equation intercept,
- b_n is the coefficient on the n^th regression variable,
- Q is daily streamflow, in cubic feet per second,
- Q^* is the streamflow centering value from the calibration data set, in cubic feet per second,
- t is time, in decimal years,

t^* is the time centering value from the calibration data set, in decimal years,

k is an integer,

π is 3.14169,

T is the seasonality term representing the decimal portion of the year starting January 1, and

e is the error associated with the regression equation or unexplained variation.

Variation in load as a function of streamflow and time are addressed with linear and squared (quadratic) terms in the regression equation.

Dissolved-solids load models using each site's calibration data set were obtained by using the "selBestModel" function in RLOADEST. This function computes nine pre-defined linear regression models that use up to seven explanatory variables based on the relation of dissolved-solids load to streamflow, time, and seasonality. The "best" model chosen by RLOADEST is the model with the lowest Akaike Information Criteria statistic (Runkel and others, 2004). Model coefficients (b_n) were estimated by using adjusted maximum likelihood estimation, and a bias correction factor was applied to the final model load estimate to address retransformation bias (Runkel and others, 2004).

The p-value associated with a variable's model coefficient is the probability that the coefficient is zero (the null hypothesis is true). A smaller p-value provides stronger evidence that the null hypothesis is unlikely to be true. The following criteria from Schaffrath (2012) were used to determine the significance of the model coefficients: $p \leq 0.01$, highly significant; $0.01 < p \leq 0.05$, significant; $0.05 < p \leq 0.10$, marginally significant; and $p > 0.10$, not significant.

The linear regression models computed by RLOADEST assume a normal distribution of the data, but water-quality data typically only approximate a normal distribution (Helsel and Hirsch, 2002). The diagnostic plots used to check the assumptions included standardized residuals versus normal quantiles, and residuals versus predicted values. A linear distribution along a 1:1 line of standardized residuals plotted versus normal quantiles indicates normality. Another assumption of the regression model is that the model residuals have equal variance. No pattern and uniformity of scatter (homoscedacity) in a plot of residuals versus predicted values indicates equal variance.

The coefficient of determination (R^2) is a statistical measure of how much the variance in the dependent variable is explained by the independent variable. An R^2 value of 0.952 indicates that 95.2 percent of the variability in the modeled load is explained by the explanatory variables. The serial correlation of the residuals (SCR) indicates whether there is dependence or correlation in time between residuals (Helsel and Hirsch, 2002). Serial correlation violates the assumption that the residuals are independent—an SCR value of 0 indicates that there is no dependence or correlation, whereas a value of 0.6 indicates that 60 percent of the variability in the residuals can be explained by time. Values of SCR less than 0.6 were considered acceptable for a model. Estimated residual variance is unexplained error in the model. Small estimated residual variance values indicate more accurate predictions, and values less than 0.1 were considered acceptable for a model.

Variables were added to or removed from the "best" model using the RLOADEST function "loadReg" to create a stronger or preferred dissolved-solids load model based on the significance of the coefficients, statistical diagnostics, and residual plots. Sine and cosine terms were added to or removed from the regression equations to address seasonal differences (Cohn and others, 1992). Additional seasonal terms account for the possibility of two or three annual cycles ($k = 2$ or 3 in equation 2) and were used to reduce the occurrence of sinusoidal patterns observed in standardized serial correlation versus time plots. Both the sine and cosine variables are required to account for the amplitude, magnitude, and the day of the peak, even if one of the pair is not significant (Cohn and others, 1992). Quadratic terms for streamflow and (or) decimal time were significant variables in some of the models. However, the possibility of multicollinearity increases when both the linear and quadratic terms for streamflow and (or) decimal time are in the regression equation, thus inflating the variance in the associated coefficients. Streamflow and decimal time were centered to prevent multicollinearity and to ensure orthogonality among predictor variables (Cohn and others, 1992). When the quadratic term was significant in the model, the linear term also was included even if it was not significant.

The preferred dissolved-solids load model developed from the calibration data set was selected based on a qualitative assessment of diagnostic statistics and plots produced by RLOADEST. The regression equations and statistical diagnostics for dissolved-solids loads estimated at the selected gaging stations are available in table A–1.

Modified residuals for a site were determined from the calibration data set and the final dissolved-solids load model using only streamflow and seasonality as the explanatory variables—time and (or) quadratic time were removed from the regression model if they were significant. Variations in the modified residuals from the model with the time variable(s) removed provide an indication of the effects of the variable over time. The modified residuals were plotted versus time, and a LOcally WEighted Scatterplot Smoothing (LOWESS) line was fit to the data (Cleveland, 1979). The LOWESS line represents the pattern through the middle of the data and was used to evaluate how the modified residuals varied with time without being strongly influenced by outliers (Helsel and Hirsch, 2002). Variations in residuals over time are not expected in the final regression model with time included as an explanatory variable because the effects of the variable are accounted for within the model. A qualitative interpretation of the LOWESS smooth line included an estimation of when the minimum and maximum modified residuals occurred, based on the year when the slope changed, and the direction of the trend before and after the date of the minimum or maximum modified residuals (Schaffrath, 2012).

Daily dissolved-solids loads in WY 1989–2013 were predicted for each site by using the developed regression equation for that site, a prediction data set containing daily streamflow values and dates, and the RLOADEST "predLoad" function. Annual dissolved-solids load was obtained by summing the estimated daily dissolved-solids loads for each water year. The annual mean dissolved-solids concentration (the average for a particular year) was calculated by dividing the annual dissolved-solids load by the annual mean streamflow and multiplying by the unit conversion factor 0.9844. The mean annual dissolved-solids concentration for a site is the average of the annual means in WY 1989–2013.

The predicted daily dissolved-solids load in WY 1989–2013 for each studied site was plotted with observed loads determined from daily mean streamflow and dissolved-solids concentrations calculated from discrete specific-conductance measurements and, where available, daily mean specific-conductance values, to visually inspect the model results. A difference between predicted and observed daily loads occurred at some of the study sites during some periods of very low or high streamflow. This indicates that the dissolved-solids load models for these sites did not capture the variability in dissolved-solids concentration, likely because of a lack of specific conductance and (or) dissolved-solids concentration data collected during extreme streamflow events. The model could under predict daily dissolved-solids loads when the observed load was larger than the predicted load during periods of very high streamflow if there was not a corresponding dissolved-solids concentration for the site to constrain the model. During periods of very low streamflow, a model for a study site could over predict loads when the observed load was smaller than the daily predicted load if a corresponding dissolved-solids concentration was not available. This variability between observed and predicted loads was not consistent among the study sites, but did occur at several sites during WY 2010 (a year with below average streamflow) and WY 2011 (a year with above average streamflow).

Trend Analysis of Predicted Dissolved-Solids Loads

Trends in predicted dissolved-solids loads at the studied sites were analyzed by using the normalized regression method described by Schaffrath (2012). The normalized regression method predicts daily dissolved-solids loads at a site using the regression equation developed for the site from its calibration data set, a prediction data set where streamflow at the site for the period of interest is the mean daily streamflow value for that period, and the RLOADEST "predLoad" function. The mean daily streamflow is the mean of the daily mean streamflow values for each day of the year over the period of interest. As an example, the mean daily streamflow on March 23 for every year in the estimation data set was specified as the mean of the daily streamflow values on March 23 from 1989 through 2013. Normalizing to the mean daily streamflow removed the variability in dissolved-solids load resulting from annual variation in streamflow within the regression model. The dissolved-solids load predicted using mean daily streamflow is called the flow-normalized load. Annual flow-normalized dissolved-solids load was calculated from the sum of the daily flow-normalized dissolved-solids loads for a given water year. Trends in flow-normalized load indicate a change in dissolved-solids concentrations or the processes that add or allow dissolved solids to enter a stream, such as a change in irrigation practices. Because streamflow is normalized, loads were cumulative downstream and trends in annual flow-normalized load at each site were comparable.

The significance of the time trend at gaging stations where the dissolved-solids load regression model included linear time, but not quadratic time, was indicated by the p-value associated with the coefficient on the time term (b_3 in equation 2). The sign on the coefficient indicates the direction of the trend, and the coefficient was used to calculate the magnitude of the trend. The annual change in dissolved-solids load, in percent, when the linear-time term is significant and the quadratic-time term is not, was calculated as

$$\text{Annual percent change in load} = (e^{b_3} - 1)\,100 \qquad (3)$$

where

e is the base of the natural logarithm 2.71828, and

b_3 is the coefficient on the linear-time term in equation 2.

This equation is described by Hirsch and others (1991) and Helsel and Hirsch (2002).

The percent change in flow-normalized dissolved-solids load for the study period WY 1989–2013 (a difference of 24 years) was calculated as

$$\text{Net percent change in flow-normalized load} = (e^{b_3 * \text{(end year – begin year)}} - 1)\,100 \qquad (4)$$

where

the end year is 2013 and the begin year is 1989.

The net percent change in dissolved-solids load divided by 100 and multiplied by the flow-normalized load in the begin year equals the change in flow-normalized dissolved-solids load for the period.

When quadratic time was significant in the regression model, the magnitude and significance of the time trend was dependent on the coefficients of both the linear and quadratic time terms (b_3 and b_4 in equation 2). The use of the quadratic time term in the predictive model to determine trends in flow-normalized dissolved-solids load results in a curved trendline (parabola) indicating that the trend varies with time. The net percent change in flow-normalized load over the period for models where linear and (or) quadratic time was significant was calculated as

$$\text{Net percent change in FNL} = ((FNL_{\text{end year}} - FNL_{\text{begin year}}) / FNL_{\text{begin year}})\ 100 \qquad (5)$$

where

FNL is flow-normalized load.

A plot of modified residuals (no time term used in the regression model) versus time, overlain with a LOWESS smooth line was used to help interpret trends in flow-normalized dissolved-solids load. The slope of the smooth line on the modified residuals plot corresponds to the direction and magnitude of the trend in flow-normalized dissolved-solids load. Qualitative interpretation of the parabolic shape of the flow-normalized dissolved-solids load trendline and the LOWESS smooth line on the modified residuals plot was done to estimate the direction and magnitude of different dissolved-solids trend segments. The magnitude was estimated based on the difference between the flow-normalized dissolved-solids load of the beginning year and the year when the slope changed, divided by the flow-normalized dissolved-solids load of the beginning year. For example, the smooth line on a modified residuals plot for the Green River near Greendale, UT, changed from a constant downward slope from 1989 to 2001 to a more gradual downward slope from 2008 to 2013 (fig. A-1). The estimated net percent change in flow-normalized load from 1989 to 2001 was determined by subtracting the flow-normalized load for 2001 from the flow-normalized load for 1989, dividing by the flow-normalized load for 1989, and multiplying by 100.

The quadratic time term was significant in regression models for the Green River near Greendale, UT; Ashley Creek near Vernal, UT; and Whiterocks River near Whiterocks, UT. A gap in dissolved-solids concentration data from WY 2001 to 2007 for the Green River near Greendale, UT, and from WY 1992 to 2008 at the two other sites likely contributes to the need for the quadratic time term in the model to best fit the calibration data. To better understand the effects of this gap in data on modeled dissolved-solids loads, a step-trend analysis was done on the flow-adjusted annual loads determined from the regression model that included the quadratic time term for these sites. Flow-adjusted loads were calculated as the residual of the relation between annual dissolved-solids load and mean annual streamflow (Vaill and Butler, 1999). The Wilcoxon Rank-Sum test (Helsel and Hirsch, 2002) was used for the step-trend analysis to determine if there was a significant difference in median flow-adjusted dissolved-solids load between the pre-gap and post-gap periods. Regression models that do not use the quadratic time term also were developed for these sites to determine an annual percent change in dissolved-solids load and to use in mass-balance load calculations.

Estimated Dissolved-Solids Loads and Trends

Dissolved-solids loads in WY 1989–2013 were determined for 16 sites in the Uinta Basin study area: 6 in the Middle Green River Basin and 10 in the Duchesne River Basin (table 3). The Duchesne River near Randlett, UT, was included in both basins. Estimated mean annual dissolved-solids loads for WY 1989–2013 ranged from 1,520 tons per year (ton/yr) at the Lake Fork River above Moon Lake, near Mountain Home, UT, gage (natural site near headwaters of stream), to 1,760,000 ton/yr at the Green River near Green River, UT, gage (farthest downstream site in study area). The net change in estimated flow-normalized dissolved-solids load from WY 1989 to 2013 ranged from 300 tons (a 16.5-percent increase) at the Whiterocks River near Whiterocks, UT, gage, to -352,000 tons (a 17.8-percent decrease) at the Green River near Green River, UT, gage. A net decrease of 28 percent in flow-normalized dissolved-solids load was modeled at the Duchesne River near Randlett, UT, site, and a net decrease between 13 and 21 percent was modeled at the three study sites on the Green River. Studied gaging stations upstream of agricultural activities had no trend or a relatively small change in flow-normalized load.

A graph showing estimated mean annual dissolved-solids load (dashed line), estimated annual dissolved-solids load using daily streamflow (dark blue bar), estimated annual dissolved-solids load without a linear time trend (light blue bar), and the trend in flow-normalized dissolved-solids load (solid line) is presented for each of the studied gaging stations during WY 1989–2013. The annual dissolved-solids load calculated from the model equation without a linear time trend was used to help visualize when the effects of the trend are most pronounced. When the annual percent change in dissolved-solids load is negative, the annual dissolved-solids load without a linear time trend is larger than the estimated annual load. When the annual percent change in load is positive, the annual dissolved-solids load without a linear time trend is smaller than the estimated annual load. Graphs showing the observed dissolved-solids load estimated from specific-conductance measurements (red and (or) green symbol) and model-predicted daily dissolved-solids load (black symbol with line) at the studied sites also are shown.

Middle Green River Basin

Green River near Greendale, Utah

Green River near Greendale, UT, (gaging station 09234500) is the most upstream site on the Green River within the study area. The site is located in a deep gorge approximately 0.5 mi downstream of Flaming Gorge Reservoir. Streamflow at Green River near Greendale, UT, has been regulated by the Flaming Gorge Dam since 1962. The primary effect of a large reservoir on dissolved-solids transport is a decrease in the seasonal and annual variation in dissolved-solids concentration downstream from the reservoir because of mixing within the reservoir (Mueller and Osen, 1988). Reservoirs decrease the seasonal variability in downstream streamflow by storing water during peak flows and releasing water during low-flow periods. Evaporation removes water from the reservoir, but leaves the dissolved solids, resulting in an eventual increase in dissolved-solids concentrations in the water released back to the stream (Vaill and Butler, 1999). The mean annual streamflow at Green River near Greendale, UT, for WY 1989–2013 is 1,670 ft^3/s (table 1).

Using a regression model to determine dissolved-solids loads that included linear time, but not quadratic time, the estimated WY 1989–2013 mean annual load is 682,000 ton/yr (table 3; fig. 6), with a mean annual dissolved-solids concentration of 405 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 7. The trend in dissolved-solids load from WY 1989–2013 at the Green River near Greendale, UT, is highly significant with an annual decrease of 0.96 percent and a net change in the flow-normalized dissolved-solids load of -158,000 tons (-20.8 percent). The LOWESS smooth line on the modified residuals (no time term used in the regression model) versus time plot has a downward slope in WY 1989–2000 and a shallower downward slope in WY 2010–2013 (fig. A-1). Dissolved-solids concentration data were not available for the site in WY 2001–2008, a period consisting of 8 consecutive years of below average streamflow. Quadratic time was significant in another model for the site (table A-1) that resulted in similar dissolved-solids

Table 3. Summary of dissolved-solids load information for gaging stations used for analysis of dissolved-solids loads and trends in the Uinta Basin study area.

[USGS, U.S. Geological Survey; mg/L, milligrams per liter; UT, Utah; NT, no significant time trend; —, not applicable]

USGS gaging station number	USGS gaging station name	Estimated water year 1989–2013 mean annual: Dissolved-solids load, in tons per year, determined from RLOADEST model	Estimated water year 1989–2013 mean annual: Dissolved-solids concentration, in mg/L, determined from RLOADEST model	Annual change in dissolved-solids load, in percent, determined from RLOADEST model	Estimated water year 1989–2013 flow-normalized dissolved-solids load: Net change, in tons	Net change, in percent	Lower 95-percent confidence level for net change, in tons	Upper 95-percent confidence level for net change, in tons
	Middle Green River Basin							
09234500	Green River near Greendale, UT	682,000	405	−0.96	−158,000	−20.8	−160,000	−155,000
09261000	Green River near Jensen, UT	1,127,000	325	−0.59	−164,000	−13.3	−170,000	−158,000
09266500	Ashley Creek near Vernal, UT	4,380	55	−0.28	−320	−6.7	−340	−290
09261700	Big Brush Creek above Red Fleet Reservoir, near Vernal, UT	4,790	130	NT	—	—	—	—
09306500	White River near Watson, UT	233,000	373	−0.97	−55,300	−20.8	−56,200	−54,400
09315000	Green River at Green River, UT	1,760,000	386	−0.81	−352,000	−17.7	−359,000	−346,000
	Duchesne River Basin							
09277500	Duchesne River near Tabiona, UT	30,200	245	NT	—	—	—	—
09279000	Rock Creek near Mountain Home, UT	4,930	68	NT	—	—	—	—
09288180	Strawberry River near Duchesne, UT	47,300	369	−0.41	−4,560	−9.4	−4,880	−4,240
09289500	Lake Fork River above Moon Lake, near Mountain Home, UT	1,520	14	NT	—	—	—	—
09291000	Lake Fork River below Moon Lake, near Mountain Home, UT	2,150	18	NT	—	—	—	—
09292500	Yellowstone River near Altonah, UT	4,360	36	NT	—	—	—	—
09295000	Duchesne River at Myton, UT	92,200	548	−0.91	−24,000	−19.6	−34,200	−12,800
09296800	Uinta River below powerplant diversion, near Neola, UT	[1] 2,570	[1] 18	NT	—	—	—	—
09299500	Whiterocks River near Whiterocks, UT	1,920	19	0.64	300	16.5	280	320
09302000	Duchesne River near Randlett, UT	172,000	722	−1.36	−68,600	−28.0	−69,100	−68,100

[1] Estimates listed are for water years 1991–2013.

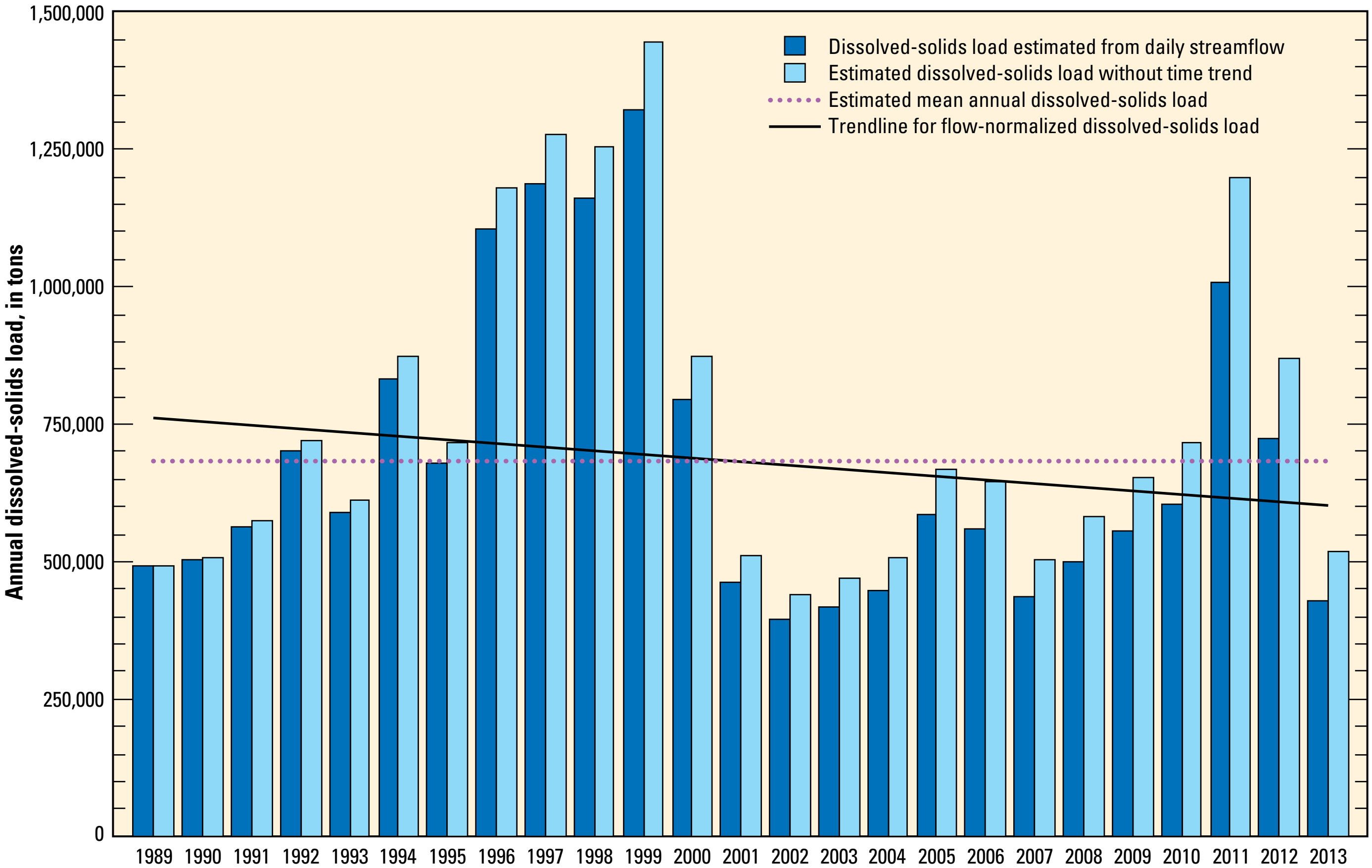

Figure 6. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09234500, Green River near Greendale, UT, during water years 1989–2013.

loads and percent change in load over time. The quadratic time model was able to better match the change in slope shown on the modified residuals versus time plot (fig. A-1), and the step-trend analysis of annual flow-adjusted loads from the quadratic time model showed that there was a highly significant decrease in flow-adjusted load (p-value <0.01) from the pre-gap to post-gap periods. The model with quadratic time was not selected as the final model for the site because of complications when used in calculations of dissolved-solids load mass balance.

The drainage area for the Green River near Greendale, UT, site is 19,350 mi^2 (table 1) of which 4,260 mi^2 does not contribute streamflow. Much of this area is undeveloped rangeland. The Big Sandy River basin in Wyoming, within the Green River near Greendale, UT, drainage basin, is reported to contribute a dissolved-solids load of about 164,000 ton/yr (U.S. Department of the Interior, 2013). Salinity control efforts in the Big Sandy River basin began in 1988 and by the end of 2012, approximately 13,500 acres of the planned 15,700 acres had been converted to improved irrigation systems with an estimated reduction in dissolved-solids load of 56,800 tons. Irrigation improvements in the Manila-Washam Salinity Project area, which drains to Flaming Gorge Reservoir near Manila, Utah, began in 2007. Of the 7,780 acres projected to receive irrigation improvements in the project area, about 3,600 acres had been completed through 2013. The reduction in dissolved-solids load resulting from these irrigation improvements was estimated to be 8,600 tons in 2013 (Natural Resources Conservation Service, 2014). The combined estimated annual reduction in dissolved-solids load resulting from salinity-control projects is about 65,400 tons, or approximately 42 percent of the decrease in flow-normalized dissolved-solids load modeled at the Green River near Greendale, UT.

A Spatially Referenced Regressions on Watershed Attributes (SPARROW) model for dissolved solids in the Upper Colorado River Basin (Kenney and others, 2009) was used to model streamflow and dissolved-solids load conditions in WY 1991 and to help determine the sources of dissolved solids. The SPARROW model predicted that 62 percent of the dissolved-solids load to the Green River near Greendale, UT, gaging station in WY 1991 was from natural sources and 38 percent from agricultural practices. Sedimentary Cenozoic rocks were attributed to be the source of approximately 50 percent of the dissolved-solids load modeled at the site. The same percentage of natural and agricultural sources of dissolved-solids load was estimated by Iorns and others (1965) for the 1914–57 average annual dissolved-solids load at the site (adjusted to 1957 development conditions).

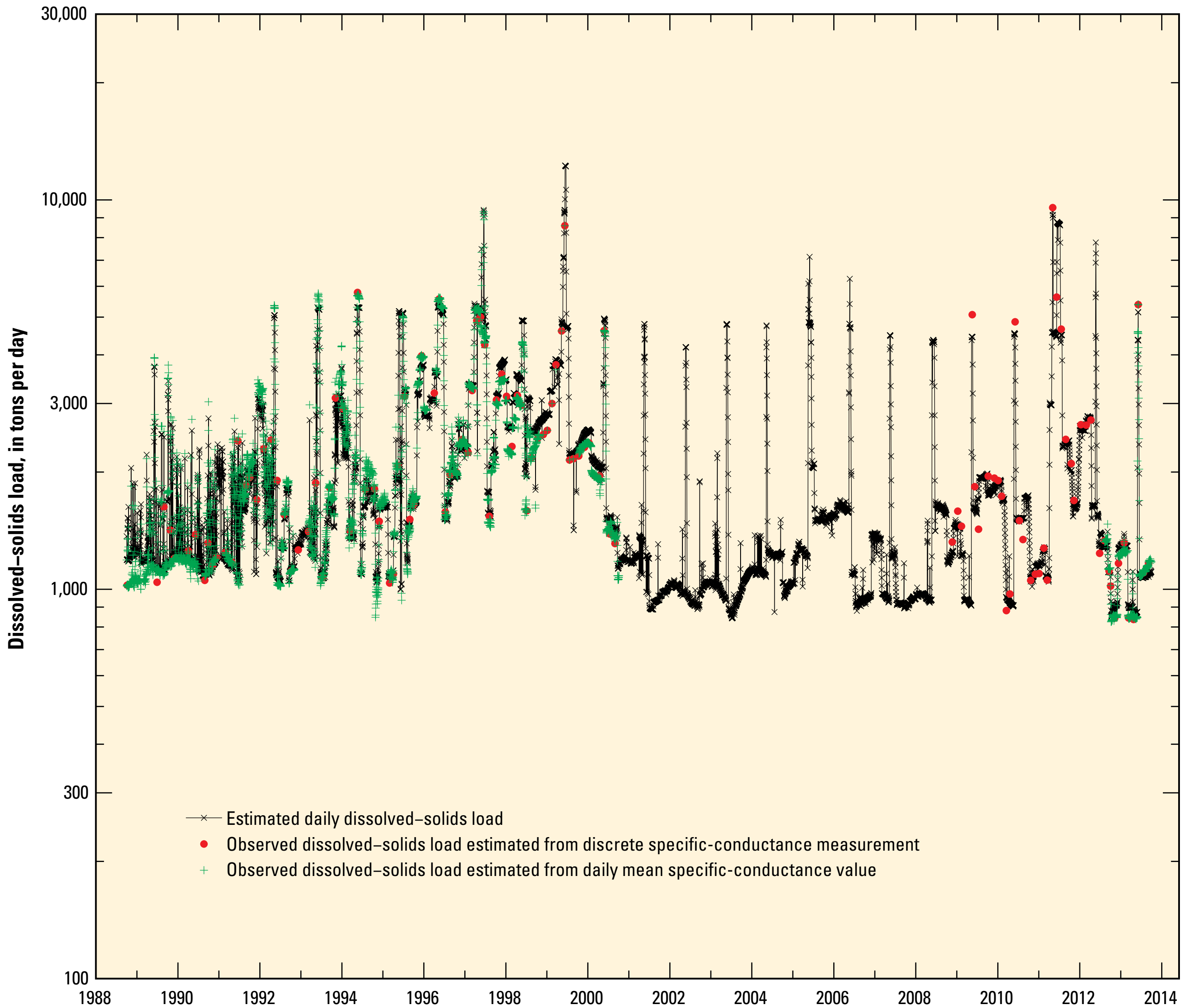

Figure 7. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09234500, Green River near Greendale, UT, during water years 1989–2013.

Green River near Jensen, Utah

Green River near Jensen, UT, (gaging station 09261000) is 92.6 mi downstream of the Green River near Greendale, UT, gaging station and has a drainage area of 29,660 mi^2, which is 10,310 mi^2 more than the drainage area for the Green River near Greendale, UT, gage. The WY 1989–2013 mean annual streamflow is 3,690 ft^3/s (table 1). The Yampa River is the only major tributary to the Green River between Green River near Greendale, UT, and Green River near Jensen, UT, and joins the Green River in Dinosaur National Monument near the Utah-Colorado state line. The streamflow of the Yampa River near Deerlodge Park, Colorado (CO), gaging station (09260050, drainage area 7,931 mi^2) is affected by transbasin diversions, storage reservoirs, and diversions for irrigation of approximately 55,500 acres (more than 90-percent flood irrigated) upstream from the gaging station (Buto and others, 2014). The WY 1989–2013 (missing WY 1995–96) mean annual streamflow at the site was 1,860 ft^3/s.

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at the Green River near Jensen, UT, is 1,127,000 ton/yr (table 3; fig. 8) with a mean annual dissolved-solids concentration of 325 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 9. The estimated WY 1989–2013 mean annual dissolved-solids load at Green River near Greendale, UT, accounts for about 61 percent of the mean annual dissolved-solids load modeled at Green River near Jensen, UT. The Yampa River typically has a lower dissolved-solids concentration than the Green River near Greendale, UT, (NWIS database) and dilutes the concentration in the Green River below the confluence. The dissolved-solids load at the Yampa River near Deerlodge Park, CO, gaging station was not estimated using RLOADEST for the WY 1989–2013 study period because streamflow data were not available for WY 1995–96. A mean annual load of 369,000 tons for WY 1984–2012 was reported by Tillman and Anning (2014) for the Yampa River near Deerlodge Park, CO. This equates to about 33 percent of the WY 1989–2013 mean annual dissolved-solids load modeled at Green River near Jensen, UT, and 21 percent of the load modeled at Green River at Green River, UT. The mean annual dissolved-solids load reported for the Yampa River near Deerlodge Park, CO, is about 83 percent of the increase in WY 1989–2013 mean annual dissolved-solids

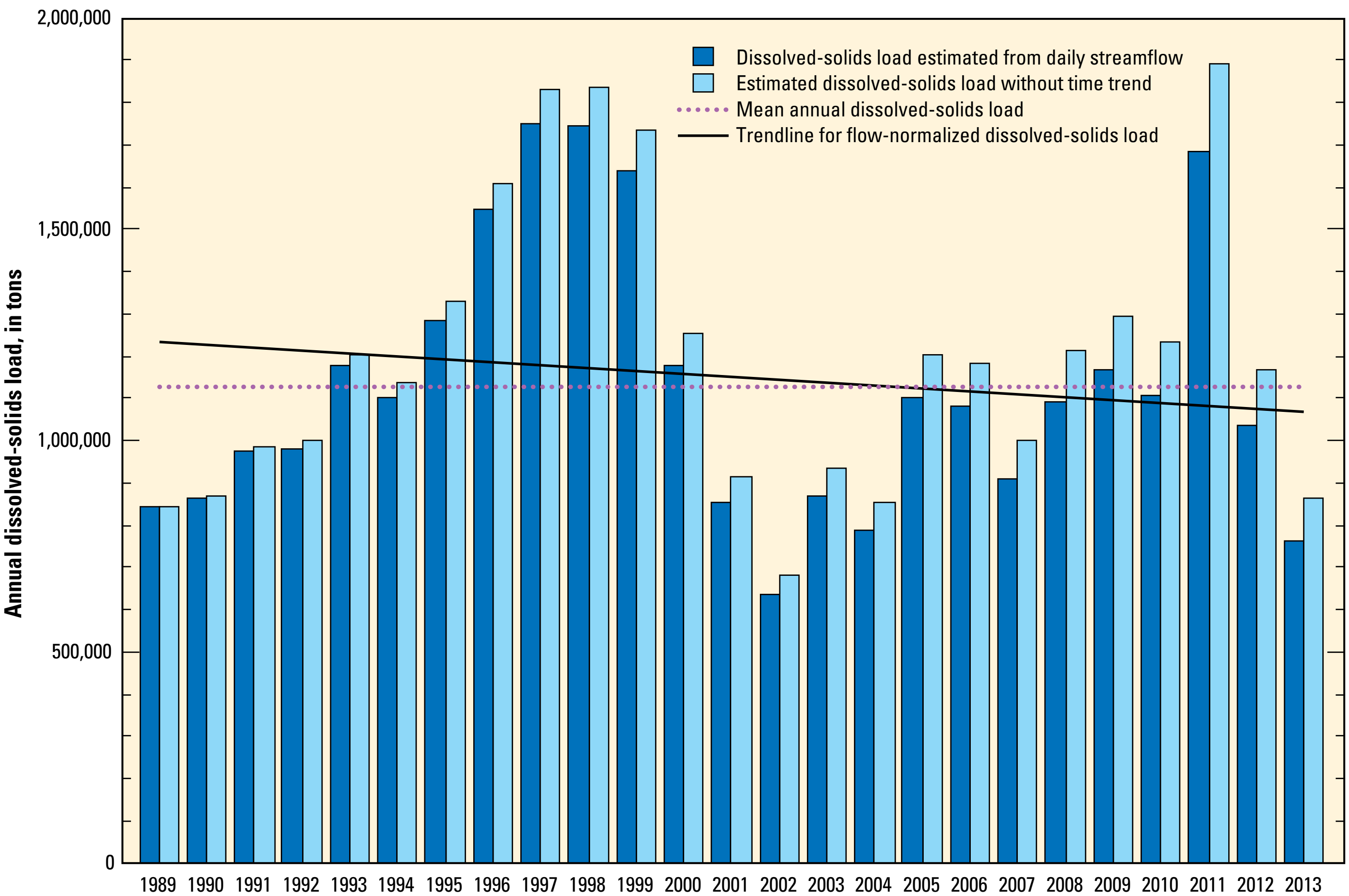

Figure 8. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09261000, Green River near Jensen, UT, during water years 1989–2013.

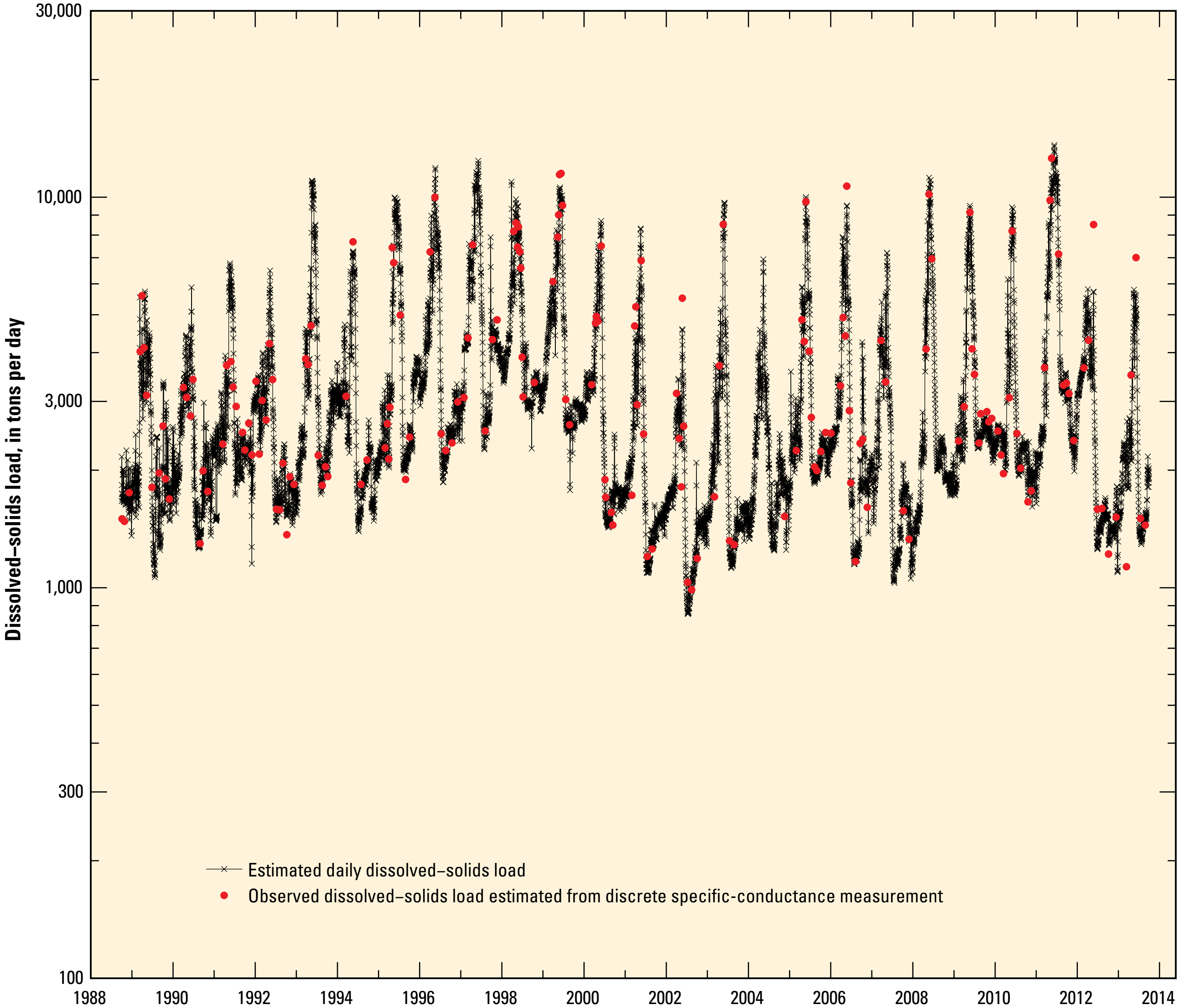

Figure 9. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09261000, Green River near Jensen, UT, during water years 1989–2013.

load (445,000 tons) in the Green River between Green River near Greendale, UT, and Green River near Jensen, UT.

The SPARROW model predicted 72 percent of the dissolved-solids load from the Yampa River basin in WY 1991 was from natural sources and 28 percent from agricultural practices (Kenney and others, 2009). In comparison, Iorns and others (1965) estimated that 85 percent of the 1914–57 average annual dissolved-solids load at the site (adjusted to 1957 development conditions) was from natural sources and 15 percent from agricultural sources. There is little irrigated agriculture in the drainage area to the Green River between the Green River near Greendale, UT, and Green River near Jensen, UT, gaging stations outside of the Yampa River Basin. After subtracting the mean annual dissolved-solids load at Green River near Greendale, UT, and Yampa River near Deerlodge Park, CO, from the load at Green River near Jensen, UT, the remaining unaccounted for mean annual load in the Green River between the Green River near Greendale, UT, and Green River near Jensen, UT, gaging stations of 76,000 tons (17 percent) is potentially from groundwater discharge, small inflows, and natural sources of dissolved solids.

The trend in dissolved-solids load from WY 1989–2013 at the Green River near Jensen, UT, site is highly significant with an annual decrease of 0.59 percent and a net change in the flow-normalized dissolved-solids load of -164,000 tons (-13.3 percent) (table 3). Part of the decrease in flow-normalized dissolved-solids load is attributed to decreases modeled at the Green River near Greendale, UT, gaging station, but the remainder is likely caused by irrigation improvements in the Yampa River Basin and (or) changes in dissolved-solids loads from natural sources.

Ashley Creek near Vernal, Utah

Ashley Creek near Vernal, UT, (gaging station 09266500) drains 101 mi^2 of the southeastern slope of the Uinta Mountains. Most of the streamflow is derived from Ashley Spring approximately 1,000 ft upstream of the site, part of a karst spring system not controlled by local topographic boundaries (Larry Spangler, U.S. Geological Survey, written commun., September 2015). During the irrigation season, water from Oaks Park Reservoir is piped into the drainage upstream from the gaging station. Part of the flow from Ashley Spring is diverted for public-supply use in Vernal City and surrounding areas in Ashley Valley (Utah Division of Water Rights written commun., April 2016). The gaging station is upstream from any irrigated agricultural fields and the water quality is affected by natural sources. Ashley Creek receives streamflow during the snowmelt runoff from Dry Fork, about 3.7 mi below the gaging station, and eventually drains to the Green River about 17 mi downstream from the Green River near Jensen, UT, gaging station after flowing through irrigated areas in Ashley Valley. The WY 1989–2013 mean annual streamflow at the site is 83 ft^3/s (table 1).

Using a regression model to determine dissolved-solids loads that included linear time, but not quadratic time, the estimated WY 1989–2013 mean annual dissolved-solids load is 4,380 tons (table 3; fig. 10) with a mean annual dissolved-solids concentration of 55 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 11. The trend in dissolved-solids load from WY 1989–2013 at Ashley Creek near Vernal, UT, is highly significant with an annual decrease of 0.28 percent and a net change in the flow-normalized dissolved-solids load of -320 tons (-6.7 percent). The LOWESS smooth line on the modified residuals (no time term used in the regression model) versus time plot has a downward slope in WY 1989–2010 and an upward slope in WY 2011–2013 (fig. A-1). Dissolved-solids concentration

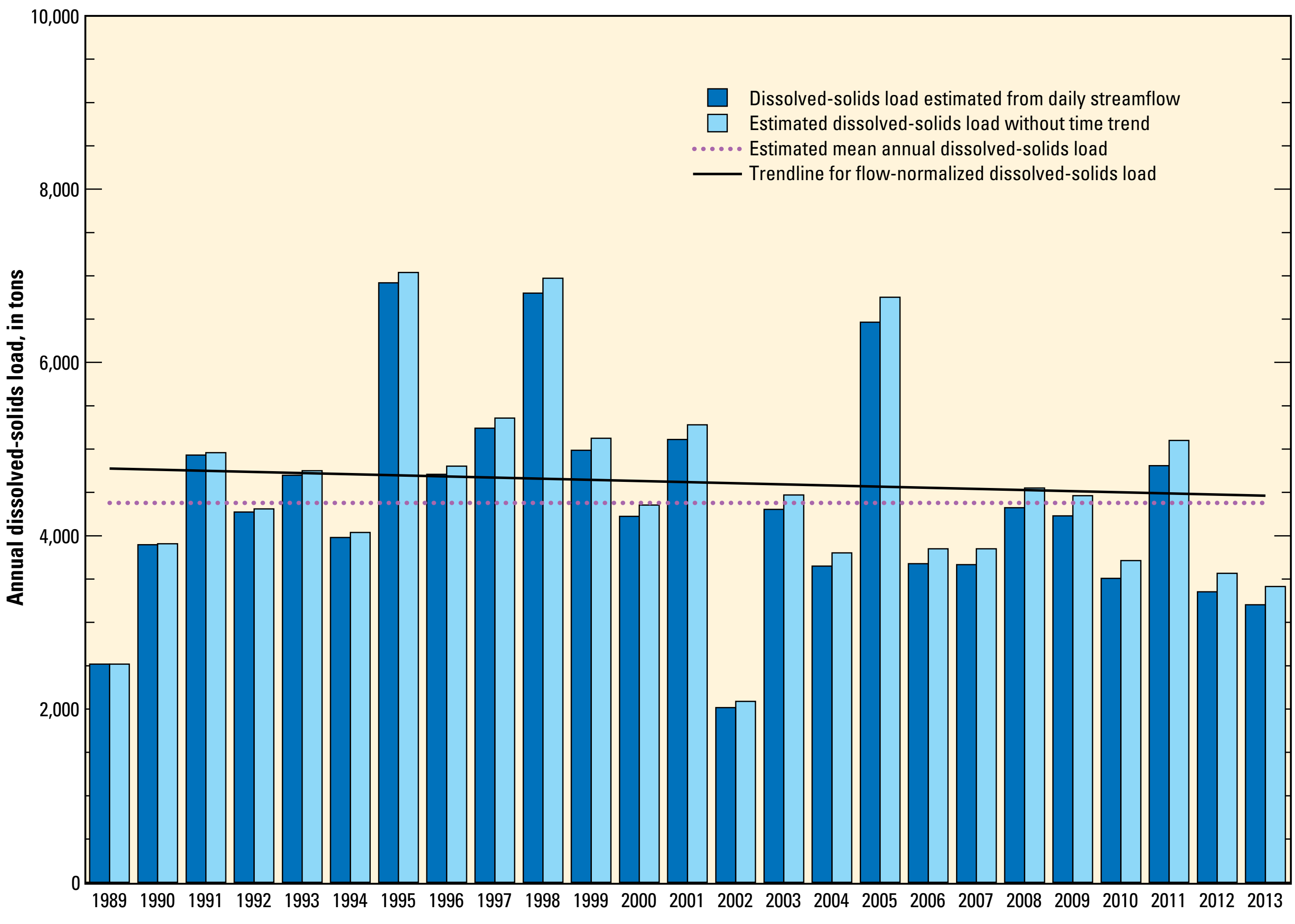

Figure 10. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09266500, Ashley Creek near Vernal, UT, during water years 1989–2013.

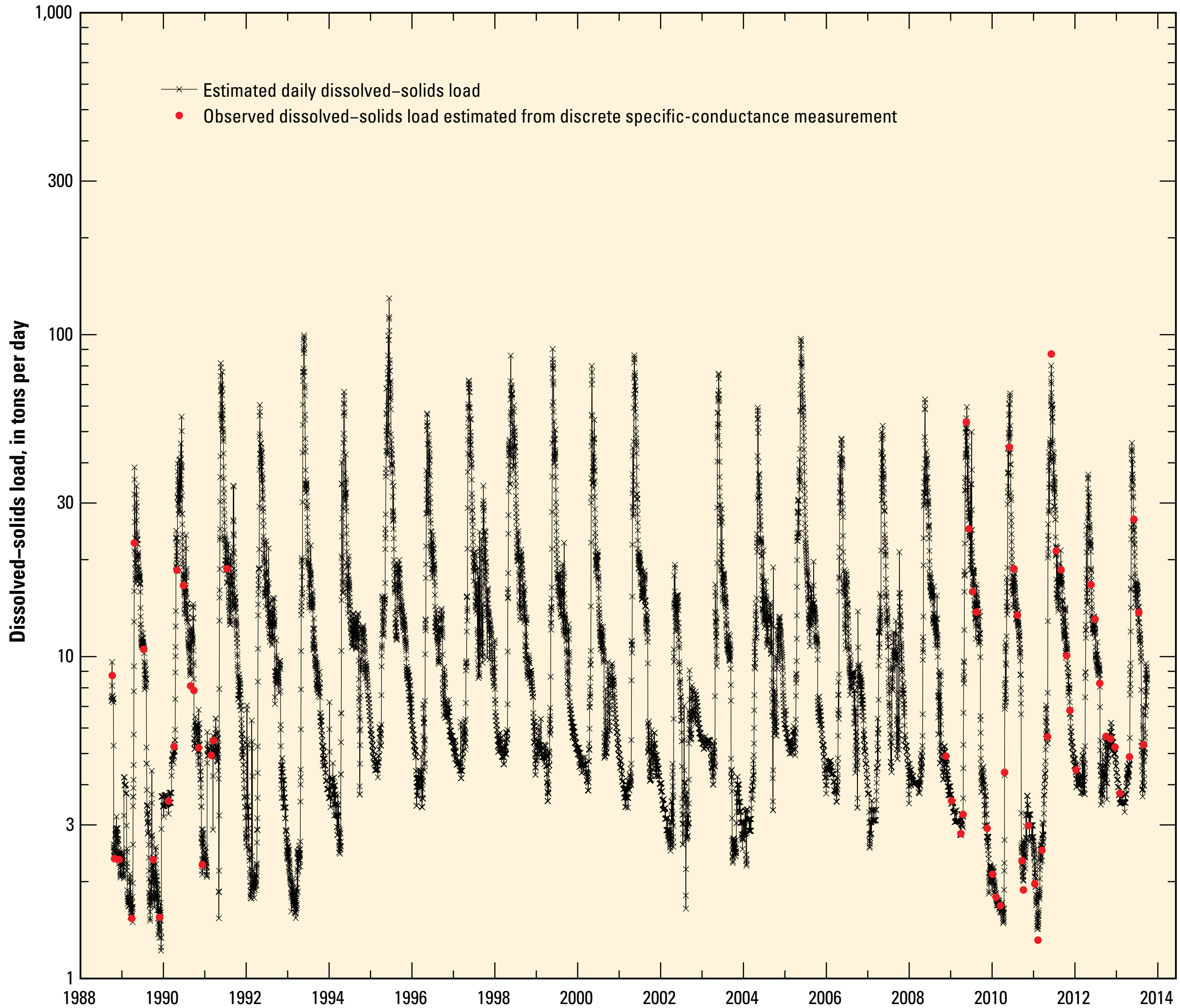

Figure 11. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09266500, Ashley Creek near Vernal, UT, during water years 1989–2013.

data were not available from the site in WY 1992–2008, and the large gap in dissolved-solids concentration data may contribute to the change in slope for the modified residuals.

Quadratic time was significant in another model for the site (table A-1) that calculated smaller dissolved-solids loads and percent change in flow-normalized dissolved-solids load over time. The quadratic time model was able to better match the change in slope shown on the modified residuals versus time plot (fig. A-1), but the step-trend analysis of annual flow-adjusted loads from the quadratic time model showed that there was no significant difference in flow-adjusted load (p-value >0.1) from the pre-gap to post-gap periods. The model with quadratic time was not selected as the final model for the site because of complications when used in calculations of dissolved-solids load mass balance.

Big Brush Creek above Red Fleet Reservoir, near Vernal, Utah

Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, (gaging station 09261700) has a drainage area of 77 mi^2, almost all of which has no irrigated agriculture. The majority of its streamflow is spring fed, mostly originating at Brush Creek Spring in the lower part of Big Brush Gorge, about 4 mi above the gaging station. Streamflow during the irrigation season is affected by releases from East Park Reservoir. The drainage overlies a karst spring system and therefore, the groundwater system is not controlled by local topographic boundaries (Larry Spangler, U.S. Geological Survey, written commun., September 2015). The gaging station is 5.5 mi upstream from the confluence of Big Brush Creek with Little Brush Creek. Little Brush Creek and Big Brush Creek converge to form Brush Creek, which drains to the Green River 12 mi downstream of the Green River near Jensen, UT, gaging station. The WY 1989–2013 mean annual streamflow at Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, is 39 ft^3/s (table 1).

The estimated WY 1989–2013 mean annual dissolved-solids load is 4,790 tons (table 3; fig. 12) with a mean annual dissolved-solids concentration of 130 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 13. The best-fit regression model to determine dissolved-solids load did not include a time term, therefore, there was no trend in flow-normalized dissolved-solids load from WY 1989–2013 at Big Brush Creek above Red Fleet Reservoir near Vernal, UT.

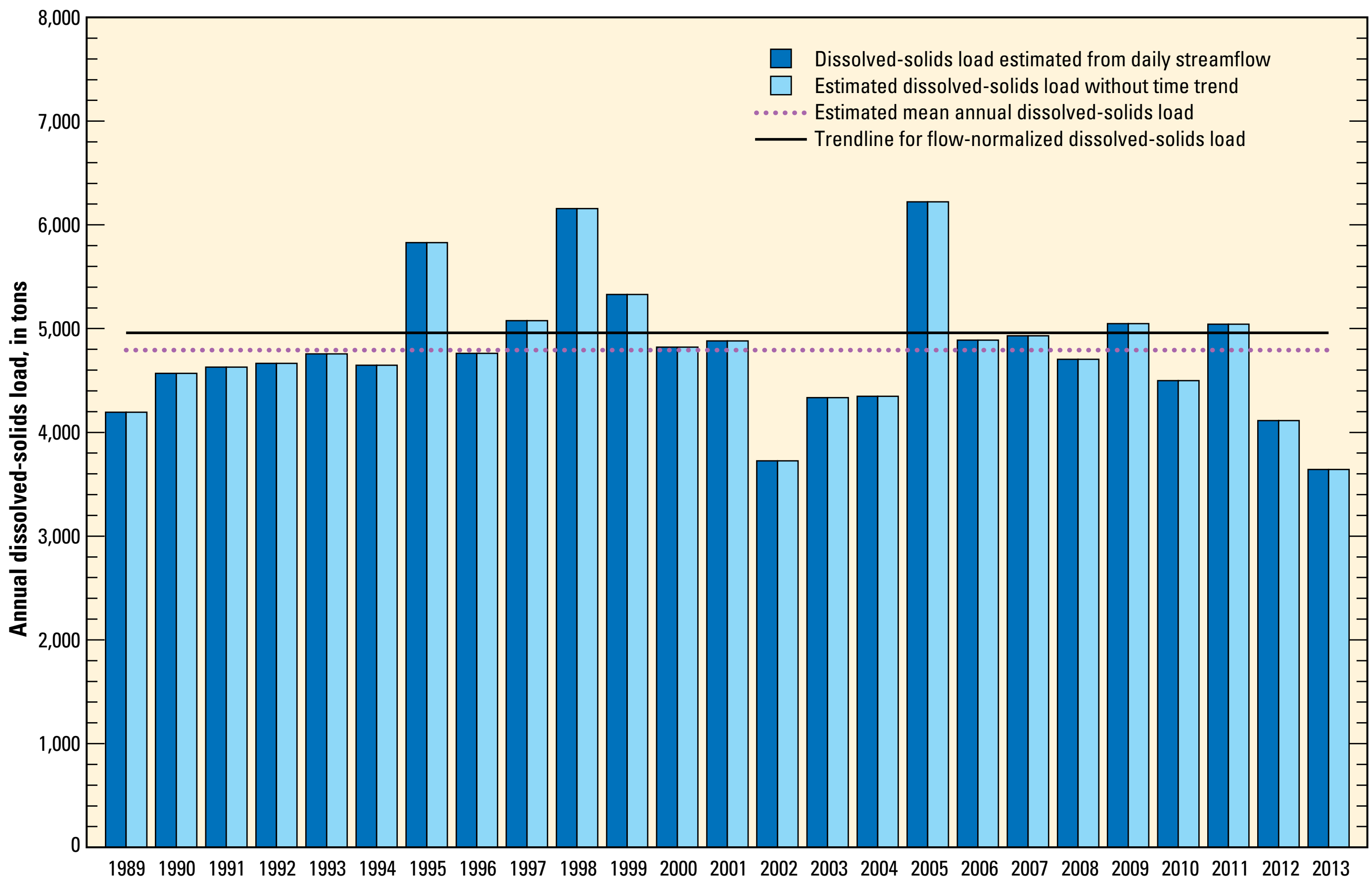

Figure 12. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09261700, Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, during water years 1989–2013.

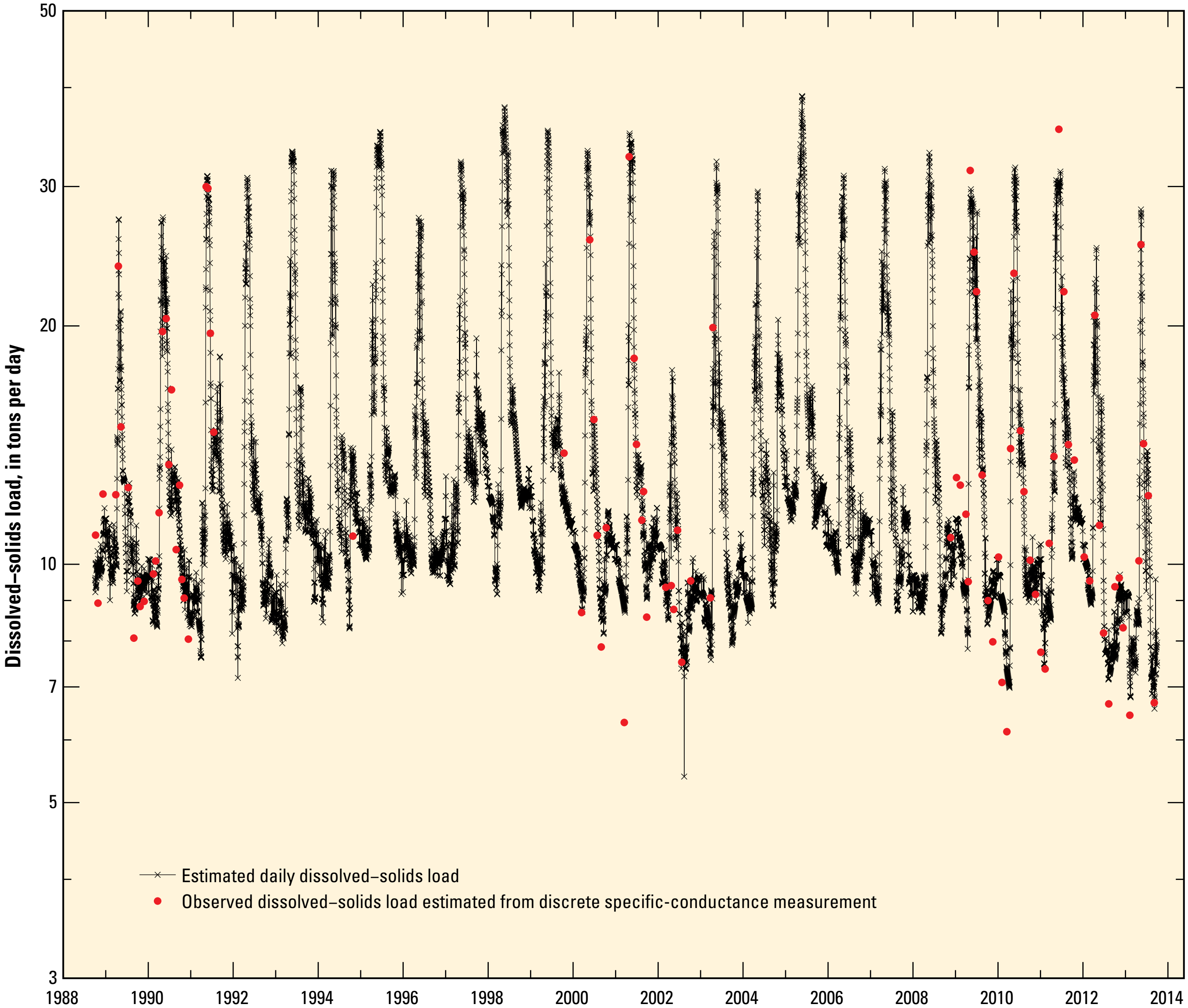

Figure 13. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09261700, Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, during water years 1989–2013.

White River near Watson, Utah

White River near Watson, UT, (gaging station 09306500) is about 8 mi downstream from the Colorado-Utah state line. The river has a drainage area of 4,020 mi^2, mainly forests and rangeland in the upper and middle parts in Colorado, and sparsely vegetated rangeland throughout the lower part in Utah. About 30,000 acres of irrigated agriculture were mapped in 2007–10 in the White River drainage in Colorado, mostly upstream from Meeker (fig. 1), but no irrigated agriculture was mapped in the drainage area below the White River near Watson, UT, gaging station (Buto and others, 2014). The White River empties into the Green River about 2 mi downstream of the mouth of the Duchesne River. The WY 1989–2013 mean annual streamflow at the site is 637 ft^3/s (table 1).

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at the White River near Watson, UT, is 233,000 tons (table 3; fig. 14) with a mean annual dissolved-solids concentration of 373 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 15. The White River flows through the Uinta Formation in the Uinta Basin downstream from the White River near Watson, UT, gaging station. Upstream from the gaging station, the river flows through the Piceance structural basin that also contains Tertiary-age deposits. Several abandoned oil and gas exploratory wells previously discharged saline groundwater to the White River near Meeker, Colorado. Reclamation plugged eight of these wells in 1980–81 and reduced salt loading to the river by about 19,000 ton/yr (Vaill and Butler, 1999).

Iorns and others (1965) estimated that about half of the 1914–57 mean annual dissolved-solids load at the White River near Watson, UT, gaging station (adjusted to development conditions in 1957) was from natural sources. The SPARROW model for 1991 predicted that 85 percent of the load at the site was from natural sources and 16 percent from agricultural practices (Kenney and others, 2009).

The trend in dissolved-solids load from WY 1989–2013 at White River near Watson, UT, is highly significant with an annual decrease of 0.97 percent and a net change in the flow-normalized dissolved-solids load of -55,300 tons (-20.8 percent).The decrease in flow-normalized dissolved-solids load is attributed to irrigation improvements in the upper parts of the drainage basin and changes in dissolved-solids loads from non-agricultural and natural sources.

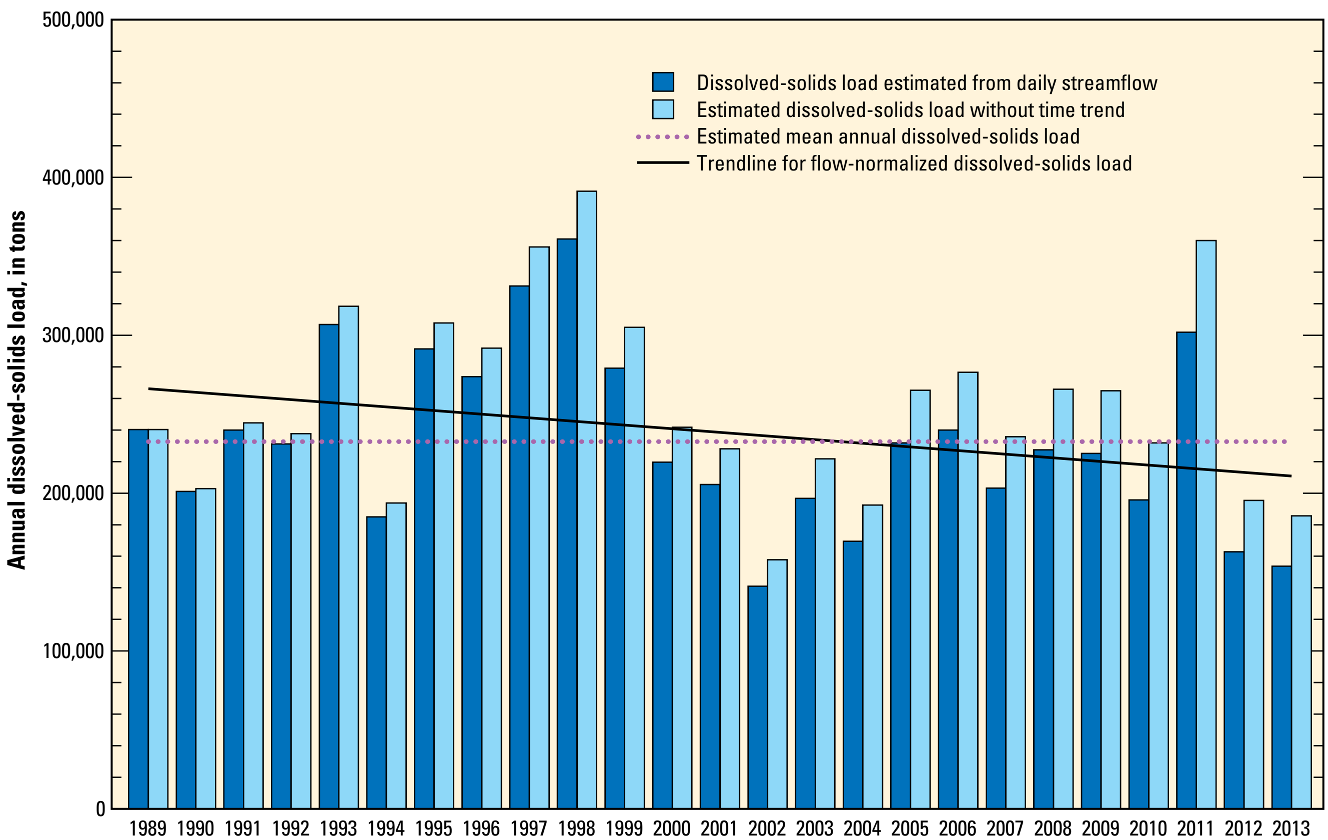

Figure 14. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09306500, White River near Watson, UT, during water years 1989–2013.

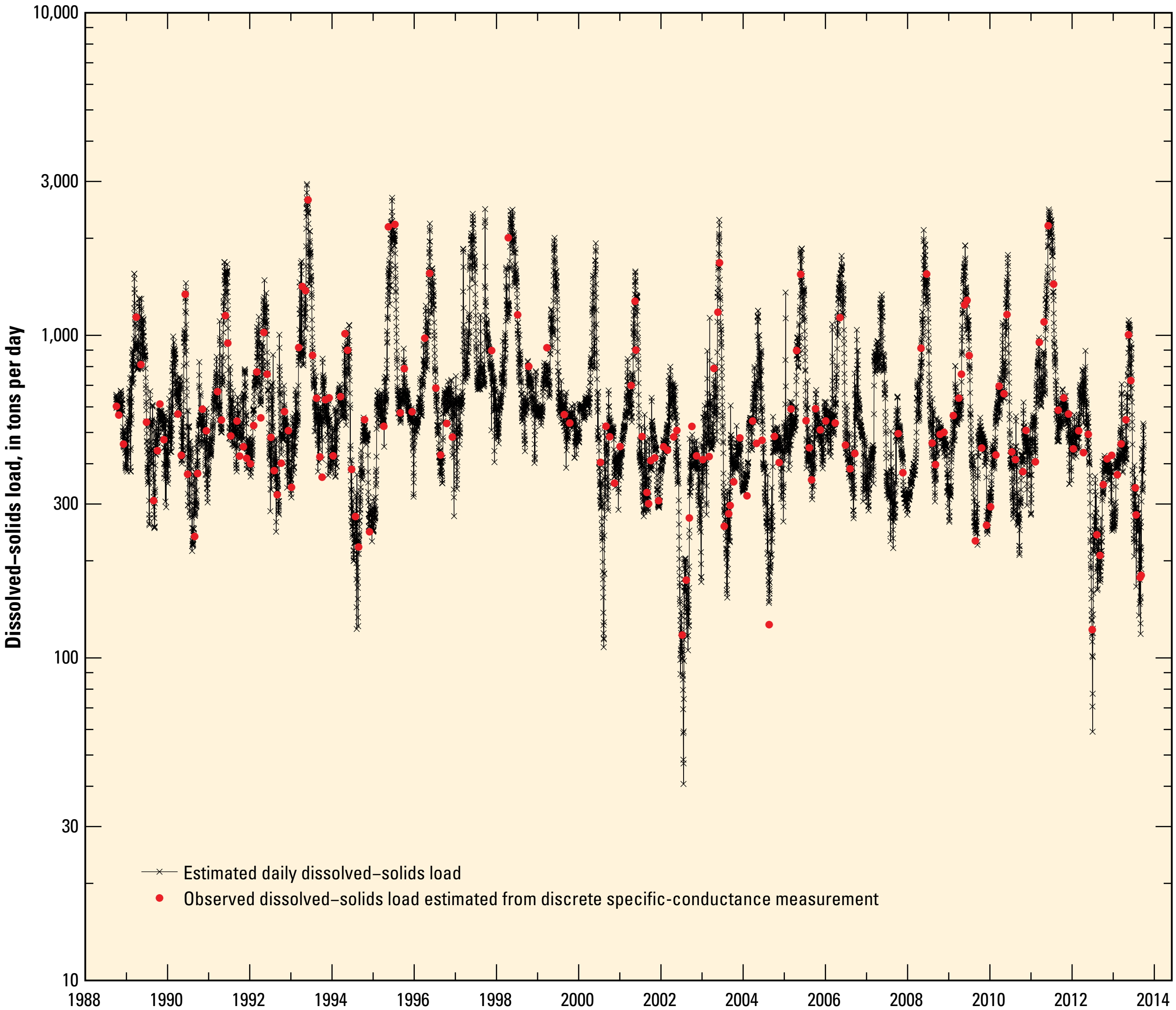

Figure 15. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09306500, White River near Watson, UT, during water years 1989–2013.

Green River at Green River, Utah

Green River at Green River, UT, (gaging station 09315000) is the farthest downstream site in the study area, with a drainage area of 44,850 mi^2 and is 118 mi upstream from the confluence of the Green and Colorado Rivers. The WY 1989–2013 mean annual streamflow at the site is 4,730 ft^3/s (table 1). Other perennial tributaries to the Green River upstream of the Green River at Green River, UT, gaging station are the Duchesne River, Pariette Draw, Willow Creek, Nine Mile Creek, Range Creek, and the Price River (fig. 2).

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at Green River at Green River, UT, was 1,760,000 tons (table 3; fig. 16) with a mean annual dissolved-solids concentration of 386 mg/L. Daily specific-conductance values are available from January 1961 to the present (2016) for the Green River at Green River, UT, gaging station. These specific-conductance values are from a point in time during the day (an instantaneous value) and are not an average value like the daily mean streamflow value for that day. The daily instantaneous specific-conductance values were not used in the RLOADEST calibration data set, but were used to check the predicted dissolved-solids load model results (fig. 17). Instead, 202 discrete measurements of specific conductance that had a corresponding dissolved-solids concentration were used to determine the final dissolved-solids load regression model (fig. 17).

Iorns and others (1965) estimated that 61 percent of the 1914–57 mean annual dissolved-solids load at the Green River at Green River, UT, gaging station (adjusted to development conditions in 1957) was from natural sources. The SPARROW model for WY 1991 predicted that 63 percent of the load at the gaging station was from natural sources and 37 percent from irrigated lands (Kenney and others, 2009). The trend in dissolved-solids load from WY 1989–2013 at Green River at Green River, UT, is highly significant with an annual decrease of 0.81 percent and a net change in the flow-normalized dissolved-solids load of -352,000 tons (-17.8 percent).

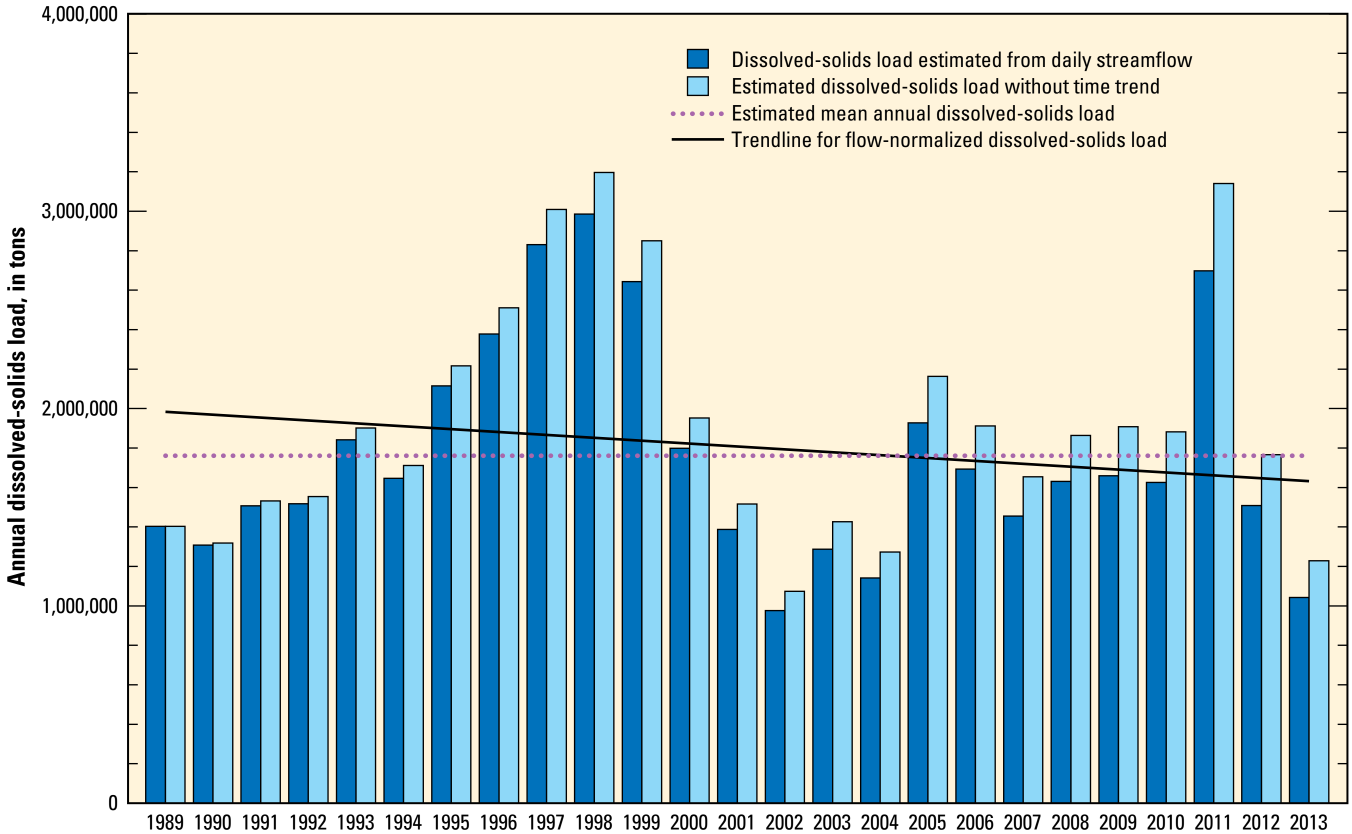

Figure 16. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09315000, Green River at Green River, UT, during water years 1989–2013.

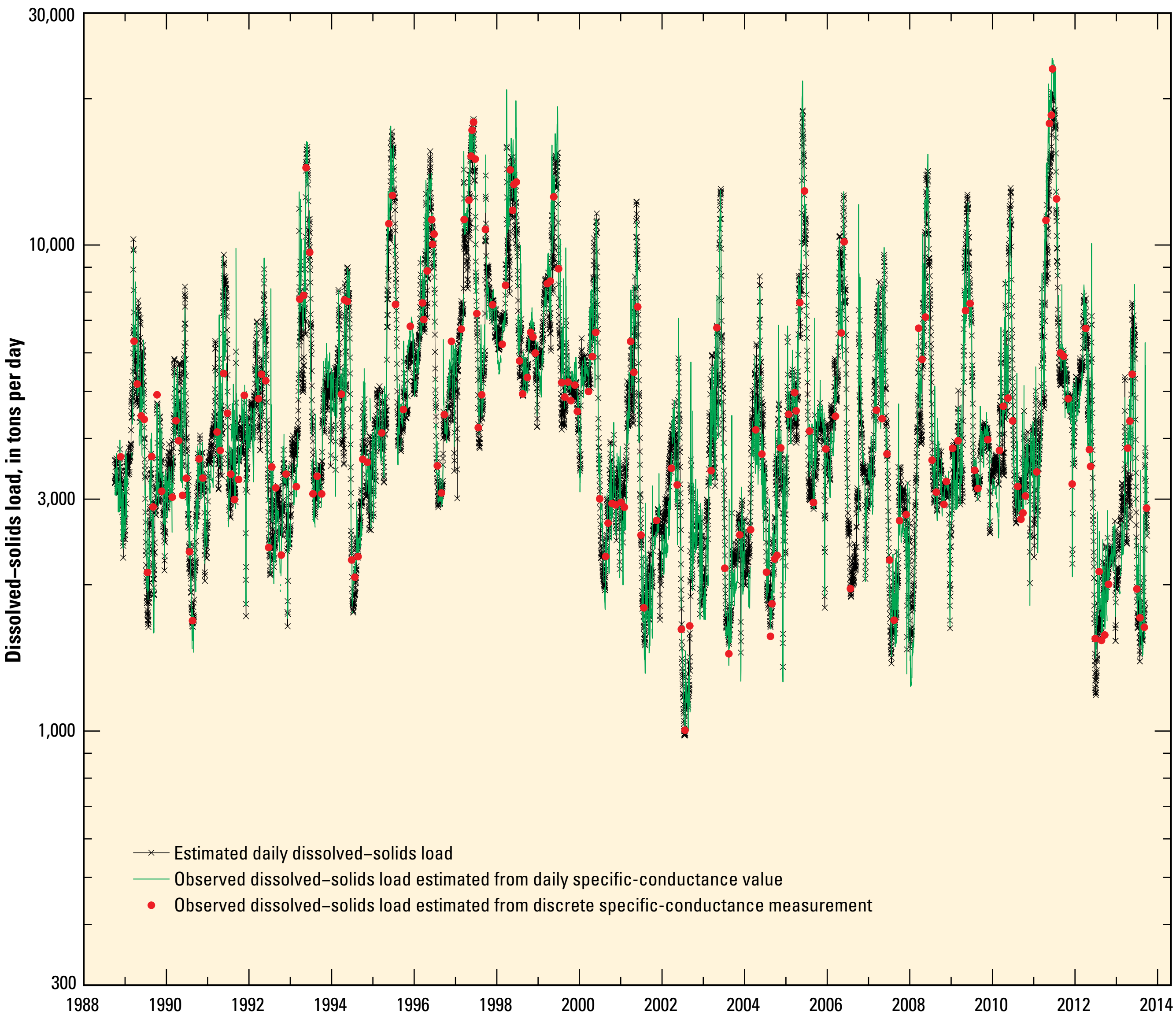

Figure 17. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09315000, Green River at Green River, UT, during water years 1989–2013.

Duchesne River Basin

Duchesne River near Tabiona, Utah

Duchesne River near Tabiona, UT, (gaging station 09277500) is the upstream site on the Duchesne River. It has a drainage area of 353 mi^2 and is 7 mi downstream from the town of Tabiona. There are several diversions above the site for irrigation, including a transbasin diversion to the Great Basin 20 mi upstream. The WY 1989–2013 mean annual streamflow at Duchesne River near Tabiona, UT, is 131 ft^3/s (table 1).

Most of the drainage area to the Duchesne River near Tabiona, UT, gaging station is natural rangeland and forest. Irrigated agriculture is located along the river's floodplain beginning at the confluence of the West Fork Duchesne River above Hanna (fig. 5). The Utah Department of Natural Resources (2013) mapped 6,110 acres of the drainage area to the Duchesne River near Tabiona, UT, as irrigated in 2012, about 4.3 percent of the total irrigated land mapped in the Duchesne River Basin. Although 78 percent of the irrigated land in the Duchesne River near Tabiona, UT, drainage area was mapped as sprinkler irrigated and 22 percent as flood irrigated in 2012, a trend in the amount of land differentiated by irrigation method could not be determined from comparisons to land mapped in 2006 (70-percent sprinkler) and 2007–2010 (79-percent sprinkler). Subirrigated land accounted for 10 percent of the total irrigated land in the drainage area in 2012. The SPARROW model for 1991 predicted that 79 percent of the dissolved-solids load at the gaging station was from natural sources and 22 percent from irrigated lands (Kenney and others, 2009).

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at Duchesne River near Tabiona, UT, is 30,200 tons (table 3; fig. 18) with a mean annual dissolved-solids concentration of 245 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 19. The best-fit regression model to determine dissolved-solids load did not include a time term, therefore, there was no trend in the WY 1989–2013 flow-normalized dissolved-solids load at the Duchesne River near Tabiona, UT, gaging station. No trend in flow-normalized dissolved-solids load at the site corresponds to little change in the amount of irrigated land in the site's drainage area according to land-use mapping done in 1992, 2000, 2006, 2007–10, and 2012.

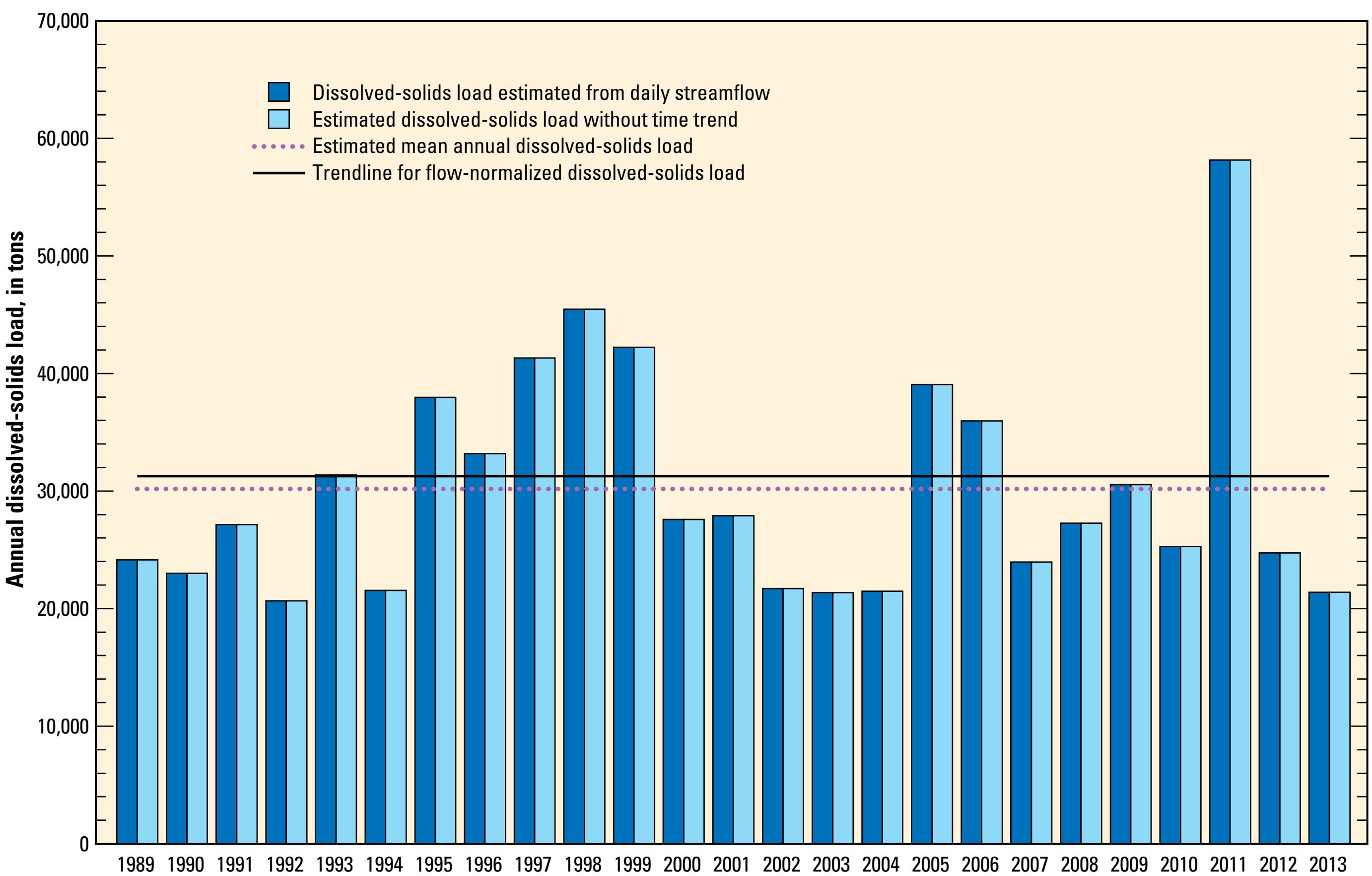

Figure 18. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09277500, Duchesne River near Tabiona, UT, during water years 1989–2013.

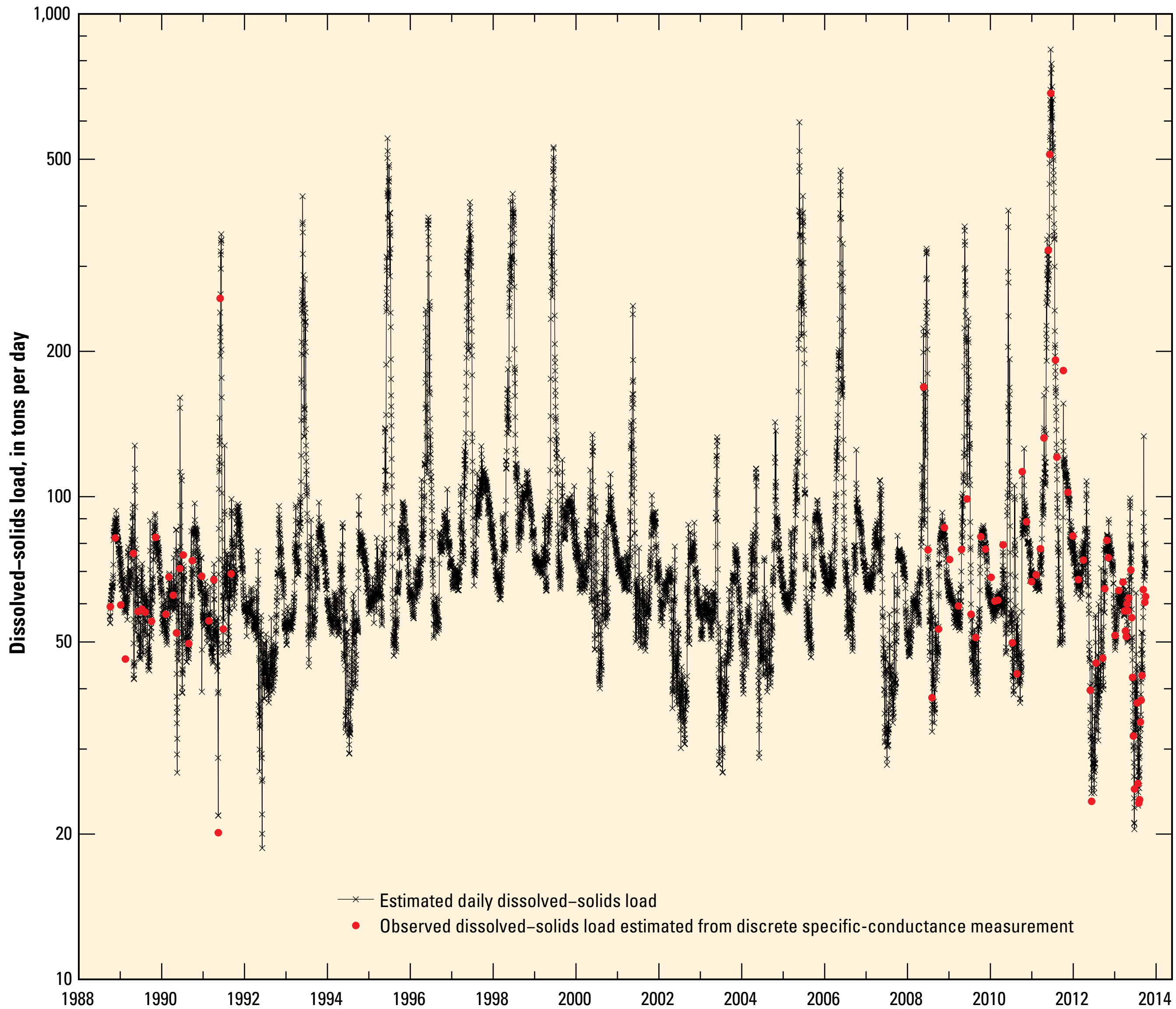

Figure 19. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09277500, Duchesne River near Tabiona, UT, during water years 1989–2013.

Rock Creek near Mountain Home, Utah

Rock Creek near Mountain Home, UT, (gaging station 09279000) drains 147 mi^2 of the southwestern slope of the Uinta Mountains. Streamflow at the site is partially regulated by the Upper Stillwater Dam, 8 mi upstream. The gaging station is upstream of any irrigated agricultural fields, and the water quality is primarily affected by natural sources. Rock Creek eventually drains to the Duchesne River about 6 mi downstream from the Duchesne River near Tabiona, UT, gaging station. The WY 1989–2013 mean annual streamflow at the site is 88 ft^3/s (table 1).

The estimated WY 1989–2013 mean annual dissolved-solids load in Rock Creek near Mountain Home, UT, is 4,930 tons (table 3; fig. 20) with a mean annual dissolved-solids concentration of 68 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 21. The best-fit regression model to determine dissolved-solids load did not include a time term, therefore, there was no trend in flow-normalized load for WY 1989–2013. The lack of a trend in dissolved-solids load over time indicates no change in natural conditions.

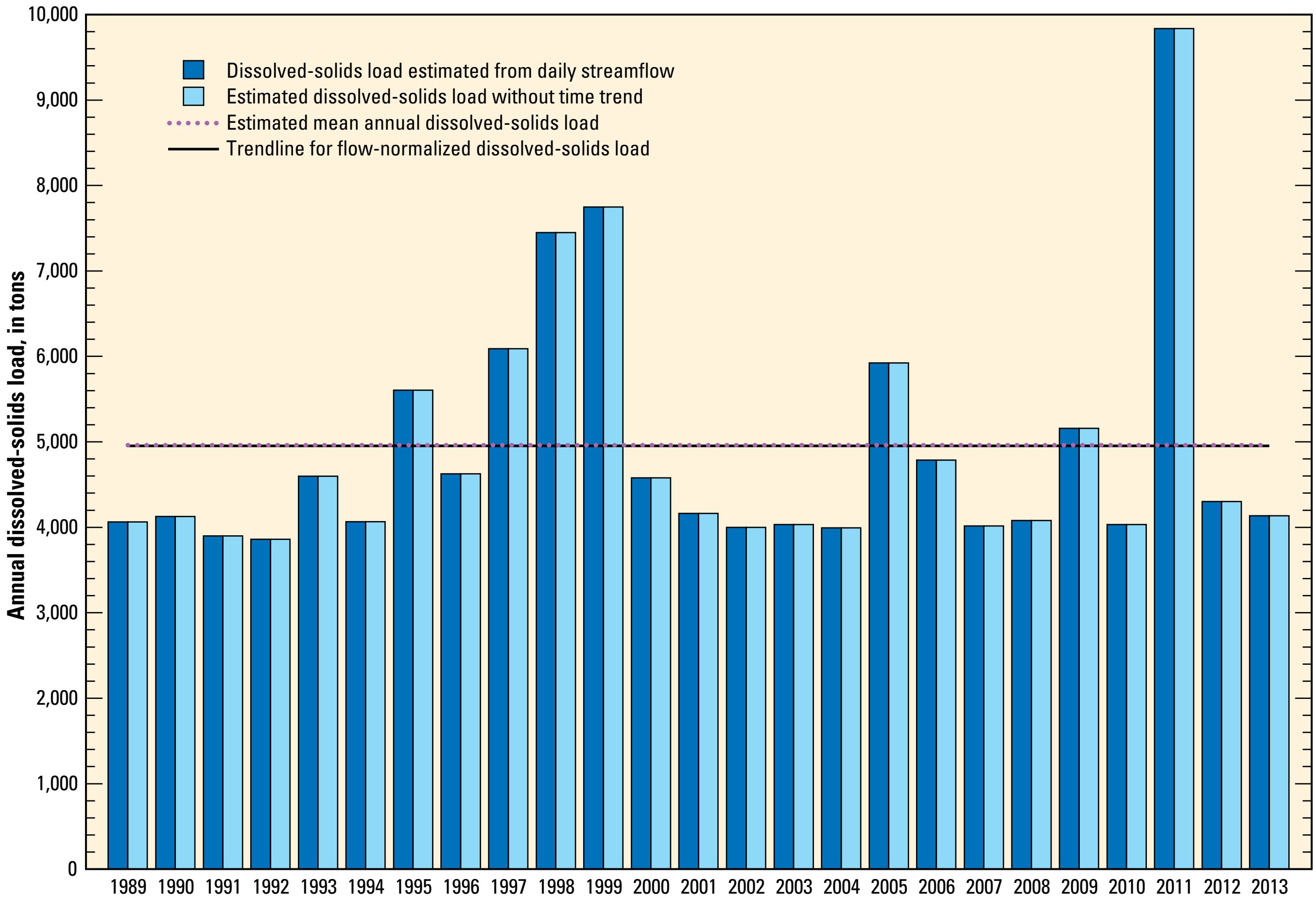

Figure 20. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09279000, Rock Creek near Mountain Home, UT, during water years 1989–2013.

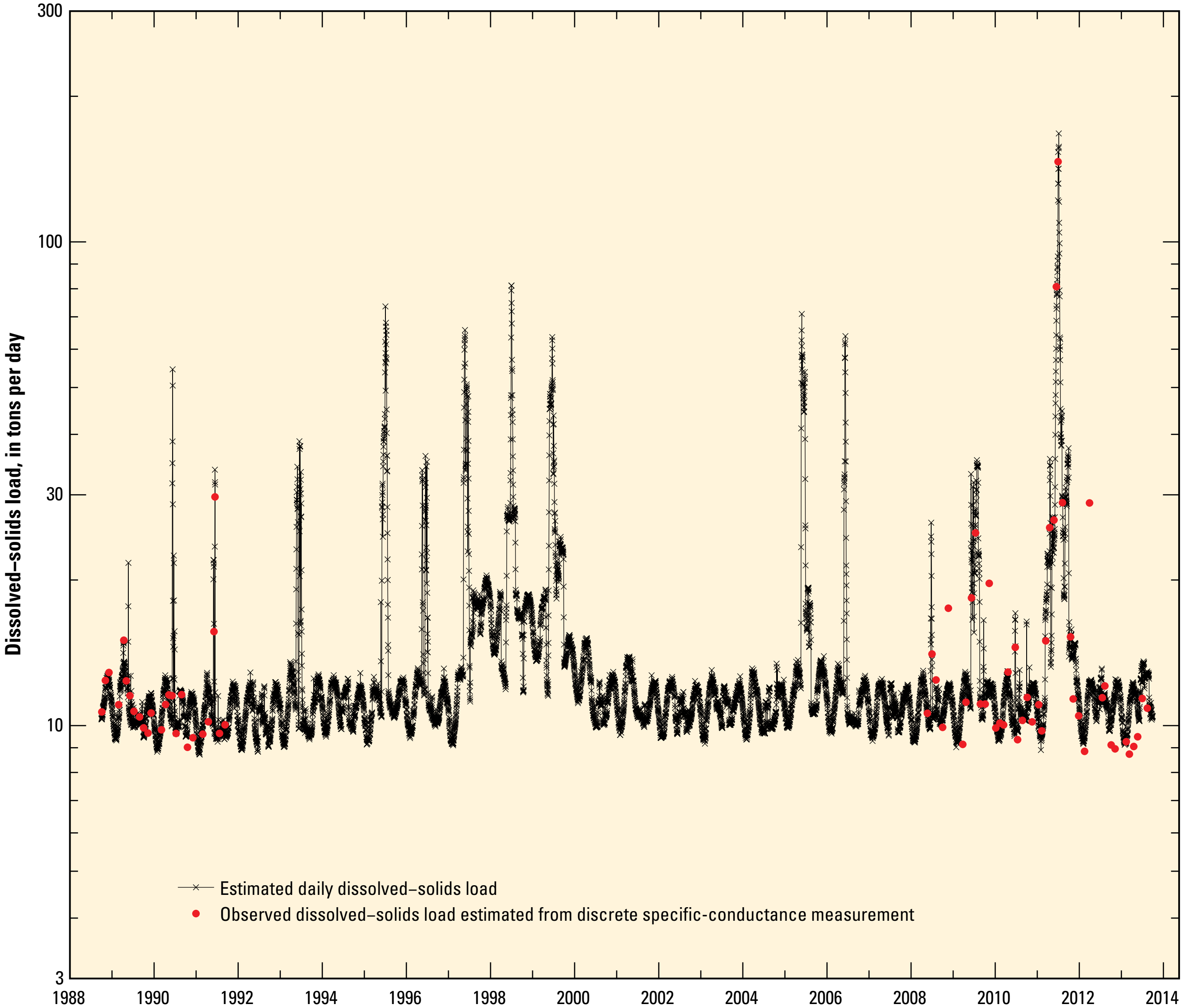

Figure 21. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09279000, Rock Creek near Mountain Home, UT, during water years 1989–2013.

Strawberry River near Duchesne, Utah

Strawberry River near Duchesne, UT, (gaging station 09288180) is 2,000 ft upstream from the high-water line for Starvation Reservoir (maximum storage capacity 167,300 acre-ft, U.S. Bureau of Reclamation, 2017) and 7.9 mi west of the town of Duchesne, UT. Streamflow is diverted above the site to the Great Basin and for irrigation near the river. The WY 1989–2013 mean annual streamflow at the site is 132 ft^3/s (table 1). The drainage area to the Strawberry River near Duchesne, UT, gaging station is 917 mi^2, most of which is natural rangeland and forest. The Utah Department of Natural Resources (2013) mapped 3,758 acres of irrigated land in the river's floodplain upstream of the site in 2012, of which 76 percent was sprinkler irrigated and 24 percent flood irrigated. In comparison, 70 percent of the irrigated land was mapped as sprinkler irrigated in 2006 (Utah Department of Natural Resources, 2013) and 71 percent in 2007–10 (Buto and others, 2014). Subirrigated land accounted for 29 percent of the total irrigated land in the drainage area in 2012. The SPARROW model for WY 1991 predicted that 87 percent of the dissolved-solids load at the gaging station was from natural sources and 13 percent from irrigated lands (Kenney and others, 2009).

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at the Strawberry River near Duchesne, UT, gaging station is 47,300 tons (table 3; fig. 22) with a mean annual dissolved-solids concentration of 369 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 23. The trend in dissolved-solids load from WY 1989–2013 at Strawberry River near Duchesne, UT, is highly significant with an annual decrease of 0.41 percent and a net change in the flow-normalized load of -4,560 tons (-9.4 percent). Changes in the amount of irrigated land in the site's drainage area varied during the mapping periods 1992, 2000, 2006, 2007–10, and 2012, and could not be used to explain the downward trend in flow-normalized dissolved-solids load modeled at the site.

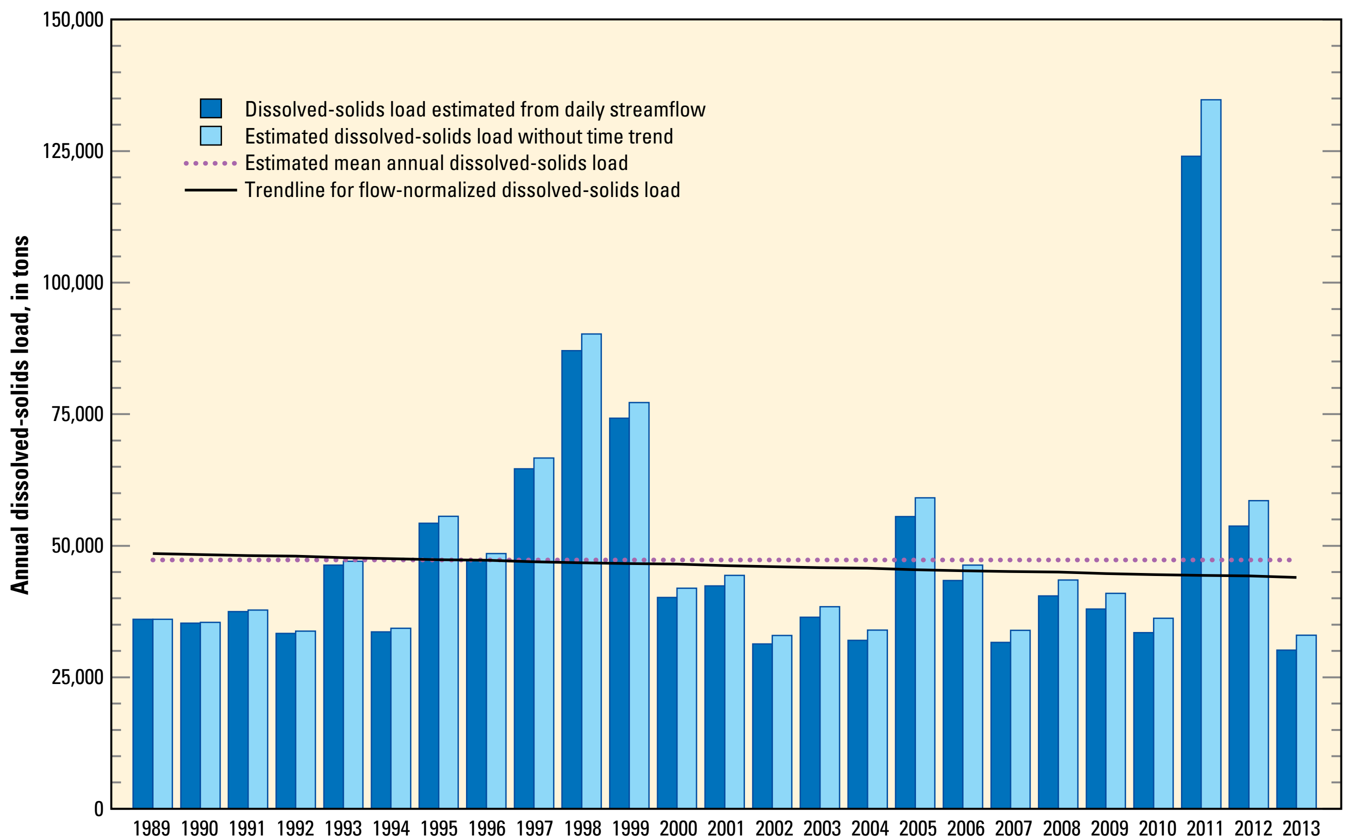

Figure 22. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09288180, Strawberry River near Duchesne, UT, during water years 1989–2013.

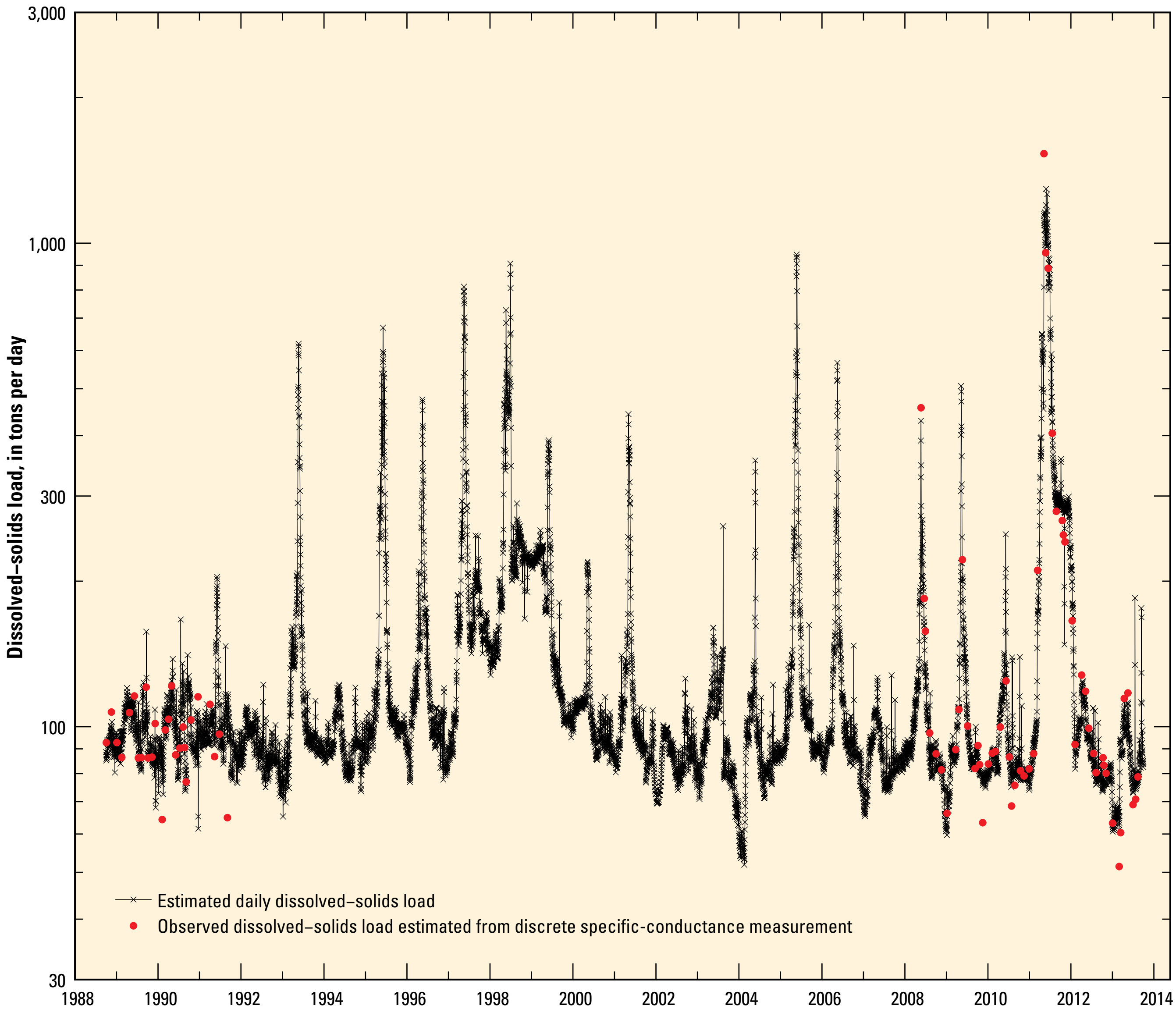

Figure 23. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09288180, Strawberry River near Duchesne, UT, during water years 1989–2013.

Lake Fork River above Moon Lake, near Mountain Home, Utah

Lake Fork River above Moon Lake, near Mountain Home, UT, (gaging station 09289500) is 2,000 ft upstream from Moon Lake at its maximum stage and less than 11 mi from the crest of the Uinta Mountains. The area draining to the site (78 mi^2) consists of forest and bare rock. The WY 1989–2013 mean annual streamflow at the site is 110 ft^3/s (table 1).

The estimated WY 1989–2013 mean annual dissolved-solids load at Lake Fork River above Moon Lake, near Mountain Home, UT, is 1,520 tons (table 3; fig. 24) with a mean annual dissolved-solids concentration of 14 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 25. Dissolved-solids concentration data were not available for the site during WY 1992–2007. The lack of a significant trend in dissolved-solids load over time indicates no change in natural conditions.

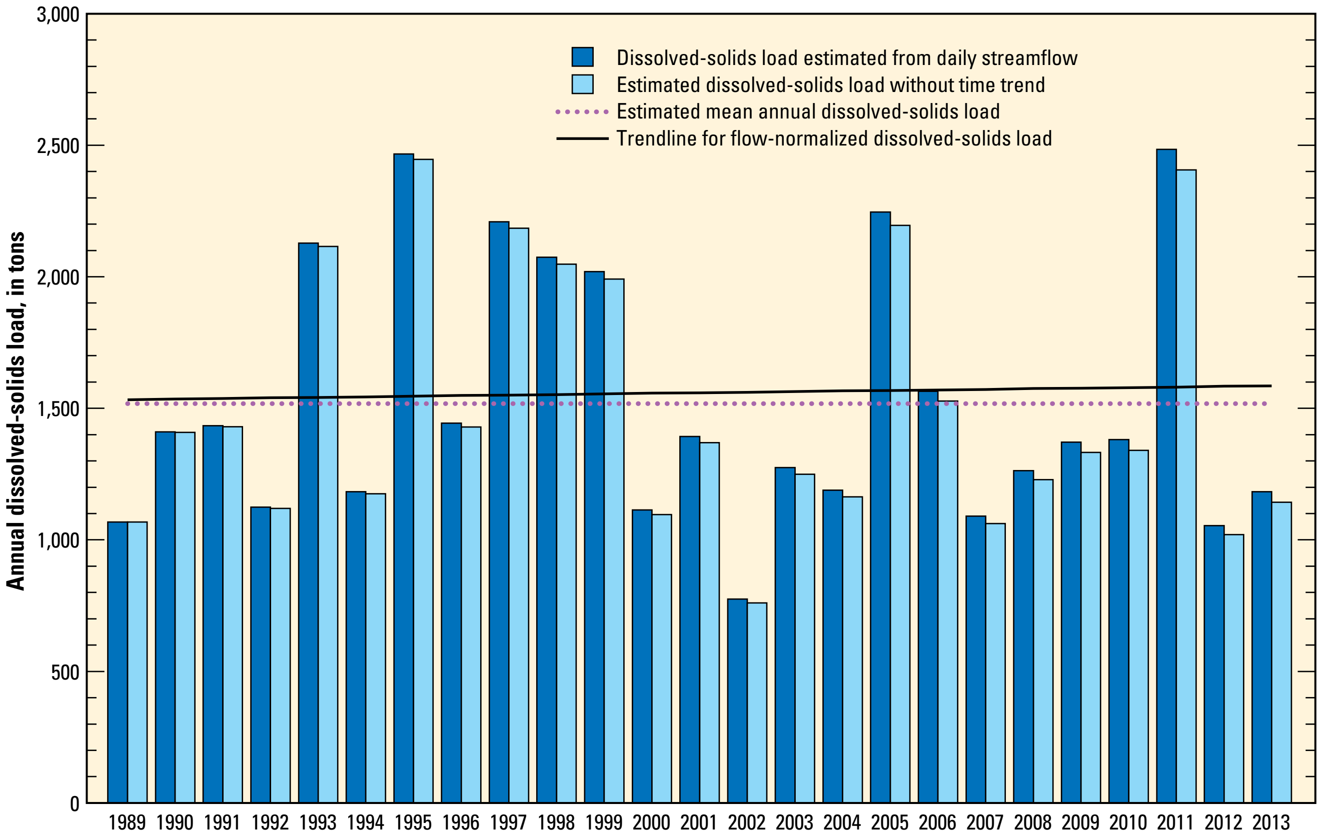

Figure 24. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09289500, Lake Fork River above Moon Lake, near Mountain Home, UT, during water years 1989–2013.

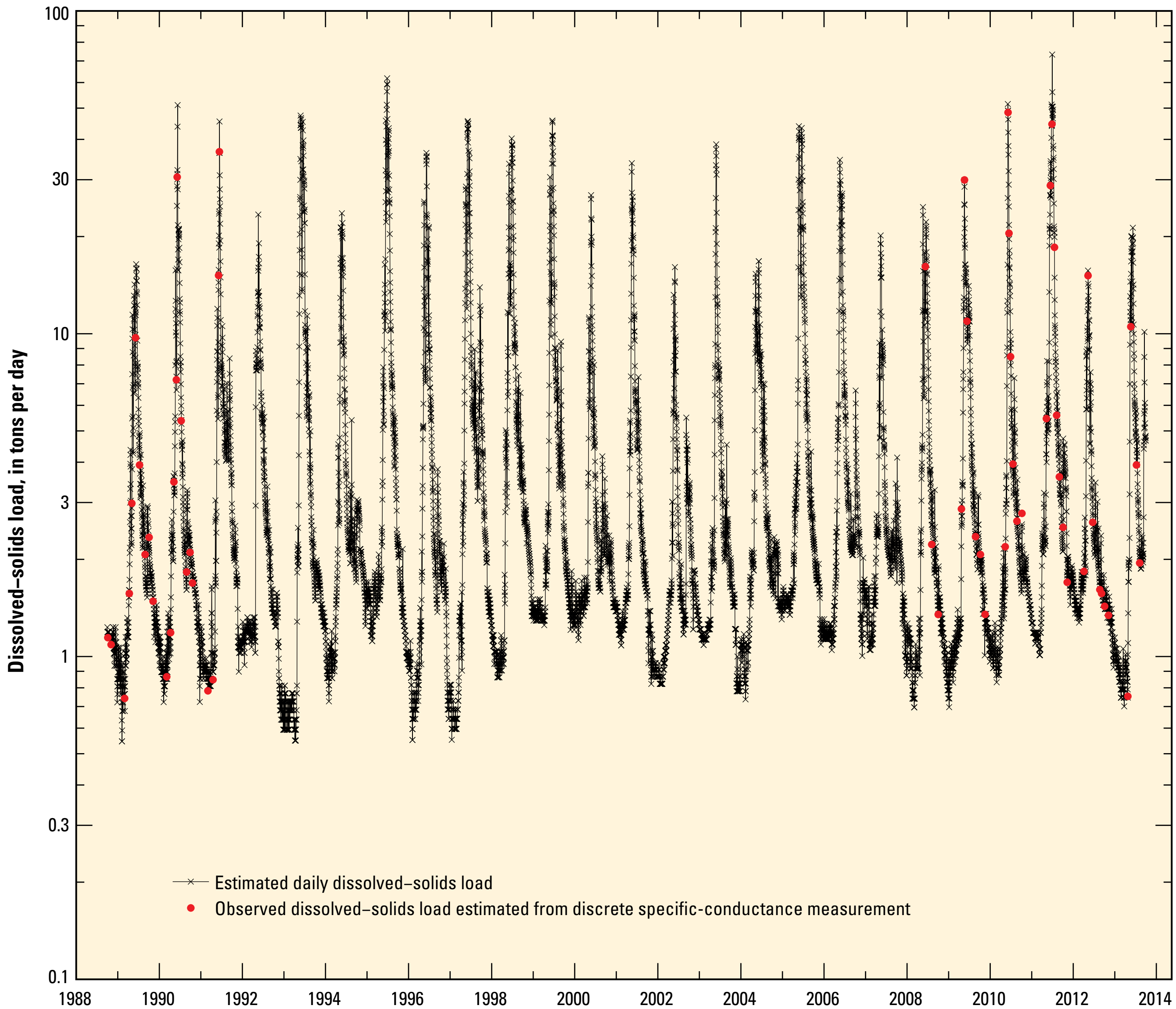

Figure 25. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09289500, Lake Fork River above Moon Lake, near Mountain Home, UT, during water years 1989–2013.

Lake Fork River below Moon Lake, near Mountain Home, Utah

Lake Fork River below Moon Lake, near Mountain Home, UT, (gaging station 09291000) is 2,000 ft downstream from the Moon Lake dam and streamflow at the site is regulated by reservoir releases. The drainage area for the site is 112 mi^2 and includes two small streams that drain to Moon Lake. The WY 1989–2013 mean annual streamflow at the site is 117 ft^3/s (table 1). There is no streamflow at the site when the reservoir gates are closed, typically from October to March, during the nonirrigation season. Water from the Lake Fork River downstream from the gaging station is diverted for irrigation in the Mountain Home and Altonah areas.

The estimated WY 1989–2013 mean annual dissolved-solids load at Lake Fork River below Moon Lake, near Mountain Home, UT, is 2,150 tons (table 3; fig.26) with a mean annual dissolved-solids concentration of 18 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 27. The best-fit regression model to determine load did not include a time term, therefore, there was no trend in flow-normalized dissolved-solids load for WY 1989–2013 at the site. The lack of a trend in dissolved-solids load over time indicates no change in natural conditions.

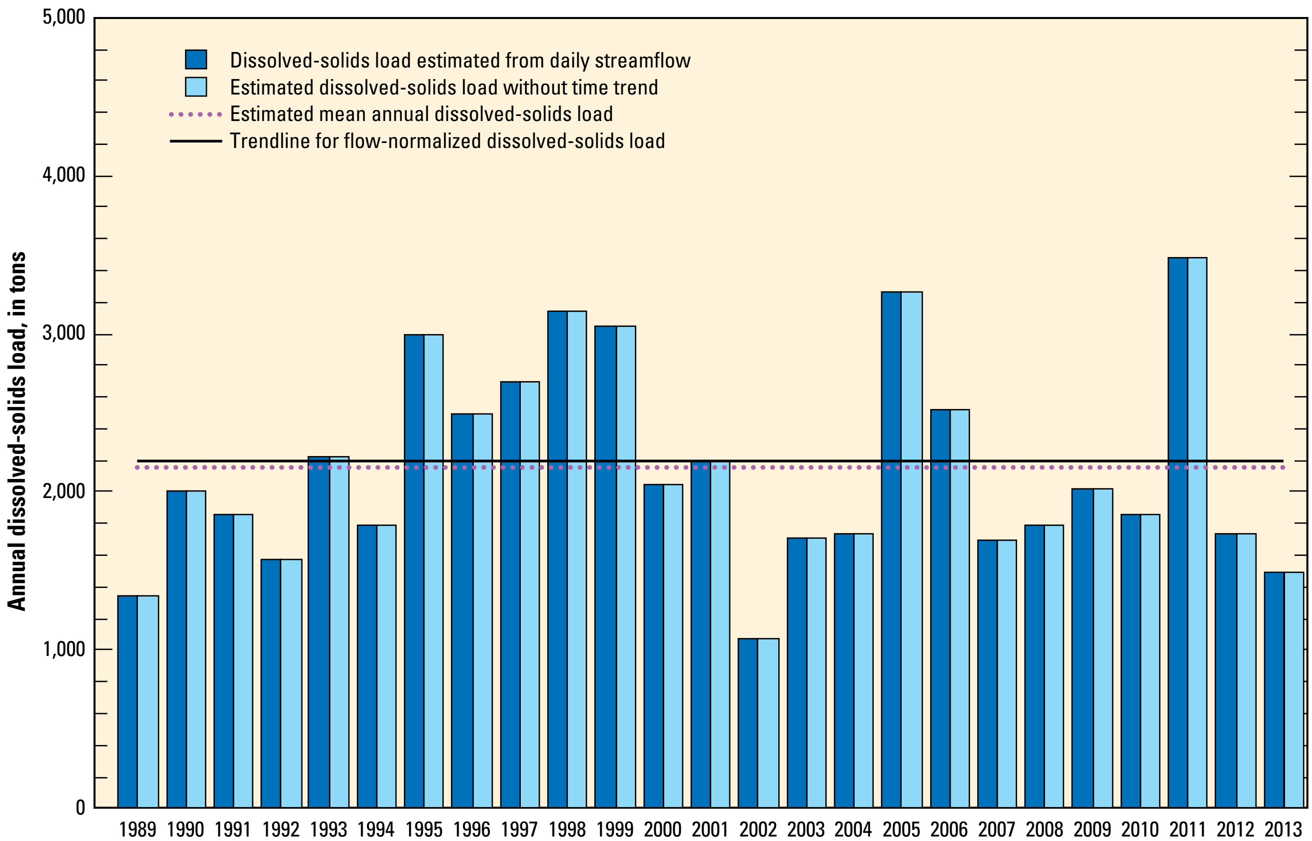

Figure 26. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09291000, Lake Fork River below Moon Lake, near Mountain Home, UT, during water years 1989–2013.

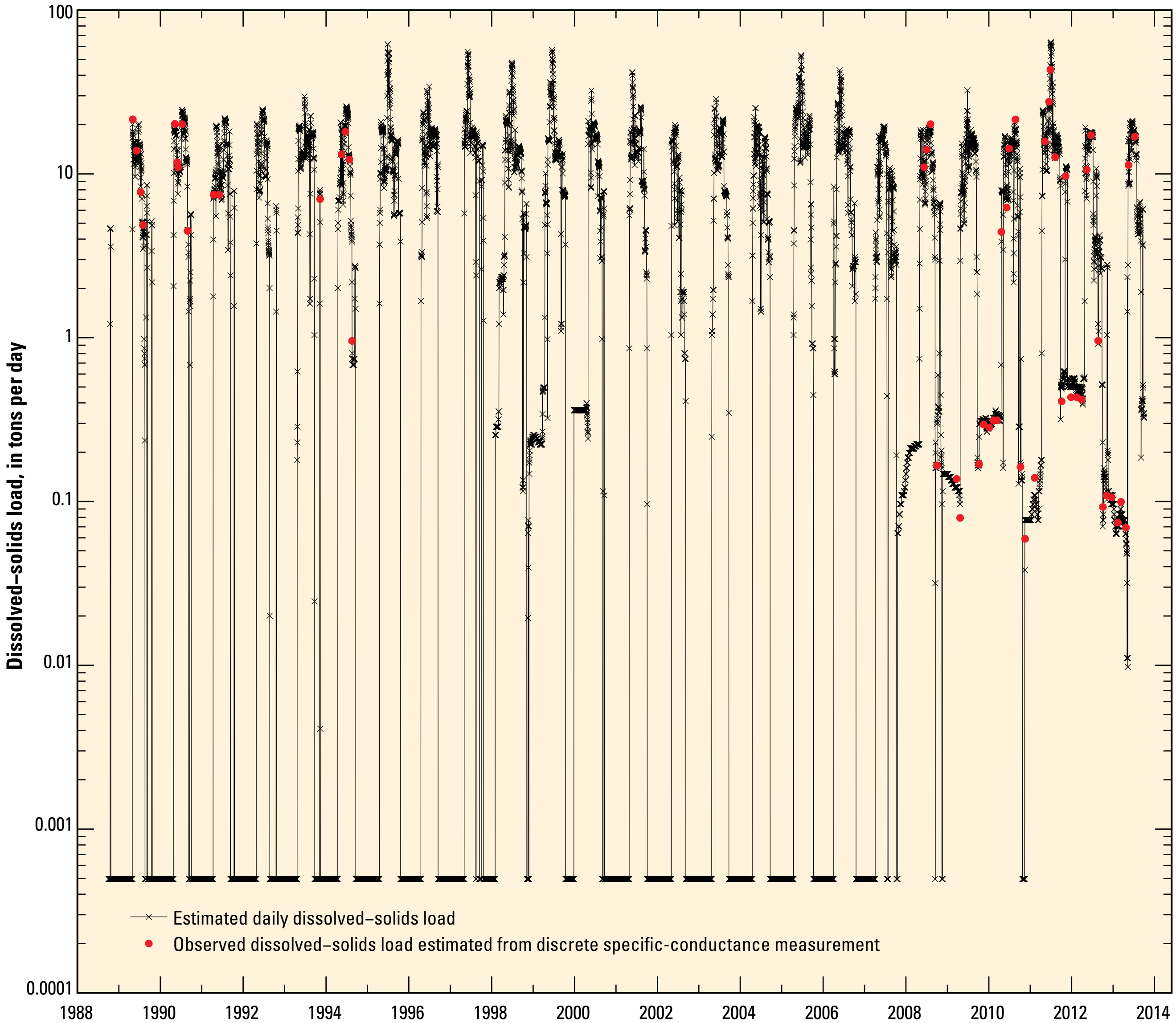

Figure 27. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09291000, Lake Fork River below Moon Lake, near Mountain Home, UT, during water years 1989–2013.

Yellowstone River near Altonah, Utah

Yellowstone River near Altonah, UT, (gaging station 09292500) is approximately 19 mi from the crest of the Uinta Mountains, upstream of any agricultural land or towns, and has a drainage area of 132 mi^2. The WY 1989–2013 mean annual streamflow at the site is 129 ft^3/s (table 1). Water is diverted from the Yellowstone River downstream from the gaging station and upstream from the confluence with the Lake Fork River, approximately 5 mi south of the gaging station, for irrigation.

The estimated WY 1989–2013 mean annual dissolved-solids load at Yellowstone River near Altonah, UT, is 4,360 tons (table 3; fig. 28) with a mean annual dissolved-solids concentration of 36 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 29. The best-fit regression model to determine load did not include a time term, therefore, there was no trend in flow-normalized dissolved-solids load for WY 1989–2013 at the site. The lack of a trend in dissolved-solids load over time indicates no change in natural conditions.

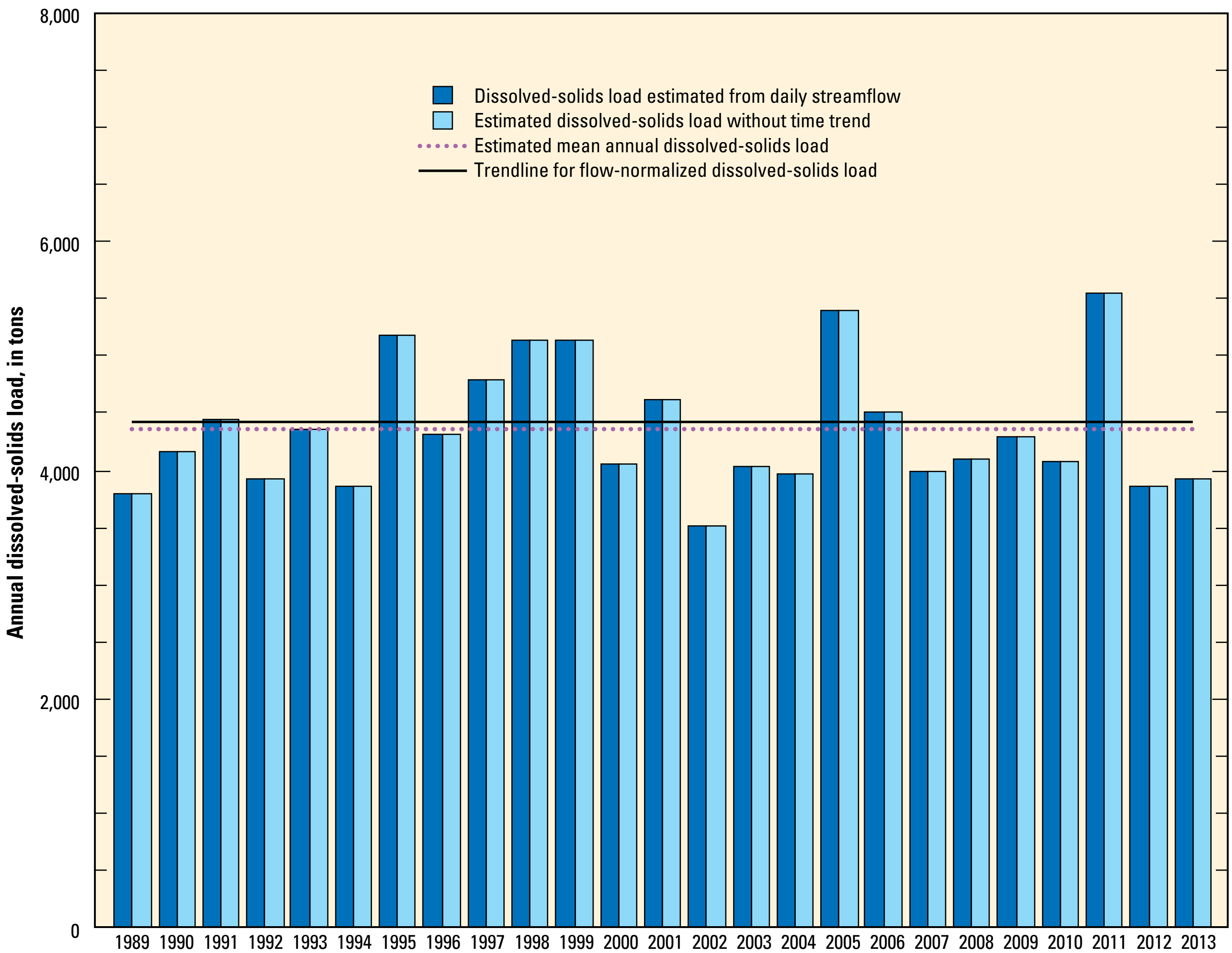

Figure 28. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09292500, Yellowstone River near Altonah, UT, during water years 1989–2013.

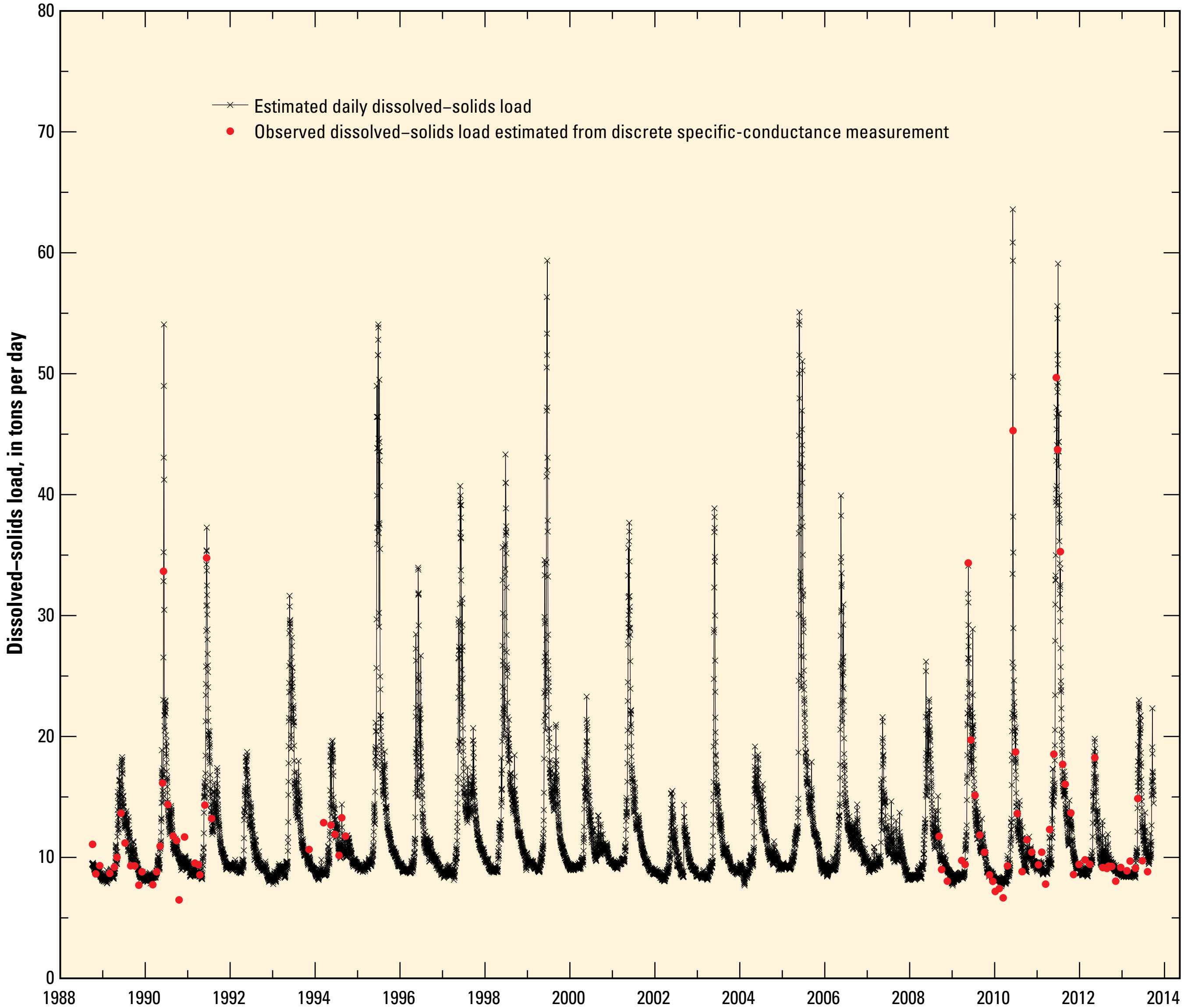

Figure 29. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09292500, Yellowstone River near Altonah, UT, during water years 1989–2013.

Duchesne River at Myton, Utah

Duchesne River at Myton, UT, (gaging station 09295000) is 3 mi downstream from the confluence with the Lake Fork River and below several large diversions for irrigation. The drainage area to the site is 2,643 mi^2, of which 1,374 mi^2 (subbasin area) is not accounted for by the upstream gaging stations Duchesne River near Tabiona, UT, and Strawberry River near Duchesne, UT. The WY 1989–2013 mean annual streamflow at Duchesne River at Myton, UT, is 237 ft^3/s (table 1). The total mean annual streamflow at Duchesne River near Tabiona, UT, and the measured tributaries Rock Creek near Mountain Home, UT; Strawberry River near Duchesne, UT; Lake Fork River below Moon Lake, near Mountain Home, UT; and Yellowstone River near Altonah, UT, is 597 ft^3/s, 360 ft^3/s more than the mean annual streamflow at Duchesne River at Myton, UT.

Water is diverted from the Duchesne River upstream of the Duchesne River at Myton, UT, gaging station and used to irrigate land downstream from the site and in Pleasant Valley, which drains to Pariette Draw. Unconsumed irrigation water in the Neola and Roosevelt areas, originally diverted from the Yellowstone River, returns to the Duchesne River below the Myton, UT, gaging station. Under natural conditions, this water would have flowed to the Duchesne River above the gaging station at Myton, UT. In addition, some irrigation water that is not consumed by plants or evaporated percolates into the subsurface and eventually drains to the river downstream of the gaging station.

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at Duchesne River at Myton, UT, is 92,200 tons (table 3; fig. 30) with a mean annual dissolved-solids concentration of 548 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 31. The Uinta Formation, a principal source of salt loading, is exposed in about 167 mi^2 of the Duchesne River

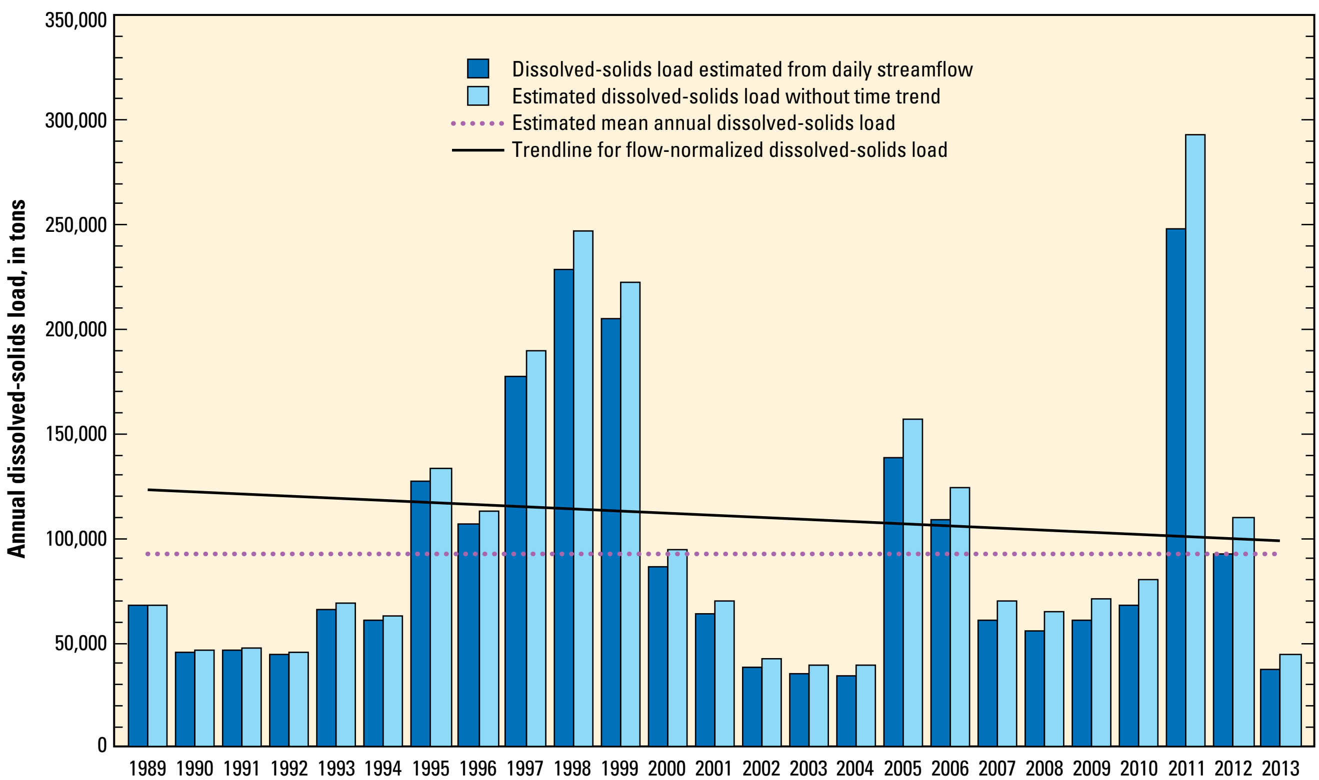

Figure 30. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09295000, Duchesne River at Myton, UT, during water years 1989–2013.

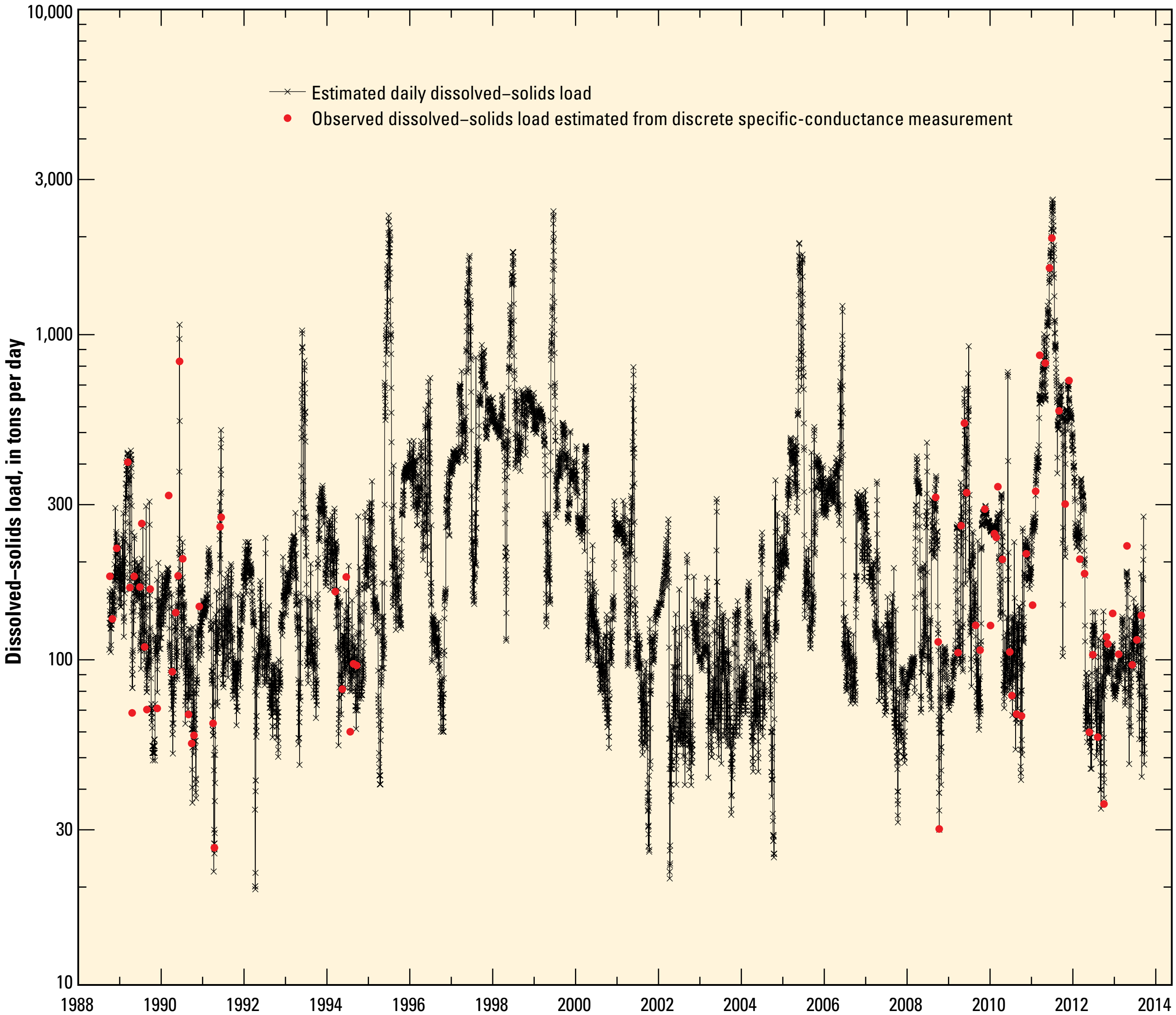

Figure 31. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09295000, Duchesne River at Myton, UT, during water years 1989–2013.

at Myton, UT, subbasin. The SPARROW model for WY 1991 predicted that 69 percent of the load at the gaging station was from natural sources and 32 percent from irrigated lands underlain by sedimentary-clastic Tertiary and Mesozoic rocks (Kenney and others, 2009).

The trend in WY 1989–2013 dissolved-solids load at the Duchesne River at Myton, UT, gaging station is highly significant with an annual decrease of 0.91 percent and a net change in the flow-normalized load of -24,000 tons (-19.6 percent). The amount of irrigated land in the Duchesne River at Myton, UT, subbasin increased from 34,717 acres in 1992 to 39,345 acres in 2012, 28 percent of the irrigated land in the Duchesne River Basin in 2012 (Utah Department of Natural Resources, 2013). Sixty six-percent of the irrigated land in the subbasin was mapped in 2012 as sprinkler irrigated and 34-percent flood irrigated. In comparison, 68 percent was sprinkler irrigated and 32-percent flood irrigated in 2006, and 66 percent was sprinkler irrigated and 34-percent flood irrigated in 2007–2010. Although the changes in irrigated land or irrigation type could not be correlated to the downward trend in flow-normalized load modeled at the site for WY 1989–2013, irrigation improvements in the drainage area (Natural Resources Conservation Service, 2015a) have likely contributed to the decrease in flow-normalized load.

Uinta River below Powerplant Diversion, near Neola, Utah

Uinta River below powerplant diversion, near Neola, UT, (gaging station 09296800) is approximately 17 mi from the crest of the Uinta Mountains. The drainage area for the site (157 mi^2) is primarily bare rock and forest. Streamflow is affected by a canal diversion about 0.75 mi upstream from the site for a hydroelectric powerplant. The WY 1991–2013 mean annual streamflow at the site is 145 ft^3/s (table 1). Water is diverted from the Uinta River downstream from the gaging station to irrigate lands in the Neola and Roosevelt areas.

The estimated WY 1991–2013 mean annual dissolved-solids load at Uinta River below powerplant diversion, near Neola, UT, is 2,570 tons (table 3; fig. 32) with a mean annual dissolved-solids concentration of 18 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 33. The best-fit regression model to determine dissolved-solids load did not include a time term, therefore, there was no trend in flow-normalized dissolved-solids load for WY 1991–2013 at the site. The lack of a trend in dissolved-solids load over time indicates no change in natural conditions.

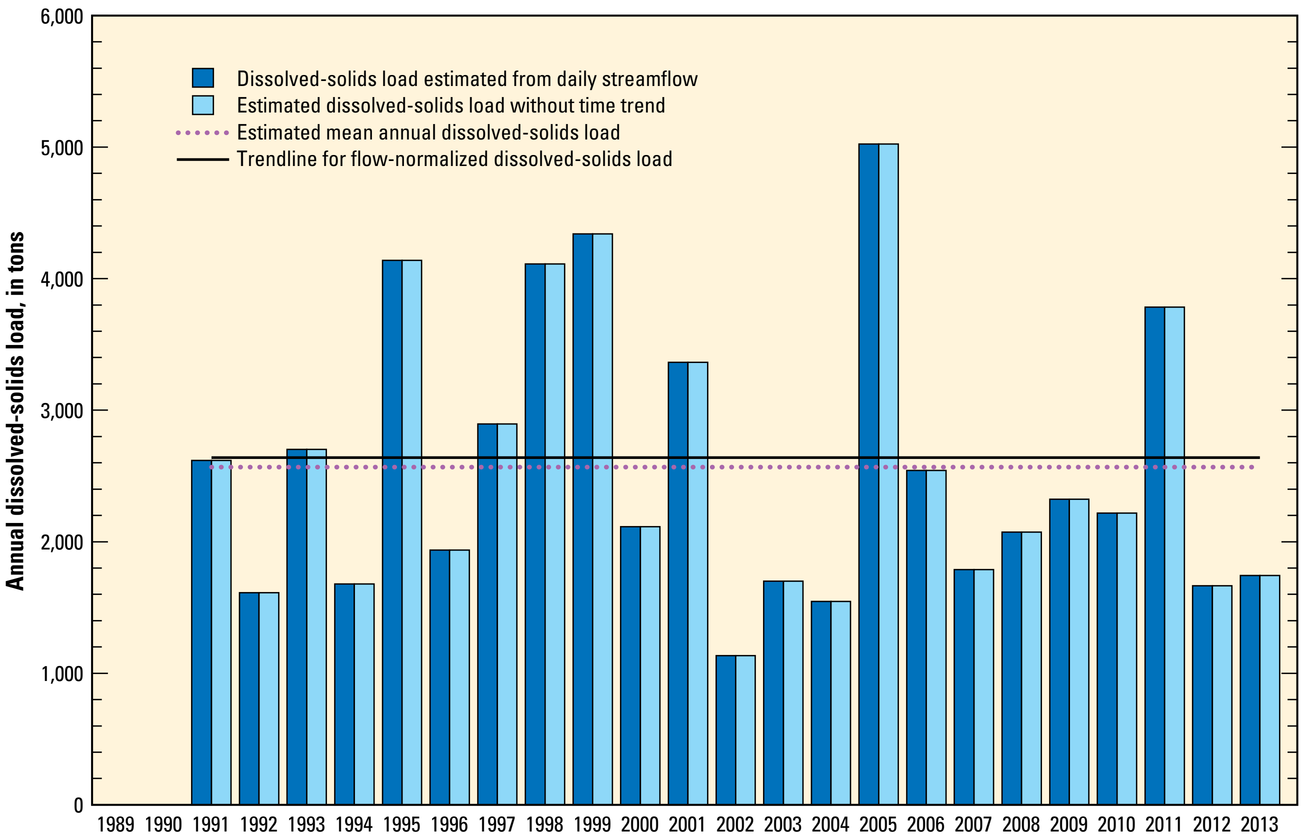

Figure 32. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09296800, Uinta River below powerplant diversion, near Neola, UT, during water years 1991–2013.

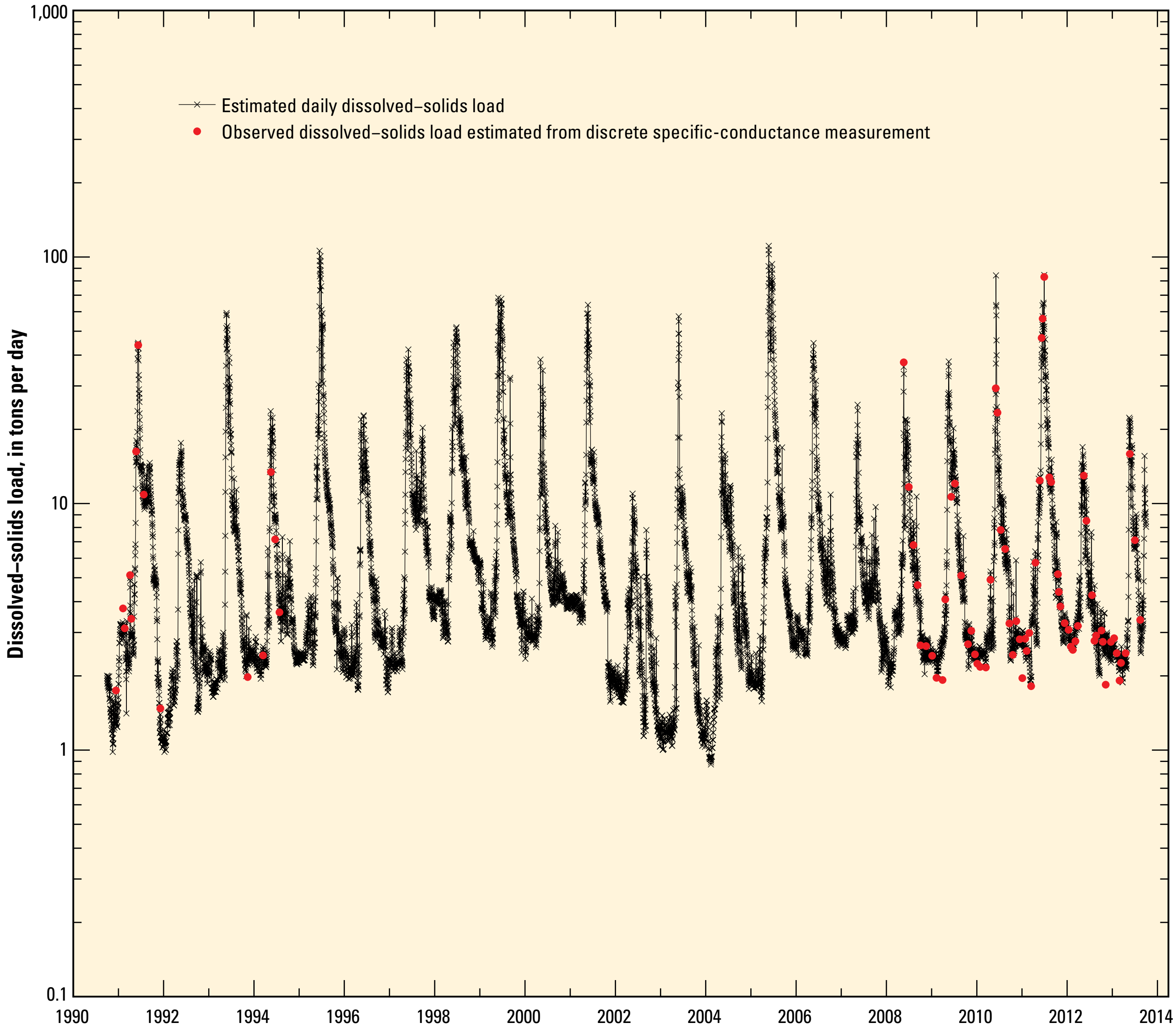

Figure 33. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09296800, Uinta River below powerplant diversion, near Neola, UT, during water years 1991–2013.

Whiterocks River near Whiterocks, Utah

Whiterocks River near Whiterocks, UT, (gaging station 09299500) is approximately 16 mi from the crest of the Uinta Mountains. The river at the gaging station has a drainage area of 109 mi^2 and flows to the Uinta River approximately 10 mi downstream. The WY 1989–2013 mean annual streamflow at the site is 106 ft^3/s (table 1). Water is diverted from the Whiterocks River downstream from the gaging station to irrigate land in the Whiterocks area.

The estimated WY 1989–2013 mean annual dissolved-solids load at Whiterocks River near Whiterocks, UT, is 1,920 tons (table 3; fig. 34) with a mean annual dissolved-solids concentration of 19 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 35. The trend in dissolved-solids load from WY 1989–2013 at the site is highly significant with an annual increase of 0.64 percent and a net change in the flow-normalized dissolved-solids load of 300 tons (16.5 percent). The LOWESS smooth line on the modified residuals (no time term used in the regression model) versus time plot has no slope in WY 1989–1994 and an upward slope in WY 2009–2013 (fig. A-1). Dissolved-solids concentration data were not available for the site in WY 1995–2008. Quadratic time was significant in another model for the site (table A-1) that calculated similar dissolved-solids loads and percent change in flow-normalized dissolved-solids load over time. The quadratic time model was able to better match the change in slope shown on the modified residual versus time plot, and the step-trend analysis of annual flow-adjusted loads from the quadratic time model showed that there was a highly significant increase in flow-adjusted load (p-value <0.01) from the pre-gap to post-gap periods. The model with quadratic time was not selected as the final model for the site because of complications when used in calculations of dissolved-solids load mass balance.

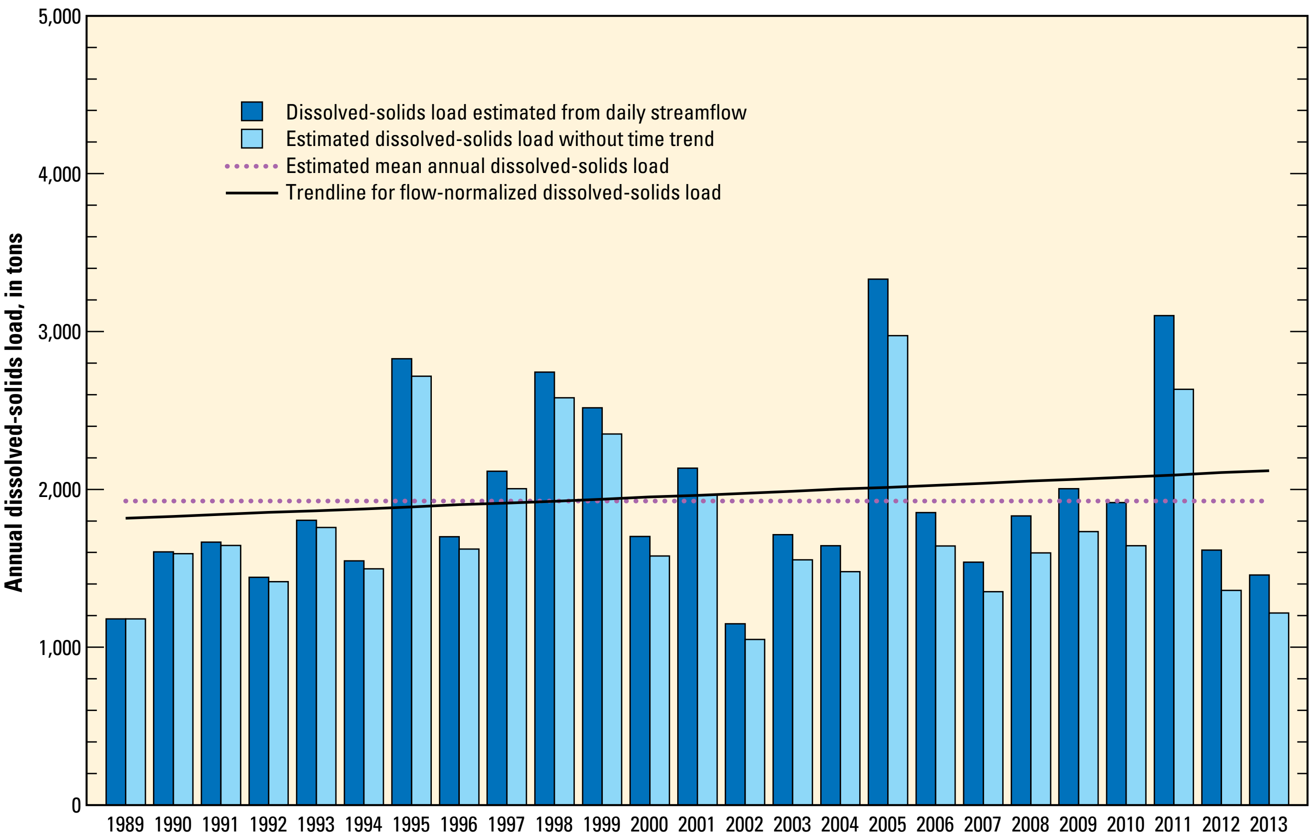

Figure 34. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09299500, Whiterocks River near Whiterocks, UT, during water years 1989–2013.

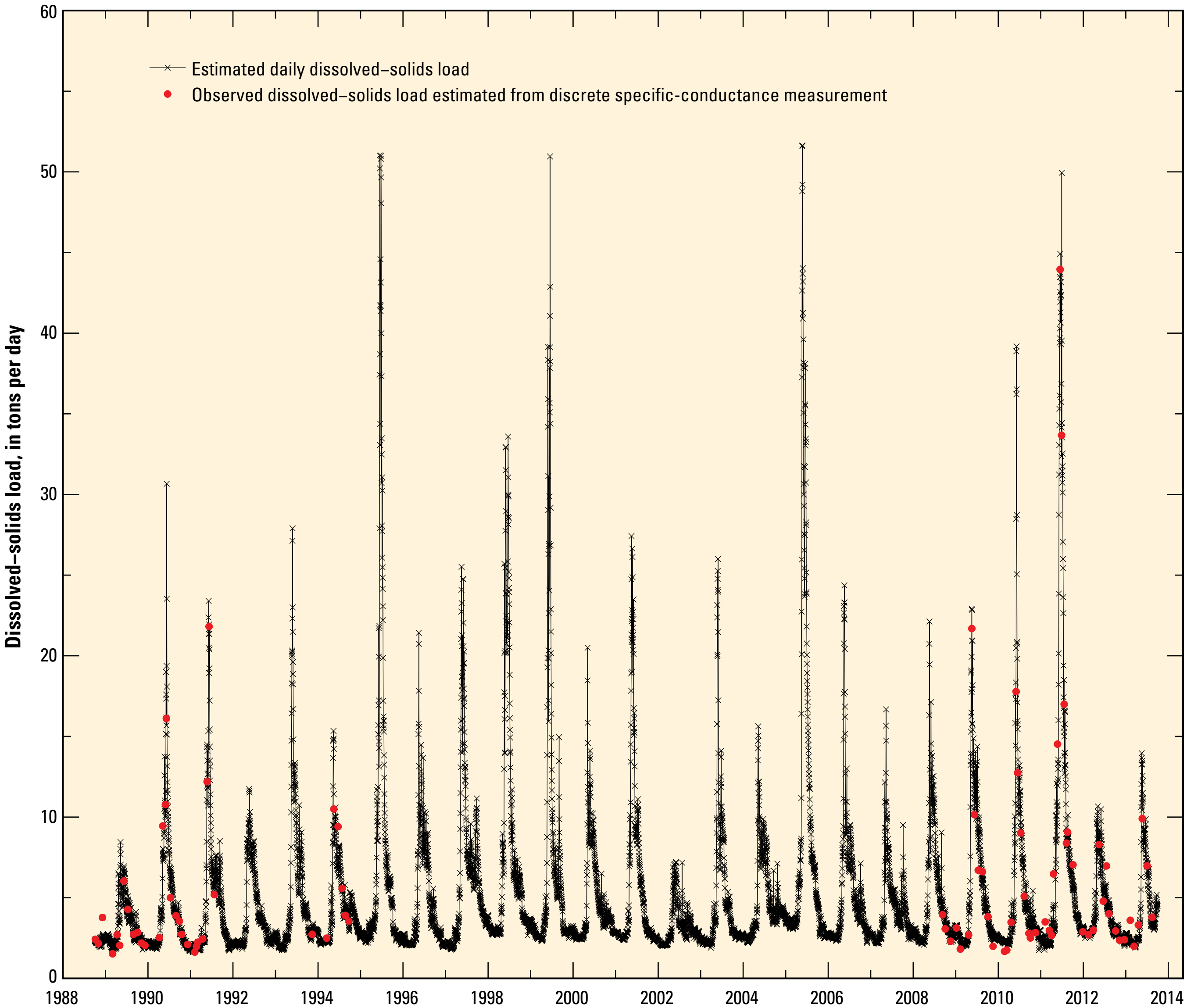

Figure 35. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09299500, Whiterocks River near Whiterocks, UT, during water years 1989–2013.

Duchesne River near Randlett, Utah

Duchesne River near Randlett, UT, (gaging station 09302000) is near the mouth of the Duchesne River Basin, about 11 mi upstream from the confluence with the Green River. The site has a drainage area of 3,790 mi^2, of which 1,123 mi^2 (subbasin area) is not accounted for by the upstream gaging stations Duchesne River near Tabiona, UT, Duchesne River near Myton, UT, and Strawberry River near Duchesne, UT. There are several large diversions for irrigation above the site, including transbasin diversions from the Colorado River Basin to the Great Basin (U.S. Bureau of Reclamation, 2017). The WY 1989–2013 mean annual streamflow at Duchesne River near Randlett, UT, is 349 ft^3/s (table 1). The site was instrumented with a data recorder and probe to measure specific conductance in October 2008. Daily mean specific-conductance values are available to the current (2013) year.

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at Duchesne River near Randlett, UT, is 172,000 tons (table 3; fig. 36) with a mean annual dissolved-solids concentration of 722 mg/L. The model-predicted daily dissolved-solids load and observed load are shown on figure 37. The trend in dissolved-solids load from WY 1989–2013 at Duchesne River near Randlett, UT, is highly significant with an annual decrease of 1.36 percent and a net change in the flow-normalized dissolved-solids load of -68,600 tons (-28.0 percent). The downward slope in the smooth line of modified residuals is less steep between WY 2000 and WY 2004 (fig. A-1), than the preceding and following years. Below average streamflow during this period resulted in smaller dissolved-solids loads.

The Duchesne River near Randlett, UT, gaging station is downstream from much of the irrigated land in the Duchesne River Basin. Irrigated land in the Duchesne River near Randlett, UT, subbasin totaled 93,103 acres in 1992 and 92,130 acres in 2012 (Utah Department of Natural Resources, 2013). In 2012, this amounted to 65 percent of the irrigated land in the Duchesne River Basin. Of the irrigated land in

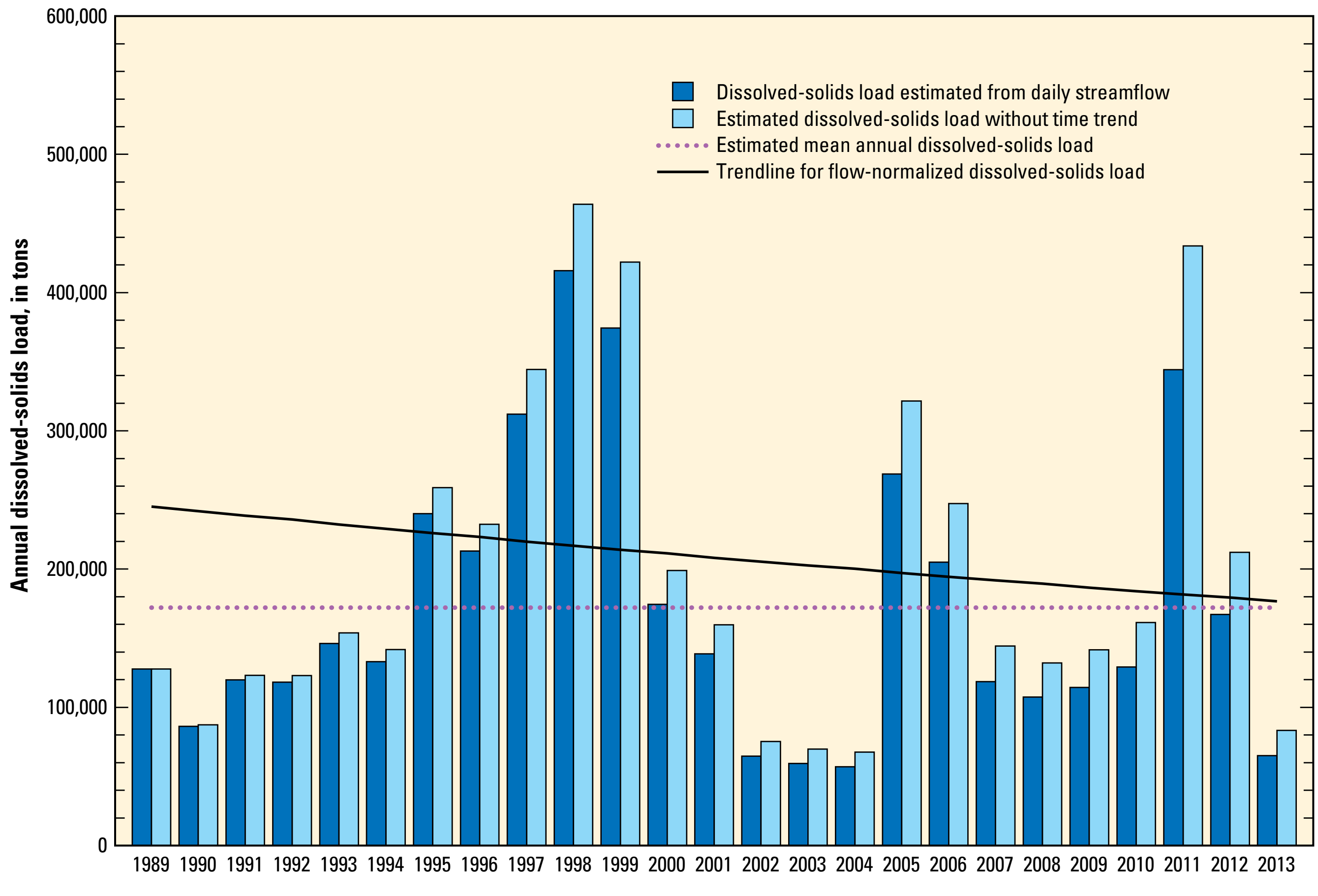

Figure 36. Estimated mean annual dissolved-solids load, estimated annual dissolved-solids load using daily streamflow, estimated annual dissolved-solids load without a linear time trend, and trendline for the flow-normalized dissolved-solids load at U.S. Geological Survey streamflow gaging station 09302000, Duchesne River near Randlett, UT, during water years 1989–2013.

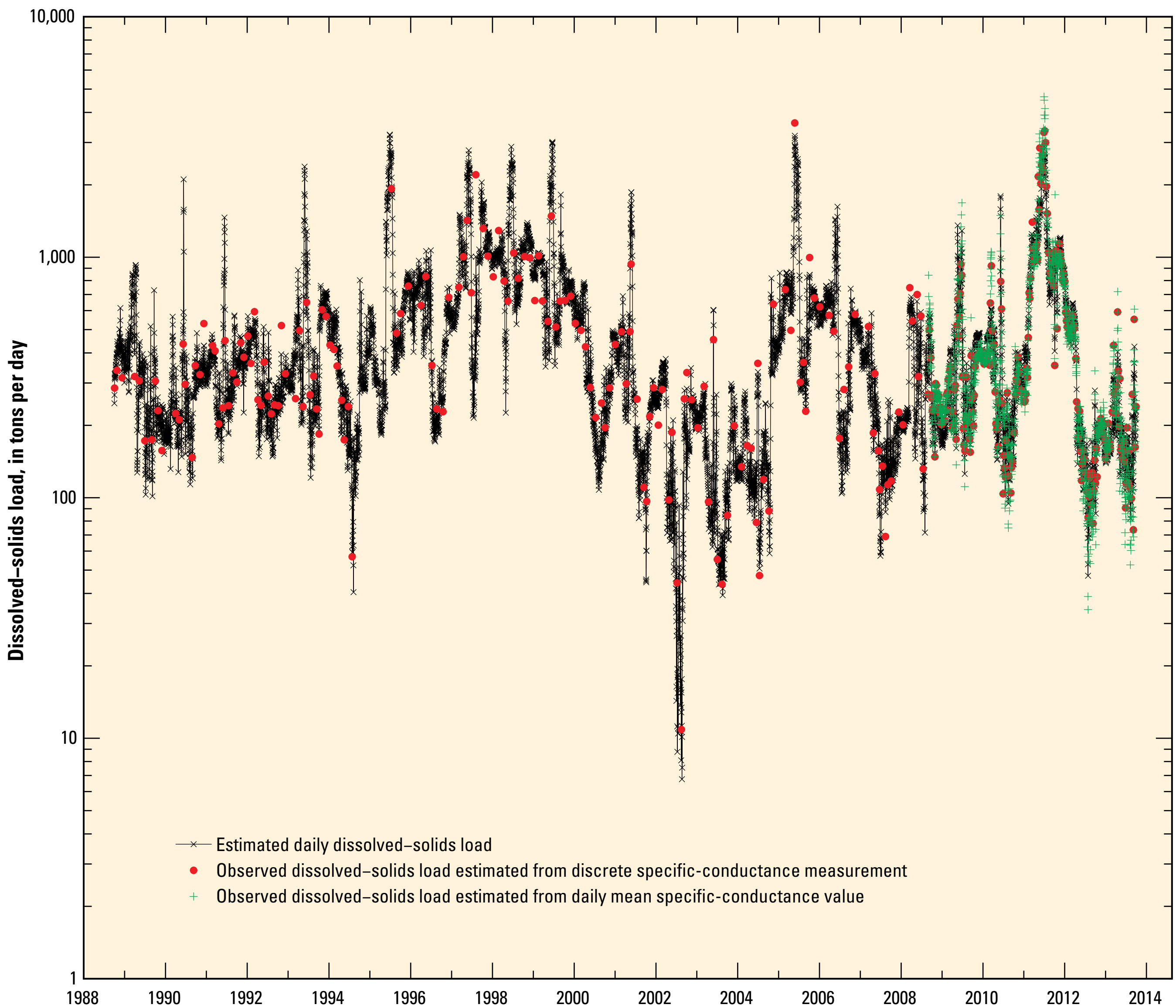

Figure 37. Observed dissolved-solids load and model-predicted daily dissolved-solids load at U.S. Geological Survey streamflow gaging station 09302000, Duchesne River near Randlett, UT, during water years 1989–2013.

the Duchesne River near Randlett, UT, subbasin, 42 percent was mapped as sprinkler irrigated and 58-percent flood irrigated in 2012 compared to 46-percent sprinkler irrigated and 54-percent flood irrigated in 2006 (Utah Department of Natural Resources, 2013), and 44-percent sprinkler irrigated and 56-percent flood irrigated in 2007–2010 (Buto and others, 2014). Although changes in irrigated land or irrigation type could not be correlated to the downward trend in WY 1989–2013 flow-normalized dissolved-solids load modeled at the site, irrigation improvements in the drainage area (Natural Resources Conservation Service, 2015a) have likely contributed to the decrease in flow-normalized dissolved-solids load.

Iorns and others (1965) estimated that 29 percent of the 1914–57 average dissolved-solids load at the Duchesne River near Randlett, UT, site (adjusted to 1957 development conditions) was from natural sources and 71 percent from agricultural sources. The SPARROW model for 1991 (Kenney and others, 2009) predicted that 47 percent of the load at the Duchesne River near Randlett, UT, site was from natural sources and 55 percent from irrigated lands (35 percent from irrigated land underlain by sedimentary-clastic Tertiary rocks such as the Duchesne Formation and Uinta Formation, and 20 percent from irrigated land underlain by sedimentary-clastic Mesozoic rocks).

Effect of Gap in Dissolved-Solids Concentration Data on Estimated Dissolved-Solids Loads

Several of the sites modeled for dissolved-solids loads did not have dissolved-solids concentration or specific-conductance data available for all or some of WY 1995–2007. To determine the effect of this data gap on estimated dissolved-solids loads, dissolved-solids concentration data from WY 1995–2007 were removed from the calibration data set for two sites that had a complete dataset, Green River near Jensen, UT, and Duchesne River near Randlett, UT, and the estimated mean annual dissolved-solids load and flow-normalized dissolved-solids load with and without the data gap were compared.

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at the Green River near Jensen, UT, gaging station was the same (1,127,000 tons) using a calibration data set with the dissolved-solids concentration data gap (95 observations) and a calibration data set without the data gap (187 observations). The trend in dissolved-solids load from WY 1989–2013 at Green River near Jensen, UT, using a calibration data set with the dissolved-solids concentration data gap is significant with an annual decrease of 0.38 percent and a net change in the flow-normalized load of -106,000 tons (-8.8 percent). In comparison, the trend in dissolved-solids load from WY 1989–2013 at the site with no data gap had an annual decrease of 0.59 percent and a net change in the flow-normalized dissolved-solids load of -164,000 tons (-13.3 percent). The overall slope of the smooth line on the modified residuals plot with no data gap (fig. A-1) corresponds to the direction and magnitude of the trend in flow-normalized dissolved-solids load. The downward slope in the smooth line steepened between WY 2000 and WY 2004, a period of below average modeled annual dissolved-solids loads (fig. 8) affected by below average streamflow (see equation 1). The dissolved-solids concentration data missing in the data gap model, but present in the no data gap model indicate that concentrations generally continued to decrease during the below average streamflow years, resulting in a larger decrease in dissolved-solids load than if concentrations had not changed.

The estimated WY 1989–2013 mean annual dissolved-solids load modeled at the Duchesne River near Randlett, UT, gaging station was 180,000 tons using a calibration data set with the dissolved-solids concentration data gap (309 observations) compared to 172,000 tons without the data gap (410 observations). The dissolved-solids load trend from WY 1989–2013 at Duchesne River near Randlett, UT, using a calibration data set with the dissolved-solids concentration data gap is highly significant with an annual decrease of 1.57 percent and a net change in the flow-normalized load of -81,000 tons (-31.6 percent). In comparison, the trend in dissolved-solids load from WY 1989–2013 at the site with no data gap was an annual decrease of 1.36 percent and a net change in the flow-normalized dissolved-solids load of -68,600 tons (-28.0 percent). The downward slope in the smooth line of modified residuals using the no data gap data set is less steep between WY 2000 and WY 2004 (fig. A-1), a period of decreasing modeled annual dissolved-solids loads (fig. 36). The change in slope was affected by below average streamflow and a corresponding larger percentage of the dissolved-solids load contributed by groundwater base flow and unconsumed irrigation water that typically have higher dissolved-solids concentrations. The regression model using the data set with the dissolved-solids concentration data gap did not account for this increase in dissolved-solids concentration, and therefore, estimated a larger annual decrease in dissolved-solids load.

Removing WY 1995–2007 dissolved-solids concentration data from the calibration data sets resulted in a smaller net change in flow-normalized dissolved-solids load from WY 1989–2013 at Green River near Jensen, UT, and a larger net change in flow-normalized dissolved-solids load at Duchesne River near Randlett, UT. The effect of the gap in dissolved-solids concentration data on the modeled net change in flow-normalized dissolved-solids loads at the natural sites Ashley Creek near Vernal, UT (-320 tons), and Whiterocks River near Whiterocks, UT (300 tons), may be similar to the Green River near Jensen, UT, where less net change was modeled without the data gap. Other sites with the data gap in areas with natural or mostly natural land cover had no modeled trend in dissolved-solids load because time was not a significant variable in the regression model. The effect of the gap in dissolved-solids concentration data on trends in flow-normalized dissolved-solids loads at the Strawberry River near Duchesne, UT, and the Duchesne River at Myton, UT, sites may be similar to the downstream site Duchesne River near Randlett, UT, where more net change in dissolved-solids load was modeled with the data gap than without the data gap because of the occurrence of irrigated lands in the drainages.

Streamflow and Dissolved-Solids Load Balances

Annual streamflow and modeled dissolved-solids loads at the studied gaging stations were balanced between upstream and downstream sites to determine how much water and dissolved solids were transported to the Duchesne River and Green River between the Greendale and Green River gaging stations and how much was derived from each drainage area. Mass-balance calculations were made on annual mean streamflow, annual dissolved-solids loads, mean annual streamflow, and flow-normalized dissolved-solids load to help estimate how much of the change in load was from natural and agricultural sources. This budgeting exercise provides information on streamflow and dissolved-solids load inputs from unmonitored areas. Previous studies by Iorns and others (1965) and Mueller and Osen (1988) also used mass-balance calculations to determine amounts, areas, and possible sources of dissolved-solids loads to sections of streams in the Upper Colorado River Basin.

Middle Green River Basin

The Green River near Greendale, UT, and Green River at Green River, UT, gaging stations were used as the inflow and outflow points on the Green River in the streamflow and dissolved-solids load mass-balance calculations. The difference in streamflow and dissolved-solids load between sites on the Green River, accounting for monitored inflow from tributaries, provide an estimation of unmonitored streamflow and dissolved-solids load entering the Green River in the study area. These calculations assume that there is no change in storage in surface or groundwater reservoirs.

Streamflow Balance

The mean annual streamflow for WY 1989–2013 at Green River near Greendale, UT (1,670 ft^3/s), was subtracted from the downstream site Green River near Jensen, UT (3,690 ft^3/s). The difference in mean annual streamflow at these two sites (2,020 ft^3/s) is attributed to inflow to the Green River between the sites (fig. 38). Most of this inflow is from the Yampa River, which has a WY 1989–2013 (missing 1995–96 data) mean annual streamflow of 1,860 ft^3/s at the Deerlodge Park, CO, gaging station.

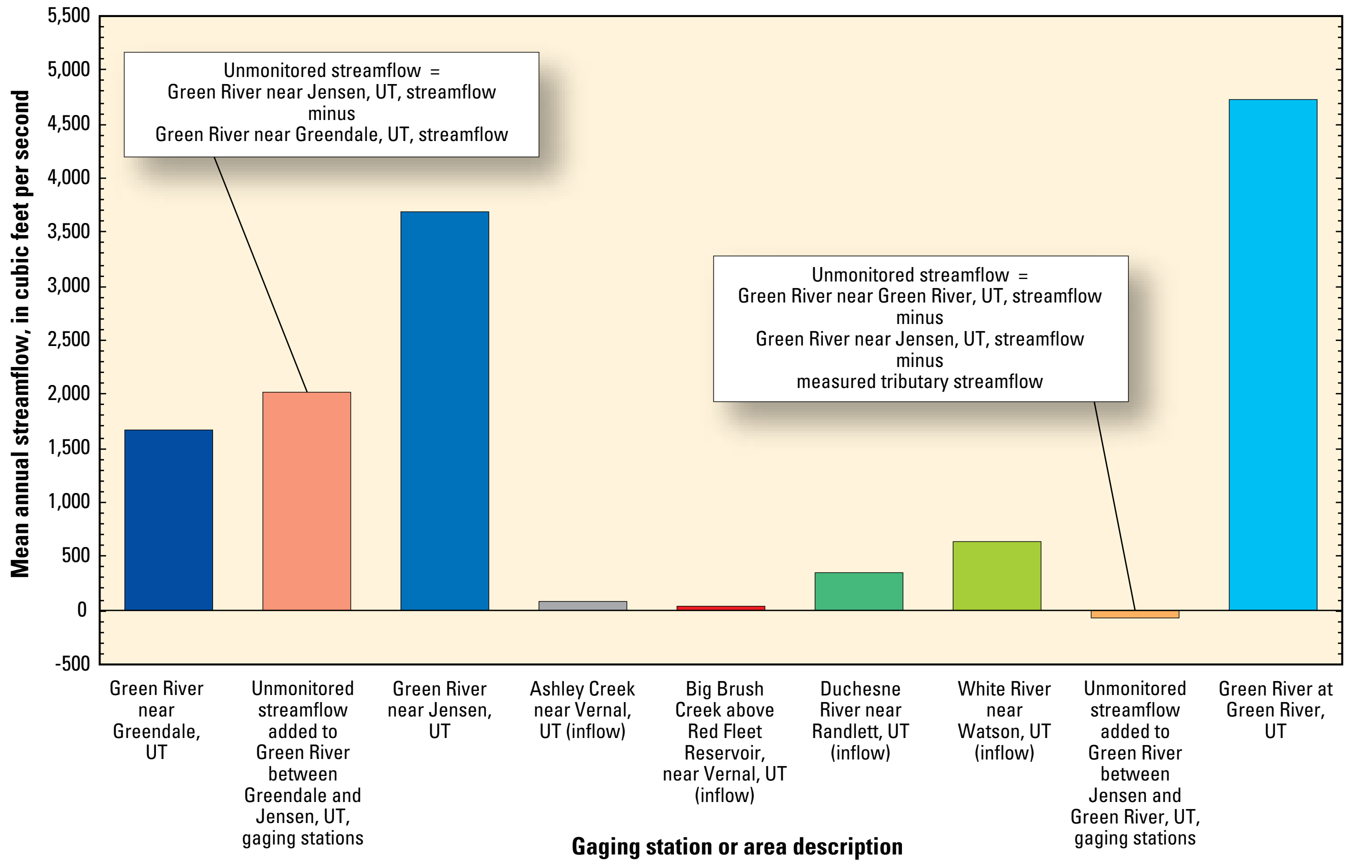

Figure 38. Mass balance of water years 1989–2013 mean annual streamflow for gaging stations used for analysis of dissolved-solids loads and trends in the Middle Green River Basin.

The Ashley Creek near Vernal, UT, and Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, gaging stations are located on the southeastern flank of the Uinta Mountains. The WY 1989–2013 mean annual streamflow at these tributary sites (83 ft^3/s and 39 ft^3/s, respectively) is less than the downstream tributaries Duchesne River near Randlett, UT, and White River near Watson, UT (349 ft^3/s and 637 ft^3/s, respectively). The WY 1989–2013 mean annual streamflow at Green River at Green River, UT, is 4,730 ft^3/s. There was a 68 ft^3/s loss in Green River streamflow between the Jensen and Green River gaging stations after subtracting streamflow at the Green River near Jensen, UT, and tributary gaging stations from streamflow at the Green River at Green River, UT, gaging station. Additional streamflow to this section of the Green River not accounted for in this water balance includes Dry Fork, Pariette Draw, Willow Creek, Nine Mile Creek, Range Creek, and the Price River. The Price River is the main source of unaccounted for inflow with a WY 2001–2013 mean annual streamflow of 76 ft^3/s at the Price River at Woodside, UT, gaging station. On the basis of streamflow mass balance, losses in streamflow (such as evapotranspiration, diversions, and losses to the groundwater system) exceed any gains from unaccounted for streamflow to the Green River between the gaging stations near Jensen, UT, and at Green River, UT.

On the basis of mass-balance calculations of WY 1989–2013 mean annual streamflow, streamflow at Green River near Greendale, UT, is 35 percent and Green River near Jensen, UT, is 78 percent of streamflow at Green River at Green River, UT (fig. 38). The tributaries Duchesne River near Randlett, UT, and White River near Watson, UT, contribute about 7 percent and 14 percent of the mean annual streamflow at Green River at Green River, UT, respectively.

Dissolved-Solids Load Balance

Mass-balance calculations of WY 1989–2013 annual and mean annual dissolved-solids loads show that Green River near Greendale, UT, contributes the largest dissolved-solids load to the Green River in the study area (table 4; figs. 39 and 40). Annual loads at the Green River near Greendale, UT, gaging station ranged from 30 percent of the load at the Green River at Green River, UT, gaging station in 2005 and 2007 to about 50 percent of the load in 1994 and 1999. The mean annual dissolved-solids load at Green River near Greendale, UT, was 39 percent of that at Green River at Green River, UT, similar to the streamflow component (35 percent). The WY 1989–2013 net change in flow-normalized load estimated at Green River near Greendale, UT, accounts for about 45 percent of the net change estimated at Green River at Green River, UT (table 4).

A mean annual dissolved-solids load of 445,000 tons in WY 1989–2013 is added to the Green River between the Green River near Greendale, UT, and Green River near Jensen, UT, gaging stations (table 4; figs. 39 and 40), determined by subtracting the dissolved-solids load at Green River near Greendale, UT, from Green River near Jensen, UT. The main source of inflow and dissolved-solids load to the Green River in this reach is the Yampa River, which had a reported WY 1984–2012 adjusted mean annual load near Deerlodge Park, CO, of about 369,000 tons (Tillman and Anning, 2014). The mean annual dissolved-solids load from the Yampa River is approximately 80 percent of the increase in dissolved-solids load in the Green River between Green River near Greendale, UT, and Green River near Jensen, UT, leaving about 76,000 tons to come from other sources. Dissolved-solids load at the Yampa River near the Deerlodge Park, CO, gaging

Table 4. Mass balance of water years 1989–2013 dissolved-solids loads for gaging stations used for analysis of dissolved-solids loads and trends in the Middle Green River Basin.

[Italicized text is calculated as the difference between components. USGS, U.S. Geological Survey; WY, water year; UT, Utah]

USGS gaging station name (number), or area description	Estimated WY 1989–2013 mean annual dissolved-solids load, in tons per year	Percent of WY 1989–2013 mean annual dissolved-solids load at Green River at Green River, UT, gaging station	Flow-normalized dissolved-solids load				
			WY 1989 load, in tons	WY 2013 load, in tons	WY 1989–2013 net change, in tons	WY 1989–2013 net change, in percent	Percent of net change modeled at Green River at Green River, UT, gaging station
Green River near Greendale, UT (09234500)	682,000	38.8	760,000	602,000	−158,000	−20.8	44.9
Unmonitored load added to Green River between Greendale and Jensen gaging stations	*445,000*	*25.3*	*472,000*	*466,000*	*-6,000*	*−1.3*	*1.7*
Green River near Jensen, UT (09261000)	1,127,000	64.0	1,232,000	1,068,000	−164,000	−13.3	46.6
Ashley Creek near Vernal, UT (09266500) (inflow)	4,380	0.2	4,780	4,460	−320	−6.7	0.1
Big Brush Creek above Red Fleet Reservoir, near Vernal, UT (09261700) (inflow)	4,790	0.3	4,960	4,690	0	0	0
Duchesne River near Randlett, UT (09302000) (inflow)	172,000	9.8	245,000	177,000	[1] −68,000	[1] −27.8	19.3
White River near Watson, UT (09306500) (inflow)	233,000	13.2	266,000	211,000	−55,300	−20.8	15.7
Unmonitored load added to Green River between Jensen and Green River gaging stations	*219,000*	*12.4*	*231,000*	*167,000*	*−64,000*	*−27.7*	*18.2*
Green River at Green River, UT (09315000)	1,760,000	100	1,984,000	1,632,000	−352,000	−17.7	100

[1] This value differs from the value in table 3 because of rounding when using three significant figures in mass-balance calculations.

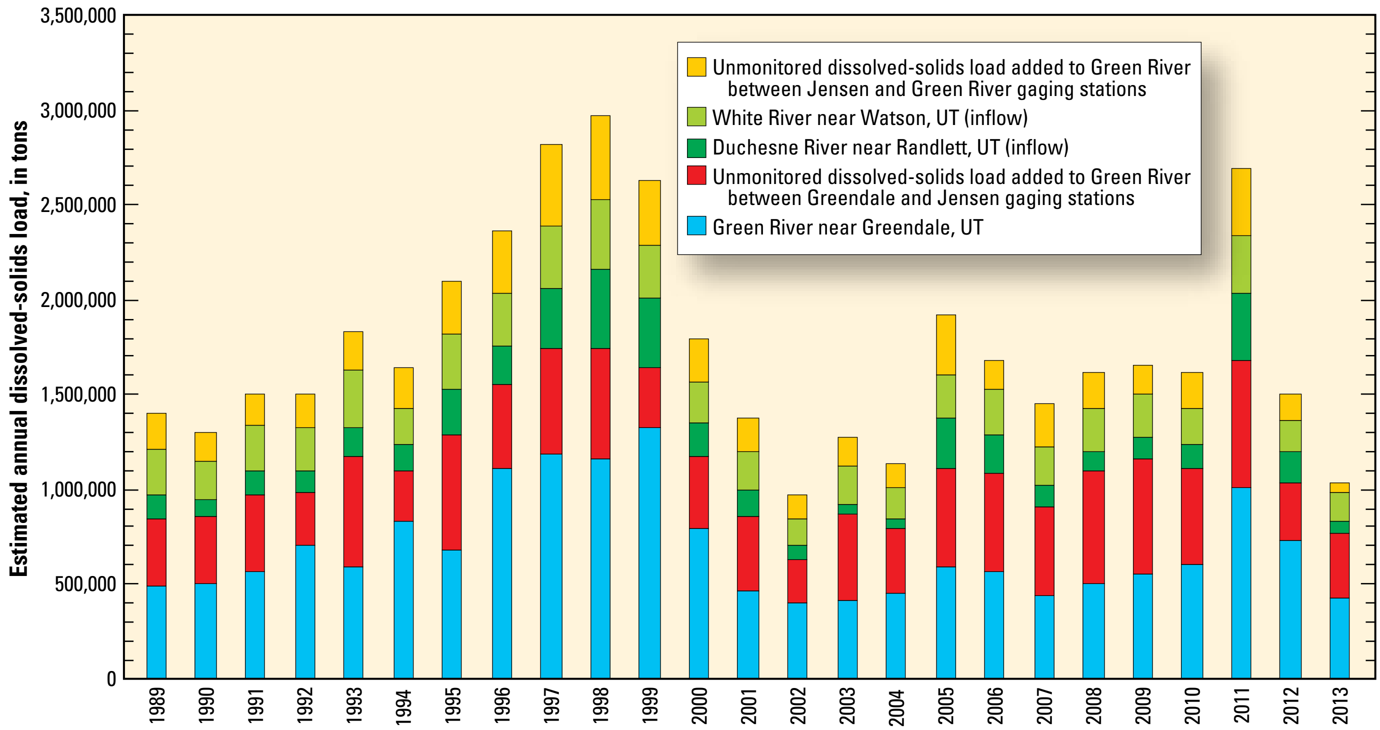

Figure 39. Mass balance of water years 1989–2013 annual dissolved-solids load for gaging stations used for analysis of dissolved-solids loads and trends in the Middle Green River Basin.

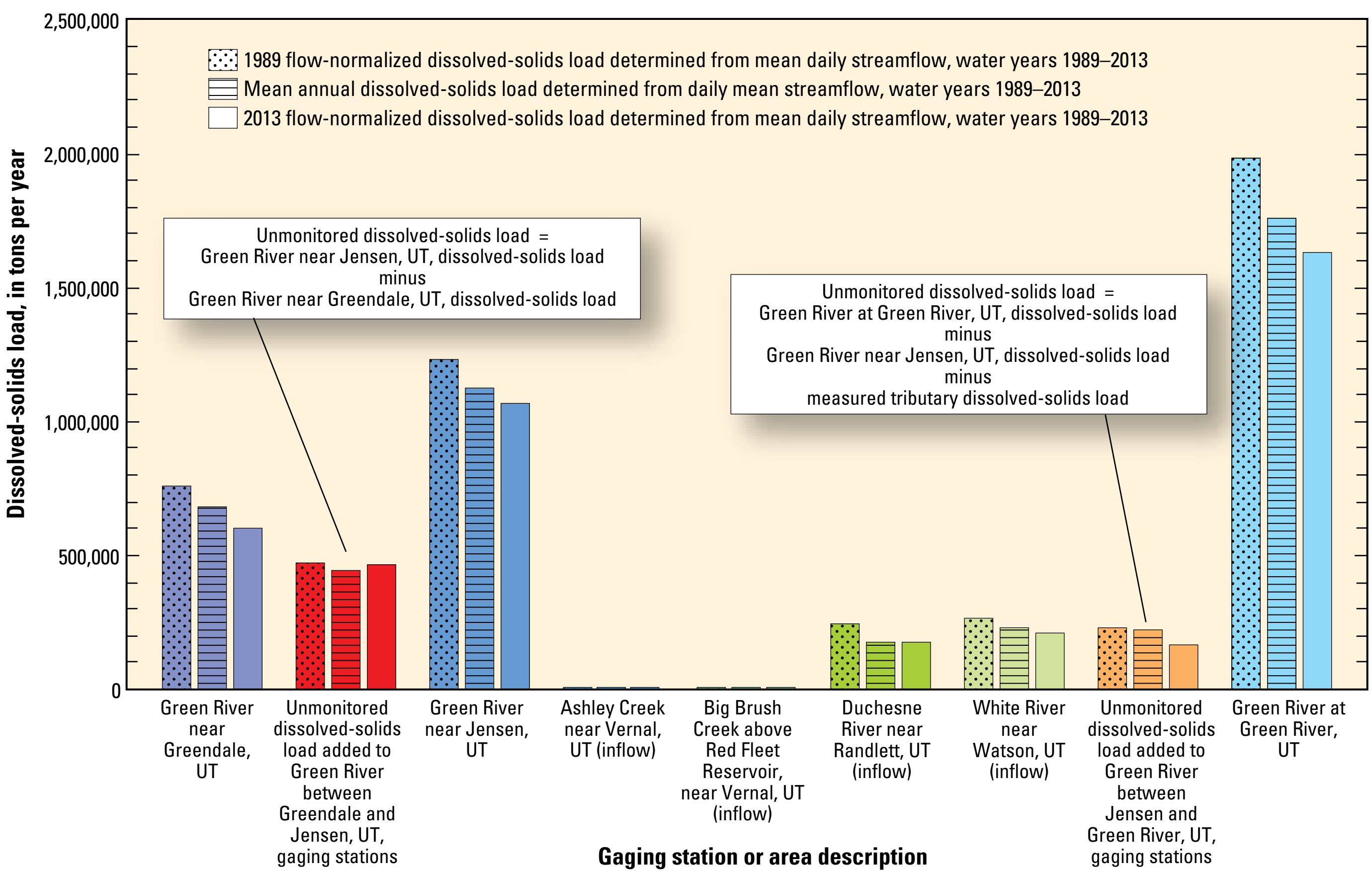

Figure 40. Mass balance of water years 1989 and 2013 flow-normalized dissolved-solids load and water years 1989–2013 mean annual dissolved-solids load for gaging stations used for analysis of dissolved-solids loads and trends in the Middle Green River Basin.

station was not modeled as part of this study because of missing daily streamflow values in WY 1995–96. There is very little irrigated land not accounted for by a gaging station in this reach of the Green River; only 213 irrigated acres were mapped just upstream from the Green River near Jensen, UT, gaging station in 2012, therefore the remaining increase in load is likely from natural sources.

The WY 1989–2013 mean annual dissolved-solids load at Green River near Jensen, UT, accounts for 64 percent of the load in the river at Green River at Green River, UT, while the Duchesne River and White River contribute 10 and 13 percent, respectively (figs. 39 and 40). The combined mean annual dissolved-solids load to Green River at Green River, UT, from Ashley Creek near Vernal, UT, and Big Brush Creek above Red Fleet Reservoir, near Vernal, UT, is about 0.5 percent. The mean annual dissolved-solids load of unmonitored inflow to the Green River from Green River near Jensen, UT, to Green River at Green River, UT—the remaining load in the mass balance—was calculated to be 219,000 tons, or about 12 percent of the mean annual load at Green River at Green River, UT. This unmonitored load added to the Green River between the Green River near Jensen, UT, and Green River at Green River, UT, gaging stations is derived from unmonitored irrigated and riparian areas, tributaries, and natural sources.

The Price River is a major source of dissolved-solids load to this unmonitored stretch of the Green River. The Price River at Woodside, UT, (gaging station 09314500) had a reported adjusted mean annual load of about 124,000 tons using data from WY 1984–2012 (Tillman and Anning, 2014). The mean annual dissolved-solids load from the Price River is 57 percent of the unmonitored dissolved-solids load in the Green River between the Green River near Jensen, UT, and Green River at Green River, UT, gaging stations, leaving approximately 95,000 tons to come from other sources. About 55,300 acres of irrigated fields were mapped in 2011 and 2012 (Utah Department of Natural Resources, 2013) in the area draining to the Green River downstream from the Green River near Jensen, UT, gaging station and not within the drainage areas to the Duchesne River near Randlett, UT, or Price River at Woodside, UT, gaging stations (fig. 5). Dissolved-solids loads from irrigated lands near Vernal, Ashley Valley, Pelican Lake, Pleasant Valley (combined 45,460 acres), and near the town of Green River (9,890 acres), are a source of the remaining unmonitored dissolved-solids load to the Green River at Green River, UT.

A mass balance was completed with WY 1989–2013 flow-normalized dissolved-solids loads estimated at sites in the Middle Green River Basin. Flow-normalized load estimated at the Green River near Greendale, UT, gaging station decreased 158,000 tons (-20.8 percent) from 760,000 tons in 1989 to 602,000 tons in 2013 and at the Green River near Jensen, UT, gaging station decreased 164,000 tons (-13.3 percent) from 1,232,000 tons in 1989 to 1,068,000 tons in 2013 (table 4 and fig. 41). The flow-normalized dissolved-solids load of

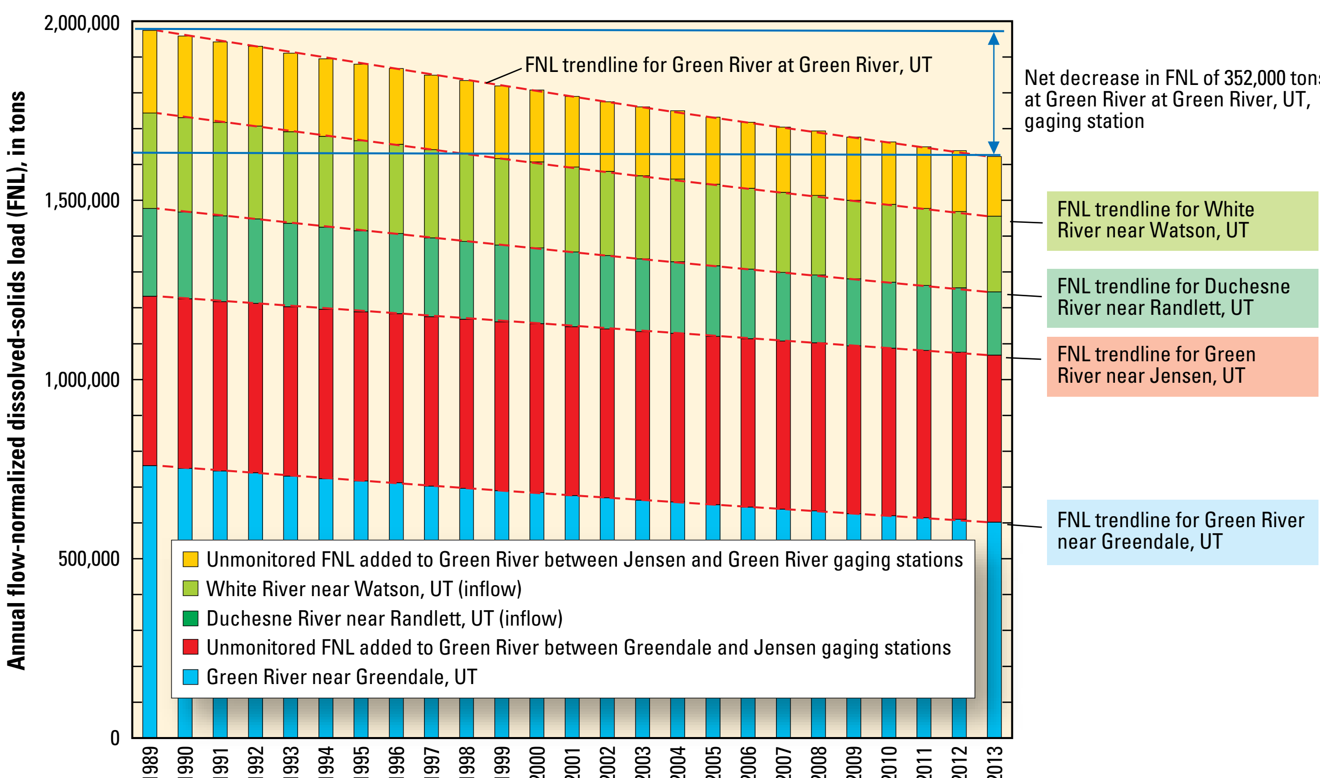

Figure 41. Mass balance of water years 1989–2013 annual flow-normalized dissolved-solids load for gaging stations used for analysis of dissolved-solids loads and trends in the Middle Green River Basin.

unmonitored inflow to the Green River between the Green River near Greendale, UT, and Green River near Jensen, UT gaging stations—mostly attributed to inflow from the Yampa River—was calculated to be 472,000 tons in 1989 and 466,000 tons in 2013 with a net decrease of 6,000 tons (-1.3 percent). Because the flow-normalized dissolved-solids load added to the Green River between these two gaging stations did not change significantly between 1989 and 2013, the decrease in flow-normalized load modeled at Green River near Jensen, UT, is attributed to the decrease in flow-normalized load modeled at Green River near Greendale, UT.

The flow-normalized dissolved-solids load modeled at Duchesne River near Randlett, UT, and White River near Watson, UT, decreased by 68,000 and 55,300 tons, or 27.8 and 20.8 percent respectively, when comparing 1989 to 2013 (table 4 and fig. 41). The drainage basins for both rivers have undergone salinity-control projects since the early 1980s to reduce the dissolved-solids load entering the Colorado River. Approximately 19 percent of the net change in flow-normalized load at Green River at Green River, UT, is from changes in load modeled at Duchesne River near Randlett, UT, and 16 percent from changes in load modeled at White River near Watson, UT.

The flow-normalized dissolved-solids load modeled at Green River at Green River, UT, decreased by 352,000 tons (-17.7 percent) when comparing 1989 to 2013 (table 4 and fig. 41). The flow-normalized dissolved-solids load of unmonitored inflow to the Green River between Green River near Jensen, UT, and Green River at Green River, UT, was calculated to be 231,000 tons in 1989 and 167,000 tons in 2013 with a net decrease of 64,000 tons (-27.7 percent). This net change in flow-normalized load that represents unmonitored inflow accounts for about 18 percent of the net change estimated at the Green River at Green River, UT, gaging station (table 4). Much of the decrease in flow-normalized dissolved-solids load of unmonitored inflow to the Green River between the Jensen and Green River, UT, sites is attributed to irrigation improvements in the Vernal, Ashley Valley, Pelican Lake, and Pleasant Valley areas, the Price River Basin, and near the town of Green River.

Duchesne River Basin

The Duchesne River near Tabiona, UT, and Duchesne River near Randlett, UT, gaging stations were used as the inflow and outflow sites on the Duchesne River in mass-balance streamflow and dissolved-solids load calculations. The difference between sites on the Duchesne River, accounting for inflow from tributaries, allowed an estimation of unmonitored streamflow and dissolved-solids load entering the river.

Streamflow Balance

The mean annual streamflow for WY 1989–2013 at the Duchesne River near Tabiona, UT, gaging station (131 ft^3/s) is 37 percent of the streamflow at the downstream site Duchesne River near Randlett, UT (349 ft^3/s) (fig. 42). The difference in mean annual streamflow at these two sites (218 ft^3/s) is affected by inflow from tributaries and unconsumed irrigation water, diversions for irrigation to areas inside and outside of the drainage basin, changes in storage within the drainage basin, and the loss of water by evapotranspiration. The combined mean annual streamflow at Duchesne River near Tabiona, UT, and monitored tributaries is almost 2.5 times the streamflow at Duchesne River near Randlett, UT.

The mean annual streamflow at Duchesne River at Myton, UT, is 40 percent of the combined streamflow at gaging stations on the Duchesne River near Tabiona, UT, and monitored tributaries. The sum of WY 1989–2013 mean annual streamflow at the tributary sites and at Duchesne River near Tabiona, UT, is 360 ft^3/s more than at the downstream site Duchesne River at Myton, UT (237 ft^3/s). The deficit in the streamflow budget for the Duchesne River at Myton, UT, gaging station is attributed to water being diverted out of its subbasin for irrigation, recharged to the groundwater system, and (or) consumed by evaporation and plants. Some of the water that is diverted for irrigation in the subbasin eventually returns to the river as groundwater discharge and irrigation tail water—runoff from agricultural lands and (or) water that passes through the canal distribution system without being applied for irrigation.

Under natural conditions (no irrigation diversions), based on WY 1989–2013 mean annual streamflow, the monitored tributaries to the Duchesne River between the Duchesne River near Tabiona, UT, and Duchesne River at Myton, UT, gaging stations (Rock Creek near Mountain Home, UT; Strawberry River near Duchesne, UT; Lake Fork River below Moon Lake, near Mountain Home, UT; and Yellowstone River near Altonah, UT) would contribute a total of 466 ft^3/s to the Duchesne River. Under WY 1989–2013 conditions, surface water is diverted from the streams to irrigate inside and outside the drainage area to the Duchesne River at Myton, UT, gaging station. Streamflow in the Yellowstone River is diverted eastward out of its drainage area during the growing season to irrigated fields in the Bluebell and Roosevelt areas. These irrigated areas drain to the Duchesne River downstream of the Duchesne River at Myton, UT, gaging station, which would receive streamflow from the Yellowstone River under natural conditions. Water is diverted from the Duchesne River upstream of the Duchesne River at Myton, UT, gaging station to irrigate land that drains to the river downstream of the gaging station and in the Pleasant Valley area that drains to Pariette Draw, outside of the Duchesne River's drainage area.

The sum of WY 1989–2013 mean annual streamflow at the monitored tributary sites Uinta River below powerplant diversion, near Neola, UT; Whiterocks River near Whiterocks, UT; and Duchesne River at Myton, UT, is 134 ft^3/s more than at the downstream gage Duchesne River near Randlett, UT. This deficit in the streamflow budget for the Duchesne River near Randlett, UT, site is attributed to water being diverted out of its subbasin, recharged to the groundwater system, and (or) consumed by evaporation and plants.

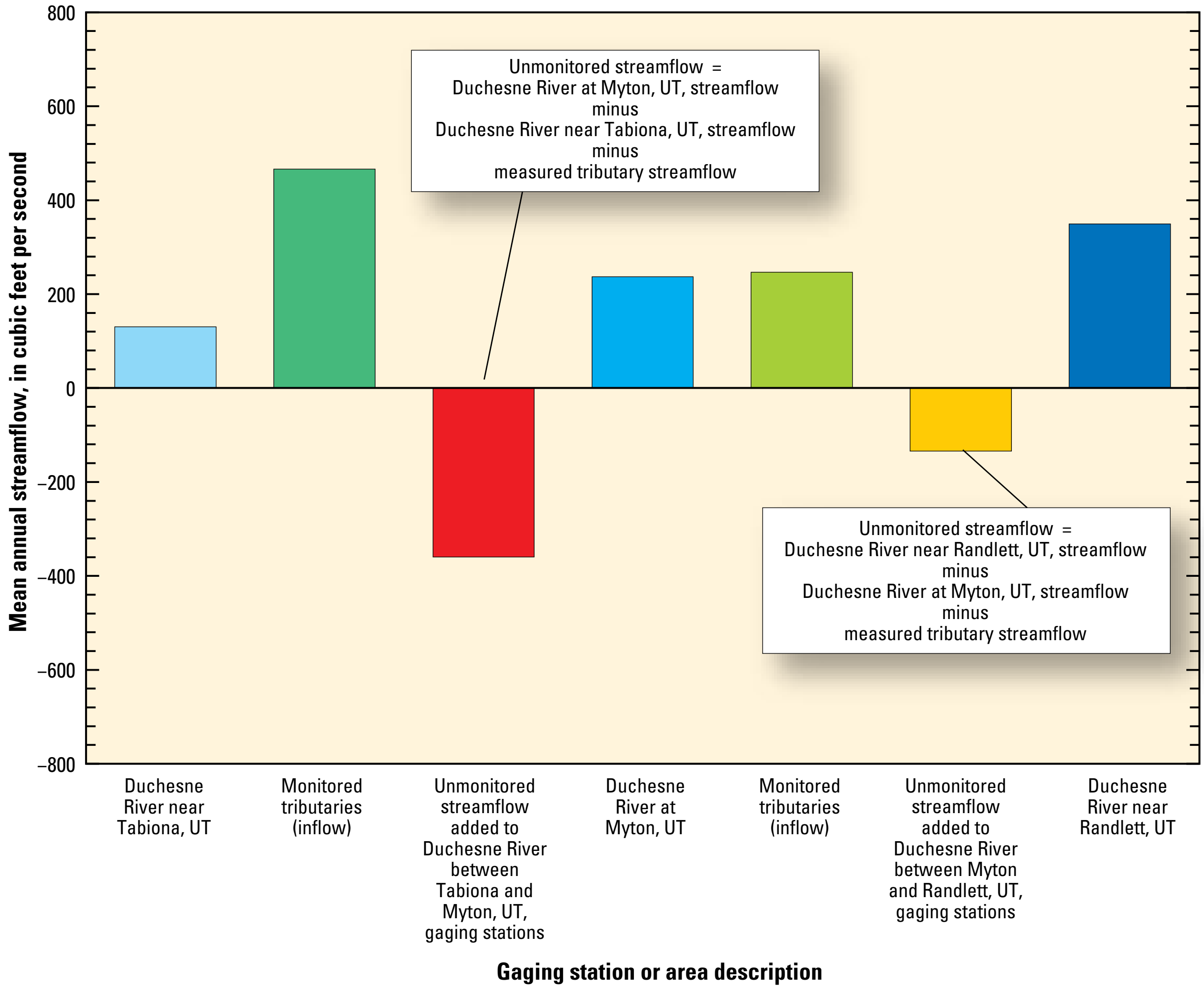

Figure 42. Mass balance of water years 1989–2013 mean annual streamflow for gaging stations used for analysis of dissolved-solids loads and trends in the Duchesne River Basin.

Under natural conditions, streamflow measured at the Uinta River below powerplant diversion, near Neola, UT, and Whiterocks River near Whiterocks, UT, gaging stations would be accounted for in streamflow measured at the Duchesne River near Randlett, UT, gaging station. On the basis of WY 1989–2013 mean annual streamflow, these monitored tributaries are estimated to contribute 246 ft^3/s to the Duchesne River between the Duchesne River at Myton, UT, and Duchesne River near Randlett, UT, gaging stations under natural conditions. Under WY 1989–2013 conditions, water is diverted for irrigation needs downstream from the Uinta River below powerplant diversion, near Neola, UT, and Whiterocks River near Whiterocks, UT, gaging stations and used to irrigate agricultural lands both inside and outside the subbasin for the Duchesne River near Randlett, UT, gaging station. In addition, some unconsumed irrigation water diverted from the Yellowstone River and from the Duchesne River upstream of the Duchesne River at Myton, UT, gaging station returns to this reach of the Duchesne River.

Dissolved-Solids Load Balance

Mass-balance calculations of WY 1989–2013 annual and mean annual dissolved-solids loads at sites in the Duchesne River Basin show unmonitored loads account for a large portion of the dissolved-solids load at the Duchesne River near Randlett, UT, gaging station (table 5; figs. 43 and 44). This gaging station is downstream of almost all of the irrigated land in the Duchesne River Basin and has a mean annual dissolved-solids load of 172,000 tons. The Duchesne River near Tabiona, UT, accounts for 18 percent of the load and the Strawberry River near Duchesne, UT, accounts for 28 percent. Combined, the tributaries Rock Creek near Mountain Home, UT; Lake Fork River below Moon Lake, near Mountain Home, UT; Yellowstone River near Altonah, UT; Uinta River below powerplant diversion, near Neola, UT; and Whiterocks River near Whiterocks, UT—all measured near their headwaters and above irrigated land—account for approximately 9 percent of the mean annual load at Duchesne River near Randlett, UT. The remaining mean annual dissolved-solids load in the balance, 75,400 tons or 44 percent of the dissolved-solids load at

Table 5. Mass balance of water years 1989–2013 dissolved-solids loads for gaging stations used for analysis of dissolved-solids loads and trends in the Duchesne River Basin.

[Italicized text is calculated as the difference between components. USGS, U.S. Geological Survey; WY, water year; UT, Utah]

USGS gaging station name (number), or area description	Estimated WY 1989–2013 mean annual dissolved-solids load, in tons per year	Percent of WY 1989–2013 mean annual dissolved-solids load at Duchesne River near Randlett, UT, gaging station	Flow-normalized dissolved-solids load				
			WY 1989 load, in tons	WY 2013 load, in tons	WY 1989–2013 net change, in tons	WY 1989–2013 net change, in percent	Percent of net change modeled at Duchesne River near Randlett, UT, gaging station
Duchesne River near Tabiona, UT (09277500)	30,200	17.6	31,300	31,300	0	0	0
Rock Creek near Mountain Home, UT (09279000) (inflow)	4,930	2.9	4,950	4,950	0	0	0
Strawberry River near Duchesne, UT (09288180) (inflow)	47,300	27.5	48,500	44,000	[1] −4,500	[1] −9.3	6.6
Lake Fork below Moon Lake, near Mountain Home, UT (09291000) (inflow)	2,150	1.3	2,190	2,190	0	0	0
Yellowstone River near Altonah, UT (09292500) (inflow)	4,360	2.5	4,410	4,410	0	0	0
Unmonitored load added to Duchesne River between Tabiona and Myton gaging stations	*3,260*	*1.9*	*31,500*	*12,000*	*−19,500*	*−61.9*	*28.4*
Duchesne River at Myton, UT (09295000)	92,200	53.6	123,000	98,800	[1] −24,200	[1] −19.7	35.3
Uinta River below powerplant diversion, near Neola, UT (09296800) (inflow)	2,470	1.4	2,640	2,640	0	0	0
Whiterocks River near Whiterocks, UT (09299500) (inflow)	1,920	1.1	1,820	2,120	300	16.5	−0.4
Unmonitored load added to Duchesne River between Myton and Randlett gaging stations	*75,400*	*43.8*	*118,000*	*73,100*	*−44,900*	*−38.1*	*65.5*
Duchesne River near Randlett, UT (09302000)	172,000	100	245,000	177,000	[1] −68,000	[1] −27.8	100

[1] This value differs from the corresponding value in table 3 because of rounding when using three significant figures in mass-balance calculations.

Duchesne River near Randlett, UT, was not accounted for at any of the upstream gages. Most of the unmonitored load in the Duchesne River Basin enters the Duchesne River between the gaging stations at Myton and near Randlett, UT, and is derived from inflow from the Uinta River downstream from the Uinta River below powerplant diversion, near Neola, UT, gaging station, groundwater discharge, unconsumed irrigation water, and tail water.

Monitored dissolved-solids loads at Duchesne River near Tabiona, UT; Strawberry River near Duchesne, UT; Rock Creek near Mountain Home, UT; Lake Fork River below Moon Lake, near Mountain Home, UT; and Yellowstone River near Altonah, UT, account for 96 percent of the WY 1989–2013 mean annual dissolved-solids load at the Duchesne River at Myton, UT, gaging station. One third of the mean annual load at Duchesne River at Myton, UT, was measured at Duchesne River near Tabiona, UT; 51 percent at Strawberry River near Duchesne, UT; and 12 percent from the other monitored gaging stations. The remaining 4 percent (3,260 tons) of the mean annual dissolved-solids load at Duchesne River at Myton, UT, is attributed to unmonitored inflow to the river between the Tabiona and Myton, UT, gaging stations (fig. 44).

Unmonitored WY 1989–2013 annual dissolved-solids loads to the Duchesne River between the Tabiona and Myton, UT, gaging stations ranged from -32,200 tons in 2003 to 80,300 tons in 1998 (fig. 43). When the annual dissolved-solids load at Duchesne River at Myton, UT, is less than the sum of the load at Duchesne River near Tabiona, UT; Strawberry River near Duchesne, UT; and the gaging stations at tributary streams in its drainage area (a negative unmonitored load), less dissolved solids and streamflow are being added to the stream. This occurs when streamflow is diverted to irrigated fields, both inside and outside of the drainage area to the gaging station. The dissolved-solids load in the stream also can decrease when a mass of dissolved solids is removed through seepage to the groundwater system or is left in the soil through evapotranspiration. Evaporation and consumptive use by plants removes some of the water and stores the concentrated salts in irrigated fields until it can be flushed into the groundwater system or to drains.

Negative values of unmonitored dissolved-solids loads to the Duchesne River between the Tabiona and Myton, UT, gaging stations occurred in years when the annual mean streamflow at Duchesne River at Myton, UT, ranged from 42 to 135 ft^3/s, less than the WY 1989–2013 average of 237 ft^3/s. Three years of below average streamflow at the site (WY 2002–04) corresponded to large negative unmonitored dissolved-solids loads to this reach of the river (-23,300 to -32,200 ton/yr). Unmonitored dissolved-solids loads to the Duchesne River at Myton, UT, gaging station were largest in years when the annual mean streamflow was highest. The highest annual mean streamflow at the site (1,120 ft^3/s)

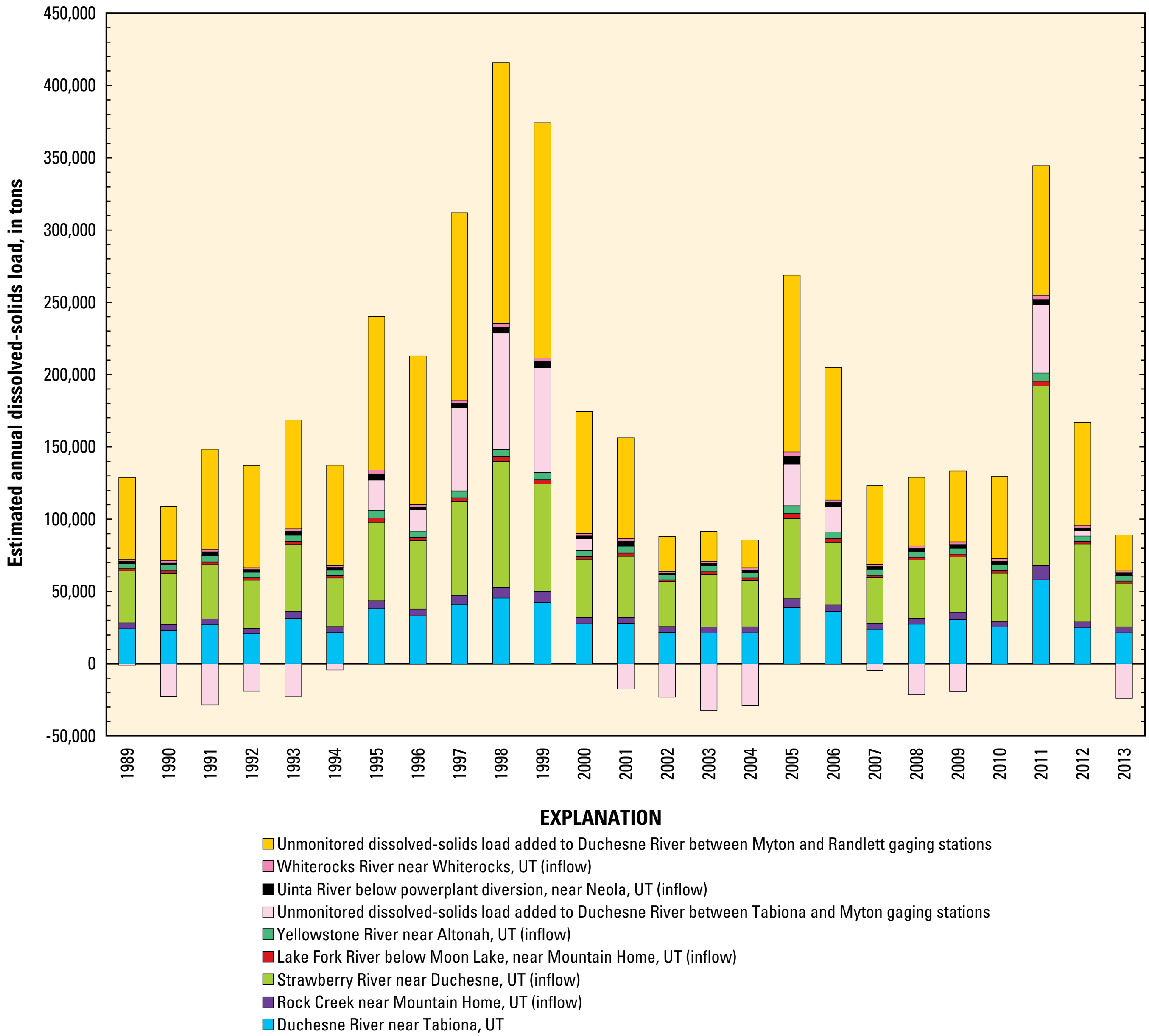

Figure 43. Mass balance of water years 1989–2013 annual dissolved-solids load for gaging stations used for analysis of dissolved-solids loads and trends in the Duchesne River Basin.

occurred in 2011 with an associated unmonitored dissolved-solids load of 47,000 tons (fig. 43). Three years of above average streamflow at the Duchesne River at Myton, UT, gaging station (WY 1997–99) corresponded to the three largest unmonitored dissolved-solids loads calculated during WY 1989–2013 (57,800–80,300 ton/yr). An explanation for the variation in unmonitored dissolved-solids load at the site is that in low streamflow years, less water is available to be diverted for irrigation, and of that diverted water, more is consumed by evapotranspiration, which leaves dissolved solids in the soil. Therefore, during low streamflow years, less water and dissolved solids return to the river as tail water and groundwater seepage. During high streamflow years, more water is available to be diverted for irrigation, which flushes salts stored in the fields into the shallow groundwater system and to tail water. This water eventually returns to the river causing an increase in dissolved-solids load. A study done in the Manila area in Utah and Wyoming found that dissolved-solids loads in water discharging from the area were largest at the beginning of irrigation seasons during years with above average amounts of precipitation, water diverted for irrigation, and streamflow (Thiros and Gerner, 2015). Conversely, years with the least amounts of water diverted for irrigation and streamflow discharging from the area had the smallest loads.

Monitored dissolved-solids loads at the upstream sites Duchesne River at Myton, UT; Uinta River below powerplant diversion, near Neola, UT; and Whiterocks River near Whiterocks, UT, accounted for 56 percent of the WY

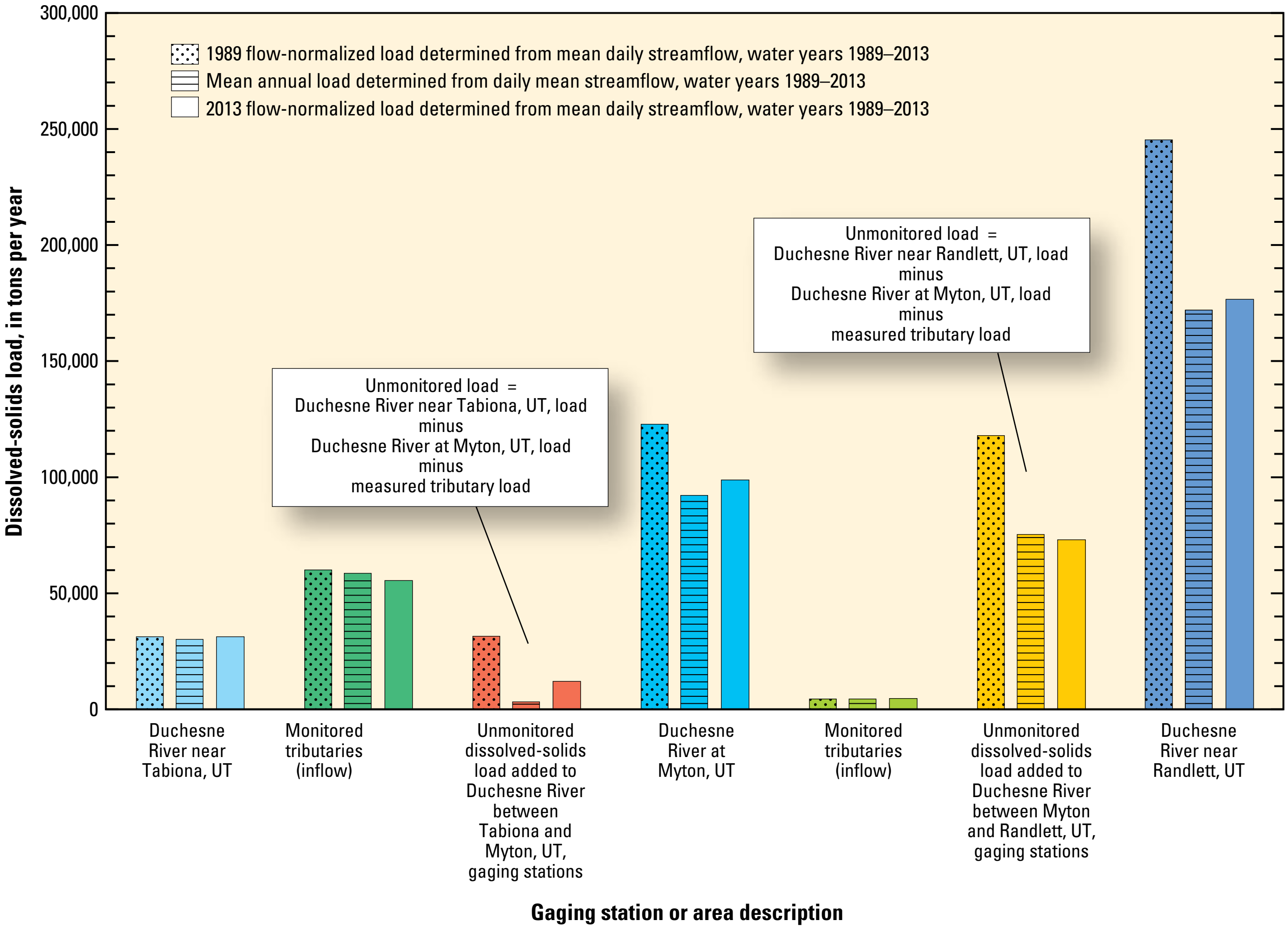

Figure 44. Water years 1989 and 2013 flow-normalized dissolved-solids load and water years 1989–2013 mean annual dissolved-solids load for gaging stations used for analysis of dissolved-solids loads and trends in the Duchesne River Basin.

1989–2013 mean annual dissolved-solids load at the Duchesne River near Randlett, UT, gaging station (fig. 44). The WY 1989–2013 mean annual streamflow and dissolved-solids load were 140 ft^3/s and 2,470 tons at Uinta River below powerplant diversion, near Neola, UT; 106 ft^3/s and 1,920 tons at Whiterocks River near Whiterocks, UT; and 237 ft^3/s and 92,200 tons at Duchesne River at Myton, UT. The difference between the sum of the upstream sites and the downstream site Duchesne River near Randlett, UT (349 ft^3/s, 172,000 tons), is a decrease in mean annual streamflow of 134 ft^3/s (-38 percent) and an increase in mean annual dissolved-solids load of 75,400 tons (44 percent).

Iorns and others (1959) balanced the mean annual streamflow and dissolved-solids load in WY 1914–57 at gaging stations upstream from agricultural lands in the Uinta River drainage, Uinta River near Neola, UT (190 ft^3/s, 4,750 tons) and Whiterocks River near Whiterocks, UT (124 ft^3/s, 3,280 tons), with streamflow and dissolved-solids loads at Duchesne River at Myton, UT (508 ft^3/s, 207,700 tons) and Duchesne River near Randlett, UT (767 ft^3/s, 459,500 tons). The Uinta River near Neola, UT, (09297000) gaging station is approximately 4 mi downstream from the Uinta River below powerplant diversion, near Neola, UT, gaging station used in this study. The difference between the sum of the upstream sites (Duchesne River at Myton, UT; Uinta River near Neola, UT; and Whiterocks River near Whiterocks, UT) and the downstream site Duchesne River near Randlett, UT, is a decrease in WY 1914–57 mean annual streamflow of 55 ft^3/s (-7 percent) and an increase in mean annual dissolved-solids load of 243,800 tons (113 percent).

A comparison of the WY 1914–57 and WY 1989–2013 periods shows there is less streamflow and dissolved-solids load at both the upstream and downstream sites in the WY 1989–2013 period. Expanded reservoirs, transbasin diversions, changes in diversions for irrigated areas both within and outside of the Duchesne River drainage area, and salinity-control projects have affected streamflow and dissolved-solids loads in the latter period. Transbasin diversions from the Duchesne River Basin near its headwaters where dissolved-solids concentrations are low result in less water available for dilution downstream.

Unmonitored WY 1989–2013 annual dissolved-solids loads to the Duchesne River between the Myton and Randlett, UT, gaging stations ranged from 19,300 tons in 2004 to 180,000 tons in 1998 (fig. 43). These values correspond to the lowest and second highest annual mean streamflow values at the Duchesne River near Randlett, UT, gaging station during the study period. Three years of above average streamflow at the site (WY 1997–99) corresponded to the three largest annual unmonitored dissolved-solids loads added to the reach during WY 1989–2013 (130,000–180,000 tons). Streamflow at the site in WY 2002–04 was the lowest during the period (48–59 ft^3/s), corresponding to the three smallest annual unmonitored dissolved-solids loads added to the reach (19,300–24,100 tons). The variability in the amount of unmonitored dissolved-solids load entering the Duchesne River between the Myton and Randlett, UT, gaging stations is controlled by streamflow and diversions for irrigation.

A mass balance was done with WY 1989–2013 flow-normalized dissolved-solids loads estimated at sites in the Duchesne River Basin (fig. 45). No trend or a relatively small change in dissolved-solids load was modeled at Duchesne River near Tabiona, UT, and the monitored tributaries in the basin. Flow-normalized dissolved-solids load estimated at Duchesne River at Myton, UT, decreased 24,200 tons (-19.7 percent) from 123,000 tons in 1989 to 98,800 tons in 2013, and at the Duchesne River near Randlett, UT, gaging station decreased 68,000 tons (-27.8 percent) from 245,000 tons in 1989 to 177,000 tons in 2013 (table 5 and fig. 45). The flow-normalized dissolved-solids load of unmonitored dissolved solids input to the Duchesne River between the Tabiona and Myton, UT, sites was calculated to be 31,500 tons in 1989 and 12,000 tons in 2013 with a net decrease of 19,500 tons (-61.9 percent). The flow-normalized dissolved-solids load of unmonitored input to the Duchesne River between the Myton and Randlett, UT, sites was calculated to be 118,000 tons in 1989 and 73,100 tons in 2013 with a net decrease of 44,900 tons (-38.1 percent). The total net WY 1989–2013 decrease in flow-normalized dissolved-solids load calculated for unmonitored inflow in the drainage area accounts for 94 percent of the decrease in flow-normalized dissolved-solids load modeled at the Duchesne River near Randlett, UT, gaging station. Irrigation improvements in the drainage area (Natural Resources Conservation Service, 2015a) have likely contributed to the decrease in flow-normalized load.

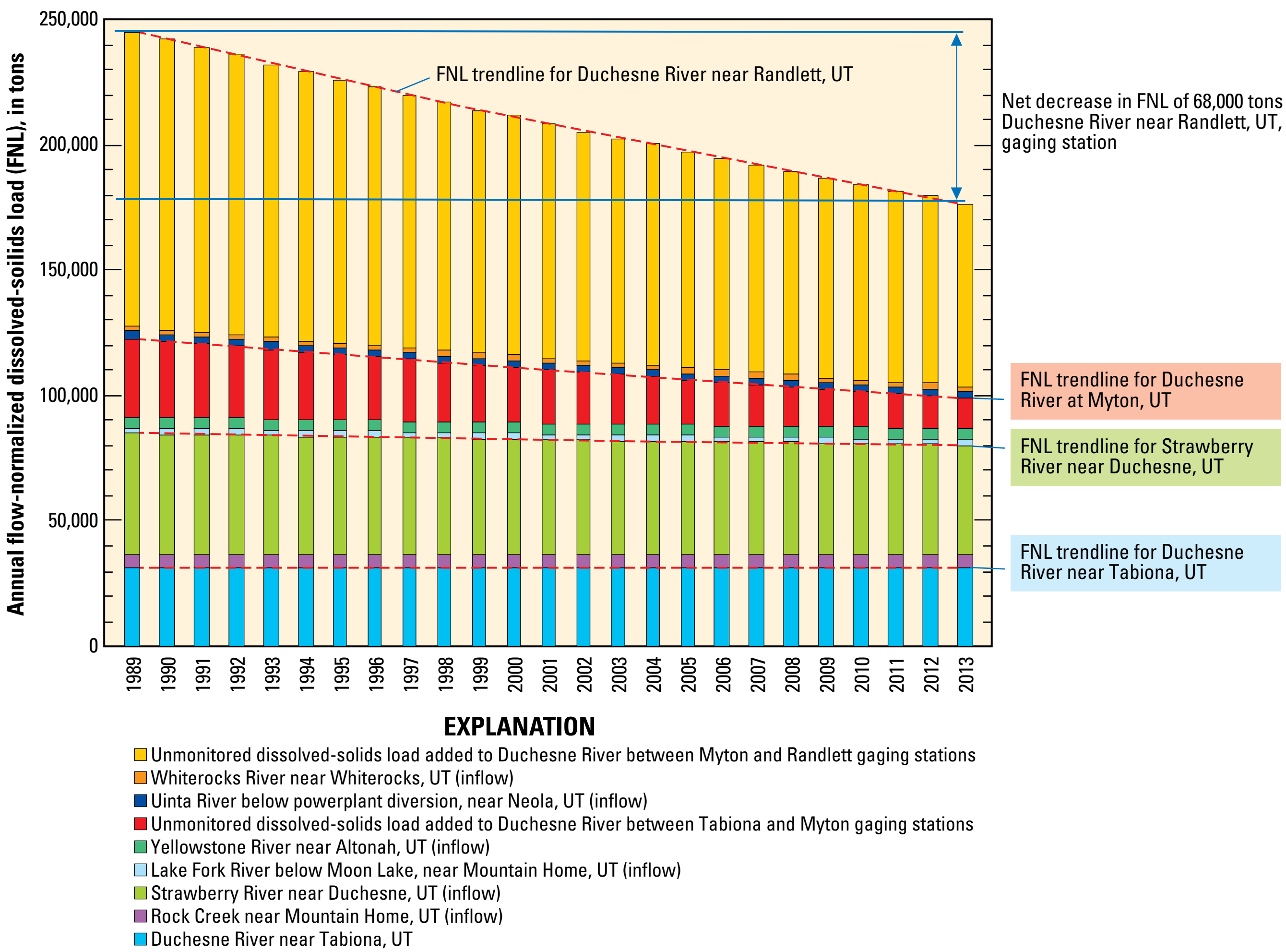

Figure 45. Mass balance of water years 1989–2013 annual flow-normalized dissolved-solids load for gaging stations used for analysis of dissolved-solids loads and trends in the Duchesne River Basin.

Comparison of Trend Analysis Results to Other Estimates of Dissolved-Solids Load Reduction

Changes in dissolved-solids loads determined from trend analysis were compared to estimates of reductions in load in the study area made by the NRCS and Reclamation and estimates based on sprinkler-irrigated acreage. Improvements to irrigation application and delivery systems in the Uinta Basin began in 1980 to reduce surplus irrigation and deep percolation. On-farm improvements, mainly the conversion from flood irrigation to sprinklers, result in more efficient application of irrigation water to crops. The NRCS estimated the dissolved-solids load in the Uinta Basin prior to 1980 to be 208,000 ton/yr from on-farm sources based on approximately 200,000 acres of flood-irrigated land (Natural Resources Conservation Service, 2015a).

The NRCS reported that 157,650 irrigated acres in the Uinta Basin were improved incrementally from 1980 to 2013, and 98,935 acres from 1989 to 2013 (96,448 acres converted to sprinkler systems, 2,378 acres received flood-irrigation improvements, and 109 acres installed a drip irrigation system; Natural Resources Conservation Service, 2015a). Conversion from flood irrigation to wheel-line or center-pivot sprinklers was estimated to reduce the dissolved-solids load by 84 and 90 percent, respectively. The NRCS calculated the annual reduction in dissolved-solids load in the Uinta Basin to be the amount of irrigated acres improved each year multiplied by the estimated pre-salinity-control project dissolved-solids yield from flood irrigated land (1.04 tons per acre) and the percent dissolved-solids load reduction resulting from the change in irrigation practice (Natural Resources Conservation Service, 2015a). The NRCS reported that on-farm improvements made from 1989 to 2013 resulted in a reduction in dissolved-solids load of 81,900 tons in 2013 (Natural Resources Conservation Service, 2015a). On the basis of the NRCS reported cumulative total of 96,448 acres converted to sprinklers in the Uinta Basin from 1989 to 2013 and the estimated pre-salinity-control project dissolved-solids yield of 1.04 tons per acre, the reduction in dissolved-solids load in 2013 is estimated to be from 84,300 tons (assuming all wheel-line sprinklers) to 90,300 tons (assuming all center-pivot sprinklers).

The NRCS estimated the dissolved-solids load in the Uinta Basin prior to 1980 to be 120,000 ton/yr from off-farm sources (Natural Resources Conservation Service, 2015a). Off-farm improvements include the lining and piping of canals and ditches. A reduction in dissolved-solids load of 41,600 tons in 2011 was estimated as a result of off-farm improvements made by Reclamation from 1999 through 2011 (URS, 2014). A reported reduction in dissolved-solids load of 11,700 tons in 2013 resulting from off-farm improvements made from 1989 to 2013 was coordinated by the NRCS (Natural Resources Conservation Service, 2015a). A reduction in dissolved-solids load of 53,300 tons in 2013 resulting from off-farm improvements in the Uinta Basin is determined by totaling the Reclamation and NRCS estimates. The sum of reductions in dissolved-solids loads estimated by the NRCS and Reclamation for on- and off-farm improvements in the Uinta Basin is 135,000 tons in 2013 (fig. 46).

The amount of sprinkler-irrigated land mapped in the drainage or subbasin area for a gaging station was used to estimate the reduction in dissolved-solids load resulting from the conversion from flood to sprinkler irrigation. Irrigated land mapped in the Uinta Basin totaled 186,800 acres in 2012, of which 109,630 were sprinkler irrigated and 77,170 flood irrigated (Utah Department of Natural Resources, 2013). A reduction in dissolved-solids load in the Uinta Basin of 95,800 tons (assuming conversion to wheel-line sprinklers) or 102,600 tons (assuming conversion to center-pivot sprinklers) is calculated using the 2012 sprinkler-irrigation acreage and a pre-salinity-control project dissolved-solids yield of 1.04 tons per acre. A reduction of 98,100 tons in 2012 was estimated assuming wheel-line sprinklers in the Duchesne River Basin and center-pivot sprinklers in the rest of the Uinta Basin (table 6 and fig. 46).

Several assumptions and limitations could cause estimates of reductions in dissolved-solids loads based on land-use mapping in the Uinta Basin to be different from estimates reported by the NRCS for 1989–2013. The acreage mapped as sprinkler irrigated in 2012 was compared to the acreage converted to sprinkler irrigation compiled by the NRCS and accumulated over time. A limitation of the NRCS-reported cumulative improved irrigation acreage is that it does not account for land that has become fallow or idle. For example, the NRCS reported that 21,920 acres were converted to sprinkler irrigation from 2006 to 2012, whereas the Utah Department of Natural Resources mapped a decrease of 7,220 acres in sprinkler-irrigated land. The discrepancy in sprinkler-irrigated land could be caused by idle and fallow lands with irrigation improvements being mapped as not irrigated in 2012 or to variations in mapping methods from 2006 to 2012. Although the area of irrigated land that received improvements was recorded every year by the NRCS, the location of these irrigation improvements was not available. Therefore, the NRCS data could not be spatially related to sprinkler-irrigated areas mapped in 2006, 2007–10, or 2012, or to trends in flow-normalized dissolved-solids loads estimated at the studied sites. Information on the spatial and temporal distribution of irrigation improvements and changes in the method used to deliver water to these lands can help improve the understanding of agriculturally derived dissolved-solids loading to streams in the study area.

Irrigated land mapped in the Duchesne River near Randlett, UT, drainage area totaled 141,340 acres in 2012, of which 72,447 were sprinkler irrigated and 68,895 flood irrigated (Utah Department of Natural Resources, 2013a). A dissolved-solids load of 83,700 tons derived from irrigated lands in the Duchesne River near Randlett, UT, drainage area in 2012 was calculated using the estimated pre-salinity-control project dissolved-solids yield of 1.04 tons per acre for flood irrigated

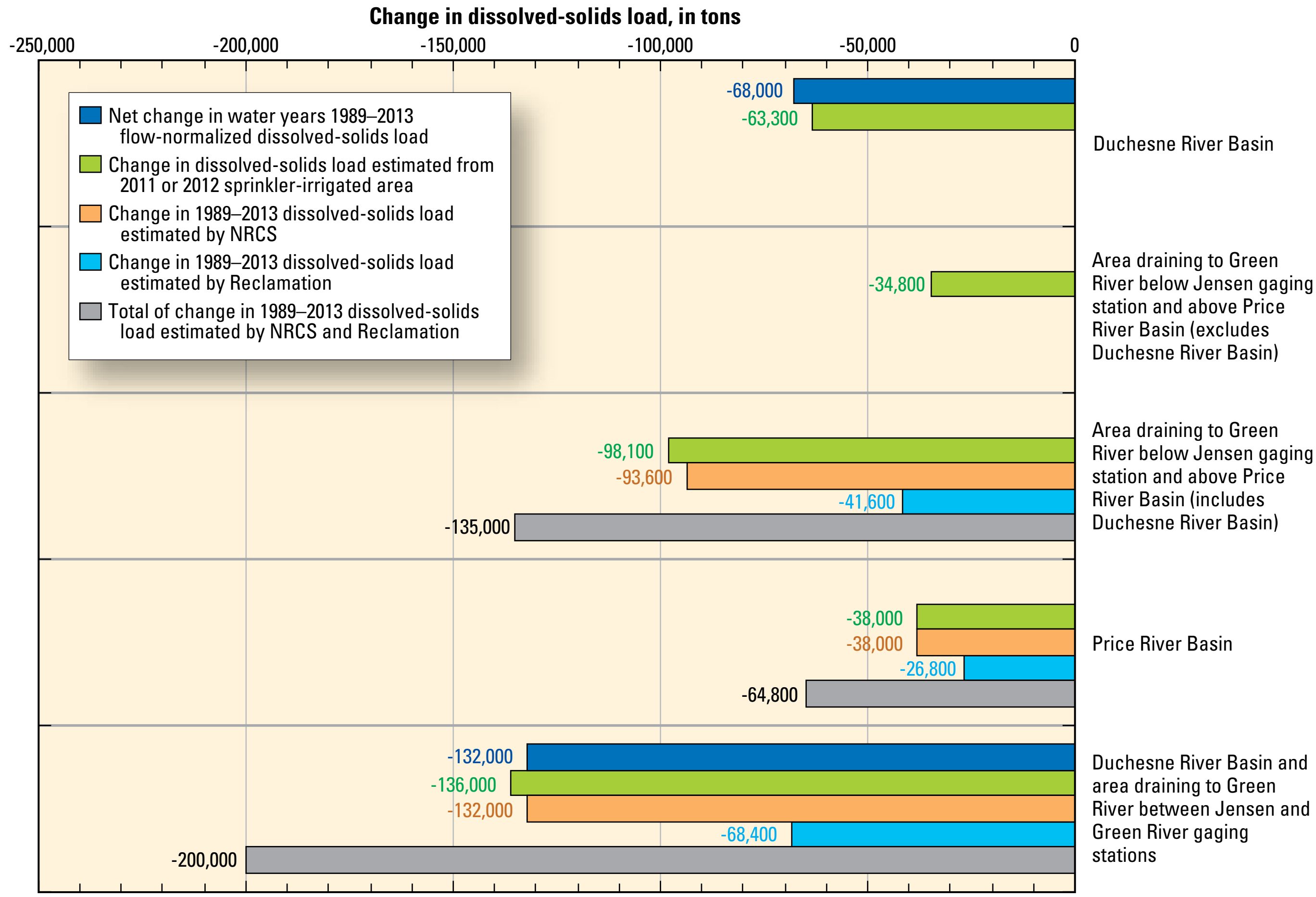

Figure 46. Change in dissolved-solids load from 1989 to 2013 estimated by the Natural Resources Conservation Service (NRCS) and Reclamation for parts of the Uinta Basin study area.

land and the dissolved-solids load reduction factor of 0.84 for wheel-line sprinklers (table 6). The WY 1989–2013 mean annual dissolved-solids load modeled at Duchesne River near Randlett, UT, is 172,000 tons, and the 2013 flow-normalized dissolved-solids load is 177,000 tons. The modeled loads include dissolved-solids loads derived from natural, agricultural, and other sources. The dissolved-solids load from natural sources and off-farm canals and ditches is included in the difference of 93,300 tons (53 percent) between the 2013 flow-normalized dissolved-solids load modeled at Duchesne River near Randlett, UT, and the 2012 dissolved-solids load estimated from irrigated lands in the drainage area for the gaging station (47 percent). The estimates of dissolved-solids load from natural and agricultural sources are similar to those predicted in 1991 by the dissolved-solids SPARROW model, 47 percent of the dissolved-solids load from natural sources and 55 percent from agricultural lands (Kenney and others, 2009), and potentially reflects the effects of additional irrigation improvements made in the drainage basin from 1992–2013.

Assuming that all of the sprinkler-irrigated land mapped in the Duchesne River Basin in 2012 was flood irrigated before converting to wheel-line sprinklers, the reduction in dissolved-solids load in the Duchesne River near Randlett, UT, drainage area is 63,300 tons. This estimated reduction in dissolved-solids load is similar to the reduction of 68,000 tons calculated as the net WY 1989–2013 change in flow-normalized dissolved-solids load at the Duchesne River near Randlett, UT, gaging station (table 6 and fig. 46).

An estimated reduction in dissolved-solids load of 33,900 tons was determined from 38,834 sprinkler-irrigated acres in the subbasin for the Duchesne River near Randlett, UT, gaging station in 2012, a pre-salinity-control project dissolved-solids yield of 1.04 tons per acre, and a dissolved-solids load reduction factor of 0.84 for conversion to wheel-line sprinklers (table 6). The Duchesne River near Randlett, UT, subbasin corresponds to the area contributing load to the Duchesne River between the Myton and Randlett, UT, gaging stations, where a net decrease in WY 1989–2013 flow-normalized dissolved-solids load of 44,900 tons was modeled. The larger reduction in flow-normalized load includes the results of off-farm improvements and other factors that affect loads in the subbasin, such as the occurrence of fallow fields in years other than the year the irrigated areas were mapped.

Table 6. Comparison of dissolved-solids load estimates in the Uinta Basin study area.

[USGS, U.S. Geological Survey; WY, water year; UT, Utah; —, no data or not applicable]

USGS gaging station name or area description	Estimated WY 1989–2013 mean annual dissolved-solids load, in tons per year[1]	WY 2013 flow-normalized dissolved-solids load, in tons	Net change in estimated WY 1989–2013 flow-normalized dissolved-solids load, in tons	2012 sprinkler-irrigated area, in acres	Estimated 2012 dissolved-solids load from sprinkler-irrigated area, in tons[2]	2012 flood-irrigated area, in acres	Estimated 2012 dissolved-solids load from flood-irrigated area, in tons	Estimated 2012 dissolved-solids load from total irrigated area, in tons	Estimated change in dissolved-solids load based on 2012 sprinkler-irrigated area, in tons	Estimated 2012 dissolved-solids load from natural or other sources, in tons[3]
Duchesne River near Tabiona, UT[4]	30,200	31,300	0	4,749	790	1,361	1,420	2,210	−4,150	29,100
Strawberry River near Duchesne, UT[4]	47,300	44,000	−4,500	2,851	474	906	942	1,420	−2,490	42,600
Unmonitored load added to Duchesne River between Tabiona and Myton gaging stations (irrigated land in Duchesne River at Myton, UT, subbasin)[4]	3,260	12,000	−19,500	26,013	4,330	13,332	13,900	18,200	−22,700	−6,200
Duchesne River at Myton, UT	92,200	98,800	−24,000	33,613	5,600	15,599	16,300	21,800	−29,300	77,000
Unmonitored load added to Duchesne River between Myton and Randlett gaging stations (irrigated land in Duchesne River near Randlett, UT, subbasin)[4]	75,400	73,100	−44,900	38,834	6,460	53,296	55,400	61,900	−33,900	11,200
Duchesne River near Randlett, UT (total irrigated land in the Duchesne River Basin)	172,000	177,000	−68,000	72,447	12,100	68,895	71,600	83,700	−63,300	93,300
Pariette Draw subbasin (Pleasant Valley)[4]	—	—	—	6,279	653	268	279	932	−5,880	—
Irrigated land draining to Green River between Jensen-Ouray and from around Pelican Lake[4]	—	—	—	30,903	3,210	8,007	8,330	11,500	−28,900	—
Irrigated land in Price River Basin[5,7]	—	—	—	13,781	7,230	9,982	32,700	39,900	−38,000	—
Irrigated area near town of Green River, Utah[6,7]	—	—	—	5,814	3,310	4,073	14,500	17,800	—	—
Unmonitored load added to Green River between Jensen and Green River gaging stations (total of irrigated land, excluding the Duchesne River Basin, draining to this reach)	219,000	167,000	−64,000	56,777	14,400	22,330	55,800	70,100	−72,800	96,900
Total for the Duchesne River Basin and unmonitored load added to Green River between Jensen and Green River gaging stations (total of irrigated land draining to this reach)	391,000	344,000	−132,000	129,224	26,500	91,225	127,400	154,000	−136,000	190,000
Green River at Green River, UT	1,760,000	1,632,000	−352,000	—	—	—	—	—	—	—

[1] Estimated WY1989–2013 mean annual dissolved-solids load determined from daily mean streamflow values and RLOADEST model.

[2] Estimated 2012 load from sprinkler-irrigated area calculated with a dissolved-solids load reduction factor of 0.84 for wheel-line sprinklers, except in the Pariette Draw subbasin and irrigated areas draining to the Jensen-Ouray reach of the Green River where a load reduction factor of 0.90 for center-pivot sprinklers was used.

[3] Estimated load from natural or other sources calculated as the difference between the 2013 flow-normalized load and the estimated 2012 load from total irrigated area.

[4] Dissolved-solids load from irrigated areas calculated with an estimated pre-salinity control project dissolved-solids yield of 1.04 tons per acre (Natural Resources Conservation Service, 2015a).

[5] Dissolved-solids load from irrigated areas calculated with an estimated pre-salinity control project dissolved-solids yield of 3.28 tons per acre (Natural Resources Conservation Service, 2015c).

[6] Dissolved-solids load from irrigated areas calculated with an estimated pre-salinity control project dissolved-solids yield of 3.56 tons per acre (Natural Resources Conservation Service, 2015d).

[7] Irrigated areas mapped in 2011 by the Utah Department of Natural Resources (2013).

Sprinkler- and flood-irrigated land mapped in 2012 in the Ashley Valley, Jensen, Pelican Lake, and Pleasant Valley areas; and in 2011 in the Price River Basin and the area near the town of Green River totaled 79,107 acres. An annual dissolved-solids load of 70,100 tons from this irrigated land was calculated by using pre-salinity-control project dissolved-solids yields reported by the NRCS (table 6). The unmonitored WY 1989–2013 mean annual dissolved-solids load added to the Green River between the Green River near Jensen, UT, and Green River at Green River, UT, gaging stations is 219,000 tons, and the 2013 flow-normalized dissolved-solids load is 167,000 tons. The dissolved-solids load from natural sources and off-farm canals and ditches is included in the difference of 96,900 tons (58 percent) between the 2013 unmonitored flow-normalized dissolved-solids load added to the Green River between the Jensen and Green River, UT, gaging stations and the 2012 dissolved-solids loads estimated from irrigated lands in the Ashley Valley, Jensen, Pelican Lake, and Pleasant Valley areas, the Price River Basin, and the area near the town of Green River (42 percent).

In 2012, 37,182 acres were sprinkler irrigated and 8,275 acres were flood irrigated in areas draining to the Green River between Jensen and Ouray, the area around Pelican Lake, and Pleasant Valley (table 6). The reduction in 2012 dissolved-solids load from these areas, assuming that all of the sprinkler-irrigated land used center-pivot sprinklers and were previously flood irrigated with a dissolved-solids yield of 1.04 tons per acre, is 34,800 tons. In 2011, the Utah Department of Natural Resources (2013) mapped 13,781 sprinkler-irrigated acres and 9,982 flood-irrigated acres in the Price River Basin and 5,814 sprinkler-irrigated acres and 4,073 flood-irrigated acres in the area near the town of Green River (table 6). The reduction in dissolved-solids load in the Price River Basin assuming that all of the sprinkler-irrigated land used wheel-line sprinklers and was previously flood irrigated with a yield of 3.28 tons per acre (Natural Resources Conservation Service, 2015c), is 38,000 tons. The assumption that all of the sprinkler-irrigated land in the area near the town of Green River was previously flood irrigated is not valid. Sprinklers were installed on about 3,400 acres not previously irrigated during the period from 2005 to 2011 (Natural Resources Conservation Service, 2015d). An estimated 15,700 tons of dissolved solids were discharged from developed land near the town of Green River, to the river between June 1, 2004, and May 31, 2005 (Gerner and others, 2006).

The estimated reduction in dissolved-solids load determined from sprinkler-irrigated land in the Ashley Valley; Jensen, Pelican Lake, and Pleasant Valley areas; and the Price River Basin is 72,800 tons (table 6). This decrease in dissolved-solids load is 8,800 tons more than the net WY 1989–2013 decrease in unmonitored flow-normalized dissolved-solids load (-64,000 tons) determined for the Green River between the Jensen and Green River, UT, gaging stations.

The reduction in dissolved-solids load resulting from on- and off-farm improvements facilitated by the NRCS and Reclamation in the Price River Basin from 1989 to 2013 was estimated to be 64,800 tons (fig. 46). A reduction of 26,800 tons was estimated from off-farm improvement projects coordinated by Reclamation in the Price River Basin (Benjamin Radcliff, U.S. Bureau of Reclamation, written commun., May 6, 2016). The reduction in dissolved-solids load from on-farm improvements facilitated by the NRCS in the Price River Basin could not be determined because their reported information includes improvements made in the San Rafael River Basin (Natural Resources Conservation Service, 2015c). The reduction in dissolved-solids load attributed to on-farm improvement projects led by NRCS in the Price River Basin was estimated by using the sprinkler-irrigated area method (table 6 and fig. 46).

The net WY 1989–2013 change in flow-normalized dissolved-solids load in the Duchesne River near Randlett, UT, and the Green River between the Jensen and Green River, UT, gaging stations determined from mass-balance calculations was compared to estimated reductions in load from on- and off-farm improvements reported by NRCS and Reclamation and estimated reductions in load determined from mapped sprinkler-irrigated areas in the Duchesne River Basin and the area draining to the Green River between the Jensen and Green River, UT, gaging stations (fig. 46). The combined NRCS and Reclamation estimates of reduction in dissolved-solids load from on- and off-farm improvements (200,000 tons) is more than the reduction in load estimated using the acreage with sprinkler improvements (136,000 tons) or the mass-balance flow-normalized load (132,000 tons).

Geology and evapotranspiration occurring in nearby riparian areas, wetlands, and ponds likely affect the estimates of reductions in dissolved-solids loads to the Green River. The occurrence of salt- bearing rocks in the Mancos Shale and Uinta Formation is prevalent in the Price River Basin and in areas of the Uinta Basin outside of the Duchesne River Basin (fig. 4). The dissolved-solids yield from irrigated lands containing these rocks could vary from the values used by the NRCS and the sprinkler-irrigated area method used to estimate reductions in dissolved-solids loads from on-farm irrigation improvements. Increasing the dissolved-solids yield for irrigated lands in the Ashley Valley, Jensen, Pelican Lake, and Pleasant Valley areas to 3.28 tons per acre, the value used in the Price River Basin, would increase the reduction in load estimated with the sprinkler-irrigated area method to 110,000 tons compared to 34,800 tons using a yield of 1.04 tons per acre.

A nonagricultural source contributing to the dissolved-solids load in the Green River between the Green River near Jensen, UT, and Green River at Green River, UT, gaging stations are 15,740 acres mapped in 2012 as riparian, wetlands, and ponds draining to the Green River, and along the Duchesne River and White River upstream of confluences with the Green River. Potential evapotranspiration exceeds the average annual precipitation in these areas, and removal of water by evapotranspiration likely concentrates dissolved solids in soils and surface and groundwater. As noted for irrigated fields, periods of high streamflow could flush the concentrated dissolved solids to the rivers, increasing the dissolved-solids load.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Colorado River Basin Salinity Control Forum, studied trends in dissolved-solids loads at selected sites in and near the Uinta Basin, Utah. The Uinta Basin study area includes the Duchesne River Basin and the Middle Green River Basin in Utah from below Flaming Gorge Reservoir, through the area surrounding the city of Vernal, to the town of Green River.

Annual dissolved-solids loads for water years (WY) 1989 through 2013 were estimated for 16 gaging stations in the study area using streamflow and water-quality data from the USGS National Water Information System database. Eight gaging stations that monitored catchments with limited or no agricultural land use (natural subbasins) were used to assess loads from natural sources. Four gaging stations that monitored catchments with agricultural land in the Duchesne River Basin were used to assess loads from agricultural sources. Four other gaging stations were included in the dissolved-solids load and trend analysis to help assess the effects of agricultural areas that drain to the Green River in the Uinta Basin, but outside of the Duchesne River Basin.

The RLOADEST statistical program was used to develop a regression model of dissolved-solids load for each gaging station by using calculated dissolved-solids concentrations and associated daily mean streamflow values and sample dates in WY 1989–2013. Mean daily streamflow values were used to estimate trends in flow-normalized dissolved-solids loads in the studied streams. Using mean daily streamflow for the study period to predict trends in load removes the effects of streamflow variability at the selected sites.

Estimated mean annual dissolved-solids loads for WY 1989–2013 ranged from 1,520 tons at the Lake Fork River above Moon Lake, near Mountain Home, Utah (UT), gaging station (natural site near headwaters of stream), to 1,760,000 tons at the Green River near Green River, UT, gaging station (farthest downstream site in study area). The studied gaging stations upstream of agricultural activities displayed no trend or only a relatively small change in flow-normalized load. The largest WY 1989–2013 net change in modeled flow-normalized load was -352,000 tons (a 17.8-percent decrease) at the Green River near Green River, UT, site.

Annual streamflow and modeled dissolved-solids loads at the studied gaging stations were balanced between upstream and downstream sites to determine how much water and dissolved solids were transported to the Duchesne River and a section of the Green River and how much was derived from each drainage area. Mass-balance calculations of WY 1989–2013 mean annual dissolved-solids loads at the studied sites show that Green River near Greendale, UT, contributed the largest load to the Green River in the study area, 39 percent of the load at the Green River at Green River, UT, gaging station. Downstream, the WY 1989–2013 mean annual load at the Green River near Jensen, UT, gaging station accounted for 64 percent of the load in the river at Green River at Green River, UT, while the Duchesne River and White River contributed 10 and 13 percent, respectively. The mean annual load of unmonitored inflow to the Green River from Green River near Jensen, UT, to Green River at Green River, UT, was calculated to be 219,000 tons, or 13 percent of the mean annual load at the Green River at Green River, UT, gaging station. The mean annual dissolved-solids load from the Price River was 57 percent of the increase in load in the Green River between the Jensen and Green River, UT, gages, leaving approximately 95,000 tons to come from other sources. Irrigated fields in the Vernal, Ashley Valley, Pelican Lake, and Pleasant Valley areas and near the town of Green River are sources of the remaining unmonitored dissolved-solids load to the Green River at Green River, UT.

The flow-normalized dissolved-solids loads estimated at Duchesne River near Randlett, UT, and White River near Watson, UT, decreased by 68,000 and 55,300 tons, or 27.8 and 20.8 percent respectively, when comparing 1989 to 2013. The drainage basins for both rivers have undergone salinity-control projects since the early 1980s to reduce the dissolved-solids load entering the Colorado River. Approximately 19 percent of the net change in flow-normalized load at Green River at Green River, UT, is from changes in load modeled at Duchesne River near Randlett, UT, and 16 percent from changes in load modeled at White River near Watson, UT. The WY 1989–2013 net change in flow-normalized load estimated at Green River near Greendale, UT, accounts for about 45 percent of the net change estimated at the Green River at Green River, UT, site.

Mass-balance calculations of WY 1989–2013 mean annual dissolved-solids loads at the studied sites in the Duchesne River Basin show that 75,400 tons per year or 44 percent of the load at the Duchesne River near Randlett, UT, gaging station was not accounted for at any of the upstream sites. Most of this unmonitored load is derived from tributary inflow, groundwater discharge, unconsumed irrigation water, and tail water.

Unmonitored WY 1989–2013 annual dissolved-solids loads to the Duchesne River between the Myton and Randlett, UT, gaging stations ranged from 180,000 tons in 1998 to 19,300 tons in 2004. The variability in the amount of unmonitored load entering the Duchesne River between the Myton and Randlett, UT, gaging stations, like that of the upstream reach between the Tabiona and Myton, UT, gaging stations, is controlled by streamflow and diversions for irrigation. In low streamflow years, less water is available to be diverted for irrigation, and of that diverted water, more is consumed by evapotranspiration, which leaves dissolved solids in the soil. Therefore, during low streamflow years, less water and dissolved solids return to the river as tail water and groundwater seepage. During high streamflow years, more water is available to be diverted for irrigation, which flushes salts stored in the fields to the shallow groundwater system, to tail water, and ultimately back to the river.

A mass balance of WY 1989–2013 flow-normalized loads estimated at sites in the Duchesne River Basin indicates that the flow-normalized load of unmonitored inflow to the

Duchesne River between the Myton and Randlett, UT, gaging stations decreased 38 percent. The total net decrease in flow-normalized load calculated for unmonitored inflow in the drainage basin accounts for 94 percent of the decrease in WY 1989–2013 flow-normalized load modeled at the Duchesne River near Randlett, UT, gaging station. Irrigation improvements in the drainage basin have likely contributed to the decrease in flow-normalized load.

Reductions in dissolved-solids loads estimated by the NRCS and Reclamation for on- and off-farm improvements in the Uinta Basin totaled about 135,000 tons in 2013 (81,900 tons from on-farm improvements and 53,300 tons from off-farm improvements). Reductions in dissolved-solids loads resulting from on- and off-farm improvements facilitated by the NRCS and Reclamation in the Price River Basin from 1989 to 2013 were estimated to be 64,800 tons.

The amount of sprinkler-irrigated land mapped in the drainage area or subbasin area for a gaging station was used to estimate the reduction in load resulting from the conversion from flood to sprinkler irrigation. Irrigated land mapped in the Uinta Basin totaled 186,820 acres in 2012, of which 109,630 acres were sprinkler irrigated and 77,170 acres flood irrigated. A reduction in dissolved-solids load in the Uinta Basin of 95,800 tons (assuming conversion to wheel-line sprinklers) or 102,600 tons (assuming conversion to center-pivot sprinklers) was calculated using the sprinkler-irrigation acreage and a pre-salinity-control project dissolved-solids yield of 1.04 tons per acre.

A reduction of 63,300 tons in dissolved-solids load in the Duchesne River near Randlett, UT, drainage area was estimated if all of the sprinkler-irrigated land mapped in 2012 is assumed to use wheel-line sprinklers and was previously flood irrigated with a load of 1.04 tons per acre. A similar reduction of 68,000 tons was calculated as the net WY 1989–2013 change in flow-normalized load at the Duchesne River near Randlett, UT, gaging station.

A reduction of 72,800 tons in dissolved-solids load from irrigation improvements was determined from sprinkler-irrigated lands in the Ashley Valley, Jensen, Pelican Lake, and Pleasant Valley areas (mapped in 2012), and the Price River Basin (mapped in 2011). This decrease in dissolved-solids load is 8,800 tons more than the decrease in unmonitored flow-normalized dissolved-solids load (-64,000 tons) determined for the Green River between the Jensen and Green River, UT, gaging stations.

The net WY 1989–2013 change in flow-normalized dissolved-solids loads in the Duchesne River near Randlett, UT, and the Green River between the Jensen and Green River, UT, gaging stations determined from mass-balance calculations was compared to reported reductions in load for on- and off-farm improvements and estimated reductions in load determined from mapped sprinkler-irrigated areas in the Duchesne River Basin and the area draining to the Green River between the Jensen and Green River, UT, gaging stations. The combined NRCS and Reclamation estimate of reduction in dissolved-solids load from on- and off-farm improvements (200,000 tons) is more than the reduction in load estimated using the acreage with sprinkler improvements (136,000 tons) or the mass-balance of flow-normalized load (132,000 tons).

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Appendix

Table A–1. Model coefficients and statistical diagnostics from regression analysis of dissolved-solids loads for selected gaging stations in the Uinta Basin study area.

[Value in italics indicates p-value greater than 0.05, but the term was included in the final regression. USGS, U.S. Geological Survey; ln, natural logarithm; Q, streamflow; *, centered value; t, decimal time in decimal years; Sin, sine function; Cos, cosine function; k, positive integer used in seasonality variables; π , 3.14169; T, seasonal time; AIC, Akaike Information Criteria; ERV, estimated residual variance; SCR, serial correlation of residual; R2, coefficient of determination; N, number of data points; —, variable not used in the regression because statistically not significant]

USGS gaging station number	Y-axis intercept	Streamflow			Decimal time			Seasonal time						Statistical diagnostics				
								k2πT, k=1		k2πT, k=2		k2πT, k=3						
		(ln Q–ln Q*)	(ln Q–ln Q*)2	ln Q*	(t–t*)	(t–t*)2	t*	Sin	Cos	Sin	Cos	Sin	Cos	AIC	ERV	SCR	R2	N
Middle Green River Basin																		
09234500	14.55	0.957	0.041	7.660	−0.010	—	2002.26	0.025	0.043	—	—	—	—	−281.3	0.005	0.570	98.22	119
[1] 09234500	14.52	0.981	*0.016*	7.660	−0.010	0.001	2002.26	0.029	0.046	—	—	—	—	−291.3	0.005	0.557	98.39	119
09261000	15.07	0.802	—	8.359	−0.006	—	2001.10	*−0.006*	0.168	0.094	−0.091	—	—	−137.0	0.027	0.161	92.56	187
09266500	9.097	0.796	−0.032	3.811	−0.003	—	2000.80	*0.021*	0.080	*−0.003*	−0.034	—	—	−136.5	0.005	0.363	99.55	59
[1] 09266500	8.951	0.806	−0.026	3.811	−0.003	0.001	2000.80	*0.022*	0.094	*0.005*	−0.040	−0.027	*0.001*	−143.8	0.004	0.229	99.64	59
09261700	9.560	0.503	*−0.032*	3.643	—	—	2001.04	*0.005*	0.138	—	—	—	—	−92.6	0.020	0.140	88.62	93
09306500	13.31	0.752	—	6.421	−0.010	—	2001.35	0.048	0.101	0.038	−0.103	—	—	−227.1	0.016	0.219	94.74	185
09315000	15.49	0.792	—	8.571	−0.008	—	2001.47	*−0.011*	0.217	0.085	−0.109	—	—	−263.2	0.015	0.147	95.88	202
Duchesne River Basin																		
09277500	11.57	0.772	—	5.189	—	—	2001.24	−0.083	0.096	*0.025*	*−0.024*	−0.029	−0.029	−166.7	0.008	0.221	97.64	91
09279000	9.719	0.551	0.101	5.068	—	—	2000.76	*0.034*	*0.068*	−0.744	*−0.048*	−0.076	*0.017*	−36.0	0.030	0.054	88.58	70
09288180	12.00	0.848	0.120	5.338	−0.004	—	2000.81	*0.034*	*0.015*	—	—	—	—	−104.7	0.015	0.171	96.29	81
09289500	8.575	0.914	*−0.011*	4.985	*0.001*	—	2000.80	—	—	—	—	—	—	−129.5	0.006	0.174	99.60	58
09291000	7.236	0.952	*−0.008*	3.246	—	—	2001.39	—	—	—	—	—	—	−70.8	0.014	0.153	99.71	54
09292500	9.481	0.461	0.067	5.209	—	—	2001.07	—	—	—	—	—	—	−116.0	0.014	0.119	92.8	85
09295000	12.22	0.657	—	4.993	−0.009	—	2000.98	—	—	—	—	—	—	0.3	0.055	−0.061	92.48	76
09296800	8.896	0.876	—	4.973	—	—	2002.02	0.132	0.128	—	—	—	—	−92.0	0.017	0.021	98.02	80
09299500	8.520	0.687	*0.034*	4.652	0.006	—	2001.07	0.073	*0.017*	*−0.015*	0.063	—	—	−46.0	0.030	0.112	95.12	84
[1] 09299500	8.421	0.750	—	4.652	0.006	0.002	2001.07	0.096	0.106	*0.007*	*0.053*	—	—	−51.6	0.028	0.062	95.43	84
09302000	12.92	0.626	−0.015	5.434	−0.014	—	2002.53	0.036	0.067	−0.074	−0.055	—	—	−239.4	0.032	0.296	95.16	410

[1] Model with quadratic time term was not selected as final model for site.

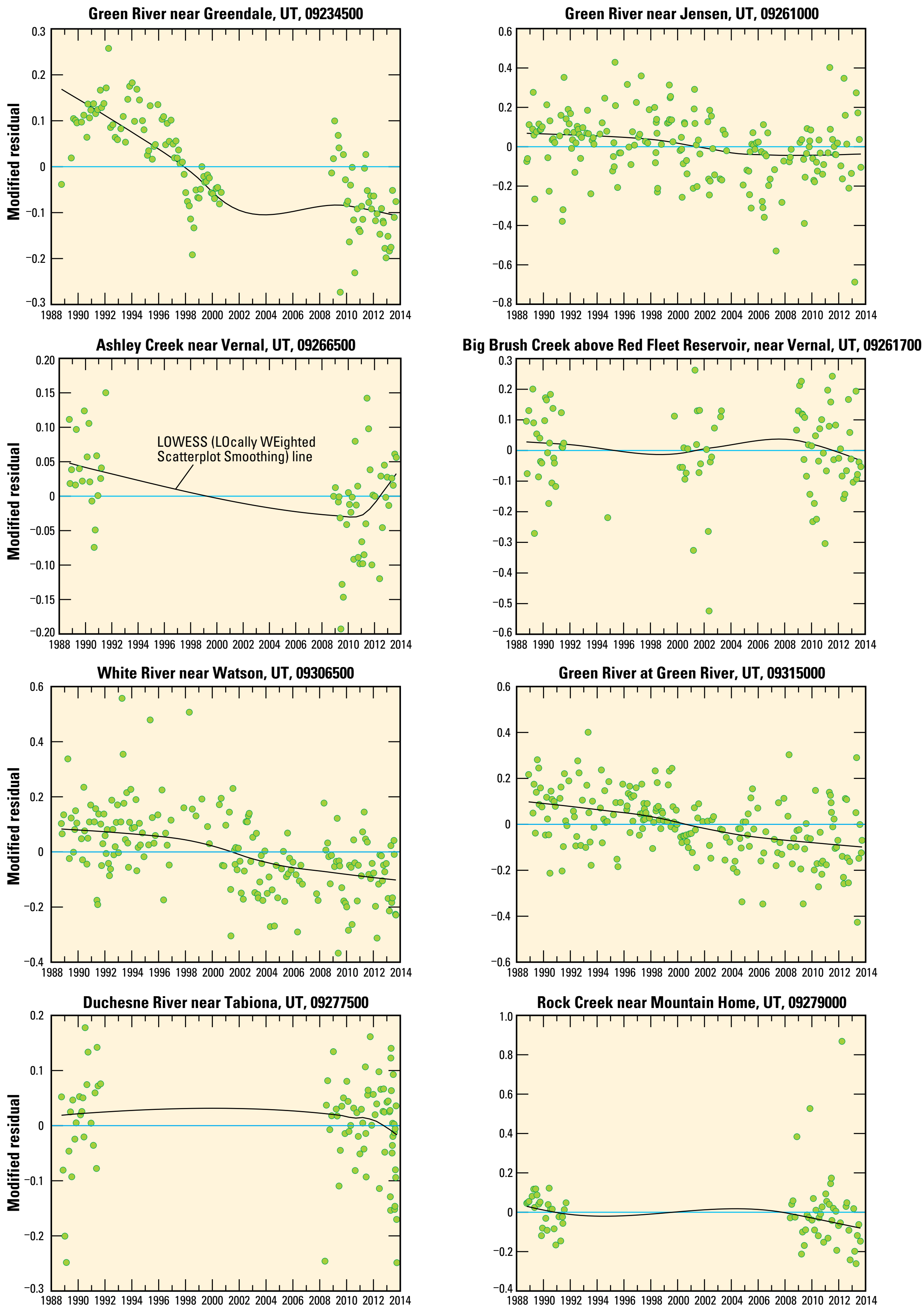

Figure A–1. Modified residuals (no time variable included in the regression model) for water years 1989 to 2013 for gaging stations modeled to determine dissolved-solids loads in the Uinta Basin study area.

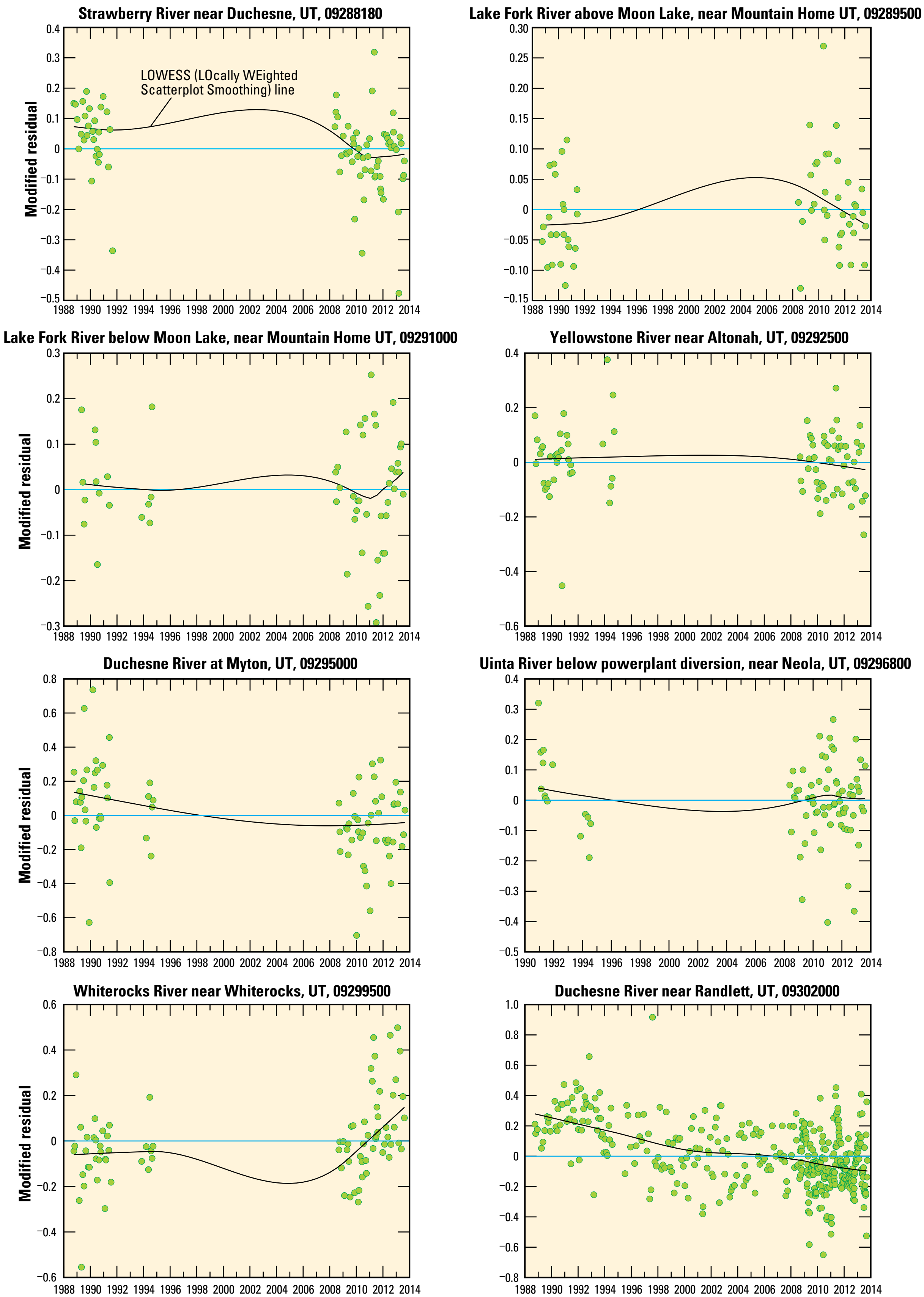

Figure A–1. Modified residuals (no time variable included in the regression model) for water years 1989 to 2013 for gaging stations modeled to determine dissolved-solids loads in the Uinta Basin study area.—Continued

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