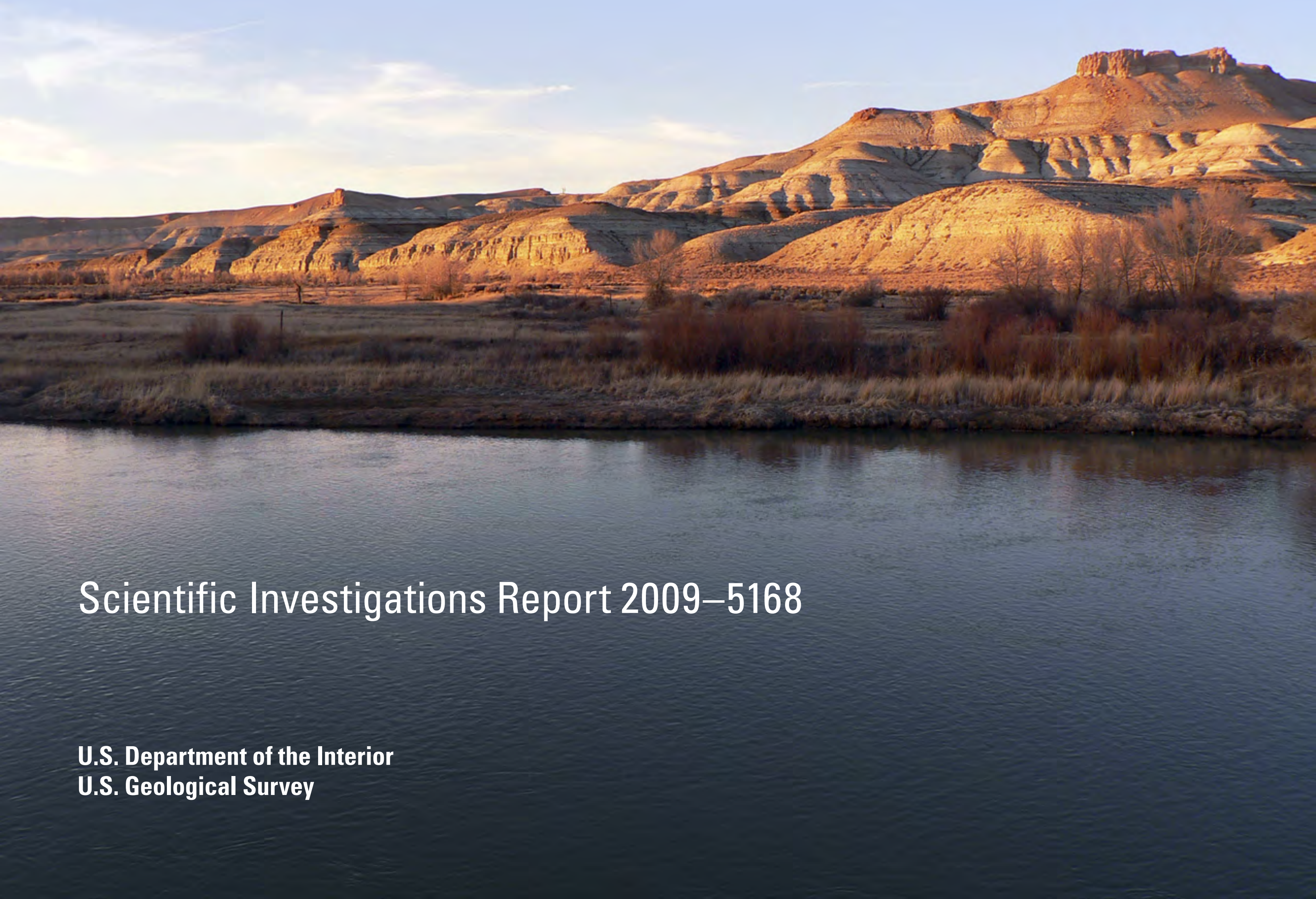
Prepared in cooperation with the Bureau of Land Management and the Wyoming Department of Environmental Quality

Specific Conductance and Dissolved-Solids Characteristics for the Green River and Muddy Creek, Wyoming, Water Years 1999–2008



Scientific Investigations Report 2009–5168

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

Cover. The banks of the Green River, Wyoming. Photograph by Kirk A. Miller, U.S. Geological Survey, taken March 22, 2007.

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KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Contents

Figures

Tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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 chemical constituents in water are given in milligrams per liter (mg/L).

Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. For example, the water year ending September 30, 2008, is called water year 2008.

Abbreviations and Symbols

<	less than
mg/L	milligrams per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
BLM	Bureau of Land Management
CRBSCF	Colorado River Basin Salinity Control Forum
JIDPA	Jonah Infill Drilling Project Area
MSE	mean square error
NWIS	National Water Information System
PAPA	Pinedale Anticline Project Area
IQR	interquartile range
p-value	significance level
R^2	coefficient of determination
USGS	U.S. Geological Survey
WDEQ	Wyoming Department of Environmental Quality
WLCI	Wyoming Landscape Conservation Initiative

Specific Conductance and Dissolved-Solids Characteristics for the Green River and Muddy Creek, Wyoming, Water Years 1999–2008

By Melanie L. Clark and Seth L. Davidson

Abstract

Southwestern Wyoming is an area of diverse scenery, wildlife, and natural resources that is actively undergoing energy development. The U.S. Department of the Interior's Wyoming Landscape Conservation Initiative is a long-term science-based effort to assess and enhance aquatic and terrestrial habitats at a landscape scale, while facilitating responsible energy development through local collaboration and partnerships. Water-quality monitoring has been conducted by the U.S. Geological Survey on the Green River near Green River, Wyoming, and Muddy Creek near Baggs, Wyoming. This monitoring, which is being conducted in cooperation with State and other Federal agencies and as part of the Wyoming Landscape Conservation Initiative, is in response to concerns about potentially increased dissolved solids in the Colorado River Basin as a result of energy development. Because of the need to provide real-time dissolved-solids concentrations for the Green River and Muddy Creek on the World Wide Web, the U.S. Geological Survey developed regression equations to estimate dissolved-solids concentrations on the basis of continuous specific conductance using relations between measured specific conductance and dissolved-solids concentrations.

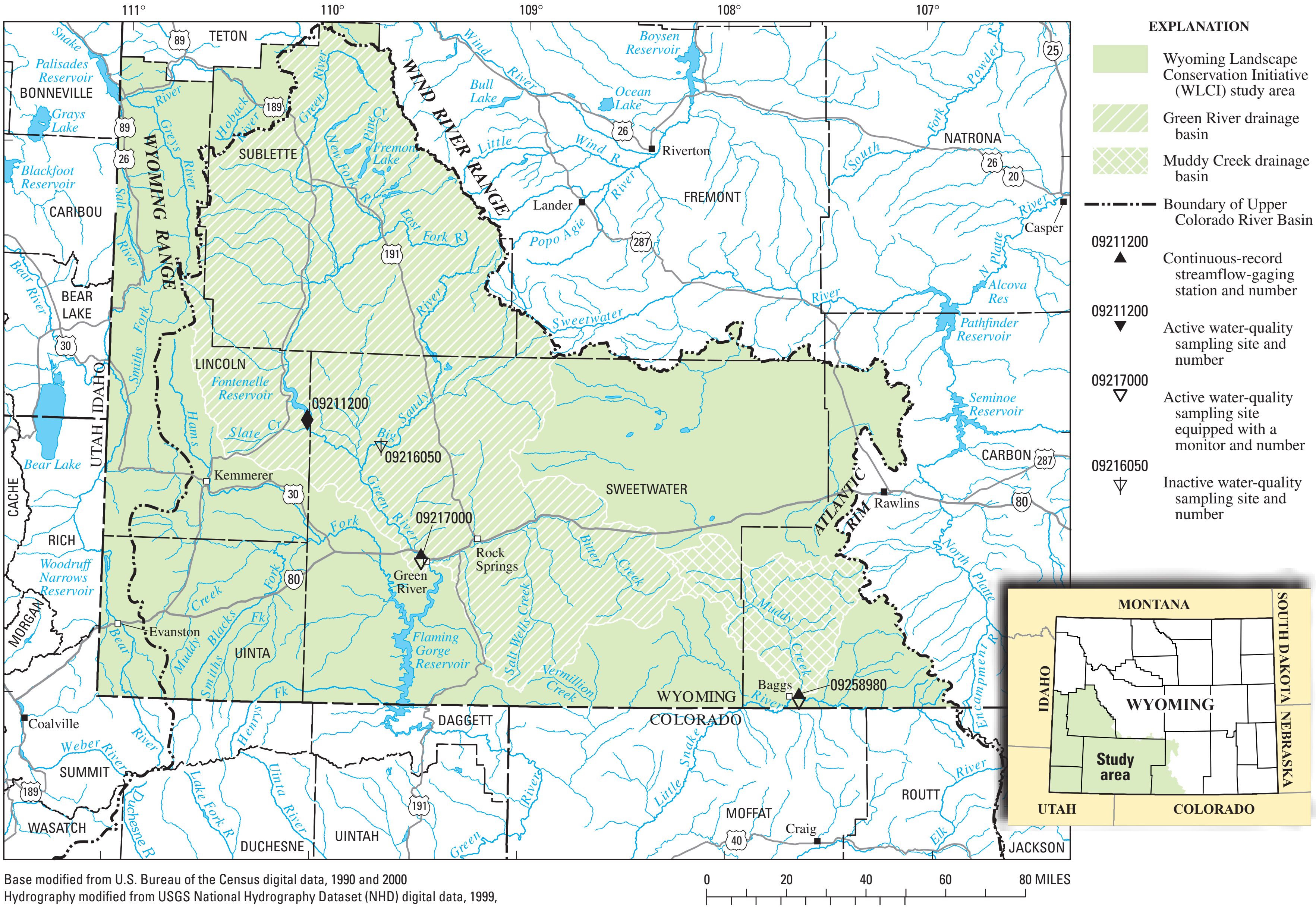
Specific conductance and dissolved-solids concentrations were less varied and generally lower for the Green River than for Muddy Creek. The median dissolved-solids concentration for the site on the Green River was 318 milligrams per liter, and the median concentration for the site on Muddy Creek was 943 milligrams per liter. Dissolved-solids concentrations ranged from 187 to 594 milligrams per liter in samples collected from the Green River during water years 1999–2008. Dissolved-solids concentrations ranged from 293 to 2,485 milligrams per liter in samples collected from Muddy Creek during water years 2006–08. The differences in dissolved-solids concentrations in samples collected from the Green River compared to samples collected from Muddy Creek reflect the different basin characteristics.

Relations between specific conductance and dissolved-solids concentrations were statistically significant for the Green River (p-value less than 0.001) and Muddy Creek (p-value less than 0.001); therefore, specific conductance can be used to estimate dissolved-solids concentrations. Using continuous specific conductance values to estimate dissolved solids in real-time on the World Wide Web increases the amount and improves the timeliness of data available to water managers for assessing dissolved-solids concentrations in the Colorado River Basin.

Introduction

Southwestern Wyoming is an area of diverse scenery, wildlife, and natural resources. It provides crucial habitat for deer, elk, pronghorn antelope, greater sage-grouse, and other nongame species. It also is actively undergoing energy development. The U.S. Geological Survey (USGS) recently completed a geology-based assessment of energy resources for southwestern Wyoming that reported a mean of 84.6 trillion cubic feet of undiscovered natural gas, a mean of 131 million barrels of undiscovered oil, and a mean of 2.6 billion barrels of undiscovered natural gas liquids in nine total petroleum systems defined for the Southwestern Wyoming Province (U.S. Geological Survey, 2002). To ensure Wyoming's wildlife and habitat remain viable in areas with energy development, the U.S. Department of the Interior implemented the Wyoming Landscape Conservation Initiative (WLCI) in cooperation with local, State, and Federal agencies. The WLCI is a long-term science-based effort to assess and enhance aquatic and terrestrial habitats at a landscape scale, while facilitating responsible energy development through local collaboration and partnerships (D'Erchia, 2008). The WLCI study area includes 15 million acres in southwestern Wyoming (fig. 1).

Assessments of water quality are important components of the WLCI objectives because energy development has the potential to affect water resources and aquatic environments. Dissolved-solids concentrations have been identified as a water-quality concern for streams in the WLCI study area. Dissolved solids primarily are composed of major cations (dissolved calcium, magnesium, potassium, and sodium), major anions (dissolved carbonate species, chloride, fluoride, and sulfate), and nonionic silica (Hem, 1985, p. 157). Specific



Base modified from U.S. Bureau of the Census digital data, 1990 and 2000
Hydrography modified from USGS National Hydrography Dataset (NHD) digital data, 1999, and U.S. Geological Survey digital data, Enhanced River Reach File, 1999
Albers Equal-area Conic projection, Standard parallels 29°30′N and 45°30′N, central meridian 107°30′W

Figure 1. Locations of selected streamflow-gaging stations and water-quality sampling sites in the Green River and Muddy Creek drainage basins, Wyoming.

conductance, which can be measured in the field, is a measure of water's ability to conduct an electrical current at 25 degrees Celsius (°C) and is a useful indicator of dissolved solids. Natural processes, such as contributions from saline springs and groundwater discharge, erosion and dissolution of sediments, and concentration effects from evaporation and transpiration, can contribute dissolved solids to streams. Activities, such as irrigation, livestock grazing, energy development, road building, urbanization, and wildlife management, also can contribute to the movement of dissolved solids to streams (Colorado River Basin Salinity Control Forum, 2008).

Most of the surface-water drainage from the WLCI study area is to the Colorado River Basin, where dissolved-solids concentrations are administered under the Salinity Control Act (Public Law 93–320). The Colorado River Basin Salinity Control Forum (CRBSCF), which is a cooperative effort among State and Federal agencies to manage dissolved solids in the Colorado River Basin, has identified rapidly expanding energy development in the Upper Colorado River Basin as a high priority issue because energy development has potential to increase dissolved-solids concentrations (Bureau of Land Management, 2008a). The Green River drainage basin and the Muddy Creek drainage basin (fig. 1), which are both part of the Colorado River Basin, are two areas experiencing energy development in the WLCI study area. An increase in dissolved-solids concentrations can adversely affect the ability to meet water-quality standards established for the Colorado River Basin and potentially affect water uses in the basin (Colorado River Basin Salinity Control Forum, 2008).

The Bureau of Land Management (BLM) administers millions of acres of public land and Federal surface and mineral estates in the WLCI study area. Energy development in the WLCI study area largely is on BLM-administered lands, including lands in the Green River drainage basin and the Muddy Creek drainage basin. The BLM coordinates salinity control efforts for the lands that it manages with the CRBSCF, with the goal of reducing the contribution of dissolved solids from lands that it administers. As part of its overall land management efforts, the BLM has developed management plans for much of the land in the WLCI study area. The Pinedale Field Office of the BLM has developed the Pinedale Resource Management Plan (Bureau of Land Management, 2008a) and the Rawlins Field Office of the BLM has developed the Rawlins Resource Management Plan (Bureau of Land Management, 2008b) to establish guidance, objectives, policies, and management actions for addressing a variety of issues on a broad scale, including energy development and water quality.

The CRBSCF has encouraged the implementation of water-quality monitoring to help assess the effectiveness of management practices. Water-quality monitoring has been conducted for decades on the Green River near Green River, Wyoming (site 09217000), by the USGS in cooperation with the Bureau of Reclamation (table 1). Historically, the monitoring was related to irrigation projects in the Green River drainage basin; however, additional current (2009) monitoring efforts have been implemented as part of the WLCI to monitor potential effects from energy development projects. Water-quality monitoring was implemented on Muddy Creek below Young Draw near Baggs, Wyoming (site 09258980), hereafter referred to as Muddy Creek near Baggs, Wyoming, during 2005 and 2006 by the USGS, in cooperation with the BLM and the Wyoming Department of Environmental Quality (WDEQ), in response to concerns about energy development in that basin (table 1). Water-quality monitoring for the Green River and Muddy Creek includes measurements of streamflow, measurements of specific conductance, and the collection of samples for laboratory analysis of dissolved-solids concentrations. Data from these measurements and analyses are electronically stored in the USGS National Water Information System (NWIS) and are available to the public from NWISWeb (U.S. Geological Survey, 2009a) at *http://waterdata.usgs.gov/nwis/.* Because of the need to provide real-time dissolved-solids concentrations for the Green River and Muddy Creek on the World Wide Web, the USGS developed regression equations to estimate dissolved-solids concentrations on the basis of continuous specific conductance using relations between measured specific conductance and dissolved-solids concentrations.

Table 1. Summary of site information for streamflow-gaging stations and water-quality sampling sites on the Green River and Muddy Creek, Wyoming, used in this report.

U.S. Geological Survey site number (fig. 1)	Site name	Drainage area (square miles)	Continuous streamflow data (water years)	Continuous specific conductance data (water years)	Discrete water-quality data (water years)
09217000	Green River near Green River, Wyoming	14,000	1999–2008	2007–08	1999–2008
09258980	Muddy Creek below Young Draw near Baggs, Wyoming	1,200	2005–08	2005–08	2006–08

Purpose and Scope

The purpose of this report is to describe specific conductance and dissolved-solids characteristics for two streams in the WLCI study area in Wyoming. Specifically, this report presents characteristics for the Green River near Green River, Wyoming, and for Muddy Creek near Baggs, Wyoming, including (1) a summary of streamflow data, (2) a summary of specific conductance data, (3) a summary of dissolved-solids concentrations, and (4) regression relations between specific conductance and dissolved solids. The scope includes data for water years 1999–2008 for the Green River and for water years 2005–08 for Muddy Creek.

Description of Drainage Basins

The Green River and Muddy Creek drainage basins are located in southwestern Wyoming (fig. 1). The drainage basins of the Green River and Muddy Creek (table 1) have different characteristics, as described in this section of the report.

Green River Drainage Basin

The Green River is one of the major river basins in Wyoming and drains the central part of the WLCI study area. The Green River near Green River, Wyoming (site 09217000, fig. 1), has a drainage area of about 14,000 square miles (about 9,740 square miles of contributing drainage area) and drains a diverse landscape. Altitudes in the drainage basin range from about 6,060 feet above the National Geodetic Vertical Datum of 1929 (NGVD 29) at the sampling site to more than 13,800 feet above NGVD 29 in the Wind River Range. The Green River in Wyoming is classified by the WDEQ as class 1 waters upstream from the New Fork River and as class 2AB waters downstream to Flaming Gorge Reservoir (Wyoming Department of Environmental Quality, 2001). Designated uses of the Green River include drinking water, game fish, non-game fish, fish consumption, other aquatic life, recreation, wildlife, agriculture, industry, and scenic value. The New Fork River, which is a major tributary in the eastern part of the upper basin, drains much of the Wind River Range. The western part of the upper basin drains the Wyoming Range. The Big Sandy River and Bitter Creek drain most of the basin between Fontenelle Reservoir and Green River, Wyoming.

The high-altitude areas of the Green River drainage basin are part of the Middle Rockies ecoregion. These areas have open forests and foothills that are partly wooded or shrub- and grass-covered (Omernick, 1987). The low-altitude areas of the Green River drainage basin are part of the Wyoming Basin ecoregion, which is largely a broad intermontane basin that is covered by arid grasslands and shrublands, supporting bunchgrasses and sagebrush (Omernick, 1987). Annual precipitation in the Green River drainage basin ranges from less than 8 inches at low altitudes to more than 40 inches in the mountainous areas (Daly and others, 1994). Annual precipitation at the climate station at Green River, Wyoming, is 8.11 inches for the period of record from 1915–2005 (Western Regional Climate Center, 2009). Average monthly maximum temperatures at Green River range from 30.8°C during July to 0.0°C during January (Western Regional Climate Center, 2009).

The geology of the Green River drainage basin is diverse. The oldest rocks in the basin are Precambrian-era igneous and metamorphic rocks that form the core of the Wind River Range (Love and Christiansen, 1985). Rock types include granite, granodiorite, granite gneiss, and schist. Paleozoic- and Mesozoic-era sedimentary rocks, including limestone, dolomite, and sandstone, occur in the mountainous areas in the northern and western parts of the upper basin. Tertiary-age sedimentary rocks of the Wasatch Formation and the Green River Formation, including shale, mudstone, marlstone, siltstone, sandstone, and limestone, underlie much of the intermontane basin upstream from Fontenelle Reservoir. Downstream from Fontenelle Reservoir, another unit of the Green River Formation, the Laney Member, which is an oil shale and marlstone, underlies most of the eastern part of the basin, and the Bridger Formation, which is a sandstone and claystone, underlies much of the western part of the basin. Quaternary-age alluvium and colluvium occur in and adjacent to stream channels.

Energy development in the upper Green River drainage basin primarily is associated with two large projects, the Pinedale Anticline Oil and Gas Exploration and Development Project (Bureau of Land Management, 2000a, 2008c) and the Jonah Infill Drilling Project (Bureau of Land Management, 2006a). The Pinedale Anticline Project Area (PAPA) encompasses more than 197,000 acres in Sublette County, Wyoming, in the eastern part of the Green River drainage basin upstream from Fontenelle Reservoir (Bureau of Land Management, 2000a). Drainage from the PAPA primarily is to the New Fork River and to the Green River. The approved project components included 700 producing wells or well pads and about 276 miles of access roads (Bureau of Land Management, 2000b). As of November 2006, the PAPA included more than 642 producing wells on 340 well pads, and the project was revised to include as many as 4,399 additional wells on no more than 600 total well pads, construction of new roads, and a pipeline corridor (Bureau of Land Management, 2008c, 2008d). Produced waters from the PAPA generally are used for industrial purposes, are treated and used for drilling and dust control, or are reinjected. Increased dissolved-solids concentrations in streams as a result of soil disturbance and increased dissolved-solids concentrations in shallow aquifers that are in connection with streams were identified as potential water-quality concerns (Bureau of Land Management, 2008c).

The Jonah Infill Drilling Project Area (JIDPA) encompasses about 30,500 acres in Sublette County, Wyoming (Bureau of Land Management, 2006a). The JIDPA is drained by intermittent and ephemeral streams that are tributaries of the New Fork River and the Green River upstream from Fontenelle Reservoir and of the Big Sandy River downstream from Fontenelle Reservoir. The project components for the

JIDPA includes drilling as many as 3,100 additional oil and gas wells within the existing JIDPA area and limits surface disturbance to a maximum of 14,030 acres (Bureau of Land Management, 2006b). Salt-loading to streams was identified as a concern because of potential disturbance of saline soils in the project area; however, salinity models predicted that this disturbance would not increase dissolved solids to the Colorado River from the Green River or Big Sandy River (Bureau of Land Management, 2006a).

Muddy Creek Drainage Basin

The Muddy Creek drainage basin is a much smaller basin and generally is physiographically and geologically less diverse than the Green River drainage basin. Muddy Creek is a tributary of the Little Snake River and drains about 1,200 square miles at site 09258980 near Baggs, Wyoming, in the southeastern part of the WLCI study area (fig. 1). Altitudes in the drainage basin range from about 6,270 feet above NGVD 29 at the sampling site to more than 8,300 feet above NGVD 29 in the upland area. The northern border of the drainage basin is part of the boundary of the Great Divide Basin and includes an upland area called the Atlantic Rim. The Sierra Madre and Continental Divide form the northeast boundary of the drainage basin. The western part of the Muddy Creek drainage basin is part of the Washakie structural basin (Bartos and others, 2006). Muddy Creek is classified by the WDEQ as class 2AB waters (Wyoming Department of Environmental Quality, 2001). Designated uses include drinking water, game fish, non-game fish, fish consumption, other aquatic life, recreation, wildlife, agriculture, industry, and scenic value. The WDEQ has listed the use support of Muddy Creek as “threatened” since 1996 because of habitat degradation associated with grazing (Wyoming Department of Environmental Quality, 2008). The Little Snake Resource Conservation District, the BLM, land owners, and other stakeholders have been involved in a Coordinated Resource Management process in the basin to improve water quality and riparian habitat problems (Ellison and others, 2008; Wyoming Department of Environmental Quality, 2008). Colorado River cutthroat trout have been reintroduced in the upper part of the Muddy Creek drainage basin as part of the process (Wyoming Department of Environmental Quality, 2008).

The entire Muddy Creek drainage basin is part of the Wyoming Basin ecoregion and is mostly covered by arid grasslands and shrublands (Omernick, 1987). Annual precipitation in the Muddy Creek drainage basin ranges from about 8 to 10 inches at low altitudes to more than 20 inches in upland areas (Daly and others, 1994). Muddy Creek is perennial in the upper part of the drainage basin near the upland areas and flows intermittently downstream where groundwater discharge sometimes is not sufficient to sustain streamflow. Annual precipitation at the climate station at Baggs, Wyoming, is 10.72 inches for the period of record from 1979–2005 (Western Regional Climate Center, 2009). Average monthly maximum temperatures at Baggs range from 30.2°C during July to 0.6°C during January (Western Regional Climate Center, 2009).

The bedrock geology of the Muddy Creek drainage basin is dominated by Cretaceous-age and Tertiary-age sedimentary rocks (Love and Christiansen, 1985). The bedrock geology of the eastern part of the Muddy Creek drainage basin is predominantly Cretaceous-age sedimentary rocks including the Steele Shale, Mesaverde Formation, and Lewis Shale of marine origin, and the Lance Formation of fluvial origin (Bartos and others, 2006). The bedrock geology immediately adjacent to Muddy Creek includes Tertiary-age sedimentary rocks of the Fort Union and Wasatch Formations. The Fort Union Formation includes sandstone, shale, and thin coal beds (Love and Christiansen, 1985). The Wasatch Formation is composed primarily of mudstone and sandstone. The Green River Formation, which is composed primarily of shale, mudstones, and sandstone, occurs in the western part of the drainage basin. Quaternary-age alluvium and colluvium occur in and adjacent to stream channels.

Energy development projects in the Muddy Creek drainage basin include the Continental Divide-Creston Natural Gas Development Project, which is mostly in the western part of the drainage basin (Bureau of Land Management, 2006c), and the Atlantic Rim Natural Gas Field Development Project, which is mostly in the eastern part of the drainage basin (Bureau of Land Management, 2006d). The Continental Divide-Creston Natural Gas Development Project encompasses about 1,100,000 acres and involves drilling and developing as many as 8,950 wells and constructing associated facilities, such as roads and compressor stations. Short-term surface disturbance areas associated with well pads, road building, pipelines, and other facilities are estimated to be about 47,060 acres for the entire project area (Bureau of Land Management, 2006c). Reinjection of water produced during gas development is proposed, and surface discharges are not planned. The Atlantic Rim Project Area encompasses about 270,080 acres, of which about 69 percent is in the Muddy Creek drainage basin (Bureau of Land Management, 2006d). The project components include drilling about 2,000 gas wells and limiting surface disturbance to a maximum of 7,600 acres at any given time (Bureau of Land Management, 2007). Gas development in the Muddy Creek drainage basin includes drilling conventional natural gas wells and coalbed natural gas wells. Dissolved-solids loading from surface discharges of produced waters is not anticipated because most of the water is reinjected, with the exception of small amounts of surface discharges that are allowed under existing permits.

Methods

Methods are described for collection of continuous and discrete streamflow and specific conductance data and for collection of discrete water-quality samples for dissolved solids determination. The data-analysis methods for statistically summarizing data and determining relations between specific conductance and dissolved solids also are described.

Data Collection

Data collection at the sampling sites on the Green River (site 09217000) and Muddy Creek (site 09258980) included continuous and discrete measurements of streamflow, continuous and discrete measurements of specific conductance, and discrete collection of water-quality samples. Methods for the collection and analysis of streamflow data are described in Rantz and others (1982). Continuous streamflow data used in this report were collected during water years 1999–2008 on the Green River (site 09217000) and during water years 2005–08 on Muddy Creek (site 09258980). Although some streamflow data were collected during water year 2004 at site 09258980, these data are not included in this report because a complete water year record was not available. Instantaneous streamflow generally was measured when water-quality samples were collected. Instantaneous streamflow is reported as cubic feet per second (ft^3/s) and total annual streamflow, or annual runoff, is reported in acre-feet (acre-ft).

Instruments for continuous measurement of specific conductance were installed during water year 2007 on the Green River (site 09217000) and during water year 2005 on Muddy Creek (site 09258980). Operation of the instruments is described in Wagner and others (2006). Continuous specific conductance was measured only during ice-free periods, which generally were from about March or April to October or November, and the data are summarized in this report as daily mean values. Discrete measurements of specific conductance were made throughout the water year when water-quality samples were collected and followed methods described in the National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, 1997–2009). Discrete measurements either were made instream by using a multiprobe meter or were made by using a probe in an aliquot of water that was composited in a churn for water-quality samples. Daily mean and discrete values of specific conductance are reported in microsiemens per centimeter at 25°C (µS/cm).

Water-quality samples were collected and processed by using methods described in the National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, 1997–2009). An equal-width-increment sampling technique with depth-integrating samplers was used when flow conditions were adequate. A hand-dip method at the centroid of flow was used for collecting samples on Muddy Creek when stream conditions were too shallow for a sampler. Samples for dissolved-solids analyses were filtered onsite by using a 0.45-micron pore-size filter and were shipped to the USGS National Water Quality Laboratory in Denver, Colorado, for analysis. Dissolved-solids concentrations can be determined by a sum-of-constituents method, in which a value is calculated by summing the concentrations of individual dissolved constituents, including major cations, major anions, nonionic silica, and selected trace elements. Dissolved-solids concentrations can be directly measured by a residue-on-evaporation method at 180°C (Fishman and Friedman, 1989). Because most of the dissolved solids in stream waters are the major ions and nonionic silica, the two methods generally produce comparable results; however, the residue-on-evaporation method may produce slightly higher concentrations than the sum-of-constituents method because all the dissolved solids present in the water are part of the residue-on-evaporation analysis. The residue-on-evaporation method was used for samples collected from the Green River (site 09217000) during water years 2001–08. The sum-of-constituents method was used for samples collected during 1999–2000 because residue-on-evaporation analyses were not available. The residue-on-evaporation method was used for all samples collected from Muddy Creek (site 09258980) during water years 2006–08. Dissolved-solids concentrations are reported in milligrams per liter (mg/L).

Data Analysis

Data for this report were summarized by using several statistical techniques. Descriptive summary statistics were computed for specific conductance and for dissolved-solids concentrations, and are displayed as boxplots. The lower and upper edges of the box indicate the 25th and 75th percentiles, respectively, and the median (50th percentile) is a line within the box. The whiskers extend from the first quartile to the minimum value and from the third quartile to the maximum value, unless the minimum or maximum value is more than 1.5 times the interquartile range (IQR) from that quartile. In that case, the whiskers extend to the lowest or highest value within 1.5 times the IQR. Values outside of this range are called outliers and are shown as individual points.

Linear regression is a statistical technique that can be used to determine the relation between two constituents. The use of this relation can be helpful in estimating data where one constituent is measured (continuous specific conductance, in this case) but the other (continuous dissolved solids) is not (Helsel and Hirsch, 1992). The simple linear regression equation can be expressed as

$$y_i = mx_i + b + e_i \qquad i = 1,2,....n, \qquad (1)$$

where

- y_i is the ith observation of the dependent variable;
- m is the slope;
- x_i is the ith observation of the independent, or explanatory, variable;
- b is the y-axis intercept;
- e_i is the random error for the ith observation; and
- n is the sample size.

The terms *m* and *b* are the parameters that need to be estimated from the data. The most common estimation technique is called ordinary least squares. S-PLUS statistical software (TIBCO Software Inc., 2008) was used to generate the regression equations in this report. Plots of the residuals from the regression equations were inspected for normality. The parameters displayed in this report for the regression equations include the mean square error (MSE), which is a measure of the variance between estimated and observed values; the coefficient of determination (R^2), which is the fraction of the variance explained by the regression; and the p-value, which is the probability that the slope is zero, indicating that there is no correlation between the two variables. The smaller the p-value is, the larger the probability that the two variables are related. For this report, a relation was determined to be statistically significant at the 95-percent confidence level. Therefore, if the calculated p-value was less than (<) 0.05, the relation is significant. Prediction intervals were determined to evaluate uncertainty of the estimated values by using the regression equation for the sites with continuous specific conductance monitors (Helsel and Hirsch, 1992). For this report, the 95-percent prediction intervals were determined for the regression equation for each site. For a given specific conductance value, the 95-percent prediction interval represents the range of dissolved-solids concentrations that is expected to occur 95 percent of the time for a given specific conductance value.

Specific Conductance and Dissolved-Solids Characteristics

Specific conductance and dissolved-solids characteristics are summarized in the following sections. Linear regression relations between specific conductance and dissolved solids also are presented. Streamflow conditions are summarized in the following section to provide context for the water-quality data.

Streamflow Conditions and Influence

Hydrologic conditions are important factors in water-quality variability and are described here to provide perspective on the potential annual and seasonal differences in water quality. Annual runoff for the Green River near Green River, Wyoming (site 09217000), ranged from about 417,100 acre-ft during water year 2002 to about 1,718,000 acre-ft during water year 1999 (fig. 2). Annual runoff for the Green River during the study period (water years 1999–2008) generally was less than the long-term period-of-record mean annual runoff; mean annual runoff was about 900,000 acre-ft for the study period and 1,160,000 acre-ft for the period of record (water years 1952–2008). Mean annual runoff of 1,133,000 acre-feet for USGS streamflow-gaging station 09211200 (fig. 1) on the Green River immediately downstream from Fontenelle Reservoir (for the period of record, water years 1964–2008; U.S. Geological Survey, 2009b) accounts for about 98 percent of the streamflow of Green River near Green River, Wyoming (site 09217000); however, the upper part of the drainage basin accounts for only about 31 percent of the total drainage area at site 09217000. The upper part of the drainage basin includes the high-altitude area in the mountain ranges, which have higher precipitation and lower evapotranspiration than the low-altitude parts of the drainage basin. Although the Big Sandy River and Bitter Creek drain much of the low-altitude parts of the basin, their combined annual runoff generally accounts for only about 2 percent of the annual runoff of the Green River near Green River, Wyoming (site 09217000). Irrigation is a consumptive use of part of the streamflow in the Big Sandy River drainage basin.

Muddy Creek is a much smaller drainage basin and has substantially less annual runoff compared to the Green River. Annual runoff for Muddy Creek (site 09258980) ranged from about 4,510 acre-ft during water year 2006 to about 18,830 acre-ft during water year 2008 (fig. 2). Comparisons to historical mean annual runoff cannot be made for Muddy Creek because the period of record is limited to water years 2005–08; however, precipitation was less than average for that same period at a climate station in Baggs, Wyoming (Western Regional Climate Center, 2009). Because Muddy Creek drains mostly low- to mid-altitude areas, which generally have low annual precipitation, the annual runoff per unit area for the Muddy Creek drainage basin (0.20 inch at site 09258980) is substantially less than that for the Green River drainage basin (1.55 inches at site 09217000).

Instantaneous streamflow can vary by orders of magnitude during a given year; thus, it is important to collect water-quality samples throughout the entire range of streamflows during a water year to adequately characterize extremes, seasonal differences, and average conditions. Instantaneous streamflow measurements during sample collection were compared with daily mean streamflow for selected sampling sites to illustrate the range of hydrologic conditions sampled at each site during the study period (fig. 3).

Daily mean streamflow for the Green River (site 09217000), which is largely controlled by releases from Fontenelle Reservoir, ranged from 390 to 9,220 ft^3/s (U.S. Geological Survey, 2009a). Instantaneous streamflows measured during sampling events at this site varied widely from 279 ft^3/s to 3,880 ft^3/s. The highest streamflows measured for the Green River generally were in late spring or early summer as a result of runoff from melting snow in the mountainous parts of the upper basin.

Daily mean streamflow for Muddy Creek (site 09258980) ranged from 0.07 to 499 ft^3/s (fig. 3). Instantaneous streamflows measured during sampling events at this site varied widely from 0.09 to 124 ft^3/s. The highest streamflows measured for Muddy Creek generally were in late winter or early spring when streamflows are increased as a result of melting snow at low to middle altitudes. Streamflow for Muddy Creek also increases during summer in response to thunderstorms. The streamflow typically responds very quickly to precipitation events; thus, collection of samples associated with extreme high-flows is difficult.

Streamflows at both sites tend to decrease in late summer through winter when groundwater discharge provides most of the base flow. Precipitation in fall and winter generally occurs in the form of snow, and surface-runoff events during this period are infrequent as a result of low temperatures (Mason and Miller, 2005). Water-quality samples collected from the two sites generally were representative of a wide variety of water-quality conditions because, with the exception of extreme high flows, a wide variety of streamflows were sampled.

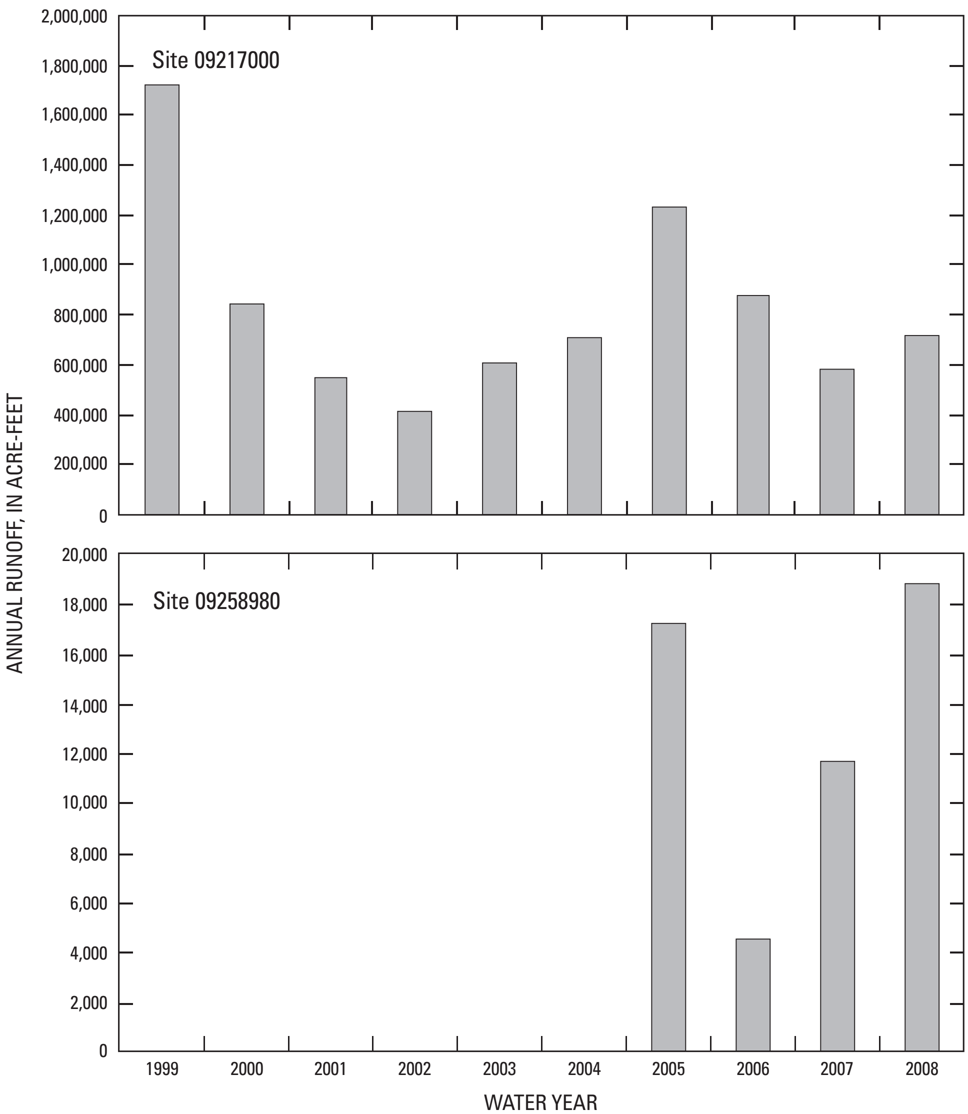


Figure 2. Annual runoff for the Green River (site 09217000) and Muddy Creek (site 09258980), Wyoming, water years 1999–2008.

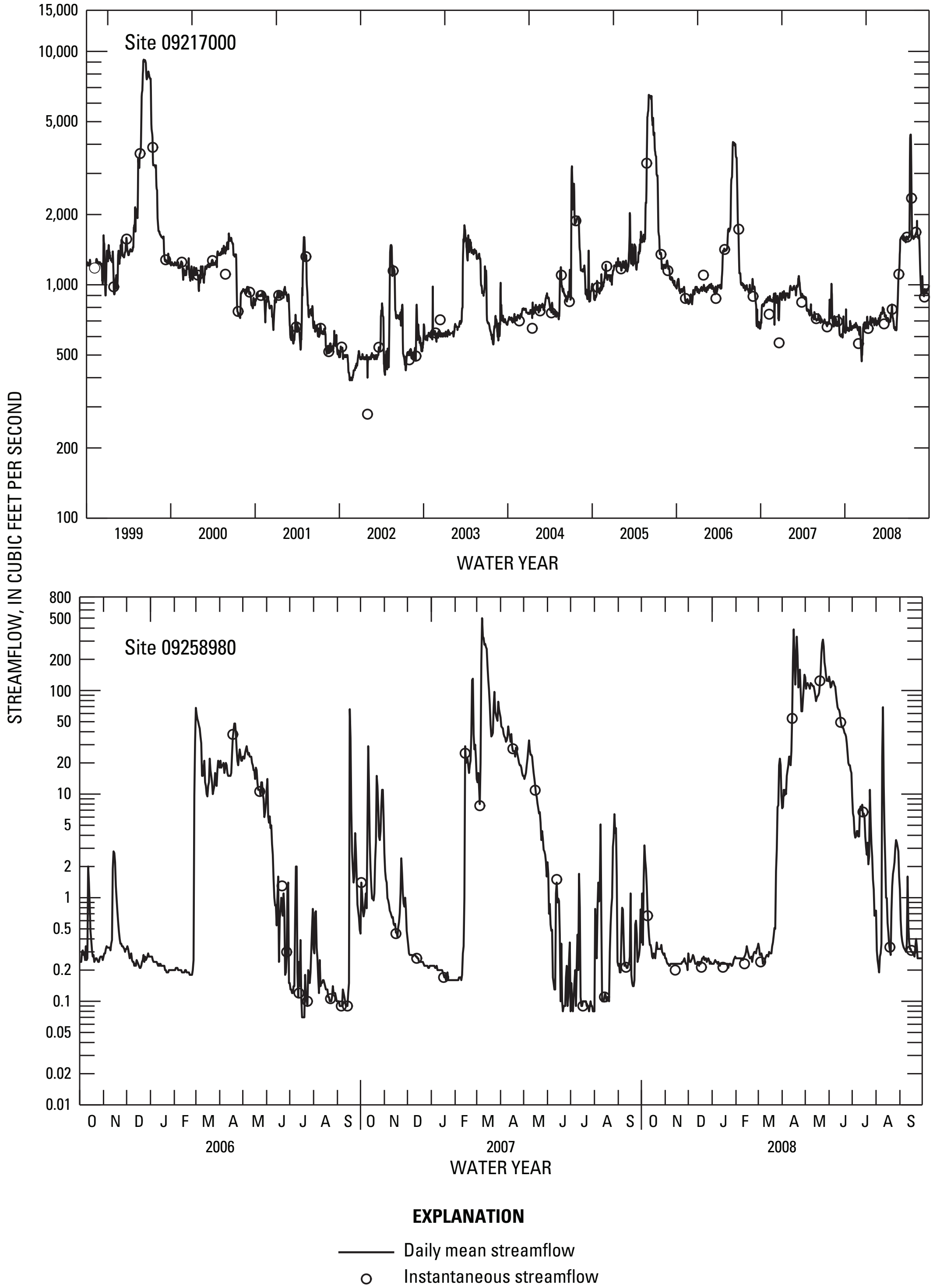


Figure 3. Daily mean streamflow and instantaneous streamflow during water-quality sampling at the Green River (site 09217000) and Muddy Creek (site 09258980), Wyoming, water years 1999–2008.

Specific Conductance Characteristics

Specific conductance was measured by using continuous monitors during ice-free periods and by discrete measurements during water-quality sample collection throughout the water year (fig. 4). Daily mean specific conductance is summarized for water years 2007–08 for the Green River near Green River, Wyoming (site 09217000), and for water years 2005–08 for Muddy Creek near Baggs, Wyoming (site 09258980). Discrete specific conductance values were measured during water years 1999–2008 at site 09217000 and during water years 2006–08 at site 09258980.

Specific conductance values (figs. 4 and 5) generally were less varied and lower for the Green River than for Muddy Creek. Daily mean specific conductance values for the Green River ranged from 316 to 779 µS/cm during water years 2007–08 (fig. 4). Discrete values during this period ranged from 332 to 587 µS/cm. Discrete values for the entire study period (water years 1999–2008) for the Green River ranged from 330 to 862 µS/cm, with a median value of 492 µS/cm (fig. 5). Daily mean specific conductance values for Muddy Creek ranged from 370 to 4,340 µS/cm during water years 2005–08 (fig. 4). Discrete values during water years 2006–08 for Muddy Creek ranged from 448 to 3,640 µS/cm, with a median value of 1,445 µS/cm (fig. 5). Because of the greater measurement frequency with the use of continuous monitors, a wider variety of water-quality conditions can be characterized in streams than is possible with discrete sampling, especially for small streams that respond quickly to changing hydrologic conditions.

A general seasonal pattern is evident in the specific conductance data for both sites, particularly for discrete values, though daily mean values were not available for winter months. Specific conductance values tended to be low during periods of high streamflow in late spring to early summer when surface runoff, which has only brief contact with basin materials, composes a large part of the streamflow. In contrast, specific conductance values tended to be high in late summer through winter because groundwater, which has been in contact with basin materials for a long time and is typically higher in specific conductance than surface runoff, composes a large part of the streamflow. A longer term pattern between water years of increasing or decreasing specific conductance values was not observed for the Green River or Muddy Creek.

Dissolved-Solids Characteristics

Samples were collected and analyzed for dissolved-solids concentrations during water years 1999–2008 for the Green River near Green River, Wyoming (site 09217000), and during water years 2006–08 for Muddy Creek near Baggs, Wyoming (site 09258980). As with specific conductance, dissolved-solids concentrations were less varied and generally lower for Green River than for Muddy Creek (fig. 6). Dissolved-solids concentrations ranged from 187 to 594 mg/L in samples collected from the Green River during water years 1999–2008. Dissolved-solids concentrations ranged from 293 to 2,485 mg/L in samples collected from Muddy Creek during water years 2006–08. The median dissolved-solids concentration for the Green River was 318 mg/L, and the median concentration for Muddy Creek was 943 mg/L.

The differences in dissolved-solids concentrations between samples collected from the Green River and samples collected from Muddy Creek reflect the different basin characteristics. As described in the section "Streamflow Conditions and Influence," most of the streamflow in the Green River originates from the upper part of the drainage basin upstream from Fontenelle Reservoir; thus, the water quality at site 09217000 also is influenced by the upper basin. For example, dissolved-solids concentrations in samples collected from Pine Creek, which is a mountain headwater stream in the northern part of the basin, ranged from 9.0 to 15 mg/L during water year 2008 (U.S. Geological Survey, 2009b). Dissolved-solids concentrations in the upper part of the Green River drainage basin near the PAPA energy development area typically are less than 100 mg/L (Bureau of Land Management, 2008d). The low dissolved-solids concentrations in streams in the upper basin are a result, in part, of the rocks that constitute the mountainous parts of the basin, particularly the Precambrian-era rocks of the Wind River Range. A recent Colorado River Basin study determined that Precambrian-era and Paleozoic-era rocks, which are resistant to physical weathering and chemical dissolution, contribute about 8 percent of the dissolved solids to streams in the Green River drainage basin in Wyoming (Anning and others, 2007). In addition to the geology, the high annual precipitation and steep gradient in the upper basin produce relatively fast stream velocities, which result in a short contact time between stream waters and basin materials.

Dissolved-solids concentrations generally increase downstream from Fontenelle Reservoir to Green River, Wyoming. Anning and others (2007) reported that the median concentration increased from 237 mg/L at a site downstream from Fontenelle Reservoir (site 09211200) to 359 mg/L near Green River, Wyoming (site 09217000). The Big Sandy River substantially contributes to the dissolved-solids concentration in the reach downstream from Fontenelle Reservoir and upstream from Green River, Wyoming (DeLong, 1977). Dissolved-solids concentrations for the Big Sandy River (site 09216050) upstream from its mouth at the Green River ranged from 187 to 7,840 mg/L during water years 1975–99 (Anning and others, 2007). Much of the Big Sandy drainage basin is underlain by the Laney Member of the Green River Formation (Love and Christiansen, 1985). Groundwater associated with the Laney Member generally is of marginal to poor quality because of high sulfate concentrations and high dissolved-solids concentrations (Mason and Miller, 2005; Anning and others, 2007), and could affect the quality of the Big Sandy River, particularly during low-flow conditions. Soils associated with the Tertiary-age rocks that have naturally high salt content and with irrigated agriculture also have been

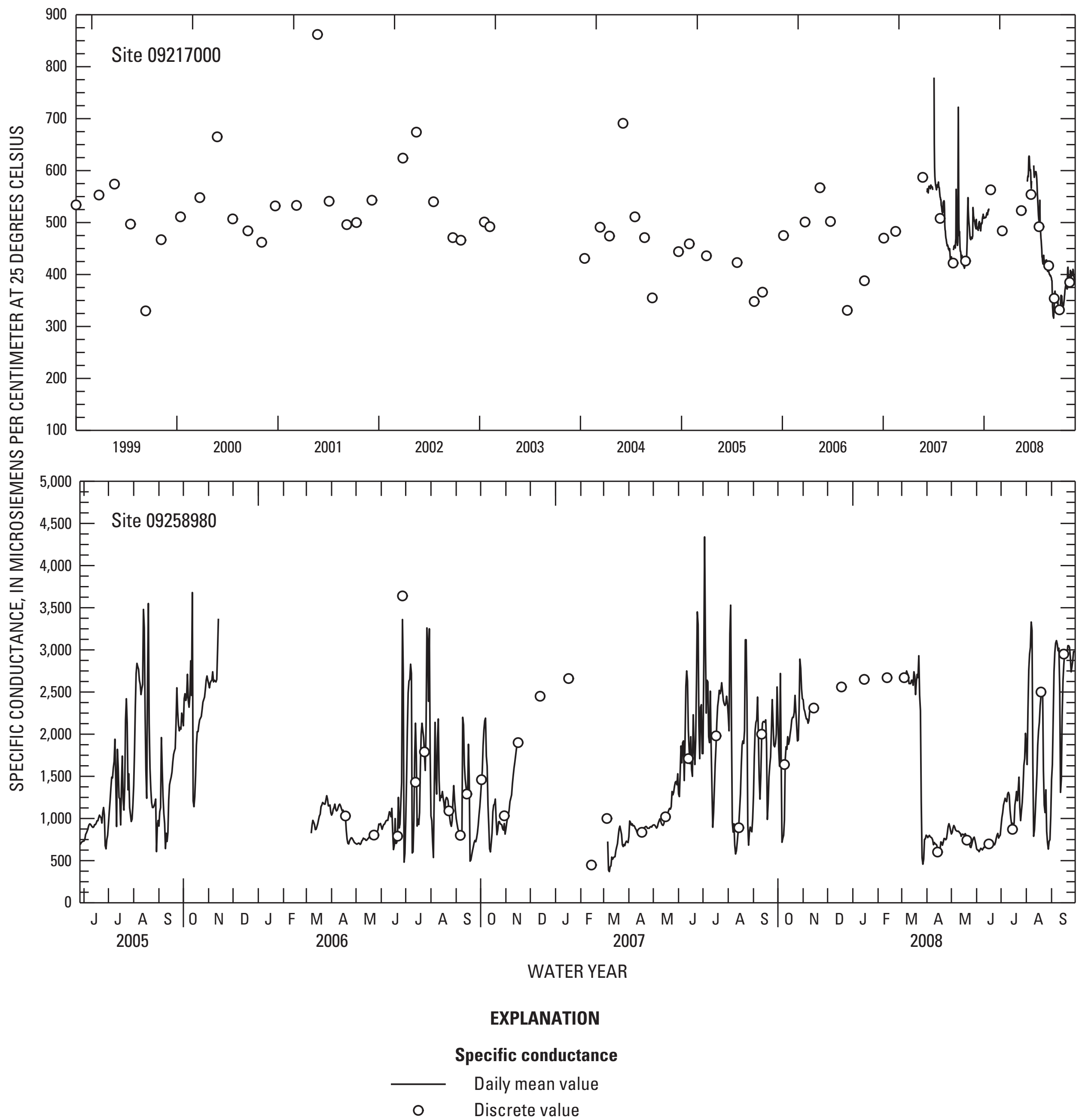


Figure 4. Daily mean and discrete values of specific conductance during water-quality sampling at the Green River (site 09217000) and Muddy Creek (site 09258980), Wyoming, water years 1999–2008.

identified as sources of dissolved solids in the lower parts of the Green River drainage basin (Bureau of Land Management, 2000a). Anning and others (2007) determined that Tertiary-age rocks contribute about 56 percent of the dissolved solids in the Green River drainage basin in Wyoming. Salinity control measures have been implemented to reduce dissolved-solids concentrations in the Big Sandy drainage basin (Wyoming Department of Environmental Quality, 2008). Anning and others (2007) reported that dissolved-solids concentrations and adjusted annual dissolved-solids concentrations have decreased by 15 percent for the Big Sandy River (site 09216050) and by 25 percent for the Green River near Green River, Wyoming (site 09217000) for their study period of 1998–2003 when compared to a base period from 1974–79. Adjusted annual concentrations reported by Anning and others (2007) have undergone a statistical procedure to remove the variation in dissolved solids that is a function of streamflow.

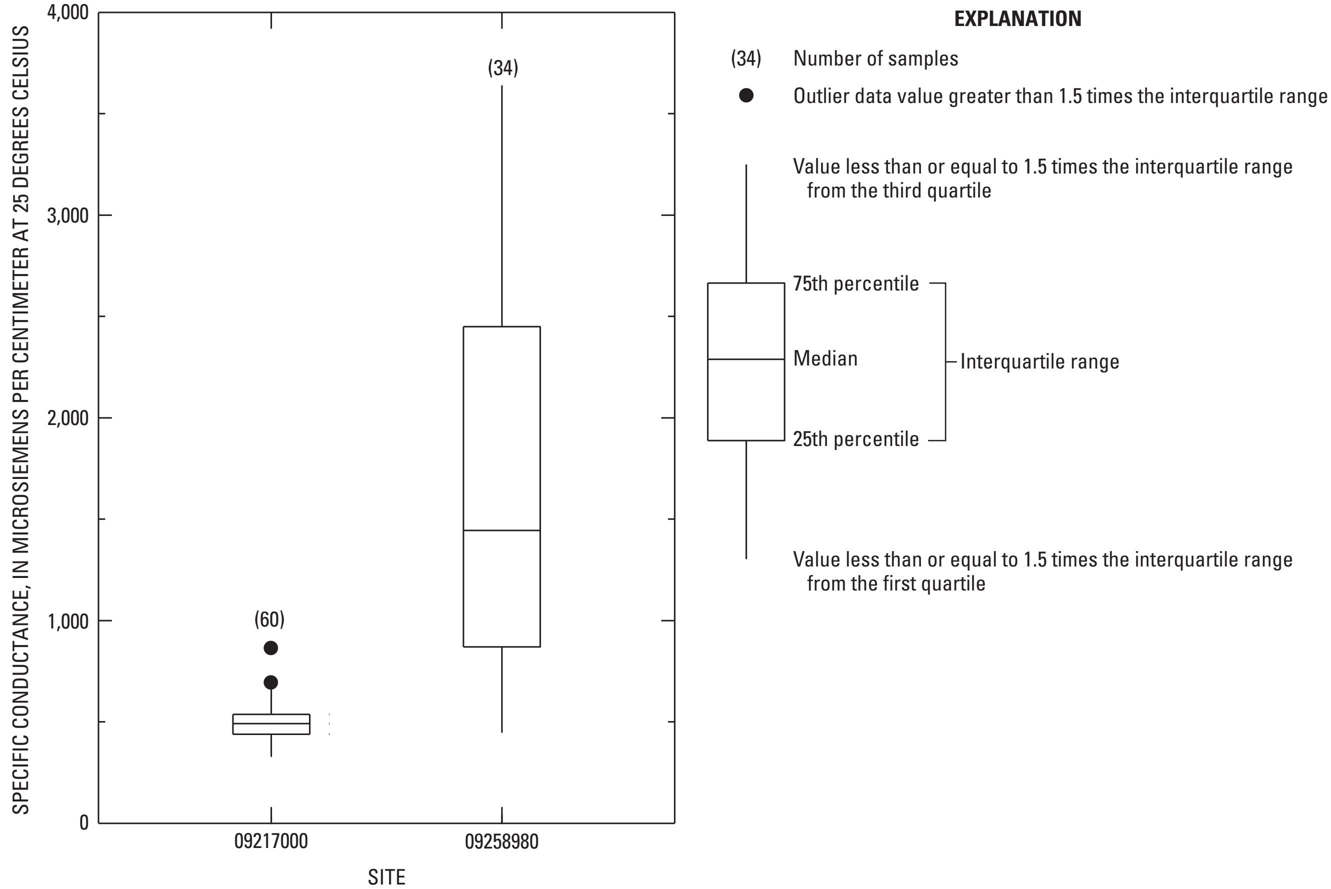


Figure 5. Specific conductance during water-quality sampling at the Green River (site 09217000), water years 1999–2008, and Muddy Creek (site 09258980), water years 2006–08, Wyoming.

The Muddy Creek drainage basin is underlain entirely by Cretaceous-age and Tertiary-age sedimentary rocks, which are more soluble than the Precambrian-era rocks of the upper Green River drainage basin. In addition, the Muddy Creek drainage basin has lower annual precipitation and higher evapotranspiration than much of the Green River drainage basin. These characteristics, combined with lower gradients that produce relatively slow stream velocities and longer contact times between stream waters and basin materials, result in high dissolved-solids concentrations in Muddy Creek. In contrast to the many perennial tributaries of the Green River, most tributaries of Muddy Creek are intermittent or ephemeral streams. The flow characteristics of intermittent and ephemeral streams affect the water quality of these streams. During periods of little to no precipitation and low runoff, salts tend to accumulate in channels and on other surfaces. As a result, dissolved solids can be flushed to streams during precipitation and increased runoff, enriching the dissolved-solids concentrations of the stream (DeLong, 1986), rather than being diluted by the precipitation as typically occurs.

Regression Equations for Estimating Dissolved Solids

Linear regression is a technique available for estimating one water-quality variable on the basis of another water-quality variable. Other studies have used specific conductance to estimate other water-quality constituents where water-quality concerns have been raised because of energy development. For example, sodium-adsorption ratios have been estimated from specific conductance values for sites in the Tongue River and Powder River drainage basins, where sodium concerns have been raised because of coalbed natural gas development (Clark and Mason, 2006; Cannon and others, 2007). Many water managers use dissolved-solids concentrations instead of specific conductance values because dissolved-solids concentrations are needed for calculating salt loads, which are a concern to water managers in the Colorado River Basin.

The relations between specific conductance (independent variable) and dissolved-solids concentration (dependent

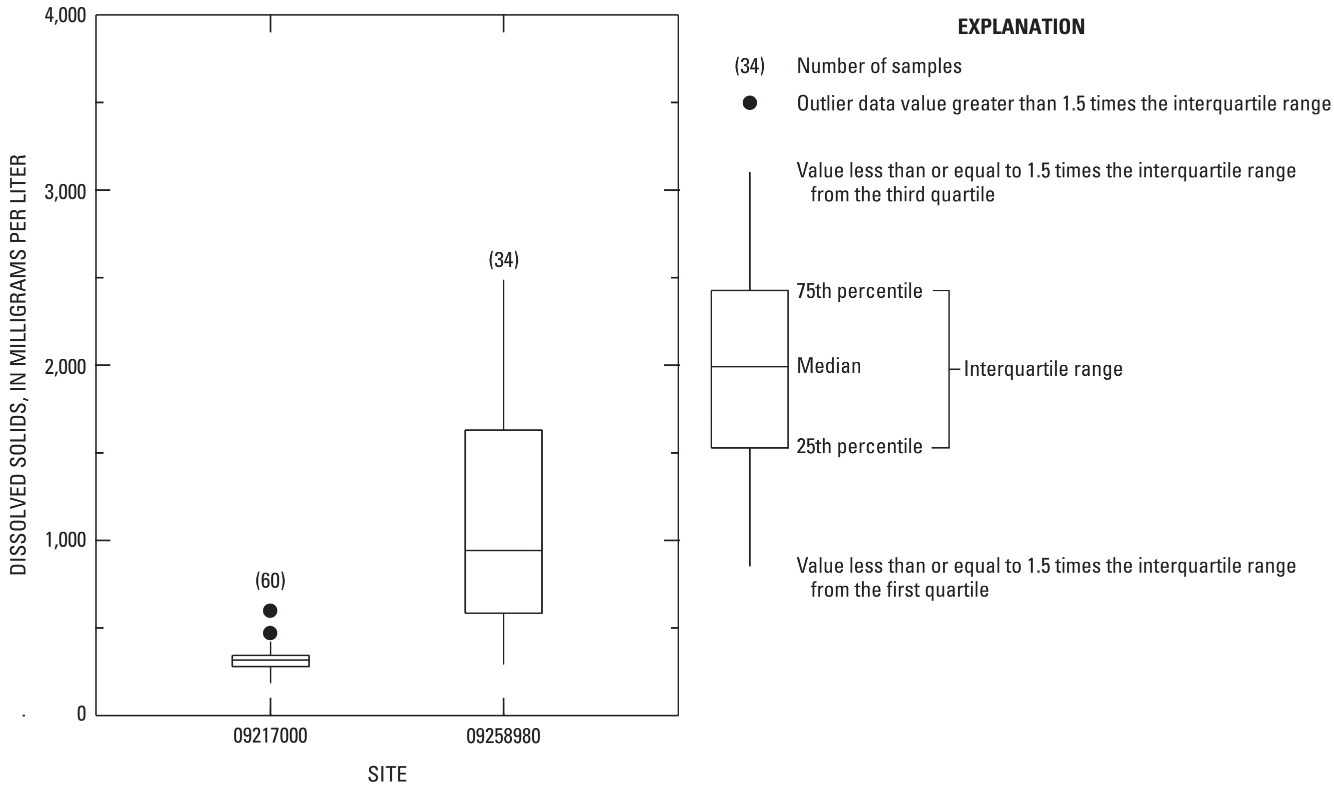


Figure 6. Dissolved-solids concentrations for samples collected during water-quality sampling at the Green River (site 09217000), water years 1999–2008, and Muddy Creek (site 09258980), water years 2006–08, Wyoming.

variable) were graphically inspected for discrete samples collected from the Green River near Green River, Wyoming (site 09217000), and Muddy Creek near Baggs, Wyoming (site 09258980, fig. 7). As expected, strong linear relations exist between specific conductance and dissolved-solids concentration; thus, linear regression equations were developed for the sites (table 2). Relations between specific conductance and dissolved-solids concentration were statistically significant for the Green River (site 09217000, p-value <0.001) and Muddy Creek (site 09258980, p-value <0.001); therefore, specific conductance can be used as a surrogate to estimate the dissolved-solids concentration. About 95 percent of the variance in dissolved solids can be explained by the regression with specific conductance for the Green River (site 09217000), and more than 99 percent of the variance in dissolved solids can be explained by the regression with specific conductance for Muddy Creek (site 09258980). The larger MSE for Muddy Creek, relative to the Green River, is expected because of the larger variance of environmental concentrations in samples from Muddy Creek compared to those from the Green River.

Linear regression equations were used to estimate dissolved-solids concentrations for the periods when daily mean specific conductance values were available for the Green River and Muddy Creek. Estimated dissolved-solids concentrations from the regression equation were compared to the measured dissolved-solids concentrations in the discrete samples from both sites (fig. 8). For the Green River (site 09217000), measured concentrations for discrete samples generally covered the range of estimated concentrations during water year 2008. During water year 2007, measured concentrations from discrete samples were not available for some periods when high specific conductance was measured on the Green River, and correspondingly when high dissolved-solids concentrations would have occurred; therefore, the discrete samples do not fully represent the range of concentrations that occurred during that water year. For Muddy Creek (site 09258980), measured dissolved-solids concentrations for discrete samples generally covered the range of estimated concentrations during water year 2006 and water year 2008; however, measured concentrations for discrete samples were not available for some periods when high specific

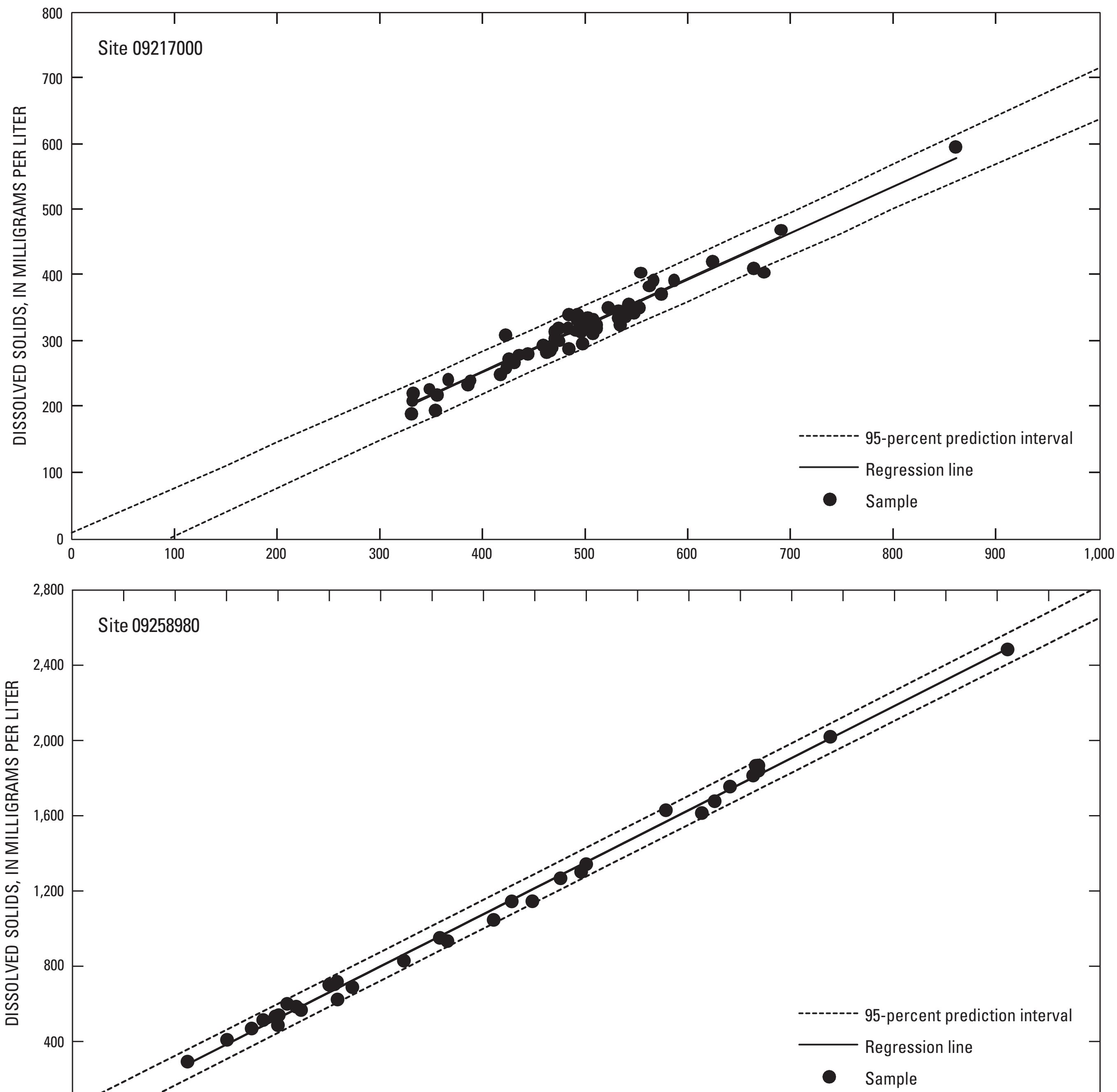


Figure 7. Relations between specific conductance and dissolved-solids concentration for the Green River (site 09217000), water years 1999–2008, and Muddy Creek (site 09258980), water years 2006–08, Wyoming.

Table 2. Regression equations for estimates of dissolved-solids concentration for the Green River (site 09217000) and Muddy Creek (site 09258980), Wyoming.

[*DS*, dissolved-solids concentration in milligrams per liter; *SC*, specific conductance in microsiemens per centimeter at 25 degrees Celsius; MSE, mean square error; R^2, coefficient of determination; <, less than]

Site number (fig. 1)	Equation	MSE	R^2	p-value
09217000	$DS = 0.7057(SC) - 31.79$	256	0.945	<0.001
09258980	$DS = 0.6920(SC) - 30.24$	1,292	.996	<.001

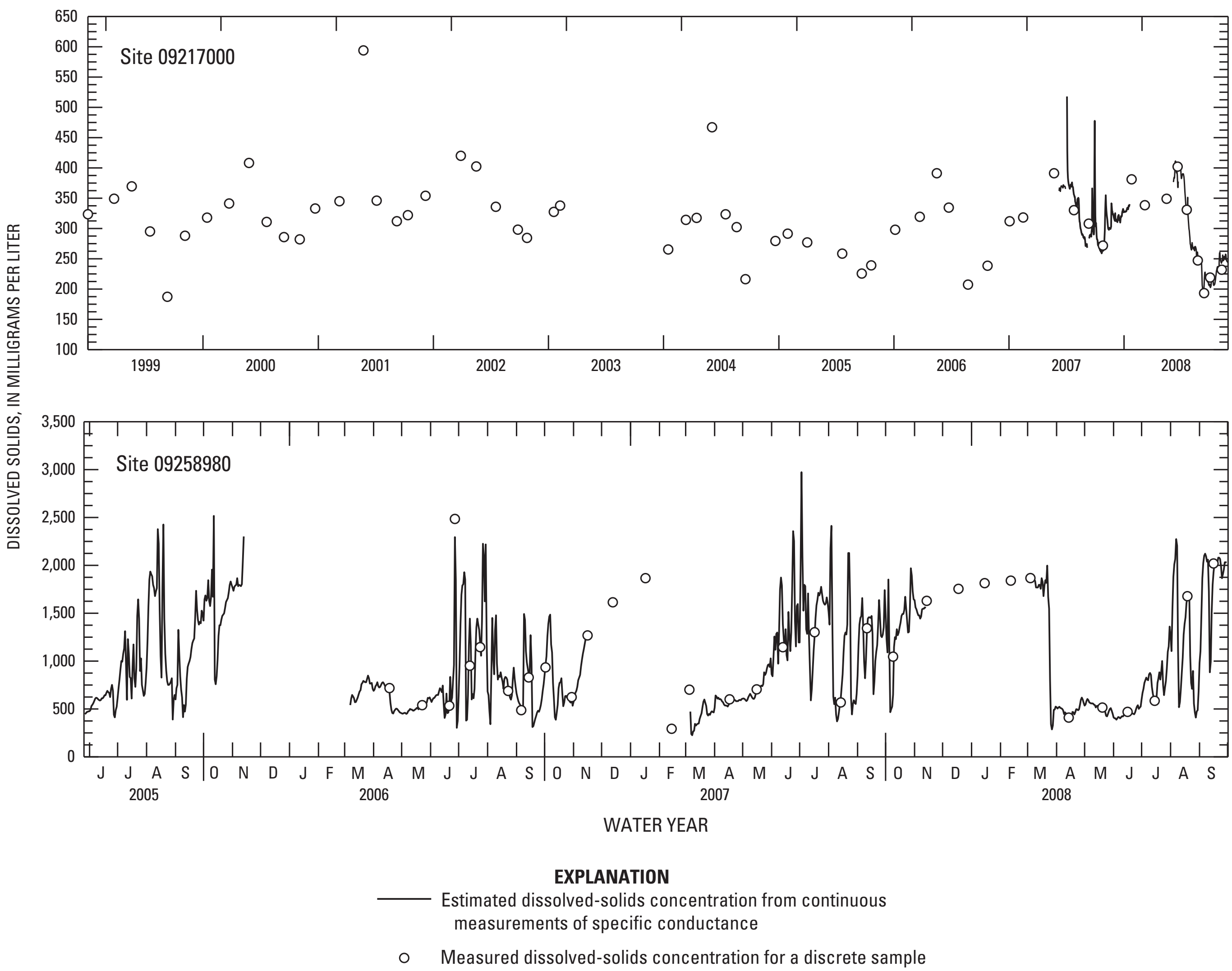


Figure 8. Measured and estimated dissolved-solids concentrations for the Green River (site 09217000) and Muddy Creek (site 09258980), Wyoming, water years 1999–2008.

conductance was measured, and correspondingly when high dissolved-solids concentrations would have occurred, during water year 2007. Dissolved-solids concentrations analyzed in samples collected from Muddy Creek (site 09258980) during water year 2007 ranged from 293 to 1,870 mg/L, whereas estimated concentrations ranged from about 225 to 2,970 mg/L. Using continuous specific conductance data to estimate dissolved-solids loads likely produces more accurate load values because loads computed using only measurements from discrete samples may underestimate (or overestimate) loads during certain periods.

With the use of continuous-recording water-quality instruments that transmit data to satellites, specific conductance data are available in near real-time on NWISWeb (U.S. Geological Survey, 2009a). Regression equations (table 2) can be incorporated into the NWISWeb software to estimate dissolved-solids concentrations for site 09217000 and site 09258980. Using continuous specific conductance values to estimate dissolved-solids concentrations in real-time on the World Wide Web increases the amount and improves the timeliness of data available to water managers for assessing dissolved-solids concentrations in the Colorado River Basin.

Summary

Southwestern Wyoming is an area of diverse scenery, wildlife, and natural resources that is actively undergoing energy development. The Department of the Interior's Wyoming Landscape Conservation Initiative is a long-term science-based effort to assess and enhance aquatic and terrestrial habitats at a landscape scale, while facilitating responsible energy development through local collaboration and partnerships. Water-quality monitoring (including streamflow, specific conductance, and dissolved solids) has been conducted by the U.S. Geological Survey on the Green River near Green River, Wyoming, and Muddy Creek near Baggs, Wyoming. This monitoring, which is being conducted in cooperation with State and other Federal agencies and as part of the Wyoming Landscape Conservation Initiative, is in response to concerns about potentially increased dissolved solids in the Colorado River Basin as a result of energy development. Because of the need to provide real-time dissolved-solids concentrations for the Green River and Muddy Creek on the World Wide Web, the U.S. Geological Survey developed regression equations to estimate dissolved-solids concentrations on the basis of continuous specific conductance using relations between measured specific conductance and dissolved-solids concentrations.

Instantaneous streamflows measured during sampling events were highly varied and ranged from 279 cubic feet per second (ft^3/s) to 3,880 ft^3/s for the Green River and from 0.09 to 124 ft^3/s for Muddy Creek. The highest streamflows measured for the Green River generally were in the late spring or early summer as a result of runoff from melting snow in the mountainous parts of the upper basin. The highest streamflows for Muddy Creek generally were during late-winter or early-spring sampling events as a result of the melting of snow at low to middle altitudes. Streamflows at both sites tend to decrease in late summer through winter when groundwater discharge provides most of the base flow. With the exception of extreme high flows, water-quality samples were collected from a wide range of streamflows at the two sites and thus were representative of a wide range of water-quality conditions.

Specific conductance and dissolved-solids concentrations were less varied and generally lower for the Green River than for Muddy Creek. The median specific conductance value for the Green River was 492 microsiemens per centimeter at 25 degrees Celsius (µS/cm), and the median value for Muddy Creek was 1,445 µS/cm. Discrete values for the entire study period (water years 1999–2008) ranged from 330 to 862 µS/cm for the Green River, and discrete values during water years 2006–08 ranged from 448 to 3,640 µS/cm for Muddy Creek.

The median dissolved-solids concentration for the site on the Green River was 318 milligrams per liter (mg/L), and the median concentration for the site on Muddy Creek was 943 mg/L. Dissolved-solids concentrations ranged from 187 to 594 mg/L in samples collected from the Green River during water years 1999–2008. Dissolved-solids concentrations ranged from 293 to 2,485 mg/L in samples collected from Muddy Creek during water years 2006–08. The difference in dissolved-solids concentrations in samples collected from the Green River compared to samples collected from Muddy Creek reflect the different basin characteristics.

Relations between specific conductance and dissolved-solids concentration were statistically significant for the Green River (p-value less than 0.001) and Muddy Creek (p-value less than 0.001); therefore, specific conductance can be used to estimate dissolved-solids concentration. Using continuous specific conductance values to estimate dissolved-solids concentrations in real-time on the World Wide Web increases the amount and improves the timeliness of data available to water managers for assessing dissolved-solids concentrations in the Colorado River Basin.

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