Prepared in cooperation with the Montana Department of Natural Resources and Conservation, Water Management Bureau

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Scientific Investigations Report 2013–5179

U.S. Department of the Interior
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Cover photograph. Looking downstream at Montana Highway 4 bridge on the Tongue River near Birney, Montana, on April 19, 2006. (Photograph by Stacy M. Kinsey, U.S. Geological Survey).

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)

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

°F=(1.8×°C)+32

Vertical coordinate information is referenced to the "National Geodetic Vertical Datum of 1988 (NGVD 88)."

Horizontal coordinate information is referenced to "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 either in milligrams per liter (mg/L) or milliequivalents per liter (meq/L).

Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

Abbreviations

acre-ft	acre-feet
ANC	acid neutralizing capacity
ANN_C	annual concentration anomaly (dimensionless)
ANN_Q	annual streamflow anomaly (dimensionless);
C	concentration, in milligrams per liter
$CaCO_3$	calcium carbonate
CBM	coal-bed methane
NED	National Elevation Dataset
FAC	flow-adjusted concentration
ft	feet
ft^3/s	cubic feet per second
HFV_C	high-frequency variability of the concentration (dimensionless).
HFV_Q	high-frequency streamflow variability (dimensionless).
log	logarithm (base 10)
<	less than
M_C	long-term mean of the log-transformed concentration, as the base-10 logarithm of milligrams per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligrams per liter
mi	miles
mi^2	square miles
M_Q	long-term mean of the log-transformed streamflow, as the base-10 logarithm of cubic feet per second
NGVD	National Geodetic Vertical Datum
NWQL	National Water Quality Laboratory
NWIS	National Water Information System
OLS season	ordinary least squares regression of concentration on time, streamflow, and
p-value	statistical significance level
PRB	Powder River structural basin
Q	daily mean streamflow, in cubic feet per second
QC	quality control
RPD	relative percent difference
SAR	sodium adsorption ratio
$SEAS_C$	seasonal concentration anomaly (dimensionless)

$SEAS_Q$	seasonal streamflow anomaly (dimensionless)
SEE	standard error of estimate, in percent
TREND	concentration trend (dimensionless)
TSM	time-series model
USGS	U.S. Geological Survey

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Abstract

The primary purpose of this report is to present information relating to flow-adjusted temporal trends in major-ion constituents and properties for 16 sampling sites in the Tongue and Powder River watersheds based on data collected during 1980–2010. In association with this primary purpose, the report presents background information on major-ion characteristics (including specific conductance, calcium, magnesium, potassium, sodium adsorption ratio, sodium, alkalinity, chloride, fluoride, dissolved sulfate, and dissolved solids) of the sampling sites and coal-bed methane (CBM) produced water (groundwater pumped from coal seams) in the site watersheds, trend analysis methods, streamflow conditions, and factors that affect trend results.

The Tongue and Powder River watersheds overlie the Powder River structural basin (PRB) in northeastern Wyoming and southeastern Montana. Limited extraction of coal-bed methane (CBM) from the PRB began in the early 1990's, and increased dramatically during the late 1990's and early 2000's. CBM-extraction activities produce discharges of water with high concentrations of dissolved solids (particularly sodium and bicarbonate ions) relative to most stream water in the Tongue and Powder River watersheds. Water-quality of CBM-produced water is of concern because of potential effects of sodium on agricultural soils and potential effects of bicarbonate on aquatic biota.

Two parametric trend-analysis methods were used in this study: the time-series model (TSM) and ordinary least squares regression (OLS) on time, streamflow, and season. The TSM was used to analyze trends for 11 of the 16 study sites. For five sites, data requirements of the TSM were not met and OLS was used to analyze trends. Two primary 10-year trend-analysis periods were selected. Trend-analysis period 1 (water years 1986–95; hereinafter referred to as period 1) was selected to represent variability in major-ion concentrations in the Tongue and Powder River watersheds before potential effects of CBM-extraction activities. Trend analysis period 2 (water years 2001–10; hereinafter referred to as period 2) was selected because it encompassed substantial CBM-extraction activities and therefore might indicate potential effects of CBM-extraction activities on water quality of receiving streams in the Tongue and Powder River watersheds. For sites that did not satisfy data requirements for the TSM, OLS was used to analyze trends for period 2 (if complete data were available) or a 6-year period (2005–10).

Flow-rate characteristics of CBM-produced water were estimated to allow general comparisons with streamflow characteristics of the sampling sites. The information on flow-rate characteristics of CBM-produced water in relation to streamflow does not account for effects of disposal, treatment, or other remediation activities on the potential quantitative effects of CBM-produced water on receiving streams. In many places, CBM-produced water is discharged into impoundments or channels in upper reaches of tributary watersheds where water infiltrates and does not directly contribute to streamflow. For Tongue River at State line (site 4) mean annual pumping rate of CBM-produced water during water years 2001–10 (hereinafter referred to as mean CBM pumping rate) was 6 percent of the mean of annual median streamflows during water years 2001–10 (hereinafter referred to as 2001–10 median streamflow). For main-stem Tongue River sites 5, 7, and 10, mean CBM pumping rate was 8–12 percent of 2001–10 median streamflow. For main-stem Powder River sites (sites 12, 13, and 16), mean CBM pumping rates were 26, 28, and 34 percent of 2001–10 median streamflows, respectively.

For main-stem Tongue River sites analyzed by using the TSM and downstream from substantial CBM-extraction activities [Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Tongue River at Birney Day School (site 7), and Tongue River at Miles City (site 10)], generally small significant or nonsignificant decreases in most constituents are indicated for period 1. For period 2 for these sites, the TSM trend results do not allow confident conclusions

concerning detection of effects of CBM-extraction activities on stream water quality. Detection of significant trends in major-ion constituents and properties for period 2 generally was infrequent, and direction, magnitudes, and significance of fitted trends were not strongly consistent with relative differences in water quality between stream water and CBM-produced water. The TSM indicated significant or generally large magnitude increases in median values of sodium adsorption ratio (SAR), sodium, and alkalinity for period 2 for sites 5 and 7, which might indicate potential effects of CBM-extraction activities on stream water. However, other factors, including operations of Tongue River Reservoir, irrigation activities, contributions of saline groundwater, and operations of the Decker coal mine, confound confident determination of causes of detected significant trends for sites 5 and 7. For all main-stem Tongue River sites, trends for period 2 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

For main-stem Powder River sites analyzed by using the TSM [Powder River at Sussex (site 11), Powder River at Arvada (site 12), Powder River at Moorhead (site 13), and Powder River near Locate (site 16)], significant or generally large magnitude decreases in median values of SAR, sodium, estimated alkalinity, chloride, fluoride, specific conductance, and dissolved solids are indicated for period 1. Patterns in trend results for period 1 for main-stem Powder River sites are consistent with effects of Salt Creek oil-brine reinjection that started in 1990. Trend results for all main-stem Powder River sites downstream from substantial CBM-extraction activities (sites 12, 13, and 16) indicate evidence of potential effects of CBM-extraction activities on stream water quality, although evidence is stronger for sites 12 and 13 than for site 16. Evidence in support of potential CBM effects includes significant increases in median values of SAR, sodium, and estimated alkalinity for period 2 for sites 12, 13, and 16 that are consistent with relative differences between stream water and CBM-produced water. Significant increases in median values of these constituents for period 2 are not indicated for Powder River at Sussex (site 11) upstream from substantial CBM-extraction activities. In interpreting the trend results, it is notable that the fitted trends evaluate changes in median concentrations and also notable that changes in median concentrations that might be attributed to CBM-extraction activities probably are more strongly evident during low to median streamflow conditions than during mean to high streamflow conditions. This observation is relevant in assessing trend results in relation to specific water-quality concerns, including effects of water-quality changes on irrigators and effects on stream biota and ecology.

Introduction

The Tongue and Powder River watersheds overlie the Powder River structural basin (PRB) in northeastern Wyoming (Wyo.) and southeastern Montana (Mont.). The PRB contains large deposits of energy resources (coal, oil, natural gas) and, since the late 1800's, extraction activities have been extensive. Limited extraction of coal-bed methane (CBM) from the PRB began in the early 1990's, and increased dramatically during the late 1990's and early 2000's (Peck, 1999; Bryner, 2002; Hower and others, 2003). Tongue and Powder River water users have historically been faced with difficulties in obtaining sufficient water of sufficient quality to maintain alfalfa production in support of ranching operations. Although natural watershed characteristics and semiarid climate have historically limited water supplies to farmers and ranchers, upstream agricultural development (for example, irrigation and water storage projects) from the 1930's to present, has prompted further concerns about reduced water supply and potential water-quality effects. In addition, CBM-extraction activities produce discharges of water with high concentrations of dissolved solids (particularly sodium and bicarbonate ions; Quillinan, 2011) relative to most stream waters in the Tongue and Powder River watersheds. Water quality of CBM-produced water is of concern because of potential effects on downstream agricultural producers who irrigate soils that can contain large amounts of clay. Surface applications of waters that have high sodium-adsorption ratio (SAR) values can result in cation exchange, with sodium replacing calcium and magnesium in clay particles of soils, thereby inducing soil swelling (Hanson and others, 1999), reducing infiltration rates, and increasing erosion.

Another concern with respect to discharge of CBM-produced water to stream channels is effects on aquatic biota. Farag and Harper (2012) reported reduced survival of fathead minnows and pallid sturgeon as a result of exposure to CBM-produced water, with sodium bicarbonate (which contains the two most dominant ions in CBM-produced water) identified as the toxic compound. Bicarbonate has been identified as the primary toxic fraction of sodium bicarbonate (Mount and others, 1997). Peterson and others (2011) reported that biological conditions were reduced in the middle reaches of the Powder River and that these reduced conditions potentially could be linked to cumulative effects from CBM-produced water.

Several studies have characterized water-quality and analyzed temporal trends in water-quality constituents in the Powder River (Clark and Mason, 2007; Wang and others, 2007; Clark, 2012) and Tongue River (Clark and Mason, 2007; Clark, 2012) watersheds. These studies primarily focused on stream sites in Wyoming, with less emphasis in Montana. Further, those analyses generally used nonparametric statistical methods (for example, the seasonal Kendall analysis), which are robust and generally do not require extensive datasets, to test for monotonic trends (single direction through the entire trend period). Parametric trend analysis procedures, which are more rigorous and sometimes require more extensive datasets, present alternative trend-analysis approaches to nonparametric procedures (Vecchia, 2005; Helsel and Hirsch, 2002). This study was done by the U.S. Geological Survey (USGS) in cooperation with the Montana Department of Natural

Resources and Conservation to test for temporal trends in water quality using two parametric trends analysis methods: a joint time-series model (TSM; Vecchia, 2005) for concentration and streamflow; and ordinary least squares regression (OLS) of concentration on time, streamflow, and season (Helsel and Hirsch, 2002). Also, this study included sites in Montana and Wyoming in the Tongue and Powder River watersheds. The trend analysis includes an extended period of record (water years 1980–2010) that encompasses conditions before and after substantial CBM-extraction activities. Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends.

Purpose and Scope

The primary purpose of this report is to present information relating to flow-adjusted temporal trends in major-ion constituents and properties for 16 sampling sites in the Tongue and Powder River watersheds based on data collected during water years 1980–2010. In association with this primary purpose, the report presents background information on water-quality characteristics of the sampling sites and CBM-produced water in the site watersheds, trend analysis methods, streamflow conditions, and factors that affect trend results. This information is presented to assist in evaluating trend results.

Trend analyses were structured to specifically aid in identification of water-quality trends that might be attributable to CBM-extraction activities in the Tongue and Powder River watersheds. The trend analyses include sites with periods of record that represent conditions before and after CBM-extraction activities and also sites located upstream and downstream from substantial CBM-extraction activities. In this report, substantial CBM-extraction activities are defined in terms of amount of water produced in association with CBM extraction and are considered to be activities that result in greater than about 500 acre-feet per year of produced water. The study period encompasses about 30 years and includes about 15 years before the start of substantial CBM-extraction activities in the watersheds. The intent of this aspect of the study design was to characterize water-quality variability before and after substantial CBM-extraction activities to aid in evaluating the magnitude of trends that might be attributable to CBM-extraction activities.

In many respects, this report complements and shares similar objectives with the study by Clark (2012) that investigated water-quality trends with a focus on Wyoming sites in the Tongue and Powder River watersheds. However, this report is based on different statistical methods, increases the geographic scope to include more Montana sites, and uses a longer study period for trend analysis.

Previous Investigations

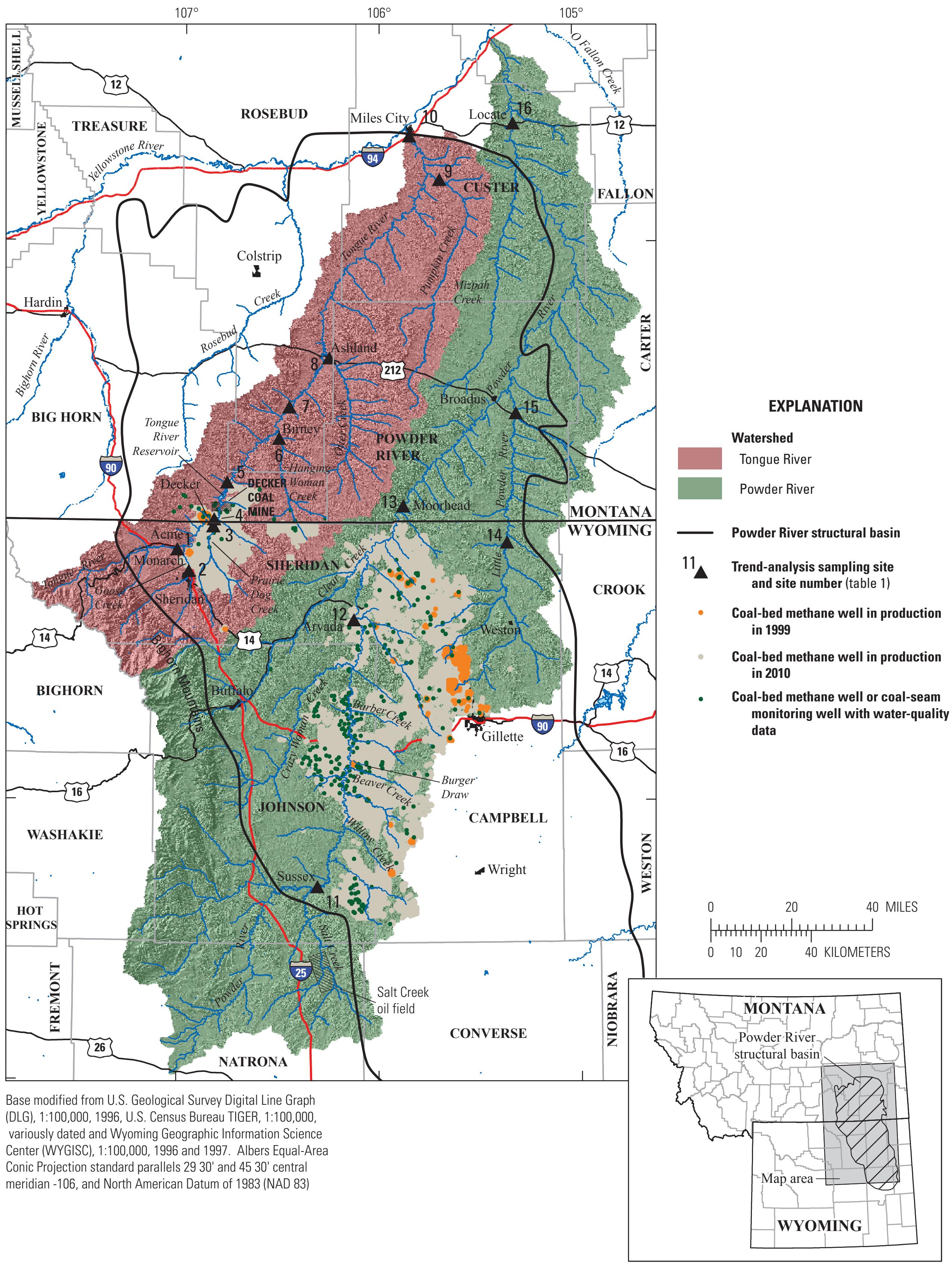
Research on potential environmental effects of CBM-extraction activities in the Tongue and Powder River watersheds has been extensive. However, discussion here of previous investigations is restricted to research specifically related to statistical analysis of flow-adjusted temporal trends in major-ion constituents and properties (Cary, 1991; Wang and others, 2007, Clark and Mason, 2007; and Clark, 2012).

Cary (1991) analyzed trends in 8 major-ion constituents and properties at 10 sites in the Powder River watershed for the period 1975–1988 by using the nonparametric seasonal Kendall test (Hirsch and Slack, 1984). Significant increasing trends in SAR were detected at five sites, two of which correspond with sites included in this report [Powder River at Sussex (site 11) and Powder River at Arvada (site 12); fig. 1, table 1]. The study period of Cary (1991) was before substantial CBM-extraction activities in the Tongue and Powder River watersheds. Cary (1991) noted that irrigation return flows and discharge of oil-field production water might increase concentrations of some constituents in the Powder River; however, specific identification of probable causes of the observed trends was not provided.

In a study of water-quality changes in the Powder River as a result of CBM development, Wang and others (2007) analyzed flow-adjusted trends in 14 different water-quality variables (primarily major-ion constituents and properties) for 4 main-stem Powder River sites using ordinary least squares regression of concentration on time and streamflow and the nonparametric seasonal Kendall test, based on data through 2002. For the period 1990–2002, no significant trends in specific conductance or SAR were detected at Powder River at Sussex (site 11; upstream from substantial CBM-extraction activities). For the same period, significant increases in specific conductance and SAR were detected for Powder River at Arvada (site 12) Powder River at Moorhead (site 13), and Powder River near Locate (site 16), which are downstream from substantial CBM-extraction activities.

Clark and Mason (2007) analyzed flow-adjusted trends in major-ion constituents and properties using the nonparametric seasonal Kendall test at sites in the Tongue and Powder River watersheds (as well as the Cheyenne and Belle Fourche River watersheds; not shown on fig. 1) for water years 1991–2005. Significant increases in SAR were detected at Powder River at Sussex (site 11) and Powder River at Arvada (site 12). Significant decreases in calcium and magnesium, and significant increases in sodium were detected at site 12.

Clark (2012) analyzed flow-adjusted trends in major-ion constituents and properties for water years 2001–10 for 17 sites generally on the main-stem streams and primary tributaries in the Tongue and Powder River watersheds. No significant trends in SAR were detected for sites in the Tongue River watershed. In the Powder River watershed, significant increases in SAR and alkalinity were detected at Powder River at Arvada (site 12). At Powder River at Moorhead (site 13), a significant increase in SAR was not detected but a significant increase in alkalinity was detected.



Base modified from U.S. Geological Survey Digital Line Graph (DLG), 1:100,000, 1996, U.S. Census Bureau TIGER, 1:100,000, variously dated and Wyoming Geographic Information Science Center (WYGISC), 1:100,000, 1996 and 1997. Albers Equal-Area Conic Projection standard parallels 29 30' and 45 30' central meridian -106, and North American Datum of 1983 (NAD 83)

Figure 1. Location of selected sampling sites, coal-bed methane (CBM) wells, and monitoring wells in CBM seams in the Tongue and Powder River watersheds, Montana and Wyoming.

Table 1. Information for sites in the Tongue and Powder River watersheds, Montana and Wyoming.

[USGS, U.S. Geological Survey; CBM, coal-bed methane; Wyo., Wyoming; OLS, ordinary least squares regression on time, streamflow, and season; Mont., Montana; TSM, time-series model]

Site number (fig. 1)	USGS site identification number	USGS site name	Abbreviated site name	Drainage area, in square miles	General site description	Substantial CBM-extraction activities in watershed upstream from site[1]	Trend analysis method	Trend analysis periods, in water years
Tongue River watershed								
1	06299980	Tongue River at Monarch, Wyo.	Tongue River at Monarch	478	Tongue River main stem	No	OLS	2005–10
2	06305500	Goose Creek below Sheridan, Wyo.	Goose Creek	392	Tongue River mountain tributary	No	OLS	2001–10, 2005–10
3	06306250	Prairie Dog Creek near Acme, Wyo.	Prairie Dog Creek	358	Tongue River plains tributary	Yes	OLS	2001–10, 2005–10
4	06306300	Tongue River at State line, near Decker, Mont.	Tongue River at State line	1,453	Tongue River main stem	Yes	TSM	2001–10, 2005–10
5	06307500	Tongue River at Tongue River Dam, near Decker, Mont.	Tongue River at Tongue River Dam	1,770	Tongue River main stem	Yes	TSM	1986–95, 2001–10
6	06307600	Hanging Woman Creek near Birney, Mont.	Hanging Woman Creek	470	Tongue River plains tributary	Yes	TSM	2005–10
7	06307616	Tongue River at Birney Day School, near Birney, Mont.	Tongue River at Birney Day School	2,621	Tongue River main stem	Yes	TSM	1986–95, 2001–10
8	06307740	Otter Creek at Ashland, Mont.	Otter Creek	707	Tongue River plains tributary	No	TSM	1986–95, 2001–10
9	06308400	Pumpkin Creek near Miles City, Mont.	Pumpkin Creek	697	Tongue River plains tributary	No	OLS	2005–10
10	06308500	Tongue River at Miles City, Mont.	Tongue River at Miles City	5,379	Tongue River main stem	Yes	TSM	1986–95, 2001–10
Powder River watershed								
11	06313500	Powder River at Sussex, Wyo.	Powder River at Sussex	3,090	Powder River main stem	No	TSM	1986–95, 2001–10
12	06317000	Powder River at Arvada, Wyo.	Powder River at Arvada	6,050	Powder River main stem	Yes	TSM	1986–95, 2001–10
13	06324500	Powder River at Moorhead, Mont.	Powder River at Moorhead	8,086	Powder River main stem	Yes	TSM	1986–95, 2001–10
14	06324970	Little Powder River above Dry Creek, near Weston, Wyo.	Little Powder River above Dry Creek	1,237	Little Powder River	Yes	TSM	1986–95, 2001–10
15	06325500	Little Powder River near Broadus, Mont.	Little Powder River near Broadus	1,974	Little Powder River	Yes	OLS	2005–10
16	06326500	Powder River near Locate, Mont.	Powder River near Locate	13,068	Powder River main stem	Yes	TSM	1986–95, 2001–10

[1]In this report, substantial CBM-extraction activities are defined in terms of amount of water produced in association with CBM extraction and are considered to be activities that result in greater than about 500 acre-feet per year of produced water.

Description of Study Area

The study area consists of the Tongue and Powder River watersheds in northeastern Wyoming and southeastern Montana (fig. 1); the watersheds overlie the PRB and account for 22 and 37 percent of surficial area of the PRB, respectively. Information on physiographic, climatic, hydrologic, and geologic characteristics, and CBM and other resource extraction activities is presented in this section of the report.

Physiographic, Climatic, and Hydrologic Characteristics

The study area includes parts of the Middle Rocky Mountains and Northwestern Great Plains ecoregions (Omernik, 1987; Woods and others, 2002; Zelt and others, 1999; Clark, 2012). Dominant land cover in the Bighorn Mountains (the primary mountainous region of the study area) is evergreen forest and mixed forest (Homer and others, 2004). Dominant land cover in the plains is shrubland and herbaceous grassland. Agricultural land cover is sparse in the study area and the main areas with pasture/hay or cultivated crops are along parts of the Tongue River, Goose Creek, and Prairie Dog Creek in the Tongue River watershed, and along Clear Creek and the Powder River in the Powder River watershed. Large strip mines produce coal in the Tongue River watershed (near Decker, Mont.) and in the Little Powder River watershed (near Gillette, Wyo.).

The Tongue River is a large tributary [drainage area of about 5,500 square miles (mi^2) near the mouth] to the Yellowstone River. Altitudes, determined by analysis of the National Elevation Dataset (NED; 30-meter digital elevation data; Gesch and others, 2002), range from about 2,350–11,700 feet (ft) above NGVD 88. Areally-weighted mean annual precipitation [1980–2010, 30-year normal; PRISM Climate Group (2012)] is about 16.5 in. for the Tongue River watershed (range of 11.6–34.9 in. across the watershed). Streamflow largely is derived from snowmelt from the Bighorn Mountains and rainfall throughout the watershed. Long-term mean annual streamflow near the mouth of the Tongue River is 409 ft^3/s based on 68 years of data collection during water years 1939–2011 for Tongue River at Miles City [site 10; USGS Water Data for Montana (*http://waterdata.usgs.gov/mt/nwis*)]. Major tributaries include Goose and Prairie Dog Creeks that enter the Tongue River in Wyoming, and Hanging Woman, Otter, and Pumpkin Creeks that enter in Montana. Hydrologic characteristics of the Tongue River are described in more detail by Clark and Mason (2007) and Clark (2012).

The Powder River is a large tributary (drainage area of about 13,000 mi^2 near the mouth) to the Yellowstone River. Altitudes range from about 2,210–13,200 ft above NGVD 88. Streamflow largely is derived from snowmelt from the Bighorn Mountains and rainfall throughout the watershed. The long-term mean annual streamflow near the mouth of the Powder River is 570 ft^3/s based on data for water years 1939–2011 for Powder River near Locate [site 16; USGS Water Data for Montana (*http://waterdata.usgs.gov/mt/nwis*)]. Major tributaries include Salt, Crazy Woman, and Clear Creeks that enter the Powder River in Wyoming, and the Little Powder River and Mizpah Creek that enter in Montana. Hydrologic characteristics of the Powder River are described in more detail by Clark and Mason (2007) and Clark (2012).

Geologic Characteristics

Geology of the Tongue and Powder River watersheds is variable (Clark, 2012). Detailed geology for the State of Wyoming is presented by Love and Christiansen (1985). Generalized maps for the Tongue and Powder River watersheds (Zelt and others, 1999) and the Powder River structural basin (Rice and others, 2002) describe the geology for the Montana part of the study area. Bedrock of the western edges of the Tongue and Powder River watersheds includes metamorphic gneiss and plutonic igneous rocks from the Precambrian era. Sedimentary rocks of marine origin from the Paleozoic and Mesozoic eras compose the Bighorn Mountains (Love and Christiansen, 1985). The bedrock of the eastern part of the Tongue River watershed and a large part of the central Powder River watershed is underlain by the Wasatch Formation. The Fort Union Formation is exposed in the northern, downstream parts of the Tongue River, Powder River, and Little Powder River watersheds.

Coal-Bed Methane and Other Resource Extraction Activities

The Powder River structural basin (PRB; fig. 1) in northeastern Wyoming and southeastern Montana is a coal-rich foreland basin primarily formed by the rise of the Black Hills uplift on the eastern side and the Hartville uplift to the southeast (Perry and Flores, 1997). The PRB accounted for about 40 percent of the U.S. coal supply in 2009 (U.S. Energy Information Administration, 2010). The main coal-bearing formation is the Tertiary Fort Union Formation (2,300–5,910 ft thick), which is low in sulfur and ash making it desirable for energy production. However, much of the coal is buried too deep to be accessible by conventional coal mining techniques (Luppens and others, 2008). The uppermost Fort Union Formation (the Tongue River Member) contains sandstone, siltstone, shale, some carbonates and conglomerates, and regionally-extensive coal beds (as much as about 250 ft thick) referred to as the Wyodak-Anderson coal zone (Flores, 2004). This coal zone is a regional aquifer within the Fort Union Formation (Daddow, 1986; Lowry and others, 1986; Bartos and Ogle, 2002) and has been a major target of CBM production since the 1990s. In general, the basin structure consists of a north-plunging asymmetric syncline. Groundwater along the southeast and western margin of the PRB flows from the Black Hills (not shown on fig. 1) and Bighorn Mountains towards the north and northeast, in a similar direction to the

Tongue and Powder Rivers flowing towards the Yellowstone River (Bates and others, 2011; Lobmeyer, 1985; Meredith and others, 2012).

Estimates of recoverable CBM from the PRB vary, but typically range from about 15–30 trillion cubic feet (Decker, 2001; Schenk and others, 2001). CBM exploration in the PRB began in the 1980's, affected by U.S. energy policy promoting (through tax credits and research funding) increased development of domestic energy sources (Bryner, 2002). The PRB has been estimated to account for about 12 percent of proved CBM reserves in the United States (National Research Council, 2010). Limited CBM extraction in the PRB started in 1993 when extraction technologies and economic factors began to provide favorable conditions for CBM development (Peck, 1999). In the late 1990's and early 2000's, CBM extraction from the PRB accelerated rapidly and at a rate exceeding any other major coal deposit in the United States (Peck, 1999; Bryner, 2002; Hower and others, 2003). That growth in CBM extraction was affected by low drilling costs for the shallow coal beds, inexpensive disposal of water by direct release at the surface in the initially developed areas of the basin (Wheaton and Donato, 2004), and favorable conditions with respect to natural gas prices and U.S. energy policy (Bryner, 2002). CBM development in the PRB increased to a peak of about 17,500 active production wells in 2008 (based on analysis of data obtained from the Montana Board of Oil and Gas Conservation [2011] and the Wyoming Oil and Gas Conservation Commission [2011]) and consequently gained attention from regulators, land and resource management agencies, special interest groups, and landowners. Heightened awareness of CBM production led to concerns largely related to water, particularly disposal of large amounts of produced water and potential wasting of high-quality groundwater resources (Keith and others, 2012).

Methane found in the generally shallow coal beds of the PRB is adsorbed onto organic matter and held in place by hydrostatic pressure; thus, groundwater in the coal bed must be extracted to produce natural gas. The PRB coal beds have a ratio of produced water to produced gas that is higher than other major CBM-producing coal beds (Rice and Nuccio, 2000). Estimates of mean annual water production per well for CBM extraction in the PRB vary, but generally range from about 15–25 acre-ft per year per well (Rice and Nuccio, 2000; Wheaton and Donato, 2004). In parts of the PRB, groundwater extraction has led to major declines in the water table (as much as about 625 ft; Clarey and others, 2010); however, 10 years of groundwater monitoring by the Montana Bureau of Mines and Geology has indicated that drawdown exceeding 20 ft rarely extends beyond 2 mi from the edge of CBM-extraction activities (Meredith and others, 2012). Typical methods of disposal of CBM-produced water in the PRB since production began have included discharge to lined and unlined holding ponds, direct discharge to surface-water channels, use for irrigation, and reinjection to groundwater (Clark, 2012; Wheaton and Donato, 2004; Sowder and others, 2010; National Research Council, 2010; Meredith and others, 2012). Selection of disposal method depends on quality of CBM-produced water, quality of either groundwaters or surface waters that receive CBM-produced water, and Federal and State regulations that govern produced-water disposal (National Research Council, 2010; Rice and Nuccio, 2000). The most common disposal method in the PRB has been discharge to holding ponds, accounting for about 64 percent of produced water (National Research Council, 2010; Clark, 2012). Holding ponds are inexpensive, if unlined, and provide disposal of CBM-produced water through infiltration to groundwater and evaporation (Sowder and others, 2010; Healy and others, 2008). Potential problems associated with CBM ponds are related to accumulation of trace elements and salts, which could potentially be released into surface water channels (by seepage into alluvium and through dams, and overtopping and failure of dams) and also might degrade underlying groundwater as CBM-produced water percolates downward beneath holding ponds (Healy and others, 2008, Sowder and others, 2010). Direct discharge of CBM-produced water (treated and untreated) to surface-water channels throughout the PRB accounts for about 20 percent of produced water (National Research Council, 2010; Clark, 2012); in 2009, annual mean direct discharge of CBM-produced water to surface-water channels in the Powder River watershed was estimated to be about 33 ft^3/s (Kempema and others, 2011). Based on analysis of permitting data provided by the Wyoming Department of Environmental Quality (Jason Thomas, Wyoming Department of Environmental Quality, written commun., July, 2012), in the Wyoming part of the Tongue River watershed about 18 percent of CBM-production wells are permitted to directly discharge to surface-water channels. In the Montana part of the Tongue River watershed, about 61–65 percent of CBM-produced water in 2009 was treated and discharged to surface-water channels (National Research Council, 2010). Currently (2013) all CBM-produced water discharge to surface-water channels in Montana must be treated.

In addition to large coal and CBM deposits, the PRB also has areas that are rich in petroleum deposits. The Salt Creek oil field in Natrona County (discovered in1889; Wegemann, 1918) is the largest oil field in Wyoming and oil-extraction activities have affected surface-water quality in the Salt Creek and Powder River watersheds (Lindner-Lunsford and others, 1992). During oil production, a mix of petroleum and water that is trapped in petroleum-bearing rocks is pumped to the surface. Produced water is then separated from the oil and disposed of by various means, including direct discharge to surface-water channels and reinjection to subsurface. Produced water from the Salt Creek oil field (hereinafter referred to as Salt Creek oil brine) typically has high concentrations of total dissolved solids, the major ions sodium and chloride, and some trace elements that either are natural constituents in the water or are added during the production and separation of the water (Lindner-Lunsford and others, 1992). Some of these constituents can be toxic to freshwater biota in receiving streams (Boelter and others, 1992). Before 1990, Salt Creek oil brine was discharged directly into Salt Creek, which flows through the Salt Creek oil field and then for about 35 mi before joining the Powder River. In 1990, deep disposal by reinjection to subsurface of most Salt Creek oil brine was implemented and resulted in a decrease of about 77 percent in direct discharge of brine to Salt Creek (Lindner-Lunsford and others, 1992).

Data Collection, Analytical Methods, Review, and Quality Control

Initially, most USGS gaging stations with associated water-quality data in the Tongue and Powder River watersheds were screened for inclusion in this study. Selection of sites for trend analysis largely was based on availability of sufficient data, with emphasis on application of the time-series model (TSM). A specific criterion used in site selection included at least 6 years of water-quality data that extended through water year 2010. Sixteen sampling sites were included in this study (table 1; fig. 1).

Streamflow Data

Daily mean streamflows at sites with continuous streamflow gages were determined by applying stage-discharge relations developed from periodic instantaneous streamflow measurements to continuous record of stage according to procedures described by Rantz and others (1982). Instantaneous streamflow at time of sampling typically was measured by using a current meter according to procedures described by Rantz and others (1982). However, some instantaneous streamflow measurements at sites with streamflow gages were obtained by recording gage heights and determining streamflow using the most current streamflow rating curve. Streamflow data are available in the USGS National Water Information System [NWIS; USGS Water Data for Montana (*http://waterdata.usgs.gov/mt/nwis*)].

Water-Quality Data

Water-quality data for 16 sites (table 1; fig. 1) in the Tongue and Powder River watersheds were compiled from NWIS [USGS Water Data for Montana (*http://waterdata.usgs.gov/mt/nwis*)]. Water-quality constituents and properties discussed in the report are related to major-ion chemistry and include specific conductance, dissolved calcium, dissolved magnesium, dissolved potassium, SAR, dissolved sodium, alkalinity, acid neutralizing capacity (ANC), dissolved chloride, dissolved fluoride, dissolved sulfate, and dissolved solids (sum of constituents).

Sampling and Analytical Methods

Field measurements were made and surface-water samples were collected in accordance with methods established by USGS (U.S. Geological Survey, 1984; Ward and Harr, 1990; Edwards and Glysson, 1999; and U.S. Geological Survey, variously dated). Samples generally were collected by using depth-integrated samplers and applying the equal-width-increment method described by Ward and Harr (1990) and Edwards and Glysson (1999). When conditions did not allow use of depth-integrated samples, multiple-vertical grab sampling techniques were used.

Samples were processed onsite using standard methods and equipment described by U.S. Geological Survey (1984) and U.S. Geological Survey (variously dated). Subsamples analyzed for major ion concentrations were filtered in the field using a filter with a pore size of 0.45 micrometer, and concentrations are reported as dissolved. Samples were sent to the USGS National Water Quality Laboratory in Lakewood, Colorado., for analysis using standard USGS methods (Fishman and Friedman, 1989; Fishman, 1993) for most major ions, and a “Standard Methods” procedure for potassium (American Public Health Association, American Water Works Association, and Water Environment Federation, 1998) starting in about water year 2004.

Sampling and analytical methods generally remained consistent during the study period for all major ions except alkalinity, which is an important water-quality property with respect to investigating potential effects of CBM-produced water. Alkalinity provides information on dissolved inorganic carbon (predominantly carbonate and bicarbonate ions). In the pH range of 5.5–8.3, bicarbonate is the dominant inorganic carbon species (Hem, 1985). At a pH of 9, bicarbonate still accounts for about 98 percent of inorganic carbon. For sites in the Tongue and Powder River watersheds, pH ranges are such that nearly all dissolved inorganic carbon can be reasonably assumed to be bicarbonate. An acid titration procedure is used to measure inorganic carbon in water samples and the result commonly is reported as milligrams per liter as calcium carbonate (or mg/L as $CaCO_3$). A complicating factor in investigating inorganic carbon characteristics for an extensive dataset is that the titration procedure is sometimes performed on filtered samples (and the result reported as alkalinity) and sometimes performed on unfiltered samples (and the result reported as acid neutralizing capacity or ANC). Alkalinity and ANC measurements can differ because of contribution to acid neutralization by suspended sediment in the unfiltered ANC samples. Magnitude of difference between alkalinity and ANC for a given water sample depends on amount and characteristics of suspended sediment in the sample. In many cases, when suspended sediment concentrations are not high, alkalinity and ANC measurements are similar. However, for samples with high suspended sediment concentrations, ANC measurements can be much higher than alkalinity measurements.

For water-quality samples collected in the Tongue and Powder River watersheds during water years 1980–97, inorganic carbon measurements predominantly were ANC measurements. Inorganic carbon measurements for water samples collected after water year 1997 predominantly were alkalinity measurements. Because of the importance of dissolved inorganic carbon with respect to evaluating potential effects of CBM-produced water, in the final datasets a single property, referred to as estimated alkalinity, was compiled by merging the ANC and alkalinity data to allow evaluation of trends for the study period. For samples with available alkalinity measurements, estimated alkalinity generally was set to the measured alkalinity. However, if percent difference in cation and anion balance for a sample was outside plus or minus 5 percent, possibly indicating that the alkalinity measurement was problematic, and an ANC measurement was available and resolved the problem, then estimated alkalinity was set to the measured ANC. For water samples with only ANC measurements, estimated alkalinity was set to the measured ANC, given the constraint of an acceptable percent difference in cation and anion balance.

Detailed investigations were done to determine potential effects of use of the estimated alkalinity property on trend analysis. There are 551 water samples collected during water years 1980–2010 for the 16 sampling sites (table 1) that have associated alkalinity and ANC measurements. Median relative percent difference (RPD) between alkalinity and ANC for the samples was -3.1 percent. RPD is calculated by using the following equation:

$$RPD = 100 \times \frac{|X - Y|}{\left[(X + Y)/2\right]} \tag{1}$$

where

RPD is the relative percent difference;

X is the alkalinity (milligrams per liter as $CaCO_3$); and

Y is the ANC (milligrams per liter as $CaCO_3$).

Although the median *RPD* is not large, it indicates a positive bias in ANC relative to alkalinity, presumably because of higher ANC values that result from presence of suspended sediment. Further, the 25th percentile *RPD* was -15 percent and the 75th percentile *RPD* was -0.00 percent. Although these values are within typical quality control (QC) acceptance criteria for replicate analyses (Taylor, 1987), they confirm positive bias in ANC. However, use of the estimated alkalinity property was determined to be acceptable for meeting study objectives based on several factors. Temporal segregation of setting estimated alkalinity to either alkalinity or ANC measurements was distinct. For water samples collected through water year 1997, ANC measurements accounted for 99 percent of assigned estimated alkalinity values. For water samples collected after water year 1997, alkalinity measurements accounted for 98 percent of assigned estimated alkalinity values. Percent differences in cation and anion balances for the two periods were similar. For water samples collected during water years 1980–97 (when ANC predominantly accounted for assigned estimated alkalinity values), mean percent difference was -0.41 percent, with 98 percent of percent differences being within the range of -7.3 to +7.1 percent. For water samples collected during water years 1998–2010 (when alkalinity predominantly accounted for assigned estimated alkalinity values), mean percent difference was -0.35 percent, with 98 percent of percent differences being within the range of -5.0 to + 5.7 percent. Thus, errors associated with positive bias in ANC relative to alkalinity were not large enough to cause much variability in proportions of major ions. Also, temporal segregation of estimated alkalinity being set to either alkalinity or ANC measurements was considered with respect to a primary objective of identifying water-quality trends that might result from introduction of CBM-produced water into native streams. Trend analysis time periods generally were structured to identify trends during distinct 10-year periods before and after start of CBM-extraction activities in the watersheds upstream from the sites. Start of CBM-extraction activities in most of the watersheds typically ranged from about 1997–99 (Clark, 2012), which closely corresponds to the timing of the change from ANC measurements to alkalinity measurements in water year 1998. Thus, trend results, relative to addressing a primary objective, probably are not strongly affected. However, positive bias because of setting estimated alkalinity predominantly to ANC for water years 1980–1997 is acknowledged. Concentrations of estimated alkalinity for trend periods before start of CBM-extraction activities might be slightly elevated relative to those after start of CBM-extraction activities. Thus, with respect to possible effects of using ANC and alkalinity determinations in the trend analysis, any increasing trends identified in estimated alkalinity after substantial CBM-extraction activities might be slightly conservative.

In this report, the term estimated alkalinity is used when data are presented that encompass the study period and include ANC and alkalinity determinations. The standard term (alkalinity) is used when data are presented that only encompass the period after 1998 when analyses almost exclusively were done on filtered samples.

Data Review and Quality Control

Because the study period is relatively long (about 30 years) and includes variability in QC practices and data-collection objectives and personnel, all water-quality data for the study period were reviewed and quality assured as consistently as reasonably possible. Initially, water-quality data were retrieved from NWIS [USGS Water Data for Montana (*http://waterdata.usgs.gov/mt/nwis*)] for the study sites (table 1, fig. 1). Final water-quality datasets included no more than one record per day. For days with multiple records in NWIS, if only one record had a complete set of the constituents determined for that day, it was selected as the record for that day. If more than one record had a complete set of the constituents determined for that day, the record nearest the center of the day was selected. If there were multiple records for a given day and none of the records were complete, the records were merged to create a single record with a complete set of constituents.

Intensive review procedures were applied to all water-quality data. Specific conductance data were reviewed by first comparing associated field and laboratory measurements, when available. If field and laboratory measurements had an *RPD* (eq. 1, with *X* equal to field measurement and *Y* equal to lab measurement) within plus or minus 5 percent, the field value was accepted. When associated field and laboratory measurements had an *RPD* outside the range of plus or minus 5 percent, dissolved solids to specific conductance ratios were examined and compared with samples collected closely in time or at similar seasonal and streamflow conditions. If field specific conductance was missing or rejected, and laboratory specific conductance was determined to be acceptable, laboratory specific conductance was included in the final dataset.

Major ion concentrations were reviewed by investigating percent differences in cation and anion balances and checked against typical ratios of individual ions to specific conductance. When percent differences in cation and anion balances were outside the range of plus or minus 5 percent, concentrations of individual ions were checked against typical ratios and clearly problematic ions were removed from the final dataset. Samples affected by removal of one or more major-ion constituents accounted for less than 1 percent of total samples. In some cases, percent differences in cation and anion balances were outside the range of plus or minus 5 percent, but clearly problematic ions could not be identified; all ions were included in the final dataset. After reviewing all samples and resolving problematic samples, there were 3,184 samples with sufficient data to calculate cation and anion balances. Mean percent difference in cation and anion balance was -0.37 percent and about 98 percent of the samples were within the range -4.8 to +5.0 percent.

Analytical results for water-quality QC samples (including field blank and replicate samples) for the study period are difficult to precisely characterize because of several factors, including the following: changes in reporting of QC information with time; changes in frequency of QC data collection with time; and changes in electronic storage of and capability of accessing QC data with time. Given these considerations, QC information for the study period is summarized as precisely as reasonably possible. Available QC samples collected at sites in the Tongue and Powder River watersheds during water years 1980–2010 are summarized in table 1.1 in supplement 1 (at the back of this report). Analytical results for available QC samples indicate acceptable quality for trend analysis.

Water Quality and Streamflow Characteristics for Selected Sampling Sites and Comparison with Water Quality and Volume Characteristics of Coal-Bed Methane Produced Water

Statistically summarizing water-quality characteristics of the sites is useful for generally describing water quality in the site watersheds and in providing general information relevant for interpretation of trend results. Comparison between water-quality characteristics of receiving streams and water-quality characteristics of CBM-produced water in the site watersheds provides context for evaluating whether any identified trends might be attributable to CBM-extraction activities. Comparison between streamflow characteristics of receiving streams and volume of CBM-produced water in the site watersheds also provides relevant information.

Water Quality and Streamflow Characteristics for Selected Sampling Sites

Statistical summaries of water-quality data for sites in the Tongue and Powder River watersheds are presented in table 1.2 in supplement 1 (at the back of this report). Data are summarized for two time periods (water years 1986–95, for sites with available data, and water years 2001–10 for all sites), corresponding to trend-analysis time periods (as discussed in the section of this report “Selection of Trend Analysis Time Periods”). Statistical distributions (boxplots) of SAR, sodium, and alkalinity for sites in the Tongue and Powder River watersheds are presented in figures 2 and 3, respectively. Statistical distributions (boxplots) are based on data collected only during water years 2001–10 because all sites had available data for the period. Mean annual streamflow for water years 2001–10 (included in table 1.3) sometimes is referenced to assist in evaluating differences in water-quality characteristics between sites.

Brief descriptions of major-ion characteristics of the sites are presented by watershed in the following paragraphs of this section of the report. Mean annual streamflow retrieved from USGS Water Data for Montana (*http://waterdata.usgs.gov/mt/nwis*) for sites with continuous streamflow data during water years 2001–10 also is presented. Information is presented for all sites, whether or not there have been substantial CBM-extraction activities in their watersheds. Specific information is presented for sodium, SAR, and alkalinity because these constituents are of primary relevance and concern with respect to potential effects of CBM-extraction activities. SAR values were calculated by using analytical results for dissolved calcium, dissolved magnesium, and dissolved sodium obtained for a given sample according to the equation:

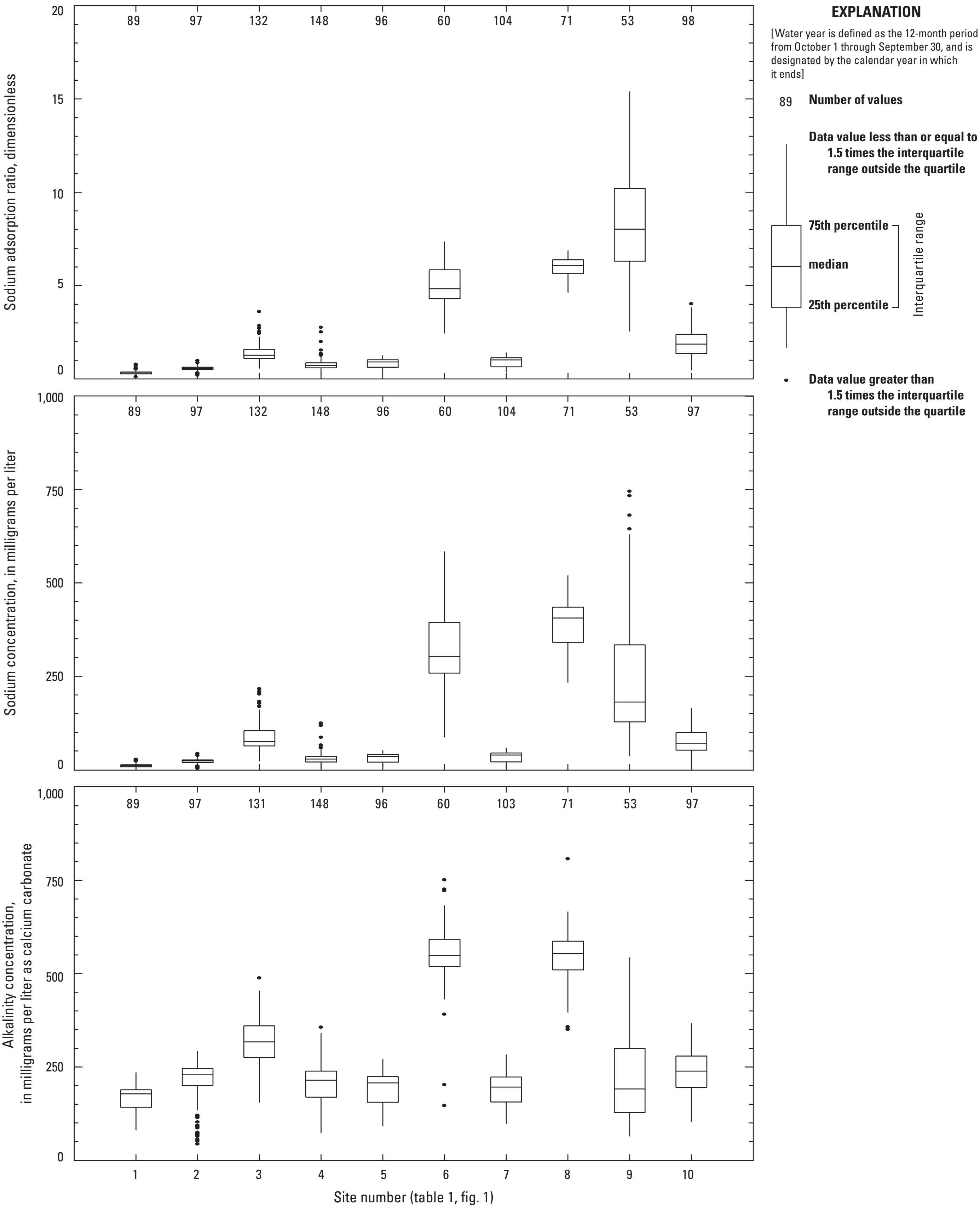


Figure 2. Statistical distributions of sodium adsorption ratio, sodium, and alkalinity for selected sites in the Tongue River watershed based on data collected during water years 2001–10.

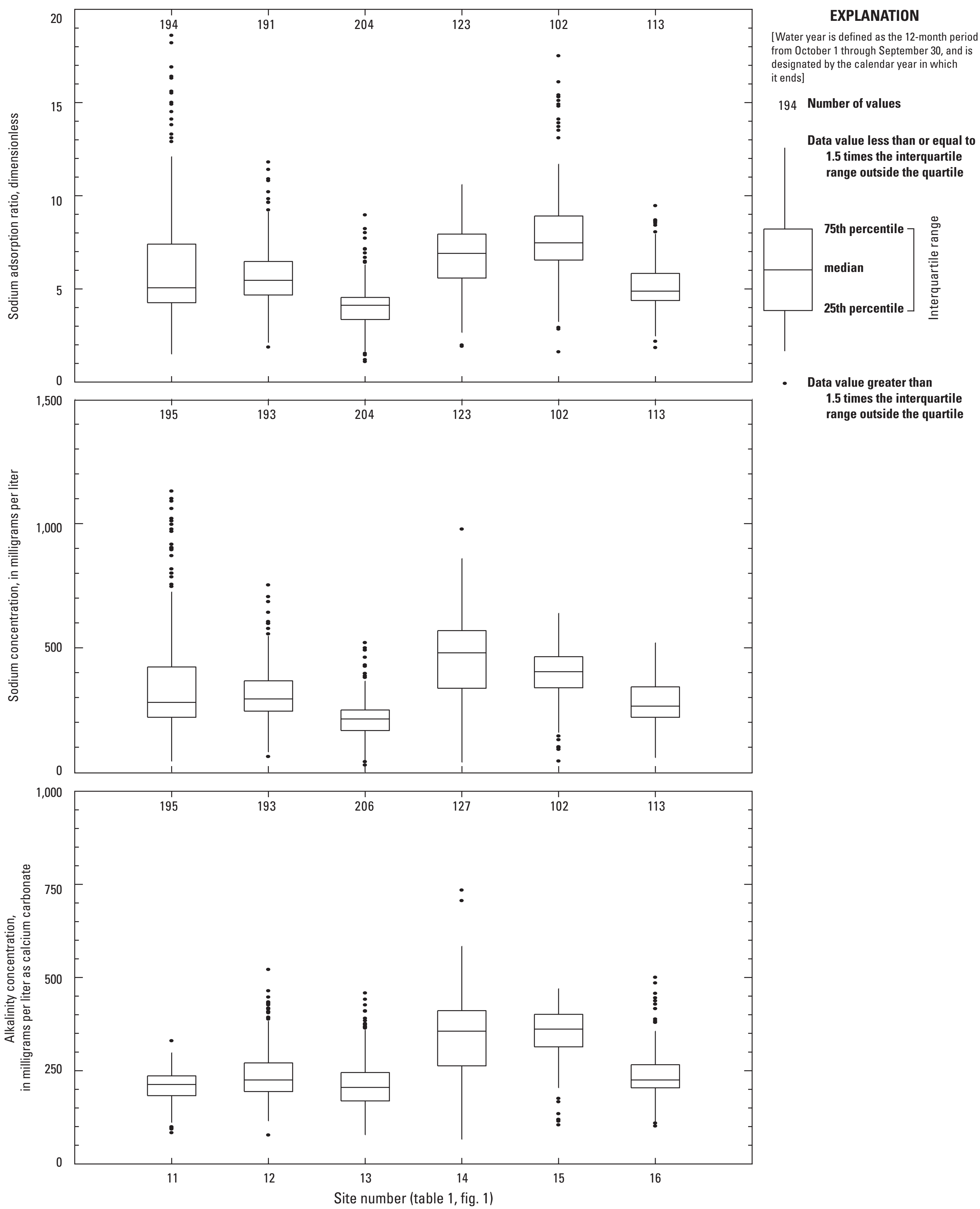


Figure 3. Statistical distributions of sodium adsorption ratio, sodium, and alkalinity for selected sites in the Powder River watershed based on data collected during water years 2001–10.

$$SAR = \frac{(Na^+)}{\sqrt{\tfrac{1}{2}\left[\left(Ca^{2+}\right)+\left(Mg^{2+}\right)\right]}} \qquad (2)$$

where Na^+, Ca^{2+}, and Mg^{2+} represent concentrations expressed in milliequivalents per liter for sodium, calcium, and magnesium, respectively.

Tongue River Watershed

Stream water-quality characteristics are variable for main-stem Tongue River sites [Tongue River at Monarch (site 1), Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Tongue River at Birney Day School (site 7), and Tongue River at Miles City (site 10); table 1.2, fig. 2], but all sites (except site 10) are generally low ionic strength (based on total concentrations of major ions in meq/L; figs. 4-5) and mixed calcium-magnesium-bicarbonate type. Water-quality for site 10 is characterized by generally high ionic strength and mixed sodium-magnesium-calcium-sulfate-bicarbonate type. There is a general downstream increase in mean specific conductance [385, 609, 586, 598, and 827 microsiemens per centimeter (µS/cm) for sites 1, 4, 5, 7, and 10, respectively; table 1.2]. Sodium and SAR are low; mean SAR is less than 1.0 for all main-stem sites except site 10 (mean SAR of 2.0). Mean alkalinities range from 164 (site 1) to 237 (site 10) mg/L as $CaCO_3$. Water-quality characteristics of the main-stem Tongue River are affected by the water being sourced primarily in the Bighorn Mountains with high precipitation, resistant geologic materials, and steep gradients (Clark, 2012). There is a general downstream increase in sodium, SAR, and sulfate affected by contributions from plains tributaries, which have higher concentrations of these constituents, and irrigation effects (especially downstream from site 5), such that sodium and sulfate are co-dominant ions at site 10 (fig. 4). Variability in major-ion concentrations tends to be smaller for sites 5 and 7 than sites 4 and 10, probably because of storage and mixing effects in Tongue River Reservoir (as discussed in the section of this report “Streamflow Conditions”). Mean annual streamflow during water years 2001–10 for sites 1, 4, 5, 7, and 10 was 216, 343, 333, 332, and 289 ft^3/s, respectively (table 1.3). The decrease in mean annual streamflow downstream from site 4 largely is because of irrigation consumptive use and evaporation from Tongue River Reservoir.

Stream water-quality characteristics for Tongue River tributary sites are variable among sites. Goose Creek (site 2) has a moderately large watershed predominantly located in the Bighorn Mountains. Water quality is low ionic strength (mean specific conductance of 583 µS/cm) and mixed magnesium-calcium-bicarbonate type (table 1.2). Mean SAR is 0.56 and mean alkalinity is 209 mg/L as $CaCO_3$. Water quality for plains tributary sites (sites 3, 6, 8, and 9; table 1.2) are moderately high ionic strength with variable type. Prairie Dog Creek (site 3; streamflows are augmented by transbasin diversions for irrigation; Clark, 2012) has a mean specific conductance of 1,450 µS/cm and is mixed magnesium-calcium-sulfate-bicarbonate type. Mean SAR is 1.4 and mean alkalinity is 315 mg/L as $CaCO_3$. Mean annual streamflow during water years 2001–10 for site 3 was 25 ft^3/s. Hanging Woman Creek (site 6) and Otter Creek (site 8) have mean specific conductance of 2,510 and 2,880 µS/cm, respectively, and are mixed sodium-magnesium-sulfate-bicarbonate type. Mean SAR values are 5.0 and 6.0 for sites 6 and 8, respectively, and mean alkalinity is 547 mg/L as $CaCO_3$ for both sites. Mean annual streamflow during water years 2001–10 for sites 6 and 8 was 0.83 and 2.6 ft^3/s, respectively. Pumpkin Creek (site 9) has a mean specific conductance of 1,500 µS/cm and is sodium-sulfate type. Mean SAR is 8.3 and mean alkalinity is 226 mg/L as $CaCO_3$. Water-quality characteristics of Tongue River plains tributaries are affected by low precipitation, soluble geologic materials, and generally low gradients that produce slow stream velocities and long contact times (Clark, 2012).

Powder River Watershed

Stream water quality generally is less variable among sites in the Powder River watershed than in the Tongue River watershed. Stream water quality for main-stem Powder River sites [Powder River at Sussex (site 11), Powder River at Arvada (site 12), Powder River at Moorhead (site 13), and Powder River near Locate, (site 16); table 1.2] is moderately high ionic strength and sodium-sulfate type. Mean specific conductance for sites 11, 12, 13, and 16 is 2,660, 2,350, 1,820, and 2,080 µS/cm, respectively. Mean SAR values for sites 11, 12, 13, and 16 are 6.6, 5.8, 4.0, and 5.2, respectively. Mean alkalinities for main-stem Powder River sites are similar, ranging from 208–242 mg/L as $CaCO_3$. These characteristics are affected by main-stem Powder River receiving contributions from both the Bighorn Mountains and plains tributaries. Salt Creek, a plains tributary with oil-extraction activities in its watershed, enters the Powder River upstream from site 11 and strongly affects water-quality of main-stem Powder River sites (Lindner-Lunsford and others, 1992; Clark, 2012). Tributaries that drain the Bighorn Mountains have a dilution effect on water-quality constituents in the Powder River downstream from site 11 (Clark, 2012). Mean annual streamflow during water years 2001–10 for sites 11, 12, 13, and 16 was 163, 192, 327, and 380 ft^3/s, respectively.

Stream water quality for Little Powder River sites [Little Powder River above Dry Creek (site 14) and Little Powder River near Broadus (site 15); table 1.2] is higher ionic strength than for main-stem Powder River sites and is sodium-sulfate type. Mean specific conductance for sites 14 and 15 are 3,150 and 2,470 µS/cm, respectively. Mean SAR values for sites 14 and 15 are 6.7 and 8.2, respectively. Mean alkalinities for sites 14 and 15 are 342 and 345 mg/L as $CaCO_3$, respectively. Water-quality characteristics of Little Powder River sites are affected by low precipitation, soluble geologic materials, and generally low gradients that produce slow stream velocities and long contact times (Clark, 2012). Mean annual streamflow during water years 2001–10 for site 14 was 17 ft^3/s.

Estimation of Volume, Flow-Rate, and Water Quality of Coal-Bed Methane (CBM) Produced Water in Selected Sampling-Site Watersheds in the Tongue and Powder River Watersheds

Water-quality, volume, and flow-rate characteristics of CBM-produced water were estimated to allow general comparisons with water-quality and streamflow characteristics of receiving streams. The boundary of the watershed upstream from each site was delineated using the Spatial Analyst extension of ArcGIS 10. The 30-meter NED was filled to prevent misrepresentation of flowlines by lakes or depressions (Poppenga and Worstell, 2008). Flow direction and flow accumulation rasters were then derived from the filled NED. The sites were snapped to locations on the nearest flowline defined by the flow accumulation raster. Final watershed boundaries were then delineated individually on the flow direction raster.

Location and production information for CBM-production wells were retrieved from Wyoming Oil and Gas Conservation Commission (2011) and Montana Board of Oil and Gas Conservation (2011), which were presumed to be the most comprehensive and accurate public sources of information concerning construction, location, and gas and water produced by CBM-production wells in the PRB in Montana and Wyoming. Locations of CBM-production wells were geospatially plotted in conjunction with the delineated watershed boundaries. CBM water-production data were summed by site watershed and by year and converted from units of barrels to acre-feet (acre-ft), but otherwise were accepted as presented in the source databases. The annual volume of produced water in acre-ft also was converted to annual mean pumping rate in ft^3/s to facilitate comparisons with streamflow data.

Water-quality data and location information for CBM wells and monitoring wells penetrating coal zones in CBM production areas were retrieved and compiled from several sources, including Campbell and others (2008); Frost and others (2002); Montana Bureau of Mines and Geology (2012); Pearson (2002); Quillinan (2011); U.S. Geological Survey (2012); and Wyoming Department of Environmental Quality (published in Quillinan, 2011). For wells with more than one sample, constituent and property values were averaged to provide a single water-quality record for a given well. Constituent concentrations in water-quality samples collected from CBM wells and monitoring wells in each sampling-site watershed were averaged to develop basin-wide general estimates of quality of CBM-produced water for each site watershed. Summary statistics for well water-quality data are presented in table 1.4 for each sampling-site watershed. The primary objective of compiling and summarizing water-quality data representative of CBM-produced water was to allow large-scale assessment of relative differences in water quality between CBM-produced water and receiving stream water of the sites. As used in this report, relative differences in water-quality between CBM-produced water and receiving stream water refer to differences that exist between the raw solutions independent from effects of biogeochemical processes that might occur between the time when CBM-produced water is pumped from an aquifer and the time that it is actually transmitted to the stream site. Consideration of relative differences between CBM-produced water and receiving stream water provides additional context for evaluating trend results; however, the summarization of water-quality data representative of CBM-produced water was not intended as a substantive detailed quantification of water-quality characteristics of CBM-produced water in the site watersheds. Water-quality characteristics of CBM-produced water from different coal zones can have large variability (Rice and others, 2000; Clarey and Stafford, 2008). However, Quillinan (2011) noted that water-quality characteristics of CBM-produced water were more strongly correlated to geographic location than to coal zone, providing a basis for meeting the primary objective of compiling and summarizing water-quality data representative of CBM-produced water.

Description of water-quality of CBM-produced water is restricted to selected major-ion constituents and properties: calcium, magnesium, SAR, sodium, alkalinity, chloride, and sulfate. Potassium and fluoride were not included because data for those constituents typically were absent from datasets for CBM wells and monitoring wells penetrating coal zones in CBM production areas. However, Brinck and others (2008) reported that CBM-produced water in the Powder River watershed had generally high fluoride concentrations (median greater than 1 mg/L); higher than fluoride concentrations for most sampling sites (table 1.2).

Comparison of Water Quality and Streamflow of Selected Sampling Sites with Water-Quality and Volume of Coal-Bed Methane (CBM) Produced Water

Water-quality and flow-rate characteristics of stream water at the sites and CBM-produced water in site watersheds were compared for sites that have had substantial CBM-extraction activities in their watersheds. Ratios of mean values of major-ion constituent and properties in stream-water samples to mean values in CBM-produced water are presented in table 1.5 to provide information on relative differences in constituents between stream water and CBM-produced water. Summary information related to volumes and flow rates of stream water and CBM-produced water is presented in table 1.3.

Differences in water-quality and flow-rate characteristics between stream water and CBM-produced water also are presented in figures 4 and 5. On the left-hand side of figures 4 and 5, Stiff plots, which show mean concentrations [in milliequivalents per liter (meq/L)] of selected major ions, provide information on total ionic strength and proportions of major ions. On the right-hand side of figures 4 and 5, line plots showing annual median streamflow and annual mean pumping rate for CBM-produced water provide information on flow-rate characteristics of CBM-produced water relative to streamflow. Annual median values for streamflow (as opposed to annual mean values) are presented to maintain consistency with the trend-analysis procedures used for this study. The trend-analysis procedures incorporate logarithm (base 10) transformation and, thus, evaluate changes in concentration and streamflow relations in reference to geometric means, which generally are more closely associated with untransformed medians than untransformed means. Annual mean pumping rate for CBM-produced water was estimated by converting total annual volume of CBM-produced water to flow rate assuming constant pumping rate during the year; thus, annual mean pumping rate does not account for effects of retention of CBM-produced water in holding ponds or other remediation activities on potential quantitative effects of CBM-produced water on receiving streams. Direct discharge data for CBM-produced water contributions to receiving streams would provide a more meaningful comparison with streamflow, but direct discharge data are not readily available on temporal and spatial scales relevant to this study.

Figures 4 and 5 and tables 1.4 and 1.5 provide information on two factors relevant to potential effects of CBM-produced water on receiving streams: (1) water quality of stream water relative to water quality of CBM-produced water; and (2) streamflow characteristics at the sites relative to flow-rate characteristics of CBM-produced water in site watersheds. However, information provided in figures 4 and 5 and tables 1.4 and 1.5 does not account for effects of disposal, treatment, or other remediation activities on potential qualitative or quantitative effects of CBM-produced water on receiving streams. In many places, CBM-produced water is discharged into impoundments or channels in upper reaches of tributary watersheds where water infiltrates and does not directly contribute to streamflow.

CBM-produced water throughout the PRB consistently is sodium-bicarbonate type, but variable in ionic strength (figs. 4 and 5; Van Voast, 2003). In general, ionic strength and sodicity of CBM-produced water in the PRB increase from southeast to northwest (Quillinan, 2011; Rice and others, 2000). This pattern reflects chemical and biological reactions along the flow paths of water in the PRB (Bates and others, 2011; Meredith and others, 2012). Flow of water in the PRB generally is toward the north or northeast, with water entering from the uplifted mountains in Wyoming and flowing toward the Yellowstone River of Montana. As water initially recharges the coal beds it dissolves calcium and magnesium salts present in soil and shallow substrate (Meredith and others, 2012). Fort Union Formation aquifer systems have long flow paths and therefore ample time for cation exchange reactions between groundwater and the prevalent clays. The cation exchange reactions increase sodium concentrations and decrease calcium and magnesium concentrations in groundwater (Daddow, 1986; Lowry and others, 1986; Bartos and Ogle, 2002; Bates and others 2011; Meredith and others, 2012). There are several areas of groundwater recharge along the western margin of the PRB especially near the Wyoming and Montana border (Bates and others, 2011). Complex biogeochemical processes associated with introduction of the recharge water to the groundwater system might also affect the low calcium and magnesium concentrations, slight decrease in sodium concentrations, and high SAR values in the area.

Tongue River Watershed

In the Tongue River watershed, located in the western part of the PRB (fig. 1), water quality of CBM-produced water generally is similar among sites, with low mean calcium and magnesium concentrations (ranging from 5.3–7.9 mg/L and 2.2–4.7 mg/L, respectively; table 1.4), which in combination with high mean sodium concentrations (ranging from 457–574 mg/L) results in high mean SAR values (ranging from 42–50). CBM-produced water in the Tongue River watershed has mean alkalinity concentrations that range from 986–1,250 mg/L as $CaCO_3$.

Sites in the Tongue River watershed with substantial CBM-extraction activities in their watersheds include Prairie Dog Creek (site 3), Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Hanging Woman Creek (site 6), Tongue River at Birney Day School (site 7), and Tongue River at Miles City (site 10). Ionic strength (based on total concentrations of major ions in meq/L) of CBM-produced water is much different from stream water at main-stem Tongue River sites (sites 4, 5, 7, and 10), but less different from stream water at plains tributary sites (sites 3 and 6). For example, ionic strength in stream water at main-stem sites (sites 4, 5, 7, and 10) is about 28–39 percent of ionic strength for CBM-produced water in the site watersheds (fig. 4). Ionic strength in stream water at plains tributary sites (sites 3 and 6) is about 70 and 120 percent, respectively, of ionic strength for CBM-produced water. For all sites in the Tongue River watershed with substantial CBM-extraction, relative differences in individual constituents between stream water and CBM-produced water (table 1.5) generally are similar: calcium, magnesium, and sulfate concentrations are higher, and SAR, sodium, alkalinity and chloride values are lower in stream water than in CBM-produced water. At main-stem Tongue River sites (sites 4, 5, and 7), SAR and sodium, in particular, are much lower in stream water relative to CBM-produced water.

Relations between streamflow and pumping rates of CBM-produced water are variable among sites in the Tongue River watershed (fig. 4, table 1.3). For Tongue River at State line (site 4) mean annual pumping rate of CBM-produced water during water years 2001–10 (hereinafter referred to as mean CBM pumping rate) was 6 percent of the mean of annual median streamflows during water years 2001–10 (hereinafter referred to as 2001–10 median streamflow). For main-stem Tongue River sites 5, 7, and 10, mean CBM pumping rate was 8–12 percent of 2001–10 median streamflow. For plains tributaries (sites 3 and 6), mean CBM pumping rates were 35 and about 700 percent of 2001–10 median streamflows, respectively.

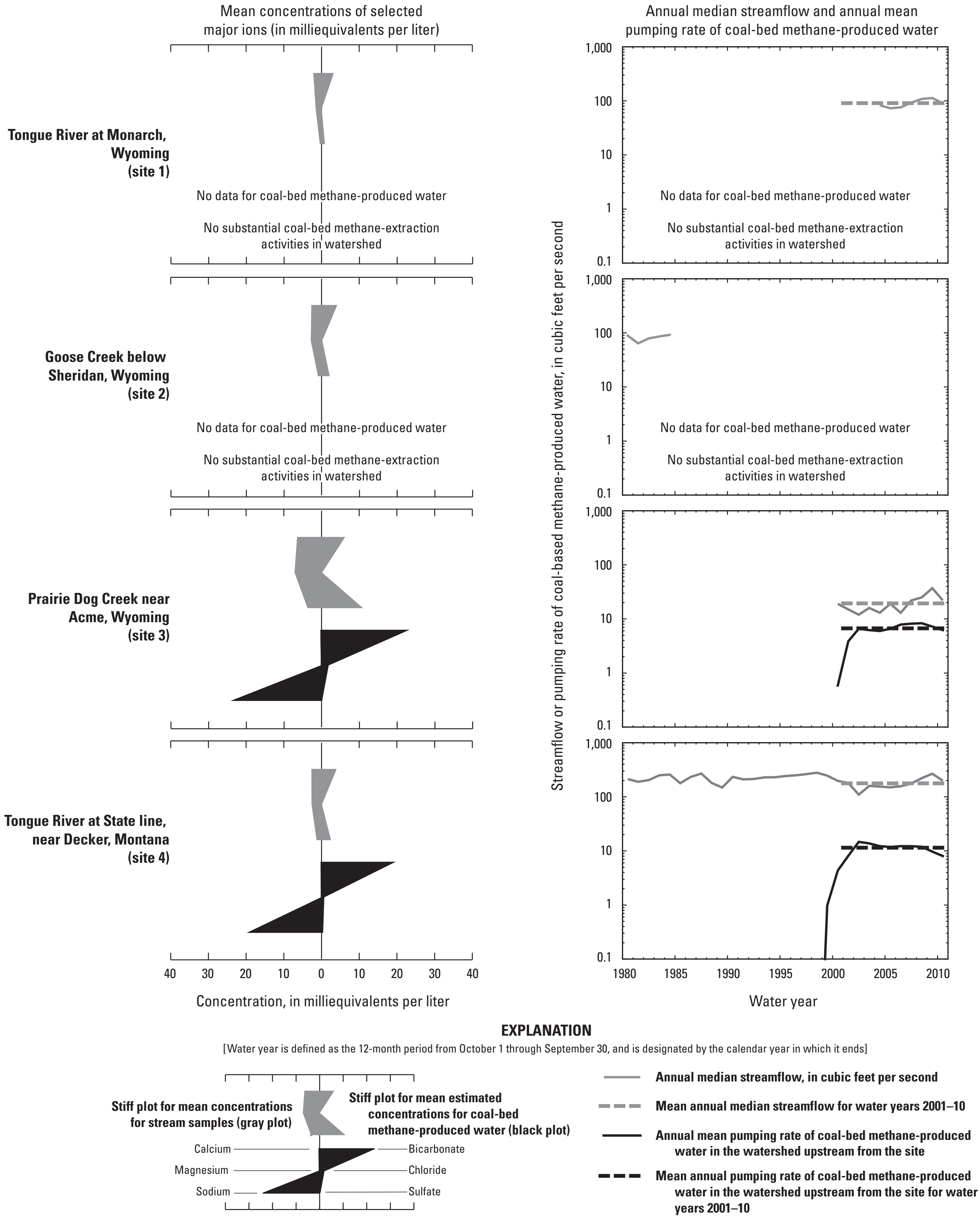


Figure 4. Selected water-quality and flow-rate characteristics for sites in the Tongue River watershed and for coal-bed methane (CBM) produced water in the watersheds upstream from the sites.

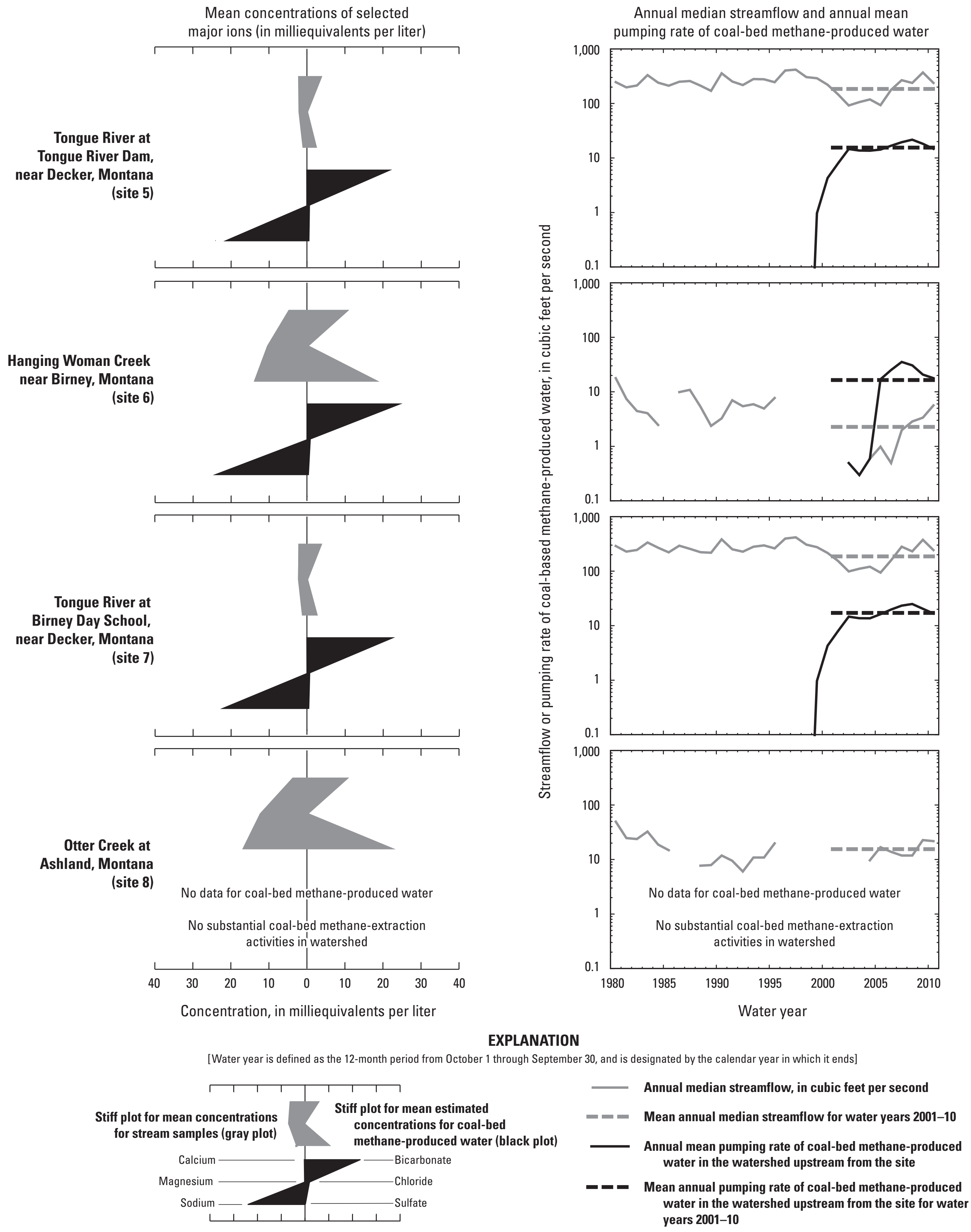


Figure 4. Selected water-quality and flow-rate characteristics for sites in the Tongue River watershed and for coal-bed methane (CBM) produced water in the watersheds upstream from the sites.—Continued

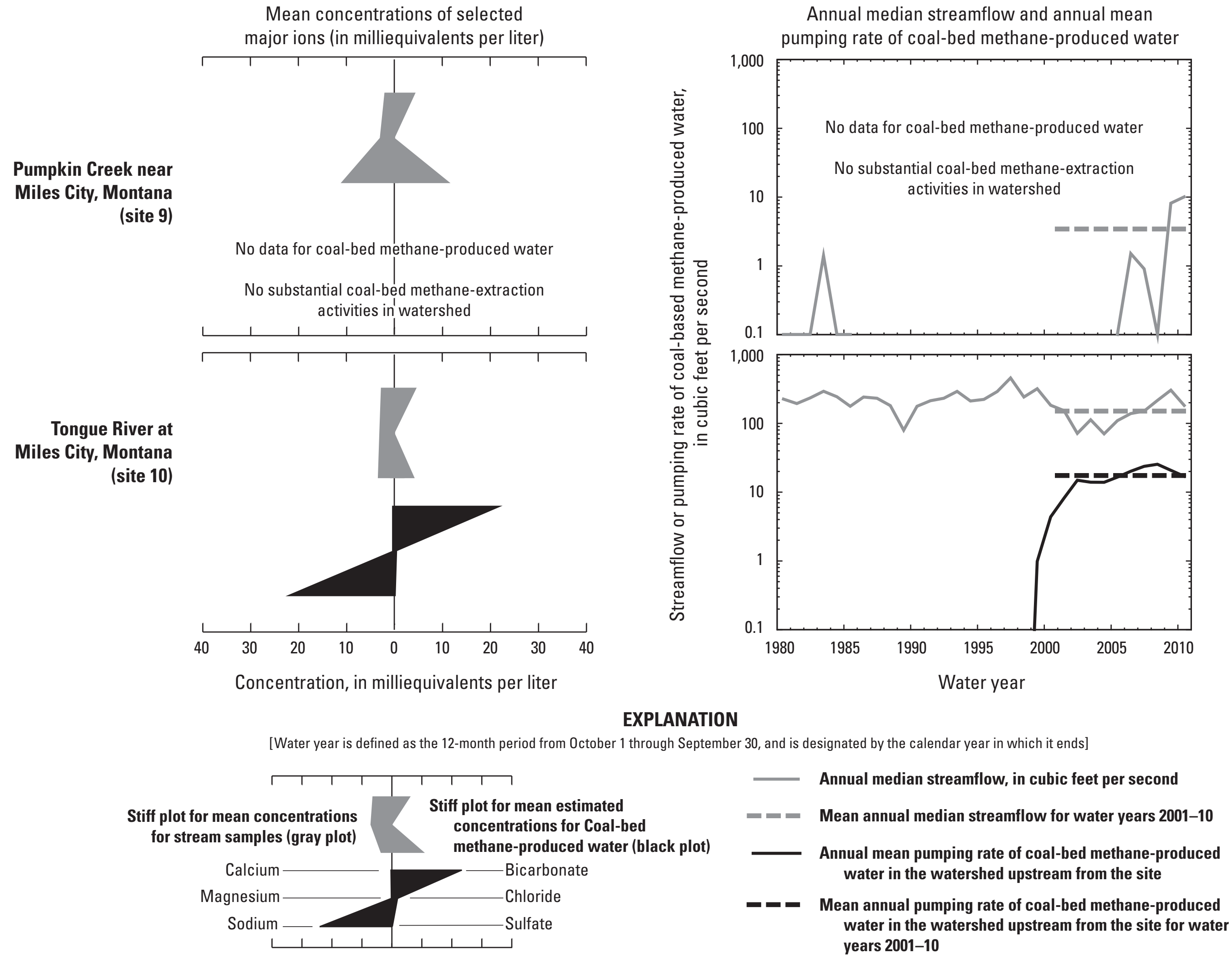


Figure 4. Selected water-quality and flow-rate characteristics for sites in the Tongue River watershed and for coal-bed methane (CBM) produced water in the watersheds upstream from the sites.—Continued

Powder River Watershed

In the Powder River watershed, located in the central part of the PRB (fig. 1), water quality of CBM-produced water is variable among sites. Sites in the Powder River watershed with substantial CBM-extraction activities include Powder River at Arvada (site 12), Powder River at Moorhead (site 13), Little Powder River above Dry Creek (site 14), Little Powder River near Broadus (site 15), and Powder River near Locate (site 16). For main-stem Powder River sites (sites 12, 13, and 16), CBM-produced water generally has higher mean calcium and magnesium concentrations (ranging from 26–28 and 16–17 mg/L, respectively) than in the Tongue River watershed. Mean sodium concentrations (ranging from 584–660 mg/L) also are slightly higher in watersheds of main-stem Powder River sites, but less so than calcium and magnesium. Thus, mean SAR values (ranging from 24–27) are much lower than in the Tongue River watershed. CBM-produced water in watersheds of main-stem Powder River sites has mean alkalinity concentrations that range from 1,640–1,900 mg/L as $CaCO_3$. For Little Powder River (sites 14 and 15), CBM-produced water has mean calcium and magnesium concentrations of 32 and 17 mg/L, respectively, mean sodium concentrations of 274 mg/L, mean SAR values of 10, and mean alkalinity concentrations of 790 mg/L as $CaCO_3$.

Ionic strength in stream water at main-stem Powder River sites (sites 12, 13, and 16) is about 62–76 percent of ionic strength for CBM-produced water in the site watersheds (fig. 5). Ionic strength in stream water at Little Powder River sites (sites 14 and 15) is about 180 and 240 percent, respectively, of ionic strength for CBM-produced water. In the Little Powder River watershed, CBM-produced water has much lower ionic strength than in watersheds of all Tongue River watershed sites and main-stem Powder River sites. Relative

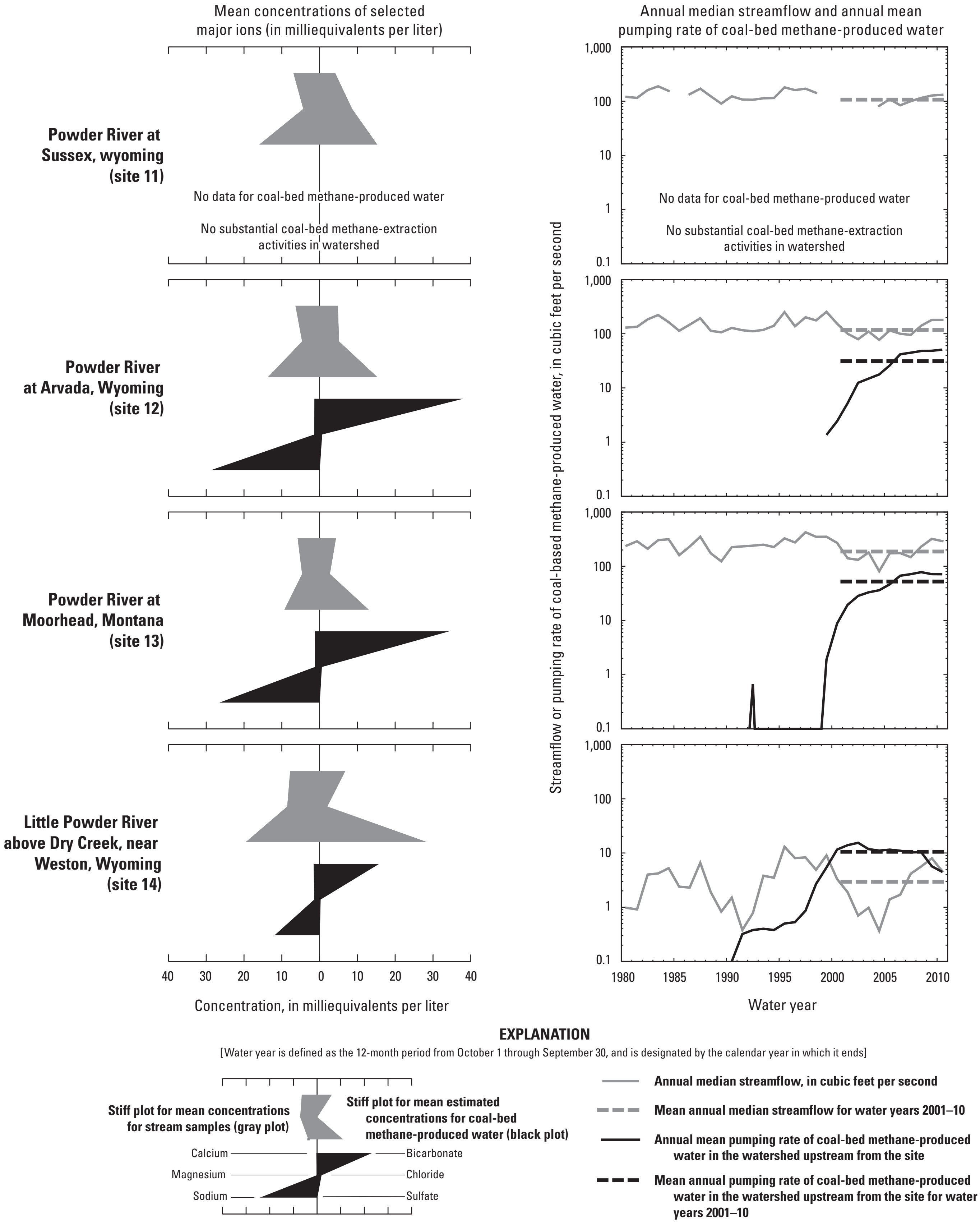


Figure 5. Selected water-quality and flow-rate characteristics for sites in the Powder River watershed and for coal-bed methane (CBM) produced water in the watersheds upstream from the sites.

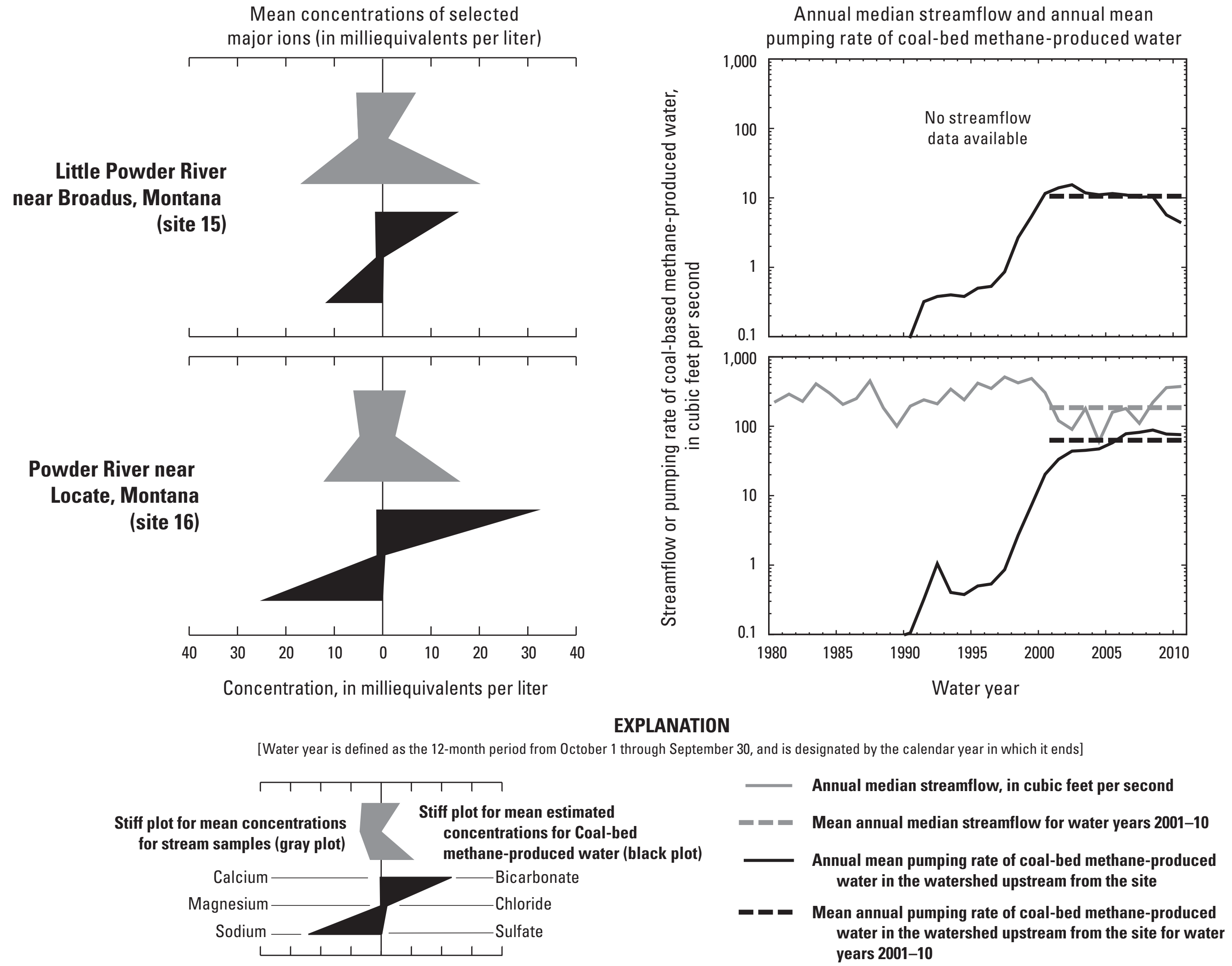


Figure 5. Selected water-quality and flow-rate characteristics for sites in the Powder River watershed and for coal-bed methane (CBM) produced water in the watersheds upstream from the sites. —Continued

differences in individual constituents between CBM-produced water and stream water (table 1.5) generally is similar among main-stem Powder River sites (sites 12, 13, and 16): calcium, magnesium, chloride, and sulfate concentrations are higher, and SAR, sodium, and alkalinity values are lower in stream water than in CBM-produced water. Relative differences are similar for Little Powder River sites (sites 14 and 15) compared to the main-stem sites, except sodium concentrations are higher in stream water than in CBM-produced water.

Relations between streamflow and pumping rates of CBM-produced water are variable among sites in the Powder River watershed (fig. 5, table 1.3). For main-stem sites (sites 12, 13, and 16), mean CBM pumping rates were 26, 28, and 34 percent of 2001–10 median streamflows, respectively. For site 14 in the Little Powder River watershed mean CBM pumping rate was about 360 percent of 2001–10 median streamflow.

Trend Analysis Methods

A variety of methods are available for analysis of water-quality trends, including nonparametric and parametric procedures (Hirsch and Slack, 1984; Helsel and Hirsch, 2002). Nonparametric procedures have been used in previous studies of water-quality trends in the Tongue and Powder River watersheds (Clark and Mason, 2007), Wang and others (2007), and Clark (2012). Two parametric trend-analysis methods were used in this study: the time-series model (TSM; Vecchia, 2005) and ordinary least squares regression (OLS) on time, streamflow, and season (Helsel and Hirsch, 2002). Both of these trend-analysis methods analyze trends in flow-adjusted concentrations (FACs); that is, the methods calculate FACs, determine best-fit fitted trends that represent temporal changes in FACs, and determine the statistical significance of the estimated changes. Flow adjustment is necessary because concentrations of many water-quality constituents are dependent on streamflow conditions that primarily are affected by climatic variability (interannual and seasonal). The intent of flow-adjustment is to identify and remove streamflow-related variability in concentration and thereby enhance capability to detect trends independent from effects of climatic variability. Flow-adjustment procedures produce FACs that are estimates of constituent concentrations after removing effects of streamflow variability. Flow-adjustment procedures vary between the TSM and OLS, which are discussed in more detail in supplements 2 and 3, respectively. In general, the primary difference between the two approaches is that TSM uses multiple flow-related variables computed from concurrent (same day as the concentration sample) and antecedent (days before the concentration sample) daily streamflow in the flow-adjustment process, whereas OLS [and the nonparametric procedures used by (Clark and Mason, 2007), Wang and others (2007), and Clark (2012)] use only concurrently measured streamflow. Thus, FACs determined by the TSM are analogous to FACs determined by OLS, in that FACs of both methods account for streamflow effects, but TSM FACs provide more detailed accounting by incorporating interannual, seasonal, and short-term streamflow variability (Vecchia, 2005). Overviews of the TSM and OLS methods are presented in the following sections of this report.

Time-Series Model (TSM)

A statistical time-series model for streamflow and constituent concentration (Vecchia, 2005) was used in this report to detect water-quality trends. Details on theory and parameter estimation for the model are described in Vecchia (2005) and the model is summarized in supplement 2 (at the back of this report). As applied in this study, the TSM required at least 15 years of continuous streamflow data and at least 10 years of water-quality data with at least 75 total samples and at least 10 samples in each 3-month season. For site and constituent combinations with data that met requirements of the TSM, only the TSM results are presented to simplify and condense presentation of results. Specific information concerning suitability of application of the TSM to the study datasets and procedures for determination of statistical significance and magnitude of trends is presented in supplement 2.

Included in supplement 2 are definitions of anomaly terms that are used in the TSM and are important in contributing to the rigor of the TSM. In analysis of concentration and streamflow relations, the TSM partitions effects of streamflow variability into separate components for interannual, seasonal, and short-term (day-to-day) variability, and relative importance of each of these components is quantified. The annual concentration anomaly (ANN_C) quantifies interannual variability in concentration that is related to interannual variability in streamflow [as determined by the annual streamflow anomaly (ANN_Q)]. For dissolved constituents, ANN_C typically indicates an inverse relation between concentration and streamflow. That is, annual median concentration will tend to be low [relative to long-term (that is, the period of analysis) median concentration] when annual median streamflow is high (relative to long-term median streamflow) and high when annual median streamflow is low. The seasonal concentration anomaly ($SEAS_C$) quantifies seasonal variability in concentration that is related to seasonal variability in streamflow [as determined by the seasonal streamflow anomaly ($SEAS_Q$)]. For dissolved constituents, $SEAS_C$ typically also indicates an inverse seasonal relation between concentration and streamflow. That is, seasonal median concentration will tend to be low (relative to annual median concentration) when seasonal median streamflow is high (relative to annual median streamflow) and high when seasonal median streamflow is low. Although ANN_C and $SEAS_C$ might indicate an inverse relation between concentration and streamflow, the strength of the relations might strongly differ among sites and constituents. For some site and constituent combinations, constituent concentration might be more sensitive to annual streamflow variability than seasonal streamflow variability and for other combinations, the reverse situation might hold. Short-term variability in concentration, also referred to as high-frequency variability (HFV_C), is variability remaining after removing ANN_C and $SEAS_C$. Similarly, high-frequency variability in streamflow (HFV_Q) is variability remaining after removing ANN_Q and $SEAS_Q$. Relations between HFV_C and HFV_Q generally are more complex than relations for ANN_C and ANN_Q and for $SEAS_C$ and $SEAS_Q$. In accounting for relations between HFV_C and HFV_Q, the TSM can account for effects of short-term streamflow variability (for example, hysteresis) and also potential serial correlation.

In this study, the TSM was selected as the preferred trend-analysis method to OLS and nonparametric methods used in previous studies [for example, Clark and Mason (2007), Wang and others (2007), and Clark (2012)]. This preference primarily is because of the large percentage of sites that had continuous streamflow data available (11 of 16 study sites) and the incorporation of continuous streamflow data for the entire study period in the TSM. Detailed analysis of continuous streamflow data provides better definition of concentration and streamflow relations through time, better handling of temporal variability in sampling frequency, and interpolation of trend patterns to periods when water-quality data are sparse or absent. The TSM accounts for effects of serial correlation, which allows for inclusion of more data in the analysis and greater flexibility in timing of sample collection. Further, the TSM incorporates interannual, seasonal, and short-term information in flow-adjustment procedures, and ANN_C and $SEAS_C$ allow quantification of interannual and seasonal components of variability in concentration and streamflow relations. The OLS method used in this study and the nonparametric methods used in previous studies [Clark and Mason (2007), Wang and others (2007), and Clark (2012)] incorporate only concurrently measured streamflow and fixed seasonal functions; thus, the concentration and streamflow relation at a given time of sampling is assumed to depend only on streamflow magnitude and season with no accounting for streamflow conditions before sampling. For example, if two water-quality samples were collected at similar streamflow magnitudes at the same time of year, the flow-adjustment applied to the samples would be identical regardless of differences in streamflow conditions before sampling. If one sample was collected during increasing streamflow (for example on the rising limb of snowmelt runoff) in a dry year and the other sample was collected at a similar streamflow during decreasing streamflow (for example on the receding limb of snowmelt runoff) in a wet year, the same flow-adjustment would be applied to concentrations of both samples; there is no accounting for interannual or short-term hysteresis factors that affect concentration and streamflow relations (Vecchia, 2005; Peterson and others, 1996; Chanat and others, 2002). The TSM, however, analyzes continuous streamflow data to determine the context of streamflow conditions associated with a given time of sampling and account for interannual, seasonal, and short-term streamflow variability in flow-adjustment procedures.

Ordinary Least Squares Regression (OLS) on Time, Streamflow, and Season

For five sites, data requirements of the TSM were not met. In these cases, OLS on time, streamflow, and season was used to analyze trends. OLS generally is regarded as an acceptable alternative trend-analysis method relative to nonparametric methods, such as the seasonal Kendall tau, when data distributions are approximately normal (Helsel and Hirsch, 2002). OLS for trend analysis was applied following guidelines presented in Helsel and Hirsch (2002) and specific information concerning application of OLS in this study is presented in supplement 3.

As applied in this study, OLS required at least 6 sequential years of water-quality data with six or more samples per year (temporally distributed consistently among years) and associated instantaneous streamflow measurements at times of sample collection. A consistent OLS model was used to provide general application for the numerous site and constituent combinations with large variability in availability of data, and water-quality and streamflow relations. In general, constituent concentrations were regressed on streamflow, decimal time, and periodic functions to represent seasonal variability in concentration and streamflow relations. Specific information concerning suitability of application of OLS to the study datasets, and procedures for determination of the statistical significance and magnitude of trends is presented in supplement 2.

Selection of Trend-Analysis Time Periods

Appropriate selection of trend analysis time periods is important because trend-analysis results are dependent on how the time periods are structured. Factors considered in selection of trend analysis time periods included the following: timing of known watershed perturbations that might have affected stream water quality; examination of residual plots from TSM and OLS analyses with no trend (that is, no decimal time term in the models); temporal distribution of available data; definition of time periods of sufficient length to provide reasonably meaningful information on temporal variability; and maintenance of consistent trend-analysis time periods among sites, where possible, to assist in comparison of results.

Two primary 10-year trend-analysis periods were selected. Trend-analysis 10-year period 1 (water years 1986–95; hereinafter referred to as period 1) was selected to represent variability in major-ion concentrations in the Tongue and Powder River watersheds before potential effects of CBM-extraction activities. Trend analysis 10-year period 2 (water years 2001–10; hereinafter referred to as period 2) was selected because it encompassed substantial CBM-extraction activities and therefore might indicate potential effects of CBM-extraction activities on water quality of receiving streams in the Tongue and Powder River watersheds. These two 10-year trend analysis periods were used for all sites that satisfied requirements for the data-intensive TSM. The intervening time interval (water years 1996–2000) between period 1 and period 2 was not specified for trend analysis, largely because sufficient data generally were not available. For sites that did not satisfy data requirements for the TSM, OLS was used to analyze trends for period 2 (if complete data were available) or a 6-year period (2005–10) to provide information on water-quality characteristics that might have been affected by CBM-extraction activities. Additional data collection at these sites will increase record length for future analysis of temporal trends. The selected OLS trend-analysis periods correspond to trend-analysis periods of Clark (2012) for sites in Wyoming in the Tongue and Powder River watersheds. Information on trend-analysis methods and time periods for sites in the Tongue and Powder River watersheds are presented in table 1.

Streamflow Conditions and Other Factors that Affect Trend Results

Several factors affect temporal trends in water quality. Climatic variability (interannual and seasonal) affects concentration and streamflow relations and is indicated in variability in streamflow conditions. Trend methods vary with respect to accounting for streamflow variability. Thus, investigating streamflow conditions during the study period is relevant to interpreting trend results. Other factors also are relevant to understanding trend-analysis procedures and interpreting trend results. The other factors discussed in this section of the report include the following: relations between unadjusted concentrations and FACs; differences in data-collection activities and frequency between sites; effects of trend-analysis period definition; how the TSM procedures account for data gaps; and data transformation. The TSM is emphasized in this section because it is the method used for most sites in this study and it provides convenient access to relevant intermediate results to show trend-analysis concepts. Streamflow conditions during the study period also are discussed, primarily based on patterns in the TSM ANN_Q for selected stations. Then, example data and trend results are presented for selected sites to provide information on flow-adjustment characteristics, variability in data-collection activities, effects of data gaps, and other factors that affect trend results.

Streamflow Conditions

In general terms, ANN_Q determined by the TSM statistically describes the temporal deviation of streamflow from long-term median daily streamflow, after smoothing out typical repetitive seasonal variability and high-frequency variability in streamflow (that is, removing $SEAS_Q$ and HFV_Q). ANN_Q essentially can be interpreted as the moving geometric mean streamflow (generally equivalent to median streamflow) and provides an estimate of central tendency in streamflow through time. Daily mean streamflow and ANN_Q for water years 1980–2010 for selected sites in the Tongue and Powder River watersheds are presented in figures 6, and 7, respectively.

Temporal patterns in streamflow conditions during water years 1980–2010 were similar in the Tongue and Powder River watersheds. During period 1, streamflow generally was near the long-term (water years 1980–2010) median with generally small short-term (about 2–3 years) deviation above and below the long-term median (figs. 6 and 7). During water years 1996–2000 (the time interval between period 1 and period 2), streamflow generally was higher than the long-term median. Substantial CBM-extraction activities began during this period, with start dates in the site watersheds generally ranging from about 1997–99 (figs. 4 and 5; and Clark, 2012). During period 2, streamflow initially was below the long-term median (water years 2001–07), but then increased to above the long-term median (water years 2008–10). This pattern generally is consistent between the Tongue River and Powder River watersheds. Variable streamflow conditions during period 2 coincide with large increases in CBM-extraction activities in the Tongue and Powder River watersheds. Variable streamflow conditions in association with a large increase in CBM-extraction activities is relevant to flow-adjustment procedures and interpretation of trend results.

Effects of Tongue River Dam operations in regulating and decreasing seasonal streamflow variability are apparent in figure 6 by comparison of streamflow at Tongue River at State line (site 4; upstream from the dam) with streamflow at Tongue River at Tongue River Dam (site 5) and Tongue River at Birney Day School (site 7), which are downstream from the dam. General operations of Tongue River Dam include capture of high streamflows during spring snowmelt runoff to fill the reservoir (Kevin Smith, Montana Department of Natural Resources and Conservation, written commun., July 2012). After the reservoir is filled, contract water marketed by the Tongue River Water Users Association is released upon call by the water users. Contract water can be delivered May through September, although contract-water releases typically start in mid-July. Depending on remaining reservoir storage and climatic conditions, fall and winter releases are set in October and typically are not adjusted until late winter or early spring. Storage and subsequent release of water from the dam mixes chemical constituents and moderates streamflow variability downstream from the dam. Regulation effects of Tongue River Dam are relevant to flow-adjustment procedures and interpretation of trend results.

Factors that Affect Trend Results and Interpretation

To provide examples of factors that affect trend results and interpretation, sodium and estimated alkalinity data are presented in figures 8 and 9 for selected main-stem Tongue River sites and figures 10 and 11 for main-stem Powder River sites. FACs and fitted trends determined by using the TSM, and unadjusted concentrations for selected sites, are presented in the figures. Sodium and estimated alkalinity were selected as example constituents because they typically have large differences in concentrations between CBM-produced water and stream water; are constituents of primary concern with respect to potential effects of CBM-produced water on stream water quality; and have different chemical properties with respect to solubility relations, and concentration and streamflow relations that are suitable for showing concepts that generally apply to most other constituents. Main-stem Tongue River sites (sites 4, 5, 7, and 10) and main-stem Powder River sites (sites 11, 12, 13, and 16) were selected for presentation in figures 8–11 to provide examples for showing concepts that generally apply to most other sites. In some cases, issues relating to sites not shown in figures 8–11 that are relevant to interpretation of trend results are discussed. Several factors that potentially affect trend results are illustrated in figures 8–11, including the following: relations between unadjusted concentrations and FACs; differences in data-collection activities and frequency between sites; effects of trend-analysis period definition; and how the TSM procedures account for data gaps.

FACs are estimates of constituent concentrations after removing effects of streamflow variability. Thus, FACs typically have less variability than unadjusted concentrations, although the strength of this pattern is variable among sites and also can be variable through time for a given site. For dissolved major-ion constituents, unadjusted concentrations tend to be low during high-streamflow conditions and high during low-streamflow conditions. During high streamflow conditions, dilute atmospheric water (as rainfall or snowmelt) with short contact with soil and rock materials accounts for a large part of streamflow. During low-streamflow conditions, stream water typically contains a larger proportion of groundwater contributions, has had more contact with geological materials, and therefore incorporated more dissolved constituents. Flow-adjustment procedures account for these characteristics and produce FACs that are representative of variability within a consistent streamflow framework.

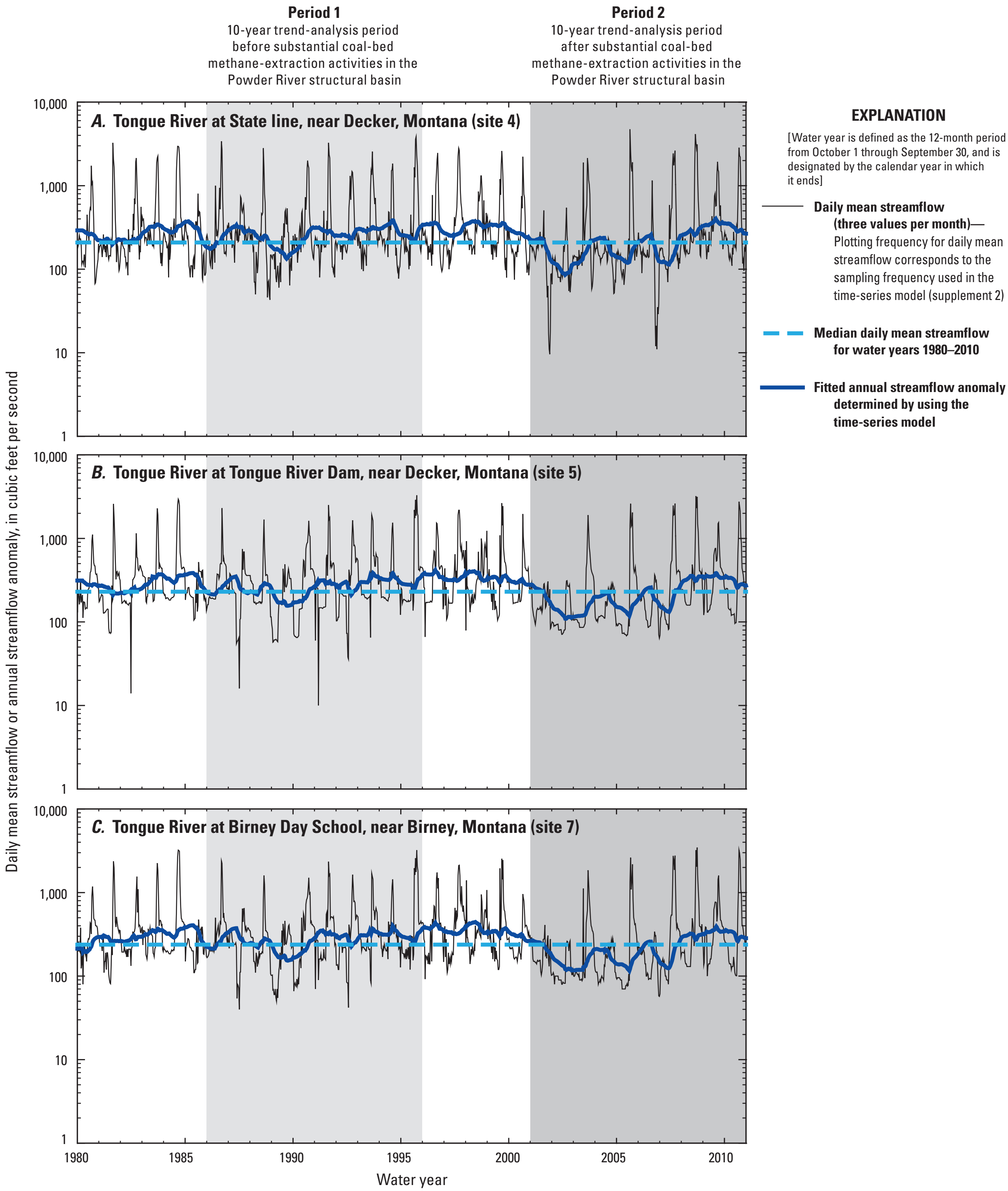


Figure 6. Daily mean streamflow (three values per month) and annual streamflow anomaly determined by using the time-series model (TSM) for sites in the Tongue River watershed, water years 1980–2010.

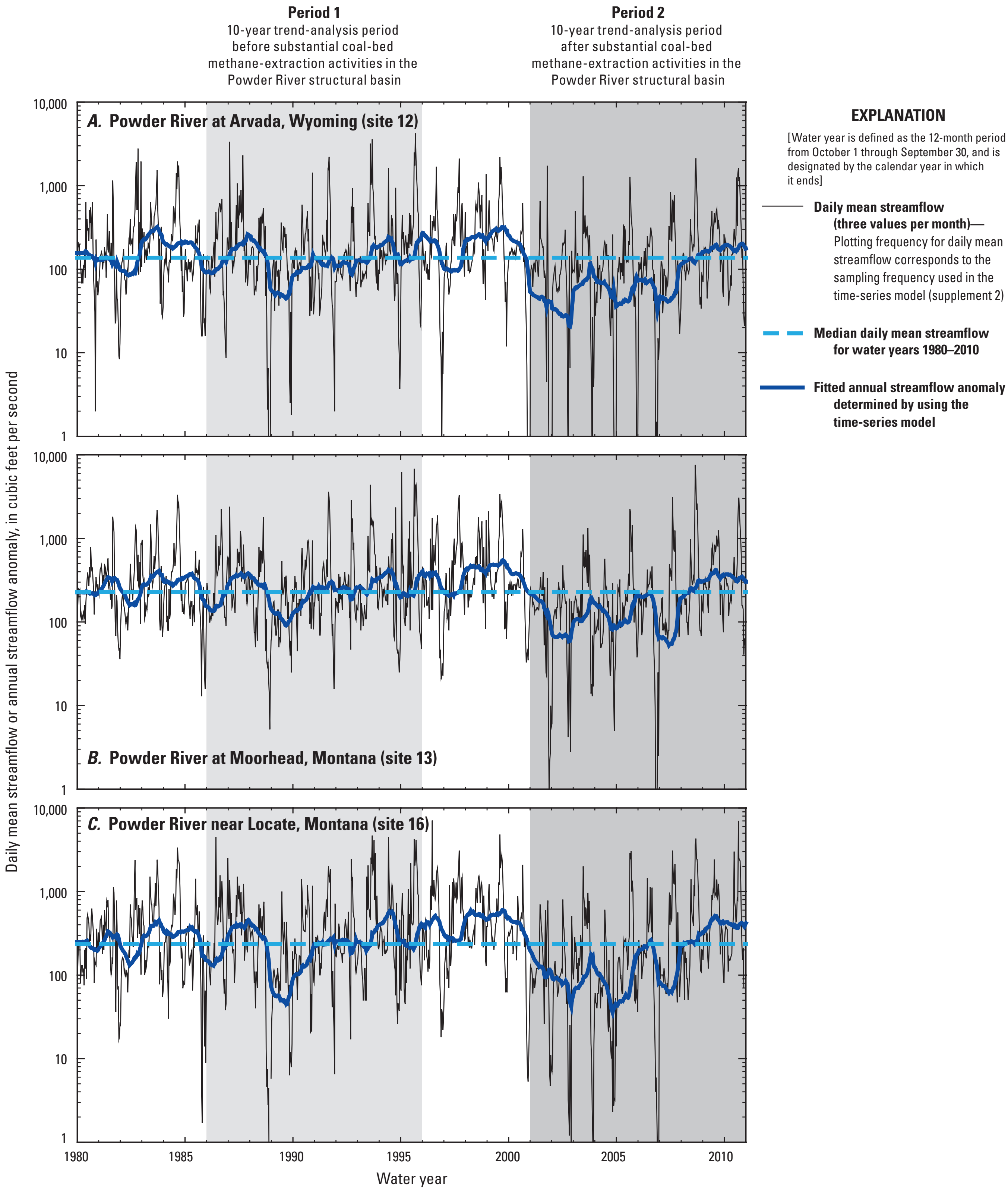


Figure 7. Daily mean streamflow (three values per month) and annual streamflow anomaly determined by using the time-series model (TSM) for sites in the Powder River watershed, water years 1980–2010.

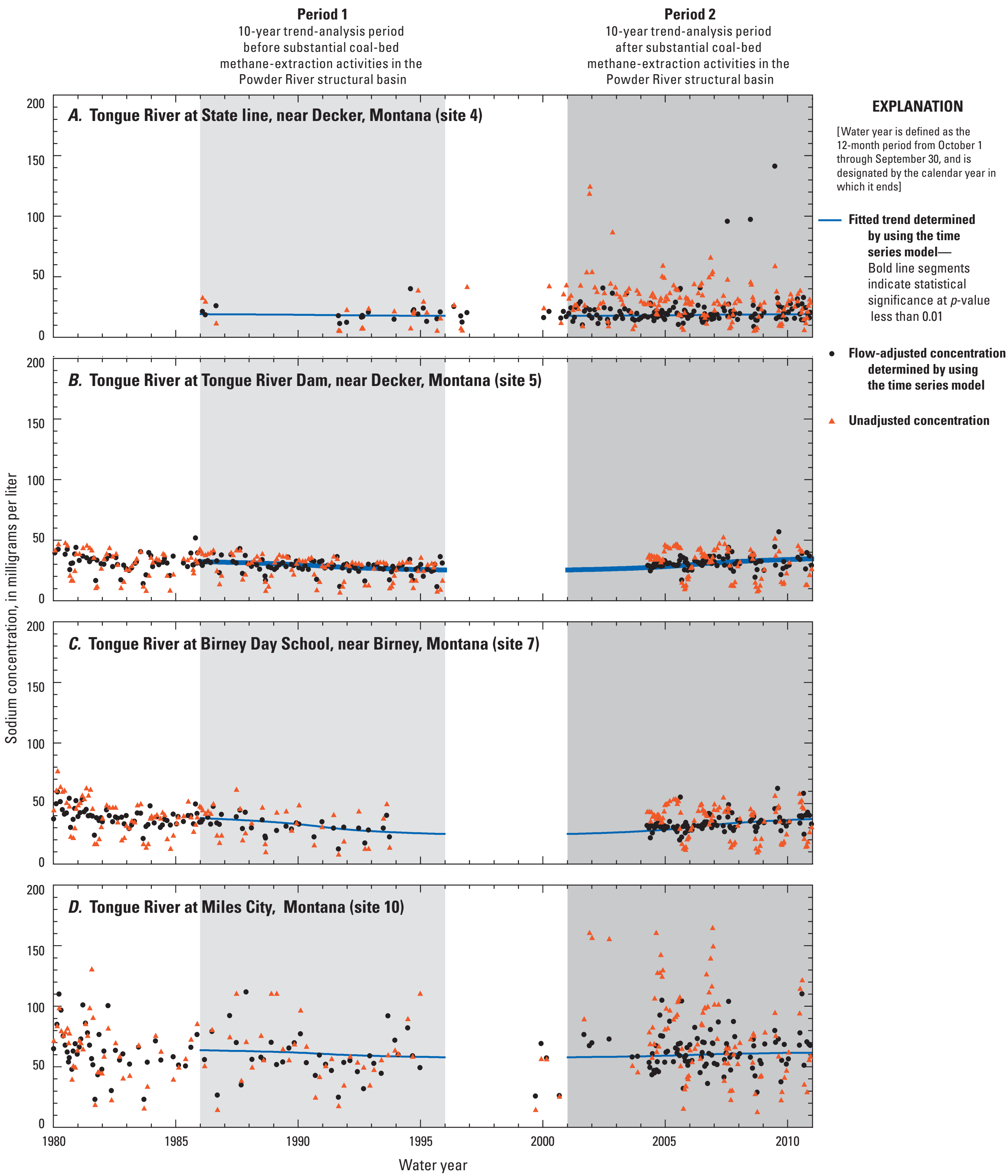


Figure 8. Sodium flow-adjusted concentrations and fitted trends determined by using the time series model (TSM), and unadjusted concentrations for sites in the Tongue River watershed, water years 1980–2010.

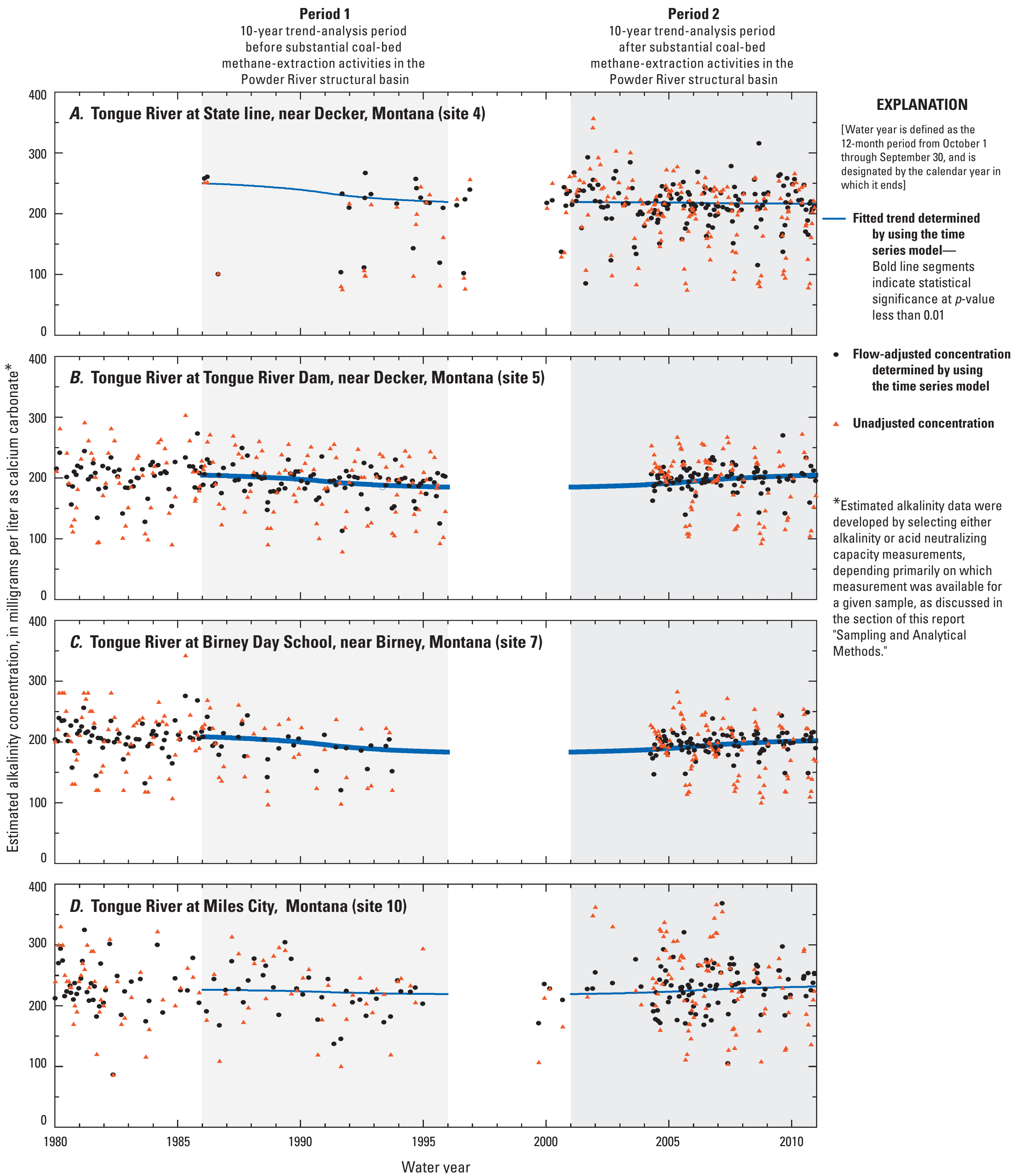


Figure 9. Estimated alkalinity flow-adjusted concentrations and fitted trends determined by using the time series model (TSM), and unadjusted concentrations for sites in the Tongue River watershed, water years 1980–2010.

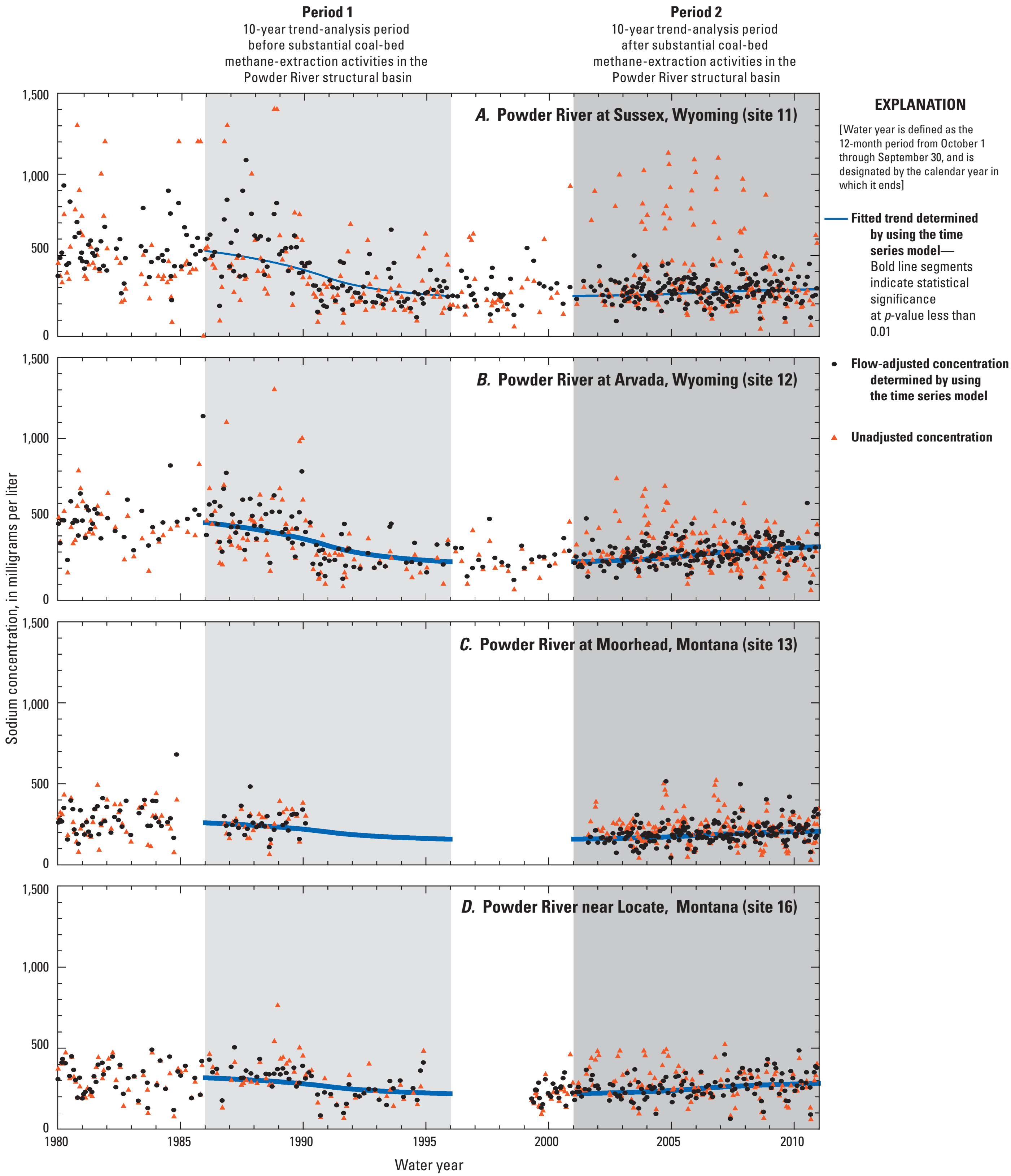


Figure 10. Sodium flow-adjusted concentrations and fitted trends determined by using the time series model (TSM), and unadjusted concentrations for sites in the Powder River watershed, water years 1980–2010.

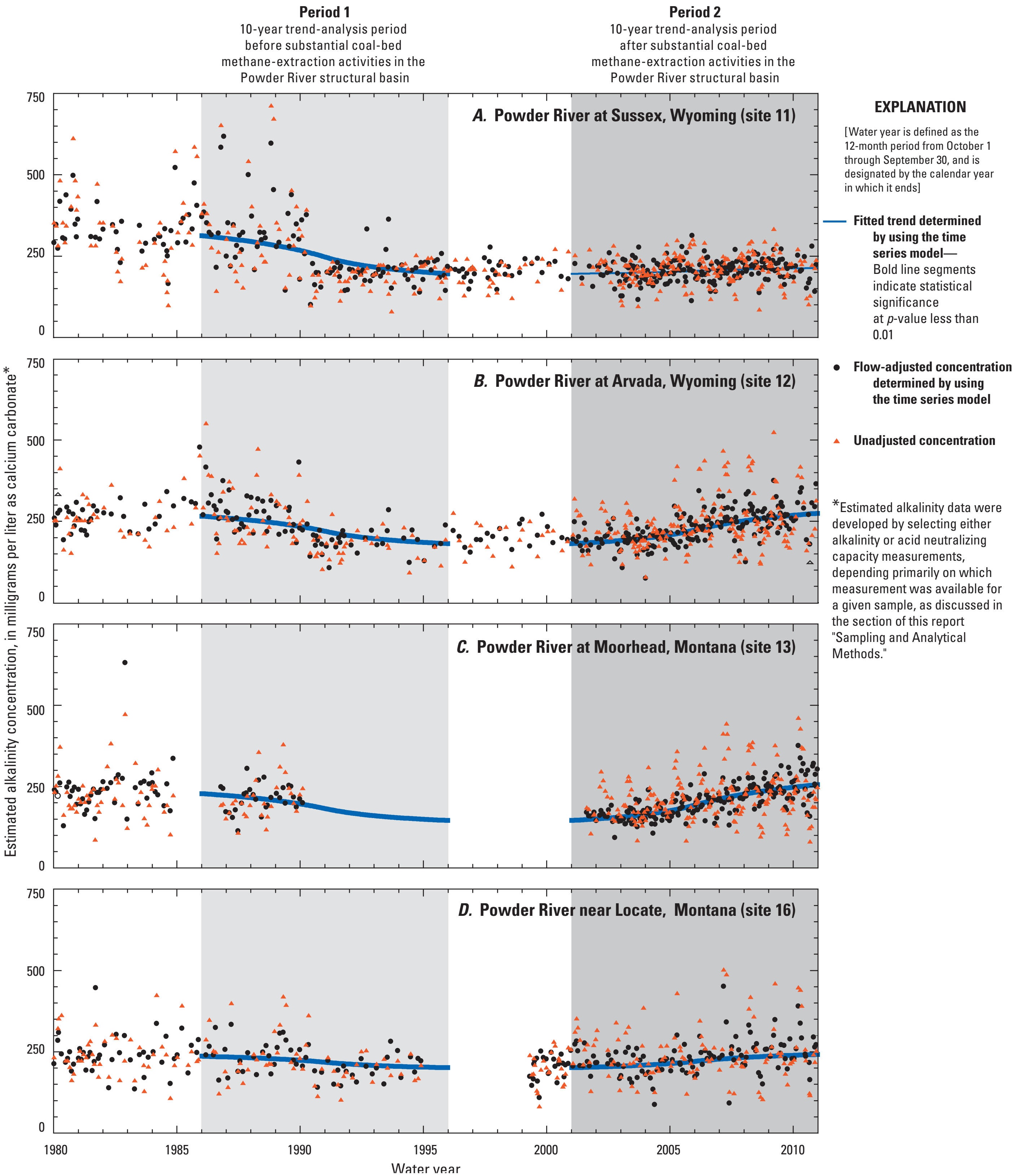


Figure 11. Estimated alkalinity flow-adjusted concentrations and fitted trends determined by using the time series model (TSM), and unadjusted concentrations for sites in the Powder River watershed, water years 1980–2010.

Thus, for typical streams in eastern Montana and Wyoming during low-streamflow conditions, FACs of dissolved major-ion constituents will tend to be less variable and lower than unadjusted concentrations. Sodium data for Powder River at Arvada (site 12; fig. 10*B*; water years 2001–05) provide an example of this pattern. Conversely, during high-streamflow conditions, FACs will tend to be less variable and higher than unadjusted concentrations. Alkalinity data for Powder River at Moorhead (site 13; fig. 11*C*; water years 2008–10) provide an example of this pattern. During near median streamflow conditions, FACs will tend to be less variable and centered within unadjusted concentrations. Alkalinity data for Tongue River at Tongue River Dam (site 5; fig. 9*B*; water years 1986–95) provide an example of this pattern. For the period 2008–10 following transition from low-streamflow to high-streamflow conditions, several sites have associated decreases in unadjusted concentrations. However, the TSM flow-adjustment procedures compensate for the streamflow variability and for some sites (for example, sites 12 and 13; figs. 10 and 11) the FACs and fitted trends indicate consistent increase in concentrations within a consistent streamflow framework. These patterns indicate importance of flow-adjusted trend analysis for identifying patterns in constituent concentrations independent from streamflow conditions.

Frequency and temporal variability in data-collection activities during the study period affect trend results. Data-collection characteristics were highly variable among sites in the Tongue and Powder River watersheds, as evidenced by the temporal distribution of unadjusted sodium data shown in figs. 8 and 10, respectively. In the Tongue River watershed, data-collection activities and frequency were variable, but all water-quality datasets have large data gaps (fig. 8). Tongue River at Monarch (site 1; not shown in fig. 8) is the only main-stem Tongue River site upstream from substantial CBM-extraction activities, but this site has sparse continuous streamflow data during the study period and the data could not be analyzed by using the TSM. Data density for the tributaries Goose Creek, Prairie Dog Creek, and Pumpkin Creek (sites 2, 3, and 9, respectively; not shown in fig. 8) generally was similar to site 1. Tongue River at State line (site 4; fig. 8*A*) is important because it is the first main-stem Tongue River site downstream from substantial CBM-extraction activities and located at the Wyoming and Montana border. However, water-quality data collection for site 4 was infrequent before substantial CBM-extraction activities and the water-quality dataset is less suitable for the TSM trend analysis than most other sites to which the TSM was applied. Larger datasets that include good seasonal representation through long time periods increase capability of the TSM to define concentration and streamflow relations and accurately quantify interannual, seasonal, and short-term effects on the relations. Because the site 4 dataset lacks good representation through a long time period, the trend results should be used with caution. Tongue River at Tongue River Dam (site 5; fig. 8*B*) had frequent water-quality data collection through water year 1995, but a large data gap during a critical period (water years 1996–2003). Tongue River at Birney Day School (site 7; fig. 8*C*) had water-quality data collection similar to site 5, but the data gap was larger, extending from 1994–2003. Water-quality data collection for the tributaries Hanging Woman Creek and Otter Creek (sites 6 and 8, respectively; not shown in fig. 8) generally was similar to sites 5 and 7, but with minor variability in start and end times of intermediate data gaps. Tongue River at Miles City (site 10; fig. 8*D*) had water-quality data collection generally similar to site 5.

Factors that limit capability to detect trends potentially attributable to CBM-extraction activities for main-stem Tongue River sites include the following: there are no main-stem Tongue River sites upstream from substantial CBM-extraction activities that have sufficient data for analysis using the TSM ; and data gaps for sites downstream from substantial CBM-extraction activities generally extend past the start of substantial CBM-extraction activities to a time when CBM-extraction activities in the Tongue River watershed were nearly constant. Further, although some main-stem Tongue River sites have datasets that are more suitable for trend analysis than others, datasets for all main-stem Tongue River sites have data gaps or time periods with infrequent sample collection. However, the datasets typically are sufficient to make general observations on how changes in water quality after the start of substantial CBM-extraction activities relate to patterns before the start of substantial CBM-extraction activities.

In the Powder River watershed, data-collection activities and frequency were variable; but datasets for main-stem Powder River sites are considered more suitable for trend analysis than datasets for main-stem Tongue River sites. Datasets for main-stem Powder River sites generally were denser and encompassed longer time periods than datasets for main-stem Tongue River sites (figs. 8 and 10). Powder River at Sussex (site 11; fig. 10*A*) is upstream from substantial CBM-extraction activities and has sufficient data collection before and after CBM-extraction activities to characterize water-quality patterns during the two periods. Powder River at Arvada (site 12; fig. 10*B*), the first site main-stem Powder River site downstream from substantial CBM-extraction activities, had water-quality data collection similar to site 11. Powder River at Moorhead (site 13; fig. 10*C*) and Powder River near Locate (site 16; fig. 10*D*) had water-quality data collection with variable data gaps (extending from water years 1991-2002 and 1995–98, respectively). Investigation of trend results for sites 13 and 16 (with data gaps) in conjunction with site 12 (with no data gaps) generally allows for evaluation of effects of CBM-extraction activities on the main-stem Powder River from near the point of first potential effects to near the mouth of the Powder River. However, the large data gap for site 13 might affect trend results (as discussed in the section of this report "Trends in Major-Ion Constituents and Properties for Selected Sampling Sites in the Tongue and Powder River Watersheds"). Water-quality data collection for the two sites on the Little Powder River (a large plains tributary to the main-stem Powder River) was variable. Little Powder River above Dry Creek (site 14; not shown in fig. 10) is downstream from substantial

CBM-extraction activities and had data collection generally similar to site 12. Little Powder River near Broadus (site 15; not shown in fig. 10) also is downstream from substantial CBM-extraction activities and had data collection restricted to the period water years 2005–10, generally similar to tributary site 2 in the Tongue River watershed.

Definition of trend-analysis periods affects trend-analysis results. For the TSM, fitted trends in FACs during a defined trend-analysis period are monotonic trends that are smoothed to produce generally consistent slopes across the middle section of the trend-analysis period that become flatter near the ends. The flatter slopes near the ends provide gradual transition from trend-analysis periods to time intervals with no trend analysis. In some cases, the fitted trends do not precisely follow the patterns in FACs and unresolved trending in FACs is apparent. For example, large and abrupt decreases in sodium and estimated alkalinity FACs at Powder River at Sussex (site 11; the first main-stem Powder River site downstream from Salt Creek) were associated with the period starting in 1990 when Salt Creek oil brine was reinjected to deep disposal (figs. 10*A* and 11*A*). Sodium and estimated alkalinity FACs indicate near complete response to the oil-brine reinjection by water year 1992 and then generally stable patterns through the end of period 1 (water year 1995; figs. 10*A* and 11*A*). However, the fitted-trend decrease in sodium and estimated alkalinity generally was distributed consistently across period 1 (figs 10*A* and 11*A*). Thus, there are short-term trend patterns in the FACs that are unresolved in the fitted trends. Although the smoothed fitted trend from the TSM was less abrupt than the apparent change in FACs, the overall change from the start to the end of the period was accurately represented. Better temporal resolution in fitted trends for site 11 (or other sites) might have been attained by defining two or more additional trend-analysis periods within the selected 10-year trend-analysis periods. However, this approach would have required detailed site-by-site trend analysis for potentially inconsistent time periods among the 16 sites in this study. An important consideration in the design of the trend-analysis structure of this study was the capability to make general comparisons among the 16 sites with respect to potential effects of CBM-extraction activities on a large-scale basis throughout consistent time periods. Further, the overall fitted trends during the defined trend-analysis periods are consistent with overall patterns in FACs (figs. 8–11).

Data gaps present complications for trend analysis. If data gaps are of long duration and include important time intervals, such as intervals during baseline conditions before known watershed perturbations or intervals during which effects of perturbations would be expected to be changing abruptly, the available data might not be sufficient to accurately define trends. During periods of data gaps within defined trend-analysis periods (indicated for several sites in figs. 8–11), the TSM interpolates forward or backward (depending on location of the data gap within the defined trend analysis period) to the start or end of the defined trend-analysis period, or to the next closest FAC, based on fitted model coefficients (Vecchia, 2003). The intervening time interval (water years 1996–2000) between period 1 and period 2 was not specified for trend analysis primarily because of the large number of sites that had no data collection during the interval. Within the interval the TSM applies a straight-line fit between the fitted trend at the end of period 1 and the start of the second trend-analysis period. Thus, changes in patterns of FACs are applied to the fitted trends within the defined trend-analysis periods. General stationarity during the interval between period 1 and period 2 is important in accurate determination of fitted trends. Large trending in FACs during the interval could result in unrepresentative fitted trends. This factor was considered in defining trend-analysis periods used in this study. In the Powder River watershed, Powder River at Sussex (site 11), Powder River at Arvada (site 12), Little Powder River above Dry Creek (site 14), and Powder River near Locate (site 16) had sufficient data during the interval between period 1 and period 2 to conclude that large trending in FACs was absent during the interval (for example, see patterns in sodium and estimated alkalinity FACs; figs. 10*A, B, D*, 11*A*, *B*, *D*). Conclusions for sites 11, 12, 14, and 16, concerning general stationarity in FACs during the interval, were extrapolated to conclude that large trending in FACs probably was absent during the interval for Powder River at Moorhead (site 13). However, site 13 lacks data during a substantial part of period 1, with no data during water years 1991–95 to define concentration and streamflow relations after Salt Creek oil brine reinjection. This data gap for site 13 might have affected trend results (as discussed in the section of this report “Trends in Major-Ion Constituents and Properties for Selected Sampling Sites in the Tongue and Powder River Watersheds”). In the Tongue River watershed, there were no sites with complete datasets during the intervening time interval between period 1 and period 2. Some sites had specific conductance data that generally indicated stationarity during the intervening period. Specific conductance generally provides an accurate indicator of ionic strength, but it might not be an accurate indicator of variability in concentrations of individual major ions if proportions of major ions in stream water change because of natural or anthropogenic causes. Also, most sites in the Tongue River watershed had data gaps during either period 1 or period 2. The issues of stationarity during the interval between period 1 and period 2, and data gaps during the trend-analysis periods are factors contributing to greater uncertainty in fitted trends for sites in the Tongue River watershed than for sites in the Powder River watershed.

An important consideration in interpreting trend results relates to the trend-analysis methods incorporating logarithm (base 10) transformation of constituent concentrations. Log-transformation results in datasets that are approximately normally distributed and allows analysis using rigorous parametric procedures. However, log-transformation decreases variability in the data relative to the original untransformed units representative of actual environmental variability. The effects of data transformation do not negatively influence a primary purpose of this study in determining water-quality trends and evaluating relative temporal changes in major-ion characteristics among sites. In the trend analyses, all data (high and low values) affect changes in flow-adjusted median values. Thus, the fitted trends truly represent unbiased estimates of overall changes in central tendency. The overall changes in central tendency are quantified with respect to geometric mean (generally equivalent to median) concentration in reference to log-transformed streamflow. In general, changes in median concentrations that might be attributed to CBM-extraction activities probably are more strongly evident during low-to-median streamflow conditions (when CBM-produced water would be expected to account for a larger proportion of streamflow) than during mean-to-high streamflow conditions. This observation is relevant in assessing trend results in relation to specific water-quality concerns, including effects of water-quality changes on agricultural producers and effects on stream biota and ecology. Trends in median concentrations in reference to log-transformed streamflow provide general information on overall temporal changes (in terms of directions and relative magnitudes) in concentrations, but might be difficult to interpret with respect to how those changes translate into specific effects on agricultural producers or stream ecology.

Trends in Major-Ion Constituents and Properties for Selected Sampling Sites in the Tongue and Powder River Watersheds

Trend results are presented in this report for all sites (by watershed), whether or not there have been substantial CBM-extraction activities in their watersheds. Summaries of trend results (tables 2–5) include information on trend directions, magnitudes, and significance, and estimated fitted trend values at the start and end of trend-analysis periods. Statistical significance of trends was based on a *p*-value less than 0.01, used by Vecchia (2005) for the TSM analysis. Magnitudes of trends are expressed as total percent change during the specified trend-analysis period; an approach also used by Vecchia (2005). Detailed trend-analysis results are presented in figures 4.1–4.16 and tables 4.1–4.4. The figures and tables present a large amount of information concerning major ion characteristics in the Tongue and Powder River watersheds. For brevity, discussion in this section generally is limited to observations concerning trend results that might relate to potential effects of CBM-extraction activities in the site watersheds. Investigation of possible causal factors of trend results for sites or time periods not affected by CBM-extraction activities was beyond the scope of this study. For TSM results, ANN_C and $SEAS_C$ coefficients are discussed to present information on relative influence of interannual and seasonal effects on concentration and streamflow relations and trend results. The TSM also incorporates short-term effects (HFV_C) on concentration and streamflow relations; however, HFV_C relations are complex and, for brevity, are not discussed.

The patterns in the fitted trends shown in figures 4.1–4.16 (as well as the directions and magnitudes of the trends presented in tables 2–5 and 4.1–4.4) are considered to provide important information beyond the strict statistical characteristics of the trend results (in terms of *p*-values and levels of significance). If CBM-extraction activities are affecting water quality, intuitively there should be increases in some major ions and associated decreases in other major ions, with relative variability dependent on water-quality characteristics for a given site and CBM-produced water in the site watershed. Data analyzed in this study are complex and variable, with respect to several factors, including concentration and streamflow relations and data-collection characteristics. Consideration of patterns in direction and magnitude of fitted trends for various major ions for a given site or among sites might provide relevant information in interpreting trend results, even though results for each major ion might not have been determined to be statistically significant; thus, in some cases nonsignificant trend results are discussed. Visualization of fitted trends in relation to FACs (as shown in figs. 4.1–4.16), on which the fitted trends are based, provides information to evaluate how trend results and determination of significance levels might be affected by variability in data collection.

Accurate FACs and fitted trends should be consistent with chemical processes. Consistency of FACs and fitted trends with chemical processes was evaluated by examining percent differences in cation and anion balances, and agreement between magnitudes of fitted trends for specific conductance and dissolved solids. Mean percent differences in cation and anion balances for fitted trends and FACs (table 4.5) were within +/- 3 percent for all sites except Tongue River at State line (site 4) and indicated general consistency with chemical processes. Percent differences in cation and anion balances for the TSM fitted trends and FACs for site 4 indicate positive bias and the range in percent differences in cation and anion balances of FACs is much larger than for other sites. For example, for the fitted trends, site 4 had a mean percent difference in cation and anion balances of +5.6 and a range of +3.4 to +7.0 percent (table 4.5). In contrast, the combined mean percent difference in cation and ion balances for the other 10 sites analyzed by using the TSM was -0.05 with a mean range of -1.4 to +1.4. For the FACs, site 4 had a mean percent difference in cation and anion balances of +4.6 and a range of -28 to +15 percent. In contrast, the combined mean percent difference in cation and ion balances for the FACs at the other 10 sites analyzed by using the TSM was -0.18 with a mean range of -5.9 to +8.0. Trend analyses for site 4 probably are affected by marginally sufficient data, which are sparse and poorly distributed during period 1, and might not be of sufficient detail for accurately determining concentration and flow relations by using the TSM. For a given site and trend-period combination, agreement between trend magnitude for specific conductance and dissolved solids was evaluated by determining whether the RPD (eq. 1, with *X* equal to trend magnitude for specific conductance and *Y* equal to trend magnitude for dissolved solids) was within the range of +/- 20 percent, or

Table 2. Summary of trend results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.

[Bold values indicate statistically significant (at p-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light gray shading indicates upward fitted trend. p-value, statistical significance level; <, less than; Mont., Montana]

Constituent or property	Fitted trend value at start of water year 1986 (start of period 1)	Fitted trend value at end of water year 1995 (end of period 1)	Estimated total percent change for period 1	Fitted trend value at start of water year 2001 (start of period 2)	Fitted trend value at end of water year 2010 (end of period 2)	Estimated total percent change for period 2
Tongue River main-stem sites						
Tongue River at State line, near Decker, Mont. (site 4, fig. 1)						
Specific conductance	773	644	**-17**	644	675	5
Calcium, dissolved	59	55	-7	55	58	5
Magnesium, dissolved	46	40	-12	40	38	-4
Potassium, dissolved	2.5	2.5	0	2.5	2.7	7
Sodium adsorption ratio	0.55	0.56	2	0.56	0.60	7
Sodium, dissolved	19	18	-7	18	19	7
"Estimated alkalinity"[2]	250	219	-12	219	216	-1
Chloride, dissolved	4.1	4.0	-2	4.0	5.3	**31**
Fluoride, dissolved	0.19	0.22	14	0.22	0.26	17
Sulfate, dissolved	94	73	-23	73	74	2
Solids, dissolved, (sum of constituents)	511	432	-16	432	425	-1
Tongue River at Tongue River Dam, near Decker, Mont. (site 5, fig. 1)						
Specific conductance	664	561	-16	561	565	1
Calcium, dissolved	59	52	**-13**	52	52	0
Magnesium, dissolved	41	32	**-22**	32	31	-1
Potassium, dissolved	3.4	2.7	**-20**	2.7	2.9	8
Sodium adsorption ratio	0.81	0.68	-16	0.68	0.94	38
Sodium, dissolved	32	25	**-21**	25	35	**36**
"Estimated alkalinity"[2]	205	185	**-10**	185	205	**11**
Chloride, dissolved	3.4	3.2	-5	3.2	3.6	13
Fluoride, dissolved	0.25	0.23	-10	0.23	0.30	33
Sulfate, dissolved	163	108	**-34**	108	116	8
Solids, dissolved, (sum of constituents)	438	342	**-22**	342	378	**10**
Tongue River at Birney Day School, near Birney, Mont. (site 7, fig. 1)						
Specific conductance	700	597	-15	597	587	-2
Calcium, dissolved	57	47	-19	47	51	9
Magnesium, dissolved	39	26	**-33**	26	32	**20**
Potassium, dissolved	3.8	2.9	**-24**	2.9	3.2	10
Sodium adsorption ratio	0.95	0.70	-27	0.70	1.0	46
Sodium, dissolved	38	25	-35	25	37	50
"Estimated alkalinity"[2]	209	184	**-12**	184	203	**10**
Chloride, dissolved	3.7	3.1	-15	3.1	3.9	25
Fluoride, dissolved	0.29	0.25	-15	0.25	0.30	19
Sulfate, dissolved	176	107	**-39**	107	130	22
Solids, dissolved, (sum of constituents)	444	313	**-30**	313	378	**21**

Table 2. Summary of trend results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.—Continued

[Bold values indicate statistically significant (at p-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light gray shading indicates upward fitted trend. p-value, statistical significance level; <, less than; Mont., Montana]

Constituent or property	Fitted trend value at start of water year 1986 (start of period 1)	Fitted trend value at end of water year 1995 (end of period 1)	Estimated total percent change for period 1	Fitted trend value at start of water year 2001 (start of period 2)	Fitted trend value at end of water year 2010 (end of period 2)	Estimated total percent change for period 2
Tongue River at Miles City, Mont. (site 10, fig. 1)						
Specific conductance	847	785	-7	785	796	1
Calcium, dissolved	61	55	-10	55	57	4
Magnesium, dissolved	44	33	**-25**	33	37	14
Potassium, dissolved	5.1	4.1	-21	4.0	4.3	6
Sodium adsorption ratio	1.6	1.5	-4	1.5	1.6	7
Sodium, dissolved	64	58	-9	58	62	7
"Estimated alkalinity"[2]	228	220	-3	220	233	6
Chloride, dissolved	4.8	4.1	**-14**	4.1	5.0	**22**
Fluoride, dissolved	0.31	0.28	-11	0.28	0.33	20
Sulfate, dissolved	234	175	**-25**	175	190	9
Solids, dissolved, (sum of constituents)	558	482	**-14**	481	505	5
Tongue River tributary sites						
Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)						
Specific conductance	2,320	2,550	10	2,550	2,720	7
Calcium, dissolved	91	94	3	94	105	12
Magnesium, dissolved	117	128	10	128	142	11
Potassium, dissolved	13	15	**18**	15	16	8
Sodium adsorption ratio	5.1	5.5	8	5.5	4.8	-13
Sodium, dissolved	308	348	13	348	329	-6
"Estimated alkalinity"[2]	486	475	-2	475	564	**18**
Chloride, dissolved	13	14	7	14	13	-8
Fluoride, dissolved	1.1	1.0	-9	1.0	1.2	14
Sulfate, dissolved	855	908	6	910	968	6
Solids, dissolved, (sum of constituents)	1,710	1,790	5	1,790	2,000	12
Otter Creek at Ashland, Mont. (site 8, fig. 1)						
Specific conductance	2,880	2,600	**-10**	2,600	2,990	**15**
Calcium, dissolved	79	68	-14	68	83	22
Magnesium, dissolved	153	136	-11	136	161	18
Potassium, dissolved	20	20	0	20	19	-3
Sodium adsorption ratio	5.8	6.0	5	6.0	5.9	-2
Sodium, dissolved	379	356	-6	356	418	17
"Estimated alkalinity"[2]	521	521	0	521	575	**11**
Chloride, dissolved	13	14	3	14	12	-13
Fluoride, dissolved	0.79	0.83	5	0.83	0.91	11
Sulfate, dissolved	1,080	908	**-16**	908	1,230	**35**
Solids, dissolved, (sum of constituents)	2,060	1,820	**-11**	1,820	2,300	**26**

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]"Estimated alkalinity" data were developed by selecting either alkalinity or acid neutralizing capacity (ANC), depending primarily on which measurement was available for a given sample, as discussed in the section of this report "Sampling and Analytical Methods."

Table 3. Summary of trend results determined by using ordinary least squares regression (OLS) on time, streamflow, and season for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 2001–10.

[Bold values indicate statistically significant (at *p*-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light gray shading indicates upward fitted trend. *p*-value, statistical significance level; <, less than; Wyo., Wyoming; Mont., Montana; NR, not reported; SEE, standard error of estimate]

Constituent or property	Fitted trend value at start of indicatedtrend-analysis period	Fitted trend value at end of indicated trend-analysis period	Estimated total percent change during indicated trend-analysis period
Tongue River at Monarch, Wyo. (site 1, fig. 1)			
Trend-analysis period water years 2005–10			
Specific conductance	339	393	**16**
Calcium, dissolved	40	46	**16**
Magnesium, dissolved	16	18	**15**
Potassium, dissolved	1.3	1.4	4
Sodium adsorption ratio	0.28	0.31	11
Sodium, dissolved	8.2	9.7	19
Alkalinity	147	172	**17**
Chloride, dissolved	1.1	1.5	**42**
Fluoride, dissolved	0.16	0.15	-7
Sulfate, dissolved	33	41	**26**
Solids, dissolved, (sum of constituents)	197	229	**16**
Goose Creek below Sheridan, Wyo. (site 2, fig. 1)			
Trend-analysis period water years 2001–10			
Specific conductance	539	567	5
Calcium, dissolved	50	52	6
Magnesium, dissolved	31	33	5
Potassium, dissolved	2.6	2.7	1
Sodium adsorption ratio	0.54	0.53	-1
Sodium, dissolved	20	20	2
Alkalinity	193	204	6
Chloride, dissolved	5.1	6.6	29
Fluoride, dissolved	0.27	0.26	-3
Sulfate, dissolved	94	95	1
Solids, dissolved, (sum of constituents)	328	342	4
Trend-analysis period water years 2005–10			
Specific conductance	546	529	-3
Calcium, dissolved	50	50	0
Magnesium, dissolved	32	29	-9
Potassium, dissolved	2.7	2.5	-6
Sodium adsorption ratio	0.53	0.50	-6
Sodium, dissolved	20	18	-8
Alkalinity	195	195	0
Chloride, dissolved	5.3	6.2	18
Fluoride, dissolved	0.26	0.26	-2
Sulfate, dissolved	95	84	-11
Solids, dissolved, (sum of constituents)	334	320	-4

Table 3. Summary of trend results determined by using ordinary least squares regression (OLS) on time, streamflow, and season for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 2001–10.—Continued

[Bold values indicate statistically significant (at *p*-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light gray shading indicates upward fitted trend. *p*-value, statistical significance level; <, less than; Wyo., Wyoming; Mont., Montana; NR, not reported; SEE, standard error of estimate]

Constituent or property	Fitted trend value at start of indicatedtrend-analysis period	Fitted trend value at end of indicated trend-analysis period	Estimated total percent change during indicated trend-analysis period
Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)			
Trend-analysis period water years 2001–10			
Specific conductance	1,270	1,480	**17**
Calcium, dissolved	118	131	12
Magnesium, dissolved	72	89	**24**
Potassium, dissolved	6.9	7.8	13
Sodium adsorption ratio	1.1	1.4	**32**
Sodium, dissolved	59	85	**43**
Alkalinity	289	323	**12**
Chloride, dissolved	3.4	5.2	**52**
Fluoride, dissolved	0.29	0.30	5
Sulfate, dissolved	418	532	**27**
Solids, dissolved, (sum of constituents)	873	1,070	**22**
Trend-analysis period water years 2005–10			
Specific conductance	1,260	1,480	**17**
Calcium, dissolved	120	127	6
Magnesium, dissolved	74	88	19
Potassium, dissolved	6.9	7.8	12
Sodium adsorption ratio	1.1	1.5	**32**
Sodium, dissolved	62	86	**41**
Alkalinity	292	321	10
Chloride, dissolved	3.4	5.4	**57**
Fluoride, dissolved	0.30	0.29	-3
Sulfate, dissolved	400	533	**33**
Solids, dissolved, (sum of constituents)	866	1,070	**23**
Pumpkin Creek near Miles City, Mont. (site 9, fig. 1)			
Trend-analysis period water years 2005–10			
Specific conductance	783	2,100	**168**
Calcium, dissolved	NR[2]	NR[2]	NR[2]
Magnesium, dissolved	NR[2]	NR[2]	NR[2]
Potassium, dissolved	5.4	12	**123**
Sodium adsorption ratio	10	9.9	-3
Sodium, dissolved	171	472	**176**
Alkalinity	178	330	**85**
Chloride, dissolved	3.0	8.2	**176**
Fluoride, dissolved	0.52	0.46	-12
Sulfate, dissolved	NR[2]	NR[2]	NR[2]
Solids, dissolved, (sum of constituents)	545	2,010	**269**

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Results not reported because of regression standard error of estimate (SEE) greater than 75 percent.

Table 4. Summary of trend results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Powder River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.

[Bold values indicate statistically significant (at *p*-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light green shading indicates upward fitted trend. *p*-value, statistical significance level; <, less than; Wyo., Wyoming; Mont., Montana]

Constituent or property	Fitted trend value at start of water year 1986 (start of period 1)	Fitted trend value at end of water year 1995 (end of period 1)	Estimated total percent change for period 1	Fitted trend value at start of water year 2001 (start of period 2)	Fitted trend value at end of water year 2010 (end of period 2)	Estimated total percent change for period 2
Powder River main-stem sites						
Powder River at Sussex, Wyo. (site 11, fig. 1)						
Specific conductance	3,120	2,160	-31	2,160	2,340	8
Calcium, dissolved	110	133	21	133	136	2
Magnesium, dissolved	47	51	9	51	49	-6
Potassium, dissolved	8.5	7.6	**-10**	7.6	9.7	**28**
Sodium adsorption ratio	9.0	5.1	**-43**	5.1	5.5	7
Sodium, dissolved	528	249	-53	249	290	17
"Estimated alkalinity"[2]	313	196	**-37**	196	213	9
Chloride, dissolved	384	143	**-63**	143	206	**44**
Fluoride, dissolved	0.91	0.68	**-25**	0.68	0.82	**20**
Sulfate, dissolved	631	718	14	718	668	-7
Solids, dissolved, (sum of constituents)	2,020	1,440	**-29**	1,440	1,550	8
Powder River at Arvada, Wyo. (site 12, fig. 1)						
Specific conductance	3,090	2,170	**-30**	2,170	2,370	9
Calcium, dissolved	132	150	**14**	150	116	**-23**
Magnesium, dissolved	61	62	2	62	52	**-16**
Potassium, dissolved	7.9	7.2	-8	7.2	11	**60**
Sodium adsorption ratio	8.6	4.2	**-51**	4.2	6.4	**53**
Sodium, dissolved	482	239	**-50**	239	333	**39**
"Estimated alkalinity"[2]	266	182	**-32**	182	275	**51**
Chloride, dissolved	321	123	**-62**	123	168	**37**
Fluoride, dissolved	0.70	0.49	**-31**	0.49	0.72	**48**
Sulfate, dissolved	818	807	-2	807	667	**-17**
Solids, dissolved, (sum of constituents)	2,050	1,500	**-27**	1,500	1,560	4
Powder River at Moorhead, Mont. (site 13, fig. 1)						
Specific conductance	2,120	1,640	**-23**	1,640	1,710	4
Calcium, dissolved	120	125	4	125	101	**-19**
Magnesium, dissolved	56	51	-9	51	47	**-7**
Potassium, dissolved	6.8	5.8	**-14**	5.8	8.5	**45**
Sodium adsorption ratio	5.0	3.0	**-39**	3.0	4.3	**41**
Sodium, dissolved	259	159	**-39**	159	208	**31**
"Estimated alkalinity"[2]	229	146	**-36**	146	256	**75**
Chloride, dissolved	152	83	**-46**	83	78	-6
Fluoride, dissolved	0.46	0.39	**-15**	0.39	0.56	**44**
Sulfate, dissolved	653	605	**-7**	605	507	**-16**
Solids, dissolved, (sum of constituents)	1,400	1,100	**-21**	1,100	1,130	3

Table 4. Summary of trend results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Powder River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.—Continued

[Bold values indicate statistically significant (at p-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light gray shading indicates upward fitted trend. p-value, statistical significance level; <, less than; Mont., Montana]

Constituent or property	Fitted trend value at start of water year 1986 (start of period 1)	Fitted trend value at end of water year 1995 (end of period 1)	Estimated total percent change for period 1	Fitted trend value at start of water year 2001 (start of period 2)	Fitted trend value at end of water year 2010 (end of period 2)	Estimated total percent change for period 2
Powder River near Locate, Mont. (site 16, fig. 1)						
Specific conductance	2,310	1,850	**-20**	1,850	2,070	12
Calcium, dissolved	127	122	-4	122	111	-9
Magnesium, dissolved	61	53	-13	53	57	7
Potassium, dissolved	7.8	6.9	**-11**	6.9	9.9	**42**
Sodium adsorption ratio	5.9	4.2	**-29**	4.2	5.4	**28**
Sodium, dissolved	317	219	**-31**	219	283	**29**
"Estimated alkalinity"[2]	237	201	**-15**	201	242	**20**
Chloride, dissolved	157	68	**-56**	68	92	**36**
Fluoride, dissolved	0.45	0.38	**-15**	0.38	0.50	**33**
Sulfate, dissolved	789	690	-13	690	735	6
Solids, dissolved, (sum of constituents)	1,650	1,300	**-21**	1,300	1,470	13
Little Powder River site						
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)						
Specific conductance	2,540	2,830	12	2,830	3,050	8
Calcium, dissolved	131	139	6	139	154	11
Magnesium, dissolved	87	92	5	92	98	6
Potassium, dissolved	17	18	**9**	18	18	1
Sodium adsorption ratio	6.1	6.5	6	6.5	7.1	10
Sodium, dissolved	361	404	12	404	465	15
"Estimated alkalinity"[2]	303	315	4	315	355	13
Chloride, dissolved	13	43	**220**	43	85	**99**
Fluoride, dissolved	0.56	0.63	**13**	0.63	0.67	6
Sulfate, dissolved	1,210	1,220	1	1,220	1,320	8
Solids, dissolved, (sum of constituents)	1,960	2,170	11	2,170	2,390	10

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]"Estimated alkalinity" data were developed by selecting either alkalinity or acid neutralizing capacity (ANC), depending primarily on which measurement was available for a given sample, as discussed in the section of this report "Sampling and Analytical Methods."

Table 5. Summary of trend results determined by using ordinary least squares regression (OLS) on time, streamflow, and season for major-ion constituents and properties for Little Powder River near Broadus, Mont. (site 15) based on analysis of data collected during water years[1] 2001–10.

[Bold values indicate statistically significant (at p-value < 0.01) trend results. Dark gray shading indicates downward fitted trend. Light gray shading indicates upward fitted trend. p-value, statistical significance level; <, less than; Mont., Montana; NR, not reported; >, greater than]

Constituent or property	Fitted trend value at start of indicated trend-analysis period	Fitted trend value at end of indicated trend-analysis period	Estimated total percent change during indicated trend-analysis period
Little Powder River near Broadus, Mont. (site 15, fig. 1)			
Trend-analysis period water years 2005–10			
Specific conductance	2,300	3,130	**36**
Calcium, dissolved	114	149	30
Magnesium, dissolved	NR[2]	NR[2]	NR[2]
Potassium, dissolved	NR[2]	NR[2]	NR[2]
Sodium adsorption ratio	6.7	7.5	11
Sodium, dissolved	348	464	**34**
Alkalinity	324	363	12
Chloride, dissolved	35	57	**61**
Fluoride, dissolved	0.67	0.64	-4
Sulfate, dissolved	854	290	**51**
Solids, dissolved, (sum of constituents)	1,650	320	**41**

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Results not reported because of nonsignificant relation between constituent and streamflow (p-value > 0.05).

the absolute value of the difference between trend magnitude for specific conductance and dissolved solids was less than 6. These criteria were met for greater than 80 percent of site and trend-period combinations. Site and trend-period combinations not meeting the criteria had nonsignificant trends for either specific conductance, dissolved solids, or both, and in almost all cases, the 95-percent confidence intervals (presented in tables 4.1–4.4) for the trend magnitude for specific conductance and dissolved solids strongly overlapped. Thus, general agreement between magnitudes of fitted trends for specific conductance and dissolved solids indicated consistency with chemical processes.

In the discussion of trend results, qualitative observations on trend magnitudes sometimes are made. Trend magnitudes were considered to be: large, if the deviation from zero was greater than about 40 percent; moderate, if the deviation from zero was within the range of about 25–40 percent; small, if the deviation from zero was within the range of about 15–25 percent; and minor, if the deviation from zero was within the range of about 0–15 percent. In some cases, when trending was within a small range at low concentrations, moderate and large trend magnitudes (on a percentage basis) qualitatively were considered to be minor or small. In all cases, when the terms “significant” or “significantly” are used, it is in reference to statistical significance (p-value less than 0.01, unless specifically stated otherwise).

Tongue River Watershed

Trends for Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Hanging Woman Creek (site 6), Tongue River at Birney Day School (site 7), Otter Creek (site 8), and Tongue River at Miles City (site 10) were determined by using the TSM (table 2, table 4.2), and for Tongue River at Monarch (site 1), Goose Creek (site 2), Prairie Dog Creek (site 3), and Pumpkin Creek (site 9) were determined by using OLS (table 3, table 4.3). Trend results are presented and discussed, on a site-by-site basis, for sites on the main-stem Tongue River and then for sites on Tongue River tributaries.

Trend Results for Selected Sampling Sites on the Main-Stem Tongue River

Trend results for main-stem Tongue River sites are variable among sites. Trend results for Tongue River at Monarch (site 1; determined by using OLS) indicate generally small but significant increases in median values of calcium, magnesium, alkalinity, chloride, sulfate, specific conductance, and dissolved solids during water years 2005–10 (table 3, table 4.2, fig. 4.1). There are no substantial CBM-extraction activities in the site watershed. A factor affecting direct comparison of trend results for site 1 (determined by using OLS) in relation to trend results for other main-stem Tongue River sites (determined by using the TSM) is that the TSM incorporates interannual, seasonal, and short-term information in flow-adjustment and trend-analysis procedures that is not accounted for in OLS.

Trend results for Tongue River at State line (site 4; determined by using the TSM) indicate a small significant decrease in median specific conductance during period 1 and a moderate significant increase in median chloride concentration during period 2 (table 2; table 4.1; fig. 4.4). ANN_C and $SEAS_C$ coefficients for site 4 (table 4.1) are highly significant and of similar magnitude for most constituents, which indicates that interannual and seasonal effects on concentration and streamflow relations were important in the trend analysis, but neither interannual nor seasonal effects was more strongly dominant. The small significant decrease in median specific conductance during period 1 is associated with nonsignificant decreases in other major ions (except fluoride and SAR) at site 4 during period 1 (table 2). However, data collection at site 4 was sparse during period 1, and the trend results should be used with caution. The pattern of decreases in major-ion constituents and properties, whether statistically significant or nonsignificant, during period 1 is weaker than (in terms of magnitude and significance) but generally directionally consistent with other main-stem Tongue River sites (table 2) and is further discussed in a following paragraph of this section of the report. There are substantial CBM-extraction activities in the site 4 watershed, but a moderate significant increase in median chloride concentration during period 2 is difficult to interpret with respect to those activities. Chloride concentration in stream water is about one-sixth of the concentration in CBM-produced water for site 4 (table 1.5). Chloride can increase in concentration between CBM-produced water discharges and holding ponds and groundwater beneath holding ponds (Healy and others, 2008; Healy and others, 2011). Thus, geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 4 watershed might have affected chloride concentrations. However, significant trends are not indicated for any constituent other than chloride during period 2 for site 4, which contributes to difficulty in interpreting chloride trend results; the chloride trend results should be used with caution. Trends at site 4 and capability to detect trends potentially attributable to CBM-extraction activities during period 2 are affected by several factors, including the following: mean CBM pumping rate in the site 4 watershed is small (about 6 percent) relative to 2001–10 median streamflow (fig. 4, table 1.3); annual mean CBM pumping rate in the site 4 watershed increased during 2001–02 then decreased during 2003–10 (fig. 4); and water-quality data for site 4 are less suitable for trend analysis than most other sites to which the TSM was applied. Percent differences in cation and anion balances (table 4.5) indicate less chemical consistency in trend results for site 4 than for other sites, which might indicate that concentration and streamflow relations for site 4 were not well defined by the TSM. Largest potential for CBM-extraction activities to affect site 4 water-quality probably was during water years 2000–02 when streamflow conditions were low and CBM-extraction activities were rapidly increasing (fig. 4). Generally high individual unadjusted and flow-adjusted concentrations of sodium and alkalinity during water years 2000–02 (figs. 8, 9, and 4.4) might indicate short-term effects of CBM-extraction activities; however, there is no strong indication of unresolved trending in FACs of any constituent during water years 2000–02 (fig. 4.4). Thus, it is difficult to confidently determine whether or not CBM-extraction activities have affected water-quality at site 4, but potential effects of CBM-extraction activities are not strongly indicated. Better determination of possible effects of CBM-extraction activities on water-quality at site 4 might be possible with consistent future water-quality monitoring.

Trend results for Tongue River at Tongue River Dam (site 5; determined by using the TSM) indicate generally small significant decreases in median concentrations of calcium, magnesium, potassium, sodium, estimated alkalinity, sulfate, and dissolved solids during period 1, and minor to moderate significant increases in median concentrations of sodium, alkalinity, and dissolved solids during period 2 (table 2; table 4.1; fig. 4.5). ANN_C and $SEAS_C$ coefficients for site 5 (table 4.1) are highly significant for most constituents. For many constituents (including calcium, magnesium, estimated alkalinity, chloride, sulfate, specific conductance, and dissolved solids), $SEAS_C$ has stronger magnitude than ANN_C, which indicates that seasonal effects on concentration and streamflow relations generally were of greater importance than interannual effects in the trend analysis. Significant or nonsignificant decreases in all major ions are indicated for period 1, a pattern generally consistent with other main-stem Tongue River sites. There are substantial CBM-extraction activities in the site 5 watershed. The moderate significant increase in median sodium, and the small significant increase in estimated alkalinity concentrations during period 2 are consistent with relative differences between stream water and CBM-produced water for site 5 (table 1.5), which might indicate effects of CBM-extraction activities on stream water. Mean sodium concentration in stream water is about one-sixteenth of the concentration in CBM-produced water; mean alkalinity concentration in stream water is about one-sixth of the concentration in CBM-produced water for site 5 (table 1.5). However, Tongue River at State line (site 4) accounts for nearly all of the streamflow contributed to site 5 and significant increases in median values of SAR, sodium, and alkalinity were not indicated for site 4. A factor that might affect differences in trend results between sites 4 and 5 is that annual mean CBM pumping rate in the site 4 watershed peaked in 2002 then decreased during 2003–10 (fig. 4, table 1.3). In contrast, annual mean CBM pumping rate in the site 5 watershed increased by about 50 percent (from 15 to 22 ft^3/s; table 1.3) during 2003–08 (primarily because of increased CBM-extraction activities in the intervening watershed between sites 4 and 5). However, the mean CBM pumping rate in the site 5 watershed still is small (about

8 percent) relative to 2001–10 median streamflow and only slightly higher than for site 4 (fig. 4). Other factors related to the intervening watershed that also might affect trend results include operations of Tongue River Reservoir, irrigation activities, contributions of saline groundwater, and operations of the Decker coal mine. Typical operations of Tongue River Reservoir capture high streamflows during spring snowmelt runoff when native streamflow would be strongly dominant as opposed to the potential contribution of CBM-produced water. The stored water is then released during summer and fall low-streamflow periods when contributions of CBM-produced water might account for a larger proportion of streamflow. Intuitively, storage and mixing of dilute spring runoff water with more concentrated water during low-streamflow periods would lessen potential effects of CBM-extraction activities during low-streamflow periods in summer and fall. Irrigation activities and groundwater contributions might increase concentrations of most major ions (National Research Council, 1989; Cary, 1991). Permitted wastewater discharges from the Decker coal mine that are contributed to the Tongue River upstream from the reservoir and directly to the reservoir also might affect major-ion relations and trend results. Better determination of water-quality effects of factors related to the intervening watershed between sites 4 and 5 might be possible with more detailed and consistent future water-quality monitoring. Thus, although significant increases in median values of sodium and estimated alkalinity during period 2 are consistent with relative differences between CBM-produced water and stream water, other factors confound confident determination of causes of the observed trends for site 5. FACs and fitted trends for period 2 for site 5 generally are within ranges of those for period 1 before substantial CBM-extraction activities (fig. 4.5).

Trend results for Tongue River at Birney Day School (site 7; determined by using the TSM) indicate small to moderate significant decreases in median concentrations of magnesium, potassium, estimated alkalinity, sulfate, and dissolved solids during period 1, and small significant increases in median concentrations of magnesium, alkalinity, and dissolved solids during period 2 (table 2; table 4.1; fig. 4.7). ANN_C and $SEAS_C$ coefficients for site 5 (table 4.1) are highly significant for most constituents. For many constituents (including calcium, magnesium, estimated alkalinity, chloride, sulfate, specific conductance, and dissolved solids), $SEAS_C$ has stronger magnitude than ANN_C, which indicates that seasonal effects on concentration and streamflow relations generally were of greater importance than interannual effects in the trend analysis. Significant or nonsignificant decreases in all major ions are indicated for period 1, a pattern generally consistent with other main-stem Tongue River sites. There are substantial CBM-extraction activities in the site 7 watershed; mean CBM pumping rate was about 9 percent of 2001–10 median streamflow (table 1.3). The significant increase in median estimated alkalinity concentration during period 2 is consistent with relative differences between stream water and CBM-produced water for site 7 (table 1.5), which might provide indication of effects of CBM-extraction activities on stream water. Mean alkalinity concentration in stream water is one-sixth of the concentration in CBM-produced water relative to stream water at site 7 (table 1.5). Although not detected as significant for site 7, magnitude of increasing trend for median sodium concentration (50 percent, 95-percent confidence interval 27–77 percent) for site 7 generally was similar to a significant increasing trend for median sodium concentration (36 percent, 95-percent confidence interval 24–50 percent) for Tongue River at Tongue River Dam (site 5; table 4.1). Site 5 accounts for nearly all of the streamflow contributed to site 7, which accounts for similarities in trend results between sites 5 and 7. Further, the site 5 and 7 watersheds have similar amounts of CBM-extraction activities. Differences in trend results between sites 5 and 7 include a small significant increase in median magnesium concentration during period 2 for site 7, which was not detected for site 5. FACs and fitted trends for period 2 for site 7 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

Trend results for Tongue River at Miles City (site 10; determined by using the TSM) indicate small significant decreases in median concentrations of magnesium, chloride, sulfate, and dissolved solids during period 1, and a small significant increase in median chloride concentration during period 2 (table 2; table 4.1; fig. 4.10). ANN_C and $SEAS_C$ coefficients for site 5 (table 4.1) are highly significant for most constituents. $SEAS_C$ had stronger magnitude than ANN_C for all constituents except fluoride, which indicates that seasonal effects on concentration and streamflow relations generally were of greater importance than interannual effects in the trend analysis. Significant or nonsignificant decreases in all major ions are indicated for period 1, a pattern generally consistent with other main-stem Tongue River sites. There are substantial CBM-extraction activities in the site 10 watershed, but the significant increase in median chloride concentration during period 2 is difficult to interpret with respect to those activities. Chloride concentration in stream water is about one-fifth of the concentration in CBM-produced water for site 10 (table 1.5). Chloride can increase in concentration between CBM-produced water discharges and holding ponds and groundwater beneath holding ponds (Healy and others, 2008; Healy and others, 2011). Thus, geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 10 watershed might have affected chloride concentrations. However, significant trends are not indicated for any constituent other than chloride during period 2 for site 10, which contributes to difficulty in interpreting chloride trend results; the chloride trend results should be used with caution. Site 10 is a long distance (about 142 river miles) downstream from Tongue River at Birney Day School (site 7) and also from locations of CBM-extraction activities in the Tongue River watershed. Site 7 accounts for nearly all of the streamflow contributed to site 10, but intervening irrigation activities and streamflow contributions from plains tributaries might strongly affect differences in water quality between sites 7 and

10. Mean annual streamflow decreases by about 10 percent between sites 7 and 10, largely because of irrigation consumptive use. FACs and fitted trends for period 2 for site 10 generally are within ranges of those for period 1 before substantial CBM-extraction activities (fig. 4.10).

A pattern of decreases, whether statistically significant or nonsignificant, in major-ion concentrations during period 1 generally was consistent among main-stem Tongue River sites (table 2), but potential causes of the pattern were unknown. Because of the unusual circumstance, this issue was investigated as thoroughly as possible given available data. Data for Tongue River at Tongue River Dam (site 5), which had the most complete representation of any main-stem site for period 1, were investigated to determine whether the TSM flow-adjustment and trend-analysis procedures provided accurate results for main-stem sites during period 1. Water-quality data collected during water years 1986–88 (near the start of period 1) and during water years 1993–95 (near the end of period 1) at generally similar streamflows (within the interquartile range for site 5 continuous-record daily mean streamflows) were compiled and statistically summarized (table 1.6). The Wilcoxon rank-sum test was used to determine whether median major ion concentrations were statistically higher (p-value less than 0.05; alpha level commonly used for the test) during water years 1986–88 than during water-years 1993–95 in samples collected at similar streamflow conditions. Statistical summaries and results of the Wilcoxon rank-sum test (table 1.6) indicated the following: the median concurrently-measured streamflow (258 ft^3/s) for 15 samples collected during water years 1986–88 was slightly higher than but not statistically different from the median streamflow (197 ft^3/s) for 17 samples collected during water years 1993–95; median concentrations of all major ions were higher in samples collected during water years 1986–88 than in samples collected during water years 1993–95; and differences in median values between the two periods were statistically significant for specific conductance, magnesium, SAR, sodium, fluoride, and sulfate. These results were judged to generally confirm that the TSM flow-adjustment and trend-analysis procedures provided accurate results for main-stem sites during period 1.

For main-stem Tongue River sites analyzed by using the TSM and downstream from substantial CBM-extraction activities [Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Tongue River at Birney Day School (site 7), and Tongue River at Miles City (site 10)], significant or nonsignificant decreases in most constituents are indicated for period 1. For period 2 for these sites, the TSM trend results do not allow confident conclusions concerning detection of effects of CBM-extraction activities on stream water quality. Detection of significant trends in major-ion constituents and properties for period 2 generally was infrequent, and direction, significance, and magnitudes of fitted trends were not strongly consistent with relative differences between stream water and CBM-produced water. The TSM indicated significant or large magnitude increases in median values of SAR, sodium, and alkalinity for period 2 for sites 5 and 7, which are consistent with relative differences between stream water and CBM-produced water and might indicate potential CBM effects. However, other factors, including operations of Tongue River Reservoir, irrigation activities, contributions of saline groundwater, and operations of the Decker coal mine, confound confident determination of causes of detected significant trends for sites 5 and 7. For all main-stem Tongue River sites, FACs and fitted trends for period 2 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

Trend Results for Selected Sampling Sites on Tongue River Tributaries

Trend results for Tongue River tributary sites are variable among sites. Trend results for Goose Creek (site 2; determined by using OLS) do not indicate any significant trends during water years 2001–10 or during water years 2005–10 (table 3; table 4.2; fig. 4.2). There are no substantial CBM-extraction activities in the site 2 watershed.

Trend results for Prairie Dog Creek (site 3; determined by using OLS) indicate generally small to large significant increases in median values of magnesium, SAR, sodium, alkalinity, chloride, sulfate, specific conductance, and dissolved solids during water years 2001–10 and similar magnitude significant increases in SAR, sodium, chloride, sulfate, specific conductance, and dissolved solids during water years 2005–10 (table 3, table 4.3, fig. 4.3). There are substantial CBM-extraction activities in the site 3 watershed; CBM pumping rate was about 35 percent of 2001–10 median streamflow (table 1.3). Significant increases in median values of SAR, sodium, alkalinity, and chloride are consistent with relative differences between stream water and CBM-produced water for site 3; these constituents are much lower in stream water relative to CBM-produced water for site 3 (table 1.5). However, significant increases in median concentrations of magnesium and especially sulfate are not consistent with relative differences between CBM-produced water and stream water. Magnesium and sulfate are about 40 and 73 times, respectively, higher in stream water relative to CBM-produced water for site 3 (table 1.5). Magnesium and sulfate can increase in concentration between CBM-produced water discharges and holding ponds, groundwater beneath holding ponds, and ephemeral channels (Healy and others, 2008; Healy and others, 2011; Patz and others, 2004). Thus, geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 3 watershed might have affected magnesium and sulfate concentrations.

Trend results for Hanging Woman Creek (site 6; determined by using the TSM) indicate a small significant increase in median potassium concentration during period 1, and a small significant increase in median estimated alkalinity concentration during period 2 (table 2; table 4.1; fig. 4.6).

ANN_C and $SEAS_C$ coefficients for site 6 (table 4.1) are highly significant for most constituents. ANN_C had stronger magnitude than $SEAS_C$ for most constituents, which indicates that interannual effects on concentration and streamflow relations generally were of greater importance than seasonal effects in the trend analysis. Further, ANN_C and $SEAS_C$ coefficients are positive for most major-ion constituents and properties, which indicates that constituent concentrations tended to be higher during higher streamflow conditions. The pattern of generally positive ANN_C and $SEAS_C$ coefficients is unusual among sites in the Tongue and Powder River watersheds to which the TSM was applied. Sites exhibiting the pattern in all cases are characterized by ephemerality. Accumulation of salts in ephemeral channels and stream banks during zero-streamflow periods and subsequent dissolution and mobilization of salts during wetter periods might contribute to the pattern. Site 6 had periods of zero streamflow in about 68 percent of years with continuous streamflow records during water years 1980–2010. There are substantial CBM-extraction activities in the site 6 watershed; mean annual volume of CBM-produced water was about 700 percent of median annual streamflow volume during period 2 (table 1.3). The significant increase in estimated alkalinity concentration during period 2 for site 6 is consistent with relative differences between stream water and CBM-produced water, but the significant increase in estimated alkalinity is difficult to interpret with respect to CBM-extraction activities. Relative differences between stream water and CBM-produced water for site 6 generally are smaller than most other sites and stream water for site 6 has slightly higher ionic strength than CBM-produced water (fig. 4). Significant changes during period 2 for site 6 were not indicated for any constituent other than "estimated alkalinity." FACs and fitted trends for period 2 for site 6 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

Trend results for Otter Creek (site 8; determined by using the TSM) indicate generally small significant decreases in median values of sulfate, specific conductance, and dissolved solids during period 1, and small to moderate significant increases in median values of estimated alkalinity, sulfate, specific conductance, and dissolved solids during period 2 (table 2; table 4.1; fig. 4.8). ANN_C and $SEAS_C$ coefficients for site 8 (table 4.1) generally are nonsignificant or of small magnitude, indicating that interannual and seasonal effects did not strongly affect concentration and streamflow relations. However, as for Hanging Woman Creek (site 6), ANN_C and $SEAS_C$ coefficients are positive for most major-ion constituents and properties for site 8, which also exhibits ephemerality. Site 8 had periods of zero streamflow in about 43 percent of years with continuous streamflow records during water years 1980–2010. There are no substantial CBM-extraction activities in the site 8 watershed. Thus, the observed significant trends in periods 1 and 2 illustrate large temporal variability in water quality in plains streams in Montana and Wyoming that are affected by complex interactions between surface water, groundwater, and geologic materials in a semiarid environment (Lambing and Cleasby, 2006; Clark, 2012; Clark and Mason, 2007).

Trend results for Pumpkin Creek (site 9; determined by using OLS) indicate large significant increases in median values of potassium, sodium, alkalinity, chloride, specific conductance, and dissolved solids during water years 2005–10 (table 3; table 4.2; fig. 4.9). There are no substantial CBM-extraction activities in the site 9 watershed. Site 9 is strongly ephemeral and had periods of zero-streamflow in 100 percent of years with continuous streamflow records during water years 1980–2010. Trend results for site 9 were not determined by using the TSM and thus there was no accounting for interannual effects on concentration and streamflow relations. Unusual interannual effects (as evidenced by generally positive ANN_C coefficients determined by using the TSM) indicated for the ephemeral tributaries Hanging Woman Creek (site 6) and, to a lesser extent, Otter Creek (site 8) might also affect concentration and streamflow relations at the highly ephemeral site 9. Streamflow conditions generally were lower near the start of water years 2005–10 and higher near the end of water years 2005–10. If interannual effects on concentration and streamflow relations for site 9 are indeed positive, not accounting for the effects for this site in particular might have strongly affected trend results. However, available data for site 9 were not sufficient for TSM analysis, and given the short period of analysis and limitations of the OLS procedure, trend results for site 9 should be used with caution.

Trend results for Tongue River tributary sites downstream from substantial CBM-extraction activities [Prairie Dog Creek (site 3) and Hanging Woman Creek (site 6)] are variable among sites. Significant increases in median values of SAR, sodium, alkalinity, and chloride during period 2 (determined by using OLS) are consistent with relative differences between stream water and CBM-produced water for site 3. Significant increases in median concentrations of magnesium and sulfate during period 2 for site 3 might have been affected by geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 3 watershed. Thus, CBM-extraction activities might have affected the observed significant increases in some major-ion constituents and properties for site 3. The significant increase in estimated alkalinity concentration during period 2 is consistent with relative differences between stream water and CBM-produced water for site 6, but the significant increase in estimated alkalinity is difficult to interpret with respect to CBM-extraction activities. Relative differences between stream water and CBM-produced water for site 6 generally are smaller than most other sites and stream water for site 6 has slightly higher ionic strength than CBM-produced water (fig. 4). Significant changes during period 2 for site 6 were not indicated for any constituent other than "estimated alkalinity." FACs and fitted trends for period 2 for site 6 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

Powder River Watershed

Water-quality trends for Powder River at Sussex (site 11), Powder River at Arvada (site 12), Powder River at Moorhead (site 13), Little Powder River above Dry Creek (site 14), and Powder River near Locate (site 16) were determined by using the TSM (table 4.4), and for Little Powder River near Broadus (site 15) were determined by using OLS (table 4.5). Trend results are presented and discussed, on a site-by-site basis, for sites on the main-stem Powder River and then for sites on the Little Powder River.

Trend Results for Selected Sampling Sites on the Main-Stem Powder River

Trend results for main-stem Powder River sites are variable among sites. Trend results for Powder River at Sussex (site 11; determined by using the TSM) indicate generally moderate to large significant decreases in median values of potassium, SAR, estimated alkalinity, chloride, fluoride, and dissolved solids during period 1, and small to large significant increases in median concentrations of potassium, chloride, and fluoride during period 2 (table 4; table 4.3; fig. 4.11). ANN_C and $SEAS_C$ coefficients for site 11 (table 4.3) are highly significant for most constituents. For most constituents (and especially potassium, SAR, sodium, chloride, and fluoride), ANN_C has stronger magnitude than $SEAS_C$, which indicates that interannual effects on concentration and streamflow relations generally were of greater importance than seasonal effects in the trend analysis. Although there are no substantial CBM-extraction activities in the site watershed, discussion of causes of significant fitted trends for site 11 is relevant to understanding trend patterns at main-stem Powder River sites that are downstream from site 11 that have substantial CBM-extraction activities in their watersheds. Site 11 is the first main-stem Powder River site downstream from the Salt Creek oil field. Reinjection of oil brine began in 1990 (Lindner-Lunsford and others, 1992) and affects changes in major ions during period 1. Salt Creek oil brine is strongly sodium chloride type; however, alkalinity concentrations also are much higher relative to Powder River water (Cary, 1991; Boelter and others, 1992). Before the oil-brine reinjection, unadjusted and flow-adjusted concentrations of some major ions (including sodium, chloride, and alkalinity) were high and highly variable (figs. 10*A*, 11*A*, 4.11). After oil-brine reinjection, sodium, chloride, and alkalinity concentrations decreased sharply at site 11 with near complete response by water year 1992. Calcium FACs increased because dilution of stream water by calcium-poor oil brine ceased (fig. 4.11). The significant decreases in sodium and estimated alkalinity associated with the oil-brine reinjection (figs. 10*A*, 11*A*; 4.11) were accompanied by decreases in variability of unadjusted and flow-adjusted concentrations (fig. 11*A*) during water years 1992–2000. For sodium, variability in unadjusted concentrations increased during water years 2001–07 (fig. 10*A*), in association with low-streamflow conditions prevalent in the Powder River watershed (fig. 7). However, the TSM results indicate that when streamflow variability is accounted for, median sodium concentration represented by the fitted trend (fig. 4.11) and variability of sodium FACs generally were similar, indicating general stationarity in sodium concentrations, during the time period following oil-brine reinjection (water years 1992–2010). For estimated alkalinity, the fitted trend as well as unadjusted and flow-adjusted concentrations indicate general stationarity during the time period following oil-brine reinjection. Differences in patterns of unadjusted concentrations between sodium and estimated alkalinity during water years 2001–07 probably relate to differences in chemical properties. Sodium is conservative and tends to remain in solution within a large range of water-quality and ionic-strength conditions (Hem, 1985). Alkalinity is much less conservative and can precipitate from solution (primarily as calcium and magnesium carbonate minerals; Hem, 1985) in high ionic strength conditions typically associated with low-streamflow conditions. Thus, during water-years 2001–07, high estimated alkalinity concentrations might have been limited by mineral precipitation in presence of relatively higher calcium concentrations (in relation to water-quality conditions before the Salt Creek oil-brine reinjection). Differences between determinations of estimated alkalinity for period 1 (when ANC predominantly accounted for the assigned estimated alkalinity values) and period 2 (when alkalinity predominantly accounted for the assigned estimated alkalinity values) probably did not affect patterns in estimated alkalinity before and after oil-brine reinjection. Largest differences between patterns in estimated alkalinity before and after oil-brine reinjection are associated with higher concentrations, generally from about the median concentration to the annual maximum concentrations. Estimated alkalinity concentrations for site 11 are inversely related to streamflow (as evidenced by negative ANN_C and $SEAS_C$ coefficients; table 4.3) and will tend to be high when streamflow is low. However, suspended sediment concentrations, which account for differences between ANC and alkalinity measurements, generally tend to be low when streamflow is low and thus probably did not strongly affect high estimated alkalinity concentrations. The significant increases in median concentrations of potassium, chloride, and fluoride (with trend magnitudes of 28, 44, and 20 percent, respectively) for site 11 during period 2 are unrelated to CBM-extraction activities and investigation of possible causal factors was beyond the scope of this study. Patterns in trend results for site 11 (upstream from substantial CBM-extraction activities) are relevant for comparison with main-stem Powder River sites downstream from site 11 and also downstream from substantial CBM-extraction activities.

For period 1, trend results for Powder River at Arvada (site 12; determined by using the TSM) indicate a small significant increase in median calcium concentration, and moderate to large significant decreases in median values of SAR, sodium, estimated alkalinity, chloride, fluoride, specific conductance, and dissolved solids (table 4; table 4.3; fig. 4.12). For period 2, trend results indicate generally large significant increases in median values of potassium, SAR, sodium, estimated alkalinity, chloride, and fluoride, and small significant decreases in median concentrations of calcium, magnesium, and sulfate (table 4; table 4.3; fig. 4.12). ANN_C and $SEAS_C$ coefficients for site 12 (table 4.3) are highly significant for most constituents. For most constituents (especially potassium, SAR, sodium, estimated alkalinity, chloride, and fluoride), ANN_C has stronger magnitude than $SEAS_C$, which indicates that interannual effects on concentration and streamflow relations generally were of greater importance than seasonal effects in the trend analysis. Patterns in trend results for site 12 for period 1 are consistent with those of Powder River at Sussex (site 11) and also indicate effects of the Salt Creek oil-brine reinjection. There are substantial CBM-extraction activities in the site 12 watershed; mean CBM pumping rate was 26 percent of 2001–10 median streamflow (table 1.3). Significant trends (increases and decreases) in median values of calcium, magnesium, SAR, sodium, estimated alkalinity, and sulfate are consistent with relative differences between stream water and CBM-produced water for site 12 (table 1.5). Similar significant trends in these constituents during period 2 are not indicated for site 11, which is upstream from CBM-extraction activities. Also, the 95-percent confidence intervals of the trend magnitudes of calcium, SAR, and alkalinity for site 12 do not overlap with confidence intervals of those constituents for site 11 (table 4.3). The 95-percent confidence interval of the trend magnitudes of sodium and sulfate for site 12 only slightly overlap with the confidence intervals of those constituents for site 11. Thus, patterns in trend results for period 2 for site 12 are much different from site 11 and consistent with relative differences between stream water and CBM-produced water, with the exception of the significant increase in median chloride concentration, which is similar between sites 12 and 11. Chloride concentration is higher in stream water relative to CBM-produced water for site 12 and based on this relation, chloride concentration might have been expected to decrease during period 2. However, trend results for site 12 indicate a significant increase in chloride concentration during period 2 (37 percent; 95-percent confidence interval 21–55 percent) similar to a significant increase in chloride concentration indicated for site 11 (44 percent; 95-percent confidence interval 24–67 percent). The significant increase in chloride concentration for site 11 during period 2 might have contributed to the significant increase in chloride concentration for site 12 during period 2. Also, chloride can increase in concentration between CBM-produced water discharges and holding ponds and groundwater beneath holding ponds (Healy and others, 2008; Healy and others, 2011). Thus, geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 12 watershed might have affected chloride concentrations. Significant decreases in median concentrations of calcium and magnesium during period 2 for site 12 might have been affected by dilution by calcium- and magnesium-poor CBM-produced water and also increased precipitation of carbonate minerals in the presence of higher alkalinity concentration. Differences in patterns of fitted trends, and unadjusted and flow-adjusted concentrations of estimated alkalinity between sites 12 and 11 also provides evidence of differences in water-quality characteristics between the sites during period 2 and potential effects of CBM-extraction activities on site 12 water quality (figs. 11*A*, 11*B*, 4.11, 4.12). Before the start of the oil-brine reinjection in 1990 (Lindner-Lunsford and others, 1992), unadjusted and flow-adjusted estimated alkalinity concentrations at site 12 were high and unadjusted concentrations were highly variable (characterized by generally high annual maxima; fig. 11*B*), similar to site 11. After the response to the oil-brine reinjection, unadjusted and flow-adjusted concentrations of estimated alkalinity at both sites indicated general stationarity in estimated alkalinity concentrations during water years 1992–2000. However, during period 2, unadjusted and flow-adjusted estimated alkalinity concentrations at site 12 increased, unadjusted concentrations became more variable (generally similar to variability in unadjusted concentrations before oil-brine reinjection), and the TSM detected a significant increase in median estimated alkalinity (fig. 11*B*). Unadjusted and flow-adjusted estimated alkalinity concentrations at site 11 indicated general stationarity during period 2, similar to the period water years 1992–2000, and the TSM did not detect a significant trend in median estimated alkalinity (fig. 11*A*). Thus, during period 2, water-quality characteristics of the Powder River differed between the site upstream from and the first site downstream from substantial CBM-extraction activities, which provide evidence of potential effects of CBM-extraction activities on Powder River water quality at site 12. FACs and fitted trends for period 2 for site 12 generally are within ranges of those for period 1 before substantial CBM-extraction activities. In the Powder River watershed, period 1 encompasses time periods before and after the Salt Creek oil-brine reinjection. It is notable that the estimated alkalinity fitted trend and unadjusted and flow-adjusted concentrations (figs. 11*B*, 4.12) at the end of period 2 were similar in magnitude to the fitted trend and unadjusted and flow-adjusted concentrations at the start of period 1, which was before the Salt Creek oil-brine reinjection.

For period 1, trend results for Powder River at Moorhead (site 13; determined by using the TSM) indicate generally small to moderate significant decreases in median values of potassium, SAR, sodium, estimated alkalinity, chloride, fluoride, specific conductance, and dissolved solids (table 4; table 4.3; fig. 4.13). For period 2, trend results indicate generally large significant increases in median concentrations of potassium, SAR, sodium, estimated alkalinity, and fluoride, and small significant decreases in median concentrations of calcium and sulfate (table 4; table 4.3; fig. 4.13). ANN_C and $SEAS_C$ coefficients for site 13 (table 4.3) are highly significant for most constituents. For most constituents (and especially potassium, SAR, sodium, estimated alkalinity, chloride, and fluoride), ANN_C has stronger magnitude than $SEAS_C$, which indicates that interannual effects on concentration and streamflow relations generally were of greater importance than seasonal effects in the trend analysis. Patterns in trend results for site 12 for period 1 are consistent with those of Powder River at Sussex (site 11) and Powder River at Arvada (site 12), and also indicate effects of the Salt Creek oil-brine reinjection; however, magnitudes of significant trends generally decreased in a downstream direction from site 12 to site 13, probably because of moderating effects of intervening tributary contributions. There are substantial CBM-extraction activities in the site 13 watershed; mean CBM pumping rate was 28 percent of 2001–10 median streamflow (table 1.3). Significant trends during period 2 (increases and decreases) in median values of calcium, SAR, sodium, estimated alkalinity, and sulfate are consistent with relative differences between stream water and CBM-produced water for site 13 (table 1.5). The significant trends during period 2 for site 13 also generally are consistent with significant trends for site 12; however, the significant decrease in median magnesium concentration and the significant increase in median chloride concentration during period 2 for site 12 are not indicated for site 13. For constituents with significant trends during period 2 for sites 13 and 12, trend magnitudes generally are similar among the sites, and for all constituents 95-percent confidence intervals for site 13 overlap with those for site 12. However, the magnitude of the significant increase in median estimated alkalinity concentration during period 2 for site 13 (75 percent; 95-percent confidence interval 56–97 percent) is larger than for site 12 (51 percent; 95-percent confidence interval 40–64 percent). The difference in estimated alkalinity trend results for period 2 between sites 12 and 13 might relate to the large data gap (water years 1990–2001) in the site 13 dataset, which might have affected the capability of the TSM to define concentration and streamflow relations after Salt Creek oil-brine reinjection as accurately for site 13 as for site 12. Similar to site 12, the 95-percent confidence intervals of the trend magnitudes of SAR and alkalinity for site 13 do not overlap with confidence intervals of those constituents for site 11 (table 4.3). Further, differences in patterns of fitted trends and unadjusted and flow-adjusted concentrations of estimated alkalinity between sites 13 and 11 (figs. 11*A*, 11*C*, 4.11, 4.13) are similar to differences between sites 11 and 12 discussed in the previous paragraph of this section of the report. Thus, significant trends during period 2 for site 13 are: consistent with relative differences between stream water and CBM-produced water (table 1.5); similar to those for site 12; and much different from those for site 11 (table 4). These factors indicate potential effects of CBM-extraction activities on site 13 water quality. FACs and fitted trends for period 2 for site 13 generally are within ranges of those for period 1 before substantial CBM-extraction activities. It is notable that the estimated alkalinity fitted trend and unadjusted and flow-adjusted concentrations (figs. 11*C*, 4.13) at the end of period 2 were similar in magnitude to the fitted trend and unadjusted and flow-adjusted concentrations at the start of period 1, which was before the Salt Creek oil-brine reinjection.

For period 1, trend results for Powder River near Locate (site 16; determined by using the TSM) indicate generally small to moderate significant decreases in median values of potassium, SAR, sodium, estimated alkalinity, chloride, fluoride, specific conductance, and dissolved solids (table 4; table 4.3; fig. 4.16). For period 2, trend results indicate generally moderate significant increases in median concentrations of potassium, SAR, sodium, estimated alkalinity, chloride, and fluoride (table 4; table 4.3; fig. 4.16). ANN_C and $SEAS_C$ coefficients for site 16 (table 4.3) are highly significant and of similar magnitude for most constituents, which indicates that interannual and seasonal effects on concentration and streamflow relations were important in the trend analysis, but neither interannual nor seasonal effects was more strongly dominant. Patterns in trend results for site 16 for period 1 are consistent with those of Powder River at Sussex (site 11), Powder River at Arvada (site 12), and Powder River at Moorhead (site 13), and also indicate effects of the Salt Creek oil-brine reinjection; however, magnitudes of significant trends generally decreased in a downstream direction from site 13 to site 16, probably because of moderating effects of intervening tributary contributions, and groundwater and surface-water interactions. Although site 16 is a long distance (greater than 150 mi) downstream from the other main-stem Powder River sites, similarities in significant fitted trends between site 16 and sites 11, 12, and 13 for period 1 provide evidence that factors affecting water quality in the upstream part of the watershed also can affect water quality at site 16; however, other land-use activities in the watershed between sites 13 and 16 also might affect water quality downstream. There are substantial CBM-extraction activities in the site 16 watershed; mean CBM pumping rate was 34 percent of 2001–10 median streamflow (table 1.3). Some of the significant trends during period 2 (including increases in median values of SAR, sodium, and estimated alkalinity) are consistent with relative differences between stream water and CBM-produced water for site 16 (table 1.5). The significant trends during period 2 for site 16 also generally are consistent with significant trends for site 13. However, magnitudes of significant trends generally decreased in a downstream direction from site 13 to site 16. Further, a significant decrease in median calcium concentration during period 2 for site 13 is not indicated for site 16, and a significant increase in median chloride concentration for site 16 during period 2 is not indicated for site 13. Causes of differences in significant trends during period 2 between sites 16 and 13 are unknown, but might relate to effects of contributions from intervening tributaries, groundwater and surface-water interactions, or geochemical interaction of stream water with geologic materials in the long channel reach between the sites. Thus, some significant trends during period 2 for site 16 are consistent with relative differences between stream water and CBM-produced water (table 1.5) and also are similar to, but generally of smaller magnitude than trends for site 13. Unlike sites 12 and 13, fitted trends for all constituents for site 16 for period 2 have 95-percent confidence intervals that overlap with confidence intervals for site 11. Trend characteristics for site 16 might indicate potential effects of CBM-extraction activities on site 16 water quality, but of smaller magnitude than potential effects on sites 12 and 13. FACs and fitted trends for period 2 for site 16 generally are within ranges of those for period 1 before substantial CBM-extraction activities. It is notable that the estimated alkalinity fitted trend and unadjusted and flow-adjusted concentrations (figs. 11*C*, 4.13) at the end of period 2 were similar in magnitude to the fitted trend and unadjusted and flow-adjusted concentrations at the start of period 1, which was before the Salt Creek oil-brine reinjection.

For main-stem Powder River sites analyzed by using the TSM [Powder River at Sussex (site 11), Powder River at Arvada (site 12), Powder River at Moorhead (site 13), and Powder River near Locate (site 16)], significant or large magnitude decreases in median values of SAR, sodium, estimated alkalinity, chloride, fluoride, specific conductance, and dissolved solids are indicated for period 1. Patterns in trend results for period 1 for main-stem Powder River sites are consistent with effects of Salt Creek oil-brine reinjection that started in 1990. Trend results for all of the main-stem Powder River sites downstream from substantial CBM-extraction activities (sites 12, 13, and 16) indicate evidence of potential effects of CBM-extraction activities on stream water quality, although evidence is stronger for sites 12 and 13 than for site 16. Evidence in support of potential CBM effects includes significant increases during period 2 in median values of SAR, sodium, and estimated alkalinity for sites 12, 13, and 16 that are consistent with relative differences between stream water and CBM-produced water. Significant increases during period 2 in median values of these constituents are not indicated for site 11 upstream from substantial CBM-extraction activities. For sites 12, 13, and 16, mean CBM pumping rates were 26, 28, and 34 percent of 2001–10 median streamflows, respectively. In interpreting the trend results, it is notable that the fitted trends evaluate changes in median concentrations and that changes in the median concentrations that might be attributed to CBM-extraction activities probably are more strongly evident during low-flow conditions than during average to high-flow conditions. This observation is relevant in assessing trend results in relation to specific water-quality concerns, including effects of water-quality changes on irrigators and effects on stream biota and ecology.

Trend Results for Selected Sampling Sites on the Little Powder River

Trend results for Little Powder River sites are variable among sites. Trend results for Little Powder River above Dry Creek (site 14; determined by using the TSM) indicate minor significant increase in median fluoride concentration during period 1 and large significant increases in median chloride concentration during period 1 and period 2 (table 4; table 4.3; fig. 4.14). ANN_C coefficients for site 14 generally are positive and nonsignificant (table 4.3). $SEAS_C$ coefficients are negative and highly significant for most constituents. The ANN_C and $SEAS_C$ coefficients indicate unusual concentration and streamflow relations for site 14, and seasonal effects on the relations were more important than interannual effects in the trend analysis. Site 14 exhibits ephemerality (with periods of zero streamflow in about 52 percent of years with continuous streamflow records during water years 1980–2010), which might have contributed to the unusual patterns in ANN_C and $SEAS_C$ coefficients. There are substantial CBM-extraction activities in the site 14 watershed; mean CBM pumping rate was about 360 percent of 2001–10 median streamflow (table 1.3). CBM-extraction activities in the site 14 watershed started in 1989, much earlier than most other sites, and might affect trend results during period 1 and period 2. Annual mean CBM pumping rates during period 1 were small (ranging from 0.05 to 0.50 ft^3/s during water years 1989–95; table 1.3), but because of the low-streamflow characteristics of site 14, the small CBM pumping rates were in some years large in relation to annual median streamflow (for example, 84 percent in water year 1991). Significant increases in median chloride concentration during period 1 and period 2 are difficult to interpret, but are not consistent with relative differences between CBM-produced water and stream water for site 14 (table 1.5). Chloride can increase in concentration between CBM-produced water discharges and holding ponds and groundwater beneath holding ponds (Healy and others, 2008; Healy and others, 2011). Thus, geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 14 watershed might have affected chloride concentrations. However, significant trends are not indicated for any other constituent, except fluoride, during either period 1 or period 2 for site 14, which contributes to difficulty in interpreting chloride trend results; the chloride trend results should be used with caution. With the exception of chloride, FACs and fitted trends for period 2 for site 14 are within ranges of those for period 1 before substantial CBM-extraction activities.

Trend results for Little Powder River near Broadus (site 15; determined by using OLS) indicate moderate to large significant increases in median values of specific conductance, sodium, chloride, sulfate, and dissolved solids during water years 2005–10 (table 5; table 4.4; fig. 4.15). Site 15 exhibits its ephemerality (with periods of zero streamflow in about 35 percent of years with continuous streamflow records during water years 1980–2010) and might have unusual concentration and streamflow relations similar to Little Powder River above Dry Creek (site 14). There are substantial CBM-extraction activities in the site 15 watershed, but there are no additional CBM-extraction activities in the intervening watershed between sites 14 and 15. Significant increases in sodium, chloride, and sulfate during water years 2005–10 are not consistent with relative differences between CBM-produced water and stream water for site 15 (table 1.5). Sodium, chloride, and sulfate can increase in concentration between CBM-produced water discharges and holding ponds, groundwater beneath holding ponds, and ephemeral channels (Healy and others, 2008; Healy and others, 2011; Patz and others, 2004). Thus, geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 15 watershed might have affected concentrations of these constituents. However, independent from potential effects of CBM-extraction activities, plains streams in Montana and Wyoming are affected by complex interactions between surface water, groundwater, and geologic materials in a semiarid environment and can exhibit large temporal variability in major-ion constituents (Lambing and Cleasby, 2006; Clark, 2012; Clark and Mason, 2007).

Trend results for Little Powder River sites downstream from substantial CBM-extraction activities [Little Powder River above Dry Creek (site 14) and Little Powder River near Broadus (site 15)] do not allow confident conclusions concerning detection of effects of CBM-extraction activities on stream water quality. CBM-extraction activities in the site 14 watershed started much earlier than most other sites and might potentially affect trend results during period 1 and period 2. Significant increases in median chloride concentration during period 1 and period 2 for site 14 are difficult to interpret, but are not consistent with relative differences between CBM-produced water and stream water for site 14 (table 1.5). Geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 14 watershed might have affected chloride concentrations. However, significant trends are not indicated for any constituent other than chloride during either period 1 or period 2 for site 14, which contributes to difficulty in interpreting chloride trend results; the chloride trend results should be used with caution. Significant increases in sodium, chloride, and sulfate during water years 2005–10 for site 15 are not consistent with relative differences between CBM-produced water and stream water for site 15 (table 1.5), but also might have been affected by interaction of CBM-produced water with soil and rock materials. However, independent from potential effects of CBM-extraction activities, plains streams in Montana and Wyoming can exhibit large temporal variability in major-ion constituents, which contributes to difficulty in interpreting trend results for site 15.

Selected Trend Results in Relation to Results of Previous Studies

This section of the report presents selected trend results from this study and discusses those results in relation to findings of previous studies. Comparisons are made between trend results from this study and those of Clark (2012). Trend results from this study also are discussed with respect to results of Kinsey and Nimick (2011) relating to potential qualitative effects of CBM-produced water on stream water.

Clark (2012) analyzed trends in flow-adjusted concentrations for 40 sites in the Tongue and Powder River watersheds (and also in the Cheyenne and Belle Fourche River watersheds; not shown in fig. 1) by using the robust seasonal Kendall test. For sites analyzed in this study and by Clark (2012) for period 2, statistically significant trend results (p-value less than 0.01) determined by using the TSM or statistically significant trend results (p-value less than 0.05) of Clark (2012) determined by using the seasonal Kendall test are presented in table 6. Significant trend results for potassium and fluoride determined by using the TSM are not included in table 6 because those constituents were not analyzed by Clark (2012). The TSM trend results generally are similar in direction to trend results determined by using the seasonal Kendall test (Clark, 2012). However, magnitudes and significance of the trend results varied between the trend methods in some cases. An important consideration in evaluating differences between the TSM and seasonal Kendall trend results is that the TSM incorporates interannual and seasonal effects on concentration and streamflow relations and allows evaluation (by comparison of ANN_C and $SEAS_C$ coefficients) of relative contributions of these effects on trend results. The seasonal Kendall analysis does not account for interannual effects on concentration and streamflow relations. Thus, consideration of ANN_C and $SEAS_C$ coefficients and relative contributions of interannual and seasonal effects on trend results is relevant to evaluating differences in trend results between the TSM and the seasonal Kendall test. Trend magnitude and significance for period 2 generally are stronger for the TSM compared to the seasonal Kendall test when ANN_C is much more strongly negative than $SEAS_C$. Examples of this pattern include the following: chloride for Powder River at Sussex (site 11); SAR and sodium for Powder River at Arvada (site 12); and SAR, sodium, and alkalinity for Powder River at Moorhead (site 13). In these cases, the TSM trend magnitudes are much larger than the trend magnitudes estimated with the seasonal Kendall test and 95-percent confidence intervals about the TSM trends do not encompass or approach the seasonal Kendall trend magnitudes. In contrast, trend magnitudes and significance for period 2 generally are similar among the TSM and the seasonal Kendall test when ANN_C is similar to or less strongly negative than $SEAS_C$. Examples of this pattern include the following: calcium, alkalinity, and sulfate for site 12; and calcium and sulfate for site 13. In these cases, the trend magnitudes of both methods generally are similar and 95-percent confidence intervals about the TSM trends encompass or approach the seasonal Kendall trend magnitudes. In most of the cases, statistical significance is indicated for both methods. For specific conductance, calcium, and sulfate for Tongue River at State line (site 4), trend magnitude and significance for period 2 are stronger for the seasonal Kendall test compared to the TSM. For site 4, ANN_C is similar to $SEAS_C$, indicating that interannual and seasonal effects on concentration and streamflow relations were of similar importance in the TSM analysis. Thus, incorporation of interannual effects on concentration and streamflow relations in the TSM does not explain differences between the methods for site 4. Percent differences in cation and anion balances (table 4.5) indicate less chemical consistency in the TSM trend results for site 4 than for other sites, which might indicate that concentration and streamflow relations for site 4 were not well defined by the TSM. The seasonal Kendall analysis of Clark (2012) might have been more sensitive in detecting trends for site 4 for period 2.

Table 6. Statistically significant trend results determined by using the time-series model (TSM; *p*-value < 0.01) and statistically significant trend results from Clark (2012; *p*-value < 0.05) for trend-analysis period 2 (water years[1] 2001–10).

[Values in parentheses indicate 95-percent confidence intervals. Light gray shading indicates statistical significance at *p*-value < 0.01. Dark gray shading indicates statistical significance at *p*-value < 0.05. *p*-value, statistical significance level; <, less than; $SEAS_C$, seasonal concentration anomaly; ANN_C, annual concentration anomaly; Mont., Montana; Wyo., Wyoming; NR, not reported; >, greater than]

Constituent or property	Results determined by using the TSM: Estimated total percent change during trend-analysis period	Results determined by using the TSM: *p*-value for individual trend	Results determined by using the TSM: $SEAS_c$ coefficient	Results determined by using the TSM: *p*-value for $SEAS_c$ coefficient	Results determined by using the TSM: ANN_c coefficient	Results determined by using the TSM: *p*-value for ANN_c coefficient	Results determined by using seasonal Kendall test (Clark, 2012): Estimated total percent change during trend-analysis period[2]	Results determined by using seasonal Kendall test (Clark, 2012): *p*-value for individual trend
Tongue River at State line, near Decker, Mont. (site 4, fig. 1)								
Specific conductance	5 (-2, 12)	0.156	-0.20	<0.001	-0.20	<0.001	15	0.040
Calcium	5 (-1, 11)	NR[3]	-0.03	0.147	-0.02	0.368	21	0.006
Chloride	31 (18, 46)	<0.001	-0.26	<0.001	-0.31	<0.001	33	0.020
Sulfate	2 (-11, 17)	NR[3]	-0.33	<0.001	-0.30	<0.001	33	0.042
Powder River at Sussex, Wyo. (site 11, fig. 1)								
Chloride	44 (24, 67)	<0.001	-0.49	<0.001	-0.84	<0.001	8	0.600
Powder River at Arvada, Wyo. (site 12, fig. 1)								
Calcium	-23 (-29, -16)	<0.001	-0.06	0.012	-0.04	0.078	-24	0.056
Magnesium	-16 (-23, -8)	<0.001	-0.12	<0.001	-0.09	<0.001	-7	0.578
Sodium adsorption ratio	53 (40, 66)	<0.001	-0.11	<0.001	-0.24	<0.001	16	0.036
Sodium	39 (25, 54)	<0.001	-0.19	<0.001	-0.29	<0.001	3	0.726
Alkalinity	51 (40, 64)	<0.001	-0.08	<0.001	-0.14	<0.001	39	0.010
Chloride	37 (21, 55)	<0.001	-0.25	<0.001	-0.49	<0.001	-5	0.661
Sulfate	-17 (-25, -9)	<0.001	-0.14	<0.001	-0.10	<0.001	-24	0.031
Powder River at Moorhead, Mont. (site 13, fig. 1)								
Calcium	-19 (-29, -8)	0.001	-0.11	<0.001	-0.12	<0.001	-18	0.096
Sodium adsorption ratio	41 (25, 59)	<0.001	-0.09	<0.001	-0.20	<0.001	5	0.474
Sodium	31 (13, 51)	<0.001	-0.14	<0.001	-0.25	<0.001	-8	0.513
Alkalinity	75 (56, 97)	<0.001	-0.07	<0.001	-0.22	<0.001	28	0.024
Sulfate	-16 (-27, -4)	0.010	-0.21	<0.001	-0.19	<0.001	-31	0.006
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)								
Chloride	99 (52, 161)	<0.001	-0.09	0.103	-0.17	<0.001	41	0.131

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Trend magnitudes in Clark (2012) were reported as slopes that reflect relative changes (per year) in units after adjustment for streamflow variability (that is, slopes in fitted trends in flow-adjusted concentrations). For a given site and constituent combination, the slope (per year) was transformed into total percent change during the indicated trend-analysis period by dividing by the median concentration for 2001–10 (reported by Clark, 2012) and multiplying times the number of years in the trend-analysis period.

[3]*p*-value for individual trend period not reported because of nonsignificant overall trend analysis (*p*-value > 0.01; table 4.1), as discussed in "Supplement 2: Summary of the Time-Series Model (TSM) as Applied in this Study."

Statistically significant trend results (*p*-value less than 0.01) determined by using OLS or statistically significant trend results (*p*-value less than 0.05) determined by using the seasonal Kendall test (Clark (2012) for water years 2001–10 and 2005–10 are presented in table 7. Significant trend results for potassium and fluoride are not included in table 7 because those constituents were not analyzed by Clark (2012). Differences in results between OLS and the seasonal Kendall test would be expected to be less than between the TSM and the seasonal Kendall test. OLS and the seasonal Kendall test both use parametric regression procedures for defining concentration and streamflow relations, and neither method accounts for interannual effects. However, OLS and the seasonal Kendall test differ with respect to accounting for seasonal effects on concentration and streamflow relations, and also with respect to the use of parametric (OLS) or nonparametric (seasonal Kendall test) techniques for estimating trend magnitudes and significance. OLS trend results for Tongue River at Monarch (site 1), Goose Creek (site 2), and Prairie Dog Creek (site 3) generally are similar in direction, magnitude, and significance to results of the seasonal Kendall test, with the exception of results for Prairie Dog Creek (site 3) for water years 2001–10 (table 7). For site 2, OLS and the seasonal Kendall test indicated no significant changes during water years 2005–10; thus, no results for site 2 are presented in table 7. For site 3, OLS results for water years 2001–10 are similar to OLS results for water years 2005–10. Also, OLS results for water years 2005–10 are similar to Clark (2012) for water years 2005–10. However, seasonal Kendall test results for water years 2001–10 are different from OLS results and also are different from seasonal Kendall test results for water years 2005–10 (table 7). Factors responsible for these differences were not evaluated in detail; however, concentration and streamflow relations in Prairie Dog Creek are complex and affected by interbasin transfers for irrigation. This factor, combined with drought conditions during the early part of water years 2001–10 might have affected trend results of OLS, the seasonal Kendall test, or both.

Kinsey and Nimick (2011) reported results of two synoptic sampling trips, during September 2005 and April 2006, to provide spatially detailed profiles of specific conductance and SAR along the length of the upper Tongue River. A series of calculations were made to project potential increases in specific conductance and SAR that might be attributable to 12 primary discharges of CBM-produced water to the Tongue River upstream from Tongue River Reservoir. Streamflow for Tongue River at State line (site 4) during the September 2005 and April 2006 synoptic sampling trips (195 and 210 ft^3/s, respectively) generally was similar to median streamflow during water years 2001–10 (177 ft^3/s; table 1.3). Kinsey and Nimick (2011) projected that, at streamflows and discharge rates of CBM-produced water during the synoptic sampling trips, CBM-produced water would increase specific conductance by about 4 percent. Estimated increases in specific conductance because of CBM-produced water (based on actual measurements made during the trips) generally agreed with projected increases, and ranged from about 4–6 percent. Kinsey and Nimick (2011) also projected that for the September 2005 synoptic sampling trip, the 12 primary discharges of CBM-produced water would increase SAR by about 34 percent. The estimated increase in SAR because of CBM-produced water (based on actual measurements made during the trip) was smaller than the projected increase, and was about 18 percent. SAR data were not available for the April 2006 trip. Results of Kinsey and Nimick (2011) concerning potential effects of CBM-produced water on stream water cannot be directly compared to the TSM trend results because of fundamental differences in analytical approaches and the precise site locations on the Tongue River that were studied. Kinsey and Nimick (2011) investigated patterns in water quality upstream from and downstream from CBM-extraction activities within short time frames and made observations on potential effects of 12 primary discharges of CBM-produced water on spatial differences in water quality. The TSM results provide information on long-term temporal changes in water quality that might relate to potential effects of CBM-produced water (contributed from the entire watershed) on stream water quality. However, there are some similarities in general findings of Kinsey and Nimick (2011) and the TSM trend results. Kinsey and Nimick (2011) indicated that projected and estimated increases in specific conductance because of CBM-produced water for Tongue River upstream from Tongue River Dam at near-median streamflow were small (about 4–6 percent). The TSM trend results indicate a nonsignificant increase in median specific conductance for period 2 for Tongue River at Tongue River Dam (site 5; 1 percent; 95-percent confidence interval -5 to 7 percent). Kinsey and Nimick (2011) indicated that projected and estimated increases in SAR (about 34 and 18 percent, respectively) for Tongue River upstream from Tongue River Dam were relatively larger than increases in specific conductance. The TSM trend results indicate a significant increase in median SAR for period 2 for site 5 (36 percent; 95-percent confidence interval 24–50 percent). Site 5 is 0.5 mi downstream from Tongue River Dam. Factors other than CBM-extraction activities (including operations of Tongue River Reservoir, irrigation activities, and operations of the Decker coal mine) might affect the TSM trend results for site 5.

Table 7. Statistically significant trend results determined by using ordinary least squares regression (OLS) on time, streamflow, and season (p-value < 0.01) and statistically significant trend results from Clark (2012; p-value < 0.05).

[Values in parentheses indicate 95-percent confidence intervals. Light gray shading indicates statistical significance at p-value < 0.01. Dark gray shading indicates statistical significance at p-value < 0.05. p-value, statistical significance level; <, less than; Wyo., Wyoming]

Constituent or property	Results determined by using OLS		Results determined by using seasonal Kendall test (Clark, 2012)	
	Estimated total percent change during trend-analysis period	*p*-value for individual trend	Estimated total percent change during trend-analysis period[1]	*p*-value for individual trend
Tongue River atMonarch, Wyo. (site 1, fig. 1)				
Trend-analysis period water years 2005–10				
Specific conductance	16 (7, 26)	<0.001	0	0.005
Calcium	16 (6, 26)	<0.001	7	0.352
Magnesium	15 (4, 28)	0.005	10	0.022
Alkalinity	17 (9, 25)	<0.001	8	0.015
Chloride	42 (21, 66)	<0.001	26	0.011
Sulfate	26 (5, 52)	0.008	17	0.040
Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)				
Trend-analysis period water years 2001–10				
Specific conductance	17 (7, 28)	<0.001	4	0.366
Magnesium	24 (11, 38)	<0.001	9	0.127
Sodium adsorption ratio	32 (19, 46)	<0.001	7	0.065
Sodium	43 (24, 65)	<0.001	13	0.081
Alkalinity	12 (3, 21)	0.005	9	0.337
Chloride	52 (34, 74)	<0.001	46	0.017
Sulfate	27 (11, 46)	<0.001	6	0.419
Trend-analysis period water years 2005–10				
Specific conductance	17 (5, 32)	0.004	0	0.005
Magnesium	19 (3, 38)	0.013	24	0.026
Sodium adsorption ratio	32 (16, 51)	<0.001	33	<0.001
Sodium	41 (17, 69)	<0.001	44	<0.001
Alkalinity	10 (0, 21)	0.041	13	0.026
Chloride	57 (36, 82)	<0.001	64	<0.001
Sulfate	33 (12, 58)	<0.001	40	<0.001

[1]Trend magnitudes in Clark (2012) were reported as slopes that reflect relative changes (per year) in units after adjustment for streamflow variability (that is, slopes in fitted trends in flow-adjusted concentrations). For a given site and constituent combination, the slope (per year) was transformed into total percent change during the indicated trend-analysis period by dividing by the median concentration for 2001–10 (reported by Clark, 2012) and multiplying times the number of years in the trend-analysis period.

Summary and Conclusions

The primary purpose of this report is to present information relating to flow-adjusted temporal trends in major-ion constituents and properties for 16 sampling sites in the Tongue and Powder River watersheds based on data collected during water years1980–2010. In association with this primary purpose, the report presents background information on water-quality characteristics of the sampling sites and CBM-produced water in the site watersheds, trend analysis methods, streamflow conditions, and factors that affect trend results.

The Tongue and Powder River watersheds overlie the Powder River structural basin (PRB) in northeastern Wyoming and southeastern Montana. The PRB contains large deposits of energy resources (coal, oil, natural gas) and, since the late 1800's, extraction activities have been extensive. Limited extraction of coal-bed methane (CBM) from the PRB began in the early 1990's and increased dramatically during the late 1990's and early 2000's. CBM-extraction activities produce discharges of water with high concentrations of dissolved solids (particularly sodium and bicarbonate ions) relative to most stream water in the Tongue and Powder River watersheds. Water-quality of CBM-produced water (groundwater pumped from coal seams) is of concern because of potential effects on downstream agricultural producers who irrigate soils that can contain large amounts of clay. Another concern with respect to discharge of CBM-produced water to stream channels is effects on aquatic biota; primarily because of potential toxicity of bicarbonate.

Water-quality and flow-rate characteristics of CBM-produced water were estimated to allow general comparisons with water-quality and streamflow characteristics of the sampling sites. The information on water-quality and flow-rate characteristics of CBM-produced water in relation to characteristics of streams does not account for effects of disposal, treatment, or other remediation activities on the potential qualitative or quantitative effects of CBM-produced water on receiving streams. For all sites in the Tongue River watershed with substantial CBM-extraction activities in their watersheds [Prairie Dog Creek (site 3), Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Hanging Woman Creek (site 6), Tongue River at Birney Day School (site 7), and Tongue River at Miles City (site 10)], relative differences in individual constituents between CBM-produced water and stream water generally are similar: calcium, magnesium, and sulfate concentrations are higher, and SAR, sodium, alkalinity, and chloride values are lower in stream water than in CBM-produced water. Relations between streamflow and pumping rates of CBM-produced water are variable among sites in the Tongue River watershed. For site 4 mean annual pumping rate of CBM-produced water during water years 2001–10 (hereinafter referred to as mean CBM pumping rate) was 6 percent of the mean of annual median streamflows during water years 2001–10 (hereinafter referred to as 2001–10 median streamflow). For main-stem Tongue River sites 5, 7, and 10, mean CBM pumping rate was 8–12 percent of 2001–10 median streamflow. For plains tributaries (sites 3 and 6), mean CBM pumping rates were 35 and about 700 percent of 2001–10 median streamflows, respectively.

Relative differences in individual constituents between CBM-produced water and stream water generally are similar among main-stem Powder River sites with substantial CBM-extraction activities in their watersheds [Powder River at Arvada (site 12), Powder River at Moorhead (site 13), and Powder River near Locate (site 16)]: calcium, magnesium, chloride, and sulfate concentrations are higher, and SAR, sodium, and alkalinity values are lower in stream water than in CBM-produced water. Relative differences are similar for Little Powder River sites [Little Powder River above Dry Creek (site 14) and Little Powder River near Broadus (site 15)], except sodium concentrations are higher in stream water than in CBM-produced water. Relations between streamflow and pumping rates of CBM-produced water are variable among sites in the Powder River watershed. For main-stem Powder River sites (sites 12, 13, and 16), mean CBM pumping rates were 26, 28, and 34 percent of 2001–10 median streamflows, respectively. For site 14 in the Little Powder River watershed mean CBM pumping rate was about 360 percent of 2001–10 median streamflow.

Two parametric trend-analysis methods were used in this study: the time-series model (TSM) and ordinary least squares regression (OLS) on time, streamflow, and season. In this study, the TSM was selected as the preferred trend-analysis method primarily because of detailed analysis of continuous streamflow data that provides better definition of concentration and streamflow relations through time and incorporation of interannual, seasonal, and short-term information in flow-adjustment procedures. The TSM was used to analyze trends for 11 of the 16 study sites. For five sites, the data requirements of the TSM were not met. In these cases, OLS was used to analyze trends. Two primary 10-year trend-analysis periods were selected. Trend-analysis 10-year period 1 (water years 1986–1995; hereinafter referred to as period 1) was selected to represent variability in major-ion concentrations in the Tongue and Powder River watersheds before potential effects of substantial CBM-extraction activities. Trend analysis 10-year period 2 (water years 2001–10; hereinafter referred to as period 2) was selected because it encompassed substantial CBM-extraction activities and therefore might indicate potential effects of CBM-extraction activities on water-quality of receiving streams in the Tongue and Powder River watersheds. These two 10-year trend analysis periods were used for all sites that satisfied requirements for the data-intensive TSM. For sites that did not satisfy data requirements for the TSM, OLS was used to analyze trends for period 2 (if complete data were available) or a 6-year period (2005–10) to provide information on water-quality characteristics that might have been affected by CBM-extraction activities. Additional data collection at these sites will increase record length for future analysis of temporal trends.

For main-stem Tongue River sites analyzed by using the TSM and downstream from substantial CBM-extraction activities [Tongue River at State line (site 4), Tongue River at Tongue River Dam (site 5), Tongue River at Birney Day School (site 7), and Tongue River at Miles City (site 10)], generally small significant or nonsignificant decreases in most constituents are indicated for period 1. For period 2 for these sites, the TSM trend results do not allow confident conclusions concerning detection of effects of CBM-extraction activities on stream water quality. Detection of significant trends in major-ion constituents and properties for period 2 generally was infrequent, and direction, significance, and magnitudes of fitted trends were not strongly consistent with relative differences between stream water and CBM-produced water. The TSM indicated significant or large magnitude increases in median values of sodium adsorption ratio, sodium, and alkalinity for period 2 for sites 5 and 7, which are consistent with relative differences between stream water and CBM-produced water and might indicate potential CBM effects. However, other factors, including operations of Tongue River Reservoir, irrigation activities, and operations of the Decker coal mine, confound confident determination of causes of detected significant trends for sites 5 and 7. For all main-stem Tongue River sites, flow-adjusted concentrations (FACs) and fitted trends for period 2 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

Trend results for Tongue River tributary sites downstream from substantial CBM-extraction activities [Prairie Dog Creek (site 3) and Hanging Woman Creek (site 6)] are variable among sites. Significant increases in median values of SAR, sodium, alkalinity, and chloride during period 2 (determined by using OLS) are consistent with relative differences between stream water and CBM-produced water for site 3. Significant increases in median concentrations of magnesium and sulfate during period 2 for site 3 might have been affected by geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 3 watershed. Thus, CBM-extraction activities might have affected the observed significant increases in some major-ion constituents and properties for site 3. The significant increase in estimated alkalinity concentration during period 2 is consistent with relative differences between stream water and CBM-produced water for site 6, but the significant increase in estimated alkalinity is difficult to interpret with respect to CBM-extraction activities. Relative differences between stream water and CBM-produced water for site 6 generally are smaller than most other sites, and stream water for site 6 has slightly higher ionic strength than CBM-produced water. Significant changes during period 2 for site 6 were not indicated for any constituent other than estimated alkalinity. FACs and fitted trends for period 2 for site 6 generally are within ranges of those for period 1 before substantial CBM-extraction activities.

For main-stem Powder River sites analyzed by using the TSM [Powder River at Sussex (site 11), Powder River at Arvada (site 12), Powder River at Moorhead (site 13), and Powder River near Locate (site 16)], significant or large magnitude decreases in median values of SAR, sodium, estimated alkalinity, chloride, fluoride, specific conductance, and dissolved solids are indicated for period 1. Patterns in trend results for period 1 for main-stem Powder River sites are consistent with effects of Salt Creek oil-brine reinjection that started in 1990. Trend results for all of the main-stem Powder River sites downstream from substantial CBM-extraction activities (sites 12, 13, and 16) indicate evidence of potential effects of CBM-extraction activities on stream water quality, although evidence is stronger for sites 12 and 13 than for site 16. Evidence in support of potential CBM effects includes significant increases during period 2 in median values of SAR, sodium, and estimated alkalinity for sites 12, 13, and 16 that are consistent with relative differences between stream water and CBM-produced water. Significant increases during period 2 in median values of these constituents are not indicated for site 11 upstream from substantial CBM-extraction activities. For sites 12, 13, and 16, mean CBM pumping rates were 26, 28, and 34 percent of 2001–10 median streamflows, respectively. In interpreting the trend results, it is notable that the fitted trends evaluate changes in median concentrations and that changes in the median concentrations that might be attributed to CBM-extraction activities probably are more strongly evident during low-flow conditions than during average to high-flow conditions. This observation is relevant in assessing trend results in relation to specific water-quality concerns, including effects of water-quality changes on irrigators and effects on stream biota and ecology.

Trend results for Little Powder River sites downstream from substantial CBM-extraction activities [Little Powder River above Dry Creek (site 14) and Little Powder River near Broadus (site 15)] do not allow confident conclusions concerning detection of effects of CBM-extraction activities on stream water quality. CBM-extraction activities in the site 14 watershed started substantially earlier than most other sites and might potentially affect trend results during period 1 and period 2. Significant increases in median chloride concentration during period 1 and period 2 for site 14 are difficult to interpret, but are not consistent with relative differences between CBM-produced water and stream water for site 14. Geochemical processes relating to interaction of CBM-produced water with soil and rock materials in holding ponds and ephemeral channels in the site 14 watershed might have affected chloride concentrations. However, significant trends are not indicated for any constituent other than chloride during either period 1 or period 2 for site 14, which contributes to difficulty in interpreting chloride trend results; the chloride trend results should be used with caution. Significant increases in sodium, chloride, and sulfate during water years 2005–10 for site 15 are not consistent with relative differences between CBM-produced water and stream water for site 15, but also might have been affected by interaction of CBM-produced water with soil and rock materials. However, independent from potential effects of CBM-extraction activities, plains streams in Montana and Wyoming can exhibit large temporal variability in major-ion constituents, which contributes to difficulty in interpreting trend results for site 15.

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Supplement 1. Summary Tables Relating to Quality-Control, Water-Quality, Streamflow, and Coal-Bed Methane (CBM) Produced-Water Data

Table 1.1. Summary information relating to quality-control samples (equipment blank and replicate samples) collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during water years[1] 1980–2010.[2]

[<, less than]

Constituent	Number of equipment blank samples	Maximum concentration in equipment blank sample, in milligrams per liter	90th percentile concentration in equipment blank samples, in milligrams per liter	Number of replicate sample pairs	Mean relative percent difference
Calcium, dissolved	69	1	0.07	133	2.3
Magnesium, dissolved	69	0.07	0.02	133	2.3
Sodium, dissolved	69	<0.2	<0.2	133	2.1
Alkalinity, as calcium carbonate	53	15	<8	110	0.32
acid neutralizing capacity, as calcium carbonate	15	45	<5	42	0.46
Chloride, dissolved	65	1	0.3	134	3.5
Sulfate, dissolved	65	0.9	0.2	134	3.7

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Prior to the early 1990's, quality-control data collected by the U.S. Geological Survey generally were not permanently archived in an electronic format and are difficult to document. The samples summarized were collected during water years 1993–2010 for blank samples and water years 1992–2010 for replicate samples.

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).

[Wyo., Wyoming; ft³/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Tongue River at Monarch, Wyo. (site 1, fig. 1)							
	Water years 2001–10							
1/2004–9/2010	Streamflow, instantaneous, ft³/s	93	27	70	96	257	181	2,520
	Specific conductance, µS/cm	93	177	330	414	385	443	545
	Calcium, mg/L	89	22	38	47	44	50	68
	Magnesium, mg/L	89	6.7	15	20	19	22	31
	Potassium, mg/L	89	0.70	1.2	1.4	1.5	1.7	4.2
	Sodium adsorption ratio, dimensionless	89	0.11	0.27	0.32	0.33	0.37	0.78
	Sodium, mg/L	89	2.4	7.7	10	11	13	27
	Alkalinity, mg/L as calcium carbonate	89	81	142	178	164	189	235
	Chloride, mg/L	89	0.54	1.2	1.5	1.6	1.9	3.6
	Fluoride, mg/L	89	0.08	0.14	0.17	0.17	0.19	0.26
	Sulfate, mg/L	89	8.3	29	44	44	54	110
	Dissolved solids (sum of constituents), mg/L	89	100	188	237	225	259	332
	Goose Creek below Sheridan, Wyo. (site 2, fig. 1)							
	Water years 2001–10							
10/2001–8/2010	Streamflow, instantaneous, ft³/s	99	3.8	47	66	148	98	1,790
	Specific conductance, µS/cm	99	110	540	639	583	690	868
	Calcium, mg/L	97	10	51	59	54	64	76
	Magnesium, mg/L	97	4.4	31	37	35	42	50
	Potassium, mg/L	97	0.80	2.3	2.8	2.8	3.2	7.3
	Sodium adsorption ratio, dimensionless	97	0.19	0.51	0.57	0.56	0.63	0.98
	Sodium, mg/L	97	2.9	19	24	22	26	42
	Alkalinity, mg/L as calcium carbonate	97	43	200	229	209	246	292
	Chloride, mg/L	98	0.71	5.0	6.3	6.9	8.0	21
	Fluoride, mg/L	98	0.07	0.25	0.29	0.27	0.32	0.42
	Sulfate, mg/L	98	10	92	110	104	125	190
	Dissolved solids (sum of constituents), mg/L	96	63	334	388	359	427	525

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)							
	Water years 2001–10							
10/2000–9/2010	Streamflow, instantaneous, ft^3/s	134	0.21	11	18	26	36	127
	Specific conductance, µS/cm	134	642	1,220	1,460	1,450	1,670	2,510
	Calcium, mg/L	132	38	111	134	130	152	209
	Magnesium, mg/L	132	20	71	88	87	104	167
	Potassium, mg/L	132	3.6	6.4	7.5	7.8	9.0	18
	Sodium adsorption ratio, dimensionless	132	0.57	1.1	1.3	1.4	1.6	3.6
	Sodium, mg/L	132	23	63	75	85	104	216
	Alkalinity, mg/L as calcium carbonate	131	155	276	317	315	359	488
	Chloride, mg/L	131	1.9	4.0	4.8	5.0	5.9	9.0
	Fluoride, mg/L	131	0.19	0.27	0.31	0.30	0.34	0.46
	Sulfate, mg/L	131	163	409	506	527	636	1,160
	Dissolved solids (sum of constituents), mg/L	130	414	848	1,020	1,040	1,230	2,030
	Tongue River at State line, near Decker, Mont. (site 4, fig. 1)							
	Water years 1986–95							
11/1985–7/1995	Streamflow, instantaneous, ft^3/s	91	48	195	271	685	576	3,840
	Specific conductance, µS/cm	91	175	310	621	553	714	991
	Calcium, mg/L	21	20	25	44	43	59	71
	Magnesium, mg/L	21	7.0	11	22	23	34	47
	Potassium, mg/L	21	0.90	1.4	1.8	2.1	2.5	5.3
	Sodium adsorption ratio, dimensionless	21	0.21	0.28	0.46	0.45	0.58	0.86
	Sodium, mg/L	21	4.4	7	15	16	22	38
	Acid-neutralizing capacity, mg/L as calcium carbonate	21	74	96	160	156	216	250
	Chloride, mg/L	20	0.20	0.50	2.4	2.2	3.4	5.1
	Fluoride, mg/L	21	0.10	0.10	0.20	0.17	0.20	0.30
	Sulfate, mg/L	21	16	31	66	80	120	210
	Dissolved solids (sum of constituents), mg/L	21	107	142	255	267	379	527

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft³/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Water years 2001–10							
10/2000–9/2010	Streamflow, instantaneous, ft³/s	162	10	134	182	430	309	5,430
	Specific conductance, µS/cm	162	186	512	636	609	729	1,280
	Calcium, mg/L	148	20	46	57	54	63	79
	Magnesium, mg/L	148	7.8	24	34	32	40	63
	Potassium, mg/L	148	1.0	2.2	2.8	2.8	3.2	8.4
	Sodium adsorption ratio, dimensionless	148	0.23	0.60	0.72	0.76	0.86	2.8
	Sodium, mg/L	148	5.0	20	28	30	35	124
	Alkalinity, mg/L as calcium carbonate	148	73	170	214	202	239	356
	Chloride, mg/L	148	0.83	3.0	4.1	4.0	5.2	7.9
	Fluoride, mg/L	147	0.08	0.21	0.28	0.27	0.31	0.68
	Sulfate, mg/L	148	20	82	122	121	151	302
	Dissolved solids (sum of constituents), mg/L	147	108	289	382	371	448	776
	Tongue River at Tongue River Dam, near Decker, Mont. (site 5, fig. 1)							
	Water years 1986–95							
10/1985–8/1995	Streamflow, instantaneous, ft³/s	99	14	178	261	479	487	3,290
	Specific conductance, µS/cm	97	190	402	650	580	728	880
	Calcium, mg/L	87	21	40	56	53	65	80
	Magnesium, mg/L	87	8.1	22	35	32	41	51
	Potassium, mg/L	86	1.2	2.3	3.2	3.1	3.7	6.0
	Sodium adsorption ratio, dimensionless	87	0.30	0.58	0.75	0.69	0.82	1.0
	Sodium, mg/L	87	6.3	19	30	26	34	41
	Acid-neutralizing capacity, mg/L as calcium carbonate	87	77	146	196	188	232	270
	Chloride, mg/L	87	0.30	2.2	3.3	3.2	4.2	7.7
	Fluoride, mg/L	87	0.10	0.20	0.20	0.24	0.30	0.50
	Sulfate, mg/L	87	23	86	140	130	170	230
	Dissolved solids (sum of constituents), mg/L	87	114	268	397	367	457	562

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft³/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Water years 2001–10							
1/2004–9/2010	Streamflow, instantaneous, ft³/s	127	55	114	240	439	430	3,250
	Specific conductance, µS/cm	126	241	482	635	586	707	804
	Calcium, mg/L	96	23	42	53	51	61	71
	Magnesium, mg/L	96	9.1	22	32	30	37	44
	Potassium, mg/L	96	1.3	2.5	3.2	3.0	3.5	4.7
	Sodium adsorption ratio, dimensionless	96	0.32	0.64	0.91	0.84	1.0	1.3
	Sodium, mg/L	96	7.2	20	35	31	41	52
	Alkalinity, mg/L as calcium carbonate	96	91	158	207	193	224	271
	Chloride, mg/L	96	1.1	2.3	4.0	3.7	4.8	6.5
	Fluoride, mg/L	96	0.12	0.22	0.30	0.28	0.33	0.41
	Sulfate, mg/L	96	28	81	132	117	150	202
	Dissolved solids (sum of constituents), mg/L	96	132	273	395	357	438	524
	Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)							
	Water years 1986–95							
10/1985–7/1995	Streamflow, instantaneous, ft³/s	90	0.01	0.49	0.96	27.0	2.33	521
	Specific conductance, µS/cm	90	226	2,200	2,735	2,483	3,165	3,600
	Calcium, mg/L	45	16	88	98	102	120	230
	Magnesium, mg/L	45	11	120	130	133	160	180
	Potassium, mg/L	46	1.5	14	15	15	16	20
	Sodium adsorption ratio, dimensionless	46	1.4	5.4	5.9	5.8	6.4	8.1
	Sodium, mg/L	45	29	340	390	378	440	500
	Acid-neutralizing capacity, mg/L as calcium carbonate	46	50	457	508	480	537	692
	Chloride, mg/L	46	4.0	13	15	16	16	50
	Fluoride, mg/L	46	0.10	0.83	1.0	1.00	1.1	2.0
	Sulfate, mg/L	46	98	963	1,100	1,092	1,300	1,700
	Dissolved solids (sum of constituents), mg/L	45	197	1,880	2,090	2,043	2,350	2,810

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Water years 2001–10							
7/2003–7/2010	Streamflow, instantaneous, ft^3/s	72	0.01	0.13	0.32	1.7	0.96	43
	Specific conductance, µS/cm	72	921	2,120	2,500	2,510	2,910	3,990
	Calcium, mg/L	60	40	89	100	100	110	195
	Magnesium, mg/L	60	34	113	128	130	148	200
	Potassium, mg/L	60	9.5	14	15	16	17	26
	Sodium adsorption ratio, dimensionless	60	2.4	4.3	4.8	5.0	5.8	7.4
	Sodium, mg/L	60	87	259	302	326	391	584
	Alkalinity, mg/L as calcium carbonate	60	146	520	548	547	592	751
	Chloride, mg/L	60	4.4	11	13	13	15	25
	Fluoride, mg/L	60	0.28	1.0	1.2	1.2	1.4	1.9
	Sulfate, mg/L	60	317	619	813	904	1,160	2,050
	Dissolved solids (sum of constituents), mg/L	60	591	1,480	1,690	1,830	2,200	3,320
	Tongue River at Birney Day School, near Birney, Mont. (site 7, fig. 1)							
	Water years 1986–95							
10/1985–6/1993	Streamflow, instantaneous, ft^3/s	75	28	191	285	514	503	3,130
	Specific conductance, µS/cm	72	241	438	644	605	765	971
	Calcium, mg/L	33	26	38	53	51	62	77
	Magnesium, mg/L	33	11	19	34	33	44	54
	Potassium, mg/L	32	1.7	2.5	3.7	3.5	4.2	5.6
	Sodium adsorption ratio, dimensionless	33	0.31	0.60	0.89	0.82	1.0	1.3
	Sodium, mg/L	33	7.4	18	33	32	43	61
	Alkalinity, mg/L as calcium carbonate	33	96	141	197	186	223	268
	Chloride, mg/L	33	0.50	2.0	3.4	3.1	4.4	5.8
	Fluoride, mg/L	32	0.10	0.20	0.30	0.26	0.30	0.40
	Sulfate, mg/L	33	34	77	160	147	200	260
	Dissolved solids (sum of constituents), mg/L	33	148	242	424	385	507	617

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Water years 2001–10							
1/2004–9/2010	Streamflow, instantaneous, ft^3/s	135	63	128	242	457	430	3,230
	Specific conductance, µS/cm	135	263	478	627	598	719	875
	Calcium, mg/L	104	27	39	50	49	58	73
	Magnesium, mg/L	104	11	22	34	31	38	48
	Potassium, mg/L	104	1.4	2.6	3.4	3.2	3.8	4.7
	Sodium adsorption ratio, dimensionless	104	0.37	0.65	1.0	0.93	1.1	1.4
	Sodium, mg/L	104	9.0	21	39	35	44	58
	Alkalinity, mg/L as calcium carbonate	103	99	158	196	191	223	282
	Chloride, mg/L	104	1.2	2.5	4.2	3.8	4.9	7.6
	Fluoride, mg/L	104	0.14	0.22	0.30	0.29	0.34	0.43
	Sulfate, mg/L	104	32	84	142	127	161	248
	Dissolved solids (sum of constituents), mg/L	103	148	266	389	366	445	581
	Otter Creek at Ashland, Mont. (site 8, fig. 1)							
	Water years 1986–95							
12/1987–9/1995	Streamflow, instantaneous, ft^3/s	67	0.03	0.65	0.93	4.3	1.8	64
	Specific conductance, µS/cm	67	325	2,550	2,750	2,682	3,000	3,960
	Calcium, mg/L	31	36	60	70	73	88	110
	Magnesium, mg/L	31	48	135	140	148	165	240
	Potassium, mg/L	31	1	17	19	19	22	26
	Sodium adsorption ratio, dimensionless	31	3.1	5.8	6.4	6.1	6.5	7.2
	Sodium, mg/L	31	120	365	410	397	435	550
	Alkalinity, mg/L as calcium carbonate	31	233	530	567	549	592	641
	Chloride, mg/L	31	4.4	13	14	16	19	35
	Fluoride, mg/L	31	0.40	0.80	0.80	0.84	1.00	1.1
	Sulfate, mg/L	31	310	940	1,100	1,071	1,200	1,700
	Dissolved solids (sum of constituents), mg/L	31	679	1,915	2,030	2,062	2,245	3,020

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Water years 2001–10							
7/2003–7/2010	Streamflow, instantaneous, ft^3/s	82	0.08	1.0	1.8	3.3	3.9	33
	Specific conductance, µS/cm	82	1,730	2,560	2,860	2,880	3,150	3,820
	Calcium, mg/L	71	50	65	80	80	89	122
	Magnesium, mg/L	71	84	133	151	153	168	231
	Potassium, mg/L	71	12	17	19	19	20	26
	Sodium adsorption ratio, dimensionless	71	4.6	5.7	6.1	6.0	6.4	6.9
	Sodium, mg/L	71	233	352	406	396	434	520
	Alkalinity, mg/L as calcium carbonate	71	350	510	554	547	587	807
	Chloride, mg/L	71	7.1	11	12	12	14	17
	Fluoride, mg/L	71	0.56	0.80	0.89	0.88	0.95	1.2
	Sulfate, mg/L	71	624	923	1,070	1,110	1,280	1,750
	Dissolved solids (sum of constituents), mg/L	71	1,230	1,840	2,110	2,110	2,300	3,040
	Pumpkin Creek near Miles City, Mont. (site 9, fig. 1)							
	Water years 2001–10							
3/2004–7/2010	Streamflow, instantaneous, ft^3/s	60	0.01	0.46	4.8	71	16	2,110
	Specific conductance, µS/cm	59	263	594	1,040	1,500	2,180	5,100
	Calcium, mg/L	53	0.97	11	31	40	45	153
	Magnesium, mg/L	53	0.37	3.6	14	36	35	184
	Potassium, mg/L	53	1.5	5.4	7.8	8.3	9.5	22
	Sodium adsorption ratio, dimensionless	53	2.6	6.3	8.0	8.3	10	15
	Sodium, mg/L	53	36	128	181	255	334	745
	Alkalinity, mg/L as calcium carbonate	53	64	128	191	226	300	544
	Chloride, mg/L	53	0.91	1.9	3.4	5.0	6.6	14
	Fluoride, mg/L	53	0.17	0.33	0.41	0.42	0.48	0.69
	Sulfate, mg/L	53	40	146	325	566	702	2,140
	Dissolved solids (sum of constituents), mg/L	53	157	407	714	1,050	1,460	3,550

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Tongue River at Miles City, Mont. (site 10, fig. 1)								
Water years 1986–95								
12/1985–9/1994	Streamflow, instantaneous, ft^3/s	91	10.0	125	226	388	361	2,630
	Specific conductance, µS/cm	88	274	668	831	797	955	1,500
	Calcium, mg/L	35	14	50	58	56	62	80
	Magnesium, mg/L	35	5.1	29	38	37	45	60
	Potassium, mg/L	36	2.4	3.7	4.0	4.4	5.2	6.5
	Sodium adsorption ratio, dimensionless	35	0.52	1.2	1.4	1.6	1.7	3.4
	Sodium, mg/L	35	14	49	58	61	72	110
	Alkalinity, mg/L as calcium carbonate	36	100	195	223	221	254	313
	Chloride, mg/L	35	0.30	3.7	4.7	4.5	5.7	8.3
	Fluoride, mg/L	35	0.10	0.25	0.30	0.28	0.30	0.40
	Sulfate, mg/L	35	45	170	210	204	265	340
	Dissolved solids (sum of constituents), mg/L	34	177	447	515	511	641	771
Water years 2001–10								
6/2001–9/2010	Streamflow, instantaneous, ft^3/s	124	6.8	78	172	393	305	3,560
	Specific conductance, µS/cm	124	294	626	834	827	1,030	1,360
	Calcium, mg/L	98	14	47	57	54	63	80
	Magnesium, mg/L	98	5.4	28	39	37	48	58
	Potassium, mg/L	98	1.8	3.9	4.8	5.0	5.8	9.0
	Sodium adsorption ratio, dimensionless	98	0.49	1.4	1.9	2.0	2.4	4.0
	Sodium, mg/L	98	12	52	71	77	99	164
	Alkalinity, mg/L as calcium carbonate	97	104	195	239	237	279	366
	Chloride, mg/L	97	1.4	3.5	5.6	5.0	6.3	7.9
	Fluoride, mg/L	97	0.16	0.28	0.34	0.33	0.39	0.51
	Sulfate, mg/L	97	39	136	211	208	273	377
	Dissolved solids (sum of constituents), mg/L	97	167	388	552	535	670	894

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Powder River at Sussex, Wyo. (site 11, fig. 1)							
	Water years 1986–95							
10/1985–9/1995	Streamflow, instantaneous, ft^3/s	105	6.4	85	138	453	249	10,700
	Specific conductance, µS/cm	100	748	1,920	2,365	2,580	3,018	6,200
	Calcium, mg/L	99	31	100	130	126	150	290
	Magnesium, mg/L	99	14	41	47	48	53	100
	Potassium, mg/L	98	2.1	6.0	7.2	8	10	23
	Sodium adsorption ratio, dimensionless	99	2.4	4.2	5.7	7.8	8.5	40
	Sodium, mg/L	99	81	225	310	381	475	1,400
	Alkalinity, mg/L as calcium carbonate	96	77	180	210	248	275	850
	Chloride, mg/L	97	16	110	190	259	320	1,200
	Fluoride, mg/L	98	0.20	0.53	0.70	0.81	0.90	2.3
	Sulfate, mg/L	97	140	530	620	690	800	1,600
	Dissolved solids (sum of constituents), mg/L	95	452	1,275	1,570	1,684	1,920	3,920
	Water years 2001–10							
11/2000–9/2010	Streamflow, instantaneous, ft^3/s	195	3.7	54	110	144	160	1,410
	Specific conductance, µS/cm	195	545	1,960	2,260	2,660	2,920	6,240
	Calcium, mg/L	194	42	123	141	139	156	288
	Magnesium, mg/L	195	13	46	52	53	59	103
	Potassium, mg/L	195	3.1	7.1	8.2	11	13	76
	Sodium adsorption ratio, dimensionless	194	1.5	4.3	5.1	6.6	7.4	21
	Sodium, mg/L	195	43	221	280	367	419	1,130
	Alkalinity, mg/L as calcium carbonate	195	83	184	213	208	236	330
	Chloride, mg/L	195	28	156	214	307	329	1,190
	Fluoride, mg/L	195	0.25	0.69	0.78	0.91	0.97	2.8
	Sulfate, mg/L	195	134	557	663	732	868	1,630
	Dissolved solids (sum of constituents), mg/L	194	319	1,290	1,500	1,750	1,920	3,880

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Powder River at Arvada, Wyo. (site 12, fig. 1)								
Water years 1986–95								
10/1985–8/1995	Streamflow, instantaneous, ft^3/s	79	2.10	85	175	476	382	5,450
	Specific conductance, µS/cm	75	880	2,010	2,400	2,614	3,100	6,200
	Calcium, mg/L	76	63	100	130	133	160	280
	Magnesium, mg/L	76	22	45	57	58	65	110
	Potassium, mg/L	76	2.3	6.0	7.1	7.7	9	17
	Sodium adsorption ratio, dimensionless	76	1.9	4.5	6.2	7.0	8.5	21
	Sodium, mg/L	76	84	238	325	383	473	1,300
	Alkalinity, mg/L as calcium carbonate	76	90	170	203	225	260	548
	Chloride, mg/L	77	22	110	190	246	320	950
	Fluoride, mg/L	77	0.20	0.50	0.60	0.65	0.70	1.4
	Sulfate, mg/L	77	280	600	730	772	910	1,600
	Dissolved solids (sum of constituents), mg/L	75	579	1,287	1,590	1,745	2,045	4,290
Water years 2001–10								
10/2000–9/2010	Streamflow, instantaneous, ft^3/s	193	0.08	70	118	196	213	2,260
	Specific conductance, µS/cm	193	651	1,990	2,270	2,350	2,610	5,170
	Calcium, mg/L	191	41	106	126	128	148	307
	Magnesium, mg/L	193	18	46	55	56	64	133
	Potassium, mg/L	192	3.4	7.9	9.2	9.7	11	22
	Sodium adsorption ratio, dimensionless	191	1.9	4.7	5.5	5.8	6.5	12
	Sodium, mg/L	193	62	245	294	314	367	752
	Alkalinity, mg/L as calcium carbonate	193	77	194	225	242	271	521
	Chloride, mg/L	193	22	130	175	184	221	514
	Fluoride, mg/L	193	0.30	0.63	0.69	0.70	0.80	1.3
	Sulfate, mg/L	193	179	557	689	734	823	2,010
	Dissolved solids (sum of constituents), mg/L	191	420	1,320	1,510	1,580	1,800	3,770

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
	Powder River at Moorhead, Mont. (site 13, fig. 1)							
	Water years 1986–95							
7/1986–11/1989	Streamflow, instantaneous, ft^3/s	98	25.00	167	315	869	744	7,540
	Specific conductance, µS/cm	87	480	1,460	1,770	1,785	2,180	2,880
	Calcium, mg/L	29	37	94	110	114	130	190
	Magnesium, mg/L	29	15	44	55	55	63	100
	Potassium, mg/L	30	2.4	5.2	6.2	6.4	7.5	10
	Sodium adsorption ratio, dimensionless	30	2.2	3.9	5.1	5.1	5.8	8.7
	Sodium, mg/L	30	62	215	270	256	310	390
	Alkalinity, mg/L as calcium carbonate	30	105	168	196	210	238	377
	Chloride, mg/L	30	29.0	113	152	150	190	280
	Fluoride, mg/L	30	0.30	0.40	0.50	0.46	0.50	0.60
	Sulfate, mg/L	30	140	530	640	649	763	1,100
	Dissolved solids (sum of constituents), mg/L	29	365	1,220	1,397	1,363	1,610	1,830
	Water years 2001–10							
5/2001–9/2010	Streamflow, instantaneous, ft^3/s	213	0.57	97	200	351	329	5,220
	Specific conductance, µS/cm	213	356	1,560	1,820	1,820	2,100	3,660
	Calcium, mg/L	204	31	98	117	116	136	204
	Magnesium, mg/L	204	10	45	54	56	65	160
	Potassium, mg/L	204	2.6	6.6	7.7	7.9	8.8	19
	Sodium adsorption ratio, dimensionless	204	1.1	3.4	4.1	4.0	4.5	9.0
	Sodium, mg/L	204	27	168	214	214	249	520
	Alkalinity, mg/L as calcium carbonate	206	78	169	205	217	245	458
	Chloride, mg/L	206	5.7	62	98	97	121	307
	Fluoride, mg/L	206	0.07	0.41	0.49	0.49	0.58	0.99
	Sulfate, mg/L	206	80	487	576	623	728	1,770
	Dissolved solids (sum of constituents), mg/L	204	216	1,060	1,240	1,250	1,450	2,700

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)								
Water years 1986–95								
10/1985–9/1995	Streamflow, instantaneous, ft^3/s	46	0.01	0.55	4.0	55	17.0	790
	Specific conductance, µS/cm	20	373	1,765	2,590	2,546	3,238	5,500
	Calcium, mg/L	45	18	80	140	134	170	300
	Magnesium, mg/L	45	7.3	63	94	89	120	160
	Potassium, mg/L	45	6.0	14	17	17	20	30
	Sodium adsorption ratio, dimensionless	45	1.5	5.1	7.2	6.7	8.6	13
	Sodium, mg/L	45	35	270	440	423	580	950
	Alkalinity, mg/L as calcium carbonate	42	69	223	307	307	405	660
	Chloride, mg/L	45	2.6	14	23	35	43	120
	Fluoride, mg/L	45	0.10	0.40	0.60	0.58	0.70	1.2
	Sulfate, mg/L	45	94	790	1,200	1,245	1,800	2,700
	Dissolved solids (sum of constituents), mg/L	42	229	1,358	2,105	2,091	2,943	4,400
Water years 2001–10								
10/2000–9/2010	Streamflow, instantaneous, ft^3/s	132	0.01	1.0	3.2	14	8.4	314
	Specific conductance, µS/cm	132	358	2,610	3,380	3,150	3,810	5,250
	Calcium, mg/L	123	18	119	163	156	188	313
	Magnesium, mg/L	123	7.4	79	111	104	129	211
	Potassium, mg/L	123	6.5	15	19	18	21	34
	Sodium adsorption ratio, dimensionless	123	1.9	5.6	6.9	6.7	7.9	11
	Sodium, mg/L	123	39	345	480	450	568	977
	Alkalinity, mg/L as calcium carbonate	127	66	267	356	342	409	734
	Chloride, mg/L	127	6.1	40	58	73	90	298
	Fluoride, mg/L	123	0.17	0.57	0.69	0.66	0.79	1.2
	Sulfate, mg/L	127	76	1,060	1,460	1,370	1,730	2,560
	Dissolved solids (sum of constituents), mg/L	123	203	1,800	2,540	2,370	2,960	4,590

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Little Powder River near Broadus, Mont. (site 15, fig. 1)								
Water years 2001–10								
3/2002–9/2010	Streamflow, instantaneous, ft^3/s	103	0.50	4.9	9.9	21	20	158
	Specific conductance, µS/cm	103	500	1,950	2,490	2,470	3,060	3,940
	Calcium, mg/L	102	13	71	120	110	150	232
	Magnesium, mg/L	102	9.0	36	61	61	86	131
	Potassium, mg/L	102	2.4	10	16	15	20	27
	Sodium adsorption ratio, dimensionless	102	1.6	6.6	7.5	8.2	8.9	18
	Sodium, mg/L	102	43	340	404	391	464	639
	Alkalinity, mg/L as calcium carbonate	102	104	314	362	345	401	470
	Chloride, mg/L	102	3.6	25	41	40	58	93
	Fluoride, mg/L	102	0.10	0.34	0.57	0.54	0.69	1.0
	Sulfate, mg/L	102	128	637	994	973	1,290	1,770
	Dissolved solids (sum of constituents), mg/L	102	310	1,340	1,820	1,810	2,280	3,020
Powder River near Locate, Mont. (site 16, fig. 1)								
Water years 1986–95								
12/1985–9/1994	Streamflow, instantaneous, ft^3/s	100	1.10	118	316	695	744	5,350
	Specific conductance, µS/cm	99	681	1,585	2,100	2,126	2,585	4,330
	Calcium, mg/L	51	51	100	130	125	145	200
	Magnesium, mg/L	51	15	50	59	60	71	100
	Potassium, mg/L	53	3.5	6.1	7.0	7.4	8	12
	Sodium adsorption ratio, dimensionless	51	2.0	3.7	5.6	5.4	6.8	11.6
	Sodium, mg/L	51	65	200	280	300	390	760
	Alkalinity, mg/L as calcium carbonate	54	100	181	210	221	245	417
	Chloride, mg/L	54	17	84	110	130	170	280
	Fluoride, mg/L	54	0.10	0.30	0.40	0.42	0.50	1.0
	Sulfate, mg/L	54	190	650	750	805	895	2,000
	Dissolved solids (sum of constituents), mg/L	51	415	1,280	1,470	1,588	1,905	3,450

Table 1.2. Summary information relating to major-ion constituents and properties in stream-water samples collected at sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during selected periods[1] (water years[2] 1986–95 and 2001–10).—Continued

[Wyo., Wyoming; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; Mont., Montana]

Period of water-quality sampling during indicated summary period	Constituent or property, units of measurement	Number of samples	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
				Water years 2001–10				
10/2000–9/2010	Streamflow, instantaneous, ft^3/s	134	0.20	77	162	445	430	7,880
	Specific conductance, µS/cm	133	625	1,850	2,100	2,080	2,530	3,580
	Calcium, mg/L	113	30	107	122	122	138	200
	Magnesium, mg/L	113	12	51	60	58	69	107
	Potassium, mg/L	113	3.2	7.5	8.5	8.8	10	16
	Sodium adsorption ratio, dimensionless	113	1.8	4.4	4.9	5.2	5.8	9.5
	Sodium, mg/L	113	58	220	265	282	343	520
	Alkalinity, mg/L as calcium carbonate	113	101	204	225	242	266	500
	Chloride, mg/L	113	15	73	97	94	120	185
	Fluoride, mg/L	113	0.26	0.41	0.45	0.46	0.51	0.78
	Sulfate, mg/L	113	149	643	784	774	942	1,280
	Dissolved solids (sum of constituents), mg/L	113	388	1,290	1,500	1,490	1,820	2,590

[1]Data summary periods were selected based on two 10-year trend analysis periods (period 1, water years 1986–95; and period 2, 2001–10), as discussed in the section of this report "Selection of Trend-Analysis Time Periods." No data are presented for period 1 for sites without adequate data for trend analysis for period 1.

[2]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Tongue River at Monarch, Wyo. (site 1, fig. 1)						
1980	--	--	--	--	--	--
1981	--	--	--	--	--	--
1982	--	--	--	--	--	--
1983	--	--	--	--	--	--
1984	--	--	--	--	--	--
1985	--	--	--	--	--	--
1986	--	--	--	--	--	--
1987	--	--	--	--	--	--
1988	--	--	--	--	--	--
1989	--	--	--	--	--	--
1990	--	--	--	--	--	--
1991	--	--	--	--	--	--
1992	--	--	--	--	--	--
1993	--	--	--	--	--	--
1994	--	--	--	--	--	--
1995	--	--	--	--	--	--
1996	--	--	--	--	--	--
1997	--	--	--	--	--	--
1998	--	--	--	--	--	--
1999	--	--	--	--	--	--
2000	--	--	--	--	--	--
2001	--	--	--	--	--	--
2002	--	--	--	--	--	--
2003	--	--	--	--	--	--
2004	105	83	--	--	--	--
2005	214	73	--	--	--	--
2006	109	76	--	--	--	--
2007	301	93	--	--	--	--
2008	310	109	--	--	--	--
2009	231	113	--	--	--	--
2010	240	90	--	--	--	--
Mean 2001–10	216	91	--	--	--	--
Goose Creek below Sheridan, Wyo. (site 2, fig. 1)						
1980	132	89	--	--	--	--
1981	160	64	--	--	--	--
1982	125	79	--	--	--	--
1983	173	86	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Goose Creek below Sheridan, Wyo. (site 2, fig. 1)—Continued						
1984	259	92	--	--	--	--
1985	--	--	--	--	--	--
1986	--	--	--	--	--	--
1987	--	--	--	--	--	--
1988	--	--	--	--	--	--
1989	--	--	--	--	--	--
1990	--	--	--	--	--	--
1991	--	--	--	--	--	--
1992	--	--	--	--	--	--
1993	--	--	--	--	--	--
1994	--	--	--	--	--	--
1995	--	--	--	--	--	--
1996	--	--	--	--	--	--
1997	--	--	--	--	--	--
1998	--	--	--	--	--	--
1999	--	--	--	--	--	--
2000	--	--	--	--	--	--
2001	--	--	--	--	--	--
2002	--	--	--	--	--	--
2003	--	--	--	--	--	--
2004	--	--	--	--	--	--
2005	--	--	--	--	--	--
2006	--	--	--	--	--	--
2007	--	--	--	--	--	--
2008	--	--	--	--	--	--
2009	--	--	--	--	--	--
2010	--	--	--	--	--	--
Mean 2001–10	--	--	--	--	--	--
Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)						
1980	34	34	--	--	--	--
1981	--	--	--	--	--	--
1982	--	--	--	--	--	--
1983	--	--	--	--	--	--
1984	--	--	--	--	--	--
1985	--	--	--	--	--	--
1986	--	--	--	--	--	--
1987	--	--	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)—Continued						
1988	--	--	--	--	--	--
1989	--	--	--	--	--	--
1990	--	--	--	--	--	--
1991	--	--	--	--	--	--
1992	--	--	--	--	--	--
1993	--	--	--	--	--	--
1994	--	--	--	--	--	--
1995	--	--	--	--	--	--
1996	--	--	--	--	--	--
1997	--	--	--	--	--	--
1998	--	--	--	--	--	--
1999	--	--	--	--	--	--
2000	23	19	431	0.59	3	3
2001	18	15	2,794	3.9	22	26
2002	19	12	4,768	6.6	35	55
2003	26	16	4,487	6.2	24	39
2004	15	13	4,329	6.0	40	46
2005	27	19	4,780	6.6	24	35
2006	14	13	5,698	7.9	56	61
2007	33	22	5,916	8.2	25	37
2008	32	25	6,029	8.3	26	33
2009	41	37	5,237	7.2	18	19
2010	26	22	4,488	6.2	24	28
Mean 2001–10	25	19	4,853	6.7	27	35
Tongue River at State line, near Decker, Mont. (site 4, fig. 1)						
1980	308	213	--	--	--	--
1981	398	190	--	--	--	--
1982	354	204	--	--	--	--
1983	447	250	--	--	--	--
1984	645	259	--	--	--	--
1985	228	179	--	--	--	--
1986	400	233	--	--	--	--
1987	324	270	--	--	--	--
1988	326	180	--	--	--	--
1989	194	149	--	--	--	--
1990	452	235	--	--	--	--
1991	451	210	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Tongue River at State line, near Decker, Mont. (site 4, fig. 1)—Continued						
1992	396	214	--	--	--	--
1993	438	229	--	--	--	--
1994	351	230	--	--	--	--
1995	606	242	--	--	--	--
1996	456	250	--	--	--	--
1997	548	263	--	--	--	--
1998	378	279	--	--	--	--
1999	494	247	709	0.98	<1	<1
2000	356	198	3,145	4.3	1	2
2001	163	180	5,873	8.1	5	5
2002	138	110	10,670	14.7	11	13
2003	350	160	9,977	13.8	4	9
2004	150	155	8,861	12.2	8	8
2005	404	150	8,571	11.8	3	8
2006	180	157	8,866	12.2	7	8
2007	540	176	8,837	12.2	2	7
2008	579	222	8,636	11.9	2	5
2009	461	267	7,018	9.7	2	4
2010	461	199	5,825	8.0	2	4
Mean 2001–10	343	177	8,313	11.5	3	6
Tongue River at Tongue River Dam, near Decker, Mont. (site 5, fig. 1)						
1980	319	250	--	--	--	--
1981	374	200	--	--	--	--
1982	326	216	--	--	--	--
1983	445	336	--	--	--	--
1984	611	244	--	--	--	--
1985	250	214	--	--	--	--
1986	406	253	--	--	--	--
1987	296	262	--	--	--	--
1988	340	215	--	--	--	--
1989	206	172	--	--	--	--
1990	426	362	--	--	--	--
1991	421	256	--	--	--	--
1992	374	220	--	--	--	--
1993	446	284	--	--	--	--
1994	348	281	--	--	--	--
1995	637	249	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Tongue River at Tongue River Dam, near Decker, Mont. (site 5, fig. 1)—Continued						
1996	480	407	--	--	--	--
1997	572	422	--	--	--	--
1998	388	308	--	--	--	--
1999	468	294	710	0.98	<1	<1
2000	350	223	3,146	4.3	1	2
2001	174	148	5,875	8.1	5	5
2002	133	93	10,680	15	11	16
2003	309	107	10,030	14	5	13
2004	162	120	9,969	14	9	12
2005	366	94	10,460	14	4	15
2006	176	180	12,280	17	10	9
2007	525	271	14,250	20	4	7
2008	578	241	15,880	22	4	9
2009	448	375	13,320	18	4	5
2010	455	241	10,800	15	3	6
Mean 2001–10	333	187	11,354	16	5	8
Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)						
1980	2.2	1.8	--	--	--	--
1981	0.62	0.75	--	--	--	--
1982	1.5	0.45	--	--	--	--
1983	2.1	0.41	--	--	--	--
1984	0.85	0.25	--	--	--	--
1985	--	--	--	--	--	--
1986	3.6	1.0	--	--	--	--
1987	0.91	1.1	--	--	--	--
1988	2.2	0.54	--	--	--	--
1989	0.35	0.24	--	--	--	--
1990	3.6	0.33	--	--	--	--
1991	1.5	0.72	--	--	--	--
1992	2.8	0.55	--	--	--	--
1993	1.9	0.60	--	--	--	--
1994	3.7	0.50	--	--	--	--
1995	7.5	0.78	--	--	--	--
1996	--	--	--	--	--	--
1997	--	--	--	--	--	--
1998	--	--	--	--	--	--
1999	--	--	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)—Continued						
2000	--	--	--	--	--	--
2001	--	--	--	--	--	--
2002	--	--	36	0.05	--	--
2003	--	--	19	0.03	--	--
2004	0.16	0.06	46	0.06	39	105
2005	0.14	0.10	1,248	1.7	1,200	1,724
2006	0.07	0.05	1,840	2.5	3,803	5,084
2007	3.3	0.20	2,591	3.6	109	1,789
2008	0.31	0.29	2,237	3.1	991	1,065
2009	1.2	0.34	1,523	2.1	175	619
2010	0.68	0.57	1,304	1.8	267	316
Mean 2001–10	0.83	0.23	1,205	1.7	200	724
Tongue River at Birney Day School, near Birney, Mont. (site 7, fig. 1)						
1980	350	293	--	--	--	--
1981	380	231	--	--	--	--
1982	331	248	--	--	--	--
1983	436	340	--	--	--	--
1984	644	273	--	--	--	--
1985	248	224	--	--	--	--
1986	404	297	--	--	--	--
1987	289	260	--	--	--	--
1988	331	225	--	--	--	--
1989	204	220	--	--	--	--
1990	422	388	--	--	--	--
1991	420	255	--	--	--	--
1992	364	230	--	--	--	--
1993	436	284	--	--	--	--
1994	347	300	--	--	--	--
1995	616	265	--	--	--	--
1996	486	401	--	--	--	--
1997	565	422	--	--	--	--
1998	371	310	--	--	--	--
1999	469	279	710	0.98	<1	<1
2000	330	218	3,146	4.3	1	2
2001	184	155	5,877	8.1	4	5
2002	133	100	10,720	15	11	15
2003	318	112	10,050	14	4	12

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Tongue River at Birney Day School, near Birney, Mont. (site 7, fig. 1)—Continued						
2004	151	122	10,010	14	9	11
2005	357	95	11,920	16	5	17
2006	165	160	14,500	20	12	13
2007	514	285	17,080	24	5	8
2008	580	233	18,320	25	4	11
2009	449	381	14,950	21	5	5
2010	474	246	12,250	17	4	7
Mean 2001–10	332	189	12,568	17	5	9
Otter Creek at Ashland, Mont. (site 8, fig. 1)						
1980	5.3	5.0	--	--	--	--
1981	2.6	2.5	--	--	--	--
1982	3.8	2.4	--	--	--	--
1983	4.7	3.3	--	--	--	--
1984	1.9	1.9	--	--	--	--
1985	2.8	1.5	--	--	--	--
1986	--	--	--	--	--	--
1987	--	--	--	--	--	--
1988	1.3	0.78	--	--	--	--
1989	0.90	0.80	--	--	--	--
1990	1.3	1.2	--	--	--	--
1991	1.1	1.0	--	--	--	--
1992	0.60	0.61	--	--	--	--
1993	2.3	1.1	--	--	--	--
1994	5.9	1.1	--	--	--	--
1995	3.5	2.0	--	--	--	--
1996	--	--	--	--	--	--
1997	--	--	--	--	--	--
1998	--	--	--	--	--	--
1999	--	--	--	--	--	--
2000	--	--	--	--	--	--
2001	--	--	--	--	--	--
2002	--	--	--	--	--	--
2003	--	--	--	--	--	--
2004	1.6	1.0	--	--	--	--
2005	1.9	1.7	--	--	--	--
2006	1.3	1.4	--	--	--	--
2007	4.4	1.2	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Otter Creek at Ashland, Mont. (site 8, fig. 1)—Continued						
2008	1.6	1.2	--	--	--	--
2009	3.3	2.3	--	--	--	--
2010	4.0	2.2	--	--	--	--
Mean 2001–10	2.6	1.6	--	--	--	--
Pumpkin Creek near Miles City, Mont. (site 9, fig. 1)						
1980	0.22	0.00	--	--	--	--
1981	0.66	0.00	--	--	--	--
1982	13	0.00	--	--	--	--
1983	16	0.14	--	--	--	--
1984	2.8	0.00	--	--	--	--
1985	6.3	0.00	--	--	--	--
1986	--	--	--	--	--	--
1987	--	--	--	--	--	--
1988	--	--	--	--	--	--
1989	--	--	--	--	--	--
1990	--	--	--	--	--	--
1991	--	--	--	--	--	--
1992	--	--	--	--	--	--
1993	--	--	--	--	--	--
1994	--	--	--	--	--	--
1995	--	--	--	--	--	--
1996	--	--	--	--	--	--
1997	--	--	--	--	--	--
1998	--	--	--	--	--	--
1999	--	--	--	--	--	--
2000	--	--	--	--	--	--
2001	--	--	--	--	--	--
2002	--	--	--	--	--	--
2003	--	--	--	--	--	--
2004	--	--	--	--	--	--
2005	12	0.00	--	--	--	--
2006	16	0.15	--	--	--	--
2007	20	0.09	--	--	--	--
2008	5.2	0.00	--	--	--	--
2009	6.8	0.81	--	--	--	--
2010	27	1	--	--	--	--
Mean 2001–10	15	15	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Tongue River at Miles City, Mont. (site 10, fig. 1)						
1980	266	224	--	--	--	--
1981	318	193	--	--	--	--
1982	297	233	--	--	--	--
1983	413	291	--	--	--	--
1984	530	242	--	--	--	--
1985	205	176	--	--	--	--
1986	417	240	--	--	--	--
1987	245	230	--	--	--	--
1988	235	180	--	--	--	--
1989	166	79	--	--	--	--
1990	341	176	--	--	--	--
1991	417	212	--	--	--	--
1992	296	230	--	--	--	--
1993	485	290	--	--	--	--
1994	355	210	--	--	--	--
1995	562	222	--	--	--	--
1996	450	288	--	--	--	--
1997	574	454	--	--	--	--
1998	293	240	--	--	--	--
1999	502	317	710	0.98	<1	<1
2000	238	182	3,146	4.3	2	2
2001	143	152	5,877	8.1	6	5
2002	68	71	10,720	15	22	21
2003	266	112	10,050	14	5	12
2004	80	70	10,010	14	17	20
2005	330	109	11,920	16	5	15
2006	147	138	14,500	20	14	15
2007	496	150	17,080	24	5	16
2008	493	214	18,320	25	5	12
2009	403	302	14,950	21	5	7
2010	461	181	12,250	17	4	9
Mean 2001–10	289	150	12,570	17	6	12
Powder River at Sussex, Wyo. (site 11, fig. 1)						
1980	154	120	--	--	--	--
1981	134	115	--	--	--	--
1982	232	160	--	--	--	--
1983	279	188	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Powder River at Sussex, Wyo. (site 11, fig. 1)—Continued						
1984	295	155	--	--	--	--
1985	--	--	--	--	--	--
1986	177	134	--	--	--	--
1987	287	170	--	--	--	--
1988	149	123	--	--	--	--
1989	115	90	--	--	--	--
1990	151	123	--	--	--	--
1991	204	107	--	--	--	--
1992	137	106	--	--	--	--
1993	284	113	--	--	--	--
1994	139	114	--	--	--	--
1995	438	180	--	--	--	--
1996	207	160	--	--	--	--
1997	219	170	--	--	--	--
1998	234	143	--	--	--	--
1999	--	--	--	--	--	--
2000	--	--	--	--	--	--
2001	--	--	--	--	--	--
2002	--	--	--	--	--	--
2003	--	--	--	--	--	--
2004	86	82	--	--	--	--
2005	121	109	--	--	--	--
2006	102	84	--	--	--	--
2007	169	100	--	--	--	--
2008	254	115	--	--	--	--
2009	165	127	--	--	--	--
2010	241	131	--	--	--	--
Mean 2001–10	163	107	--	--	--	--
Powder River at Arvada, Wyo. (site 12, fig. 1)						
1980	184	130	--	--	--	--
1981	162	134	--	--	--	--
1982	300	184	--	--	--	--
1983	330	221	--	--	--	--
1984	378	164	--	--	--	--
1985	137	113	--	--	--	--
1986	230	147	--	--	--	--
1987	336	193	--	--	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Powder River at Arvada, Wyo. (site 12, fig. 1)—Continued						
1988	156	113	--	--	--	--
1989	129	106	27	0.04	--	--
1990	190	128	--	--	--	--
1991	241	116	--	--	--	--
1992	167	111	--	--	--	--
1993	378	118	--	--	--	--
1994	182	140	--	--	--	--
1995	634	250	--	--	--	--
1996	253	137	--	--	--	--
1997	311	201	--	--	--	--
1998	315	176	--	--	--	--
1999	427	254	986	1.4	<1	1
2000	175	153	1,759	2.4	1	2
2001	129	100	3,780	5.2	4	5
2002	111	79	9,001	12	11	16
2003	172	110	10,760	15	9	14
2004	87	77	12,840	18	20	23
2005	176	115	18,800	26	15	23
2006	119	100	30,240	42	35	42
2007	205	95	32,280	45	22	47
2008	366	141	34,740	48	13	34
2009	234	180	35,140	49	21	27
2010	323	180	36,800	51	16	28
Mean 2001–10	192	118	22,440	31	16	26
Powder River at Moorhead, Mont. (site 13, fig. 1)						
1980	282	240	--	--	--	--
1981	362	289	--	--	--	--
1982	359	210	--	--	--	--
1983	476	303	--	--	--	--
1984	657	315	--	--	--	--
1985	219	160	--	--	--	--
1986	382	230	--	--	--	--
1987	484	351	--	--	--	--
1988	270	173	--	--	--	--
1989	160	123	27	0.04	<1	<1
1990	353	225	1	0.00	<1	<1
1991	489	233	1	0.00	<1	<1

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Powder River at Moorhead, Mont. (site 13, fig. 1)—Continued						
1992	348	240	483	0.67	<1	<1
1993	584	250	--	--	--	--
1994	311	226	--	--	--	--
1995	794	327	--	--	--	--
1996	461	275	--	--	--	--
1997	608	424	--	--	--	--
1998	504	350	3	<0.01	<1	<1
1999	700	351	1,381	1.9	<1	1
2000	321	270	6,360	8.8	3	3
2001	150	140	14,060	19	13	14
2002	165	131	20,540	28	17	22
2003	290	180	23,960	33	11	18
2004	117	81	26,110	36	31	45
2005	339	173	33,550	46	14	27
2006	164	175	48,390	67	41	38
2007	348	147	51,760	71	21	49
2008	724	230	56,360	78	11	34
2009	448	320	51,760	71	16	22
2010	527	291	51,560	71	14	24
Mean 2001–10	327	187	37,810	52	16	28
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)						
1980	5.7	1.0	--	--	--	--
1981	6.1	0.91	--	--	--	--
1982	27	4.0	--	--	--	--
1983	19	4.2	--	--	--	--
1984	34	5.3	--	--	--	--
1985	10	2.4	--	--	--	--
1986	19	2.3	--	--	--	--
1987	16	6.6	--	--	--	--
1988	5.5	1.9	--	--	--	--
1989	4.0	0.83	38	0.05	1	6
1990	14	1.5	75	0.10	1	7
1991	4.0	0.38	232	0.32	8	84
1992	1.5	0.78	275	0.38	25	49
1993	24	3.8	292	0.40	2	11
1994	29	3.5	273	0.38	1	11
1995	57	13	362	0.50	1	4

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)—Continued						
1996	56	8.1	387	0.53	1	7
1997	54	8.3	621	0.86	2	10
1998	11	4.9	1,940	2.7	25	55
1999	27	9.1	3,921	5.4	20	60
2000	4.9	3.3	8,372	12	236	350
2001	7.9	1.9	10,090	14	176	733
2002	1.7	0.70	11,160	15	925	2,201
2003	8.2	1.0	8,540	12	144	1,204
2004	2.0	0.37	8,005	11	563	3,029
2005	8.2	1.4	8,340	12	141	823
2006	10	1.7	7,971	11	115	648
2007	50	4.2	7,433	10	21	247
2008	39	5.7	7,509	10	26	184
2009	31	8.0	4,117	5.7	18	71
2010	14	4.6	3,242	4.5	31	97
Mean 2001–10	17	2.9	7,640	11	61	358
Little Powder River near Broadus, Mont. (site 15, fig. 1)						
1980	--	--	--	--	--	--
1981	--	--	--	--	--	--
1982	--	--	--	--	--	--
1983	--	--	--	--	--	--
1984	--	--	--	--	--	--
1985	--	--	--	--	--	--
1986	--	--	--	--	--	--
1987	--	--	--	--	--	--
1988	--	--	--	--	--	--
1989	--	--	38	0.05	--	--
1990	--	--	75	0.10	--	--
1991	--	--	232	0.32	--	--
1992	--	--	275	0.38	--	--
1993	--	--	292	0.40	--	--
1994	--	--	273	0.38	--	--
1995	--	--	362	0.50	--	--
1996	--	--	387	0.53	--	--
1997	--	--	621	0.86	--	--
1998	--	--	1,940	2.7	--	--
1999	--	--	3,921	5.4	--	--

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Little Powder River near Broadus, Mont. (site 15, fig. 1)—Continued						
2000	--	--	8,372	12	--	--
2001	--	--	10,090	14	--	--
2002	--	--	11,160	15	--	--
2003	--	--	8,540	12	--	--
2004	--	--	8,005	11	--	--
2005	--	--	8,340	12	--	--
2006	--	--	7,971	11	--	--
2007	--	--	7,433	10	--	--
2008	--	--	7,509	10	--	--
2009	--	--	4,117	5.7	--	--
2010	--	--	3,242	4.5	--	--
Mean 2001–10	--	--	7,640	11	--	--
Powder River near Locate, Mont. (site 16, fig. 1)						
1980	275	227	--	--	--	--
1981	370	290	--	--	--	--
1982	439	228	--	--	--	--
1983	538	408	--	--	--	--
1984	667	300	--	--	--	--
1985	284	206	--	--	--	--
1986	493	250	--	--	--	--
1987	557	450	--	--	--	--
1988	240	184	--	--	--	--
1989	180	100	66	0.09	<1	<1
1990	338	195	76	0.11	<1	<1
1991	443	240	233	0.32	<1	<1
1992	339	210	759	1.0	<1	<1
1993	752	342	292	0.40	<1	<1
1994	573	240	272	0.38	<1	<1
1995	897	417	362	0.50	<1	<1
1996	697	350	387	0.53	<1	<1
1997	787	512	621	0.86	<1	<1
1998	606	421	1,943	2.7	<1	1
1999	821	487	5,302	7.3	1	1
2000	319	304	14,730	20	6	7
2001	183	120	24,150	33	18	28
2002	123	90	31,690	44	36	49
2003	275	180	32,500	45	16	25

Table 1.3. Summary information relating to volumes and rates of streamflow and coal-bed methane (CBM) produced water in watersheds for sites in the Tongue and Powder River watersheds, based on data collected during water years[1] 1980–2010.—Continued

[CBM, coal-bed methane; Wyo., Wyoming; --, no data; Mont., Montana; <, less than]

Water year or summary statistic	Annual mean streamflow, in cubic feet per second	Annual median streamflow, in cubic feet per second	Annual volume of CBM-produced water, in acre-feet	Annual mean pumping rate of CBM-produced water, in cubic feet per second	Annual mean pumping rate of CBM-produced water relative to annual mean streamflow, in percent	Annual mean pumping rate of CBM-produced water relative to annual median streamflow, in percent
Powder River near Locate, Mont. (site 16, fig. 1)—Continued						
2004	79	60	34,120	47	59	78
2005	390	159	41,890	58	15	36
2006	261	180	56,360	78	30	43
2007	477	110	59,200	82	17	75
2008	748	221	63,870	88	12	40
2009	547	360	55,880	77	14	21
2010	713	372	54,800	76	11	20
Mean 2001–10	380	185	45,450	63	17	34

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

Table 1.4. Summary information relating to major-ion constituents and properties in groundwater samples collected from coal-bed methane (CBM) wells and monitoring wells in coal beds in the watersheds upstream from sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during water years[1] 2001–10.

[mg/L, milligrams per liter; Wyo., Wyoming; Mont., Montana]

Constituent or property, units of measurement	Number of wells sampled[2]	Data sources[3]	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Samples collected in the site 3 watershed (Prairie Dog Creek near Acme, Wyo.)								
Calcium, mg/L	4	4, 7	4.0	4.8	5.5	6.0	6.8	9.0
Magnesium, mg/L	4	4, 7	2.0	2.0	2.0	2.2	2.2	3.0
Sodium adsorption ratio, dimensionless	4	4, 7	41	48	51	50	52	55
Sodium, mg/L	4	4, 7	497	527	538	554	565	642
Alkalinity, mg/L as calcium carbonate	4	4, 7	1,140	1,160	1,170	1,170	1,180	1,200
Chloride, mg/L	4	4, 7	4.5	4.9	13	67	76	239
Sulfate, mg/L	4	4, 7	0.04	0.55	4.4	7.2	11	20
Samples collected in the site 4 watershed (Tongue River at State line, near Decker, Mont.)								
Calcium, mg/L	15	3, 4, 7	2.4	3.6	4.5	5.3	6.0	11
Magnesium, mg/L	15	3, 4, 7	1.1	1.9	2.0	2.5	3.0	5.0
Sodium adsorption ratio, dimensionless	15	3, 4, 7	20	40	44	43	51	55
Sodium, mg/L	15	3, 4, 7	265	377	413	457	538	756
Alkalinity, mg/L as calcium carbonate	15	3, 4, 7	577	822	926	986	1,170	1,640
Chloride, mg/L	15	3, 4, 7	2.9	4.3	6.5	26	22	239
Sulfate, mg/L	15	3, 4, 7	0.04	5.3	17	21	34	61
Samples collected in the site 5 watershed (Tongue River at Tongue River Dam, near Decker, Mont.)								
Calcium, mg/L	27	3, 4, 7	2.4	4.4	6.8	7.9	8.8	36
Magnesium, mg/L	28	3, 4, 7	1.1	2.0	3.0	4.4	4.2	31
Sodium adsorption ratio, dimensionless	27	3, 4, 7	10	39	44	42	51	70
Sodium, mg/L	28	3, 4, 7	265	377	470	511	662	782
Alkalinity, mg/L as calcium carbonate	28	3, 4, 7	577	856	1,060	1,110	1,390	1,650
Chloride, mg/L	28	3, 4, 7	2.9	5.8	11	22	21	239
Sulfate, mg/L	28	3, 4, 7	0.04	5.5	17	22	31	77
Samples collected in the site 6 watershed (Hanging Woman Creek near Birney, Mont.)								
Calcium, mg/L	15	3, 6, 7	4.4	5.2	5.8	6.5	6.4	16
Magnesium, mg/L	14	3, 6, 7	2.0	2.6	3.2	3.1	3.5	4.2
Sodium adsorption ratio, dimensionless	14	3, 6, 7	38	42	47	48	54	65
Sodium, mg/L	15	3, 6, 7	452	498	567	574	590	797
Alkalinity, mg/L as calcium carbonate	15	3, 6, 7	907	1,090	1,210	1,250	1,350	1,760
Chloride, mg/L	15	3, 6, 7	15	21	25	29	31	68
Sulfate, mg/L	12	3, 6	0.30	6.3	12	15	25	42
Samples collected in the site 7 watershed (Tongue River at Birney Day School, near Birney, Mont.)								
Calcium, mg/L	43	3, 4, 6, 7	1.5	4.9	6.0	7.3	8.0	36
Magnesium, mg/L	43	3, 4, 6, 7	0.58	2.1	3.0	3.9	3.8	31
Sodium adsorption ratio, dimensionless	42	3, 4, 6, 7	10	40	47	45	52	70
Sodium, mg/L	44	3, 4, 6, 7	265	408	527	530	646	797
Alkalinity, mg/L as calcium carbonate	44	3, 4, 6, 7	577	921	1,150	1,150	1,380	1,760
Chloride, mg/L	44	3, 4, 6, 7	2.9	7.6	18	24	27	239
Sulfate, mg/L	41	3, 4, 6, 7	0.04	5.0	14	20	26	77

Table 1.4. Summary information relating to major-ion constituents and properties in groundwater samples collected from coal-bed methane (CBM) wells and monitoring wells in coal beds in the watersheds upstream from sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during water years[1] 2001–10.—Continued

[mg/L, milligrams per liter; Wyo., Wyoming; Mont., Montana]

Constituent or property, units of measurement	Number of wells sampled[2]	Data sources[3]	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Samples collected in the site 10 watershed (Tongue River at Miles City, Mont.)								
Calcium, mg/L	50	3, 4, 6, 7	1.5	4.5	6.0	7.8	8.0	48
Magnesium, mg/L	50	3, 6, 7	0.55	2.0	3.0	4.7	4.0	53
Sodium adsorption ratio, dimensionless	49	3, 4, 6, 7	0.46	39	47	44	52	73
Sodium, mg/L	51	3, 4, 6, 7	19	404	537	520	624	797
Alkalinity, mg/L as calcium carbonate	51	3, 4, 6, 7	352	917	1,160	1,130	1,300	1,760
Chloride, mg/L	51	3, 4, 6, 7	2.9	7.7	18	23	26	239
Sulfate, mg/L	48	3, 4, 6	0.04	2.7	9.6	18	25	77
Samples collected in the site 12 watershed (Powder River at Arvada, Wyo.)								
Calcium, mg/L	181	1, 4, 5, 7	2.0	19	27	28	32	120
Magnesium, mg/L	181	1, 4, 5, 7	2.0	11	15	17	20	57
Sodium adsorption ratio, dimensionless	181	1, 4, 5, 7	5.5	19	27	27	33	66
Sodium, mg/L	181	1, 4, 5, 7	155	499	701	660	831	1,310
Alkalinity, mg/L as calcium carbonate	186	1, 4, 5, 7	411	1,450	1,980	1,900	2,310	3,460
Chloride, mg/L	186	1, 4, 5, 7	4.9	14	24	24	33	127
Sulfate, mg/L	146	1, 4, 5, 7	0.02	0.02	0.02	1.8	0.10	55
Samples collected in the site 13 watershed (Powder River at Moorhead, Mont.)								
Calcium, mg/L	229	1, 4, 5, 7	2.0	18	25	26	31	120
Magnesium, mg/L	230	1, 4, 5, 7	0.62	9.0	14	16	19	57
Sodium adsorption ratio, dimensionless	229	1, 4, 5, 7	5.5	18	26	25	32	66
Sodium, mg/L	230	1, 4, 5, 7	155	413	619	610	797	1,310
Alkalinity, mg/L as calcium carbonate	240	1, 4, 5, 7	390	1,180	1,710	1,720	2,230	3,460
Chloride, mg/L	238	1, 4, 5, 7	4.9	11	19	22	30	127
Sulfate, mg/L	175	1, 4, 5, 7	0.02	0.02	0.02	1.9	0.69	55
Samples collected in the site 14 watershed (Little Powder River above Dry Creek, near Weston, Wyo.)								
Calcium, mg/L	16	2, 4, 5, 7	13	22	28	32	36	66
Magnesium, mg/L	17	2, 4, 5, 7	6.0	9.0	14	17	20	49
Sodium adsorption ratio, dimensionless	16	2, 4, 5, 7	7.0	8.3	11	10	11	13
Sodium, mg/L	17	2, 4, 5, 7	202	240	262	274	300	384
Alkalinity, mg/L as calcium carbonate	20	2, 4, 5, 7	557	629	753	790	929	1,160
Chloride, mg/L	20	2, 4, 5, 7	7.0	8.0	9.0	9.4	11	14
Sulfate, mg/L	13	2, 4, 5, 7	0.02	0.04	0.27	3.1	3.0	24
Samples collected in the site 15 watershed (Little Powder River near Broadus, Mont.)								
Calcium, mg/L	16	2, 4, 5, 7	13	22	28	32	36	66
Magnesium, mg/L	17	2, 4, 5, 7	6.0	9.0	14	17	20	49
Sodium adsorption ratio, dimensionless	16	2, 4, 5, 7	7.0	8.3	11	10	11	13
Sodium, mg/L	17	2, 4, 5, 7	202	240	262	274	300	384
Alkalinity, mg/L as calcium carbonate	20	2, 4, 5, 7	557	629	753	790	929	1,160
Chloride, mg/L	20	2, 4, 5, 7	7.0	8.0	9.0	9.4	11	14
Sulfate, mg/L	13	2, 4, 5, 7	0.02	0.04	0.27	3.1	3.0	24

Table 1.4. Summary information relating to major-ion constituents and properties in groundwater samples collected from coal-bed methane (CBM) wells and monitoring wells in coal beds in the watersheds upstream from sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during water years[1] 2001–10.—Continued

[mg/L, milligrams per liter; Wyo., Wyoming; Mont., Montana]

Constituent or property, units of measurement	Number of wells sampled[2]	Data sources[3]	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Samples collected in the site 16 watershed (Powder River near Locate, Mont.)								
Calcium, mg/L	249	1, 2, 3, 4, 5, 6, 7	2.0	18	25	26	31	120
Magnesium, mg/L	249	1, 2, 3, 4, 5, 6, 7	0.62	9.0	14	16	19	57
Sodium adsorption ratio, dimensionless	249	1, 2, 3, 4, 5, 6, 7	5.5	15	26	24	31	66
Sodium, mg/L	249	1, 2, 3, 4, 5, 6, 7	155	373	590	584	786	1,310
Alkalinity, mg/L as calcium carbonate	262	1, 2, 3, 4, 5, 6, 7	390	1,090	1,610	1,640	2,190	3,460
Chloride, mg/L	263	1, 2, 3, 4, 5, 6, 7	4.9	10	18	21	30	127
Sulfate, mg/L	190	1, 2, 3, 4, 5, 6, 7	0.02	0.02	0.02	2.0	0.92	55

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Some wells were sampled more than once. In these cases, concentrations for all samples for the given well were averaged for each constituent to provide a single set of concentrations.

[3]Data sources are designated by numbers that correspond to the following references:

1. Campbell and others (2008).
2. Frost and others (2002).
3. Montana Bureau of Mines and Geology (2012).
4. Pearson (2002).
5. Quillinan (2011).
6. U.S. Geological Survey (2012).
7. Wyoming Department of Environmental Quality, published in Quillinan (2011).

Table 1.5. Relative differences (ratios) in mean values of major-ion constituents and properties between stream-water samples (table 1.2) and coal-bed methane (CBM) groundwater samples (table 1.4) for sites in the Tongue and Powder River watersheds, Montana and Wyoming, based on data collected during water years[1] 2001–10.

[Wyo., Wyoming; Mont., Montana]

Constituent or property	Ratio[2]
Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)	
Calcium	22
Magnesium	40
Sodium adsorption ratio	0.03
Sodium	0.20
Alkalinity	0.30
Chloride	0.08
Sulfate	73
Tongue River at State line, near Decker, Mont. (site 4, fig. 1)	
Calcium	10
Magnesium	13
Sodium adsorption ratio	0.02
Sodium	0.07
Alkalinity	0.20
Chloride	0.15
Sulfate	6
Tongue River at Tongue River Dam, near Decker, Mont. (site 5, fig. 1)	
Calcium	6
Magnesium	7
Sodium adsorption ratio	0.02
Sodium	0.06
Alkalinity	0.17
Chloride	0.17
Sulfate	5
Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)	
Calcium	15
Magnesium	42
Sodium adsorption ratio	0.10
Sodium	0.57
Alkalinity	0.44
Chloride	0.45
Sulfate	60
Tongue River at Birney Day School, near Birney, Mont. (site 7, fig. 1)	
Calcium	7
Magnesium	8
Sodium adsorption ratio	0.02
Sodium	0.07
Alkalinity	0.17
Chloride	0.16
Sulfate	6
Tongue River at Miles City, Mont. (site 10, fig. 1)	
Calcium	7
Magnesium	8
Sodium adsorption ratio	0.05
Sodium	0.15
Alkalinity	0.21
Chloride	0.22
Sulfate	12
Powder River at Arvada, Wyo. (site 12, fig. 1)	
Calcium	5
Magnesium	3
Powder River at Arvada, Wyo. (site 12, fig. 1)—Continued	
Sodium adsorption ratio	0.21
Sodium	0.48
Alkalinity	0.13
Chloride	8
Sulfate	408
Powder River at Moorhead, Mont. (site 13, fig. 1)	
Calcium	4
Magnesium	4
Sodium adsorption ratio	0.16
Sodium	0.35
Alkalinity	0.13
Chloride	4
Sulfate	328
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)	
Calcium	5
Magnesium	6
Sodium adsorption ratio	0.67
Sodium	2
Alkalinity	0.43
Chloride	8
Sulfate	442
Little Powder River near Broadus, Mont. (site 15, fig. 1)	
Calcium	3
Magnesium	4
Sodium adsorption ratio	0.82
Sodium	1
Alkalinity	0.44
Chloride	4
Sulfate	314
Powder River near Locate, Mont. (site 16, fig. 1)	
Calcium	5
Magnesium	4
Sodium adsorption ratio	0.22
Sodium	0.48
Alkalinity	0.15
Chloride	4
Sulfate	387

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Ratios greater than one indicate higher concentrations in stream water than in CBM-produced water and indicate the multiple of the relation. For example, a ratio of 22 for calcium at Prairie Dog Creek (site 3) indicates that the mean calcium concentration in the stream water is 22 times higher than in the CBM-produced water. Ratios less than one indicate lower concentrations in stream water than in CBM-produced water and the multiple of the relation is determined by dividing one by the ratio. For example, a ratio of 0.15 for sodium at Prairie Dog Creek (site 3) indicates that the mean sodium concentration in the stream water is 1/0.15 = one-sixth of the concentration in CBM-produced water.

Supplement 2. Summary of the Time-Series Model (TSM) as Applied in this Study

The theory and parameter estimation for the time-series model (TSM) are described in detail in Vecchia (2005). In the TSM, log-transformed concentration data were partitioned into several components according to equation 1:

$$\log(C) = M_C + ANN_C + SEAS_C + TREND + HFV_C \qquad (1)$$

where

- log denotes the base-10 logarithm;
- C is the concentration, in milligrams per liter;
- M_C is the long-term mean of the log-transformed concentration, as the base-10 logarithm of milligrams per liter;
- ANN_C is the annual concentration anomaly (dimensionless);
- $SEAS_C$ is the seasonal concentration anomaly (dimensionless);
- $TREND$ is the concentration trend (dimensionless); and
- HFV_C is the high-frequency variability of the concentration (dimensionless).

In equation 1, the annual concentration anomaly (ANN_C), seasonal concentration anomaly ($SEAS_C$), and high-frequency variability (HFV_C) terms represent natural variability in concentration for different time scales. ANN_C is an estimate of the interannual variability in concentration that can be attributed to long-term (that is, the period of analysis) variability in streamflow. Extended droughts and wet periods can change the chemical composition of streamflow by changing the degree of contact between surface runoff and soil particles, and changing the relative composition of runoff among groundwater, overland flow, and subsurface flow (Vecchia, 2005).

$SEAS_C$ is an estimate of the seasonal variability in concentration that can be attributed to seasonal variability in streamflow or to factors other than variability in streamflow. For example, the seasonal snow-accumulation and snowmelt cycle causes seasonal fluctuations in streamflow and water quality. Seasonality also might affect the relative amount of streamflow that comes from natural sources as compared to CBM-related sources and thus might cause seasonal fluctuations in concentration that are more complicated than a simple relation between concentration and streamflow could produce.

HFV_C is an estimate of the variability in concentration for time scales that are smaller than the seasonal time scale (time scales of several days to several weeks). Thus, high-frequency variability is the variability that remains after the removal of seasonal and annual anomalies and trends. Day-to-day changes in meteorological conditions might cause high-frequency variability in concentration and streamflow. The high-frequency variability depends on a time-series model, called a periodic autoregressive moving average model, that accounts for the presence of serial correlation among concentrations (for example, the tendency for high or low values to persist for several days to several weeks before returning to normal levels) (Vecchia, 2005).

TREND is an estimate of the long-term systematic changes in concentration during the study period that are unrelated to long-term variability in streamflow. For this report, a significant trend might indicate changes in CBM-extraction activities that change the chemical composition of surface water or changes in other activities, such as agricultural practices or irrigation, that can change the amount of major ions that reach the stream. *TREND* consists of piecewise monotonic trends during specified trend-analysis periods. The overall significance of *TREND* (determined by using the generalized likelihood ratio principle; Vecchia, 2005; appendix 1) specifies whether there were any significant changes during any of the specified trend-analysis periods. For a given site and constituent combination, if *TREND* was determined to be nonsignificant, the trends for all of the specified trend-analysis periods were considered nonsignificant and p-values were not reported. Infrequently, overall significance of *TREND* could not be determined or was unusually small (and thus, *TREND* was assumed to be nonsignificant), but the individual trend coefficient for a specified trend-analysis period was highly significant and of large magnitude. In these cases, with *TREND* included in the model, the numerical procedure for minimizing the likelihood function apparently converged to a local, rather than global, minimum and produced unrealistic results relative to the model without *TREND* included. However, trend directions and magnitudes for these infrequent cases generally were consistent with trends for other constituents that would be expected to behave in a similar manner, and with trends for upstream or downstream sites. Therefore, the TSM was presumed to provide reasonably accurate trend magnitudes for the specified trend-analysis period and overall trend patterns were not strongly affected. For a given site and constituent combination, if *TREND* was determined to be significant, the slope coefficient (γ; Vecchia, 2005; appendix 1) for the trend for each specified trend-analysis period was used to determine the significance and magnitude of the trend for the specified trend-analysis period. The null hypothesis in the test for trend significance in a given trend analysis period is that there is no trend (that is, $\gamma = 0$). If the two-tailed p-value for γ was less than the selected alpha level (0.01 in this report), the null hypothesis was rejected and the trend was determined to be significant. Determination of a nonsignificant trend (that is, a *p*-value greater than 0.01) does not imply that the null hypothesis is accepted (that is, that there is no trend). It indicates that within the statistical framework of the analysis, a significant trend was not detected. The magnitude of the trend for a specified trend-analysis period is expressed as the percent difference between the geometric mean concentration at the end of the period and the geometric mean concentration at the start of the period and is determined by the equation

$$\%\Delta FAC = 100(10^{\gamma} - 1) \tag{2}$$

where

$\%\Delta FAC$ is the percent change in the geometric mean of the flow-adjusted concentration; and

γ is the slope coefficient of the trend for the specified trend-analysis period in log-transformed units.

Log-transformed concentrations that have ANN_C and $SEAS_C$ removed are referred to in this report as flow-adjusted concentrations. Using equation 2, the flow-adjusted concentration is defined as:

$$FAC = \log(C) - ANN_C - SEAS_C = M_C + TREND + HFV_C \tag{3}$$

where

FAC is the flow-adjusted concentration, as the base-10 logarithm of milligrams per liter. The *FAC*s defined by equation 3 are analogous to *FAC*s defined in previous publications as the residuals from a regression model that relates concentration to concurrent daily streamflow (Helsel and Hirsch, 2002); however, the TSM approach generally is more effective than a regression-based approach for removing streamflow-related variability (Vecchia, 2005). Time series plots showing the FACs along with the fitted trend (M_C+*TREND*) illustrate long-term changes in median concentration that might indicate effects of changing CBM development on water quality in the selected watersheds.

The key to making TSM a powerful trend analysis tool is that the entire time series of daily streamflow data are used in the model, not just streamflow for the days when water-quality samples are available. The model assumes a three-per-month, or approximately 10-day, sampling frequency. Each month is divided into three intervals—days 1–10, days 10–20, and day 21 through the end of the month. If a water-quality sample is available for a particular interval, it is paired with daily streamflow for the same day of the water-quality sample. If no water-quality sample is available, the concentration value for the interval is missing and streamflow for the middle of the interval (day 5, 15, or 25) is used. If more than one water-quality sample is available for the interval, the sample nearest to the midpoint of the interval is used. The log-transformed streamflow time series (consisting of three values per month) is divided into an annual anomaly, seasonal anomaly, and high-frequency variability according to the following equation,

$$\log(Q) = M_Q + ANN_Q + SEAS_Q + HFV_Q \tag{4}$$

where

Q is daily mean streamflow, in cubic feet per second;

M_Q is the mean of the log-transformed streamflow for the entire trend analysis period, as the base-10 logarithm of cubic feet per second;

ANN_Q is the annual streamflow anomaly, computed as the one-year lagged moving average of $\log(Q) - M_Q$ (dimensionless);

$SEAS_Q$ is the seasonal streamflow anomaly, computed as the 3-month lagged moving average of $\log(Q) - M_Q - ANN_Q$ (dimensionless); and

$HFV_Q = \log(Q) - M_Q - ANN_Q - SEAS_Q$ is the high-frequency streamflow variability (dimensionless).

The streamflow anomalies from equation 4 are used as predictor variables for concentration (eq. 3). For example, ANN_C is assumed to equal a constant coefficient (estimated from the time series model) times ANN_Q. The different scales of streamflow variability often affect concentration in different ways. The relation between HFV_C and HFV_Q can be particularly complicated, changing depending on the time-of-year and the degree of serial correlation in the concentration data and cross-correlation between concentration and streamflow.

The TSM residuals for each site and constituent combination were graphically examined to verify the model assumptions that the residuals had constant variance, were serially uncorrelated, and were approximately normally distributed. Because of the application of the TSM to the large number of site and constituent combinations, and practical considerations to keep the trend periods comparable among sites and constituents, some minor deviations of the residuals from model assumptions [such as small changes in residual variance through time and short-term (about 1–2 years) unresolved trending in the residuals] was tolerated. In cases where unresolved residual trends were considered to be large enough to possibly affect the magnitudes and significance levels of reported fitted trends, more complicated trend models were tested, and in all cases the more complicated models did not change the general findings and conclusions of this report. Therefore, the reported TSM results were judged to provide acceptable fits representative of linearity through nearly all of the range in *FAC*s for a given site and constituent combination. For each site and constituent combination, the fit of the TSM can be assessed by examination of the fitted trends in relation to the *FAC*s that are shown in figures 4.4–4.8, 4.10–4.14, and 4.16. The distribution of the *FAC*s about the fitted trend lines shows the extent to which the residuals might exhibit non-constant variance or unresolved trends.

Supplement 3. Summary of Ordinary Least Squares Regression of Water-Quality Constituents on Time, Streamflow, and Season, as Applied in this Study

Ordinary least squares regression of water-quality constituents on time, streamflow, and season (OLS) was applied in this study following guidelines presented in Helsel and Hirsch (2002). The regression model used is represented by the equation:

$$\log(C_t) = b_0 + b_1 T_t + b_2 Q_t + b_3 \sin(2\pi T_t) + b_4 \cos\text{in}(2\pi T_t) + b_5 \sin(4\pi T_t) + b_6 \cos\text{in}(4\pi T_t) + E_t \quad (1)$$

where

log denotes the base-10 logarithm;

C_t is the value of the water-quality constituent or property, in indicated units of measurement, at time *t*;

b_0 is the intercept;

b_1 through b_6 are the estimated slope b_1 coefficients associated with the various explanatory variables;

T_t is decimal time at time *t*;

Q_t is instantaneous streamflow at the time of sampling, in cubic feet per second and variously transformed;

$\sin(2\pi T_t), \cos\text{in}(2\pi T_t), \sin(4\pi T_t), \text{and } \cos\text{in}(4\pi T_t)$ are periodic functions that describe seasonal variability; and

E_t is an approximately normally distributed random error.

Use of OLS for trend analysis involves regression of constituent concentration [log(C_t), eq. (1)] on streamflow [Q_t, eq. (1)], which inherently provides for flow adjustment and quantifies concentration and streamflow relations. The residuals from the regression of concentration on streamflow represent flow-adjusted concentrations (FACs; Helsel and Hirsch, 2002). Including periodic functions that describe seasonal variability [$\sin(2\pi T_t), \cos\text{in}(2\pi T_t), \sin(4\pi T_t), \text{and } \cos\text{in}(4\pi T_t)$, eq. (1)] accounts for the effect of repetitive seasonal variability on concentration and streamflow relations. The residuals from the regression of concentration on streamflow and the periodic functions represent changes in concentration and streamflow relations through the trend-analysis period. Including decimal time [T_t, eq. (1)] in the model provides quantification of the change in concentration and streamflow relations through time and describes the temporal trend in FACs for the specified trend-analysis period. The slope coefficient for decimal time [b_1, eq. (1)] is used to determine the significance and magnitude of the trend. The null hypothesis in the test for trend significance is that there is no trend (that is, $b_2 = 0$). If the two-tailed *p*-value for b_2 is less than the selected alpha level (0.01 in this report), the null hypothesis is rejected and the trend is determined to be significant. Determination of a nonsignificant trend (that is, a *p*-value greater than 0.01) does not imply that the null hypothesis is accepted (that is, that there is no trend). It indicates that within the statistical framework of the analysis, a significant trend was not detected. The magnitude of the trend is expressed as the percent difference between the geometric mean concentration at the end of the period and the geometric mean concentration at the start of the period and is determined by the equation

$$\%\Delta FAC = 100(10^{(Nb_1)} - 1), \quad (2)$$

where

$\%\Delta FAC$ is the percent change in the geometric mean of the flow-adjusted concentration; and

N is the number of years in the trend-analysis period.

Application of linear regression for flow-adjusted trend analysis requires that the data are normally distributed and that relations between the response variable (a given water-quality constituent) and the combined explanatory variables (time, streamflow, and periodic functions that describe seasonal variability) can be appropriately represented by a linear fit. Further, the relation between the water-quality constituent and streamflow must be statistically significant. Data for many water-quality constituents typically do not conform to a normal distribution because of positive skew (Helsel and Hirsch, 2002). To approximate normality, constituent concentrations were transformed to logarithm (base 10) units.

Best-fit streamflow transformations were determined based on examination of 10 different logarithmic, power, and hyperbolic streamflow transformations. For a given site, the transformation that consistently produced the lowest standard errors among all constituents and properties was selected. Regression diagnostics (including influence and leverage statistics and examination of residuals for normality and homoscedasticity) were reviewed to confirm the acceptability of the selected streamflow transformation in the regression model.

In accounting for seasonal variability, 2π and 4π sine and cosine terms were included in the regression model for all site and constituent combinations. During exploratory analysis, different multiples of π were evaluated for significant influence in the regression model, and the 2π and 4π terms frequently, but not always, were significant. Inclusion of the periodic functions when they were not significant in the regression model for some site and constituent combinations probably had small effect on the trend analysis results.

Accounting for serial correlation was important in the trend analysis. Most sites were sampled on a monthly or bimonthly basis during water years 2001–10 and significant serial correlation was present. Initially, all samples for a given site were included in the analysis and significant serial correlation was determined if the Spearman's correlation coefficient on the lag-one residuals produced a *p*-value less than 0.05 (Helsel and Hirsch, 2002). When serial correlation was significant, the original data were reduced until serial correlation was not significant. The data reduction was done in a systematic stepwise manner with testing of serial correlation at each of the following steps:

1. Removing the second sample in months with more than one sample;
2. Dividing each year into 10 equally spaced intervals and selecting the sample closest in time to the midpoint of each interval, with all other samples removed;
3. Repeating step 2 with eight and six equally spaced intervals until significant serial correlation was resolved.

In a few cases, the selected sample nearest to the midpoint of a given interval was determined to result in a large influential outlier and was replaced with the next closest sample to the midpoint of the interval.

The regression model results for each site and constituent combination were evaluated by examining the significance of the concentration and streamflow relation, the standard error of prediction, influence and leverage statistics, and homoscedasticity and normality of residuals. For a given site and constituent combination, trend results were not reported if the concentration and streamflow relation was nonsignificant (*p*-value greater than 0.05) or the regression model had a standard error of prediction greater than 75 percent. None of the regression models were affected by significant influence. Because of the application of a consistent regression model to the large number of site and constituent combinations, and practical considerations to keep the trend periods comparable among sites and constituents, some minor deviations of the residuals from model assumptions were tolerated. However, the reported regression model results were judged to provide acceptable fits representative of linearity through nearly all of the range in FACs for a given site and constituent combination. For each site and constituent combination, the fit of the regression model can be assessed by examination of the fitted trends in relation to the FACs that are shown in figures 4.1, 4.2, 4.3, 4.9, and 4.15. For plotting purposes, the FACs were determined by adding the residuals from the regression of concentration on streamflow to the geometric mean concentration based on data collected during water years 2001–2010. The distribution of the FACs about the fitted trend lines shows the extent to which the regression model results were affected by factors such as residual heteroscedasticity and curvature.

Supplement 4. Tables and Figures Presenting Detailed Trend-Analysis Results

Table 4.1. Trend-analysis results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; SEAS$_C$, seasonal concentration anomaly; ANN$_C$, annual concentration anomaly; Mont., Montana; NR, not reported; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during water years 1986–95 (period 1)	*p*-value for individual trend[2]	Estimated total percent change during water years 2001–10 (period 2)	*p*-value for individual trend[2]	*p*-value for overall trend analysis[2]	SEAS$_C$ coefficient	*p*-value for SEAS$_C$ coefficient	ANN$_C$ coefficient	*p*-value for ANN$_C$ coefficient
Tongue River at State line, near Decker, Mont. (site 4, fig. 1)										
Specific conductance	282	-17 (-22, -10)	<0.001	5 (-2, 12)	0.156	<0.001	-0.20	<0.001	-0.20	<0.001
Calcium, dissolved	175	-7 (-17, 5)	NR[3]	5 (-1, 11)	NR[3]	0.427	-0.03	0.147	-0.02	0.368
Magnesium, dissolved	175	-12 (-28, 7)	NR[3]	-4 (-10, 2)	NR[3]	0.180	-0.25	<0.001	-0.15	<0.001
Potassium, dissolved	174	0 (-29, 20)	NR[3]	7 (-4, 20)	NR[3]	0.600	-0.47	<0.001	-0.53	<0.001
Sodium adsorption ratio	174	2 (-15, 24)	NR[3]	7 (-5, 20)	NR[3]	0.680	-0.39	<0.001	-0.45	<0.001
Sodium, dissolved	175	-7 (-17, 21)	NR[3]	7 (-7, 24)	NR[3]	1.000	-0.26	<0.001	-0.21	<0.001
"Estimated alkalinity"[4]	177	-12 (-22, 1)	NR[3]	-1 (-6, 4)	NR[3]	0.154	-0.13	<0.001	-0.13	<0.001
Chloride, dissolved	175	-2 (-43, 24)	0.876	31 (18, 46)	<0.001	<0.001	-0.26	<0.001	-0.31	<0.001
Fluoride, dissolved	176	14 (-10, 44)	NR[3]	17 (4, 31)	NR[3]	0.058	-0.22	<0.001	-0.36	<0.001
Sulfate, dissolved	177	-23 (-24, 4)	NR[3]	2 (-11, 17)	NR[3]	0.039	-0.33	<0.001	-0.30	<0.001
Solids, dissolved, (sum of constituents)	174	-16 (-30, 3)	NR[3]	-1 (-8, 6)	NR[3]	0.355	-0.25	<0.001	-0.19	<0.001
Tongue River at Tongue River Dam, near Decker, Mont. (site 5, fig. 1)										
Specific conductance	304	-16 (-19, -12)	NR[3]	1 (-5, 7)	NR[3]	1.000	-0.17	<0.001	-0.06	0.008
Calcium, dissolved	240	-13 (-16, -9)	<0.001	0 (-6, 6)	0.910	<0.001	-0.11	<0.001	0.01	0.681
Magnesium, dissolved	240	-22 (-26, -17)	<0.001	-1 (-9, 7)	0.702	<0.001	-0.24	<0.001	-0.11	0.001
Potassium, dissolved	239	-20 (-25, -15)	<0.001	8 (-3, 19)	0.159	<0.001	-0.26	<0.001	-0.29	<0.001
Sodium adsorption ratio	227	-16 (-20, -11)	NR[3]	38 (28, 49)	NR[3]	0.541	-0.18	<0.001	-0.28	<0.001
Sodium, dissolved	240	-21 (-26, -16)	<0.001	36 (24, 50)	<0.001	<0.001	-0.15	<0.001	-0.25	<0.001
"Estimated alkalinity"[4]	240	-10 (-13, -6)	<0.001	11 (5, 17)	<0.001	<0.001	-0.15	<0.001	-0.04	0.099
Chloride, dissolved	240	-5 (-14, 4)	NR[3]	13 (-1, 29)	NR[3]	0.560	-0.25	<0.001	-0.15	0.008
Fluoride, dissolved	240	-10 (-17, -1)	NR[3]	33 (19, 49)	NR[3]	1.000	-0.22	<0.001	-0.29	<0.001
Sulfate, dissolved	240	-34 (-39, -29)	<0.001	8 (-3, 21)	0.171	<0.001	-0.29	<0.001	-0.12	0.007
Solids, dissolved, (sum of constituents)	240	-22 (-26, -18)	<0.001	10 (3, 18)	0.006	<0.001	-0.22	<0.001	-0.07	0.020
Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)										
Specific conductance	206	10 (0, 20)	0.035	7 (-4, 18)	0.208	0.006	0.08	<0.001	0.18	<0.001
Calcium, dissolved	155	3 (-5, 13)	NR[3]	12 (0, 25)	NR[3]	0.012	0.12	<0.001	0.12	<0.001

Table 4.1. Trend-analysis results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.—Continued

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; $SEAS_C$, seasonal concentration anomaly; ANN_C, annual concentration anomaly; Mont., Montana; NR, not reported; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during water years 1986–95 (period 1)	*p*-value for individual trend[2]	Estimated total percent change during water years 2001–10 (period 2)	*p*-value for individual trend[2]	*p*-value for overall trend analysis[2]	$SEAS_C$ coefficient	*p*-value for $SEAS_C$ coefficient	ANN_C coefficient	*p*-value for ANN_C coefficient
Hanging Woman Creek near Birney, Mont. (site 6, fig. 1)—Continued										
Magnesium, dissolved	156	10 (1, 20)	0.023	11 (0, 22)	0.042	<0.001	0.10	<0.001	0.14	<0.001
Potassium, dissolved	156	18 (8, 30)	<0.001	8 (-3, 20)	0.134	<0.001	0.09	0.032	0.20	<0.001
Sodium adsorption ratio	157	8 (-1, 18)	NR[3]	-13 (-23, -2)	NR[3]	0.224	0.03	0.258	0.13	<0.001
Sodium, dissolved	156	13 (1, 27)	NR[3]	-6 (-19, 9)	NR[3]	0.015	0.07	0.002	0.06	<0.001
“Estimated alkalinity”[4]	157	-2 (-10, 6)	0.547	18 (8, 30)	<0.001	0.002	-0.08	<0.001	-0.06	<0.001
Chloride, dissolved	157	7 (-8, 25)	NR[3]	-8 (-23, 10)	NR[3]	0.705	0.09	0.007	0.12	<0.001
Fluoride, dissolved	137	-9 (-17, -1)	NR[3]	14 (3, 27)	NR[3]	0.097	-0.18	<0.001	-0.17	<0.001
Sulfate, dissolved	157	6 (-8, 23)	NR[3]	6 (-12, 28)	NR[3]	0.043	0.18	<0.001	0.28	<0.001
Solids, dissolved, (sum of constituents)	155	5 (-5, 15)	NR[3]	12 (0, 26)	NR[3]	0.037	0.11	<0.001	0.18	<0.001
Tongue River at Birney Day School, near Birney, Mont. (site 7, fig. 1)										
Specific conductance	277	-15 (-19, -10)	<0.001	-2 (-8, 5)	0.606	<0.001	-0.19	<0.001	-0.10	0.001
Calcium, dissolved	194	-19 (-25, -12)	NR[3]	9 (-2, 21)	NR[3]	1.000	-0.13	<0.001	-0.06	0.077
Magnesium, dissolved	194	-33 (-39, -26)	<0.001	20 (6, 36)	0.004	<0.001	-0.24	<0.001	-0.19	<0.001
Potassium, dissolved	193	-24 (-33, -14)	<0.001	10 (-6, 29)	0.230	<0.001	-0.28	<0.001	-0.37	<0.001
Sodium adsorption ratio	190	-27 (-34, -19)	NR[3]	46 (28, 66)	NR[3]	0.092	-0.19	<0.001	-0.32	<0.001
Sodium, dissolved	194	-35 (-43, -25)	NR[3]	50 (27, 77)	NR[3]	0.161	-0.16	<0.001	-0.22	<0.001
“Estimated alkalinity”[4]	193	-12 (-17, -7)	<0.001	10 (3, 18)	0.004	<0.001	-0.13	<0.001	-0.06	0.009
Chloride, dissolved	193	-15 (-26, -2)	NR[3]	25 (5, 50)	NR[3]	0.224	-0.26	<0.001	-0.10	0.075
Fluoride, dissolved	193	-15 (-26, -2)	NR[3]	19 (1, 41)	NR[3]	1.000	-0.18	<0.001	-0.30	<0.001
Sulfate, dissolved	194	-39 (-49, -28)	<0.001	22 (0, 49)	0.050	<0.001	-0.28	<0.001	-0.18	0.011
Solids, dissolved, (sum of constituents)	193	-30 (-36, -22)	<0.001	21 (7, 37)	0.002	<0.001	-0.21	<0.001	-0.13	0.003
Otter Creek at Ashland, Mont. (site 8, fig. 1)										
Specific conductance	206	-10 (-14, -5)	<0.001	15 (8, 22)	<0.001	<0.001	0.01	0.694	0.04	<0.001
Calcium, dissolved	164	-14 (-21, -6)	NR[3]	22 (10, 36)	NR[3]	0.012	0.07	<0.001	0.06	0.004
Magnesium, dissolved	164	-11 (-19, -1)	NR[3]	18 (4, 33)	NR[3]	0.051	-0.01	0.565	0.07	0.003
Potassium, dissolved	163	0 (-8, 9)	NR[3]	-3 (-15, 11)	NR[3]	0.891	-0.02	0.581	-0.00	0.955

Table 4.1. Trend-analysis results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.—Continued

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; $SEAS_C$, seasonal concentration anomaly; ANN_C, annual concentration anomaly; Mont., Montana; NR, not reported; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during water years 1986–95 (period 1)	*p*-value for individual trend[2]	Estimated total percent change during water years 2001–10 (period 2)	*p*-value for individual trend[2]	*p*-value for overall trend analysis[2]	$SEAS_c$ coefficient	*p*-value for $SEAS_c$ coefficient	ANN_c coefficient	*p*-value for ANN_c coefficient
Otter Creek at Ashland, Mont. (site 8, fig. 1)—Continued										
Sodium adsorption ratio	164	5 (0, 9)	0.041	-2 (-7, 4)	0.455	0.003	-0.04	<0.001	-0.01	0.317
Sodium, dissolved	163	-6 (-13, 2)	NR[3]	17 (7, 29)	NR[3]	1.000	-0.02	0.352	0.00	0.820
“Estimated alkalinity”[4]	164	0 (-6, 6)	0.991	11 (4, 18)	0.002	<0.001	-0.07	<0.001	-0.05	<0.001
Chloride, dissolved	162	3 (-14, 23)	NR[3]	-13 (-30, 9)	NR[3]	0.303	-0.07	0.129	0.01	0.825
Fluoride, dissolved	150	5 (-4, 15)	NR[3]	11 (-1, 24)	NR[3]	0.027	-0.13	<0.001	-0.10	<0.001
Sulfate, dissolved	163	-16 (-24, -8)	<0.001	35 (21, 51)	<0.001	<0.001	0.00	0.945	0.08	<0.001
Solids, dissolved, (sum of constituents)	161	-11 (-18, -3)	0.005	26 (14, 39)	<0.001	<0.001	-0.00	0.843	0.04	0.038
Tongue River at Miles City, Mont. (site 10, fig. 1)										
Specific conductance	310	-7 (-13, -2)	NR[3]	1 (-6, 10)	NR[3]	0.163	-0.24	<0.001	-0.13	<0.001
Calcium, dissolved	185	-10 (-15, -5)	NR[3]	4 (-2, 12)	NR[3]	1.000	-0.10	<0.001	-0.04	0.039
Magnesium, dissolved	185	-25 (-31, -18)	<0.001	14 (2, 27)	0.016	<0.001	-0.23	<0.001	-0.16	<0.001
Potassium, dissolved	186	-21 (-27, -13)	NR[3]	6 (-5, 17)	NR[3]	0.040	-0.41	<0.001	-0.27	<0.001
Sodium adsorption ratio	185	-4 (-13, 6)	NR[3]	7 (-5, 21)	NR[3]	1.000	-0.31	<0.001	-0.25	<0.001
Sodium, dissolved	185	-9 (-19, 2)	NR[3]	7 (-7, 22)	NR[3]	0.082	-0.20	<0.001	-0.17	<0.001
“Estimated alkalinity”[4]	185	-3 (-9, 3)	NR[3]	6 (-2, 14)	NR[3]	0.366	-0.19	<0.001	-0.14	<0.001
Chloride, dissolved	183	-14 (-22, -5)	0.002	22 (8, 39)	0.001	0.004	-0.26	<0.001	-0.12	<0.001
Fluoride, dissolved	184	-11 (-19, -2)	NR[3]	20 (6, 35)	NR[3]	0.042	-0.09	<0.001	-0.15	<0.001
Sulfate, dissolved	183	-25 (-33, -17)	<0.001	9 (-5, 24)	0.201	0.002	-0.32	<0.001	-0.20	<0.001
Solids, dissolved, (sum of constituents)	182	-14 (-21, -7)	<0.001	5 (-5, 15)	0.341	<0.001	-0.27	<0.001	-0.16	<0.001

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Determination of and distinction between *p*-value for individual trend and *p*-value for overall trend analysis are discussed in “Supplement 2: Summary of the Time-Series Model (TSM) as Applied in this Study.”

[3]*p*-value for individual trend period not reported because of nonsignificant overall trend analysis (*p*-value > 0.01), as discussed in “Supplement 2: Summary of the Time-Series Model (TSM) as Applied in this Study.”

[4]“Estimated alkalinity” data were developed by selecting either alkalinity or acid neutralizing capacity (ANC), depending primarily on which measurement was available for a given sample, as discussed in the section of this report “Sampling and Analytical Methods.”

Table 4.2. Trend-analysis results determined by using ordinary least squares regression (OLS) on time, streamflow, and season for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 2001–10.

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; SEE, standard error of estimate, in percent; Wyo., Wyoming; log10, logarithm (base 10); HYP, hyperbolic transformation described by 1/(1+(*b**Q)), where b is a constant (as indicated) and *Q* is streamflow, in cubic feet per second; Mont., Montana; NR, not reported]

Constituent or property	Number of samples	Estimated total percent change during trend-analysis period	*p*-value for individual trend	Streamflow transformation	*p*-value for streamflow coefficient	SEE of regression	*p*-value for regression
Tongue River at Monarch, Wyo. (site 1, fig. 1)							
Trend-analysis period water years 2005–10							
Specific conductance	58	16 (7, 26)	<0.001	log10(*Q*)	<0.001	9	<0.001
Calcium, dissolved	57	16 (6, 26)	<0.001	log10(*Q*)	<0.001	10	<0.001
Magnesium, dissolved	57	15 (4, 28)	0.005	log10(*Q*)	<0.001	13	<0.001
Potassium, dissolved	57	4 (-13, 24)	0.650	log10(*Q*)	<0.001	21	<0.001
Sodium adsorption ratio	57	11 (-5, 30)	0.157	log10(*Q*)	<0.001	19	<0.001
Sodium, dissolved	57	19 (-2, 44)	0.059	log10(*Q*)	<0.001	23	<0.001
Alkalinity	57	17 (9, 25)	<0.001	log10(*Q*)	<0.001	8	<0.001
Chloride, dissolved	57	42 (21, 66)	<0.001	log10(*Q*)	<0.001	19	<0.001
Fluoride, dissolved	57	-7 (-18, 5)	0.205	log10(*Q*)	<0.001	15	<0.001
Sulfate, dissolved	57	26 (5, 52)	0.008	log10(*Q*)	<0.001	22	<0.001
Solids, dissolved, (sum of constituents)	57	16 (6, 28)	<0.001	log10(*Q*)	<0.001	11	<0.001
Goose Creek below Sheridan, Wyo. (site 2, fig. 1)							
Trend-analysis period water years 2001–10							
Specific conductance	68	5 (-9, 21)	0.449	HYP (*b*=0.01)	<0.001	16	<0.001
Calcium, dissolved	68	6 (-9, 22)	0.429	HYP (*b*=0.01)	<0.001	17	<0.001
Magnesium, dissolved	68	5 (-12, 26)	0.534	HYP (*b*=0.01)	<0.001	20	<0.001
Potassium, dissolved	68	1 (-21, 29)	0.933	HYP (*b*=0.01)	<0.001	28	<0.001
Sodium adsorption ratio	68	-1 (-11, 10)	0.818	HYP (*b*=0.01)	<0.001	12	<0.001
Sodium, dissolved	68	2 (-14, 20)	0.806	HYP (*b*=0.01)	<0.001	19	<0.001
Alkalinity	67	6 (-9, 22)	0.427	HYP (*b*=0.01)	<0.001	16	<0.001
Chloride, dissolved	68	29 (1, 64)	0.032	HYP (*b*=0.01)	<0.001	28	<0.001
Fluoride, dissolved	68	-3 (-17, 13)	0.639	HYP (*b*=0.01)	<0.001	18	<0.001
Sulfate, dissolved	68	1 (-16, 22)	0.882	HYP (*b*=0.01)	<0.001	21	<0.001
Solids, dissolved, (sum of constituents)	67	4 (-10, 21)	0.569	HYP (*b*=0.01)	<0.001	17	<0.001
Trend-analysis period water years 2005–10							
Specific conductance	44	-3 (-20, 18)	0.729	HYP (*b*=0.01)	<0.001	19	<0.001
Calcium, dissolved	44	0 (-19, 22)	0.970	HYP (*b*=0.01)	<0.001	20	<0.001
Magnesium, dissolved	44	-9 (-28, 16)	0.422	HYP (*b*=0.01)	<0.001	24	<0.001
Potassium, dissolved	44	-6 (-31, 27)	0.652	HYP (*b*=0.01)	0.015	30	<0.001
Sodium adsorption ratio	44	-6 (-17, 7)	0.296	HYP (*b*=0.01)	<0.001	13	<0.001
Sodium, dissolved	44	-8 (-26, 14)	0.402	HYP (*b*=0.01)	<0.001	21	<0.001
Alkalinity	44	0 (-18, 21)	0.995	HYP (*b*=0.01)	<0.001	19	<0.001
Chloride, dissolved	44	18 (-12, 58)	0.231	HYP (*b*=0.01)	<0.001	29	<0.001
Fluoride, dissolved	44	-2 (-19, 19)	0.829	HYP (*b*=0.01)	<0.001	19	<0.001
Sulfate, dissolved	44	-11 (-30, 14)	0.314	HYP (*b*=0.01)	<0.001	25	<0.001
Solids, dissolved, (sum of constituents)	44	-4 (-22, 17)	0.619	HYP (*b*=0.01)	<0.001	20	<0.001

Table 4.2. Trend-analysis results determined by using ordinary least squares regression (OLS) on time, streamflow, and season for major-ion constituents and properties for sites in the Tongue River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 2001–10.—Continued

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; SEE, standard error of estimate, in percent; Wyo., Wyoming; log10, logarithm (base 10); HYP, hyperbolic transformation described by 1/(1+(*b**Q)), where *b* is a constant (as indicated) and *Q* is streamflow, in cubic feet per second; Mont., Montana; NR, not reported]

Constituent or property	Number of samples	Estimated total percent change during trend-analysis period	*p*-value for individual trend	Streamflow transformation	*p*-value for streamflow coefficient	SEE of regression	*p*-value for regression
Prairie Dog Creek near Acme, Wyo. (site 3, fig. 1)							
Trend-analysis period water years 2001–10							
Specific conductance	99	17 (7, 28)	<0.001	HYP (*b*=0.1)	<0.001	15	<0.001
Calcium, dissolved	97	12 (2, 22)	0.014	HYP (*b*=0.1)	<0.001	15	<0.001
Magnesium, dissolved	97	24 (11, 38)	<0.001	HYP (*b*=0.1)	<0.001	18	<0.001
Potassium, dissolved	97	13 (0, 29)	0.046	HYP (*b*=0.1)	<0.001	21	<0.001
Sodium adsorption ratio	97	32 (19, 46)	<0.001	HYP (*b*=0.1)	<0.001	16	<0.001
Sodium, dissolved	97	43 (24, 65)	<0.001	HYP (*b*=0.1)	<0.001	23	<0.001
Alkalinity	96	12 (3, 21)	0.005	HYP (*b*=0.1)	<0.001	13	<0.001
Chloride, dissolved	96	52 (34, 74)	<0.001	HYP (*b*=0.1)	<0.001	21	<0.001
Fluoride, dissolved	96	5 (-2, 13)	0.159	HYP (*b*=0.1)	<0.001	12	<0.001
Sulfate, dissolved	96	27 (11, 46)	<0.001	HYP (*b*=0.1)	<0.001	22	<0.001
Solids, dissolved, (sum of constituents)	95	22 (10, 36)	<0.001	HYP (*b*=0.1)	<0.001	17	<0.001
Trend-analysis period water years 2005–10							
Specific conductance	59	17 (5, 32)	0.004	HYP (*b*=0.1)	<0.001	14	<0.001
Calcium, dissolved	57	6 (-6, 20)	0.271	HYP (*b*=0.1)	<0.001	15	<0.001
Magnesium, dissolved	57	19 (3, 38)	0.013	HYP (*b*=0.1)	<0.001	18	<0.001
Potassium, dissolved	57	12 (-6, 33)	0.171	HYP (*b*=0.1)	<0.001	21	<0.001
Sodium adsorption ratio	57	32 (16, 51)	<0.001	HYP (*b*=0.1)	<0.001	16	<0.001
Sodium, dissolved	57	41 (17, 69)	<0.001	HYP (*b*=0.1)	<0.001	23	<0.001
Alkalinity	57	10 (0, 21)	0.041	HYP (*b*=0.1)	<0.001	12	<0.001
Chloride, dissolved	57	57 (36, 82)	<0.001	HYP (*b*=0.1)	<0.001	18	<0.001
Fluoride, dissolved	57	-3 (-12, 7)	0.516	HYP (*b*=0.1)	<0.001	12	<0.001
Sulfate, dissolved	57	33 (12, 58)	<0.001	HYP (*b*=0.1)	<0.001	21	<0.001
Solids, dissolved, (sum of constituents)	57	23 (7, 41)	0.002	HYP (*b*=0.1)	<0.001	17	<0.001
Pumpkin Creek near Miles City, Mont. (site 9, fig. 1)							
Trend-analysis period water years 2005–10							
Specific conductance	41	168 (56, 360)	<0.001	HYP (*b*=0.1)	<0.001	63	<0.001
Calcium, dissolved	38	NR[2]	NR[2]	HYP (b=0.1)	<0.001	94	<0.001
Magnesium, dissolved	38	NR[2]	NR[2]	HYP (*b*=0.1)	<0.001	148	<0.001
Potassium, dissolved	38	123 (47, 239)	<0.001	HYP (*b*=0.1)	0.005	42	<0.001
Sodium adsorption ratio	38	-3 (-27, 28)	0.783	HYP (*b*=0.1)	<0.001	27	<0.001
Sodium, dissolved	38	176 (49, 410)	<0.001	HYP (*b*=0.1)	<0.001	65	<0.001
Alkalinity	38	85 (24, 178)	0.002	HYP (*b*=0.1)	<0.001	40	<0.001
Chloride, dissolved	38	176 (41, 439)	0.002	HYP (*b*=0.1)	<0.001	72	<0.001
Fluoride, dissolved	38	-12 (-31, 12)	0.236	HYP (*b*=0.1)	<0.001	23	<0.001
Sulfate, dissolved	38	NR[2]	NR[2]	HYP (*b*=0.1)	<0.001	99	<0.001
Solids, dissolved, (sum of constituents)	38	269 (87, 627)	<0.001	HYP (*b*=0.1)	<0.001	73	<0.001

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Results not reported because of SEE greater than 75 percent.

Table 4.3. Trend-analysis results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Powder River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; $SEAS_C$, seasonal concentration anomaly; ANN_C, annual concentration anomaly; Wyo., Wyoming; NR, not reported; Mont., Montana; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during water years 1986–95 (period 1)	*p*-value for individual trend[2]	Estimated total percent change during water years 2001–10 (period 2)	*p*-value for individual trend[2]	*p*-value for overall trend analysis[2]	$SEAS_c$ coefficient	*p*-value for $SEAS_c$ coefficient	ANN_c coefficient	*p*-value for ANN_c coefficient
Powder River at Sussex, Wyo. (site 11, fig. 1)										
Specific conductance	392	-31 (-35, -26)	NR[3]	8 (1, 16)	NR[3]	1.000	-0.26	<0.001	-0.28	<0.001
Calcium, dissolved	383	21 (14, 29)	NR[3]	2 (-5, 9)	NR[3]	1.000	-0.04	0.230	-0.02	0.478
Magnesium, dissolved	384	9 (3, 16)	NR[3]	-6 (-11, 0)	NR[3]	0.020	-0.15	<0.001	-0.07	0.006
Potassium, dissolved	383	-10 (-17, -3)	0.007	28 (16, 40)	<0.001	<0.001	-0.30	<0.001	-0.44	<0.001
Sodium adsorption ratio	383	-43 (-49, -36)	<0.001	7 (-8, 23)	0.388	<0.001	-0.05	0.142	-0.16	0.009
Sodium, dissolved	385	-53 (-57, -48)	NR[3]	17 (3, 32)	NR[3]	1.000	-0.27	<0.001	-0.39	<0.001
"Estimated alkalinity"[4]	372	-37 (-42, -32)	<0.001	9 (-1, 20)	0.072	0.005	-0.17	<0.001	-0.16	<0.001
Chloride, dissolved	383	-63 (-67, -58)	<0.001	44 (24, 67)	<0.001	<0.001	-0.49	<0.001	-0.84	<0.001
Fluoride, dissolved	375	-25 (-30, -20)	<0.001	20 (11, 29)	<0.001	<0.001	-0.28	<0.001	-0.42	<0.001
Sulfate, dissolved	383	14 (6, 23)	NR[3]	-7 (-15, 1)	NR[3]	0.278	-0.15	<0.001	-0.08	0.024
Solids, dissolved, (sum of constituents)	369	-29 (-33, -24)	<0.001	8 (0, 16)	0.054	<0.001	-0.25	<0.001	-0.26	<0.001
Powder River at Arvada, Wyo. (site 12, fig. 1)										
Specific conductance	332	-30 (-34, -25)	<0.001	9 (1, 18)	0.025	<0.001	-0.14	<0.001	-0.20	<0.001
Calcium, dissolved	329	14 (5, 22)	<0.001	-23 (-29, -16)	<0.001	<0.001	-0.06	0.012	-0.04	0.078
Magnesium, dissolved	331	2 (-5, 11)	0.545	-16 (-23, -8)	<0.001	<0.001	-0.12	<0.001	-0.09	<0.001
Potassium, dissolved	330	-8 (-15, -1)	0.018	60 (46, 75)	<0.001	<0.001	-0.17	<0.001	-0.29	<0.001
Sodium adsorption ratio	329	-51 (-55, -48)	<0.001	53 (40, 66)	<0.001	<0.001	-0.11	<0.001	-0.24	<0.001
Sodium, dissolved	331	-50 (-55, -46)	<0.001	39 (25, 54)	<0.001	<0.001	-0.19	<0.001	-0.29	<0.001
"Estimated alkalinity"[4]	331	-32 (-36, -27)	<0.001	51 (40, 64)	<0.001	<0.001	-0.08	<0.001	-0.14	<0.001
Chloride, dissolved	332	-62 (-66, -57)	<0.001	37 (21, 55)	<0.001	<0.001	-0.25	<0.001	-0.49	<0.001
Fluoride, dissolved	323	-31 (-39, -22)	<0.001	48 (27, 72)	<0.001	<0.001	-0.06	0.011	-0.17	<0.001
Sulfate, dissolved	332	-2 (-9, 7)	0.704	-17 (-25, -9)	<0.001	<0.001	-0.14	<0.001	-0.10	<0.001
Solids, dissolved, (sum of constituents)	328	-27 (-32, -21)	<0.001	4 (-4, 13)	0.362	<0.001	-0.15	<0.001	-0.19	<0.001
Powder River at Moorhead, Mont. (site 13, fig. 1)										
Specific conductance	374	-23 (-27, -18)	<0.001	4 (-3, 12)	0.258	<0.001	-0.14	<0.001	-0.21	<0.001
Calcium, dissolved	276	4 (-7, 17)	0.451	-19 (-29, -8)	0.001	<0.001	-0.11	<0.001	-0.12	<0.001

Table 4.3. Trend-analysis results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Powder River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.—Continued

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; $SEAS_C$, seasonal concentration anomaly; ANN_C, annual concentration anomaly; Wyo., Wyoming; NR, not reported; Mont., Montana; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during water years 1986–95 (period 1)	*p*-value for individual trend[2]	Estimated total percent change during water years 2001–10 (period 2)	*p*-value for individual trend[2]	*p*-value for overall trend analysis[2]	$SEAS_c$ coefficient	*p*-value for $SEAS_c$ coefficient	ANN_c coefficient	*p*-value for ANN_c coefficient
Powder River at Moorhead, Mont. (site 13, fig. 1)—Continued										
Magnesium, dissolved	277	-9 (-19, 1)	0.075	-7 (-19, 5)	0.222	<0.001	-0.24	<0.001	-0.21	<0.001
Potassium, dissolved	278	-14 (-22, -5)	0.002	45 (29, 63)	<0.001	<0.001	-0.17	<0.001	-0.28	<0.001
Sodium adsorption ratio	277	-39 (-45, -32)	<0.001	41 (25, 59)	<0.001	<0.001	-0.09	<0.001	-0.20	<0.001
Sodium, dissolved	278	-39 (-46, -30)	<0.001	31 (13, 51)	<0.001	<0.001	-0.14	<0.001	-0.25	<0.001
"Estimated alkalinity"[4]	282	-36 (-42, -29)	<0.001	75 (56, 97)	<0.001	<0.001	-0.07	<0.001	-0.22	<0.001
Chloride, dissolved	282	-46 (-52, -38)	<0.001	-6 (-18, 8)	0.359	<0.001	-0.17	<0.001	-0.29	<0.001
Fluoride, dissolved	281	-15 (-25, -5)	0.004	44 (26, 65)	<0.001	<0.001	-0.05	0.084	-0.18	<0.001
Sulfate, dissolved	282	-7 (-18, 5)	0.204	-16 (-27, -4)	0.010	<0.001	-0.21	<0.001	-0.19	<0.001
Solids, dissolved, (sum of constituents)	276	-21 (-30, -12)	<0.001	3 (-9, 16)	0.650	<0.001	-0.19	<0.001	-0.23	<0.001
Little Powder River above Dry Creek, near Weston, Wyo. (site 14, fig. 1)										
Specific conductance	237	12 (0, 25)	NR[3]	8 (-5, 22)	NR[3]	0.045	-0.07	0.003	0.00	0.972
Calcium, dissolved	246	6 (-4, 19)	NR[3]	11 (-4, 27)	NR[3]	0.127	-0.09	<0.001	-0.00	0.984
Magnesium, dissolved	246	5 (-7, 20)	NR[3]	6 (-9, 25)	NR[3]	1.000	-0.13	<0.001	0.02	0.431
Potassium, dissolved	246	9 (1, 18)	NR[3]	1 (-9, 11)	NR[3]	0.028	-0.11	0.009	-0.06	0.915
Sodium adsorption ratio	247	6 (-1, 13)	0.097	10 (0, 20)	0.038	0.007	-0.05	<0.001	-0.06	<0.001
Sodium, dissolved	247	12 (0, 25)	0.050	15 (-1, 33)	0.055	0.008	-0.05	<0.001	-0.00	0.009
"Estimated alkalinity"[4]	245	4 (-6, 15)	NR[3]	13 (0, 27)	NR[3]	0.049	-0.06	0.007	-0.03	0.072
Chloride, dissolved	252	220 (156, 300)	<0.001	99 (52, 161)	<0.001	<0.001	-0.09	0.103	-0.17	<0.001
Fluoride, dissolved	244	13 (4, 23)	0.003	6 (-4, 18)	0.234	0.002	-0.08	<0.001	-0.12	<0.001
Sulfate, dissolved	251	1 (-10, 13)	0.919	8 (-6, 24)	0.250	0.001	-0.10	<0.001	0.01	0.603
Solids, dissolved, (sum of constituents)	238	11 (-1, 24)	NR[3]	10 (-5, 27)	NR[3]	0.116	-0.11	<0.001	-0.02	0.349
Powder River near Locate, Mont. (site 16, fig. 1)										
Specific conductance	341	-20 (-26, -14)	<0.001	12 (2, 23)	0.020	<0.001	-0.11	<0.001	-0.16	<0.001
Calcium, dissolved	242	-4 (-12, 4)	0.298	-9 (-18, 1)	0.069	0.001	-0.05	0.037	-0.04	0.101
Magnesium, dissolved	242	-13 (-21, -5)	NR[3]	7 (-5, 20)	NR[3]	0.015	-0.12	<0.001	-0.06	0.020
Potassium, dissolved	243	-11 (-17, -5)	<0.001	42 (31, 54)	<0.001	<0.001	-0.19	<0.001	-0.20	<0.001

Table 4.3. Trend-analysis results determined by using the time-series model (TSM) for major-ion constituents and properties for sites in the Powder River watershed, Wyoming and Montana, based on analysis of data collected during water years[1] 1980–2010.—Continued

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; $SEAS_C$, seasonal concentration anomaly; ANN_C, annual concentration anomaly; Wyo., Wyoming; NR, not reported; Mont., Montana; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during water years 1986–95 (period 1)	*p*-value for individual trend[2]	Estimated total percent change during water years 2001–10 (period 2)	*p*-value for individual trend[2]	*p*-value for overall trend analysis[2]	$SEAS_C$ coefficient	*p*-value for $SEAS_C$ coefficient	ANN_C coefficient	*p*-value for ANN_C coefficient
Powder River near Locate, Mont. (site 16, fig. 1)—Continued										
Sodium adsorption ratio	242	-29 (-34, -24)	<0.001	28 (17, 40)	<0.001	<0.001	-0.12	<0.001	-0.17	<0.001
Sodium, dissolved	242	-31 (-37, -24)	<0.001	29 (14, 47)	<0.001	<0.001	-0.10	<0.001	-0.14	<0.001
"Estimated alkalinity"[4]	245	-15 (-20, -9)	<0.001	20 (11, 30)	<0.001	<0.001	-0.10	<0.001	-0.09	<0.001
Chloride, dissolved	246	-56 (-61, -51)	<0.001	36 (16, 59)	<0.001	<0.001	-0.16	<0.001	-0.28	<0.001
Fluoride, dissolved	245	-15 (-22, -9)	<0.001	33 (21, 47)	<0.001	<0.001	-0.02	0.323	-0.10	<0.001
Sulfate, dissolved	246	-13 (-21, -3)	NR[3]	6 (-6, 21)	NR[3]	0.015	-0.13	<0.001	-0.12	<0.001
Solids, dissolved, (sum of constituents)	241	-21 (-28, -13)	<0.001	13 (1, 26)	0.035	<0.001	-0.14	<0.001	-0.14	<0.001

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Determination of and distinction between *p*-value for individual trend and *p*-value for overall trend analysis are discussed in "Supplement 2: Summary of the Time-Series Model (TSM) as Applied in this Study."

[3]*p*-value for individual trend period not reported because of nonsignificant overall trend analysis (*p*-value > 0.01), as discussed in "Supplement 2: Summary of the Time-Series Model (TSM) as Applied in this Study."

[4]"Estimated alkalinity" data were developed by selecting either alkalinity or acid neutralizing capacity (ANC), depending primarily on which measurement was available for a given sample, as discussed in the section of this report "Sampling and Analytical Methods."

Table 4.4. Trend-analysis results determined by using ordinary least squares regression (OLS) on time, streamflow, and season for major-ion constituents and properties for Little Powder River near Broadus, Mont. based on analysis of data collected during water years[1] 2001–10.

[Values in parentheses indicate 95-percent confidence intervals. Gray shading indicates statistical significance at *p*-value < 0.01. *p*-value, statistical significance level; <, less than; SEE, standard error of estimate, in percent; Mont., Montana; log10, logarithm (base 10); HYP, hyperbolic transformation described by 1/(1+(*b**Q)), where *b* is a constant (as indicated) and *Q* is streamflow, in cubic feet per second; NR, not reported; >, greater than]

Constituent or property	Number of samples	Estimated total percent change during trend-analysis period	*p*-value for individual trend	Streamflow transformation	*p*-value for streamflow coefficient	SEE of regression	*p*-value for regression
Little Powder River near Broadus, Mont. (site 15, fig. 1)							
Trend-analysis period water years 2005–10							
Specific conductance	35	36 (16, 59)	<0.001	HYP (*b*=0.01)	<0.001	14	<0.001
Calcium, dissolved	35	30 (3, 64)	0.015	HYP (*b*=0.01)	0.027	20	<0.001
Magnesium, dissolved	35	NR[2]	NR[2]	HYP (*b*=0.01)	0.079	24	<0.001
Potassium, dissolved	35	NR[2]	NR[2]	HYP (*b*=0.01)	0.365	19	<0.001
Sodium adsorption ratio	35	11 (-2, 26)	0.069	HYP (*b*=0.01)	<0.001	11	<0.001
Sodium, dissolved	35	34 (12, 59)	<0.001	HYP (*b*=0.01)	<0.001	15	<0.001
Alkalinity	35	12 (-4, 31)	0.106	HYP (*b*=0.01)	<0.001	13	<0.001
Chloride, dissolved	35	61 (32, 98)	<0.001	HYP (*b*=0.01)	0.002	18	<0.001
Fluoride, dissolved	35	-4 (-19, 13)	0.556	HYP (*b*=0.01)	0.003	15	<0.001
Sulfate, dissolved	35	51 (22, 87)	<0.001	HYP (*b*=0.01)	<0.001	19	<0.001
Solids, dissolved, (sum of constituents)	35	41 (17, 69)	<0.001	HYP (b=0.01)	<0.001	16	<0.001

[1]Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2009 is the period from October 1, 2008, through September 30, 2009.

[2]Results not reported because of nonsignificant relation between constituent and streamflow (*p*-value > 0.05).

Table 4.5. Information on percent differences in cation and anion balances for fitted trends and flow-adjusted concentrations for selected sampling sites in the Tongue and Powder River watersheds, Montana and Wyoming.

[Wyo., Wyoming; OLS, ordinary least squares regression on time, streamflow, and season; Mont., Montana; TSM, time-series model]

Site number (fig. 1)	USGS site name	Trend analysis method	Mean (and range) of percent differences in the cation and anion balances for fitted trends	Mean (and range) of percent differences in the cation and anion balances (range) for flow-adjusted concentrations
		Tongue River watershed		
1	Tongue River at Monarch, Wyo.	OLS	-1.1 (-1.8 to -0.44)	-1.0 (-2.4 to +0.24)
2	Goose Creek below Sheridan, Wyo.	OLS	-0.08 (+0.02 to -0.06)	+0.48 (+0.34 to +0.60)
3	Prairie Dog Creek near Acme, Wyo.	OLS	+0.50 (+0.29 to +0.74)	+0.48 (+0.37 to +0.63)
4	Tongue River at State line, near Decker, Mont.	TSM	+5.6 (+3.4 to +7.0)	+4.6 (-28 to +15)
5	Tongue River at Tongue River Dam, near Decker, Mont.	TSM	+1.8 (+0.68 to +2.7)	+0.68 (-7.0 to +10)
6	Hanging Woman Creek near Birney, Mont.	TSM	+1.3 (-0.35 to +3.2)	+0.48 (-6.1 to +11)
7	Tongue River at Birney Day School, near Birney, Mont.	TSM	-1.7 (-3.0 to -0.35)	-1.0 (-5.6 to +5.7)
8	Otter Creek at Ashland, Mont.	TSM	+0.46 (-2.0 to +1.5)	-0.07 (-6.4 to +7.1)
9	Pumpkin Creek near Miles City, Mont.	OLS	+2.9 (-0.63 to +9.7)	+0.24 (-0.60 to +2.5)
10	Tongue River at Miles City, Mont.	TSM	-0.47 (-0.79 to -0.18)	+0.05 (-11 to +7.3)
		Powder River watershed		
11	Powder River at Sussex, Wyo.	TSM	+0.23 (-2.3 to +3.8)	-0.22 (-10 to +10)
12	Powder River at Arvada, Wyo.	TSM	+0.28 (-1.6 to +2.1)	-0.14 (-9.0 to +10)
13	Powder River at Moorhead, Mont.	TSM	-0.60 (-1.1 to +0.90)	0.00 (-7.0 to +6.2)
14	Little Powder River above Dry Creek, near Weston, Wyo.	TSM	-1.5 (-3.0 to +0.54)	-1.5 (-15 to +6.7)
15	Little Powder River near Broadus, Mont.	OLS	-1.8 (-2.6 to -0.98)	-1.6 (-2.2 to -1.1)
16	Powder River near Locate, Mont.	TSM	-0.34 (-0.49 to +0.08)	+0.64 (-7.3 to +6.2)

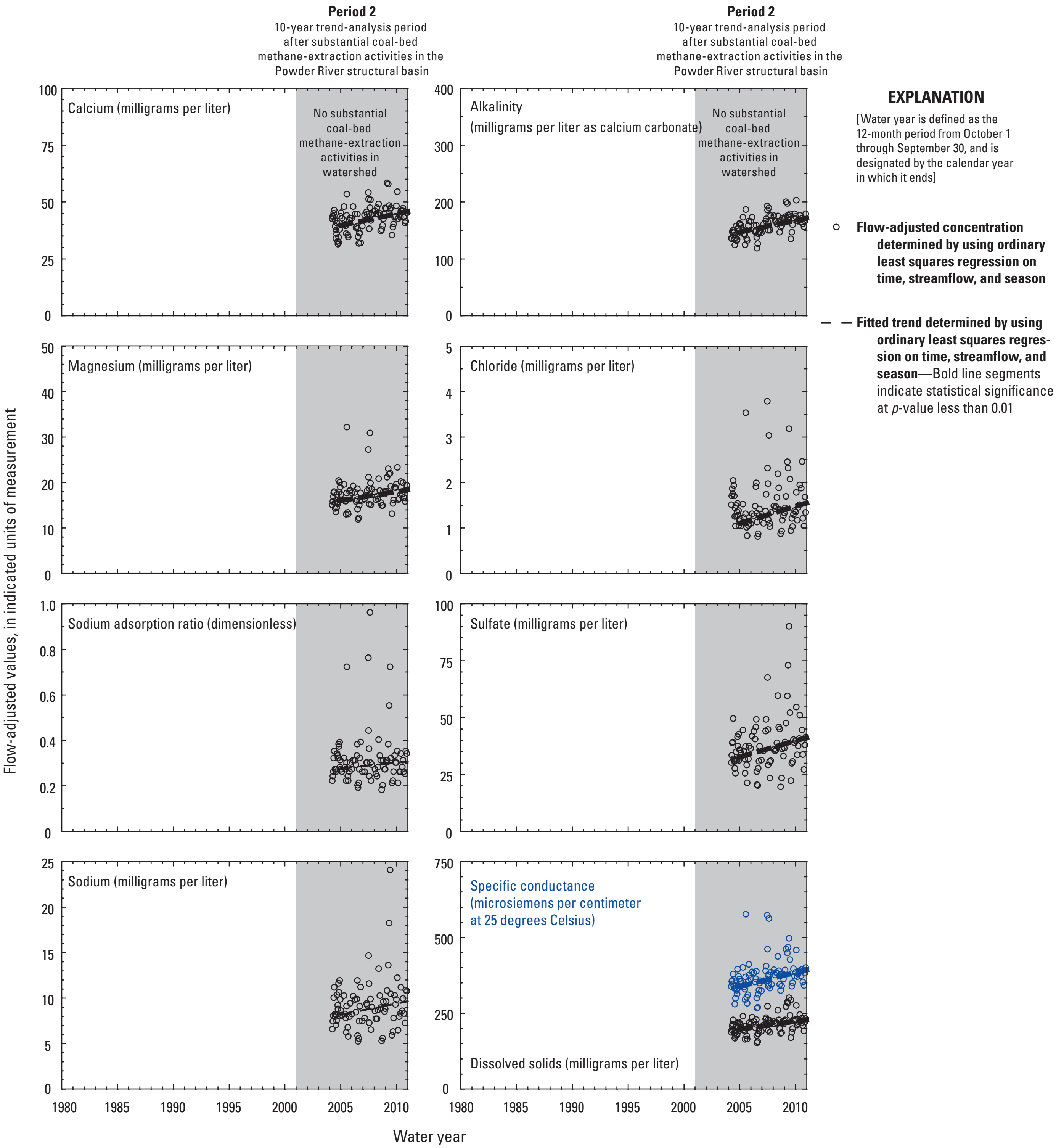


Figure 4.1. Fitted trends determined by using ordinary least squares regression (OLS) on time, streamflow, and season for selected major-ion constituents and properties for site 1 (Tongue River at Monarch, Wyo.; station 06299980), based on analysis of available data collected during water years 2001–2010.

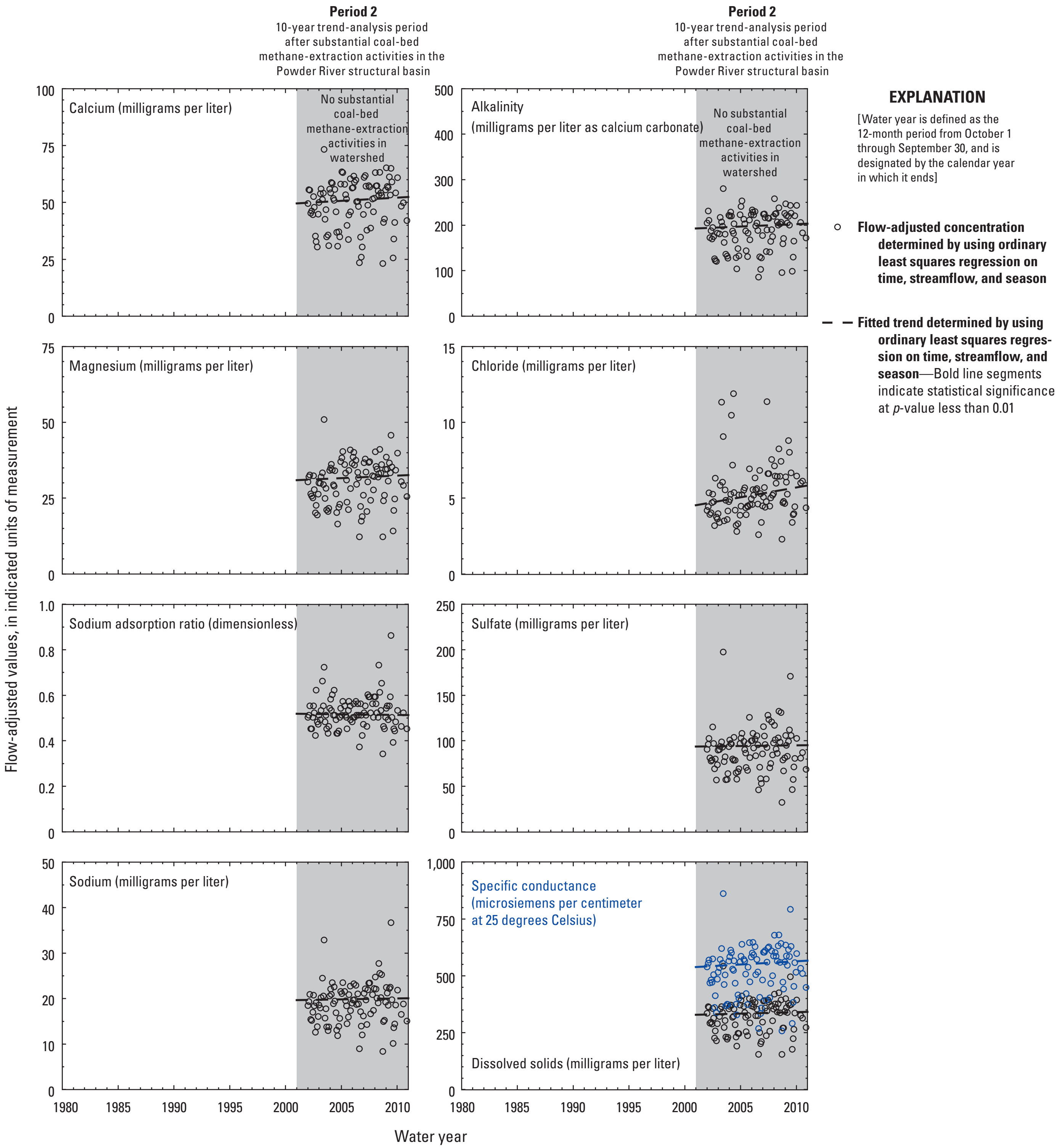


Figure 4.2. Fitted trends determined by using ordinary least squares regression (OLS) on time, streamflow, and season for selected major-ion constituents and properties for site 2 (Goose Creek below Sheridan, Wyo.; station 06305500).

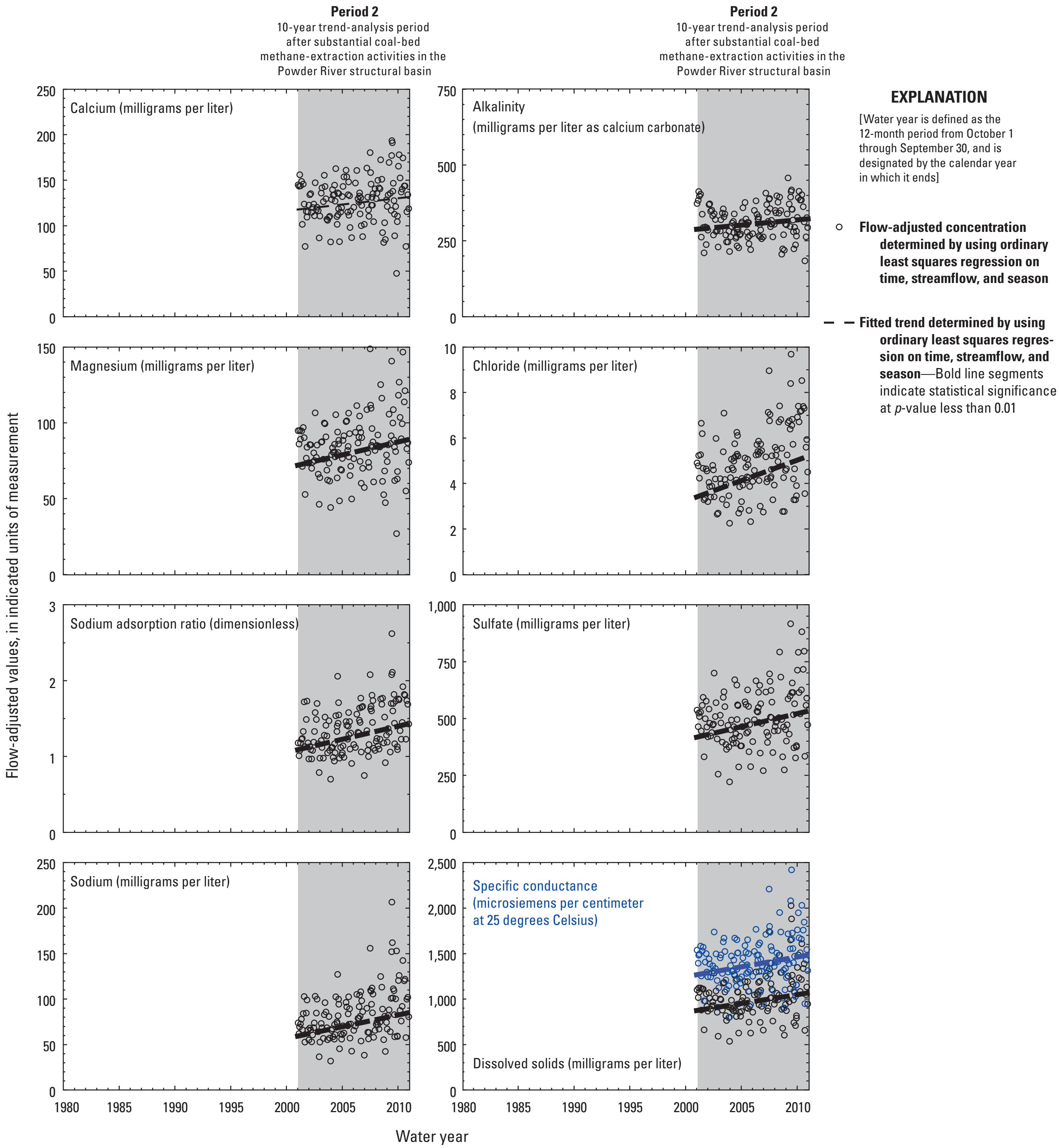


Figure 4.3. Fitted trends determined by using ordinary least squares regression (OLS) on time, streamflow, and season for selected major-ion constituents and properties for site 3 (Prairie Dog Creek near Acme, Wyo.; station 06306250).

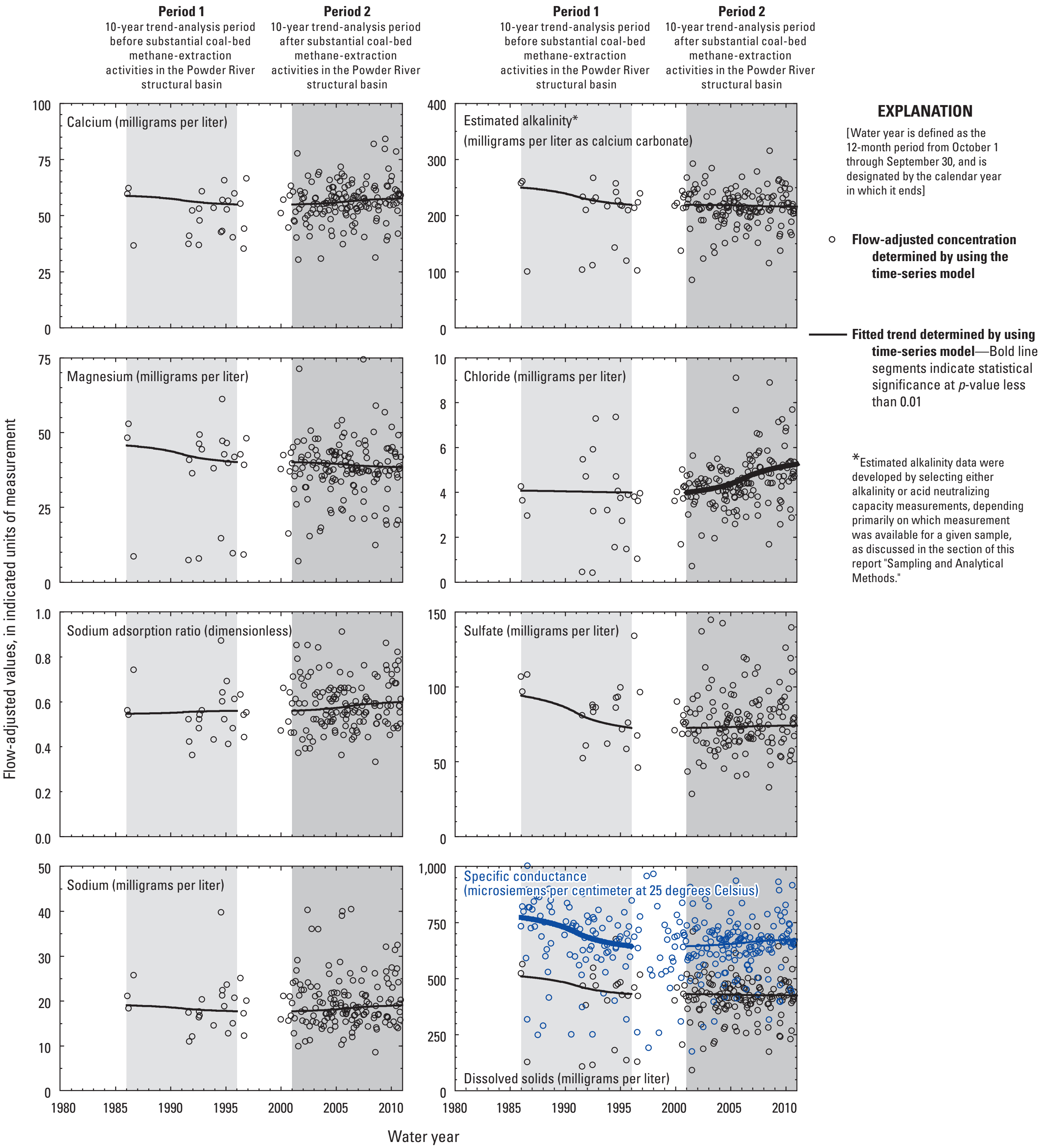


Figure 4.4. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 4 (Tongue River at State line, near Decker, Mont.; station 06306300).

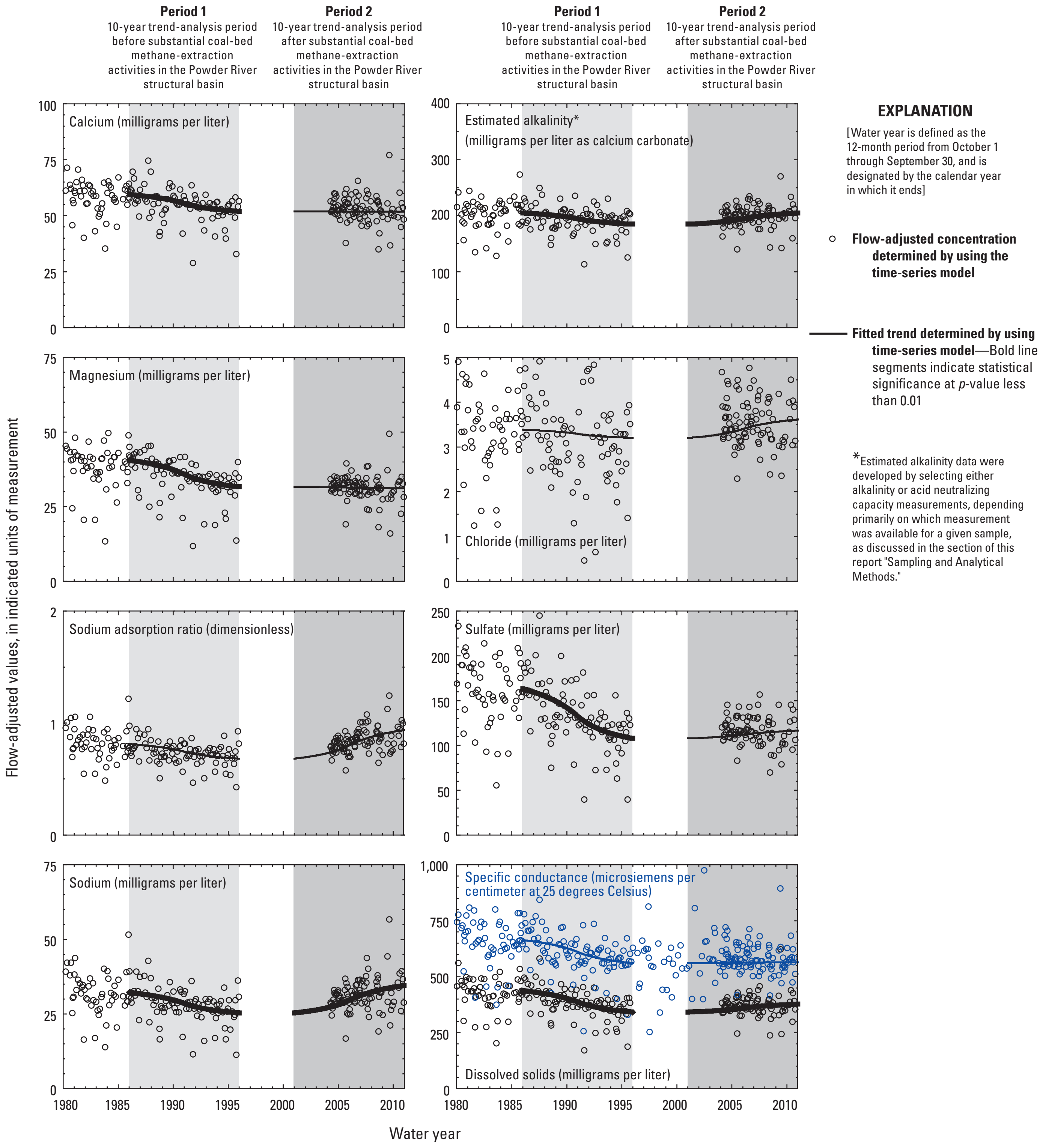


Figure 4.5. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 5 (Tongue River at Tongue River Dam, near Decker, Mont.; station 06307500).

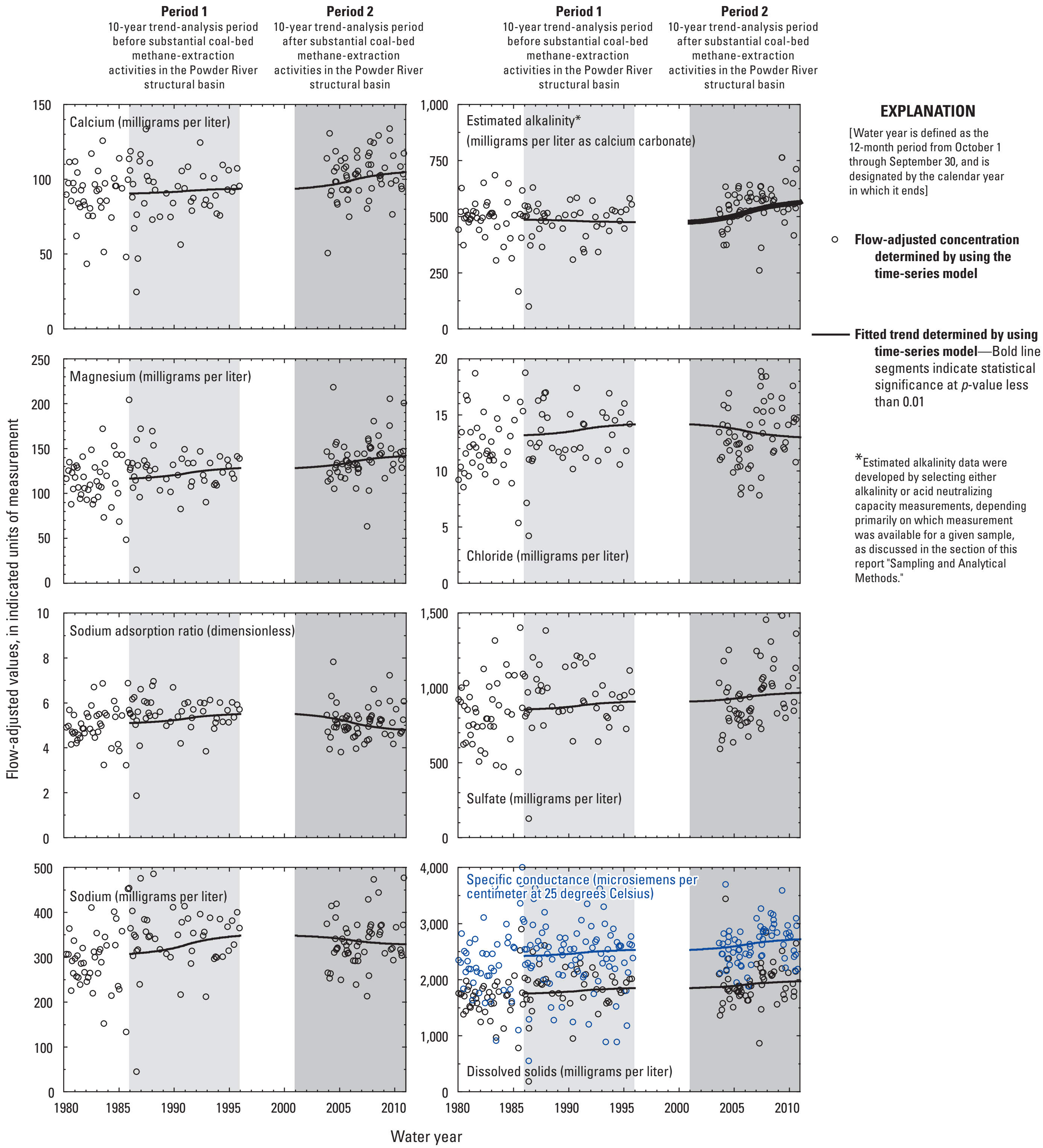
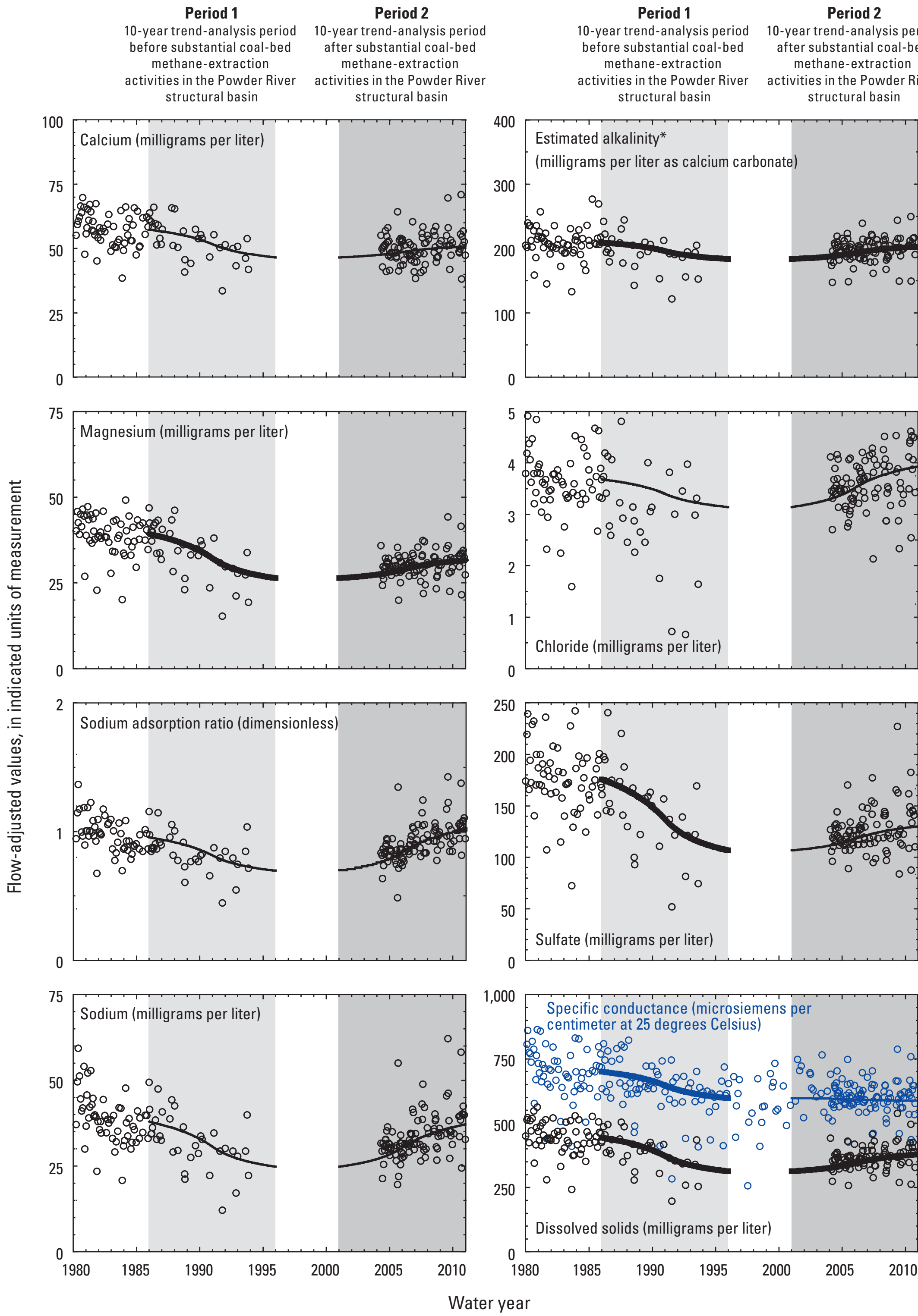


Figure 4.6. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 6 (Hanging Woman Creek near Birney, Mont.; station 06307600).



EXPLANATION

[Water year is defined as the 12-month period from October 1 through September 30, and is designated by the calendar year in which it ends]

○ **Flow-adjusted concentration determined by using the time-series model**

—— **Fitted trend determined by using time-series model**—Bold line segments indicate statistical significance at *p*-value less than 0.01

*Estimated alkalinity data were developed by selecting either alkalinity or acid neutralizing capacity measurements, depending primarily on which measurement was available for a given sample, as discussed in the section of this report "Sampling and Analytical Methods."

Figure 4.7. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 7(Tongue River at Birney Day School, near Birney, Mont.; station 06307616).

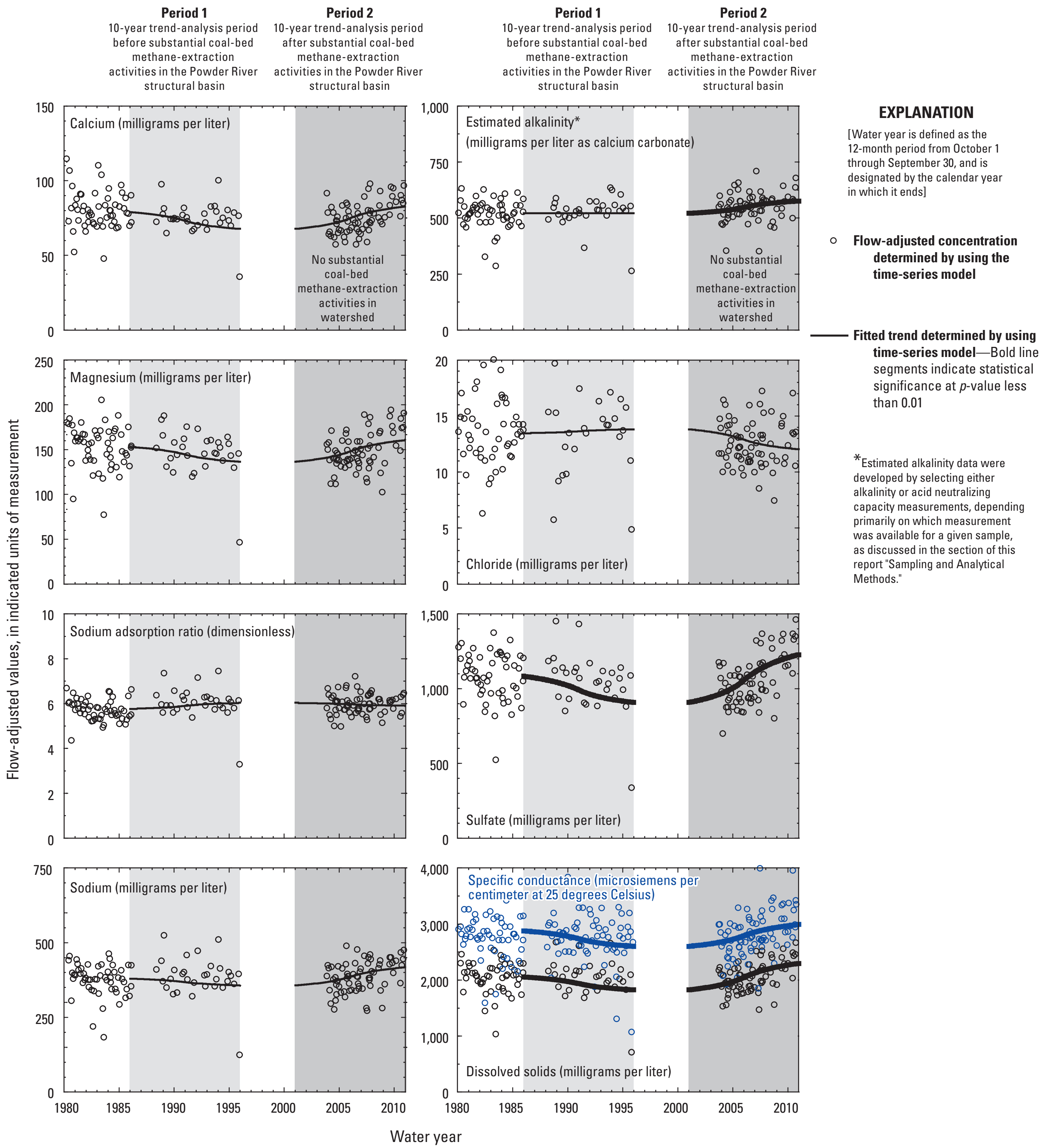


Figure 4.8. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 8 (Otter Creek at Ashland, Mont.; station 06307740).

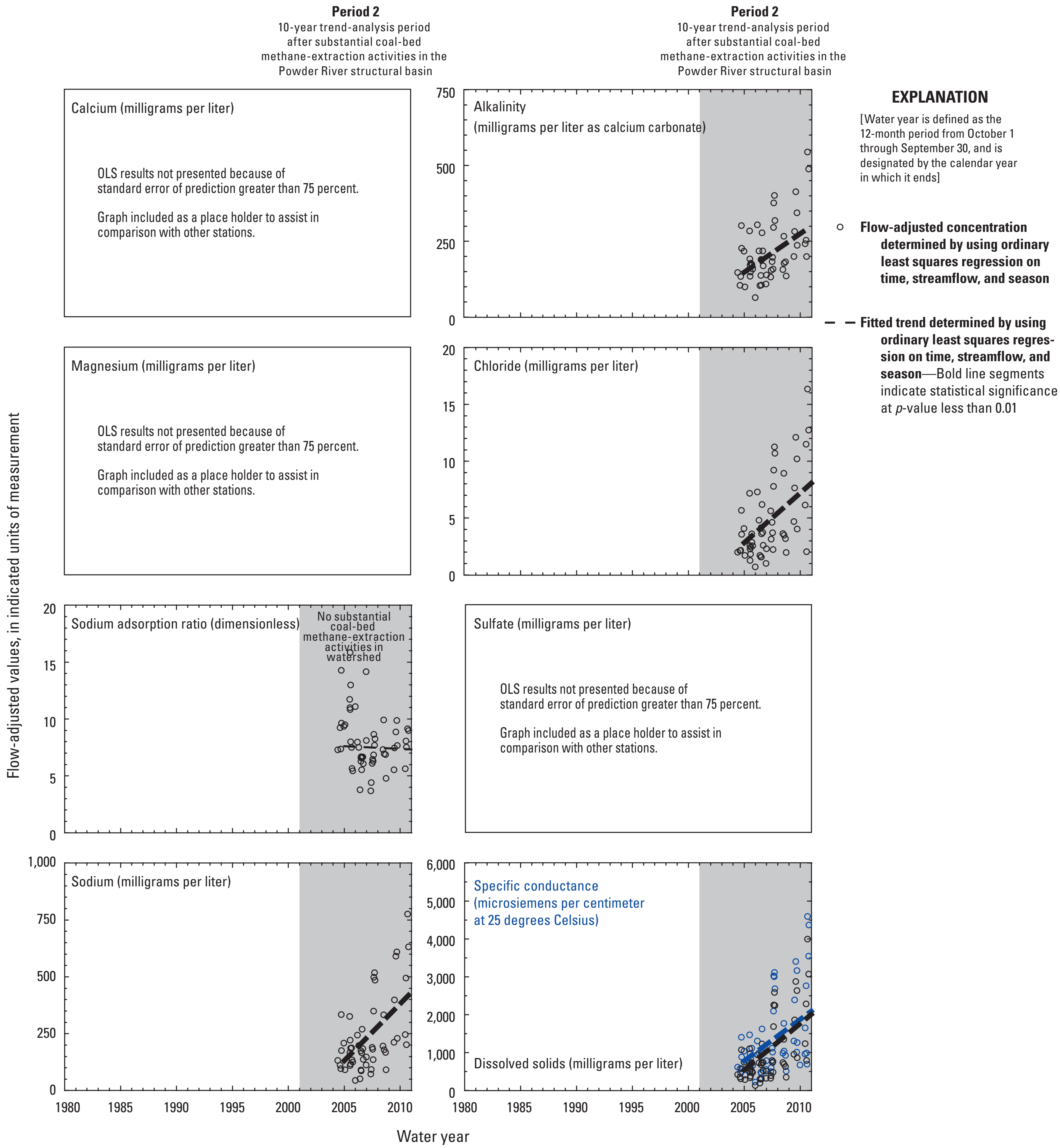


Figure 4.9. Fitted trends determined by using ordinary least squares regression (OLS) on time, streamflow, and season for selected major-ion constituents and properties for site 9 (Pumpkin Creek near Miles City, Mont.; station 06308400).

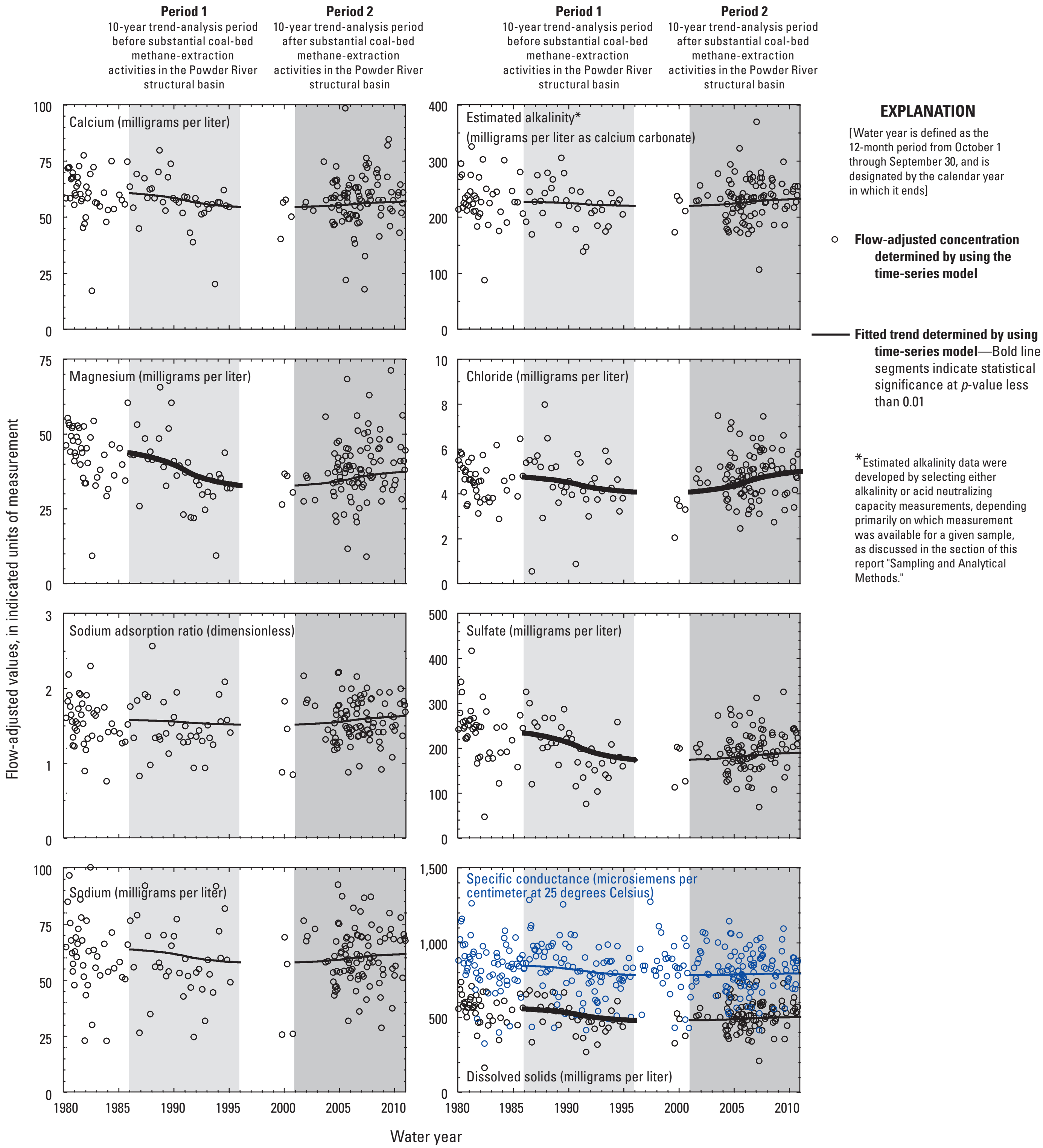


Figure 4.10. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 10 (Tongue River at Miles City, Mont.; station 06308500).

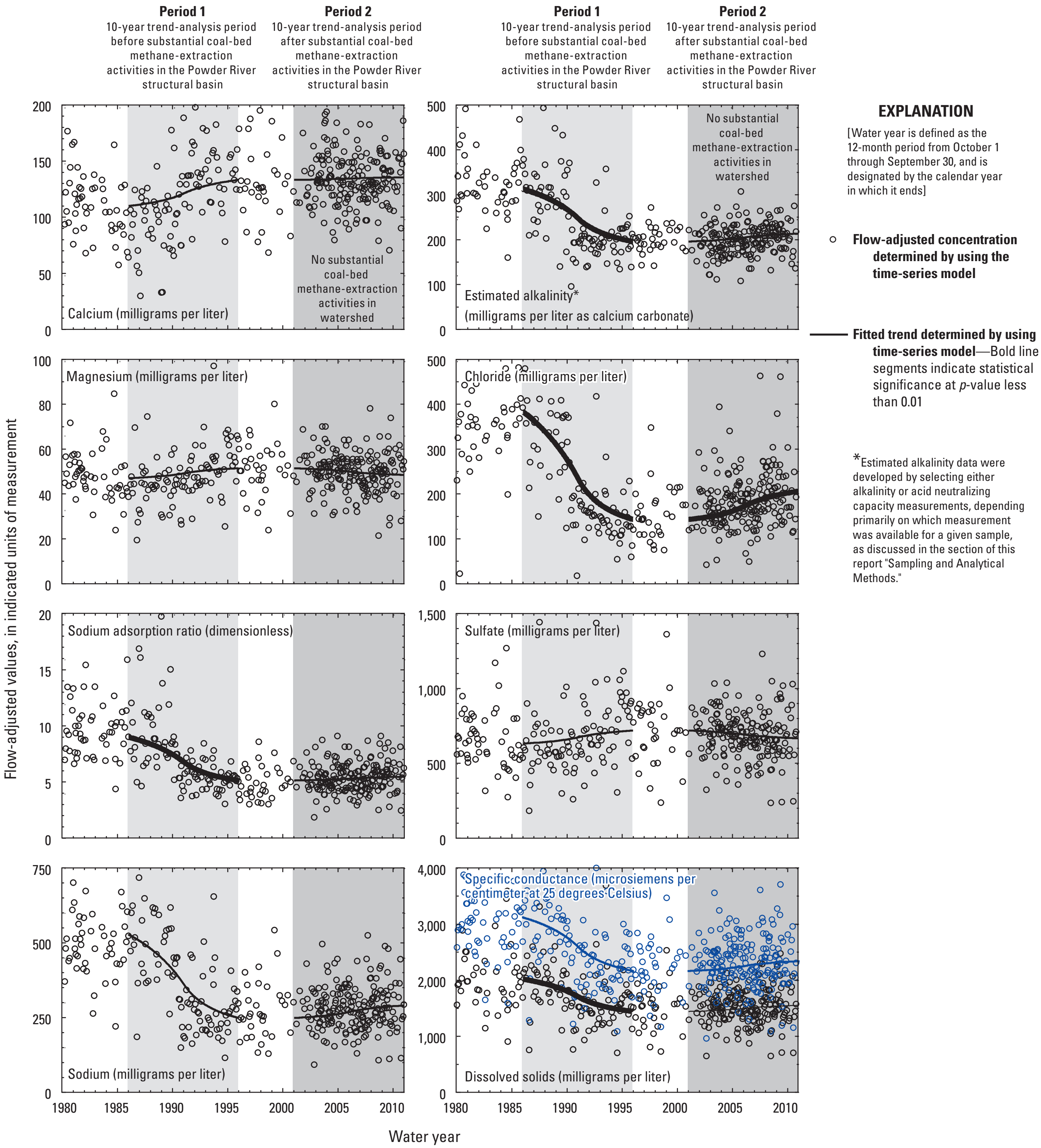


Figure 4.11. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 11 (Powder River at Sussex, Wyo.; station 06313500).

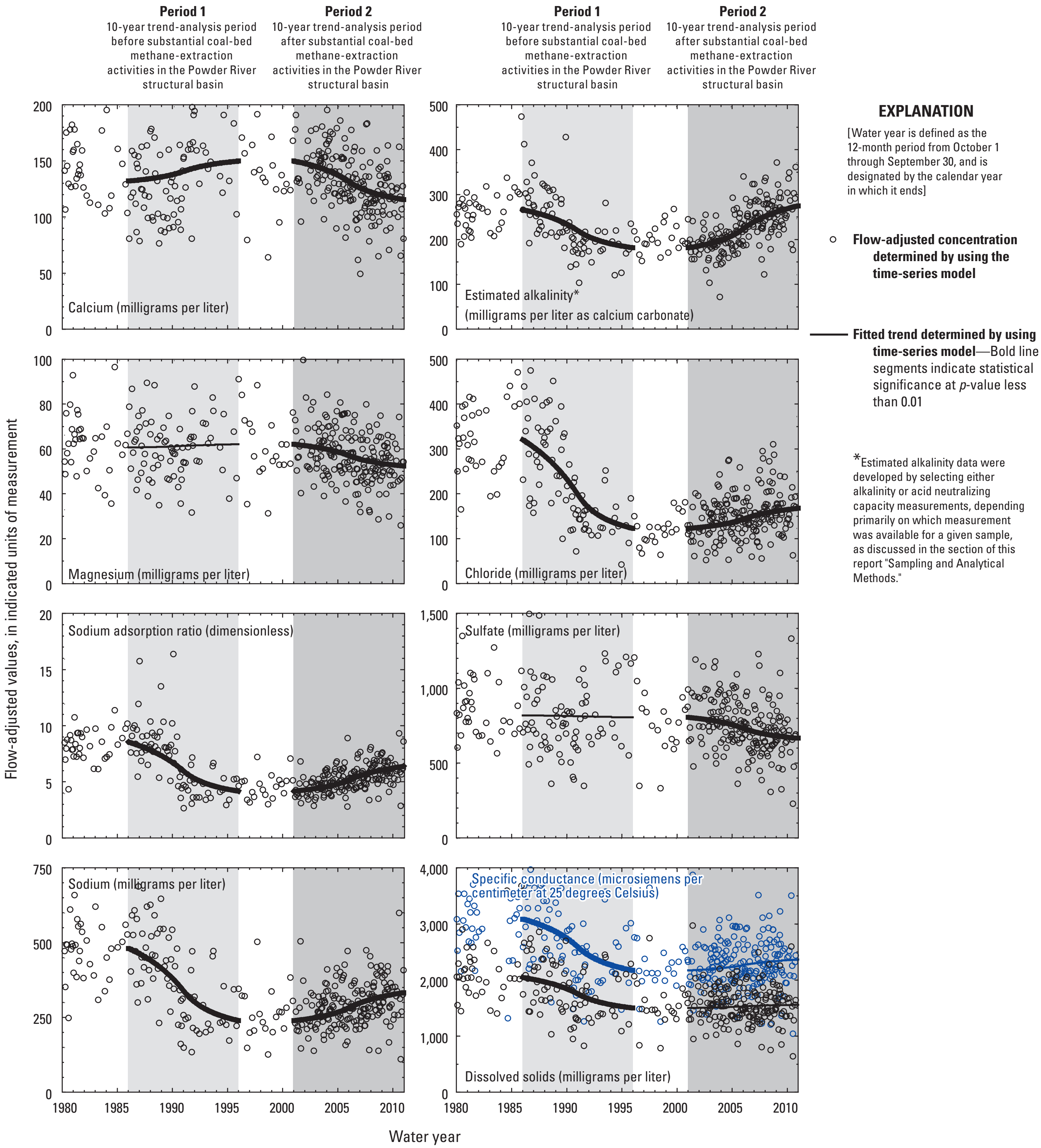


Figure 4.12. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 12 (Powder River at Arvada, Wyo.; station06317000).

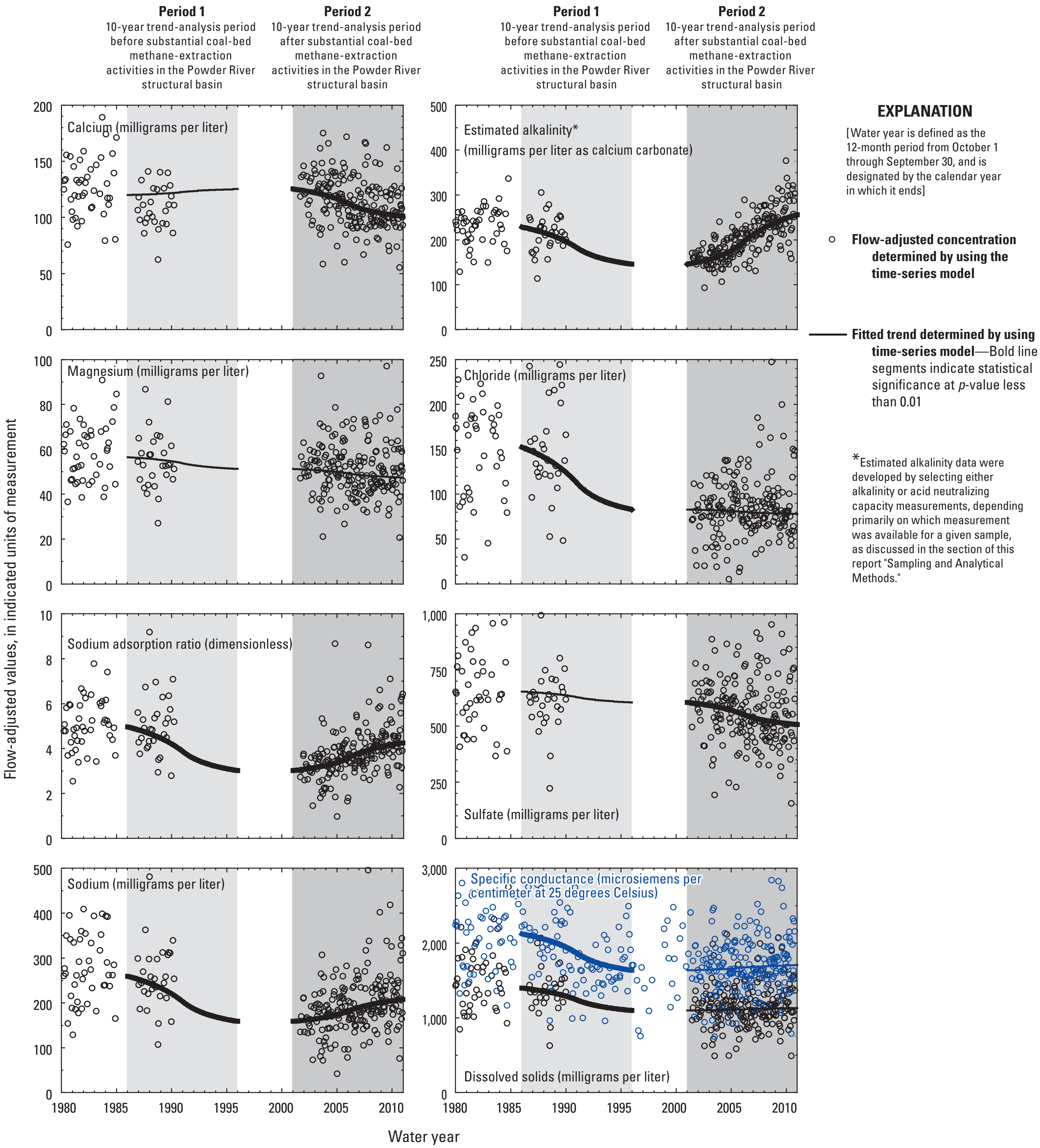


Figure 4.13. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 13 (Powder River at Moorhead, Mont.; station 06324500).

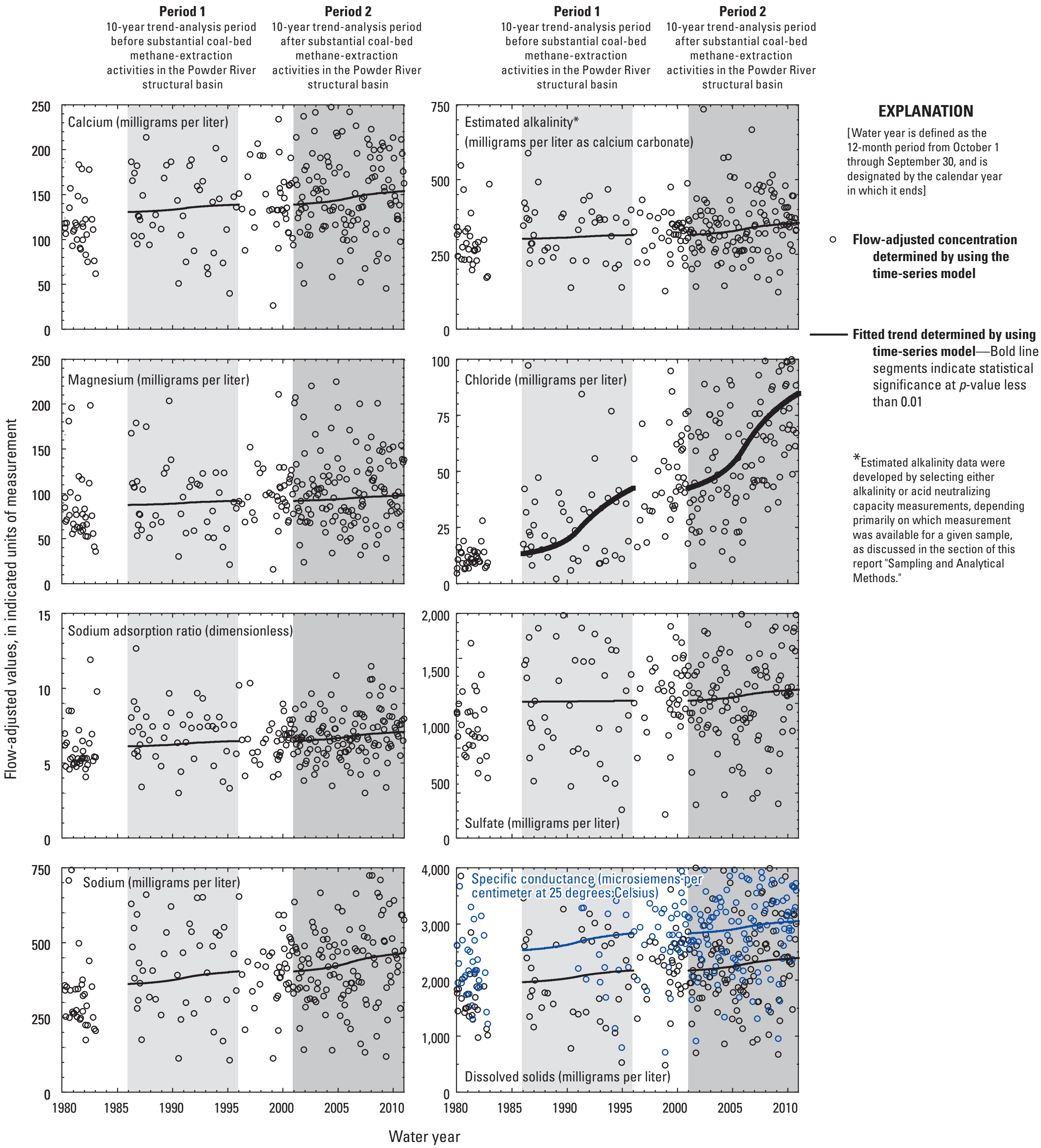


Figure 4.14. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 14 (Little Powder River above Dry Creek, near Weston, Wyo.; station 06324970).

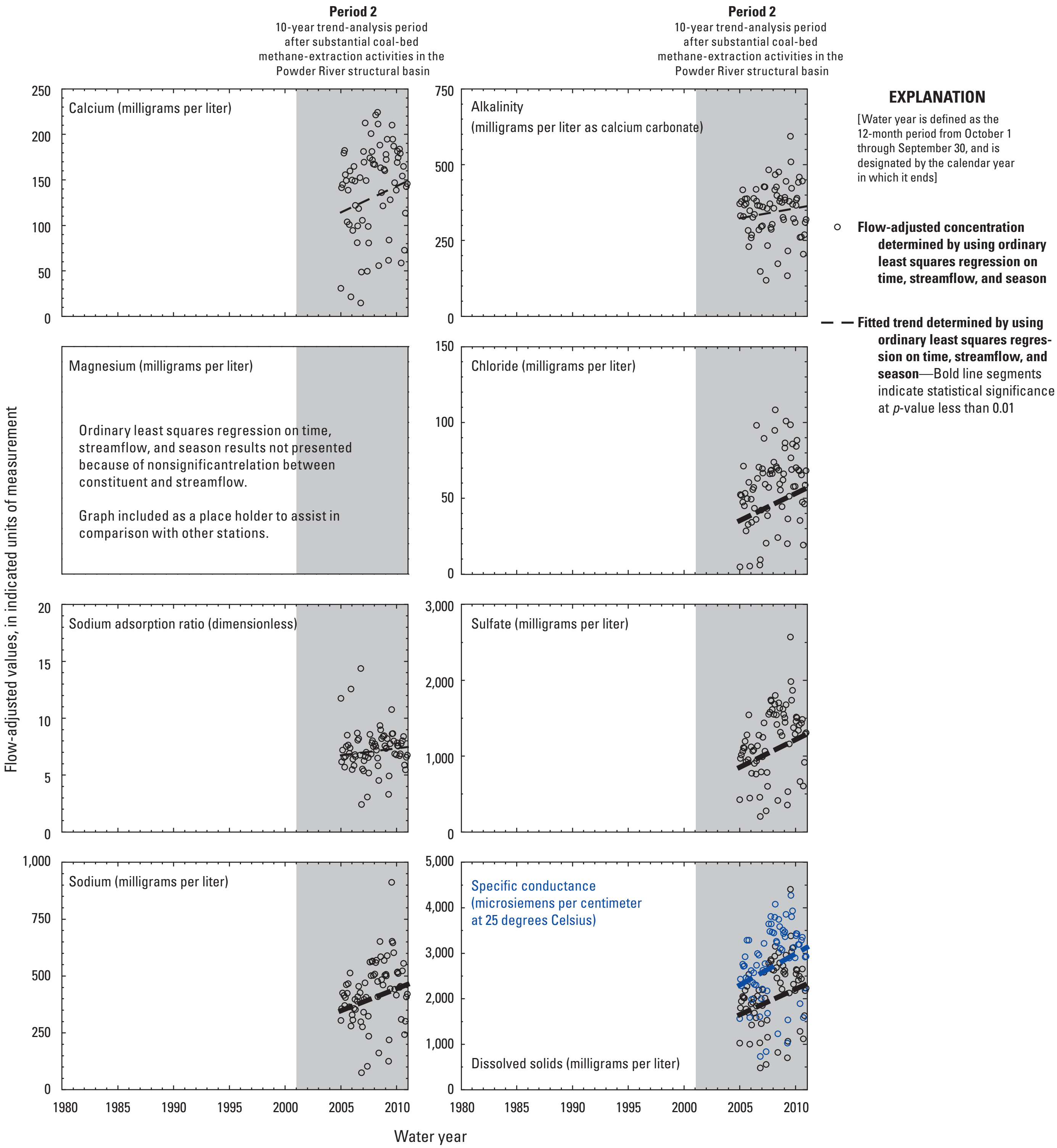


Figure 4.15. Fitted trends determined by using ordinary least squares regression (OLS) on time, streamflow, and season for selected major-ion constituents and properties for site 15 (Little Powder River near Broadus, Mont.; station 06325500).

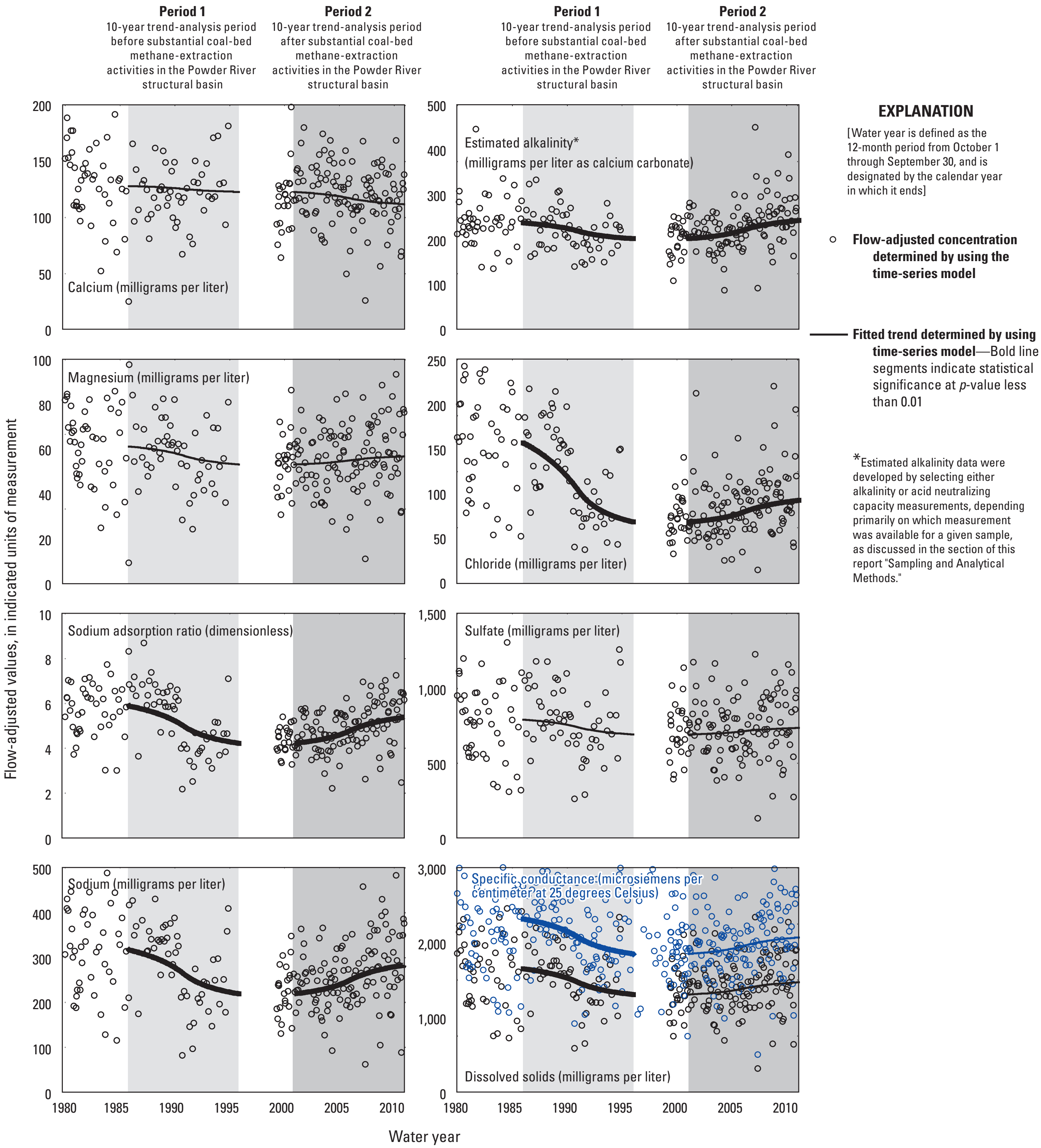


Figure 4.16. Fitted trends determined by using the time-series model for selected major-ion constituents and properties for site 16 (Powder River near Locate, Mont.; station 06326500).

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Director, USGS Montana Water Science Center
3162 Bozeman Avenue
Helena, MT 59601
(406) 457–5900

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