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Modern (1992–2011) and Projected (2012–99) Peak Snowpack and May–July Runoff for the Fort Peck Lake and Lake Sakakawea Watersheds in the Upper Missouri River Basin

Scientific Investigations Report 2015–5135

Version 1.2, June 2016

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

Cover. Upper right photograph: View of the Garrison Dam and Lake Sakakawea.
Lower left photograph: View of the Fort Peck Dam and Fort Peck Lake.
Photographs by Omaha District, U.S. Army Corps of Engineers.

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By John F. Stamm, Dennis Todey, Barbara Mayes Boustead, Shawn Rossi, Parker A. Norton, and Janet M. Carter

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per day (in/d)	25.4	millimeter per day (mm/d)
seconds per foot	0.3048	seconds per meter
	Energy	
megawatt hour (MWh)	3,600,000,000	joule (J)
watt per meter squared (W/m^2)	0.3172	British thermal unit (Btu) per hour per square foot

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

°C=(°F-32)/1.8

Datum

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

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

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

Supplemental Information

A runoff year is defined as the period July–June (begins July 1 and ends June 30 of specified year).

Abbreviations

AIC	Akaike's Information Criterion
AMJ	April, May, June
AOGCM	Atmosphere-Ocean General Circulation Model
CCSM	Community Climate System Model
CCSM3	Community Climate System Model, version 3.0
CCSM4	Community Climate System Model, version 4.0
HCN	U.S. Historical Climatology Network
JAS	July, August, September
JFM	January, February, March
OND	October, November, December
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCP 8.5	representative concentration pathway of 8.5 watts per meter squared
SNOTEL	snowpack telemetry
SWE	snow water equivalent
USGS	U.S. Geological Survey

Modern (1992–2011) and Projected (2012–99) Peak Snowpack and May–July Runoff for the Fort Peck Lake and Lake Sakakawea Watersheds in the Upper Missouri River Basin

By John F. Stamm,[1] Dennis Todey,[2] Barbara Mayes Boustead,[3] Shawn Rossi,[3] Parker A. Norton,[1] and Janet M. Carter[1]

Abstract

Mountain snowpack is an important contributor to runoff in the Upper Missouri River Basin; for example, high amounts of winter and spring precipitation in the mountains and plains in 2010–11 were associated with the peak runoff of record in 2011 in the Upper Missouri River Basin. To project trends in peak mountain snowpack and runoff in the upcoming decades, multiple linear regression models of peak mountain snowpack and total May–July runoff were developed for the Fort Peck Lake (above Fort Peck Dam) and lower Lake Sakakawea watersheds (between Fort Peck and Garrison Dams) in the Upper Missouri River Basin. Input to regression models included seasonal estimates of precipitation, air temperature, and total reference evapotranspiration stratified by elevation. Calibration was based on records from 107 weather stations from 1991 to 2011. Regressed annual peak mountain snowpack was used as input to the transfer function of May–July runoff. Peak snowpack and May–July runoff were projected for 2012–99 on the basis of air temperature and precipitation from the Community Climate System Model (CCSM) output. Two estimates of projected peak snowpack and May–July runoff for 2012–99 were computed: one estimate was based on output from the CCSM, version 3.0 (CCSM3), and the second estimate was based on output from the CCSM, version 4.0 (CCSM4). The significance of projected trends was based on the Kendall's tau nonparametric test.

Annual peak snowpack was projected to have a downward trend for the Fort Peck Lake watershed and no trend for the lower Lake Sakakawea watershed. Projections of May–July runoff had a significant downward trend for the Fort Peck Lake, lower Lake Sakakawea, and Lake Sakakawea (combination of Fort Peck Lake and lower Lake Sakakawea) watersheds. Downward trends in projected May–July runoff indicated that power production at Fort Peck Dam might be affected particularly in the later part of the simulation (2061–99); however, confidence in projected May–July runoff for the later part of the simulation was less certain because bias-corrected air temperatures from CCSM3 and CCSM4 commonly fell outside of the observed range used for calibration. Projected May–July runoff combined for the Fort Peck Lake and lower Lake Sakakawea watersheds were on the order of magnitude of the 2011 flood for 1 simulation year for each of the CCSM-based simulations. High peak snowpack and precipitation in April, May, and June in the plains was associated with large May–July runoff events; therefore, high precipitation at lower elevations in the Fort Peck Lake and lower Lake Sakakawea watersheds was a factor in the simulation of extreme runoff events at the magnitude of the 2011 flood.

Introduction

The Missouri River is the longest river in the United States, and the Missouri River Basin is the second largest drainage basin in the United States (Kammerer, 1990). From its headwaters in western Montana, the Missouri River flows about 2,300 miles (mi) to its confluence with the Mississippi River (fig. 1). The drainage area of the Missouri River of 529,000 square miles (mi^2) accounts for nearly one-half the drainage area of the Mississippi River Basin (Kammerer, 1990). Six dams and reservoirs are along the main stem of the Missouri River and compose the Missouri River reservoir system: Fort Peck Dam forming Fort Peck Lake (Montana), Garrison Dam forming Lake Sakakawea (North Dakota), Oahe Dam forming Lake Oahe (South Dakota), Big Bend Dam forming Lake Sharpe (South Dakota), Fort Randall Dam forming Lake Francis Case (South Dakota), and Gavins Point Dam forming Lewis and Clark Lake (South Dakota and Nebraska).

[1]U.S. Geological Survey.

[2]South Dakota State University.

[3]National Weather Service.

The Missouri River Basin above Gavins Point Dam is referred to as the Upper Missouri River Basin (fig. 1).

The combined storage capacity of the six main-stem dams, 72.4 million acre-feet (acre-ft), makes the Missouri River reservoir system the largest in North America (U.S. Army Corps of Engineers, 2013a). The Missouri River reservoir system is regulated to serve the eight congressionally authorized purposes of flood control, water supply, water-quality control, navigation, hydroelectric power generation, irrigation, recreation, and fish and wildlife (including threatened and endangered species). During 1968–2011, mean annual gross power production was 1,047,594 and 2,253,338 megawatt hours (MWh) for the hydroelectric power plants of Fort Peck and Garrison Dams, respectively (fig. 2). Maximum annual gross power generation was 1,662,509 MWh (in 1976) and 3,350,271 MWh (in 1975) for the Fort Peck and Garrison Dams, respectively, for 1968–2011. Mean annual inflow to Fort Peck Lake and Lake Sakakawea for 1968–2011 was 10,200 and 23,000 cubic feet per second (ft^3/s), respectively (U.S. Army Corps of Engineers, 2015).

The U.S. Army Corps of Engineers (2006, revised plate A–3) identified three periods of drought since 1954 on the basis of annual runoff at Sioux City, Iowa: 1954–61, 1987–92, and 2000–5. Drought was defined as years when less than median runoff occurred for more than 3 consecutive calendar years. Annual streamflow of the Missouri River at the U.S. Geological Survey (USGS) streamgage at Bismarck, North Dakota (streamgage 06342500; fig. 3), about 65 mi downstream from Garrison Dam (fig. 1), was below the median annual streamflow for 1954–2013 of 21,490 ft^3/s for water years 1955–64, 1987–95, 2001–10, and 2013 (U.S. Geological Survey, 2014). A water year begins October 1 and ends September 30, and is designated by the calendar year in which the water year ends. The 2011 runoff was the highest annual streamflow of record at the Bismarck, N. Dak., streamgage (fig. 3) and for much of the Missouri River (National Oceanic and Atmospheric Administration, 2012). Recent variability in climate is expressed by the change from conditions that produced the flood of 2011 to the “flash” drought of 2012 (Hoerling and others, 2013). A flash drought is defined as having a sudden onset and having identified effects on agriculture, fire potential, livestock health, and other effects (Svoboda and others, 2002). Annual streamflow changed from 53,210 ft^3/s in water year 2011 to 25,010 ft^3/s in water year 2012.

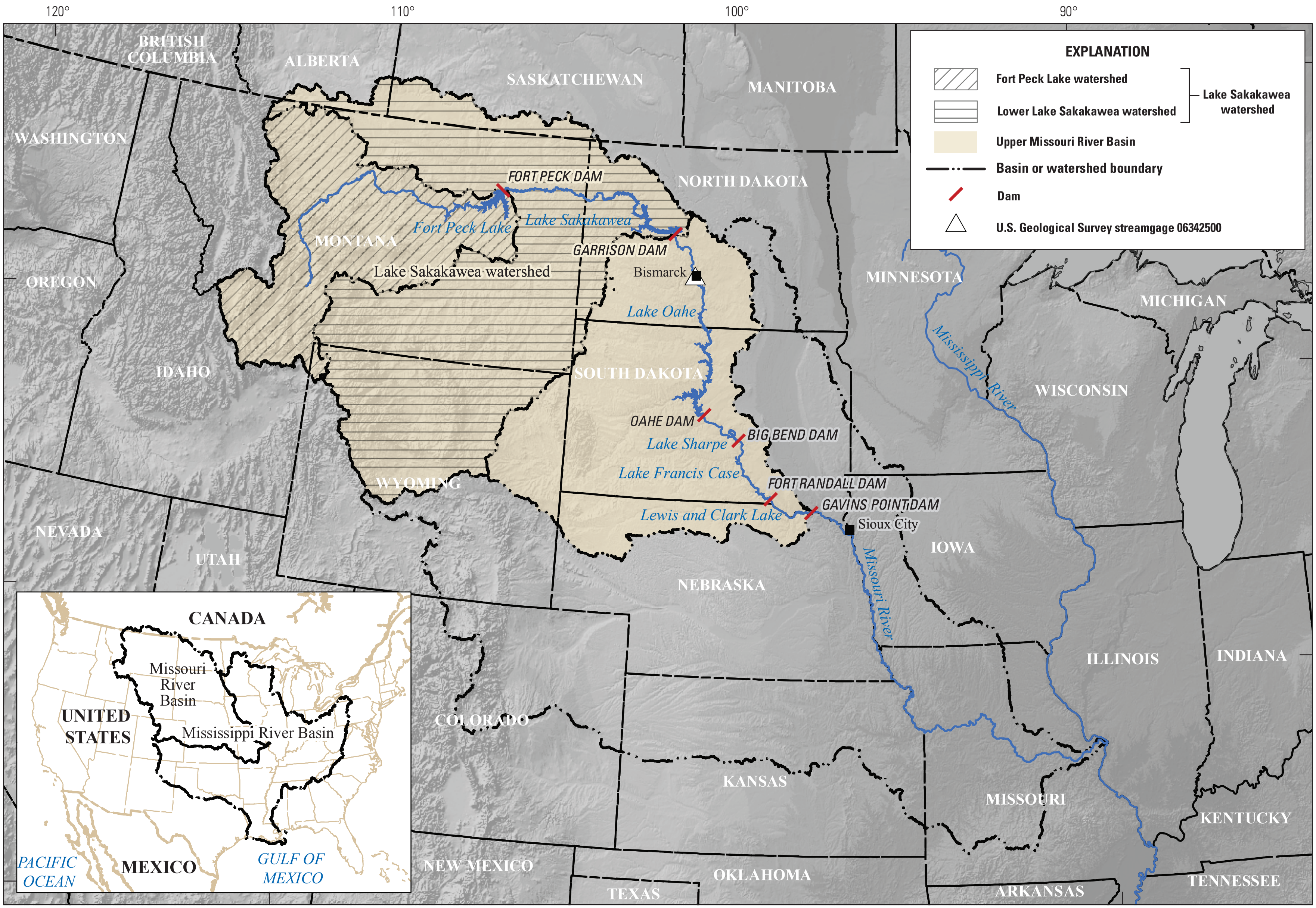
The flood of 2011 was associated with exceptional thickness of snowpack and high precipitation that fell December 2010 through April 2011. Vining and others (2013) described the climatology of this event, which is summarized herein. Snow water equivalent (SWE) in the Rocky Mountains of Montana and Wyoming was 111 to more than 150 percent of the mean SWE at snowpack telemetry (SNOTEL) sites operated by the U.S. Department of Agriculture Natural Resources Conservation Service (Natural Resources Conservation Service, 2014). Above normal precipitation for December 2010 through May 2011 was also recorded at weather stations in the Great Plains of Montana, North Dakota, and South Dakota. May 2011 precipitation was exceptionally high, and rainfall amounts in Montana nearly were equal to normal annual total rainfall.

The flood of 2011 and flash drought of 2012 might be hypothesized as natural variability within an assumed stationary climate or extremes reflecting a changing and nonstationary climate. Stationarity is the concept that natural systems fluctuate within a fixed window of variability for a given period (Milly and others, 2008). Stationarity in natural systems has been compromised by human disturbances and should no longer be assumed by water resource managers (Milly and others, 2008). Indicators of nonstationarity in characteristics of streamflow have been identified for drainage basins within the Missouri River Basin (Hirsch, 2011; Hirsch and Ryberg, 2011; Norton and others, 2014).

The need for adaptive management strategies in response to climate variability and projected climate change prompted the U.S. Army Corps of Engineers and Bureau of Reclamation to establish pilot studies to address several targeted research questions. One such research question posed (U.S. Army Corps of Engineers, 2012, p. 2) was, “Is mountain snowpack and subsequent runoff changing due to changes in climate, and is the Missouri River Basin, therefore, more susceptible to droughts and floods?” This research question was posed to address issues of projected climate change for long-term planning and management (Brekke and others, 2011). Herein, the term “projected” will be used instead of “future” to reflect that there are many possible future trajectories in climate and societal response, a few of which are selected for simulation by global climate models (Nakićenović and Swart, 2000; Vuuren and others, 2011). The U.S. Army Corps of Engineers and Bureau of Reclamation identified several technical steps required for long-term planning and management. The three technical steps of greatest concern were the following:

1. Make decisions on how to use climate change information,
2. Assess natural system responses, and
3. Communicate results and uncertainties to decision makers.

The U.S. Army Corps of Engineers completed a pilot research study (Grode and others, 2014) in collaboration with the USGS, National Weather Service, U.S. Department of Agriculture Natural Resources Conservation Service, and South Dakota State University to help address the aforementioned research question. Additional assistance was needed to address the research question that was posed, and to address the technical steps in the context of climate variability, projected climate, and responses of mountain snowpack and associated runoff. As a result, the U.S. Geological Survey, in cooperation with the Climate Preparedness and Resilience Community of Practice of the U.S. Army Corps of Engineers, completed a followup study to simulate modern (1992–2011) and projected (2012–99) mountain peak snowpack and



Base modified from U.S. Geological Survey digital data. Scale ranges from 1:100,000 to 1:2,000,000
Albers Equal-Area Conic projection

Figure 1. Missouri River Basin and study area consisting of the drainage basins above Garrison and Fort Peck Dams. Associated watersheds are the Fort Peck Lake and Lake Sakakawea watersheds. The lower Lake Sakakawea watershed excludes the area of the Fort Peck Lake watershed.

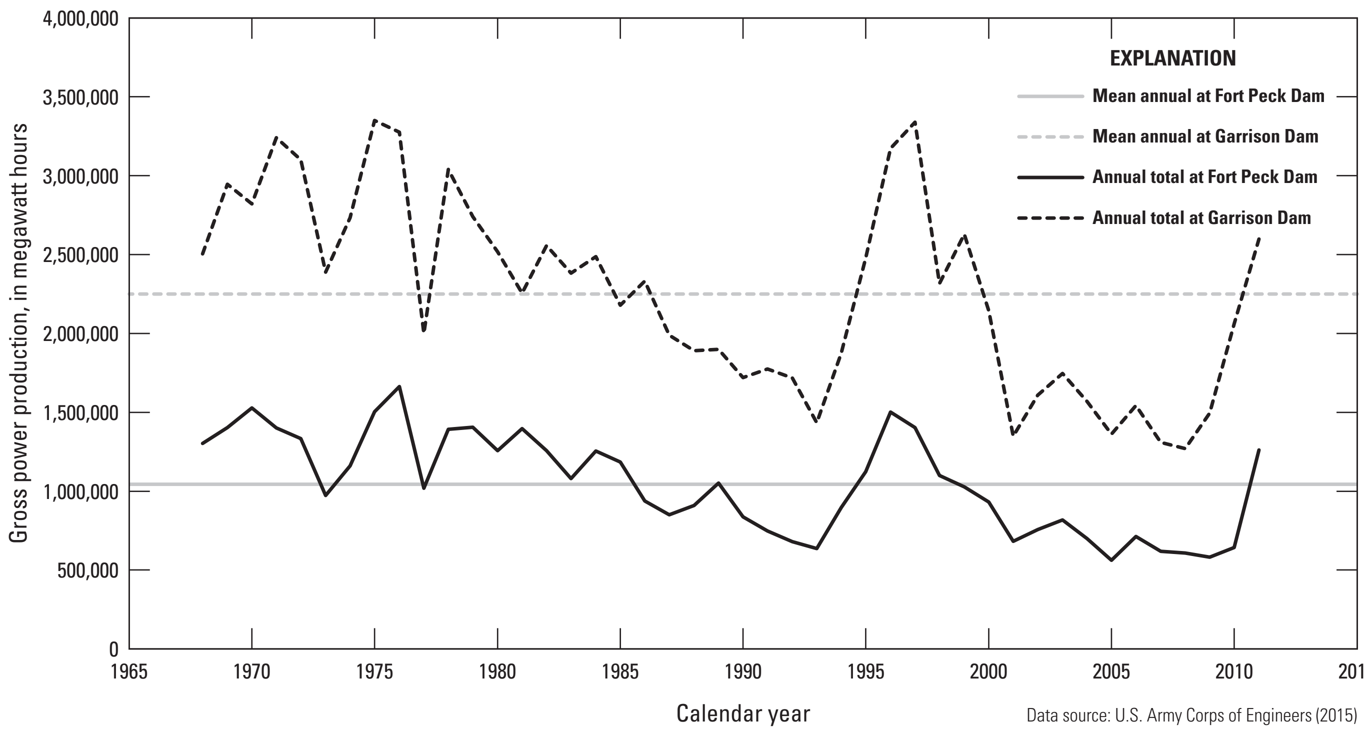


Figure 2. Gross power generation from the hydroelectric power plants at Fort Peck and Garrison Dams, 1968–2011.

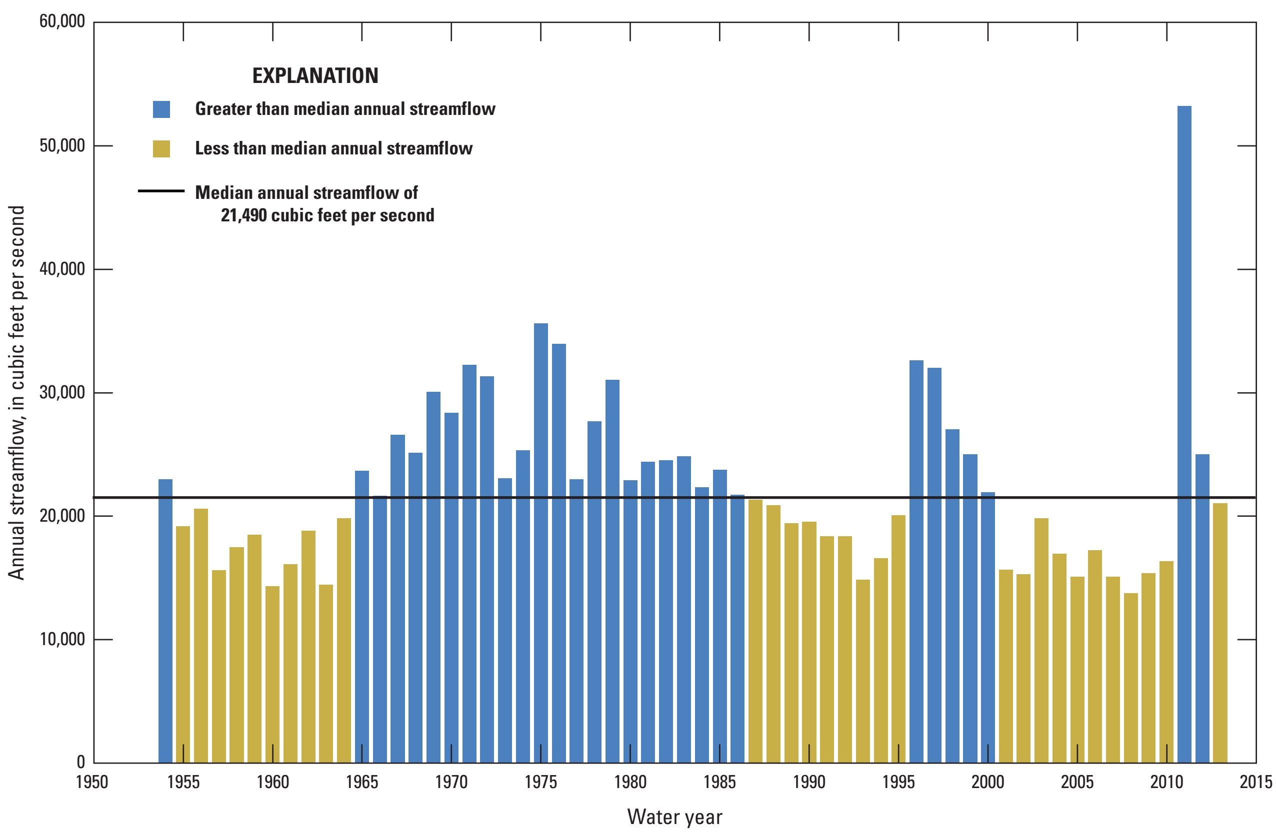


Figure 3. Annual streamflow of the Missouri River at Bismarck, North Dakota (U.S. Geological Survey streamgage 06342500), showing years with annual flows greater than and less than median annual streamflow for water years 1954–2013. Streamflow data from U.S. Geological Survey (2014).

May–July runoff into Fort Peck Lake and Lake Sakakawea in the upper part of the Missouri River Basin. Additional objectives of this study were to determine if May–July runoff as projected for 2012–99 might produce runoff events on the magnitude of the 2011 flood, develop insights to processes associated with such events, and determine if projected May–July runoff might drop below the magnitude required to maintain power generation at hydroelectric dams.

Purpose and Scope

The purpose of this report is to present results of simulations of modern (1992–2011) and projected (2012–99) peak snowpack and May–July runoff into Fort Peck Lake and Lake Sakakawea. Peak mountain snowpack is the maximum height of snow recorded at selected stations in the Rocky Mountains in a given year, and is hereafter referred to as "peak snowpack." Peak snowpack is reported as SWE, which is defined as the height of water produced by melting a column of snow with potentially varying snow density and possibly containing water retained by capillary forces (Garstka, 1964, p. 10–6). In the Upper Missouri River Basin, much of the May–July runoff is derived from the melting of snowpack, and generally during this time almost one-half of the total annual runoff is conveyed through the Missouri River reservoir system (U.S. Army Corps of Engineers, 2006). Herein, runoff is reported as total volume in thousand acre-feet for May–July. This report also describes projected May–July runoff to 2099 in relation to the magnitude of the 2011 flood and magnitudes required to maintain power generation at hydroelectric dams.

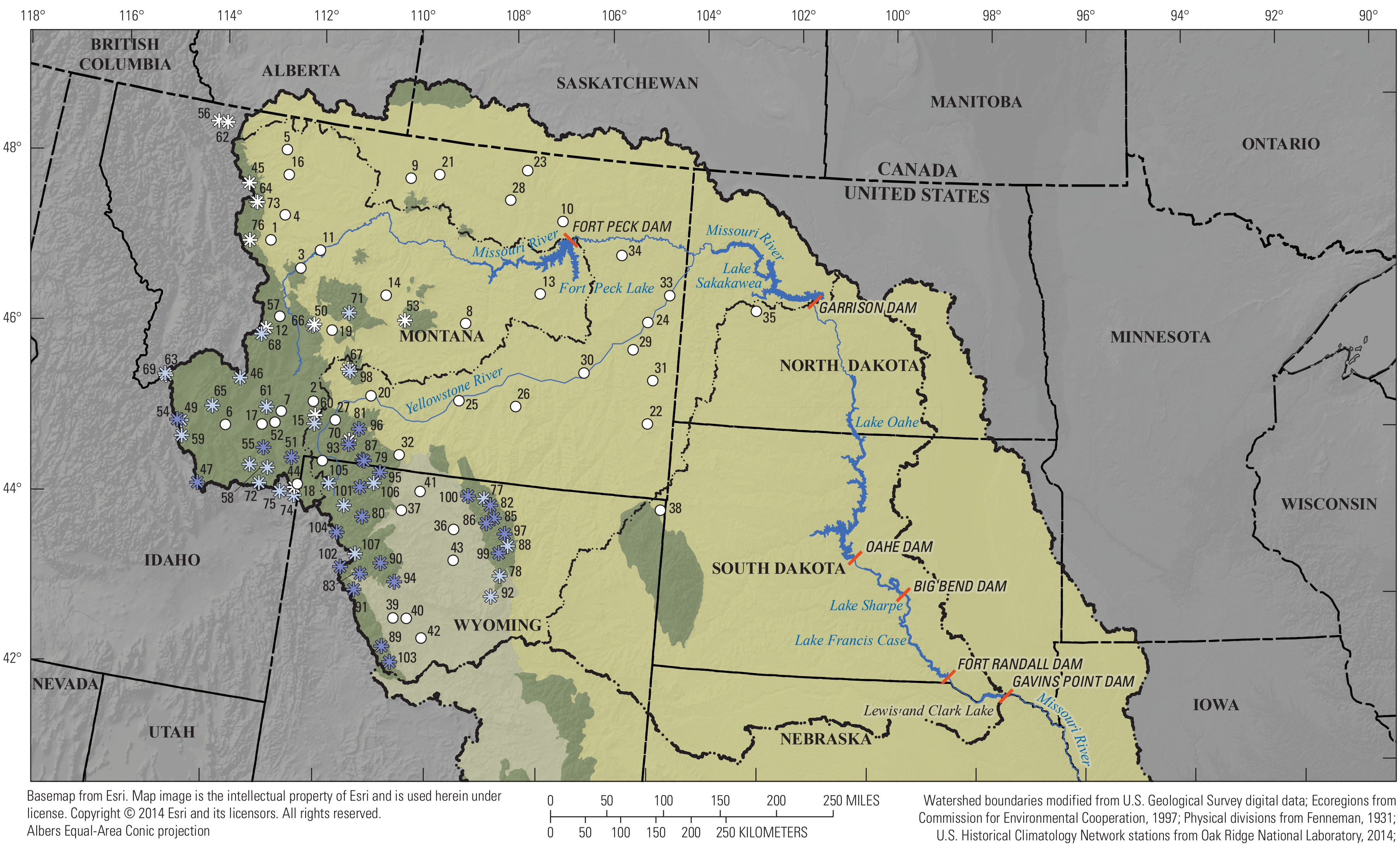
Description of the Study Area

The study area is the Lake Sakakawea watershed, which is located in the northern part of the Upper Missouri River Basin (figs. 1 and 4). The Fort Peck Lake watershed is located along the Missouri River within the headwaters of the Lake Sakakawea watershed. The part of the Lake Sakakawea watershed that does not include the Fort Peck Lake watershed is hereinafter referred to as the "lower Lake Sakakawea watershed;" therefore, runoff from the Lake Sakakawea watershed is the product of runoff from the Fort Peck Lake and lower Lake Sakakawea watersheds. The drainage areas of the Fort Peck Lake and lower Lake Sakakawea watersheds are 57,500 and 123,900 mi^2, respectively, with a combined area for the Lake Sakakawea watershed of 181,400 mi^2 (U.S. Army Corps of Engineers, 2013b). The lower Lake Sakakawea watershed includes the drainage area of the Yellowstone River (fig. 4). The headwaters of the Yellowstone River and the Fort Peck Lake watershed are part of the high elevations of the Rocky Mountains physical division, hereinafter referred to as the "Rocky Mountains" (Fenneman, 1931). About 36,020 mi^2 (62 percent) of the Fort Peck Lake watershed and 93,345 mi^2 (75 percent) of the lower Lake Sakakawea watershed lies within the Great Plains ecoregion and physical division, hereinafter referred to as the "Great Plains" (Fenneman, 1931) (fig. 4).

Climate of the Missouri River Basin and Lake Sakakawea Watershed

The climate of the Missouri River Basin, based on a first order Köppen classification (Peel and others, 2007), can be described as arid and cold in the west, cold in the northeast, and temperate to the south. The climate of the Missouri River Basin was described by the U.S. Army Corps of Engineers (2006) as having large variability in air temperature and precipitation produced by the interaction of air masses from the Gulf of Mexico, Pacific Ocean, and polar air masses from Canada (fig. 1). Air masses from the Gulf of Mexico affect summer weather, and air masses from the Pacific Ocean and Canada affect winter weather. Precipitation in the Missouri River Basin is a result of cyclonic fronts in winter and thunderstorms in the summer (U.S. Army Corps of Engineers, 2006).

The climate of the Missouri River Basin and the Lake Sakakawea watershed can be described on the basis of the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly and others, 1994, 2002). The PRISM interpolates weather station observations of monthly total precipitation and monthly means of minimum and maximum daily air temperature to a 2.5 arc-minute grid for the conterminous United States. The PRISM output corresponding to the 1981–2010 climate normal (a climate normal is a 30-year period) is described herein. For the Missouri River Basin and the Lake Sakakawea watershed, precipitation falls mostly in May–July (fig. 5) during which thunderstorms are common (U.S. Army Corps of Engineers, 2006). The combination of high precipitation and high minimum and maximum air temperature during these months (fig. 5) results in high amounts of runoff directly from precipitation and derived from snowmelt; therefore climate, mountain snowpack, and runoff for these months were the focus of this study. Monthly precipitation for the Lake Sakakawea watershed has a slightly bimodal distribution with one peak for May–July and a second smaller peak for September (fig. 5). Annual precipitation has an east-west gradient with the least amount of annual precipitation in the western part of the Missouri River Basin and the greatest amount of annual precipitation in the eastern part (fig. 6); however, there also is an elevation gradient such that the Rocky Mountains have higher annual precipitation than the adjacent Great Plains (fig. 4). The largest spatial gradient in annual precipitation is in the vicinity of the 100th meridian of longitude. Mean annual daily maximum air temperature is generally warmest in the southern part and coolest in the western part of the Missouri River Basin (fig. 6) such as in the headwater areas of the Lake Sakakawea watershed. Mean annual daily minimum air temperature roughly follows a north-south gradient with the warmest air temperatures in the southern part of the Missouri River Basin (fig. 6).



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Albers Equal-Area Conic projection

Watershed boundaries modified from U.S. Geological Survey digital data; Ecoregions from Commission for Environmental Cooperation, 1997; Physical divisions from Fenneman, 1931; U.S. Historical Climatology Network stations from Oak Ridge National Laboratory, 2014; SNOTEL stations from Natural Resources Conservation Service, 2014

EXPLANATION

Ecoregions (and physical divison)

- Northwestern Forested Mountains (Rocky Mountains)
- North American Desert (Rocky Mountains)
- Great Plains (Great Plains)

Basin or watershed boundary

Dam

38 **U.S. Historical Climatology Network station (HCN) with index number from table 1**

Natural Resources Conservation Service snowpack telemetry station (SNOTEL), with index number from table 1

- 53 Elevation less than 7,000 feet above North American Vertical Datum of 1988 (NAVD 88)
- 92 Elevation between 7,000 and 8,500 feet above NAVD 88
- 103 Elevation greater than 8,500 feet above NAVD 88

Figure 4. Location of the study area showing ecosystem regions, physical divisions, and U.S. Historical Climatology Network and snowpack telemetry stations used in analyses.

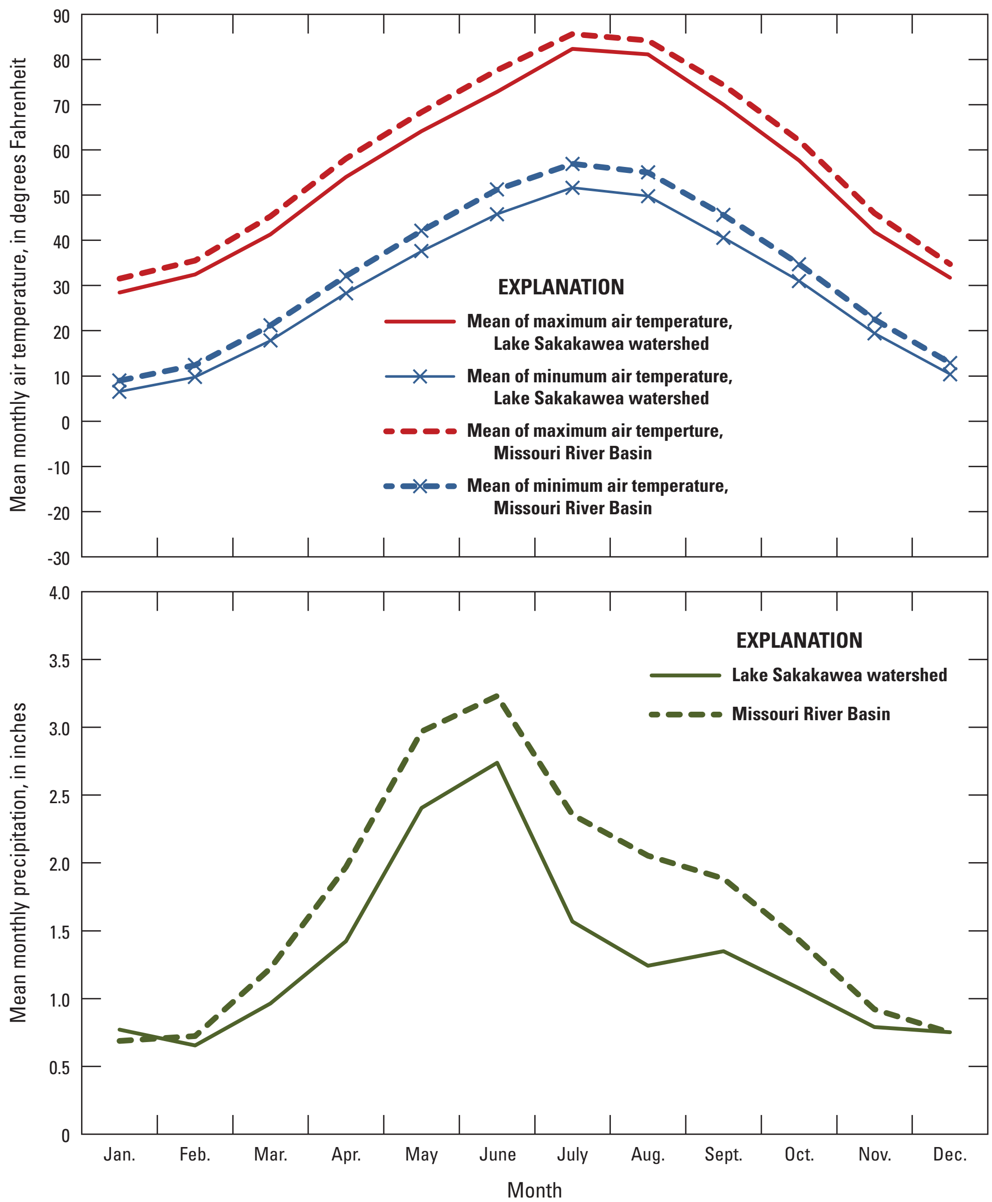


Figure 5. Annual cycle of mean monthly air temperature and precipitation for 1981–2010 derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly and others, 1994, 2002), Lake Sakakawea watershed and Missouri River Basin.

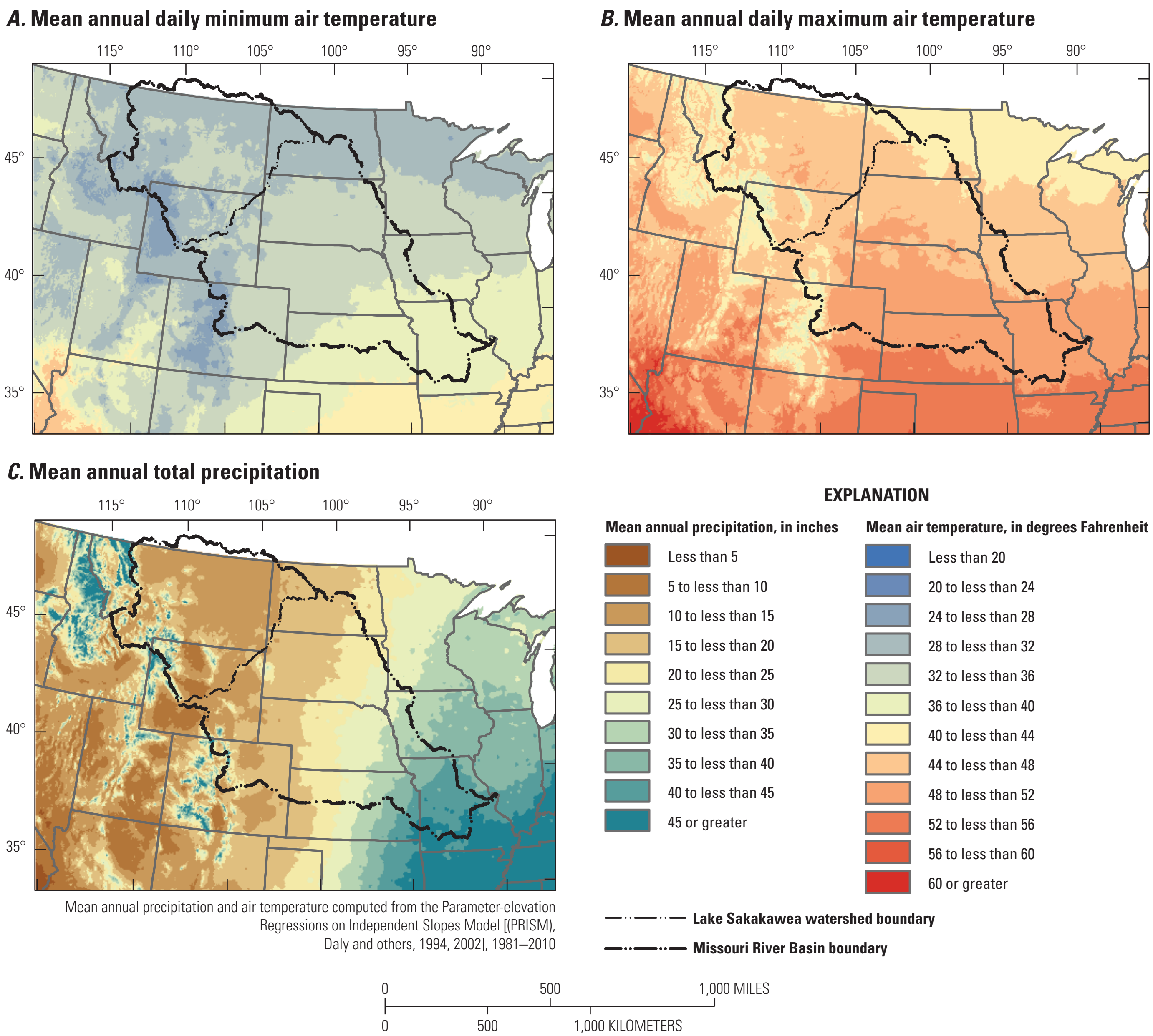


Figure 6. Mean annual temperature and precipitations based on Parameter-elevation Regression on Independent Slopes Model (PRISM) output for 1981–2010. *A*, mean annual daily minimum air temperature; *B*, mean annual daily maximum air temperature; and, *C*, mean annual total precipitation.

Approach and Methods

Modern (1992–2011) and projected (2012–99) peak snowpack and May–July runoff were estimated using transfer functions calibrated on the basis of seasonal means of mean air temperature and total precipitation recorded at the location of U.S. Historical Climatology Network (HCN) stations and Natural Resources Conservation Service SNOTEL stations. The use of the term “transfer function” was taken from paleoclimate research (Bradley, 1999) and implies a strong relation between “regressed” (dependent) variables and “regressor” (explanatory) variables [terminology as described by Davis (2002)], which might be considered a “proxy” of the regressed variable; for example, in paleoclimate applications tree-ring widths are proxies for annual or seasonal precipitation. Herein, the regressor variable precipitation might be considered a proxy for snowpack. Projected peak snowpack and May–July runoff to 2099 were computed on the basis of applying transfer functions to the output from two versions (3.0 and 4.0) of the Community Climate System Model (CCSM), which is an Atmosphere-Ocean General Circulation Model (AOGCM) of global climate. This research was funded as a pilot study and as such was not an exhaustive evaluation of projected climate scenarios based on ensembles of AOGCM output.

The transfer functions were multiple linear regression models in which a regressed variable was estimated using a set of regressor variables; for example, in a simple linear model:

$$Y = a_0 + a_1X_1 + a_2X_2 \quad (1)$$

where

Y	is the regressed (dependent) variable,
a_0	is the intercept,
a_1 and a_2	are coefficients, and
X_1 and X_2	are the regressor (explanatory) variables.

Peak snowpack and May–July runoff were regressed variables. Regressor variables used to regress peak snowpack included seasonal means of mean air temperature and total precipitation. The transfer function for May–July runoff included these same regressor variables plus peak snowpack and seasonal total reference evapotranspiration. Regressed and regressor variables for the calibration period, 1992–2011, were computed on the basis of HCN and SNOTEL station records of monthly air temperature and precipitation. The HCN and SNOTEL stations used are listed in table 1, and locations are shown in figure 4. Regressor variables for the projection period (2012–99) were computed from downscaled CCSM output of monthly air temperature and precipitation interpolated to the location of HCN and SNOTEL stations. Separate transfer functions of peak snowpack and May–July runoff were calibrated and validated for the Fort Peck Lake and lower Lake Sakakawea watersheds.

Several regressor variables were computed by stratifying HCN and SNOTEL station records of air temperature and precipitation by watershed, season, and elevation. Stratification by watershed was by extraction of stations within the Fort Peck and lower Lake Sakakawea watersheds. Stratification by elevation was by further extracting stations by three elevation zones:

- plains, less than 7,000 feet (ft);
- foothills, from 7,000 to 8,000 ft; and
- mountains, greater than 8,500 ft.

These terms are not meant to imply physiographic setting of individual stations; for example, a station assigned to the plains elevation zone may not necessarily be in the Great Plains, and could be located in a mountain valley. All elevations described hereinafter are in units of feet above the North American Vertical Datum of 1988 (NAVD 88). Stratification by seasons were relative to a 12-month period ending within the runoff season (May–July) and were defined as: July, August, September (JAS); October, November, December (OND); January, February, March (JFM); and April, May, June (AMJ). Note that JAS and OND were taken from the calendar year preceding JFM and AMJ. The seasons JAS, OND, JFM, and AMJ are herein collectively (July–June) referred to as a "runoff year," which is referred to by the calendar year for JFM and AMJ; thus, runoff year 1992 begins July 1, 1991, and ends June 30, 1992. Stratified by watershed, elevation, and season, the HCN and SNOTEL station records were then averaged to compute regressor variables. The regressor variables for the peak snowpack transfer function were the following:

- Watershed spatial average of the seasonal means of daily mean air temperature for each elevation zone (12 variables for each watershed), and
- Watershed spatial average of seasonal mean of total precipitation for each elevation zone (12 variables for each watershed).

The peak snowpack transfer function for each watershed could, therefore, include as much as 24 regressor variables. Names of regressor variables used in scripts and data files are listed in table 2.

Bootstrap methods (Efron, 1979) were used to compute regressor variables for calibration and validation of transfer functions. The bootstrap method increases the number of records available for calibration by iteratively removing HCN and SNOTEL stations and recomputing regressor variables for each year using the remaining stations. The HCN and SNOTEL stations removed with each bootstrap iteration are listed in table 3. Regressor variables were bootstrapped four times, which resulted in an additional 80 records (20 years, bootstrapped four times) and a total of 100 records for calibration and validation; that is, the 100 records include 20 records computed using all stations and an additional 80 records bootstrapped by iteratively removing stations. A total of 5 records were randomly selected from the 100 records for validation. The remaining 95 records were used for calibration of the transfer function.

Stepwise regression was used to reduce the number of regressor variables in a model. Stepwise regression iteratively includes regressor variables and evaluates the model's improvement with each step using the Akaike's Information Criterion (AIC) (Akaike, 1974; Adler, 2010). Draper and Smith (1981) suggest caution when relying on automated methods such as stepwise techniques to develop multiple linear regression models. Therefore, three measures were considered in evaluating improvement in the model: the AIC; the incremental increase in the multiple R^2 (coefficient of determination [Ott, 1993]) with the addition of a regressor variable; and effects that addition of a new regressor variable had on the coefficient of regressor variables already in the multivariate model. The R statistical program, version 3.0.2 (described by Adler, 2010), was the statistical analysis package used in this study.

The transfer function for May–July runoff included additional regressor variables to those previously described. Additional variables for each watershed included total reference evapotranspiration, stratified by season and elevation zone (plains, foothills, mountains) for an additional 12 regressor variables, and peak snowpack as one additional regressor

Table 1. U.S. Historical Climate Network and snowpack telemetry stations used for analyses.

[HCN, U.S. Historical Climate Network; SNOTEL, snowpack telemetry]

Station number	Station name	Latitude (arc-degrees)	Longitude (arc-degrees)	Elevation[a] (feet)	Station type	Watershed	Index number (fig. 4)
240364	AUGUSTA	47.4931	-112.3964	4,069	HCN	Fort Peck Lake	1
241044	BOZEMAN_MONTANA_ST_U	45.6622	-111.0453	4,912	HCN	Fort Peck Lake	2
241552	CASCADE_5_S	47.2194	-111.7100	3,359	HCN	Fort Peck Lake	3
241737	CHOTEAU	47.8206	-112.1919	3,844	HCN	Fort Peck Lake	4
242173	CUT_BANK_AP	48.6033	-112.3753	3,837	HCN	Fort Peck Lake	5
242409	DILLON_WMCE	45.2128	-112.6447	5,227	HCN	Fort Peck Lake	6
242793	ENNIS	45.3394	-111.7111	4,952	HCN	Fort Peck Lake	7
243013	FLATWILLOW_4_ENE	46.8511	-108.3133	3,132	HCN	Fort Peck Lake	8
243110	FT._ASSINNIBOINE	48.4983	-109.7972	2,612	HCN	Fort Peck Lake	9
243558	GLASGOW_INTL_AP	48.2139	-106.6214	2,285	HCN	Fort Peck Lake	10
243751	GREAT_FALLS_AP	47.4733	-111.3822	3,663	HCN	Fort Peck Lake	11
244055	HELENA_AP_ASOS	46.6056	-111.9636	3,827	HCN	Fort Peck Lake	12
244522	JORDAN	47.3144	-106.9103	2,619	HCN	Fort Peck Lake	13
245761	MOCCASIN_EXP_STN	47.0575	-109.9514	4,299	HCN	Fort Peck Lake	14
246157	NORRIS_MADISON_PH	45.4856	-111.6325	4,744	HCN	Fort Peck Lake	15
248501	VALIER	48.3089	-112.2511	3,809	HCN	Fort Peck Lake	16
248597	VIRGINIA_CITY	45.2925	-111.9481	5,771	HCN	Fort Peck Lake	17
248857	WEST_YELLOWSTONE	44.6500	-111.1000	6,657	HCN	Fort Peck Lake	18
248930	WHITE_SULPHUR_SPRINGS_2	46.5436	-110.9000	5,039	HCN	Fort Peck Lake	19
240780	BIG_TIMBER	45.8328	-109.9503	4,099	HCN	Lower Lake Sakakawea	20
241722	CHINOOK	48.5883	-109.2256	2,419	HCN	Lower Lake Sakakawea	21
242689	EKALAKA	45.8903	-104.5461	3,424	HCN	Lower Lake Sakakawea	22
243089	FORKS_4_NNE	48.7778	-107.4536	2,598	HCN	Lower Lake Sakakawea	23
243581	GLENDIVE	47.1064	-104.7183	2,076	HCN	Lower Lake Sakakawea	24
244345	HUNTLEY_EXP_STN	45.9228	-108.2444	3,033	HCN	Lower Lake Sakakawea	25
244364	HYSHAM_25_SSE	45.9353	-107.1375	3,099	HCN	Lower Lake Sakakawea	26
245080	LIVINGSTON_12_S	45.4836	-110.5689	4,869	HCN	Lower Lake Sakakawea	27
245338	MALTA_7_E	48.3939	-107.7286	2,230	HCN	Lower Lake Sakakawea	28
245668	MILDRED_5_N	46.7614	-104.9619	2,483	HCN	Lower Lake Sakakawea	29
245690	MILES_CITY_AP	46.4267	-105.8825	2,623	HCN	Lower Lake Sakakawea	30
246601	PLEVNA	46.4178	-104.5164	2,779	HCN	Lower Lake Sakakawea	31

Table 1. U.S. Historical Climate Network and snowpack telemetry stations used for analyses.—Continued

Station number	Station name	Latitude (arc-degrees)	Longitude (arc-degrees)	Elevation[a] (feet)	Station type	Watershed	Index number (fig. 4)
246918	RED_LODGE	45.1797	-109.2497	5,636	HCN	Lower Lake Sakakawea	32
247382	SAVAGE	47.4536	-104.3378	1,975	HCN	Lower Lake Sakakawea	33
248569	VIDA_6_NE	47.8800	-105.3686	2,284	HCN	Lower Lake Sakakawea	34
322365	DUNN_CENTER_1E	47.3467	-102.5869	2,204	HCN	Lower Lake Sakakawea	35
480540	BASIN	44.3789	-108.0314	3,836	HCN	Lower Lake Sakakawea	36
481840	CODY	44.5219	-109.0633	5,081	HCN	Lower Lake Sakakawea	37
481905	COLONY	44.8711	-104.1533	3,479	HCN	Lower Lake Sakakawea	38
482595	DIVERSION_DAM	43.2281	-108.9489	5,574	HCN	Lower Lake Sakakawea	39
487115	PAVILLION	43.2458	-108.6942	5,439	HCN	Lower Lake Sakakawea	40
487388	POWELL_FLD_STN	44.7764	-108.7592	4,369	HCN	Lower Lake Sakakawea	41
487760	RIVERTON	43.0308	-108.3742	4,954	HCN	Lower Lake Sakakawea	42
489770	WORLAND	44.0108	-107.9686	4,059	HCN	Lower Lake Sakakawea	43
489905	YELLOWSTONE_PK_MAMMOTH	44.9767	-110.6964	6,228	HCN	Lower Lake Sakakawea	44
307	BADGER_PASS	48.1300	-113.0200	6,900	SNOTEL	Fort Peck Lake	45
315	BASIN_CREEK	45.8000	-112.5200	7,180	SNOTEL	Fort Peck Lake	46
318	BEAGLE_SPRINGS	44.4700	-112.9800	8,850	SNOTEL	Fort Peck Lake	47
347	BLACK_BEAR	44.5100	-111.1300	8,170	SNOTEL	Fort Peck Lake	48
355	BLOODY_DICK	45.1700	-113.5000	7,600	SNOTEL	Fort Peck Lake	49
360	BOULDER_MOUNTAIN	46.5600	-111.2900	7,950	SNOTEL	Fort Peck Lake	50
385	CARROT_BASIN	44.9600	-111.2900	9,000	SNOTEL	Fort Peck Lake	51
403	CLOVER_MEADOW	45.0200	-111.8500	8,600	SNOTEL	Fort Peck Lake	52
427	CRYSTAL_LAKE	46.7900	-109.5100	6,050	SNOTEL	Fort Peck Lake	53
436	DARKHORSE_LAKE	45.1700	-113.5800	8,600	SNOTEL	Fort Peck Lake	54
448	DIVIDE	44.7900	-112.0600	7,800	SNOTEL	Fort Peck Lake	55
482	FLATTOP_MTN.	48.8000	-113.8600	6,300	SNOTEL	Fort Peck Lake	56
487	FROHNER_MEADOW	46.4400	-112.1900	6,480	SNOTEL	Fort Peck Lake	57
568	LAKEVIEW_RIDGE	44.5900	-111.8200	7,400	SNOTEL	Fort Peck Lake	58
576	LEMHI_RIDGE	44.9900	-113.4400	8,100	SNOTEL	Fort Peck Lake	59
578	LICK_CREEK	45.5000	-110.9700	6,860	SNOTEL	Fort Peck Lake	60
603	LOWER_TWIN	45.5100	-111.9200	7,900	SNOTEL	Fort Peck Lake	61
613	MANY_GLACIER	48.8000	-113.6700	4,900	SNOTEL	Fort Peck Lake	62
638	MOOSE_CREEK	45.6700	-113.9500	6,200	SNOTEL	Fort Peck Lake	63
649	MOUNT_LOCKHART	47.9200	-112.8200	6,400	SNOTEL	Fort Peck Lake	64

Table 1. U.S. Historical Climate Network and snowpack telemetry stations used for analyses.—Continued

Station number	Station name	Latitude (arc-degrees)	Longitude (arc-degrees)	Elevation[a] (feet)	Station type	Watershed	Index number (fig. 4)
656	MULE_CREEK	45.4100	-112.9600	8,300	SNOTEL	Fort Peck Lake	65
690	PICKFOOT_CREEK	46.5800	-111.2700	6,650	SNOTEL	Fort Peck Lake	66
700	PORCUPINE	46.1100	-110.4700	6,500	SNOTEL	Fort Peck Lake	67
722	ROCKER_PEAK	46.3600	-112.2600	8,000	SNOTEL	Fort Peck Lake	68
727	SADDLE_MTN.	45.6900	-113.9700	7,940	SNOTEL	Fort Peck Lake	69
754	SHOWER_FALLS	45.4000	-110.9600	8,100	SNOTEL	Fort Peck Lake	70
781	SPUR_PARK	46.7800	-110.6200	8,100	SNOTEL	Fort Peck Lake	71
813	TEPEE_CREEK	44.7900	-111.7100	8,000	SNOTEL	Fort Peck Lake	72
847	WALDRON	47.9200	-112.7900	5,600	SNOTEL	Fort Peck Lake	73
858	WHISKEY_CREEK	44.6100	-111.1500	6,800	SNOTEL	Fort Peck Lake	74
860	WHITE_ELEPHANT	44.5300	-111.4100	7,710	SNOTEL	Fort Peck Lake	75
876	WOOD_CREEK	47.4500	-112.8100	5,960	SNOTEL	Fort Peck Lake	76
309	BALD_MTN.	44.8000	-107.8400	9,380	SNOTEL	Lower Lake Sakakawea	77
325	BEAR_TRAP_MEADOW	43.8900	-107.0600	8,200	SNOTEL	Lower Lake Sakakawea	78
326	BEARTOOTH_LAKE	44.9400	-109.5700	9,360	SNOTEL	Lower Lake Sakakawea	79
350	BLACKWATER	44.3800	-109.7900	9,780	SNOTEL	Lower Lake Sakakawea	80
363	BOX_CANYON	45.2700	-110.2500	6,670	SNOTEL	Lower Lake Sakakawea	81
377	BURGESS_JUNCTION	44.7900	-107.5300	7,880	SNOTEL	Lower Lake Sakakawea	82
379	BURROUGHS_CREEK	43.7000	-109.6700	8,750	SNOTEL	Lower Lake Sakakawea	83
384	CANYON	44.7200	-110.5100	7,870	SNOTEL	Lower Lake Sakakawea	84
402	CLOUD_PEAK_RESERVOIR	44.4000	-107.0600	9,860	SNOTEL	Lower Lake Sakakawea	85
451	DOME_LAKE	44.5700	-107.3000	8,880	SNOTEL	Lower Lake Sakakawea	86
480	FISHER_CREEK	45.0600	-109.9400	9,100	SNOTEL	Lower Lake Sakakawea	87
512	HANSEN_SAWMILL	44.2600	-106.9800	8,360	SNOTEL	Lower Lake Sakakawea	88
525	HOBBS_PARK	42.8700	-109.0900	10,100	SNOTEL	Lower Lake Sakakawea	89
560	KIRWIN	43.8600	-109.3200	9,550	SNOTEL	Lower Lake Sakakawea	90
585	LITTLE_WARM	43.5000	-109.7500	9,370	SNOTEL	Lower Lake Sakakawea	91
625	MIDDLE_POWDER	43.6300	-107.1800	7,760	SNOTEL	Lower Lake Sakakawea	92
635	MONUMENT_PEAK	45.2200	-110.2400	8,850	SNOTEL	Lower Lake Sakakawea	93
676	OWL_CREEK	43.6600	-109.0100	8,975	SNOTEL	Lower Lake Sakakawea	94
683	PARKER_PEAK	44.7300	-109.9100	9,400	SNOTEL	Lower Lake Sakakawea	95
696	PLACER_BASIN	45.4200	-110.0900	8,830	SNOTEL	Lower Lake Sakakawea	96
703	POWDER_RIVER_PASS	44.1600	-107.1300	9,480	SNOTEL	Lower Lake Sakakawea	97

Table 1. U.S. Historical Climate Network and snowpack telemetry stations used for analyses.—Continued

Station number	Station name	Latitude (arc-degrees)	Longitude (arc-degrees)	Elevation[a] (feet)	Station type	Watershed	Index number (fig. 4)
725	S_FORK_SHIELDS	46.0900	-110.4300	8,100	SNOTEL	Lower Lake Sakakawea	98
751	SHELL_CREEK	44.5000	-107.4300	9,580	SNOTEL	Lower Lake Sakakawea	99
798	SUCKER_CREEK	44.7200	-107.4000	8,880	SNOTEL	Lower Lake Sakakawea	100
806	SYLVAN_LAKE	44.4800	-110.1600	8,420	SNOTEL	Lower Lake Sakakawea	101
822	TOGWOTEE_PASS	43.7500	-110.0600	9,580	SNOTEL	Lower Lake Sakakawea	102
826	TOWNSEND_CREEK	42.7000	-108.9000	8,700	SNOTEL	Lower Lake Sakakawea	103
837	TWO_OCEAN_PLATEAU	44.1500	-110.2200	9,240	SNOTEL	Lower Lake Sakakawea	104
862	WHITE_MILL	45.0500	-109.9100	8,700	SNOTEL	Lower Lake Sakakawea	105
875	WOLVERINE	44.8000	-109.6600	7,650	SNOTEL	Lower Lake Sakakawea	106
878	YOUNTS_PEAK	43.9300	-109.8200	8,350	SNOTEL	Lower Lake Sakakawea	107

[a]Elevation reported as height above the North American Vertical Datum of 1988.

Table 2. Names and units of regressed and regressor variables for seasons and elevation zones as used in transfer functions.

[Peak snowpack is used as a regressed and regressor variable. Variables are computed for a runoff year, which is defined as beginning July 1 and ending the following June 30 of the specified year. Elevation ranges for the plains, foothills, and mountains elevation zones are height in feet above the North American Vertical Datum of 1988. <, less than; >, greater than]

Regressed variables[a]			
PEAKSWE Peak snowpack, as snow water equivalent (SWE), in inches			
MJJRO May–June runoff, in acre-feet			
Regressor variables[a,b]			
PEAKSWE Peak snowpack, as SWE, in inches			
Season	**Plains (<7,000 feet)**	**Foothills (7,000–8,500 feet)**	**Mountains (>8,500 feet)**
Seasonal mean of daily mean temperature, in degrees Fahrenheit			
July, August, September	TAVEJASPLN	TAVEJASFTH	TAVEJASMTN
October, November, December	TAVEONDPLN	TAVEONDFTH	TAVEONDMTN
January, February, March	TAVEJFMPLN	TAVEJFMFTH	TAVEJFMMTN
April, May, June	TAVEAMJPLN	TAVEAMJFTH	TAVEAMJMTN
Seasonal total precipitation, in inches			
July, August, September	PRECJASPLN	PRECJASFTH	PRECJASMTN
October, November, December	PRECONDPLN	PRECONDFTH	PRECONDMTN
January, February, March	PRECJFMPLN	PRECJFMFTH	PRECJFMMTN
April, May, June	PRECAMJPLN	PRECAMJFTH	PRECAMJMTN
Seasonal total reference evapotranspiration, in inches			
July, August, September	EVAPJASPLN	EVAPJASFTH	EVAPJASMTN
October, November, December	EVAPONDPLN	EVAPONDFTH	EVAPONDMTN
January, February, March	EVAPJFMPLN	EVAPJFMFTH	EVAPJFMMTN
April, May, June	EVAPAMJPLN	EVAPAMJFTH	EVAPAMJMTN

[a]Variable names are expressed in capital letters using Courier type font.

[b]These variable names are composed of letter combinations designating various abbreviations. The first four letters designate TAVE, mean of daily mean temperature; PREC, total precipitation; or EVAP, total reference evapotranspiration. The next three letters designate seasons as JAS, July, August, September; OND, October, November, December; JFM, January, February, March; or AMJ, April, May, June. The last three letters designate the elevation zones as PLN, plains elevation zone; FTH, foothills elevation zone; or MTN, mountains elevation zone.

variable for each watershed. This added 13 additional regressor variables, for a total of 37 regressor variables available for calibration of the May–July runoff transfer function for a given watershed (table 2).

Historical Climatology Network and Snowpack Telemetry Station Data

Historical weather station data were compiled from HCN records (Oak Ridge National Laboratory, 2014), and included monthly mean of daily mean surface air temperature, and monthly total precipitation. Historical weather station data also were compiled from the SNOTEL station records (Natural Resources Conservation Service, 2014), which also included monthly mean of daily mean surface air temperature, and monthly total precipitation. In addition, SNOTEL station records included daily snowpack as SWE height, in inches. Links to digital HCN and SNOTEL data used for this study are provided in appendix 1.

Runoff year 1992 was selected as the start of the calibration period on the basis of available snowpack data, which were more limiting than available air temperature and precipitation data. Computation of defined regressor variables required complete station records from July 1991 through June 2011 resulting in a population of 107 stations of which 44 were HCN stations and 63 were SNOTEL stations (table 1). A total of 16 HCN stations were within the Rocky Mountains physiographic division and 28 were within the Great Plains physiographic division. Two HCN stations were outside of the lower Lake Sakakawea watershed boundary, but were close to the boundary (within about 12 mi) and were, therefore, included in the analyses. All HCN stations were below 7,000 ft (maximum elevation of 6,657 ft). All SNOTEL stations were within the Rocky Mountains physiographic division, and eight SNOTEL stations that were outside the Missouri River Basin,

Table 3. Station numbers excluded to bootstrap air temperature and precipitation regressor variables used for calibration and validation.

[Station numbers correspond to stations listed in table 1.]

Elevation zone	Bootstrap iteration			
	1	2	3	4
Fort Peck Lake watershed				
Plains[a]	243558	243110	244522	243013
Foothills[b]	860	448	603	727
Mountains[c]	403	436	318	385
Lower Lake Sakakawea watershed				
Plains[a]	247382	243581	322365	245338
Foothills[b]	875	625	384	377
Mountains[c]	826	862	379	696

[a]Less than 7,000 feet above the North American Vertical Datum of 1988 (NAVD 88).

[b]From 7,000 to 8,000 feet above the NAVD 88.

[c]Greater than 8,000 feet above the NAVD 88.

but close to the basin boundary (within about 20 mi) were included in analyses. Within the Fort Peck Lake watershed, 13 SNOTEL stations were below 7,000 ft (minimum elevation of 4,900 ft) and in the plains elevation zone, 15 stations were between 7,000 and 8,500 ft and in the foothills elevation zone, and 4 stations were above 8,500 ft (maximum elevation of 9,000 ft) and in the mountains elevation zone (fig. 4). Within the lower Lake Sakakawea watershed, 1 SNOTEL station was below 7,000 ft (minimum elevation of 4,900 ft), 9 stations were between 7,000 and 8,500 ft, and 21 stations were above 8,500 ft (maximum elevation of 10,100 ft) (fig. 4).

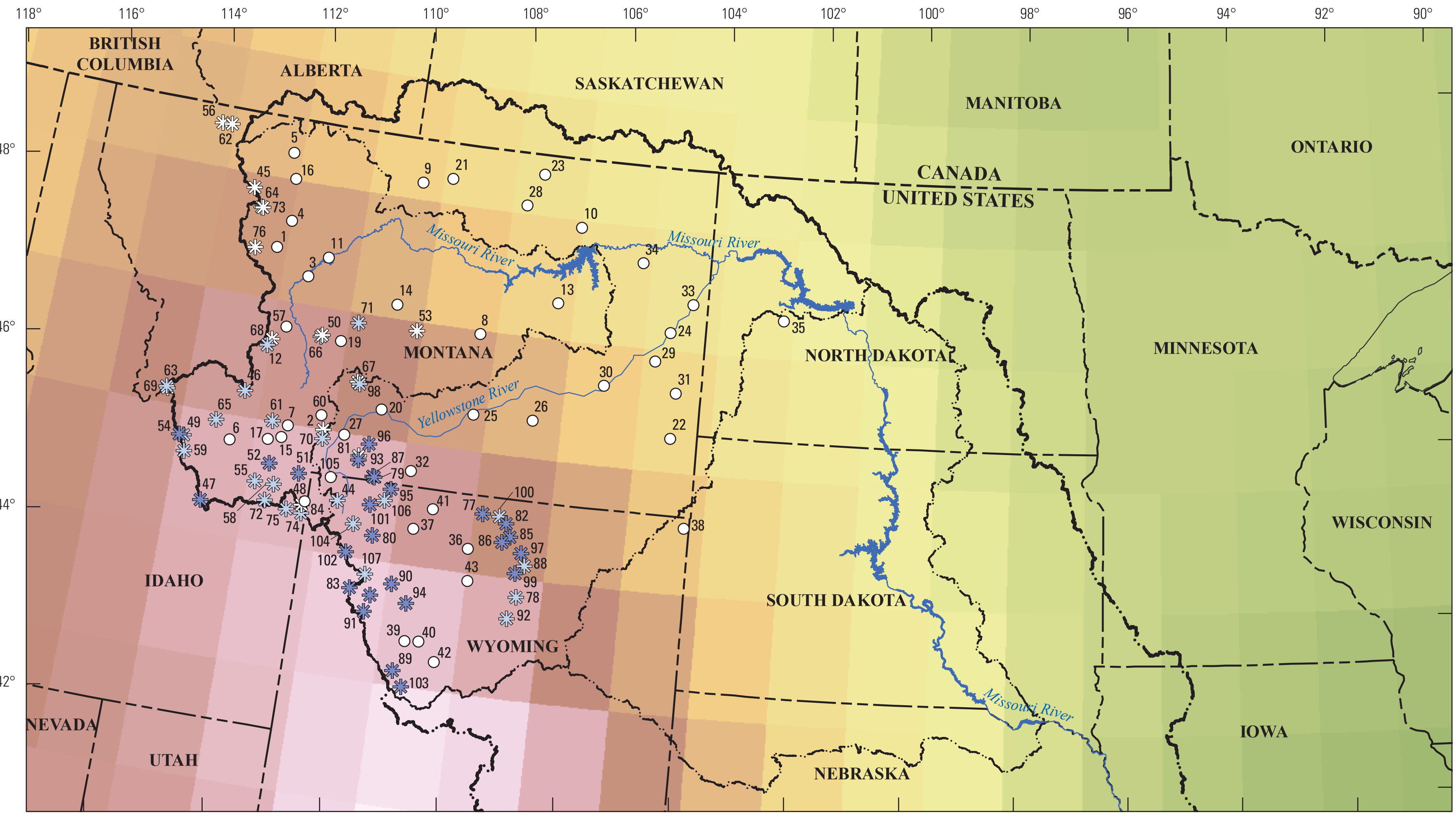
Community Climate System Model Output

Peak snowpack and May–July runoff were computed on the basis of regressor variables derived from station observations, and also on the basis of daily precipitation and mean air temperature output from the CCSM, version 3.0 (CCSM3; Vertenstein and others, 2004) and from the CCSM, version 4.0 (CCSM4; Gent and others, 2011; Vertenstein and others, 2013). The CCSM3 and CCSM4 output for runoff years 1992–2099 were downloaded for analyses. Internet access to CCSM output is described in appendix 2. The CCSM3 output for 2000–99 assumes the A2 emission scenario (Nakićenović and Swart, 2000), and the CCSM4 assumes a representative concentration pathway of 8.5 watts per meter squared (RCP 8.5) of greenhouse gas forcing for 2005–2100 (Vuuren and others, 2011). The A2 emission scenario describes a world that places more importance on economy (A scenario) over environment (B scenario) and has regional responses to climate (2 scenario) more so than global cooperation (1 scenario). The A2 emission scenario is not the worst case scenario, but is a high emission scenario. The A2 emission scenario has been selected by the North American Regional Climate Change Assessment Program for dynamical downscaling (Mearns and others, 2009). The RCP 8.5 is a revised version of the A2 emission scenario (Vuuren and others, 2011). For these two reasons, the A2 and its revised version, RCP 8.5, were selected for this study.

Because of the nature of AOGCMs, projected peak snowpack and May–July runoff computed on the basis of CCSM input will not precisely match that observed. For this reason, output for years preceding 2000 for CCSM3 and 2005 for CCSM4 are referred to as contemporary climate simulations, and years afterwards are referred to as projected climate simulations. The term “contemporary climate” implies that the model attempts to capture the characteristics of climate for a period, but is not constrained to match years (or months or days) precisely. To provide an analogy of the contrast between observed historical and contemporary climate, consider the behavior of walking a dog. A good model for the behavior of yesterday’s walk is walking a dog along the same route today; however, you will not take the exact same steps, and neither will the dog, but you will be representing the dynamics of how you and the dog behaved yesterday. If you were constrained to follow exactly the same steps and timing of the previous day, you would not capture the appropriate response to changing external forcings, such as your response to a car approaching an intersection or a squirrel that distracts the dog. In a similar manner, contemporary climate simulated by AOGCMs is not constrained to hindcast historical climate precisely, but rather is a simulation of the dynamical behavior of weather and climate variability given external forcings (hydroclimatology). In this case, the forcing is increasing greenhouse gases.

Herein, historical climate will refer to simulations based on HCN and SNOTEL station observations for the period 1992–2011, contemporary climate will refer to simulations based on CCSM output for the period 1992–2011, and projected climate will refer to simulations based on CCSM output for the period 2012–99. The term “projected climate” also will be used when describing time series that span the contemporary and projected climate periods (1992–2099). Output for specific years simulated on the basis of CCSM output will be referred to as “simulation year,” such as simulation year 2058. This is to emphasize that peak snowpack or May–July runoff estimated on the basis of CCSM output is not a prediction for that actual calendar year.

The grid spacing of CCSM3 output is about 1.4 arc-degrees of latitude and longitude, and the grid spacing for CCSM4 is about 0.94 arc-degrees of latitude by 1.25 arc-degrees of longitude. The CCSM grid spacing results in a generalized representation of terrain in the study area; for example, terrain representation (topography) for CCSM3 (fig. 7) has grid elevations less than 7,500 ft in the Upper Missouri River Basin, and the Rocky Mountains are represented as a single broad mountain range. As such, the climate dynamics at stations, such as might be typical for mountain settings



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Albers Equal-Area Conic projection

0 100 200 300 MILES
0 100 200 300 KILOMETERS

Watershed boundaries modified from U.S. Geological Survey digital data;
U.S. Historical Climatology Network stations from Oak Ridge National Laboratory, 2014;
SNOTEL stations from the Natural Resources Conservation Service, 2014

EXPLANATION

Community Climate System Model, version 3.0 topography

7,500 feet

0 feet

Basin or watershed boundary

38 **U.S. Historical Climatology Network station (HCN) with index number from table 1**

Natural Resources Conservation Service snowpack telemetry station (SNOTEL), with index number from table 1

84 Elevation less than 7,000 feet above North American Vertical Datum of 1988 (NAVD 88)

92 Elevation between 7,000 and 8,500 feet above NAVD 88

103 Elevation greater than 8,500 feet above NAVD 88

Figure 7. Representation of topography by the Community Climate System Model, version 3.0.

or plains, might not be well matched to the dynamics of the associated CCSM grid point.

The CCSM3 and CCSM4 output for July 1991–June 2099 (runoff years 1992–2099) of monthly mean air temperature and daily precipitation at grid points was interpolated to the locations of HCN and SNOTEL stations using a distance-squared weight applied to the four CCSM grid points surrounding the station. As a result, two sets of interpolated air temperature and precipitation were computed: one based on CCSM3 output and a second based on CCSM4 output. Links to interpolated CCSM3 and CCSM4 output are provided in appendix 3.

Interpolated CCSM output was bias corrected for each month. Bias correction represent the difference between interpolated CCSM and observed (at HCN and SNOTEL stations) estimates of mean monthly air temperature and mean daily precipitation for July 1991–June 2011. Bias for daily precipitation was computed by adjusting CCSM output only for days with computed precipitation. An error was computed as the difference between observed monthly means of daily precipitation from HCN and SNOTEL station records and monthly means from bias-adjusted CCSM output. Bias adjustment potentially resulted in negative precipitation for some daily values, which were reset to zero. After negative values were reset to zero, error was recomputed. Bias was iteratively adjusted until error was within a tolerance of 0.001 inch per day (in/d) for a given month. Links to the bias-adjusted CCSM3 and CCSM4 output are provided in appendix 4. Regressor variables as described in the "Approach and Methods" section were similarly computed using bias-corrected CCSM3 and CCSM4 output for runoff years 1992–2099. Because the CCSM-derived regressor variables were not used for calibration of transfer functions, the bootstrap method was not needed.

Bias correction shifts the mean, but bias correction has little or no effect on the standard deviation of CCSM output. Standard deviation of precipitation could be affected by bias correction because the minimum value is bounded by zero, whereas the maximum value is not bounded. The following departures of regressor variables computed using bias-corrected CCSM3 and CCSM4 output for 1992–2011 from regressor variables computed from HCN and SNOTEL stations (tables 4–6) were noted:

- greater standard deviation of OND, JFM, and AMJ air temperature for CCSM3 and CCSM4 output;
- greater standard deviation of CCSM3 precipitation with the exception of JFM for foothills and plains of the lower Lake Sakakawea watershed; and
- minimum and maximum precipitation for CCSM3 commonly exceeding the bounds of that observed.

Because bias-corrected CCSM3 output has greater standard deviation than that observed, and exceeds the bounds of that observed, confidence is reduced in simulations based on CCSM3 output relative to that based on CCSM4 output.

Peak Snowpack

Peak snowpack was used as a regressed and regressor variable. It was used as a regressor variable in the transfer function of May–July runoff. Peak snowpack is defined herein as the maximum daily snowpack recorded in a 12-month period from July through June. As such, the days considered in computation of peak snowpack span 2 calendar years. Peak snowpack was computed from daily snowpack at SNOTEL sites (fig. 4), and appendix 1 provides links to these data. The distribution of elevation ranges for SNOTEL stations are described previously in the "Historical Climatology Network and Snowpack Telemetry Station Data" section. All SNOTEL stations were located in the Rocky Mountains physiographic division. Peak snowpack is recorded as SWE with units of height, in inches.

Peak snowpack as a regressed or regressor variable represents the mean peak snowpack for all SNOTEL stations in a watershed for each runoff year. Bootstrapping was used to compute additional records for each runoff year. Stations removed for each bootstrap iteration are listed in table 7. As with other regressor variables, peak snowpack was computed for the Fort Peck and lower Lake Sakakawea watersheds. Sufficient records were not available to stratify peak snowpack by elevation and delete stations for the bootstrap method; therefore, peak snowpack was not stratified by elevation. In addition, given that peak snowpack is a regressed variable, stratification by elevation would require canonical regression techniques (Hotelling, 1936; Glahn, 1968) to simultaneously regress peak snowpack for each elevation zone. Future research might consider the use of canonical regression, which would allow for computation of peak snowpack and May–July runoff simultaneously.

Reference Evapotranspiration

Reference evapotranspiration is the evapotranspiration from a 4.72-in. high crop with a surface resistance of 21 seconds per foot; an albedo of 0.23; and closely resembles a surface that is shaded, well-watered, and covered by growing grass (Irmak and Haman, 2003). Reference evapotranspiration was computed using the methodology of Hargreaves and Samani (1985), and is a function of latitude and monthly means of maximum, mean, and minimum air temperature. These functions are described by Snyder and Eching (2002) and Svoboda and others (2002). Links to the Python scripts used to compute reference evapotranspiration at HCN and SNOTEL station locations, including input and output data, are provided in appendix 5. The Python scripts compute reference evapotranspiration for the historical, contemporary, and projected periods.

Total reference evapotranspiration for each season and elevation zone is a regressor variable in the transfer function of May–July runoff (table 2). As with other regressor variables, separate sets of regressor variables for total reference

Table 4. Standard deviation of seasonal precipitation and air temperature for 1992–2011 from observations at Historical Climate Network and snow telemetry stations, and Community Climate System Model, version 3.0 and version 4.0.

[JAS, July, August, September; OND, October, November, December; JFM, January, February, March; AMJ, April, May, June; OBS, observations at snow telemetry stations; CCSM3, Community Climate System Model, version 3.0; CCSM4, Community Climate System Model, version 4.0]

Elevation zone	Standard deviation of seasonal precipitation, in inches											
	JAS			OND			JFM			AMJ		
	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4
Fort Peck Lake watershed												
Plains	1.8	2.3	1.4	1.3	1.8	1.2	1.2	1.5	0.9	1.6	2.3	1.6
Foothills	1.6	3.3	1.5	2.4	3.6	1.8	2.1	2.7	1.6	2.3	3.4	1.8
Mountains	1.3	4.2	1.8	2.4	4.1	2.0	2.5	3.1	1.8	2.4	3.9	1.8
Lower Lake Sakakawea watershed												
Plains	1.0	1.6	1.1	0.7	1.1	0.7	0.5	0.9	0.5	1.4	1.7	1.4
Foothills	1.2	2.3	1.7	1.7	2.3	1.5	1.6	1.2	1.0	2.2	3.1	2.0
Mountains	1.3	2.5	1.9	2.1	2.6	1.7	2.2	1.6	1.3	2.5	3.4	2.0

Elevation zone	Standard deviation of seasonal air temperature, in degrees Fahrenheit											
	JAS			OND			JFM			AMJ		
	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4
Fort Peck Lake watershed												
Plains	2.4	2.3	1.8	2.4	4.0	3.7	2.9	4.2	5.7	1.7	2.3	2.5
Foothills	2.7	2.4	1.7	2.5	3.5	2.9	2.3	3.9	5.0	2.2	2.2	2.9
Mountains	2.6	2.4	1.6	2.6	3.3	2.8	2.1	3.8	4.9	2.3	2.3	3.0
Lower Lake Sakakawea watershed												
Plains	2.3	2.3	2.0	2.8	3.9	3.6	3.4	3.9	5.6	1.7	2.4	2.7
Foothills	2.4	2.6	1.8	2.6	3.4	2.8	2.4	4.0	5.0	2.1	2.4	2.9
Mountains	2.3	2.6	1.8	2.5	3.3	2.8	2.2	4.0	4.9	2.3	2.4	3.0

evapotranspiration were computed for the Fort Peck Lake and lower Lake Sakakawea watersheds. Regressor variables for the historical and projected periods were computed using methods described for air temperature and precipitation. Regressor variables for the historical period were bootstrapped by excluding the stations listed in table 7. Bootstrapped records were randomly sampled to provide 95 records for calibration and 5 records for validation.

Modern (1992–2011) and Projected (2012–99) Peak Snowpack

The peak snowpack transfer functions (models) for the Fort Peck Lake and lower Lake Sakakawea watersheds were calibrated for runoff years 1992–2011. All dates included in this section are for runoff years. The calibrated models (transfer functions) then were used to estimate modern (1992–2011) and projected (2012–99) peak snowpack for the Fort Peck Lake and lower Lake Sakakawea watersheds.

Model Calibration

The peak snowpack transfer function was calibrated using multiple linear regression on regressor variables that represented seasonal means of air temperature and precipitation records at HCN and SNOTEL stations stratified by elevation and watershed for the period of 1992–2011. Regressor variables were bootstrapped, and the regressed variable (peak snowpack) also was bootstrapped by excluding SNOTEL stations listed in table 7. Stepwise regression was used to reduce the number of regressor variables from 24 to 22 for the Fort Peck Lake and lower Lake Sakakawea watershed transfer functions. The incremental change in multiple R^2 values with addition of variables was used to reduce the number of variables computed by stepwise regression to five for the Fort Peck Lake watershed transfer function and four for the lower Lake Sakakawea transfer function (table 8). The change in multiple R^2 values with addition of regressor variables is shown in figure 8, and the resulting transfer functions had multiple R^2 values of 0.92 and 0.96 for the Fort Peck Lake and lower Lake Sakakawea watersheds, respectively. The regressor

Table 5. Minimum value of seasonal precipitation and air temperature for 1992–2011 from observations at Historical Climate Network and snow telemetry stations, and Community Climate System Model, version 3.0 and version 4.0.

[JAS, July, August, September; OND, October, November, December; JFM, January, February, March; AMJ, April, May, June; OBS, observations at snow telemetry stations; CCSM3, Community Climate System Model, version 3.0; CCSM4, Community Climate System Model, version 4.0]

Elevation zone	Minimum value of seasonal precipitation, in inches											
	JAS			OND			JFM			AMJ		
	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4
Fort Peck Lake watershed												
Plains	2.1	0.5	1.9	3.2	2.5	3.7	2.9	2.6	2.7	6.6	3.6	6.2
Foothills	2.7	0.2	2.0	5.4	3.2	6.0	5.3	3.0	5.4	8.0	2.8	8.2
Mountains	3.1	0.2	2.6	5.4	3.2	6.3	5.1	2.5	6.0	8.1	1.2	7.8
Lower Lake Sakakawea watershed												
Plains	2.1	0.7	1.6	1.1	0.7	1.0	1.0	0.8	0.8	3.9	3.1	4.1
Foothills	3.1	0.8	3.0	4.8	2.3	4.5	3.6	3.7	4.1	6.2	3.3	7.2
Mountains	3.5	0.9	2.9	5.6	2.5	5.6	4.4	4.7	5.3	6.0	2.9	7.9

Elevation zone	Minimum value of seasonal air temperature, in degrees Fahrenheit											
	JAS			OND			JFM			AMJ		
	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4
Fort Peck Lake watershed												
Plains	52	54	56	26	23	21	19	16	15	44	42	43
Foothills	45	47	50	21	19	19	17	13	12	36	35	34
Mountains	43	46	48	20	19	19	17	12	11	33	33	32
Lower Lake Sakakawea watershed												
Plains	59	60	62	27	26	22	20	17	14	50	49	49
Foothills	46	47	50	23	20	20	17	14	12	36	37	37
Mountains	43	44	47	20	17	18	15	11	9	33	33	34

variables and associated coefficients for the transfer functions are listed in table 8, and models for both watersheds have the following common regressors:

- precipitation in JFM and OND had the largest coefficient of regressor variables for both watersheds, but was associated with the foothills elevation zone for the Fort Peck Lake watershed and the mountain elevation zone for the lower Lake Sakakawea watershed;
- air temperature in OND for the plains elevation zone was included in both regression equations; and
- precipitation in JFM for the mountains elevation zone was included in both models, but has the smallest coefficient of precipitation variables for the Fort Peck Lake watershed transfer function.

In summary, regressor variables with highest coefficients were associated with JFM and OND precipitation, and the foothills and mountains for the Fort Peck Lake watershed, in contrast to the mountains for the lower Lake Sakakawea watershed. This might reflect bias in the elevation distribution of SNOTEL stations in the study area. Although all SNOTEL stations were in the Rocky Mountains, the Fort Peck Lake watershed had SNOTEL stations at lower elevations than SNOTEL stations in the lower Lake Sakakawea watershed. The elevation of SNOTEL stations ranged from 4,900 to 9,000 ft for the Fort Peck Lake watershed in contrast to 6,670 to 10,100 ft for the lower Lake Sakakawea watershed (table 1, fig. 4); therefore, the Fort Peck Lake watershed regression model was calibrated to peak snowpack at elevations more closely aligned with the foothills elevation zone.

Modern (1992–2011) Peak Snowpack as Snow Water Equivalent

Peak snowpack for the Fort Peck Lake watershed and for the lower Lake Sakakawea watershed (figs. 9 and 10, respectively) was computed as snow water equivalent (in inches) for runoff years 1992–2011 using calibration and validation regressor variables computed from HCN and SNOTEL station records. Plots of the relation between regressed peak snowpack and observed peak snowpack show a close

Table 6. Maximum value of seasonal precipitation and air temperature for 1992–2011 from observations at Historical Climate Network and snow telemetry stations, and Community Climate System Model, version 3.0 and version 4.0.

[JAS, July, August, September; OND, October, November, December; JFM, January, February, March; AMJ, April, May, June; OBS, observations at snow telemetry stations; CCSM3, Community Climate System Model, version 3.0; CCSM4, Community Climate System Model, version 4.0]

Elevation zone	Maximum value of seasonal precipitation, in inches											
	JAS			OND			JFM			AMJ		
	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4
Fort Peck Lake watershed												
Plains	10.3	9.3	6.4	8.1	8.9	7.8	6.6	7.9	6.2	12.4	12.8	11.5
Foothills	9.2	13.8	8.4	15.6	16.5	11.8	11.3	12.8	11.1	15.7	17.6	14.5
Mountains	7.5	17.4	9.6	15.6	18.8	13.1	13.4	14.1	11.7	15.9	18.8	15.4
Lower Lake Sakakawea watershed												
Plains	6.3	6.4	5.2	3.6	5.1	3.3	2.5	3.7	3.1	9.6	9.0	8.2
Foothills	7.5	9.1	9.9	11.8	12.7	9.3	9.1	8.7	8.0	13.8	16.7	14.2
Mountains	8.3	10.5	10.4	13.8	12.3	11.2	11.9	10.7	10.0	15.6	18.3	15.5

Elevation zone	Maximum value of seasonal air temperature, in degrees Fahrenheit											
	JAS			OND			JFM			AMJ		
	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4	OBS	CCSM3	CCSM4
Fort Peck Lake watershed												
Plains	62	62	62	37	37	36	31	32	36	50	51	53
Foothills	56	56	55	32	32	30	25	28	31	43	42	46
Mountains	54	55	54	31	30	29	24	26	30	42	40	45
Lower Lake Sakakawea watershed												
Plains	69	69	68	39	39	38	33	33	36	56	57	60
Foothills	56	58	56	32	32	31	24	29	29	45	45	48
Mountains	53	54	52	30	30	28	22	26	27	42	42	45

correspondence for the calibration and validation datasets (figs. 9–12); and based on a paired Student's t-test (Ott, 1993), means of regressed and observed peak snowpack were not significantly different from zero at a 0.05 probability (table 9).

Peak snowpack also was computed for 1992–2011 on the basis of regressor variables computed from CCSM3 and CCSM4 output for the Fort Peck Lake watershed and for the lower Lake Sakakawea watershed (figs. 9 and 10, respectively). As previously described in the "Community Climate System Model Output" section, regressed peak snowpack computed on the basis of CCSM3 and CCSM4 will not precisely match that observed for each year; however, the goal is to match the hydroclimatology of that observed. Student's t-tests, assuming unequal variances of populations, indicate no significant differences between observed mean peak snowpack and regressed mean peak snowpack from CCSM3 and CCSM4 at a 0.05 probability for the Fort Peck Lake and lower Lake Sakakawea watersheds (table 9).

For the Fort Peck Lake and lower Lake Sakakawea watersheds, mean peak snowpack regressed from CCSM3 and CCSM4 for 1992–2011 were similar to observed mean peak snowpack at SNOTEL stations (table 10). The maximum peak snowpack regressed from CCSM3 and CCSM4 was under-predicted for both watersheds. The minimum peak snowpack regressed from CCSM3 was under-predicted for both watersheds, regressed from CCSM4 for the Fort Peck Lake watershed was underpredicted, and regressed from CCSM4 for the lower Lake Sakakawea watershed was overpredicted. The standard deviation of peak snowpack regressed by CCSM3 was similar to that observed, and was underpredicted by CCSM4.

Table 7. Station numbers excluded to bootstrap the regressed and regressor variables for peak snowpack.

[Station numbers correspond to stations listed in table 1.]

Watershed	Bootstrap iteration			
	1	2	3	4
Fort Peck Lake	403	436	318	385
Lower Lake Sakakawea	826	862	379	696

Table 8. Coefficients of peak snowpack transfer functions for the Fort Peck Lake and lower Lake Sakakawea watersheds.

[All variables were significant at the 0.001 probability. --, not applicable]

Fort Peck Lake watershed		Lower Lake Sakakawea watershed	
Regression equation intercept = 35.56		Regression equation intercept = 3.68	
Variable[a,b]	Coefficient	Variable[a,b]	Coefficient
PRECJFMFTH	0.75	PRECONDMTN	0.86
PRECONDFTH	0.71	PRECJFMMTN	1.28
TAVEAMJPLN	-0.53	PRECAMJMTN	0.51
PRECJFMMTN	0.39	TAVEONDPLN	-0.26
TAVEONDPLN	-0.25	--	--

[a]Variable names are expressed in captial letters using Courier type font.

[b]These variable names are composed of letter combinations designating various abbreviations as defined in table 2. Abbreviations applicable to the variables in this table follow: TAVE, mean of daily mean temperature; PREC, total precipitation; OND, October, November, December; JFM, January, February, March; AMJ, April, May, June; PLN, plains elevation zone; FTH, foothills elevation zone; MTN, mountains elevation zone.

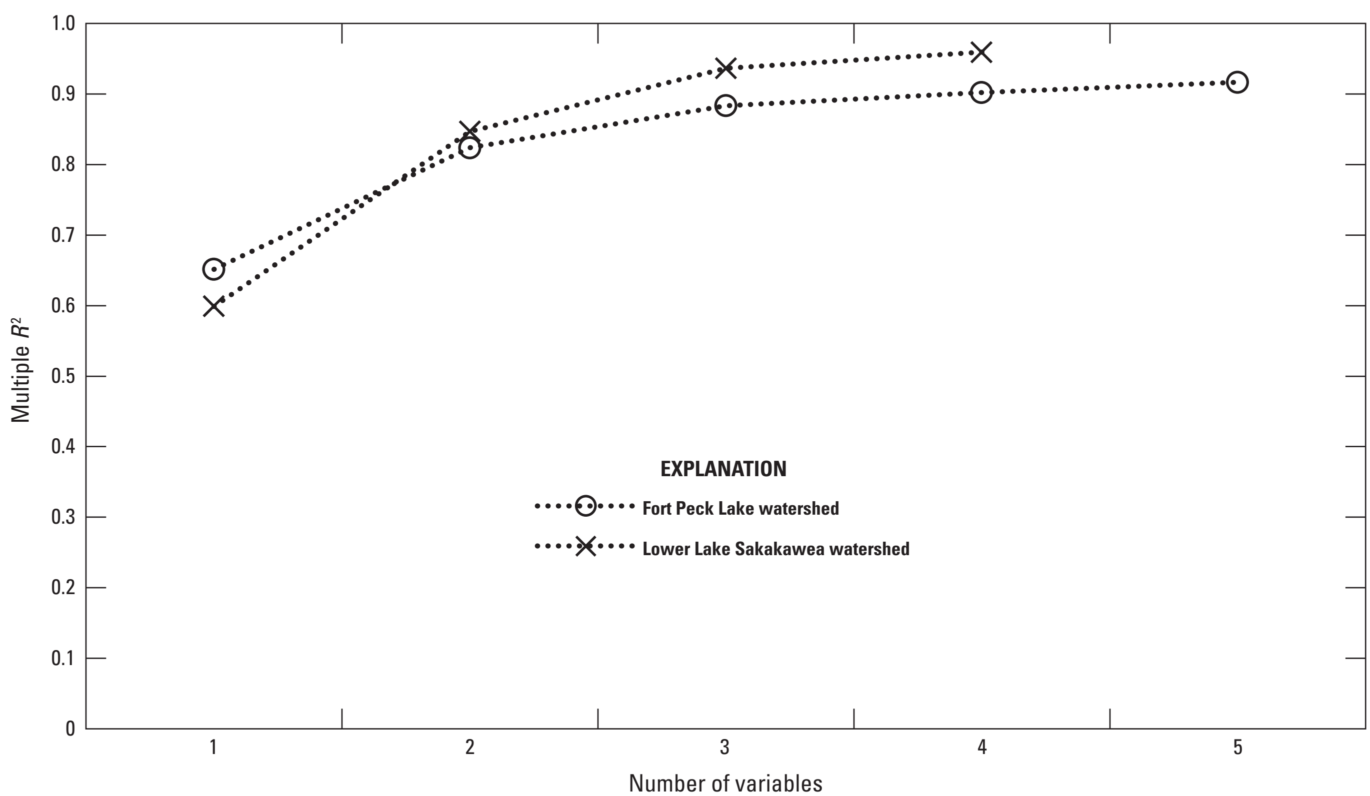

Figure 8. Incremental increase in multiple coefficient of determination (R^2) values with addition of regressor variables in table 8.

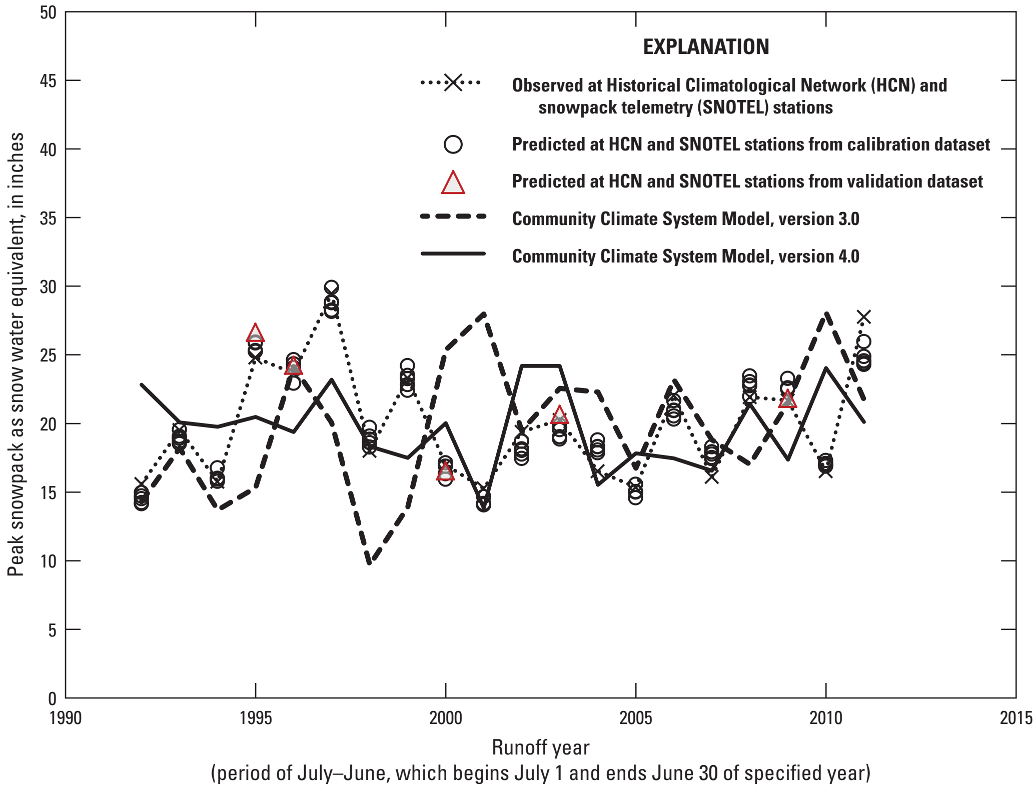

Figure 9. Peak snowpack for runoff years 1992–2011 for the Fort Peck Lake watershed. Multiple calibration points for each runoff year are a product of the bootstrap method.

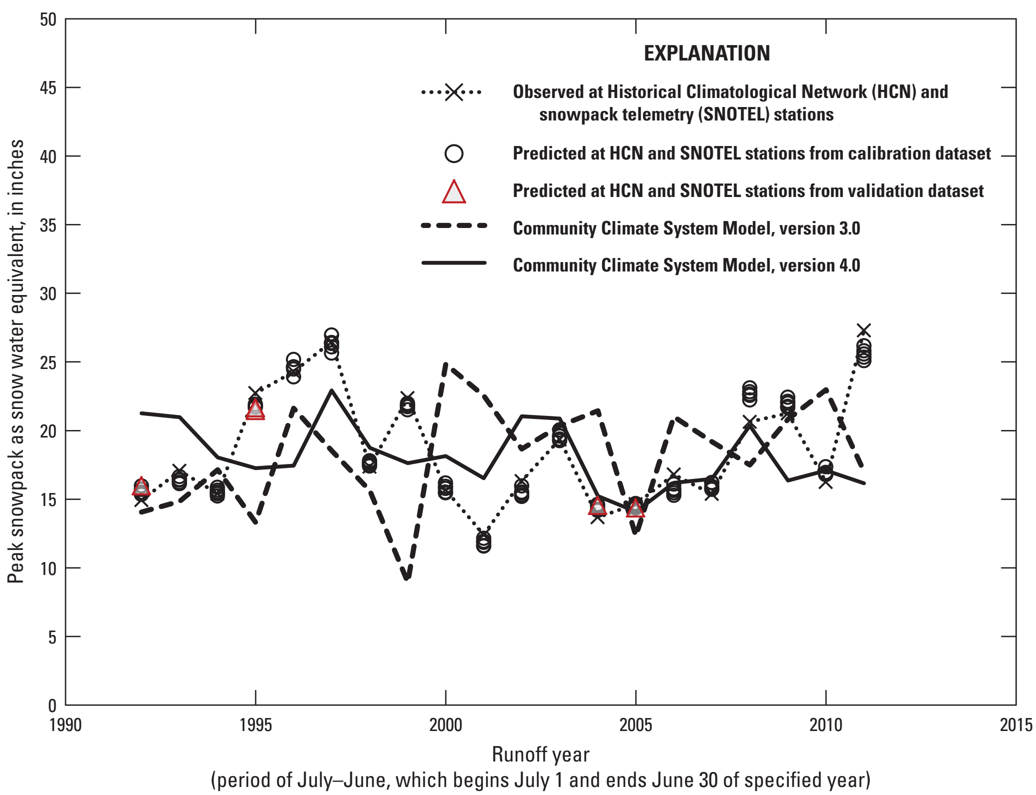

Figure 10. Peak snowpack as snow water equivalent for a runoff years 1992–2011 for the lower Lake Sakakawea watershed. Multiple calibration points for each runoff year are a product of the bootstrap method.

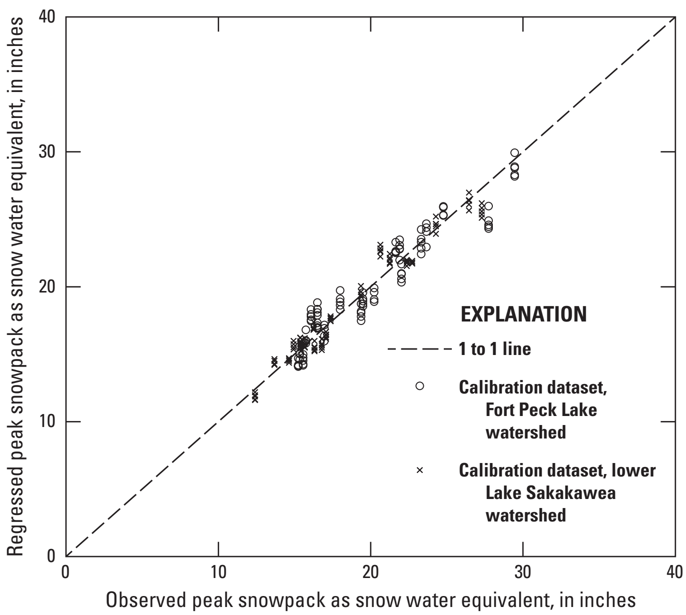

Figure 11. Relation between regressed peak snowpack and observed peak snowpack at snowpack telemetry stations used for calibration, Fort Peck Lake and lower Lake Sakakawea watersheds.

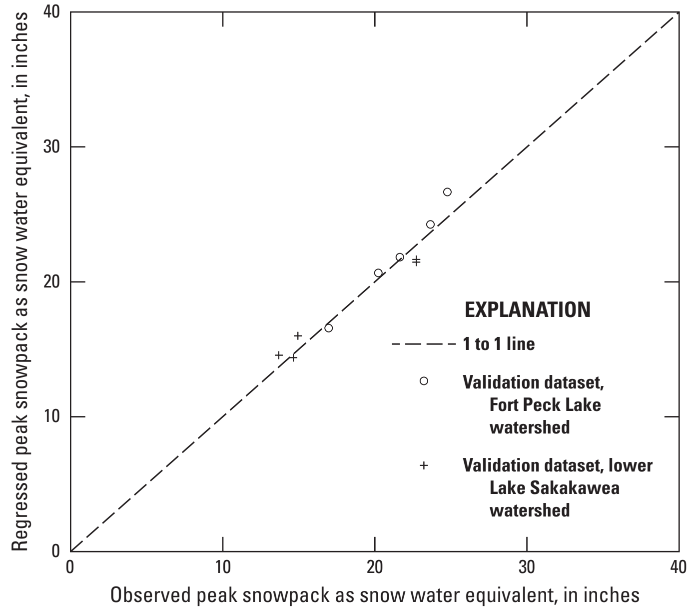

Figure 12. Relation between regressed peak snowpack and observed peak snowpack at snowpack telemetry stations used for validation, Fort Peck Lake and lower Lake Sakakawea watersheds.

Table 9. Results of paired Student's t-tests for the null hypothesis that observed and regressed peak snowpack have equal means.

[Means were not significantly different at the 0.05 probability for all tests. Student's t-tests for validation and calibration datasets are paired, and for Community Climate System Model, versions 3 and 4, are two-tailed, and two-samples with unequal variance. CCSM3, regressed from transfer function applied to the Community Climate System Model, version 3.0 output; CCSM4, regressed from transfer function applied to the Community Climate System Model, version 4.0]

Dataset	Fort Peck Lake watershed		Lower Lake Sakakawea watershed	
	t-value	Probability	t-value	Probability
Calibration	0.987	0.326	0.080	0.936
Validation	-1.380	0.239	0.277	0.796
CCSM3	0.199	0.843	0.285	0.777
CCSM4	0.250	0.805	0.343	0.734

Table 10. Summary statistics for observed and regressed peak snowpack for runoff years 1992–2011.

[A runoff year is the period July–June (begins July 1 and ends June 30 of specified year). CCSM3, regressed from the Community Climate System Model, version 3.0 output; CCSM4, regressed from the Community Climate System Model, version 4.0 output]

Statistic	Peak snowpack as snow water equivalent, in inches					
	Fort Peck Lake watershed			Lower Lake Sakakawea watershed		
	Observed	CCSM3	CCSM4	Observed	CCSM3	CCSM4
Mean	19.99	19.70	19.70	18.52	18.14	18.14
Maximum	29.47	28.08	24.19	27.30	24.84	22.93
Minimum	15.27	9.70	13.85	12.41	8.95	14.10
Standard deviation	4.25	4.93	2.97	4.30	4.04	2.36

Projected (2012–99) Peak Snowpack

Peak snowpack as snow water equivalent (in inches) was projected for runoff years 2012–99 by applying the transfer function for peak snowpack to regressor variables computed from CCSM3 and CCSM4 output for the Fort Peck Lake and lower Lake Sakakawea watersheds (figs. 13–14, respectively). Trends for the projection period were tested for significance using the Kendall's tau nonparametric test (Kendall, 1938). Change in variance was tested for significance using the Breusch-Pagan test (Breusch and Pagan, 1979). Significance was based on a 0.05 probability of a Type I error: reject null hypothesis of "no trend" when no trend exists.

Projected peak snowpack for 2012–99 for the Fort Peck Lake watershed indicate significant downward trends in regressed peak snowpack computed on the basis of CCSM3 and CCSM4 output (fig. 13). During the 88-year period 2012–99, 17 and 25 percent of years had peak snowpack less than the minimum observed for 1992–2011 for CCSM3 and CCSM4, respectively. The regressed peak snowpack for CCSM3 and CCSM4 for the final 10 years (2090–99) was below the observed minimum peak snowpack for 4 and 6 years, respectively, and below observed mean peak snowpack for 9 and 10 years, respectively. Downward trends in peak snowpack were consistent with the observed downward trends in annual streamflow for this region for 1960–2010 as reported by Norton and others (2014).

In contrast to the Fort Peck Lake watershed, projected peak snowpack for 2012–99 for the lower Lake Sakakawea watershed indicates no trends in regressed peak snowpack computed on the basis of CCSM3 and CCSM4 output (fig. 14); however, the variance of projected peak snowpack as computed from CCSM3 output increased substantially, which resulted in projections for the later part of the time series that were outside of the observed range (fig. 14). During the 88-year period 2012–99, 2 and 0 percent of years had peak snowpack less than the minimum observed for 1992–2011 for CCSM3 and CCSM4, respectively. The contrast of the two watersheds reflects the differences in regressor variables in the respective transfer functions. Downward trends in peak snowpack would be associated with upward trends in air temperature regressor variables (fig. 15). The transfer function for the Fort Peck Lake watershed includes two regressor variables for air temperature compared to one regressor variable for air temperature for the lower Lake Sakakawea watershed transfer function (table 8). Coefficients for air temperature regressors are also larger for the Fort Peck Lake watershed transfer functions than in the lower Lake Sakakawea transfer function (table 8). In summary, peak snowpack in the Fort Peck Lake watershed could be hypothesized to be more sensitive to air temperature than in the lower Lake Sakakawea watershed. This may reflect the lower elevations of SNOTEL stations in the Fort Peck Lake watershed, which would be associated with higher air temperatures that could affect snowpack.

Calibration of statistical models, such as the transfer functions used herein, generally assume that regressed variables will be computed on the basis of regressor variables within the range used for calibration. As previously described, projected peak snowpack had a trend for the Fort Peck Lake watershed that resulted in peak snowpack outside of the range observed for 1992–2011. The CCSM3 and CCSM4 regressor variables that represent seasonal air temperature were analyzed by summing the number of years in a moving 10-year window that were outside of the range used for calibration (table 11). In general for both watersheds, regressor variables that represent seasonal air temperature had on average 5 to 6 years within moving 10-year windows that were outside of bounds used for calibration by runoff year 2060 and increasing in subsequent years. In the final 10 years (2090–99), on average 9 years were outside the range used for calibration; therefore, regressed peak snowpack for 2060–99 would have less certainty than for preceding years. This uncertainty will also hold for projections of May–July runoff for 2060–99 that are described in the "May–July Runoff" section. Trends for these periods might remain of value, but actual values of peak snowpack or May–July runoff would be less certain.

Modern (1992–2011) and Projected (2012–99) May–July Runoff

The May–July runoff transfer functions (models) for the Fort Peck Lake and lower Lake Sakakawea watersheds were calibrated for runoff years 1992–2011. All dates included in this section are for runoff years. The calibrated models (transfer functions) then were used to estimate modern (1992–2011) and projected (2012–99) May–July runoff for the watersheds. The projected May-July runoff was used to project power generation at Fort Peck and Garrison Dams for the period 2012–99 and to determine whether projected runoff would be on the order of magnitude as that observed in 2011.

Model Calibration

The transfer function for May–July runoff was calibrated using multivariate linear regression and stepwise techniques, similar to the methodology described for peak snowpack, for 1992–2011. The methodology differs in that a logarithmic transformation was applied to May–July runoff. This transformation restricts regressed May–July runoff to values greater than zero. Regressor variables used for calibration, validation, and projection include those used for peak snowpack with the addition of peak snowpack and seasonal evapotranspiration for elevation zones. The model was calibrated using bootstrapped peak snowpack (from SNOTEL station records) as a regressor variable. Bootstrap methods were used to increase the number of records for calibration and validation by excluding stations listed in table 3 as described in the "Approach and Methods" section; however, May–July runoff records could not be bootstrapped for calibration and validation because May–July

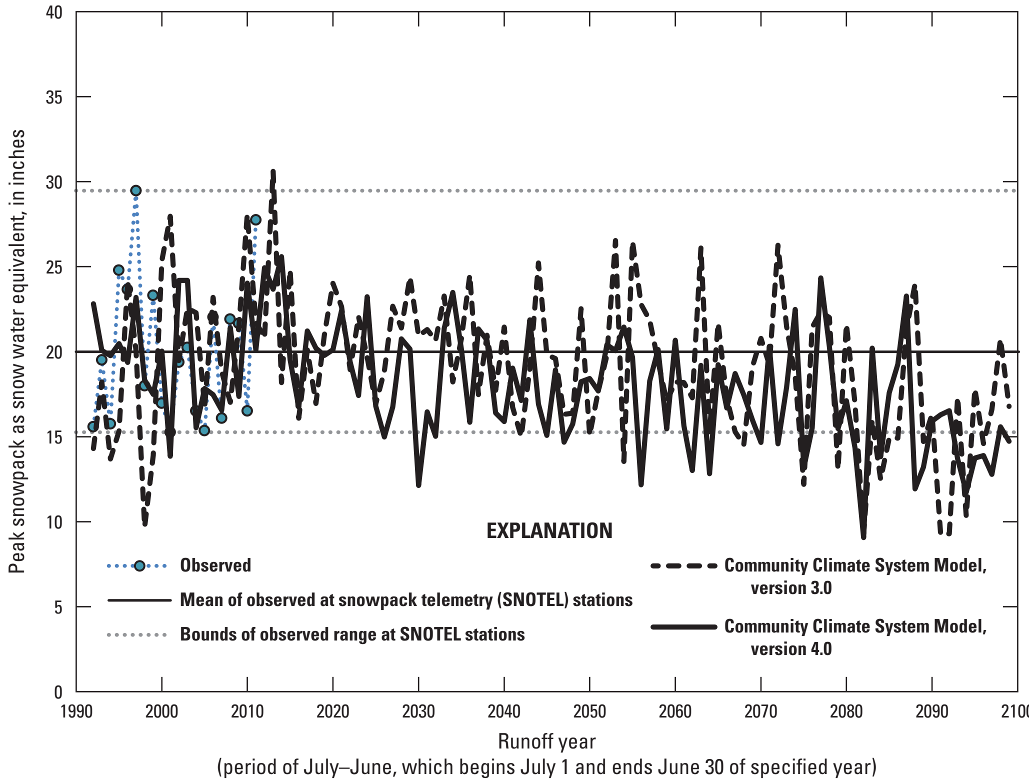

Figure 13. Projections of peak snowpack for runoff years 1992–2099 for the Fort Peck Lake watershed. The Community Climate System Model, version 3.0 assumes the A2 emission scenario and version 4.0 assumes representative concentration pathway 8.5.

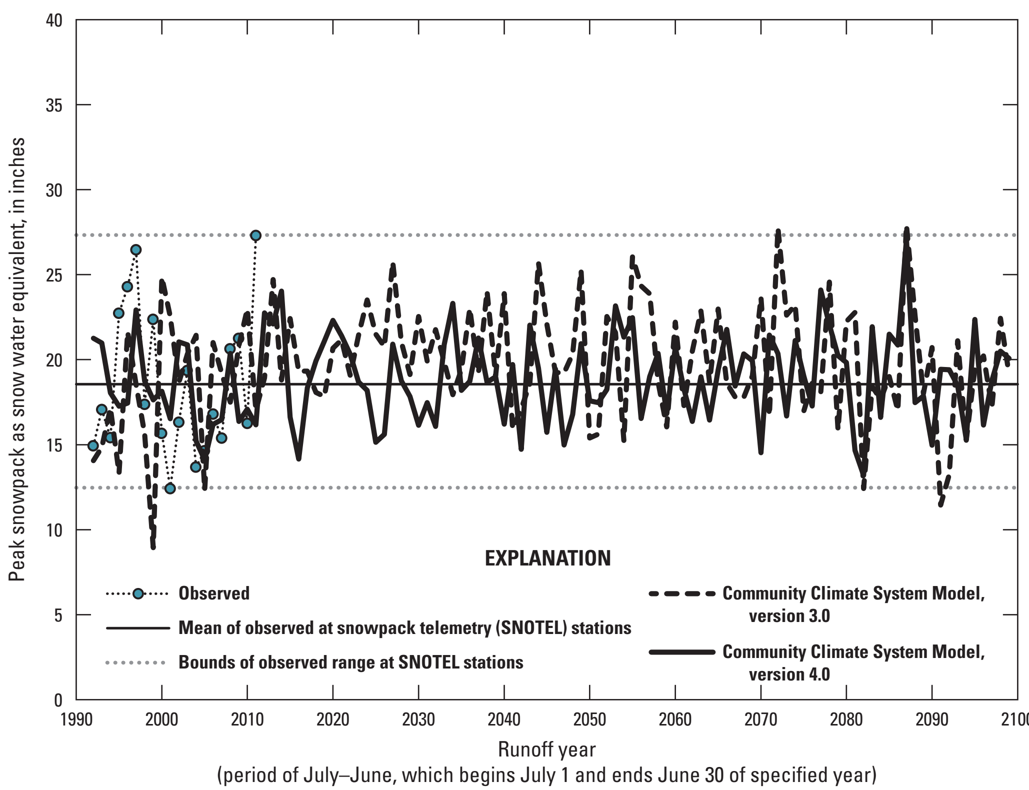

Figure 14. Projections of peak snowpack for runoff years 1992–2099 for the lower Lake Sakakawea watershed. The Community Climate System Model, version 3.0 assumes the A2 emission scenario and version 4.0 assumes representative concentration pathway 8.5.

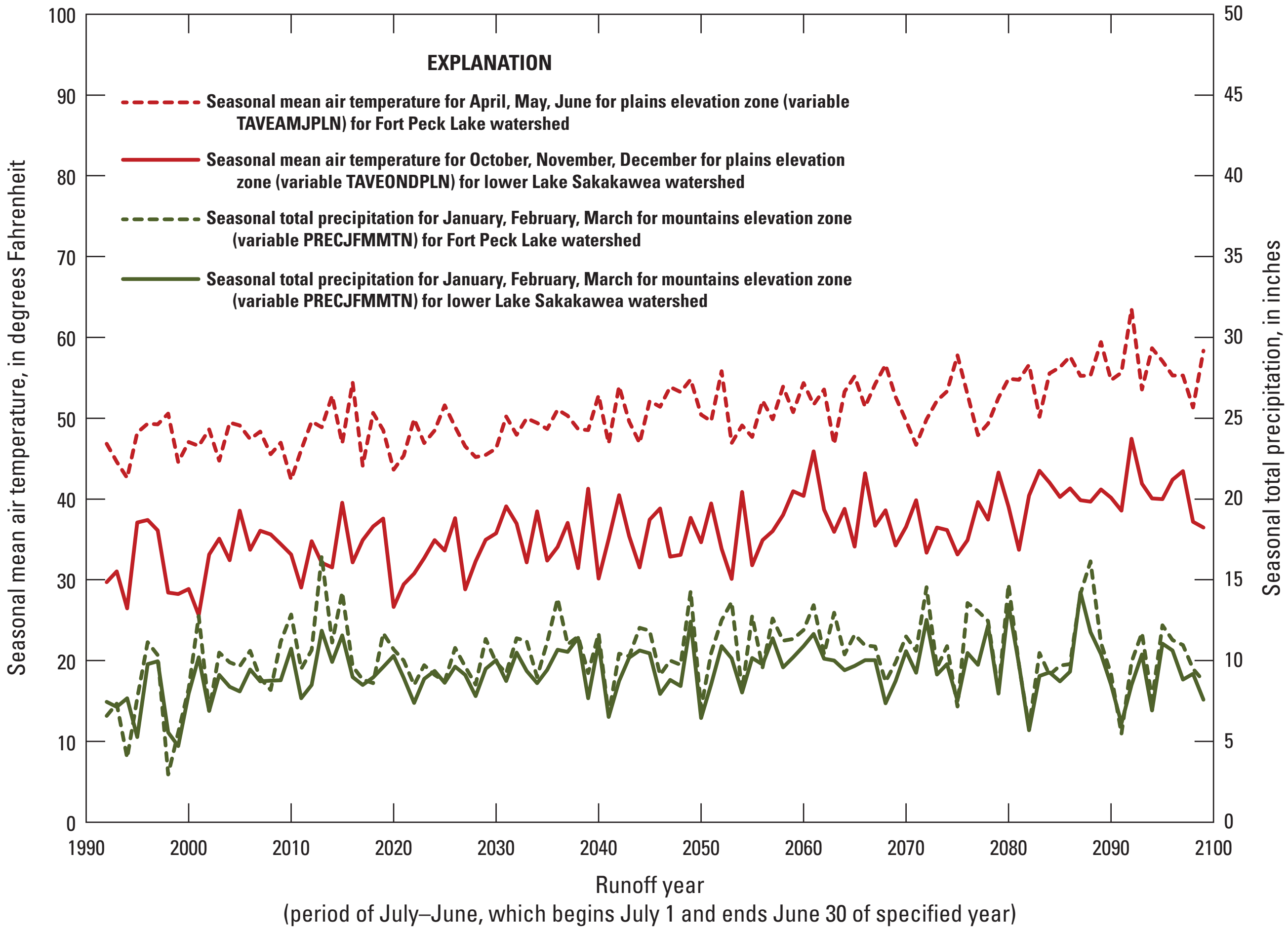

Figure 15. Projected regressor variables for air temperature and precipitation for the plains elevation zone and mountains elevation zones for selected seasons.

runoff is computed on the basis of records at a single station. Projections of May–July runoff included projected peak snowpack as a regressor variable.

Stepwise regression selected 29 and 26 regressor variables, out of 37 available (table 2), for the Fort Peck Lake and lower Lake Sakakawea watershed transfer functions, respectively. The incremental change in multiple R^2 with addition of variables was used to reduce the number of variables computed by stepwise regression to five for the Fort Peck Lake watershed and to four for the lower Lake Sakakawea watershed (table 12). The change in multiple R^2 values with the addition of regressor variables is shown in figure 16, and the resulting transfer function had multiple R^2 values of 0.94 and 0.95 for the Fort Peck Lake and lower Lake Sakakawea watersheds, respectively. Regressor variables and associated coefficients for the transfer functions for both watersheds have the following common regressors:

- peak snowpack,
- precipitation in AMJ for the plains elevation range, and
- reference evapotranspiration for JAS for the foothills.

In summary, peak snowpack in the mountains was an important regressor variable, but regressor variables for the plains and foothill zones were also important. In particular, precipitation in the later part of the runoff season (AMJ) was an important regressor variable.

Modern (1992–2011) May–July Runoff

May–July runoff for the Fort Peck Lake and lower Lake Sakakawea watersheds, and the Lake Sakakawea watershed (both watersheds combined), was computed for runoff years 1992–2011 using calibration and validation regressor variables computed from HCN and SNOTEL station records (figs. 17–19). Plots of relations between computed May–July runoff and observed May–July runoff show a close correspondence for predictions computed on the basis of both calibration and validation datasets (figs. 20 and 21, respectively) for the Fort Peck Lake and lower Lake Sakakawea watersheds; however, the May–July runoff for the lower Lake Sakakawea watershed was slightly overestimated on the order of about 5 percent by the transfer function. Means of computed and

Table 11. Mean number of years within a 10-year moving window, rounded off to the nearest integer, for which regressor variables representing air temperature and precipitation were outside of the range used for calibration of transfer functions.

[A runoff year is the period July–June (begins July 1 and ends June 30 of specified year). Air temperature regressors are means for April, May, June, and for October, November, December for the plains elevation zone. Precipitation regressors are means for January, February, March, and for October, November, December for the foothills and mountains elevation zones. CCSM3, Community Climate System Model, version 3.0; CCSM4, Community Climate System Model, version 4.0]

10-year window ending in runoff year	Air-temperature regressors				Precipitation regressors			
	Fort Peck Lake watershed		Lower Lake Sakakawea watershed		Fort Peck Lake watershed		Lower Lake Sakakawea watershed	
	CCSM3	CCSM4	CCSM3	CCSM4	CCSM3	CCSM4	CCSM3	CCSM4
2021	4	2	3	2	2	1	0	0
2022	2	2	3	2	2	0	0	0
2023	2	2	3	2	1	0	0	0
2024	2	2	2	2	1	0	0	0
2025	2	1	2	2	1	0	0	0
2026	2	1	2	2	1	0	0	0
2027	2	2	2	2	1	0	0	0
2028	2	2	2	2	1	0	0	0
2029	2	2	2	2	1	0	0	0
2030	1	1	1	2	1	0	0	0
2031	2	2	2	2	1	0	0	0
2032	2	2	2	2	1	1	0	0
2033	2	2	2	2	1	1	0	0
2034	2	2	2	1	1	1	0	0
2035	2	2	2	1	1	1	0	0
2036	2	2	2	1	2	1	0	0
2037	2	2	3	1	2	1	0	0
2038	2	2	3	1	2	1	0	0
2039	2	2	3	2	2	1	0	0
2040	2	2	4	1	2	1	0	0
2041	2	1	3	1	2	1	0	0
2042	2	1	4	1	2	1	0	0
2043	2	1	4	1	2	1	0	0
2044	2	1	4	1	2	1	0	0
2045	2	1	4	1	3	1	0	0
2046	2	2	4	1	2	1	0	0
2047	3	2	4	1	2	1	0	0
2048	4	3	5	2	2	1	0	0
2049	4	3	5	2	2	1	1	0
2050	4	3	5	2	2	1	1	0
2051	4	3	5	3	2	1	1	0
2052	4	3	5	2	2	1	1	0
2053	4	3	4	3	3	0	1	0
2054	4	4	5	4	2	1	1	0
2055	4	4	4	4	2	1	1	0
2056	4	4	4	5	3	1	1	0
2057	3	4	4	5	3	1	1	0
2058	3	3	4	4	3	1	1	0

Table 11. Mean number of years within a 10-year moving window, rounded off to the nearest integer, for which regressor variables representing air temperature and precipitation were outside of the range used for calibration of transfer functions.—Continued

10-year window ending in runoff year	Air-temperature regressors				Precipitation regressors			
	Fort Peck Lake watershed		Lower Lake Sakakawea watershed		Fort Peck Lake watershed		Lower Lake Sakakawea watershed	
	CCSM3	CCSM4	CCSM3	CCSM4	CCSM3	CCSM4	CCSM3	CCSM4
2059	3	4	4	5	3	1	1	0
2060	4	5	5	6	4	1	1	0
2061	4	5	5	5	4	1	1	0
2062	5	6	5	6	4	1	1	0
2063	5	6	5	6	4	1	1	0
2064	6	7	5	5	4	1	1	0
2065	6	7	6	5	4	1	1	0
2066	7	7	6	6	3	1	1	0
2067	7	8	7	6	3	1	1	0
2068	8	9	7	7	3	1	1	0
2069	8	8	6	6	2	1	1	0
2070	7	8	5	6	2	1	1	0
2071	7	8	5	6	2	1	0	0
2072	7	7	5	6	2	1	1	0
2073	7	7	5	6	2	1	1	0
2074	6	6	5	6	2	2	1	0
2075	6	6	5	6	1	1	1	0
2076	6	6	5	5	2	1	1	0
2077	6	6	5	6	2	2	1	1
2078	6	6	4	6	3	2	1	1
2079	6	6	5	6	3	2	1	1
2080	6	6	6	7	3	2	2	1
2081	6	6	6	6	3	1	2	1
2082	7	6	6	7	2	2	1	1
2083	7	7	7	7	2	2	1	1
2084	7	8	7	8	2	2	1	1
2085	7	8	8	9	2	2	1	1
2086	8	9	8	9	2	2	1	1
2087	8	9	9	9	2	2	2	1
2088	8	9	10	10	2	2	1	1
2089	8	9	10	10	2	2	1	1
2090	9	10	10	10	1	2	1	1
2091	8	10	10	10	1	2	1	1
2092	8	10	10	10	1	1	1	1
2093	9	10	10	10	2	1	1	1
2094	9	10	10	10	2	1	1	1
2095	9	10	10	10	2	1	1	1
2096	9	10	10	10	2	1	1	1
2097	9	10	10	10	2	0	0	1
2098	9	9	9	9	1	0	0	1
2099	9	9	9	9	1	0	0	1

Table 12. Coefficients of May–July runoff transfer functions for the Fort Peck Lake and lower Lake Sakakawea watersheds.

[All variables were significant at the 0.001 probability. --, not applicable]

Fort Peck Lake watershed		Lower Lake Sakakawea watershed	
Regression equation intercept = 3.086		Regression equation intercept = 3.953	
Variable[a,b]	Coefficient	Variable[a,b]	Coefficient
PEAKSWE	0.029	PEAKSWE	0.030
PRECAMJPLN	0.061	PRECAMJPLN	0.053
EVAPJASFTH	-0.053	TAVEAMJPLN	-0.018
PRECONDPLN	0.030	EVAPJASFTH	-0.011
EVAPONDPLN	-0.082	--	--

[a]Variable names are expressed in captial letters using Courier type font.

[b]These variable names are composed of letter combinations designating various abbreviations as defined in table 2. Abbreviations applicable to the variables in this table follow: PEAKSWE, Peak snowpack, as snow water equivalent, in inches; PREC, total precipitation; EVAP, total reference evaporation; TAVE, mean temperature; AMJ, April, May, June; JAS, July, August, September; OND, October, November, December; AMJ, April, May, June; PLN, plains elevation zone; FTH, foothills elevation zone.

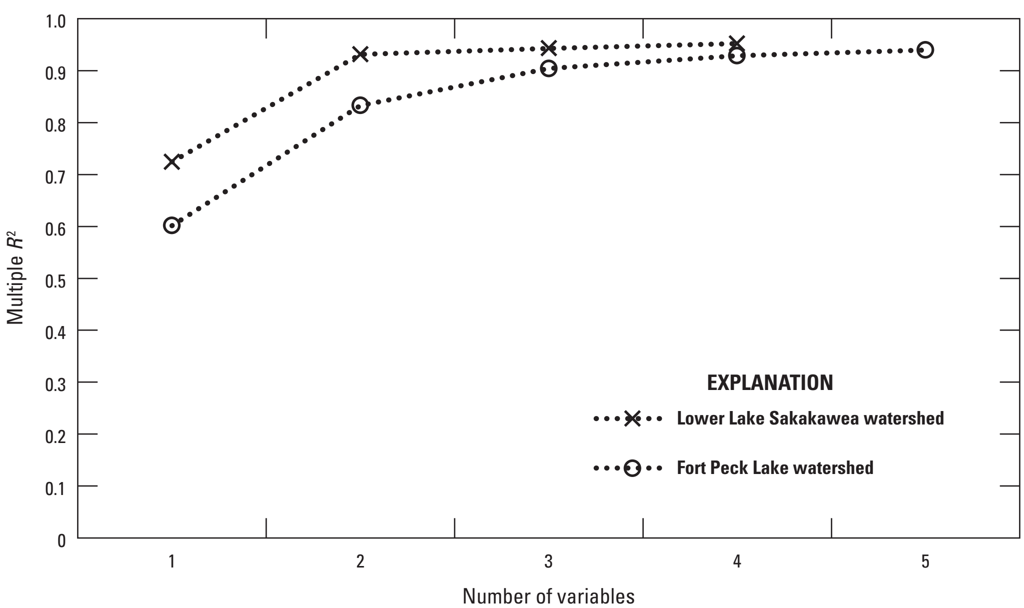

Figure 16. Incremental increase in multiple coefficient of determination (R^2) values with addition of regressor variables in table 12.

observed May–July runoff were not significantly different on the basis of a paired Student's t-test on the calibration and validation datasets (table 13).

May–July runoff also was computed for 1992–2011 using regressor variables computed from CCSM3 and CCSM4 output for all watersheds (figs. 22–24). As previously described, regressed mean May–July runoff for 1992–2011 computed on the basis of CCSM3 and CCSM4 will not precisely match that observed for each year, but the goal is to match the observed hydroclimatology. Student's t-test indicate no significant difference at a 0.05 probability between means of observed May–July runoff and regressed May–July runoff from CCSM3 and CCSM4 output for both watersheds, and of combined May–July runoff for both watersheds (table 13). May–July runoff for 1992–2011 computed from CCSM3 output generally falls within the range of that observed (figs. 22–24), but minimum values have a negative bias (lower than observed), and the standard deviation for CCSM3 output for the Fort Peck Lake watershed is greater than that observed (table 14). May–July runoff for 1992–2011 computed from CCSM4 output falls within the range of that observed (figs. 22–24); however, the standard deviation for CCSM4 output is less than that observed (table 14). For these reasons, it might be expected that May–July runoff projected for 2012–99 from CCSM4 output might be more conservatively estimated than that from CCSM3 output particularly for simulation years with lower projected flows.

Projected (2012–99) May–July Runoff

May–July runoff was projected for 2012–99 by applying the transfer function to regressor variables computed from CCSM3 and CCSM4 output. Trends for 2012–99 were tested for significance using the Kendall's tau nonparametric test (Kendall, 1938) at a 0.05 probability. Projected May–July runoff for 2012–99 for the Fort Peck Lake, lower Lake Sakakawea, and Lake Sakakawea (combined watersheds of Fort Peck Lake and lower Lake Sakakawea) watersheds indicates significant downward trends as regressed from CCSM3 and CCSM4 output; however, in contrast, when the time series is limited to 2012–60, no trends in May–July runoff were significant for the three watersheds. Variance in May–July runoff for 2012–99 for the Fort Peck watershed and the Lake Sakakawea watershed (combined watersheds) significantly decreased as regressed from CCSM4 output computed on the basis of the Breusch-Pagan test (Breusch and Pagan, 1979). There were no significant changes in variance when analyses were limited to 2012–60.

Trends in projected May–July runoff for 2012–99 for the Fort Peck Lake watershed regressed from CCSM3 and CCSM4 output resulted in runoff that was less than the minimum observed particularly in records subsequent to simulation year 2060. For 2060–99 (39 years), regressed May–July runoff from CCSM3 and CCSM4 output was less than the minimum observed for 13 and 21 years, respectively. This contrasts with the 1 and 5 years that were less than the minimum May–July runoff in 2012–60 as regressed from CCSM3 and CCSM4 output, respectively; however, regressed May–July runoff for 2060–99 should be interpreted with caution; as described in the "Peak Snowpack" section, a caveat of the methodology is that regressor variables for 2060–99 commonly were outside of the range of calibration. For 2060–99, regressed runoff for the lower Lake Sakakawea watershed was less than the minimum May–July runoff observed for 11 and 8 years as regressed from CCSM3 and CCSM4 output, respectively. This contrasts with 1 year that was less than the minimum May–July runoff as regressed from CCSM3 and CCSM4 output for 2012–60.

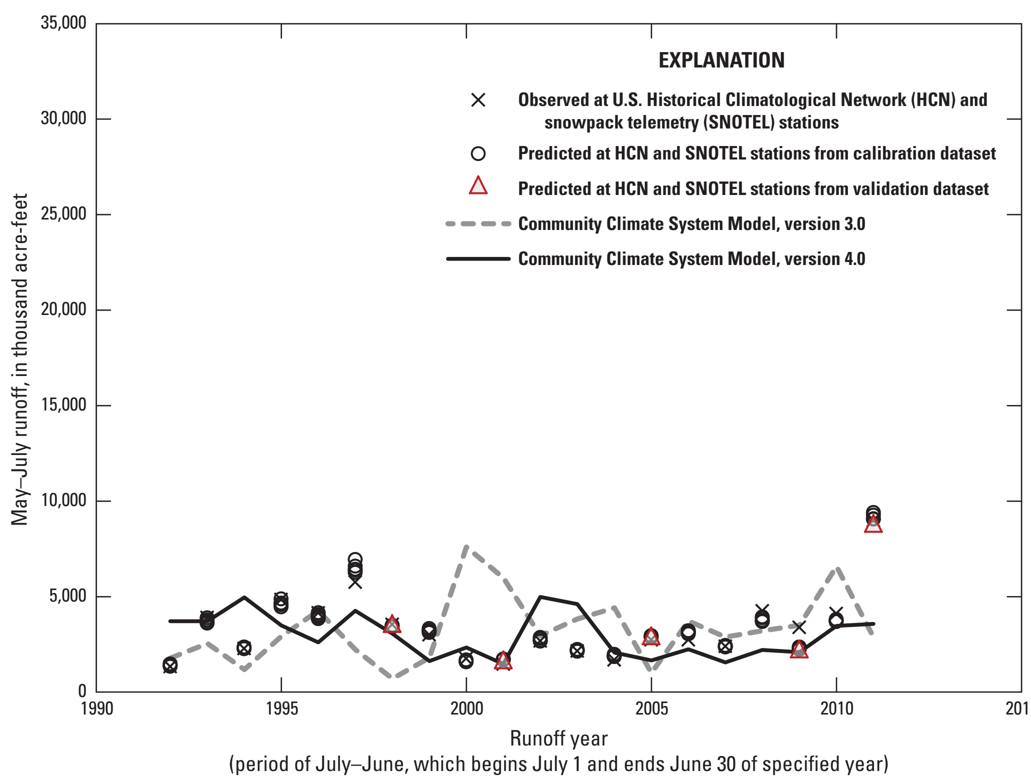

Figure 17. May–July runoff for runoff years 1992–2011 for the Fort Peck Lake watershed. Multiple calibration points for each runoff year are a product of the bootstrap method.

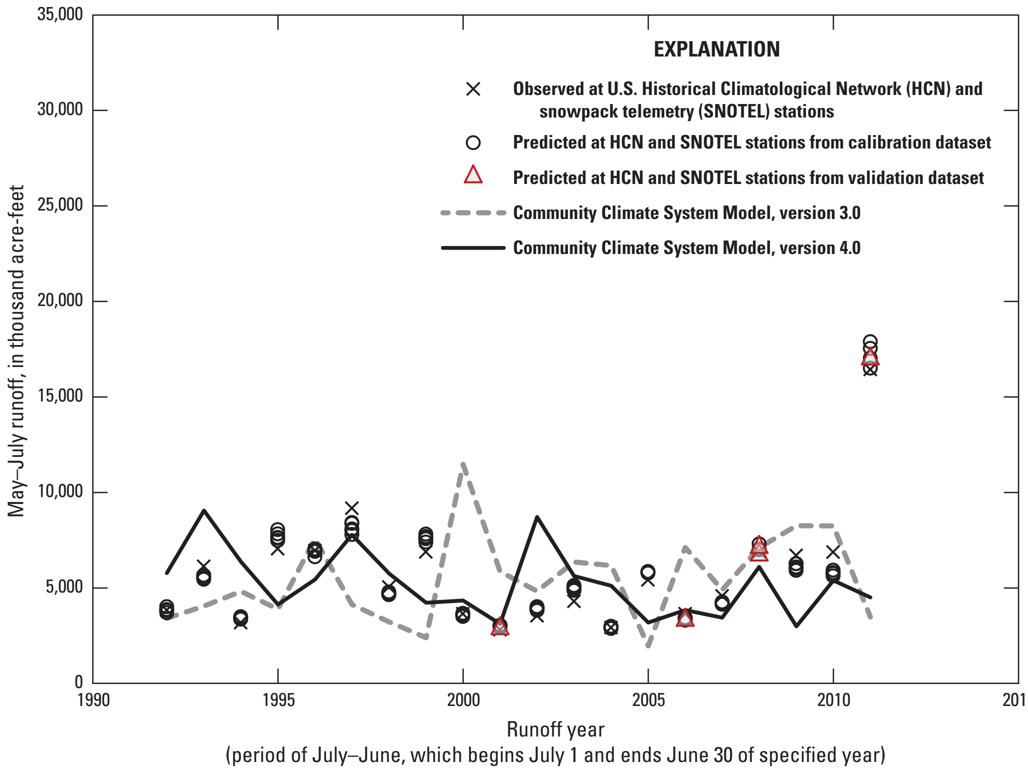

Figure 18. May–July runoff for runoff years 1992–2011 for the lower Lake Sakakawea watershed. Multiple calibration points for each runoff year are a product of the bootstrap method.

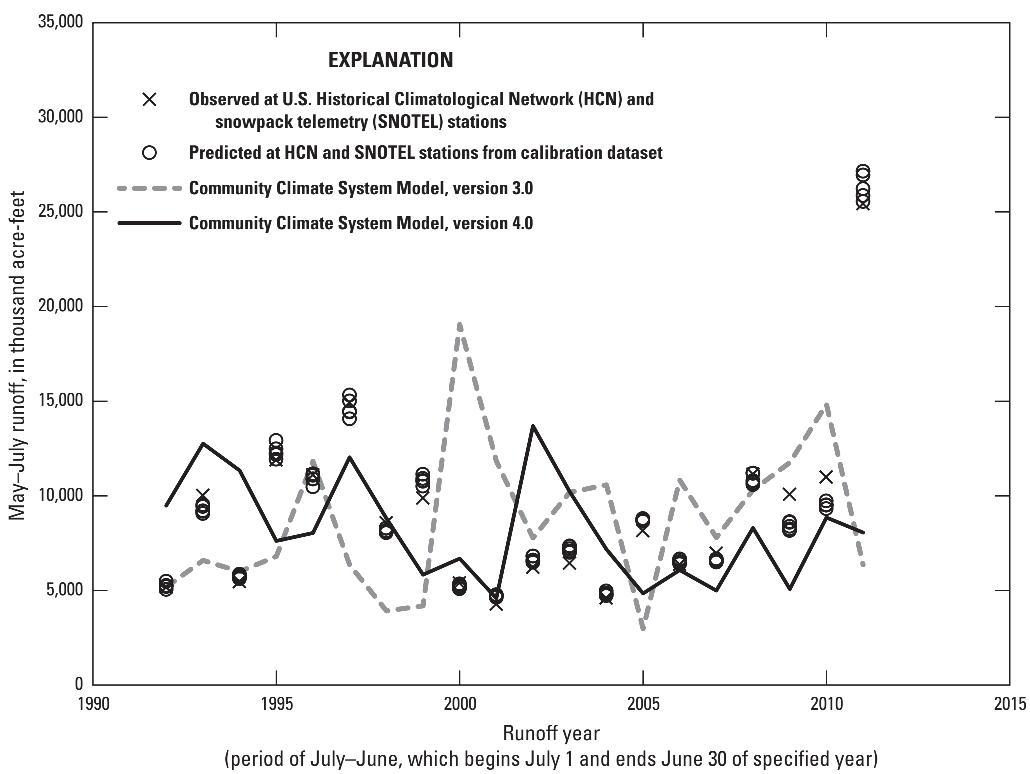

Figure 19. May–July runoff for runoff years 1992–2011 for the Lake Sakakawea watershed (Fort Peck Lake and lower Lake Sakakawea watersheds combined). Multiple calibration points for each runoff year are a product of the bootstrap method.

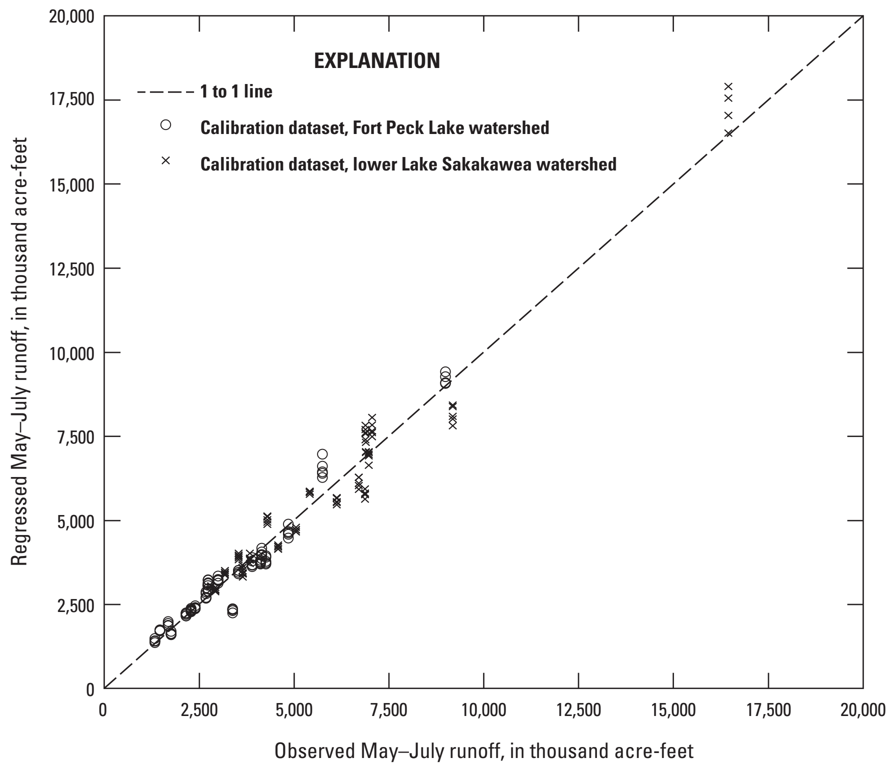

Figure 20. Relation between regressed and observed May–July runoff used for calibration, Fort Peck Lake and lower Lake Sakakawea watersheds.

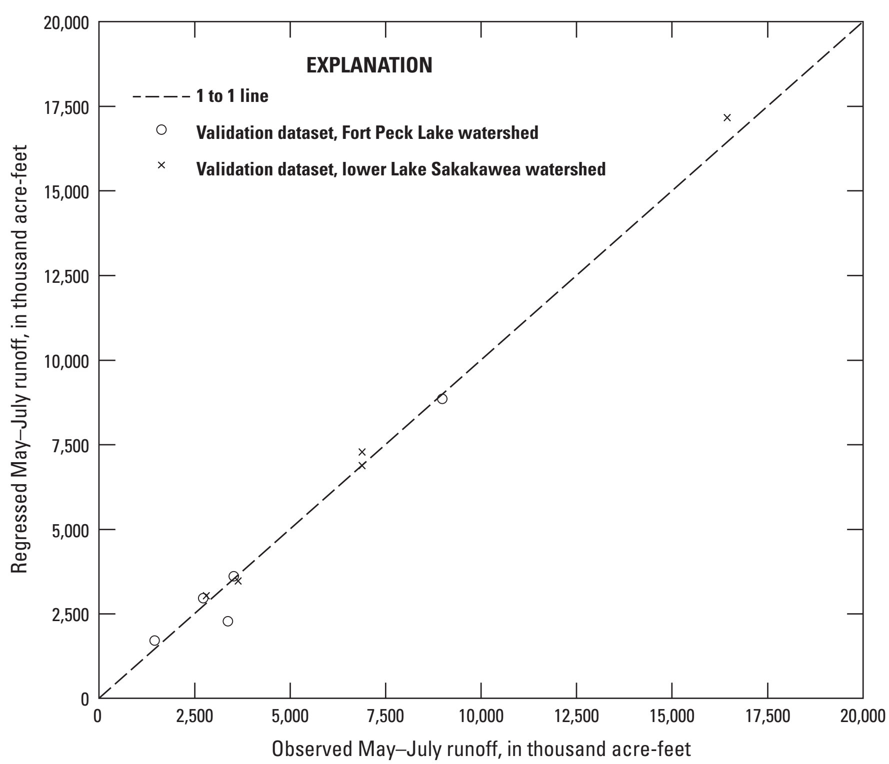

Figure 21. Relation between regressed and observed May–July runoff used for validation, Fort Peck Lake and lower Lake Sakakawea watersheds.

Table 13. Results of Student's t-tests for the null hypothesis that observed and regressed May–July runoff have equal means.

[Means were not significantly different at the 0.05 probability for all tests. Student's t-tests for validation and calibration datasets are paired, and for Community Climate System Model, versions 3 and 4, are two-tailed, and two-samples with unequal variance. CCSM3, regressed from transfer function applied to the Community Climate System Model, version 3.0 output; CCSM4, regressed from transfer function applied to the Community Climate System Model, version 4.0]

Dataset	Fort Peck Lake watershed		Lower Lake Sakakawea watershed	
	t-value	Probability	t-value	Probability
Calibration	0.192	0.848	0.152	0.880
Validation	0.656	0.548	-1.384	0.239
CCSM3	0.110	0.913	0.392	0.698
CCSM4	0.794	0.433	0.706	0.486

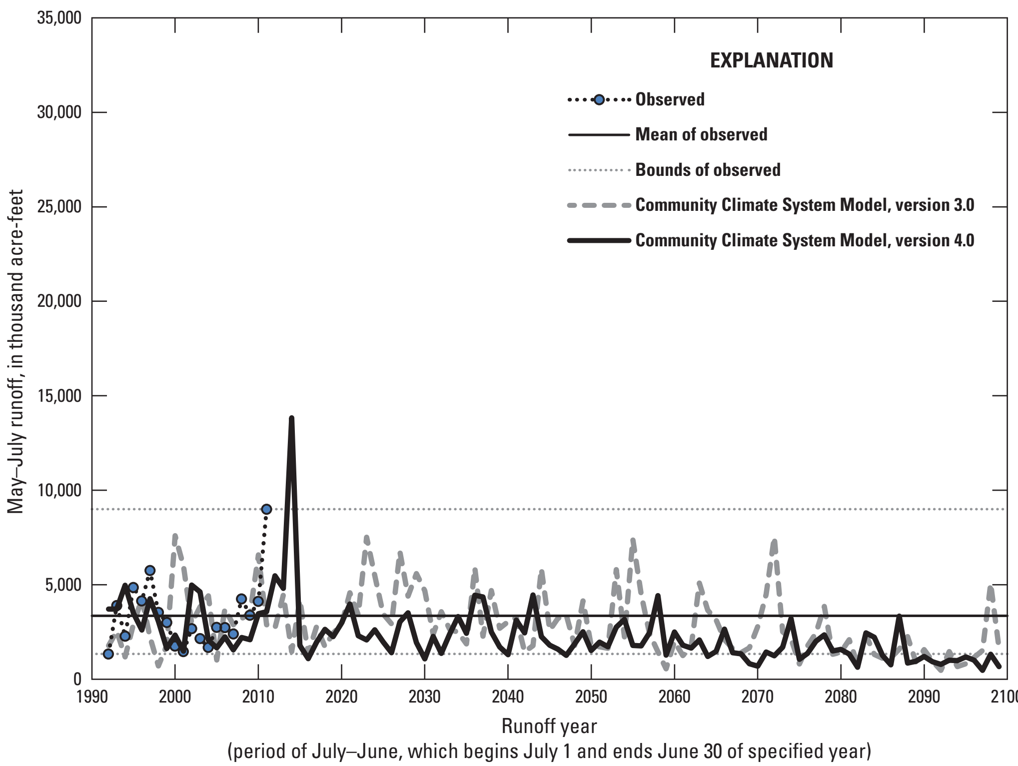

Figure 22. Projections of May–July runoff for runoff years 1992–2099 for the Fort Peck Lake watershed. The Community Climate System Model, version 3.0 assumes the A2 emission scenario and version 4.0 assumes representative concentration pathway 8.5.

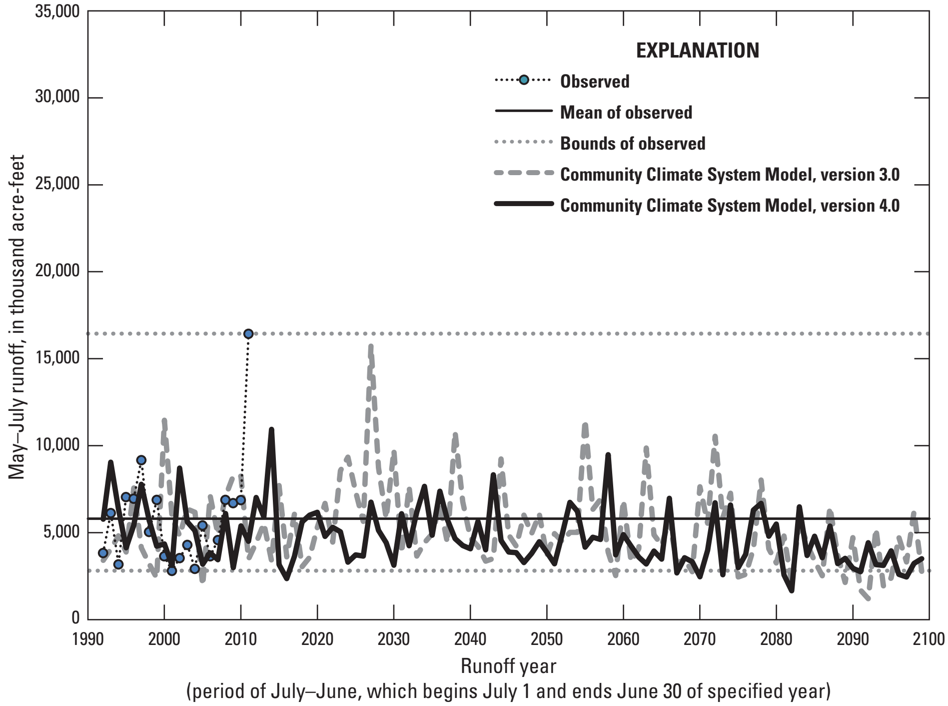

Figure 23. Projections of May–July runoff for runoff years 1992–2099 for the lower Lake Sakakawea watershed. The Community Climate System Model, version 3.0 assumes the A2 emission scenario and version 4.0 assumes representative concentration pathway 8.5.

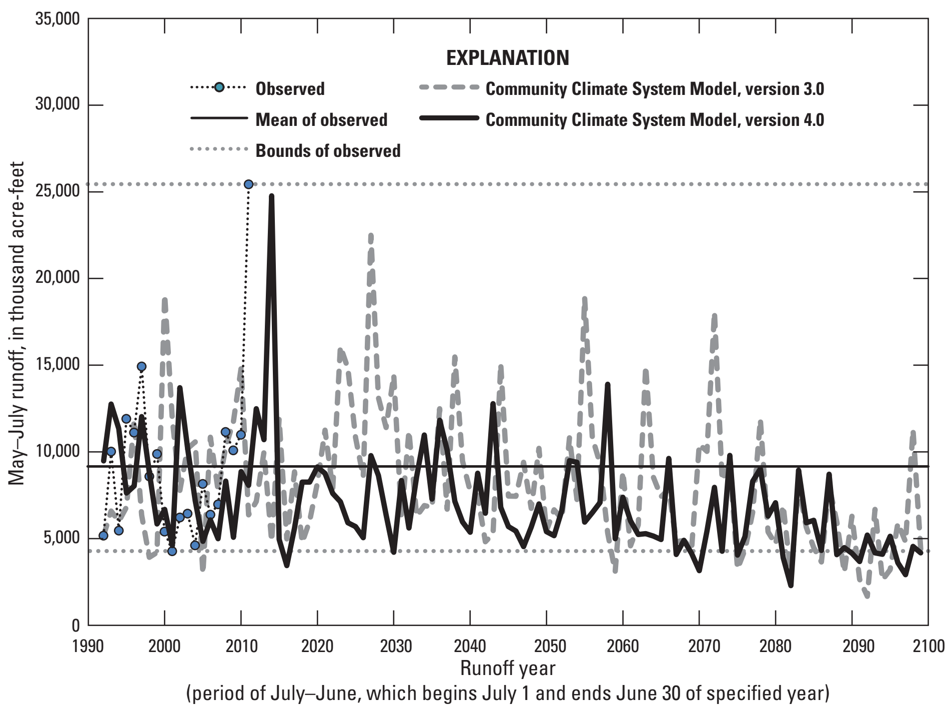

Figure 24. Projections of May–July runoff for runoff years 1992–2099 for the Lake Sakakawea watershed (Fort Peck Lake and lower Lake Sakakawea watersheds combined). The Community Climate System Model, version 3.0 assumes the A2 emission scenario and version 4.0 assumes representative concentration pathway 8.5.

Table 14. Summary statistics for observed and regressed May–July runoff for runoff years 1992–2011.

[A runoff year is the period of July–June (begins July 1 and ends June 30 of specified year). CCSM3, regressed from the Community Climate System Model, version 3.0 output; CCSM4, regressed from the Community Climate System Model, version 4.0 output]

Statistic	May–July runoff for 1992–2011, in thousand acre-feet								
	Fort Peck Lake watershed			Lower Lake Sakakawea watershed			Lake Sakakawea watershed		
	Observed	CCSM3	CCSM4	Observed	CCSM3	CCSM4	Observed	CCSM3	CCSM4
Mean	3,361	3,299	2,985	5,802	5,464	5,244	9,163	8,762	8,229
Maximum	8,999	7,596	4,982	16,441	11,467	9,055	25,440	19,062	13,698
Minimum	1,340	699	1,479	2,812	1,966	2,986	4,278	2,979	4,594
Standard deviation	1,777	1,814	1,156	3,068	2,353	1,754	4,797	3,994	2,717

Projected Power Production and Runoff Magnitudes

Fort Peck and Garrison Dams have had a mean annual discharge of 10,200 ft^3/s and 23,000 ft^3/s, respectively, available to supply reservoir water for power production. For comparison to May–July runoff, these means correspond to 7,382 and 16,645 thousand acre-ft per year for Fort Peck and Garrison Dams, respectively. Adjusting annual total runoff to that for a 91-day period results in 1,860 and 4,195 thousand acre-ft per 91 days for Fort Peck and Garrison Dams, respectively. May–July runoff would be expected to be greater than these adjusted values of runoff given that much of the annual flow occurs in this period. May–July runoff for the Fort Peck Lake watershed was projected to periodically fall below 1,840 thousand acre-ft for a total of 11 and 15 years for 2012–60 (22 and 31 percent of years), and for a total of 24 and 31 years for 2061–99 (60 and 78 percent of years), as regressed from CCSM3 and CCSM4 output, respectively; therefore, projected trends in runoff indicate power production from the Fort Peck Dam watershed might be periodically affected by low runoff in upcoming decades. The Garrison Dam, which impounds Lake Sakakawea (combined runoff from Fort Peck Lake and lower Lake Sakakawea watersheds), was projected to have mean annual discharges that fall below 23,000 ft^3/s for only 1 year for 2012–60, and 8 and 15 years (20 and 35 percent of years) for 2060–99 as regressed from CCSM3 and CCSM4 output, respectively; therefore, projected downward trends in May–July runoff are not indicated to affect power production from the Garrison Dam watershed as strongly as indicated for the Fort Peck Dam.

May–July runoff on the order of magnitude of the peak of record observed in 2011 (25,400 thousand acre-ft) were projected for the Lake Sakakawea watershed (two watersheds combined). Regressed May–July runoff for the Lake Sakakawea was projected to include one event of this magnitude as regressed from CCSM3 output (22,500 thousand acre-ft in simulation year 2027) and one event of this magnitude as regressed from CCSM4 output (24,800 thousand acre-ft in simulation year 2014) (fig. 24). These events will be referred to as event 1 and event 2, respectively. It is important to clarify that these results do not predict events of this magnitude in these actual calendar years. Event 1 was a product of high May–July runoff from the Fort Peck Lake watershed, whereas event 2 was a product of high May–July runoff from the lower Lake Sakakawea watershed. Both simulation years with these events have high peak snowpack and high precipitation in AMJ for the plains elevation zone (figs. 25 and 26), which are the two regressors with strongest loadings in the transfer functions. An event of the magnitude of the 2011 observed event was due to regressors that reflected high peak snowpack in the mountains followed by a season of high precipitation in the plains; therefore, plains precipitation (which might fall as snow in AMJ) is indicated to be an important factor in large runoff events.

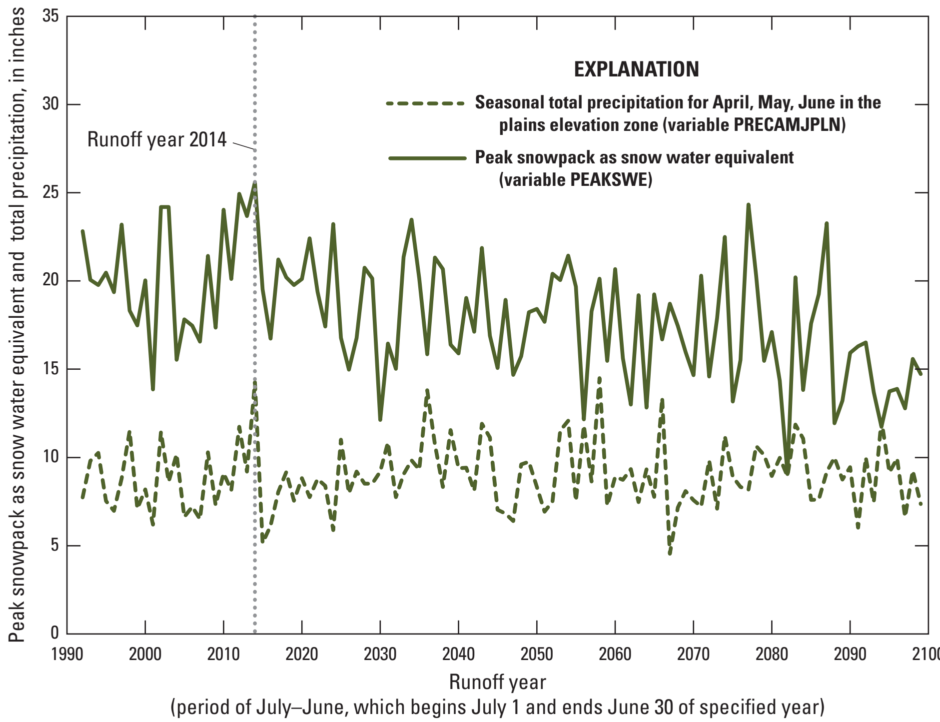

Figure 25. April, May, June precipitation for the plains elevation zone and peak snowpack in the Fort Peck Lake watershed (Fort Peck Lake and lower Lake Sakakawea watersheds combined) as interpolated from Community Climate System Model, version 4.0 output.

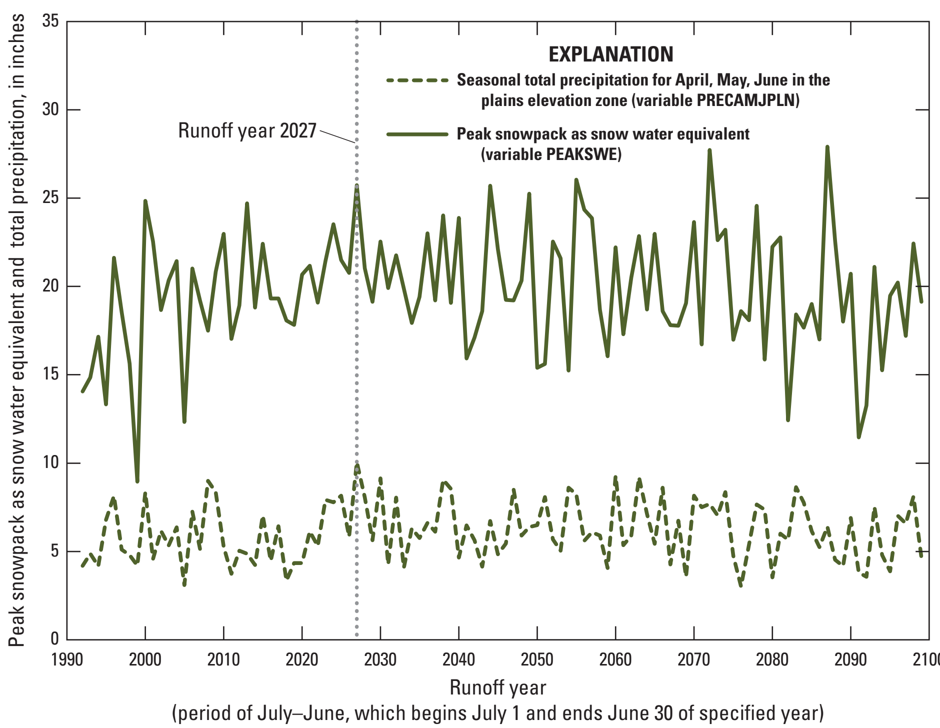

Figure 26. April, May, June precipitation for the plains elevation zone and peak snowpack in the lower Lake Sakakawea watershed as interpolated from Community Climate System Model, version 3.0 output.

Summary

Mountain snowpack is an important contributor to runoff in the Upper Missouri River Basin; for example, high amounts of winter and spring precipitation in the mountains and plains in 2010–2011 were associated with the peak runoff of record in the Upper Missouri River Basin. The U.S. Army Corps of Engineers completed a pilot research study in collaboration with the U.S. Geological Survey, National Weather Service, U.S. Department of Agriculture Natural Resources Conservation Service, and South Dakota State University to help assess if mountain snowpack and runoff was changing because of changes in climate. The U.S. Geological Survey, in cooperation with the Climate Preparedness and Resilience Community of Practice of the U.S. Army Corps of Engineers, completed a followup study to simulate modern (1992–2011) and projected (2012–99) mountain peak snowpack and May–July runoff into Fort Peck Lake and Lake Sakakawea in the upper part of the Missouri River Basin. Additional objectives of this study were to determine if May–July runoff projected for 2012–99 might produce runoff events on the magnitude of the 2011 flood, develop insights to processes associated with such events, and to determine if projected May–July runoff might drop below the magnitude required to maintain power generation at hydroelectric dams.

Simulations were based on the calibration of transfer functions using multiple linear regression and stepwise regression techniques. Regressor (explanatory) variables represented seasonal air temperature and precipitation. Regressor variables for May–July runoff also included peak snowpack and seasonal total reference evapotranspiration. The calibration period was 1992–2011 because of the limitations of available records from 107 weather stations. Two watersheds were considered: (1) the Fort Peck Lake watershed and (2) the lower Lake Sakakawea watershed, which was defined as the part of the Lake Sakakawea watershed below Fort Peck Dam. Peak snowpack and May–July runoff were projected for 2012–99 on the basis of air temperature and precipitation interpolated from output from Community Climate System Model, version 3.0 (CCSM3) and version 4.0 (CCSM4) to the locations of weather and snow telemetry stations, and bias corrected to station monthly means.

Projected peak snowpack for 2012–99 for the Fort Peck Lake watershed indicated significant downward trends in regressed peak snowpack computed on the basis of CCSM3 and CCSM4 output. In contrast, projected peak snowpack for 2012–99 for the lower Lake Sakakawea watershed indicated no trends in regressed peak snowpack computed on the basis of CCSM3 and CCSM4 output. Projected May–July runoff for 2012–99 for the Fort Peck Lake, lower Lake Sakakawea, and Lake Sakakawea (combined watersheds of Fork Peck Lake and lower Lake Sakakawea) watersheds regressed on the basis of CCSM3 and CCSM4 output had significant downward trends for 2012–99; however, when time series were limited to 2012–60, trends were not significant.

Projected trends in runoff indicate power production from the Fort Peck Dam might be periodically affected by low runoff in upcoming decades. Regressed May–July runoff for 2012–99 for the two watersheds combined (Lake Sakakawea watershed) was projected to have events of the magnitude of the observed flood of 2011: 24,800 thousand acre-feet in simulation year 2014 based on CCSM4 output, and 22,500 thousand acre-feet in simulation year 2027 based on CCSM3 output. Analysis of regressor variables indicated that high peak snowpack and high precipitation for AMJ in the foothills combined in these simulation years to produce peaks in either the Fort Peck Lake watershed or lower Lake Sakakawea watershed, which translated into peak runoff on the order of magnitude of the 2011 flood for the Lake Sakakawea watershed (combined watersheds). A caveat of the statistical approach used for this study was that simulations for 2060–99 are commonly based on regressor variables that fall outside of the range used for calibration; therefore, results for 2060–99 were interpreted with caution.

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Appendixes

Appendix 1. Air Temperature and Precipitation at Stations

This appendix contains links to digital data tables in text format (.txt) of monthly mean air temperature and total precipitation, and daily snow water equivalent (SWE) at the locations of U.S. Historical Climatology Network (HCN) and snowpack telemetry (SNOTEL) stations used in analyses in this report (see "Approach and Methods" section, table 1). The file "*HCN_SNOTEL_data.zip*" contains compressed files in two directories. The first directory is named "Daily" and contains daily SNOTEL data. The second directory is named "Monthly" and contains monthly means of daily mean air temperature and monthly precipitation at HCN and SNOTEL stations. Files named "*README.txt*" are in directories and provide additional information on file names and data formats.

Appendix 2. Community Climate System Model Output

This appendix describes the Community Climate System Model, version 3.0 (CCSM3) and version 4.0 (CCSM4) that were accessed for this study through the Earth System Grid data portal (https://www.earthsystemgrid.org/home.htm). The postprocessed atmospheric data for contemporary climate simulated by CCSM3 are available at
https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm.b30.030e.html
and for projected climate are available at
https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm.b30.042e.html.
Daily precipitation files accessed from these websites include the following:

- "*b30.030e.cam2.h3.PRECC.1990-01-01_cat_1999-12-31.nc*,"
- "*b30.030e.cam2.h3.PRECL.1990-01-01_cat_1999-12-31.nc*,"
- "*b30.042e.cam2.h3.PRECC.2000-01-01_cat_2009-12-31.nc,*" and
- "*b30.042e.cam2.h3.PRECL.2000-01-01_cat_2009-12-31.nc*."

Output files for monthly mean air temperature are a set of files, one for each decade, starting sequentially from 1990–99 for air temperature with example file names formats as follows:

- "*b30.030e.cam2.h0.TREFMNAV.1990-01_cat_1999-12.nc*,"
- "*b30.030e.cam2.h0.TREFMXAV.1990-01_cat_1999-12.nc,*" and
- "*b30.030e.cam2.h0.TREFMAV.1990-01_cat_1999-12.nc*."

Associated output files for projected air temperature have example filename formats (starting with the decade 2000–09 and ending with decade 2090–99):

- "*b30.042e.cam2.h0.TREFMNAV.2000-01_cat_2009-12.nc*," and
- "*b30.042e.cam2.h0.TREFMXAV.2000-01_cat_2009-12.nc*."

File names starting with "b30" indicate the CCSM3, the "042" indicates the A2 emissions scenario, and "cam2" indicates the Community Atmosphere Model output (as opposed to the ocean model part the CCSM3.) The variables PRECC and PRECL indicate convective precipitation and frontal (large-scale) precipitation, respectively; TREF is temperature at a 2-meter (6.6-ft) reference height; and MNAV and MXAV are the monthly means of daily minimum and maximum air temperature, respectively. The suffix "nc" refers to Network Common Data Form file format, which is supported by the University Corporation for Atmospheric Research (http://www.unidata.ucar.edu/software/netcdf).

The postprocessed atmospheric data for contemporary climate simulated by CCSM3 are available at
https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.b40.20th.track1.1deg.009.html
and for projected climate are available at
https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.b40.rcp8_5.1deg.002.html.

The CCSM4 output files of daily precipitation and monthly air temperature files accessed include the following:

- *"b40.20th.track1.1deg.009.cam2.h1.PRECC.185010101-20051231.nc*,"
- *"b40.20th.track1.1deg.009.cam2.h1.PRECL.185010101-20051231.nc*,"
- *"b40.20th.track1.1deg.009.cam2.h0.TREFMNAV.185001-200512.nc*,"
- *"b40.20th.track1.1deg.009.cam2.h0.TREFMXAV.185001-200512.nc*,"
- *"b40.rcp8_5.1deg.002.cam2.h1.PRECC.18500101-20051231.nc*,"
- *"b40.rcp8_5.1deg.002.cam2.h1.PRECL.18500101-20051231.nc*,"
- *"b40.rcp8_5.1deg.002.cam2.h0.TREFMNAV.18500101-20051231.nc*," and
- *"b40.rcp8_5.1deg.002.cam2.h0.TREFMXAV.18500101-20051231.nc*."

File names starting with "b40" indicate the CCSM4, "20th" indicates the 20th century, but includes 1850–2005, and "rcp8_5" is representative concentration pathway 8.5 watts per meter squared. File names are otherwise labelled similarly to CCSM3 file names.

Appendix 3: Interpolated Community Climate System Model Output

The Community Climate System Model, version 3.0 (CCSM3) and version 4.0 (CCSM4) output were interpolated to the location of U.S. Historical Climatology Network (HCN) and snowpack telemetry (SNOTEL) stations used in this study (see "Approach and Methods" section, table 1). The interpolation equation was a function of the inverse distance squared of a station to the surrounding four CCSM grid points. The file "interpolated_CCSM_output.zip" contains compressed files of interpolated CCSM3 and CCSM4 output. The file "README.txt" is in the archived directory and provides additional information on file names and formats used.

Appendix 4: Bias-Corrected Community Climate System Model Output

The Community Climate System Model, version 3.0 (CCSM3) and version 4.0 (CCSM4) output were bias corrected on the basis of U.S. Historical Climatology Network (HCN) and snowpack telemetry (SNOTEL) station records used in this study (see "Approach and Methods" section, table 1). The file "bias_corrected_CCSM_output.zip" contains compressed files of bias corrected CCSM3 and CCSM4 output. The file "README.txt" is in the archived directory and provides addition information on file names and formats used.

Appendix 5. R and Python Scripts

This supplemental section contains links to scripts written in Python Notebook and the R statistical program that were used in data analyses. Data analyses include computation of reference evapotranspiration; calibration, validation, and projections of the transfer functions for peak snowpack and May–July runoff; and Kendall's tau trend analyses.

The file "reference_evapotranspiration.zip*"* is a compressed set of files that contain two Python Notebook (ipynb) scripts ("*ETmon-STNS.ipynb"* and "*ETmon-CCSM.ipynb"*) and associated input and output files. The file "*README.txt"* within the folder further explains the files and data formats. The "*ETmon-STNS.ipynb"* script reads location information and climate data (air temperature) at input U.S. Historical Climate Network (HCN) and snowpack telemetry (SNOTEL) stations, and computes monthly reference evapotranspiration at station locations. Similarly, the "*ETmon-CCSM.ipynb"* script computes monthly reference evapotranspiration from CCSM output interpolated to the locations of HCN and SNOTEL stations, and bias corrected.

The file "peak_snowpack.zip" is a compressed set of files that contain the R script for calibration and application (such as climate projections) of the transfer function for peak snowpack, and input and output files. Within the R script *StepF.R*, the watershed is selected by the text string "SAKA" to indicate the lower Lake Sakakawea watershed or by "FTPK" to indicate the Fort Peck Lake watershed. The supplied version is for the lower Lake Sakakawea watershed, and the text "SAKA" would need to be replaced by "FTPK" to run the script for the Fort Peck Lake watershed. The compressed file also contains the R script *KT.R*, which was used to compute significance of temporal trends on the basis of the Kendall's tau test (Kendall, 1938). Input and output files for *KT.R* also are included in the compressed file. The compressed file contains the R script *BP.R* which was used to compute the Breusch-Pagan test (Breusch and Pagan, 1979). Input and output files are included in the compressed file. The file "*README.txt*" within the folder provides additional information about the files and data formats.

The supplemental file "May-July_runoff.zip" is a compressed set of files that contain the R script for calibration and application (such as climate projections) of the transfer function for May–July runoff, and input and output files. Within this R script *StepF.R*, the text string "SAKA" indicates the lower Lake Sakakawea watershed, which can be replaced with "FTPK" to indicate the Fort Peck Lake watershed, as similarly described for calibration of the peak snowpack transfer function. The compressed file also contains the R script *KT.R*, which was used to compute significance of temporal trends on the basis of the Kendall's tau test. Input and output files for *KT.R* also are included in the compressed file. The compressed file contains the R script *BP.R*, which was used to compute the Breusch-Pagan test. Input and output files for *BP.R* also are included in the compressed file. The file "*README.txt*" within the folder provides additional information about the files and data formats.

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