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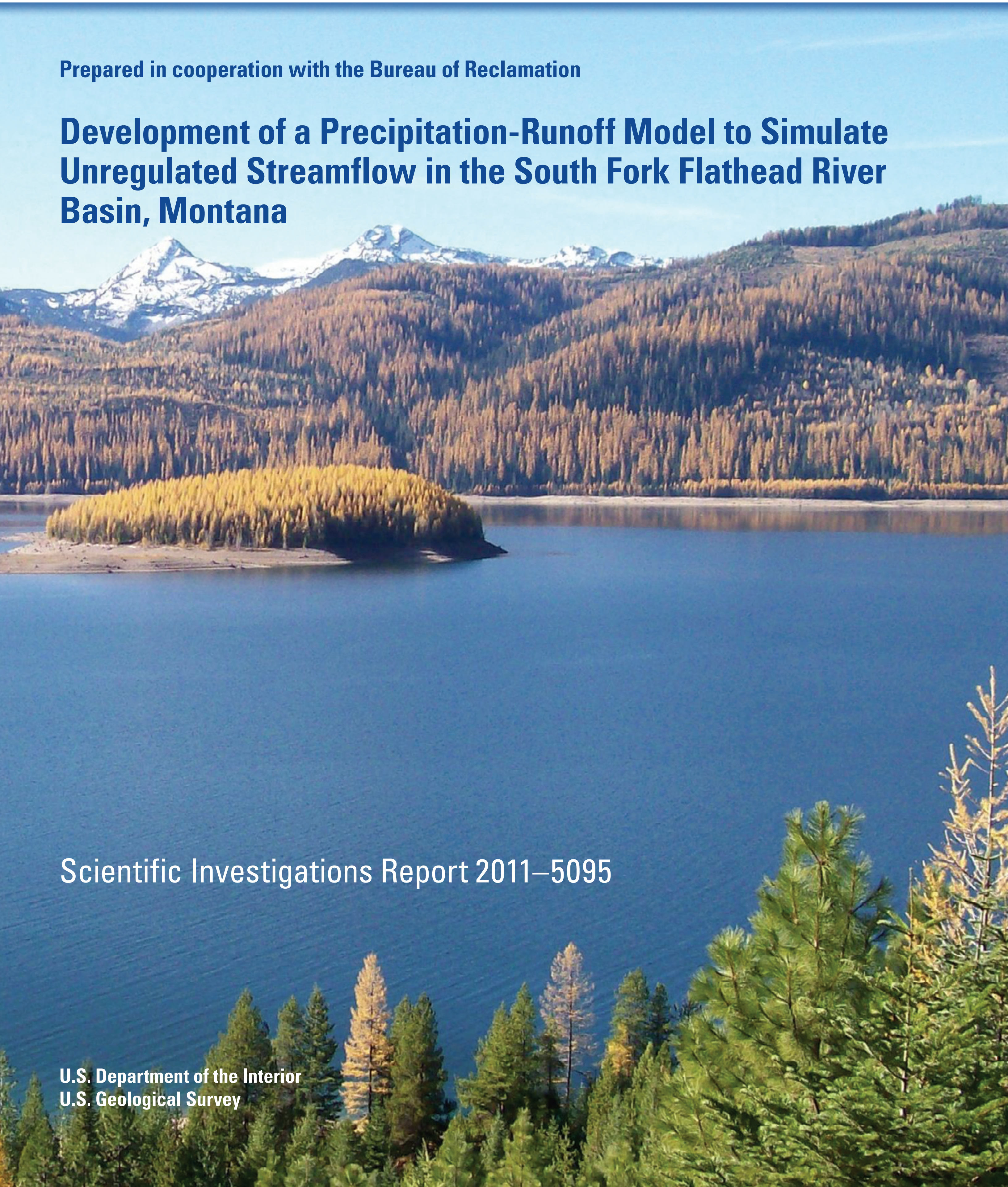

Prepared in cooperation with the Bureau of Reclamation

Development of a Precipitation-Runoff Model to Simulate Unregulated Streamflow in the South Fork Flathead River Basin, Montana

Scientific Investigations Report 2011–5095

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

Cover. Hungry Horse Reservoir, Montana. Photograph by Jim Finley, U.S. Geological Survey, taken October 24, 1997.

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Inch/pound to SI

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
inch per day (in/d)	25.4	millimeter per day (mm/d)
langley (Ly)	41,841	joule/square meter (J/m^2)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

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

°C=(°F-32)/1.8

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

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

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

Water year, as used in this report, refers to the 12-month period October 1 through September 30. It is designated by the calendar year in which it ends.

Acronyms used in this report:

DEM	digital elevation model
HRU	hydrologic response unit
GIS	Geographic Information System
LUCA	Let Us Calibrate
MODIS	Moderate Resolution Imaging Spectroradiometer
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PE	potential evapotranspiration

PRMS	Precipitation-Runoff Modeling System
QU	unregulated streamflow
Reclamation	Bureau of Reclamation
SCA	snow-covered area
SNOTEL	snowpack telemetry
SR	solar radiation
SWE	snow-water equivalent
USGS	U.S. Geological Survey

Definitions for Streamflow, Potential Evapotranspiration, and Solar Radiation Terminology

annual mean streamflow	arithmetic mean of all daily mean streamflow values for a single specified year
daily mean streamflow	mean streamflow for a single specified day
mean annual streamflow	arithmetic mean of all annual mean streamflow values for the period of record or for a specific period of multiple years
mean daily streamflow	arithmetic mean of all daily mean streamflow values for a specified day for the period of record or for a specific period of multiple years
mean monthly potential evapotranspiration	arithmetic mean of all monthly mean potential evapotranspiration values for a specified month for the period of record or for a specific period of multiple years
mean monthly streamflow	arithmetic mean of all monthly mean streamflows for a specified month for the period of record or for a specific period of multiple years
mean monthly solar radiation	arithmetic mean of all monthly mean solar radiation values for a specified month for the period of record or for a specific period of multiple years
monthly mean potential evapotranspiration	arithmetic mean of all daily mean potential evapotranspiration values for a single specified month in a single specified year
monthly mean streamflow	arithmetic mean of all daily mean streamflow values for a single specified month in a single specified year
monthly mean solar radiation	arithmetic mean of all daily mean solar radiation values for a single specified month in a single specified year

Development of a Precipitation-Runoff Model to Simulate Unregulated Streamflow in the South Fork Flathead River Basin, Montana

By Katherine J. Chase

Abstract

This report documents the development of a precipitation-runoff model for the South Fork Flathead River Basin, Mont. The Precipitation-Runoff Modeling System model, developed in cooperation with the Bureau of Reclamation, can be used to simulate daily mean unregulated streamflow upstream and downstream from Hungry Horse Reservoir for water-resources planning. Two input files are required to run the model. The time-series data file contains daily precipitation data and daily minimum and maximum air-temperature data from climate stations in and near the South Fork Flathead River Basin. The parameter file contains values of parameters that describe the basin topography, the flow network, the distribution of the precipitation and temperature data, and the hydrologic characteristics of the basin soils and vegetation.

A primary-parameter file was created for simulating streamflow during the study period (water years 1967–2005). The model was calibrated for water years 1991–2005 using the primary-parameter file. This calibration was further refined using snow-covered area data for water years 2001–05. The model then was tested for water years 1967–90. Calibration targets included mean monthly and daily mean unregulated streamflow upstream from Hungry Horse Reservoir, mean monthly unregulated streamflow downstream from Hungry Horse Reservoir, basin mean monthly solar radiation and potential evapotranspiration, and daily snapshots of basin snow-covered area.

Simulated streamflow generally was in better agreement with observed streamflow at the upstream gage than at the downstream gage. Upstream from the reservoir, simulated mean annual streamflow was within 0.0 percent of observed mean annual streamflow for the calibration period and was about 2 percent higher than observed mean annual streamflow for the test period. Simulated mean April– July streamflow upstream from the reservoir was about 1 percent lower than observed streamflow for the calibration period and about 4 percent higher than observed for the test period. Downstream from the reservoir, simulated mean annual streamflow was 17 percent lower than observed streamflow for the calibration period and 12 percent lower than observed streamflow for the test period. Simulated mean April–July streamflow downstream from the reservoir was 13 percent lower than observed streamflow for the calibration period and 6 percent lower than observed streamflow for the test period.

Calibrating to solar radiation, potential evapotranspiration, and snow-covered area improved the model representation of evapotranspiration, snow accumulation, and snowmelt processes. Simulated basin mean monthly solar radiation values for both the calibration and test periods were within 9 percent of observed values except during the month of December (28 percent different). Simulated basin potential evapotranspiration values for both the calibration and test periods were within 10 percent of observed values except during the months of January (100 percent different) and February (13 percent different). The larger percent errors in simulated potential evaporation occurred in the winter months when observed potential evapotranspiration values were very small; in January the observed value was 0.000 inches and in February the observed value was 0.009 inches. Simulated start of melting of the snowpack occurred at about the same time as observed start of melting. The simulated snowpack accumulated to 90–100 percent snow-covered area 1 to 3 months earlier than observed snowpack. This overestimated snowpack during the winter corresponded to underestimated streamflow during the same period.

In addition to the primary-parameter file, four other parameter files were created: for a “recent” period (1991–2005), a historical period (1967–90), a “wet” period (1989–97), and a “dry” period (1998–2005). For each data file of projected precipitation and air temperature, a single parameter file can be used to simulate a single streamflow value for each day of simulation, or all five parameter files can be used to simulate a range of streamflow values for each day of simulation.

Introduction

The South Fork Flathead River flows into the Flathead River in northwestern Montana and ultimately into the Clark Fork of the Columbia River (fig. 1). Hungry Horse Reservoir is at the lower end of the South Fork Flathead River and stores water behind Hungry Horse Dam. Hungry Horse Dam, which was completed in 1952, is operated by the Bureau of Reclamation (Reclamation) for power generation, flood control, recreation, and flow augmentation for endangered species. Releases from Hungry Horse Dam are managed to meet minimum flow requirements below Hungry Horse Dam and on the main stem Flathead River at Columbia Falls for bull trout and to provide spring and summer flow augmentation for salmon and steelhead in the Columbia River (Mary Mellema, Bureau of Reclamation, written commun., 2010). These current demands on the streamflow and reservoir storage together with potential future demands for water stored in Hungry Horse Reservoir pose many challenges to water resources planners and managers. In order to assist with water-resources planning efforts, in 2006 the U.S. Geological Survey, in cooperation with Reclamation, began a study to develop a precipitation-runoff model for the South Fork Flathead River Basin upstream from Hungry Horse Reservoir to simulate daily, monthly, and annual streamflow for water-resources planning.

Purpose and Scope

This report documents the development of a precipitation-runoff model for the South Fork Flathead River Basin in northwestern Montana (fig. 1). The Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983) was used to simulate daily mean unregulated streamflow upstream and downstream from Hungry Horse Reservoir. Streamflow data from two USGS streamflow gaging stations, one upstream from and one downstream from Hungry Horse Reservoir, were used for model calibration (fig. 1). These gaging stations are the South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800; “upstream gage”), and South Fork Flathead River near Columbia Falls, Mont. (12362500; “downstream gage”). The downstream gage is equivalent to the Reclamation gage Hungry Horse Montana (HGHM) - South Fork Flathead River near Columbia Falls at Hungry Horse, MT. Because the measured streamflow record for the downstream gage reflects reservoir operations as much or more than natural flow conditions, the model was not calibrated to the measured streamflow record for this station. Instead the model was calibrated to an adjusted streamflow record generated by Reclamation (Bureau of Reclamation, 2006) to represent unregulated streamflow.

Two input files are required to run the model. The time-series data file contains daily precipitation data and daily minimum and maximum air-temperature data from climate stations in and near the South Fork Flathead River Basin. The parameter file contains values of parameters that describe the basin topography, the flow network, the distribution of the precipitation and temperature data, and the hydrologic characteristics of the basin soils and vegetation.

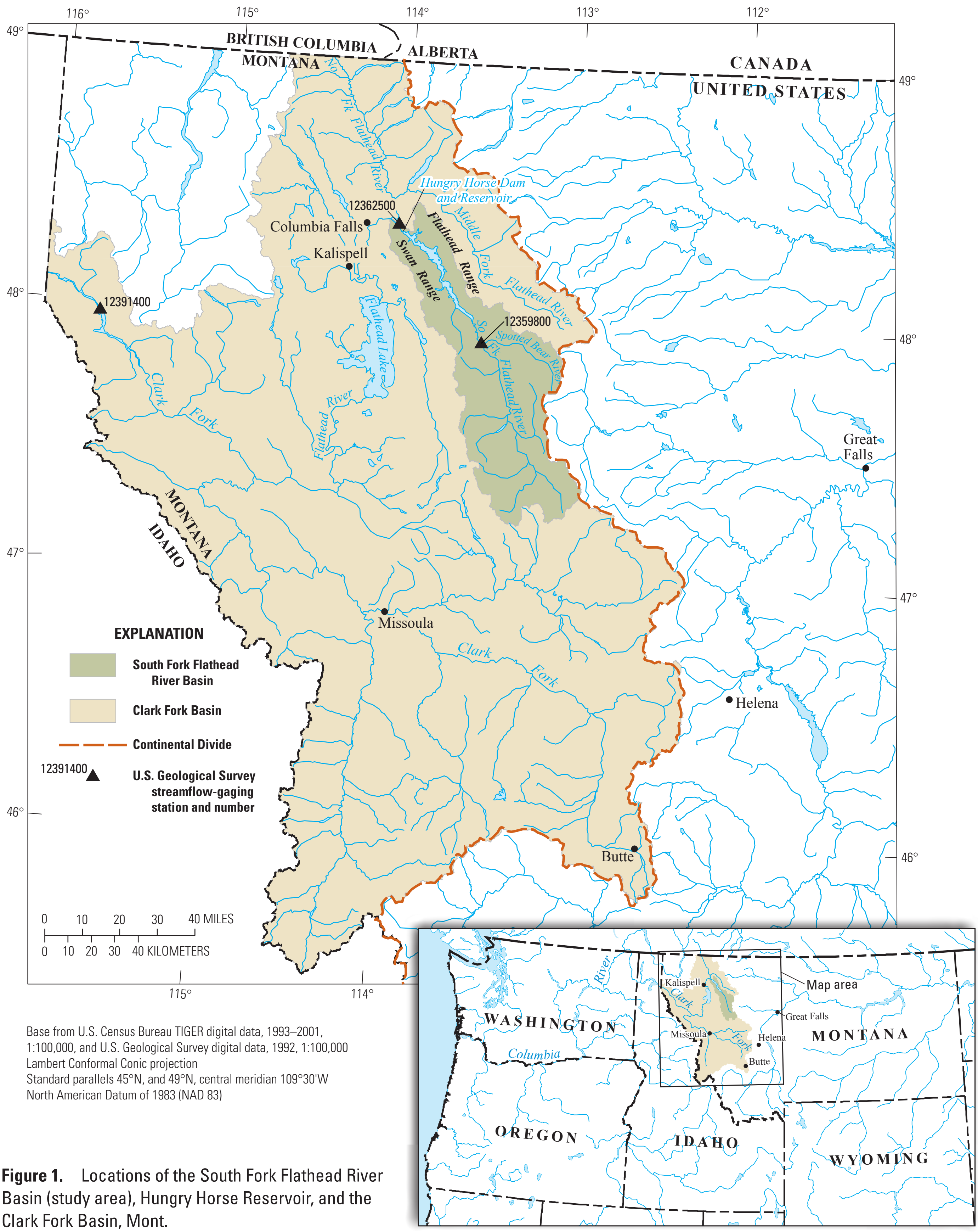
This report also describes development and calibration of a primary-parameter file and four alternate parameter files. The primary-parameter file was created for simulating streamflow during water years 1967–2005 (referred to as the study period; water year, as used in this report, refers to the 12-month period October 1 through September 30, and is designated by the calendar year in which it ends). The model was calibrated using water years 1991–2005 and tested using water years 1967–90. Simulated and observed values of mean monthly and daily mean streamflow, basin mean monthly solar radiation (SR), basin mean monthly potential evapotranspiration (PE), and basin daily snow-covered area (SCA) were compared during model calibration. Four alternate parameter files were created to represent specific hydrologic conditions or data abundance during four portions of the study period.

Description of the Study Area

The South Fork Flathead River Basin (fig. 1) is on the west side of the Continental Divide in northwestern Montana. The basin has a drainage area of 1,663 square miles (mi^2) upstream from the gaging station, South Fork Flathead River near Columbia Falls, Mont. (12362500; Berkas and others, 2005). The basin is about 105 miles (mi) long and as much as 28 mi wide and ranges in elevation from about 3,000 feet (ft; above NAVD 88) at the confluence with the Flathead River to more than 8,800 ft along the southern divide. The basin is situated within a national forest, is mostly undeveloped, and is covered with forests of lodgepole pine, douglas fir, and ponderosa pine (Powell and others, 1993; Zhu and Evans, 1994). About 65 percent of the basin lies within areas designated as wilderness. Most of the basin is in steep terrain (mean basin slope of 33 percent) underlain by metasedimentary rocks (Simons and Rorabaugh, 1971; Raines and Johnson, 1996). The narrow stream valleys are filled with unconsolidated alluvium, unconsolidated glacial deposits, and sedimentary rocks. The rocks throughout the basin generally are overlain by sandy, silty soils that are 40–50 inches (in.) thick, except in the stream valleys, where soils are as much as 60 in. thick (Wolock, 1997).

The South Fork Flathead River flows northwest, between the Swan Range on the west and the Flathead Range and the Continental Divide on the east (fig. 1). The river is tributary to the Flathead River, which ultimately joins the Clark Fork of the Columbia River.

Hungry Horse Dam, on the South Fork Flathead River about 5 mi upstream from the mouth, controls Hungry Horse Reservoir, which stores 3,467,000 acre-feet (acre-ft) of water at a reservoir water-surface elevation of 3,560 ft (Mary Mellema, written commun., 2010). Active storage of 2,982,000 acre-ft is used for hydroelectric power generation, recreation, fish and wildlife habitat, flood control, and



Base from U.S. Census Bureau TIGER digital data, 1993–2001, 1:100,000, and U.S. Geological Survey digital data, 1992, 1:100,000
Lambert Conformal Conic projection
Standard parallels 45°N, and 49°N, central meridian 109°30'W
North American Datum of 1983 (NAD 83)

Figure 1. Locations of the South Fork Flathead River Basin (study area), Hungry Horse Reservoir, and the Clark Fork Basin, Mont.

endangered species flow augmentation. Hungry Horse Reservoir is about 30 mi long and ranges from about 1 to 3 mi wide.

The Clark Fork Basin has greater mean annual precipitation than most other basins in Montana (PRISM Climate Group, Oregon State University, 2006), and a substantial portion of that precipitation falls within the South Fork Flathead River Basin (fig. 2). As shown in figure 2, mean annual precipitation in the South Fork Flathead River Basin ranges from less than 31 in. near the mouth of the basin to more than 81 in. along the western edge of the basin (PRISM Climate Group, Oregon State University, 2006). According to Simons and Rorabaugh (1971), about 50 percent of the mean annual precipitation occurs from October through February, generally as snow. Only 10 percent of the annual precipitation falls during July and August, typically as rain.

The drainage area of the South Fork Flathead River is 8 percent of the drainage area of the Clark Fork at the Montana-Idaho border, yet the South Fork Flathead River Basin produced more than 17 percent of the mean annual streamflow for the entire Clark Fork Basin within Montana during water years 1967–2005 (U.S. Geological Survey, 2009). For water years 1967–2005, the mean annual streamflow for Clark Fork below Noxon Rapids Dam, near Noxon, Mont. (12391400), near the Montana-Idaho border (fig. 1) was 19,800 cubic feet per second (ft^3/s; U.S. Geological Survey, 2009). During the same period, the unregulated mean annual streamflow generated by Reclamation (Bureau of Reclamation, 2006) for South Fork Flathead River near Columbia Falls, Mont. (12362500), was 3,490 ft^3/s. Therefore, management of flow releases from Hungry Horse Reservoir can have a substantial effect on streamflow in the Clark Fork at least as far downstream as the Montana-Idaho border.

On average, the coldest month of the year in the South Fork Flathead River Basin is January and the warmest month is July. At the climate station at Hungry Horse Dam, the minimum January mean air temperature is 16.0°F and the maximum July mean air temperature is 80.1°F (National Oceanic and Atmospheric Administration, 2001). Snow is present throughout the basin from January through March.

Development of the Precipitation-Runoff Model

The Precipitation-Runoff Modeling System (PRMS) was used to model the precipitation-runoff characteristics of the South Fork Flathead River Basin. The PRMS model was calibrated using a parameter file representative of average conditions for the study period (1967–2005). The model was calibrated to accurately represent hydrologic processes reflected in six sets of observations including mean monthly streamflow at the upstream and downstream gages and basin snow-covered area. Observed and simulated values were compared to calibrate the model and assess the ability of the model to accurately simulate the basin's hydrologic response to precipitation events.

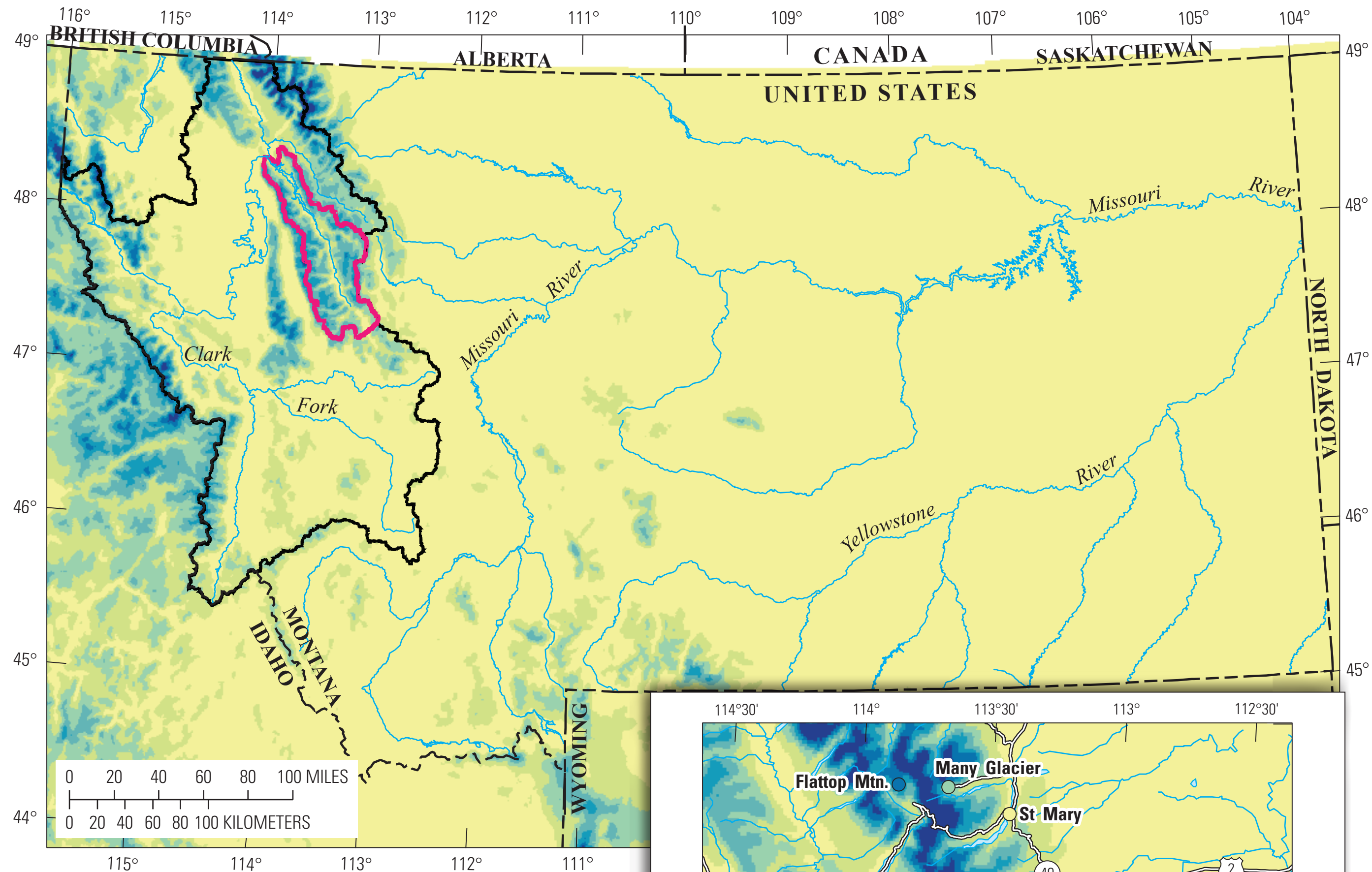
Description of the Precipitation-Runoff Modeling System

A Precipitation-Runoff Modeling System (PRMS) model was developed to simulate hydrologic processes occurring in the South Fork Flathead River Basin. The PRMS is a distributed-parameter, physically-based precipitation-runoff model (Leavesley and others, 1983; U.S. Geological Survey, 2007) that uses different modules (subroutines) to simulate the hydrologic processes occurring in a basin. The basin was divided into hydrologic response units (HRUs) consisting of smaller basins that were assumed to have a relatively uniform response to precipitation events and snowmelt. The PRMS is conceptualized as a series of reservoirs (impervious zone, soil zone, subsurface, and groundwater) that contribute to runoff. For each HRU, a water balance is computed each day, and an energy balance is computed twice each day. The sum of the water balances of all HRUs, weighted by unit area, equals the daily basin hydrologic response (Hay, Leavesley, Clark, and others; 2006). The physical processes represented by the South Fork Flathead River Basin PRMS model are illustrated in figure 3, and the 15 modules included in the model are described in table 1.

The PRMS can be used to simulate daily mean streamflow using two input files. The time-series data file contains daily precipitation data and daily minimum and maximum air-temperature data from climate stations in and near the South Fork Flathead River Basin. The parameter file contains values of parameters that describe the basin topography, the stream network, the distribution of the precipitation and temperature data, and the hydrologic characteristics soils and vegetation in the basin.

Time-Series Data

Time-series data are used in the PRMS for two purposes: for model input and for model calibration. Precipitation and air-temperature data are required as an input to simulate streamflow. Different time-series data files containing precipitation and air temperature can be used to simulate historical periods or predict the basin's hydrologic response to possible future climate and streamflow conditions. In addition, streamflow, solar radiation, potential evapotranspiration, snow-covered area, and snow-water equivalent data can be used for model calibration. The time-series data used in the model were obtained from a variety of sources including: USGS, Reclamation, the National Oceanic and Atmospheric Administration Cooperative Observer Program, and the U.S. Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center, Snow Survey and Water Supply Forecasting Program.



Base from PRISM Climate Group, Oregon State University, raster digital data, 2006, 1:24,000; U.S. Census Bureau TIGER digital data, streams amd lakes, 1994, 1:100,000; Montana river basins from Bonneville Power Administration Portland Office, 1991, 1:2,000,000
Lambert Conformal Conic projection
Standard parallels 45°N, and 49°N, central meridian 107°W
North American Datum of 1983 (NAD 83)

EXPLANATION

Mean annual precipitation (1971–2000), in inches

- Less than (<) 31
- 31–<41
- 41–<51
- 51–<61
- 61–<71
- 71–<81
- 81–114

South Fork Flathead River Basin

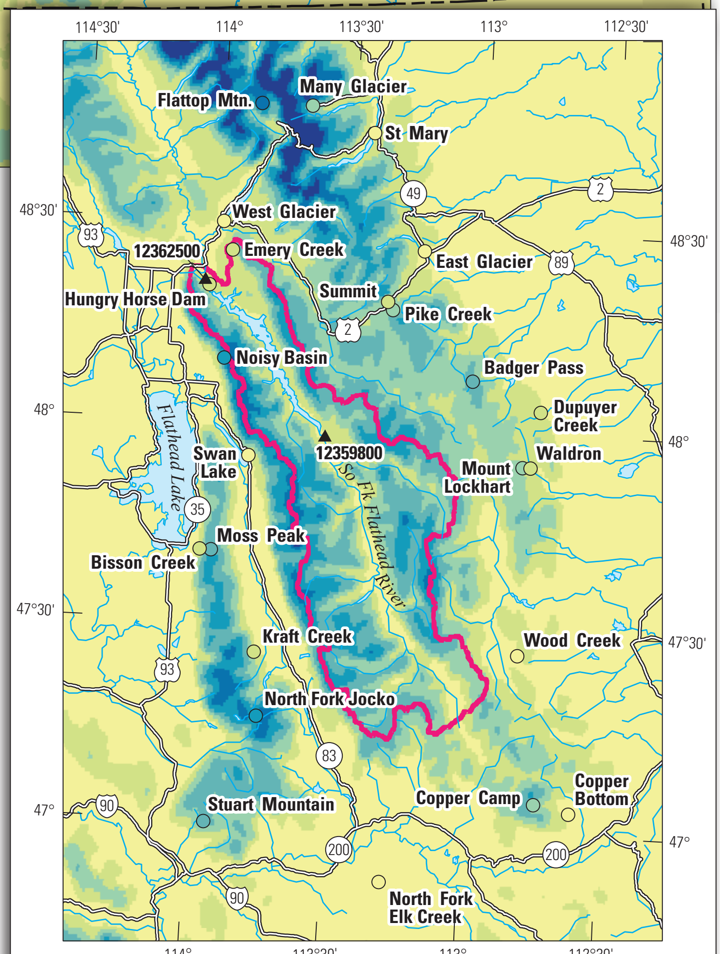
Clark Fork River Basin

Climate stations—Mean annual precipitation, in inches

- Less than 31
- 31–<41
- 41–<51
- 51–<61
- 61–<81

Period of record for Stuart Mountain is 1994–2006.

12359800 ▲ **U.S. Geological Survey streamflow-gaging station and number**



Base from PRISM Climate Group, Oregon State University, raster digital data, 2006, 1:24,000; and U.S. Census Bureau TIGER digital data, 1993, 1:100,000
Lambert Conformal Conic projection
Standard parallels 45°N, and 49°N, central meridian 107°W
North American Datum of 1983 (NAD 83)

Figure 2. Mean annual precipitation for Montana, 1971–2000, and for selected climate stations, 1990–2006.

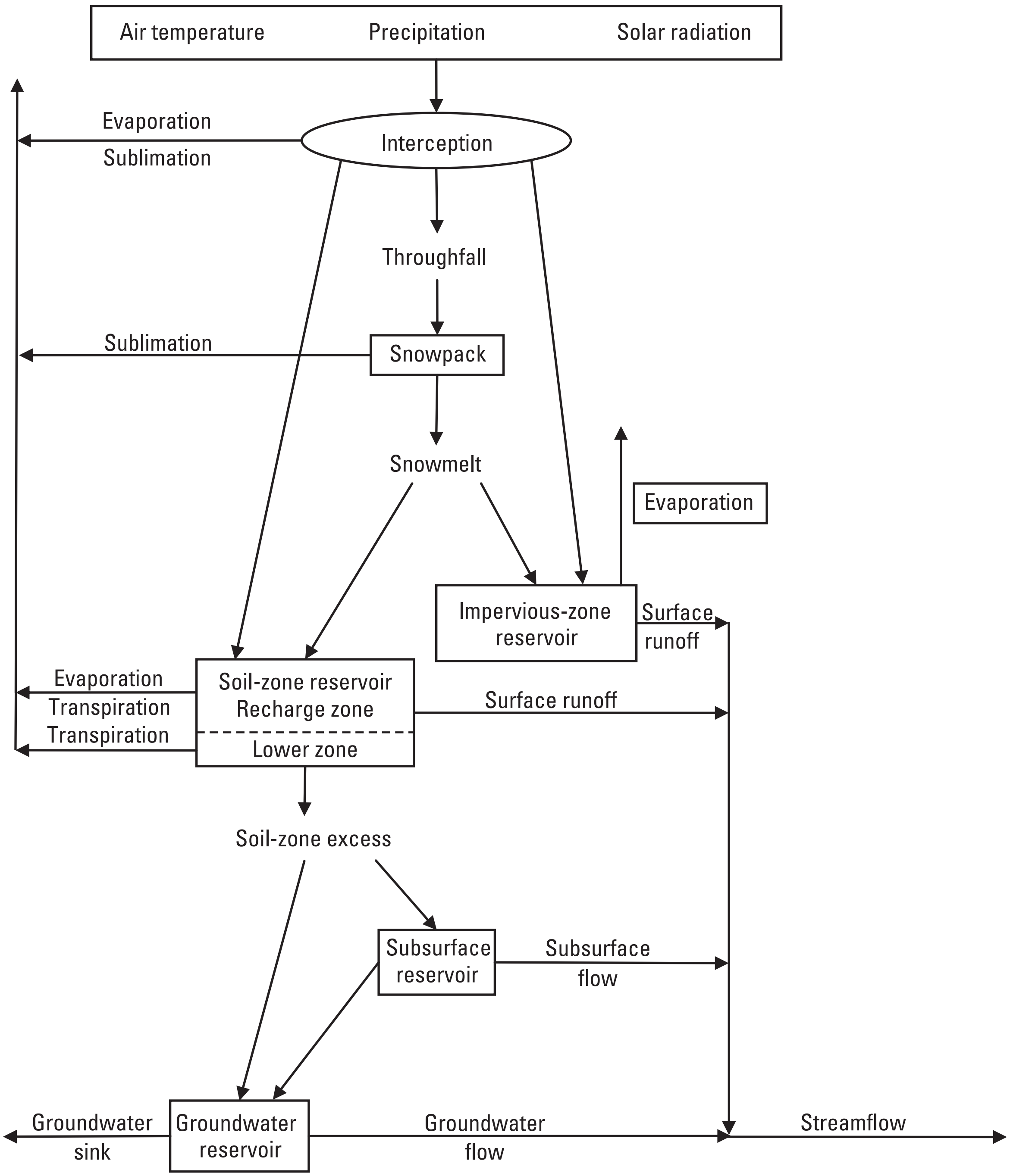


Figure 3. Hydrologic processes represented by the Precipitation-Runoff Modeling System.

Table 1. Modules used in the Precipitation-Runoff Modeling System.

[Abbreviation: HRU, hydrologic response unit]

Name of module used	Module function
basin	Declares basin and HRU physical parameters.
basin_sum	Sums values for daily, monthly, annual, and total streamflow for the basin.
ddsolrad	Computes daily solar radiation from temperature/cloud-cover relation.
gwflow	Sums inflow to groundwater and computes outflow to streamflow.
hru_sum	Sums values for daily, monthly, annual, and total streamflow for each HRU.
intcp	Computes amount of intercepted rain and snow, evaporation from intercepted rain and snow, and net rain and snow that reaches the soil or snowpack.
obs	Reads input variables from the designated data file.
potet_jh	Determines whether transpiration is occurring and computes potential evapotransiration using the Jensen-Haise (1963) approach.
smbal	Computes soil-moisture mass balance, including addition of infiltration, computation of actual evapotranspiration, and seepage to subsurface and groundwater.
snowcomp	Initiates development of a snowpack and simulates snow accumulation and depletion processes using an energy-budget approach.
soltab	Computes potential solar radiation and sunrise and sunset times for a horizontal surface and for any slope/aspect combination.
srunoff_smidx	Computes surface runoff and infiltration for each HRU using a nonlinear variable-source-area method.
ssflow	Sums inflows to subsurface reservoirs and calculates outflow to groundwater and streams.
streamflow_subbasin	Computes daily streamflow as the sum of surface, subsurface, and groundwater flow contributions at the basin outlet and at internal subbasins.
xyz_dist	Distributes precipitation and minimum and maximum temperature to HRUs.

Precipitation and Air Temperature

Precipitation and air-temperature data used in the model were originally collected by two agencies. Historical records of daily precipitation and daily minimum and maximum air temperature for climate stations in and near the South Fork Flathead River Basin (figs. 2 and 4, table 2) were collected by the National Oceanic and Atmospheric Administration Cooperative Observer Program (National Oceanic and Atmospheric Administration, 2009). Historical records of daily precipitation and daily minimum and maximum air temperature for snowpack telemetry (SNOTEL) stations in and near the basin were collected by the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), National Water and Climate Center, Snow Survey and Water Supply Forecasting Program (Natural Resources Conservation Service, 2009). Lauren Hay (U.S. Geological Survey, written commun., 2007) obtained the data from the agencies by using a computer application called the Downsizer (Ward-Garrison and others, 2009) and then estimated missing data by using regression relations developed from concurrent data for the stations of interest and surrounding climate stations (Hay and others, 2002).

SNOTEL air-temperature data and SNOTEL precipitation data are archived differently by the NRCS. SNOTEL air-temperature data reported by the NRCS for a particular date are for the previous day, whereas precipitation data are for that particular day (Roy Kaiser, Natural Resources Conservation Service, oral commun., 2007). The SNOTEL air-temperature data were shifted back 1 day before being used in the model for this study.

Streamflow

Streamflow data for model calibration were obtained from two sources. Streamflow data for the upstream gage (South Fork Flathead River above Twin Creek near Hungry Horse, Mont.; 12359800), were obtained from the U.S. Geological Survey National Water Information System (U.S. Geological Survey, 1998) by using the Downsizer (Ward-Garrison and others, 2009). Unregulated streamflow data for the downstream gage (South Fork Flathead River near Columbia Falls, Mont.; 12362500) were obtained from Reclamation (Bureau of Reclamation, 2006). The observed streamflow data for this gage reflected the effects of reservoir operations as much as natural flow conditions and therefore could not be used for model calibration without adjustment. The unregulated streamflow data were generated by Reclamation using streamflow data from the U.S. Geological Survey gage South Fork Flathead River near Columbia Falls, Mont. (12362500), water-surface elevations for Hungry Horse Reservoir, and area-capacity tables (John Roache, Bureau of Reclamation, written commun., 2007).

Solar Radiation, Potential Evapotranspiration, Snow-Covered Area, and Snow-Water Equivalent

Observed solar radiation (SR), potential evapotranspiration (PE), snow-covered area (SCA), and snow-water equivalent (SWE) data were used for model calibration and assessment. SR and PE data were derived for the South Fork Flathead River Basin by following procedures developed by Hay, Leavesley, Clark, and others (2006). Basin mean monthly SR values were interpolated from regression analysis of data for calendar years 1961–90 from a nationwide climate network of NRCS SNOTEL stations and National Weather Service (NWS) climate stations (Hay, Leavesley, Clark, and others, 2006). Basin mean monthly PE values were calculated for 1956–90 from the free-water evaporation atlas of Farnsworth and others (1982). These SR and PE datasets were chosen to be consistent with other PRMS modeling efforts across the United States (Hay, Leavesley, Clark, and others, 2006).

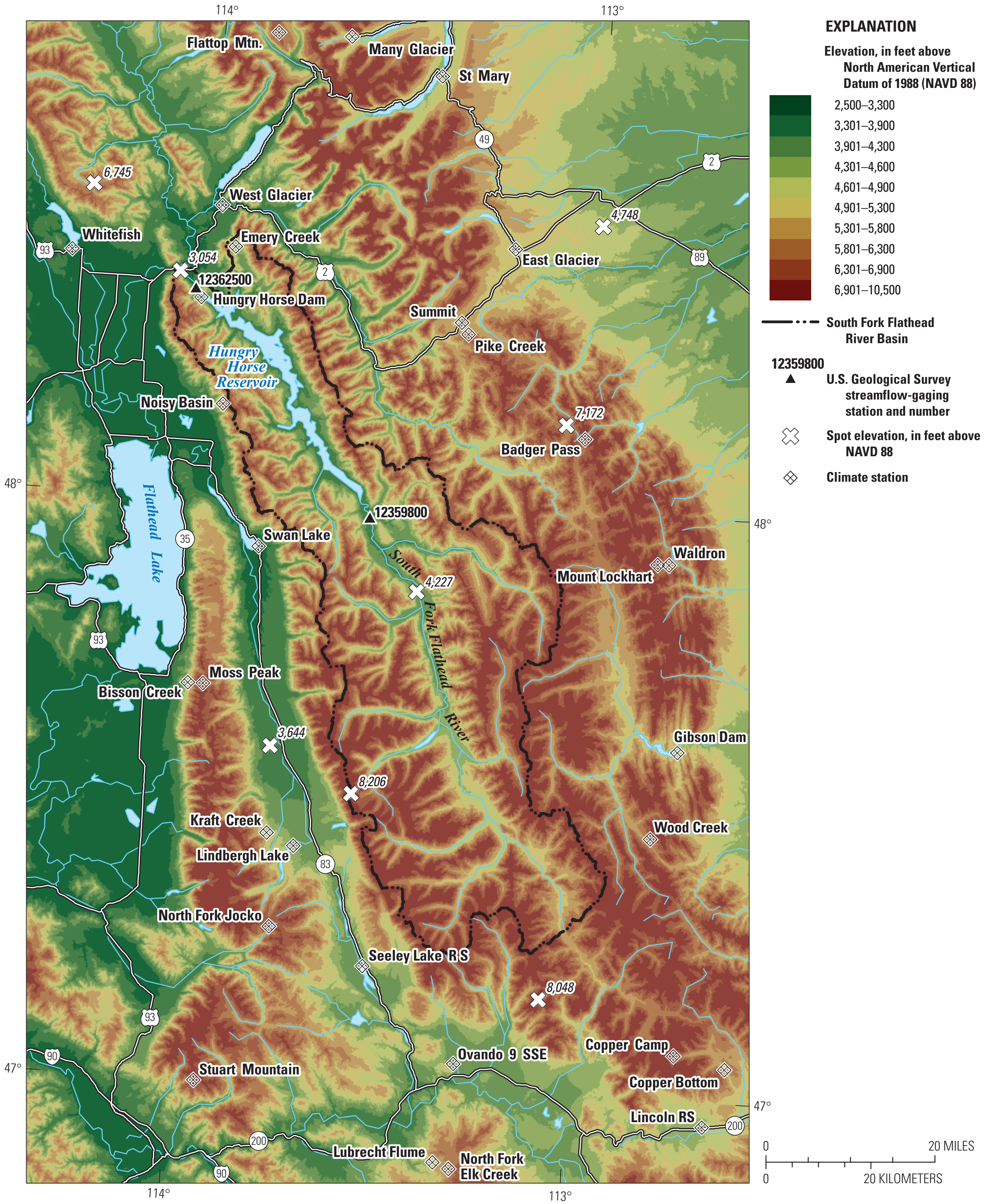
Remotely sensed SCA data were obtained by Lauren Hay (personal commun., 2007) from the University of Colorado National Snow and Ice Data Center, Boulder, Colo. (Hall and others, 2006). Hay used the Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra Snow Cover 5-Min L2 Swath 500m data (Hall and others, 2006) from February 24, 2000, to September 30, 2005, to develop daily snapshots of SCA by using methods described by Hay, Leavesley, and Clark (2006). Each observed SCA value had associated errors due to cloud cover or other factors; these positive and negative error values for each observed SCA value were included in the MODIS data. The error values were added to the observed SCA to estimate error bounds (fig. 5). The differences between the lower and upper bounds are often much more than 10 percent because of the large uncertainties in the MODIS data. However, a general pattern of snowpack accumulation (increasing SCA during October through February) and snowpack melt (decreasing SCA during May through June) can be interpreted from the plotted averages between upper and lower bounds for days when the differences between the upper and lower bounds were less than 10 percent (fig. 5).

Snow-water equivalent data from two NRCS sites were used for model assessment. SWE data from the Emery Creek SNOTEL station (13A24S; Natural Resources Conservation Service, 2006) and Spotted Bear snow-course station (13B02; Natural Resources Conservation Service, 2008) were compared to simulated SWE near each station (fig. 6).

Delineation of the Basin Boundary, Hydrologic Response Units, and Subbasins

A digital elevation model (DEM) with a cell size of 211 ft by 211 ft was obtained from the USGS National Elevation Dataset (U.S. Geological Survey, 1999). The boundary for the South Fork Flathead River Basin was delineated using the GIS Weasel (Viger and Leavesley, 2007), which is a tool that helps organize and extract data from spatial datasets for models like the PRMS. The GIS Weasel was then used to divide the basin into HRUs. First, a drainage network (fig. 6) consisting of connected cells in the DEM was delineated wherever the drainage area upstream from a DEM cell was equal to or greater than about 3 mi^2; this 3-mi^2 threshold resulted in a drainage network of suitable density for the model. Next, the basin was divided into catchment areas such that one catchment existed on each side of each drainage link in the drainage network. This subdivision method is called the two-plane contributing area method in the GIS Weasel. Then the delineation was further refined by delineating Hungry Horse Reservoir and aggregating smaller (less than 0.009-mi^2 or about 6-acre) catchment areas with neighboring catchment areas. Each resulting catchment became an HRU. The 106 HRUs resulting from this delineation are shown in figure 6.

In addition to the HRUs, subbasins were delineated to allow outputs of streamflow at locations inside the basin (interior nodes) as well as at the basin outlet. Values of simulated streamflow at locations corresponding to the upstream and downstream gages (interior nodes 1 and 5, respectively, fig. 6) were used for model calibration. Additionally, streamflow entering the east and west sides of the reservoir (interior nodes 2 and 3, respectively) was simulated. By default, the PRMS sums streamflow from all the HRUs and then reports streamflow at the outlet of the basin on a daily, monthly, and annual basis. A module was therefore added to the PRMS model to sum the streamflow from all the HRUs within individual subbasins (fig. 6). Tools in the GIS Weasel were used to divide the basin into six subbasins and to assign each HRU to one of these subbasins.



Base from U.S. Geological Survey National Elevation Dataset (NED) raster digital data, 1999, 1:24,000; and U.S. Census Bureau TIGER digital data, 1993 and 1994, 1:100,000
Lambert Conformal Conic projection, Standard parallels 45°N, and 49°N, central meridian 107°W
North American Datum of 1983 (NAD 83), and North American Vertical Datum of 1988 (NAVD 88)

Figure 4. Locations of climate stations and streamflow-gaging stations in and near the South Fork Flathead River Basin, Mont.

Table 2. Data for climate stations used in the precipitation-runoff model.

[Data obtained from National Oceanic and Atmospheric Administration (2009) and Natural Resources Conservation Service (2009) by Lauren Hay (U.S. Geological Survey, oral commun., 2007) by using a tool called the “downsizer” (Ward-Garrison and others, 2009). Elevations are referenced to North American Vertical Datum of 1988 (NAVD 88). Data from climate stations also were used, in some instances, to calculate multiple-linear-regression lapse-rate parameters to distribute precipitation and air-temperature data to hydrologic response units. Abbreviations: PRMS, Precipitation Runoff Modeling System; precip/no precip determination, climate station is used to determine whether or not there is precipitation in the basin. Symbol: --, records not used as input time-series data file for PRMS]

Station number in PRMS	Station name (fig. 4)	Station identification number[1]	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (feet)	Period of record air temperature	Period of record precipitation	Record(s) used as input time-series data file for PRMS	Record(s) used to calculate multiple linear regression lapse-rate parameters for the primary-parameter file
1	SWAN LAKE	248087	47.92	113.84	3,100	1963–2006	1950–2006	--	Precipitation and maximum and minimum air temperature.
2	WHITEFISH	248902	48.41	114.36	3,100	1965–2006	1948–2006	--	Maximum air temperature.
3	WEST GLACIER	248809	48.50	113.98	3,153	1948–2006	1948–2006	--	Precipitation and maximum and minimum air temperature.
4	HUNGRY HORSE DAM	244328	48.34	114.02	3,159	1948–2006	1948–2006	Air temperature	Maximum and minimum air temperature.
6	SEELEY LAKE R S	247448	47.21	113.52	4,101	1948–2006	1948–2006	Air temperature	Precipitation.
7	LINDBERGH LAKE	245043	47.41	113.71	4,321	1959–2006	1959–2006	Air temperature, precipitation, precip/no precip detemination	Precipitation and minimum air temperature.
8	OVANDO 9 SSE	246304	46.88	113.06	4,324	1976–2006	1976–2006	--	Precipitation.
9	EMERY CREEK	13A24S	48.43	113.94	4,350	1989–2006	1980–2006	Air temperature	Precipitation and maximum air temperature.
10	ST MARY	247292	48.74	113.43	4,560	1981–2006	1981–2006	--	Precipitation.
11	LINCOLN RS	245040	46.96	112.65	4,573	1948–2006	1948–2006	Air temperature, precip/no precip determination	Maximum and minimum air temperature.
12	GIBSON DAM	243489	47.60	112.75	4,590	1948–2006	1948–2006	Air temperature, precipitation	Minimum air temperature.
13	LUBRECHT FLUME	13C38S	46.88	113.32	4,678	1982–2006	1978–2006	Air temperature	Precipitation and maximum and minimum air temperature.
14	KRAFT CREEK	13B22S	47.43	113.78	4,751	1990–2006	1980–2006	--	Precipitation and maximum and minimum air temperature.
15	EAST GLACIER	242629	48.45	113.22	4,806	1971–2006	1949–2006	--	Precipitation.
16	MANY GLACIER	13A27S	48.80	113.67	4,902	1986–2006	1978–2006	--	Precipitation and minimum air temperature.
17	BISSON CREEK	13B25S	47.68	114.00	4,921	1992–2006	1992–2006	--	Precipitation and maximum and minimum air temperature.
18	COPPER BOTTOM	12B16S	47.06	112.60	5,200	1990–2006	1979–2006	--	Maximum air temperature.
19	SUMMIT	247978	48.32	113.35	5,233	1948–2006	1948–2001	--	Maximum and minimum air temperature.
20	WALDRON	12B13S	47.92	112.79	5,600	1989–2006	1978–2006	Air temperature	Precipitation and minimum air temperature.

Table 2. Data for climate stations used in the precipitation-runoff model.—Continued

[Data obtained from National Oceanic and Atmospheric Administration (2009) and Natural Resources Conservation Service (2009) by Lauren Hay (U.S. Geological Survey, oral commun., 2007) by using a tool called the "downsizer" (Ward-Garrison and others, 2009). Elevations are referenced to North American Vertical Datum of 1988 (NAVD 88). Data from climate stations also were used, in some instances, to calculate multiple-linear-regression lapse-rate parameters to distribute precipitation and air-temperature data to hydrologic response units. Abbreviations: PRMS, Precipitation Runoff Modeling System; precip/no precip determination, climate station is used to determine whether or not there is precipitation in the basin. Symbol: --, records not used as input time-series data file for PRMS]

Station number in PRMS	Station name (fig. 4)	Station identification number[1]	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (feet)	Period of record air temperature	Period of record precipitation	Record(s) used as input time-series data file for PRMS	Record(s) used to calculate multiple linear regression lapse-rate parameters for the primary-parameter file
22	PIKE CREEK	13A26S	48.30	113.33	5,928	1988–2006	1980–2006	Air temperature	Precipitation and maximum air temperature.
23	WOOD CREEK	12B17S	47.45	112.81	5,961	1989–2006	1978–2006	Air temperature	Precipitation and minimum air temperature.
24	NOISY BASIN	13A25S	48.16	113.95	6,040	1989–2006	1978–2006	Air temperature	Precipitation and maximum air temperature.
25	NORTH FORK ELK CREEK	13C31S	46.87	113.28	6,250	1988–2006	1978–2006	--	Minimum air temperature.
26	FLATTOP MTN.	13A19S	48.80	113.86	6,299	1982–2006	1978–2006	--	Precipitation and maximum air temperature.
27	NORTH FORK JOCKO	13B07S	47.27	113.76	6,329	1989–2006	1989–2006	Air temperature	Precipitation and maximum air temperature.
28	MOUNT LOCKHART	12B12S	47.92	112.82	6,401	1988–2006	1978–2006	Air temperature	Precipitation and maximum and minimum air temperature.
29	MOSS PEAK	13B24S	47.68	113.96	6,781	1989–2006	1985–2006	Air temperature	Maximum and minimum air temperature.
30	BADGER PASS	13A15S	48.13	113.02	6,900	1988–2006	1979–2006	--	Precipitation and maximum air temperature.
31	COPPER CAMP	12B14S	47.08	112.73	6,949	1982–2006	1978–2006	--	Precipitation and maximum air temperature.
32	STUART MOUNTAIN	13C01S	47.00	113.93	7,402	1994–2006	1994–2006	--	Precipitation and maximum and minimum air temperature.

[1] Station identification numbers containing letters indicate Snowpack Telemetry (SNOTEL) stations.

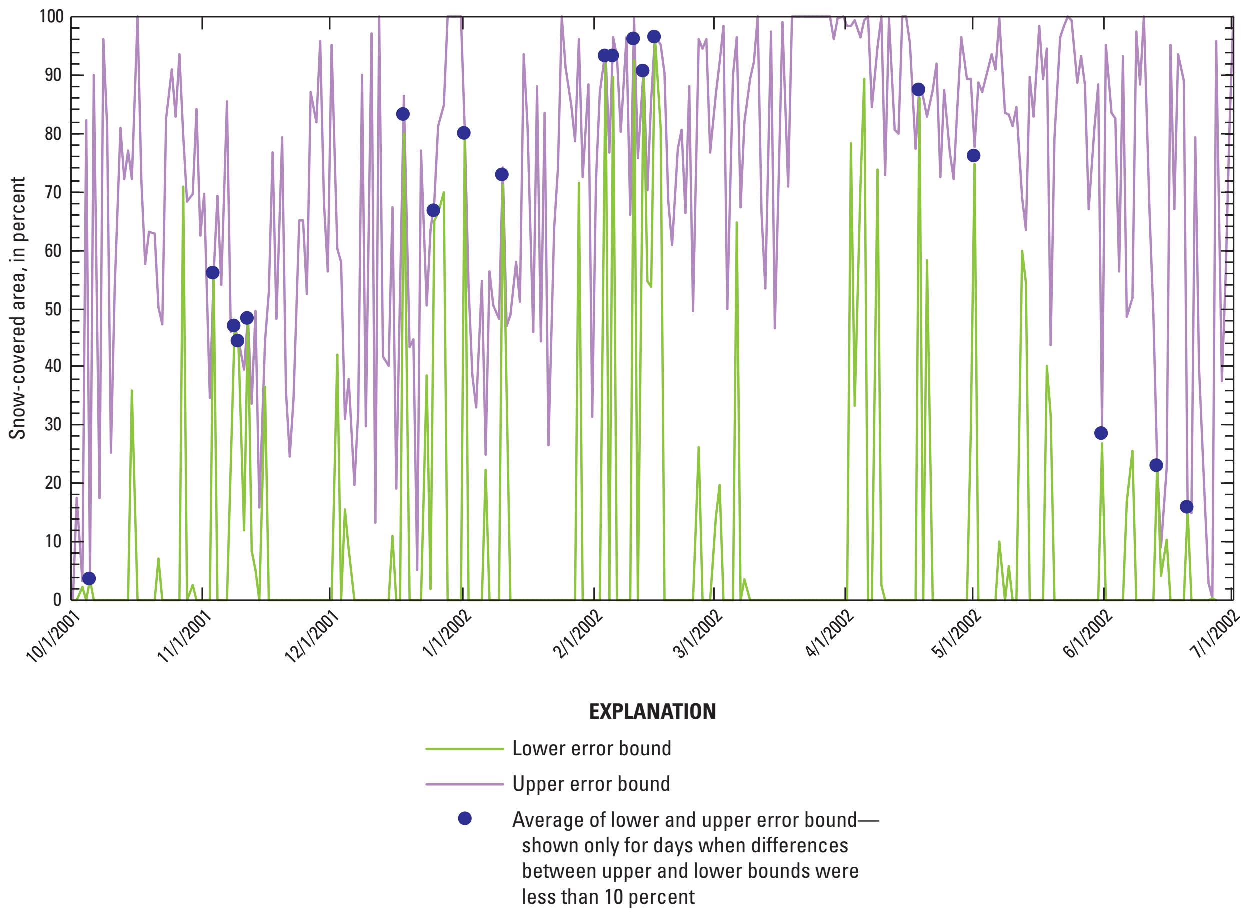


Figure 5. Observed snow-covered area (SCA) calculated from Moderate Resolution Imaging Spectroradiometer (MODIS) output for the South Fork Flathead River Basin, Mont., October 1, 2001–July 1, 2002. (SCA values from Lauren E. Hay, U.S. Geological Survey, written commun., September 9, 2007.)

Initial Parameter Values

Initial parameter values were obtained either using the GIS Weasel or from default values (Leavesley and others, 1983). Some of the initial parameter values, such as parameter values describing vegetation types for each HRU, were calculated from existing datasets and were not adjusted during the calibration process (discussed in “Physical Characteristics of the Hydrologic Response Units”). Other parameter values, such as those describing water-holding capacity of soils in each HRU, were far more difficult to calculate or estimate based on existing information; these parameter values were adjusted during the calibration process.

Physical Characteristics of the Hydrologic Response Units

Parameter values that describe mean slope, aspect, and elevation for each HRU were extracted from the DEM using the GIS Weasel. The GIS Weasel also was used to calculate initial parameter values from datasets for soils (Wolock, 1997), land cover (Zhu, 1994), and forest type and density (Powell and others, 1993; Zhu and Evans, 1994). The GIS Weasel parameterization process and datasets are described in detail by Viger and Leavesley (2007). Some initial parameter values, such as the Jensen-Haise (1963) PE coefficients and

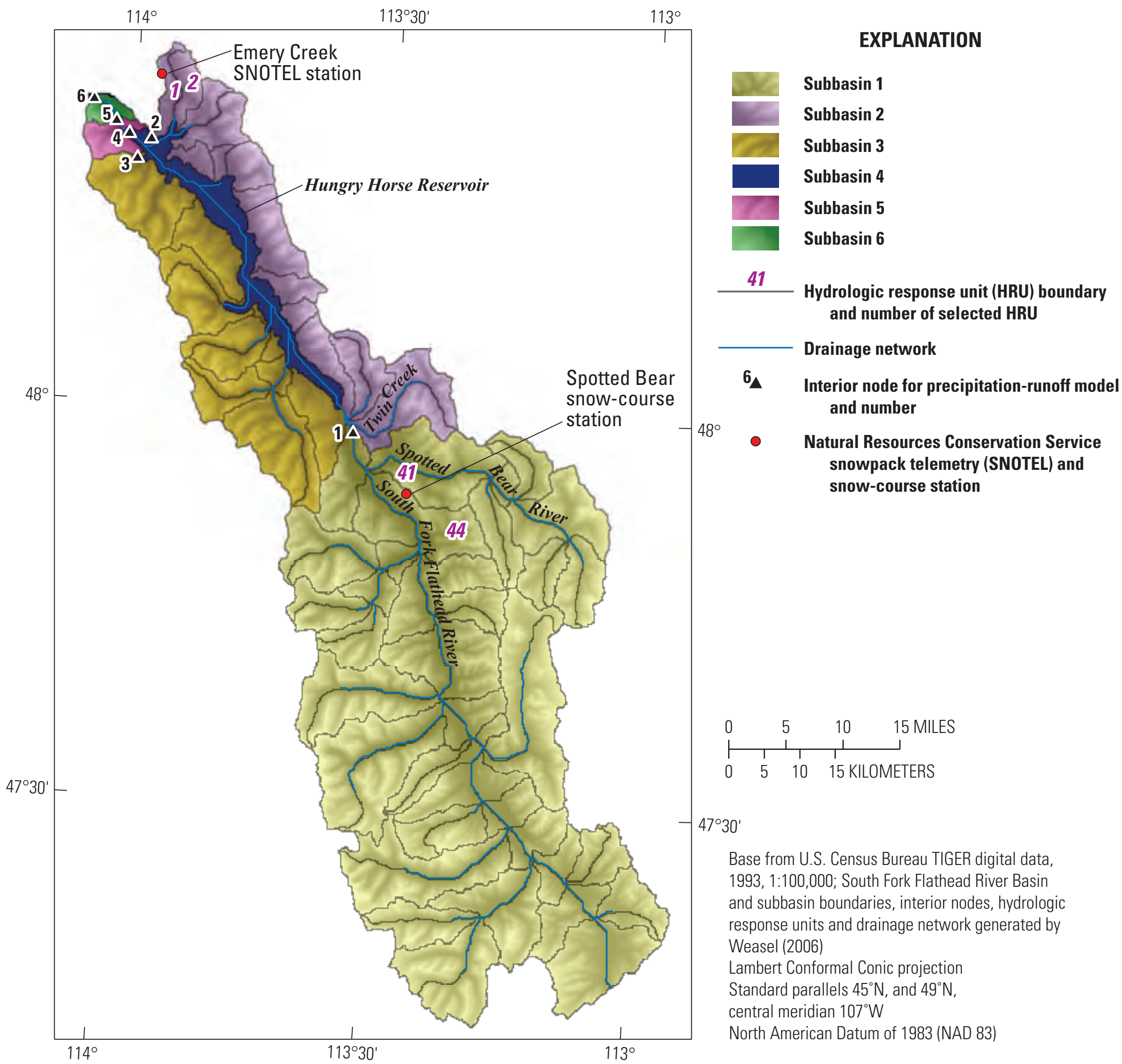


Figure 6. Subbasins, hydrologic response units, drainage network, locations of interior nodes, and Natural Resources Conservation Service snowpack telemetry (SNOTEL) and snow-course stations for the precipitation-runoff model, South Fork Flathead River Basin, Mont.

coefficients used to estimate groundwater routing and storage, were default values (Leavesley and others, 1983).

Some parameter values derived from the GIS data-sets were adjusted during calibration, whereas others were not. For example, soils information from Wolock (1997) was used to estimate initial values for the parameter that describes the maximum water depth for the soil recharge zone (soil_rechr_max, table 3). Initial values of this parameter ranged from 1.25 to 1.65 in.; these values were adjusted during calibration because they were difficult to estimate based on the existing data. Information from Zhu (1994) was used to determine the cover type (cov_type, table 3) on each HRU. The dominant cover type for the South Fork Flathead Basin was trees (cov_type=3). These cover type values were not changed during calibration, because vegetation types could be identified with a higher level of certainty than the soil characteristics.

The model for the South Fork Flathead River Basin does not explicitly simulate the hydrology of burned-over land. More specifically, the parameter values for soils, land cover, and forest type do not reflect changes caused by periodic forest fires. These changes can affect the timing and magnitude of low streamflow and peak streamflow, especially during runoff events immediately after the fires (Moody and Martin, 2001).

Distribution of Precipitation and Air-Temperature Data

A method developed by Hay and others (2002) was used to distribute precipitation and air-temperature data from a group of climate stations to each HRU in the South Fork Flathead River Basin on the basis of longitude, latitude, and elevation of the centroid of each HRU. This distribution method involved first developing regression equations to relate location and elevation of selected climate stations in and near the basin to monthly precipitation and air-temperature data at those climate stations (table 2). Then these regression equations were used to estimate daily precipitation and air temperature at each HRU based on the precipitation and air temperature at selected climate stations and on the location and elevation of the centroid of the HRU.

Model Calibration—Development of the Primary-Parameter File

A precipitation-runoff model is only a numerical approximation of real physical processes, therefore, calibration is an important part of model development. During calibration, values of selected parameters are modified until simulated values of selected calibration targets match the observed values of those calibration targets. The ultimate calibration target is streamflow, but other calibration targets, such as SR, PE, and SCA, were used as well. This approach was used because Hay, Leavesley, Clark, and others (2006) showed that a model can be well calibrated to a single calibration target (for example streamflow) without accurately simulating intermediate hydrologic processes (for example SR, PE, and snow accumulation). Values for selected parameters for the primary-parameter file are included in table 3. These parameter values appear reasonable based on documentation from other PRMS models (Hay, Leavesley, Clark, and others; 2006; Koczot and others, 2004).

Calibration Approach

A split-sample test, similar to that used by Hay, Leavesley, Clark, and others (2006), was used for calibration of the model. The observed period of record was split into two periods—the model was calibrated with data representing one period (calibration period) and tested against data representing the other period (test period). Previous studies have shown that approximately 8 years of data are needed to achieve precipitation-runoff model results that are insensitive to the period selected (Yapo and others, 1996). For the primary-parameter file, the model was calibrated for water years 1991–2005. This calibration was further refined using snow-covered area data for water years 2001–05. The model then was tested for water years 1967–90. The parameter values determined during the calibration period were used for the test period. Differences between simulated and observed values were used to examine how well the model simulated precipitation/runoff processes using the precipitation and air-temperature data.

An automated calibration computer program called **L**et **U**s **Ca**librate (LUCA; Hay and Umemoto, 2006) was used for calibration by adjusting parameter values until the simulated values of calibration targets matched the observed values as closely as possible. Within LUCA, a stepwise, multiple-objective calibration method similar to the method used by Hay, Leavesley, Clark, and others (2006) was used to calibrate the model for the South Fork Flathead River Basin. The calibration process was started using an initial parameter file containing the parameter values discussed in the section “Initial Parameter Values.” Calibration was performed in several steps. In each calibration step, simulated and observed values for one of the calibration targets (table 4) were compared and values of the parameters associated with that calibration target were adjusted to obtain the best agreement between simulated and observed calibration target values. Multiple targets were used for calibration. These calibration targets were mean monthly SR, mean monthly PE, mean monthly and daily mean streamflow at the upstream gage, mean monthly unregulated streamflow (QU), calculated by Reclamation, at the downstream gage, and daily basin SCA.

Because SR and PE affect the overall water balance in the basin, values of parameters associated with SR and PE (table 4) were adjusted first. Then, values of parameters associated with mean monthly streamflow (also related to the overall water balance) were adjusted. After the water-balance parameters were adjusted, the parameters associated with daily mean streamflow were adjusted. Finally, values of parameters associated with SCA were adjusted in a separate calibration stage for water years 2001–2005. The parameters listed in table 4 for each calibration target were determined from a single parameter sensitivity analysis conducted by using Monte Carlo techniques (Hay, Leavesley, Clark, and others, 2006).

The model was calibrated to two streamflow datasets from the upstream gage but only one streamflow dataset from the downstream gage. The daily mean QU data calculated by Reclamation for the downstream gage contained occasional negative values; therefore these daily mean data were unsuitable for calibration. Thus, mean monthly and daily mean streamflow data from the upstream gage were used for calibration but only mean monthly streamflow from the downstream gage were used for calibration.

Calibrated Model Simulations Using the Primary-Parameter File

The calibration of the model using the primary-parameter file mostly was evaluated by comparing simulated and observed streamflow. Simulated means of streamflow for long (year) and short (day) periods were compared to observed flows. Solar radiation and potential evapotranspiration also were used to evaluate model calibration as well as snow-covered area and snow-water equivalent.

Comparison of Simulated and Observed Streamflow

The model was developed to simulate long-term average and short-term average streamflow. The Bureau of Reclamation requested a precipitation-runoff model that could simulate long-term mean annual streamflow, mean seasonal streamflow for the runoff period (April–July; hereinafter referred to as mean April–July streamflow), and mean monthly streamflow. Reclamation also wanted to simulate short-term average streamflow, such as annual mean streamflow, monthly mean streamflow, and daily mean streamflow. Comparisons of simulated and observed streamflow for these time frames are discussed in this section.

Mean Annual, Mean April–July, and Mean Monthly Streamflow

At the upstream gage, simulated mean annual streamflow and simulated mean April–July streamflow differed from observed values by 0.0 to about 4 percent for the study period (water years 1967–2005). Simulated mean annual streamflow was within 0.0 percent of observed mean annual streamflow for the calibration period (water years 1991–2005) and was about 2 percent higher than observed mean annual streamflow for the test period (water years 1967–90; table 5; positive percent error indicates that simulated streamflow was overestimated). Simulated mean April–July streamflow was about 1 percent lower than observed streamflow for the calibration period and about 4 percent higher than observed for the test period.

Simulated and observed mean monthly streamflow values for the calibration period (water years 1991–2005) and the test period (water years 1967–90) at the upstream gage are shown in figure 7*A* and table 5. The percentage difference between simulated and observed mean monthly streamflow was largest in August, when the simulated mean monthly streamflow was 73 percent larger than observed for the calibration period and 84 percent larger than observed for the test period. Differences between simulated and observed mean monthly streamflow for other months ranged from -44 to 29 percent for the calibration period and -54 to 38 percent for the test period.

The differences between simulated and observed mean annual and mean April–July streamflow were larger at the downstream gage than at the upstream gage, probably because two streamflow datasets were used for calibration at the upstream gage and only one streamflow dataset was used for calibration at the downstream gage, as discussed in the "Calibration Approach" section. At the downstream gage, the simulated mean annual streamflow was 17 percent lower than the observed mean annual streamflow for the calibration period. The simulated mean annual streamflow was 12 percent lower than the observed mean annual streamflow for the test period (table 5). At the same gage, the simulated mean April–July streamflow was 13 percent lower than the observed streamflow for the calibration period. The simulated mean April–July streamflow was about 6 percent lower than observed streamflow for the test period.

Interestingly, the mean annual and mean April–July streamflow values were underestimated at the downstream gage. Evaporation removes water from the basin at Hungry Horse Reservoir, upstream from the downstream gage. Because evaporative losses from the reservoir were not included in the model, streamflow values should have been overestimated at the downstream gage.

Simulated and observed mean monthly streamflow values at the downstream gage are included in figure 7*B* and table 5. At the downstream gage, the percentage differences between simulated and observed mean monthly streamflow were largest in November for the calibration period (-62 percent different) and in December for the test period (-70 percent different). Differences between simulated and observed mean monthly streamflow for the other months ranged from -58 percent to about 50 percent for the calibration period and from -62 percent to 61 percent for the test period.

Annual Mean, Monthly Mean, and Daily Mean Streamflow

Annual mean streamflow was within 30 percent (plus or minus) of observed annual mean streamflow at the upstream gage except for water years 1972, 1978, and 1993 (fig. 8, table 6). Annual mean streamflow was within 30 percent (plus or minus) of observed annual mean streamflow at the downstream gage except for water years 1972, 1985, and 2005 (fig. 8, table 6). No winter (December–March) streamflow records are available for the upstream gage for water years 1985–2005; thus, the observed annual mean streamflow (fig. 8*A*, table 6) for this period is likely higher than it would be if the winter data, which typically reflect low-flow conditions, were included. For consistency with the observed data, simulated annual mean streamflow values reported in figure 8*A* and table 6 do not include data for December–March streamflow for water years 1985–2005.

Annual mean streamflow at the upstream gage was underestimated for some water years and overestimated for other water years, whereas annual mean streamflow at the downstream gage generally was underestimated (table 6). Streamflow at the upstream gage was underestimated by more than 20 percent for water years 1972, 1985, and 2005, and was overestimated by more than 20 percent for water years 1975, 1978, 1987–89, 1993, and 1995. Streamflow at the downstream gage was underestimated by more than 20 percent for 11 of the 39 water years simulated but was overestimated by more than 20 percent for only 1 water year (1978).

Data for monthly mean streamflow at the upstream and downstream gages for water years 1967–2005 are plotted in figures 9 and 10. The shapes of the annual hydrographs of the simulated and observed monthly mean streamflow are similar, though the observed peak monthly mean streamflow did not always occur in the same month as the simulated peak monthly mean streamflow. Simulated peak monthly mean streamflow values at the upstream gage (fig. 9) were underestimated by more than 2,000 ft^3/s in water years 1972, 1974, 1985, 1996, 1999, and 2002. Simulated peak monthly

Table 3. Sources, values, and ranges for selected Precipitation-Runoff Modeling System parameters for the primary-parameter file for the South Fork Flathead River Basin, Mont.

[Abbreviations: HRU, hydrologic response unit; in., inches; ft, feet; GIS, Geographic Information System]

Model parameter	Description of parameter	Value or range of values (or cover type) used in model	Source of parameter values	
			GIS derived[1]	Calibrated[2]
	HRU (distributed) parameters			
cov_type	Vegetation cover type (bare soil, grasses, shrubs, trees)	Grasses, shrubs, trees	X	
covden_sum	Vegetation cover density (decimal percent) for summer	0–0.99	X	
covden_win	Vegetation cover density (decimal percent) for winter	0–0.97	X	
gwflow_coef	Groundwater rounding coefficient to obtain the groundwater flow contribution to streamflow	0.02		X
gwstor_init	Storage in each groundwater reservoir at the beginning of the simulation (in.)	1.7	X	
hru_area	HRU area (acres)	595–36,914	X	
hru_aspect	HRU aspect (degrees)	0–315	X	
hru_elev	Mean HRU elevation (ft)	3,429–6,118	X	
hru_percent_impervious	HRU impervious area as a decimal percent of the total HRU area	0	X	
hru_slope	HRU slope in decimal percent (vertical ft/horizontal ft)	0.063–0.45	X	
jh_coef_hru	Air temperature coefficient used in the Jensen-Haise (1963) potential evapotranspiration computations for each HRU	15–18	X	
rad_trncf	Transmission coefficient for short-wave radiation through the winter canopy (decimal percent)	0.069–0.99	X	
smidx_coef	Coefficient in the nonlinear surface-runoff contributing-area algorithm	0.00011		X
smidx_exp	Exponent in the nonlinear surface-runoff contributing-area algorithm	0.2		X
snarea_thresh	Maximum snow-water equivalent below which the snow-covered area depletion curve is applied (in.)	1.1–20		X
snow_intcp	Snow interception storage capacity for the major vegetation type on an HRU (in.)	0.0045–0.1	X	
soil2gw_max	Maximum amount of soil water excess for an HRU that is routed directly to the associated groundwater reservoir each day (in.)	0.16		X
soil_moist_max	Maximum available water-holding capacity of soil profile (in.)	9.1–10		X
soil_rechr_max	Maximum value for available water in the soil recharge zone (in.)	2.7–3.2		X
soil_type	HRU soil type (sand, loam, or clay)	Loam	X	
srain_intcp	Summer interception storage capacity for the major vegetation type on an HRU (in.)	0.022–0.050	X	
ssrcoef_sq	Nonlinear subsurface routing coefficient to route subsurface storage to streamflow	0.019		X
tmax_adj	HRU maximum temperature adjustment (degrees Fahrenheit) to HRU temperature, based on the slope and aspect of the HRU	-1.7–1.7	X	
tmin_adj	HRU minimum temperature adjustment (degrees Fahrenheit) to HRU temperature, based on the slope and aspect of the HRU	-1.7–1.7	X	
wrain_intcp	Winter rain interception storage capacity for the major vegetation type on an HRU (in.)	0.0022–0.050	X	

Table 3. Sources, values, and ranges for selected Precipitation-Runoff Modeling System parameters for the primary-parameter file for the South Fork Flathead River Basin, Mont.—Continued

[Abbreviations: HRU, hydrologic response unit; in., inches; ft, feet; GIS, Geographic Information System]

Model parameter	Description of parameter	Value or range of values (or cover type) used in model	Source of parameter values	
			GIS derived[1]	Calibrated[2]
	Selected non-distributed parameters			
adjmix_rain	Monthly factor to adjust rain proportion in a mixed rain/snow event (decimal percent)	0.042–1.2		X
adjust_rain	Precipitation adjustment factor for rain days (decimal fraction)	0.002–1.0		X
adjust_snow	Precipitation adjustment factor for snow days (decimal fraction)	0.127–1.0		X
cecn_coef	Convection condensation energy coefficient	19.7		X
dday_intcp	Intercept in the temperature degree-day relation (dday[3])	-44 – -8.7		X
emis_noppt	Emissivity of air on days without precipitation (decimal fraction)	1		X
freeh2o_cap	Free-water holding capacity of snowpack (expressed as decimal fraction of total snowpack water equivalent)	0.023		X
jh_coef	Monthly air temperature coefficient used in the Jensen-Haise (1963) potential evapotranspiration computations	0.0050–0.033		X
potet_sublim	Proportion of potential evapotranspiration sublimated from snow surface (decimal fraction)	0.75		X
tmax_allrain	Monthly maximum temperature (degrees Fahrenheit) above which all precipitation is simulated as rain	54–63		X
tmax_allsnow	Monthly maximum temperature (degrees Fahrenheit) below which all precipitation is simulated as snow	30–30		X
tmax_index	Monthly index temperature used to determine precipitation adjustments to solar radiation (degrees Fahrenheit)	63–84		X

[1] Computed using the Weasel (Viger and Leavesley, 2006) geographic information system (GIS) from digital coverages.

[2] Parameters that (a) cannot be estimated from available data and are adjusted during calibration or (b) have initial estimates from measured or published data that were adjusted during calibration.

[3]degree-day (dday) is a PRMS modeling unit used in the equations to estimate solar radiation (U.S. Geological Survey, 2007).

Table 4. Calibration targets and parameters used in the LUCA calibration procedure for the primary-parameter file for the precipitation-runoff model.

[Table modified from Hay, Leavesley, Clark, and others (2006). Abbreviations: LUCA, **L**et **U**s **Ca**librate; SR, solar radiation; PE, potential evapotranspiration; NRMSE, normalized root mean square error; HRU, hydrologic response unit; SCA, snow-covered area; downstream gage, streamflow downstream from Hungry Horse Reservoir, South Fork Flathead River near Columbia Falls, Mont. (12362500), this gage is equivalent to the Bureau of Reclamation site HGHM - South Fork Flathead River near Hungry Horse, MT; the observed streamflow data for this gage were adjusted to represent unregulated streamflow (Bureau of Reclamation, 2006); upstream gage, streamflow upstream from Hungry Horse Reservoir, (12359800) South Fork Flathead River above Twin Creek, Mont.]

Calibration target	Objective function	Parameters used to calibrate model	Parameter description
Basin mean monthly SR	Sum of the absolute difference in the logarithms of simulated and observed SR	dday_intcp	Intercept in temperature degree-day relation.
		tmax_index	Index temperature used to determine precipitation adjustments to SR.
Basin mean monthly PE	Sum of the absolute difference in the logarithms of simulated and observed PE	jh_coef	Coefficient used in Jensen-Haise PE computations (Jensen and Haise, 1963).
Mean monthly streamflow, downstream gage	NRMSE	adjust_rain	Precipitation adjustment factor for rain days.
		adjust_snow	Precipitation adjustment factor for snow days.
		psta_nuse	Binary indicator for using climate station in precipitation-distribution calculations.
		psta_freq_nuse	Binary indicator for using climate station in precipitation-frequency calculations.
Mean monthly streamflow, upstream gage	NRMSE	adjust_rain	Precipitation-adjustment factor for rain days.
		Adjust_snow	Precipitation-adjustment factor for snow days.
		psta_nuse	Binary indicator for using climate station in precipitation-distribution calculations.
		psta_freq_nuse	Binary indicator for using climate station in precipitation-frequency calculations.
Daily mean streamflow, upstream gage	NRMSE	adjmix_rain	Factor to adjust rain proportion in mixed rain/snow event.
		tmax_allrain	If HRU maximum temperature is greater than or equal to this value, precipitation assumed rain.
		tmax_allsnow	If HRU maximum temperature is less than or equal to this value, precipitation assumed snow.
		tsta_nuse	Binary indicator for using climate station in temperature-distribution calculations.
		cecn_coef	Convection condensation energy coefficient.
		emis_noppt	Emissivity of air on days without precipitation.
		freeh2o_cap	Free-water holding capacity of snowpack.
		potet_sublim	Proportion of PE that is sublimated from snow surface.
		smidx_coef	Coefficient for nonlinear surface-runoff contributing-area algorithm.
		smidx_exp	Exponent for nonlinear surface-runoff contributing-area algorithm.
		gwflow_coef	Groundwater routing coefficient.
		ssrcoef_sq	Coefficient to route subsurface storage to streamflow.
		soil2gw_max	Maximum rate of soil-water excess moving to groundwater.
		soil_moist_max	Maximum available water-holding capacity of soil profile.
		soil_rechr_max	Maximum available water-holding capacity of soil-recharge zone.
		tmax_allsnow	If HRU maximum temperature is below this value, precipitation assumed to be snow.
		snarea_thresh	Maximum threshhold water equivilant below which the SCA curve is applied.
Daily basin SCA	Sum of the absolute difference between simulated and observed SCA	adjmix_rain	Factor to adjust rain proportion in mixed rain/snow event.
		tmax_allsnow	If HRU maximum temperature is below this value, precipitation assumed to be snow.
		snarea_thresh	Maximum threshold water equivalent below which the SCA curve is applied.

mean streamflow values at the downstream gage (fig. 10) were underestimated by more than 2,000 ft^3/s in water years 1968, 1972, 1973, 1974, 1976, 1985, 1990, 1991, 1996, and 1998–2005. Simulated peak monthly mean streamflow values at both gages (figs. 9 and 10) were overestimated by more than 2,000 ft^3/s in water years 1967, 1975, and 1980. In addition, simulated peak monthly mean streamflow values were overestimated at the upstream gage by more than 2,000 ft^3/s in water years 1993 and 1997. Observed runoff events at both gages during the low-flow season (October–December) were simulated for water years 1971, 1974, 1976, 1977, 1991, 1997, 1999, but were not simulated for several other water years.

Values of simulated and observed daily mean streamflow were compared for three different periods to examine the model's sensitivity to different climate conditions. Hydrographs of simulated and observed daily mean streamflow at the upstream and downstream gages for water years 1968–72 are shown in figure 11*A*. The overall shapes of the annual hydrographs of simulated and observed daily streamflow for water years 1968–72 are similar, even though data for those years were not used for calibration. The model did not simulate the runoff events observed in September–October 1968, did simulate a runoff event in February 1971, and did not simulate a runoff event in March–April 1972. The runoff events missing from the simulations could have resulted from localized storms that were not recorded at the climate stations used in the model or from precipitation falling on areas burned by fires. As discussed in the section "Physical Characteristics of the Hydrologic Response Units," no explicit changes were made to the model parameter values to reflect the effects of fires on the hydrologic characteristics of the basin. Water years 1989–93 (fig. 11*B*) spanned part of the test period (water years 1967–90) and part of the calibration period (water years 1991–2005). The shapes of the hydrographs of simulated and observed streamflow were similar, but the model overestimated peak streamflow in water years 1989, 1991, and 1993. Water years 2001–05 (fig. 11*C*) spanned part of the calibration period. Several streamflow peaks during water year 2002 were underestimated by the model. Also, the model did not simulate the magnitude and timing of observed runoff peaks in water years 2003 and 2004. Other runoff events in water year 2005 were not simulated by the model. These runoff events could have resulted from storms that were not recorded at precipitation gages or from precipitation falling on areas burned by fires.

Comparison of Simulated and Observed Mean Monthly Solar Radiation and Potential Evapotranspiration

Simulated basin mean monthly values of solar radiation (SR) and potential evapotranspiration (PE) for both the calibration and test periods as well as observed SR (calendar years 1961–90) and PE (calendar years 1956–70) are shown in figure 12. As discussed in the section "Solar Radiation, Potential Evapotranspiration, Snow-Covered Area, and Snow-Water Equivalent," these SR and PE observed datasets were chosen for consistency with other PRMS modeling efforts across the United States. Simulated basin mean monthly SR values for both the calibration and test periods (fig. 12*A*) were within 9 percent of observed values except during the month of December (28 percent different). Simulated mean monthly PE values for both the calibration and test periods (fig. 12*B*) were within 10 percent of observed values except during the months of January (100 percent different) and February (13 percent different). The larger errors in simulated PE occurred in the winter months when observed PE values were very small; in January the observed value was 0.000 in. and in February the observed value was 0.009 in.

Comparison of Simulated and Observed Snow-Covered Area

After the model was calibrated to the snow-covered area (SCA) data, simulated start of melting of the snowpack occurred at about the same time as observed start of melting for water years 2001–05 (fig. 13). However, the simulated snowpack accumulated to 90 to 100 percent SCA 1 to 3 months earlier in the season than the observed snowpack, both before and after calibration. This overestimated snowpack generally corresponded with underestimated streamflow during December–February (fig. 7). For instance, the simulated SCA generally was greater than observed SCA for December and January (fig. 13), and values of the simulated mean monthly streamflow for those months at the downstream and upstream gages were lower than values of the observed mean monthly streamflow (fig. 7). This underestimated fall–winter streamflow was followed by overestimated streamflow in May and June when the snowpack melted. This overestimation of fall–winter SCA, and thus the underestimation of fall–winter mean monthly streamflow, could have been due to unreliable results produced by the regression equations that were used to distribute air-temperatures from the climate stations to the HRUs. The differences also could have been due to incorrect values for other parameters, such as the temperatures at which precipitation fell as snow instead of rain.

Comparison of Simulated and Observed Snow-Water Equivalent

Snow-water equivalent (SWE) data for the NRCS Emery Creek SNOTEL station northeast of Hungry Horse Reservoir (13A24S; Natural Resources Conservation Service, 2006; fig. 6) were compared to simulated snow accumulation and melt at the HRUs close to Emery Creek (HRUs 1 and 2). For all but 7 of the water years that the comparison was made, the observed SWE at Emery Creek tended to be higher than the simulated SWE at both HRUs 1 and 2, typically by about 5 to 10 in. (fig. 14*A*). Intuitively, the greater observed SWE at Emery Creek should have melted more slowly than the smaller simulated SWE at HRUs 1 and 2. However, observed SWE for Emery Creek and simulated SWE for HRUs 1 and 2 accumulated and dissipated at about the same time. Emery Creek is at an elevation of 4,350 ft (above NAVD 88) whereas the average

Table 5. Simulated (primary-parameter file) and observed mean monthly, mean annual, and mean April–July streamflow for the calibration and test periods.

[Upstream gage, South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. Downstream gage, South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir (equivalent to Bureau of Reclamation site "HGHM - South Fork Flathead River near Columbia Falls at Hungry Horse, MT." The observed streamflow data for this gage were adjusted to represent unregulated streamflow (Bureau of Reclamation, 2006). Percent error is equal to (simulated minus observed) divided by observed. Negative percent errors indicate simulations underestimated; positive percent errors indicate simulations overestimated. Abbreviation: ft^3/s, cubic feet per second. Symbol: --, data not available]

Month	Streamflow, upstream gage[1]			Streamflow, downstream gage		
	Mean simulated (ft^3/s)	Mean observed (ft^3/s)	Error (percent)	Mean simulated (ft^3/s)	Mean observed (ft^3/s)	Error (percent)
Calibration period: water years 1991–2005						
Mean monthly						
October	380	510	-25	490	969	-49
November	462	829	-44	645	1,710	-62
December[1]	--	--	--	685	1,250	-45
January[1]	--	--	--	447	1,060	-58
February[1]	--	--	--	885	1,150	-23
March[1]	--	--	--	1,320	1,610	-18
April	3,400	2,650	28	5,160	4,860	6.2
May	6,670	7,230	-7.7	9,630	11,500	-16
June	6,490	7,300	-11	8,260	10,800	-24
July	2,910	2,440	19	3,640	3,560	2.2
August	1,240	716	73	1,590	1,060	50
September	633	492	29	817	830	-1.6
Mean annual						
Mean	2,770	2,770	0.0	2,800	3,360	-17
Mean for April–July						
Mean	4,870	4,910	-0.81	6,670	7,680	-13
Test period: water years 1967–90						
Mean monthly						
October	445	592	-25	588	1,090	-46
November	366	617	-41	485	1,270	-62
December	229	495	-54	333	1,120	-70
January	265	475	-44	462	1,120	-59
February	394	532	-26	577	1,090	-47
March	486	596	-18	985	1,470	-33
April	2,780	2,390	16	4,880	4,570	6.8
May	7,510	7,820	-4.0	10,900	12,200	-11
June	8,610	8,850	-2.7	11,000	12,800	-14
July	3,840	2,790	38	4,770	3,930	21
August	1,470	799	84	1,880	1,170	61
September	752	594	27	967	1,050	-7.9
Mean annual						
Mean	2,260	2,210	2.3	3,150	3,570	-12
Mean for April–July						
Mean	5,690	5,460	4.2	7,890	8,380	-5.8

[1] As of water year 1985, no winter (December–March) streamflow data are available for this gage. Because December–March tend to be low-flow months, mean annual streamflows for water years 1985 to 2005 are higher than they would be if winter flows were included. For consistency with observed data, simulated annual mean streamflow values for water years 1985–2005 also do not include December–March streamflow data.

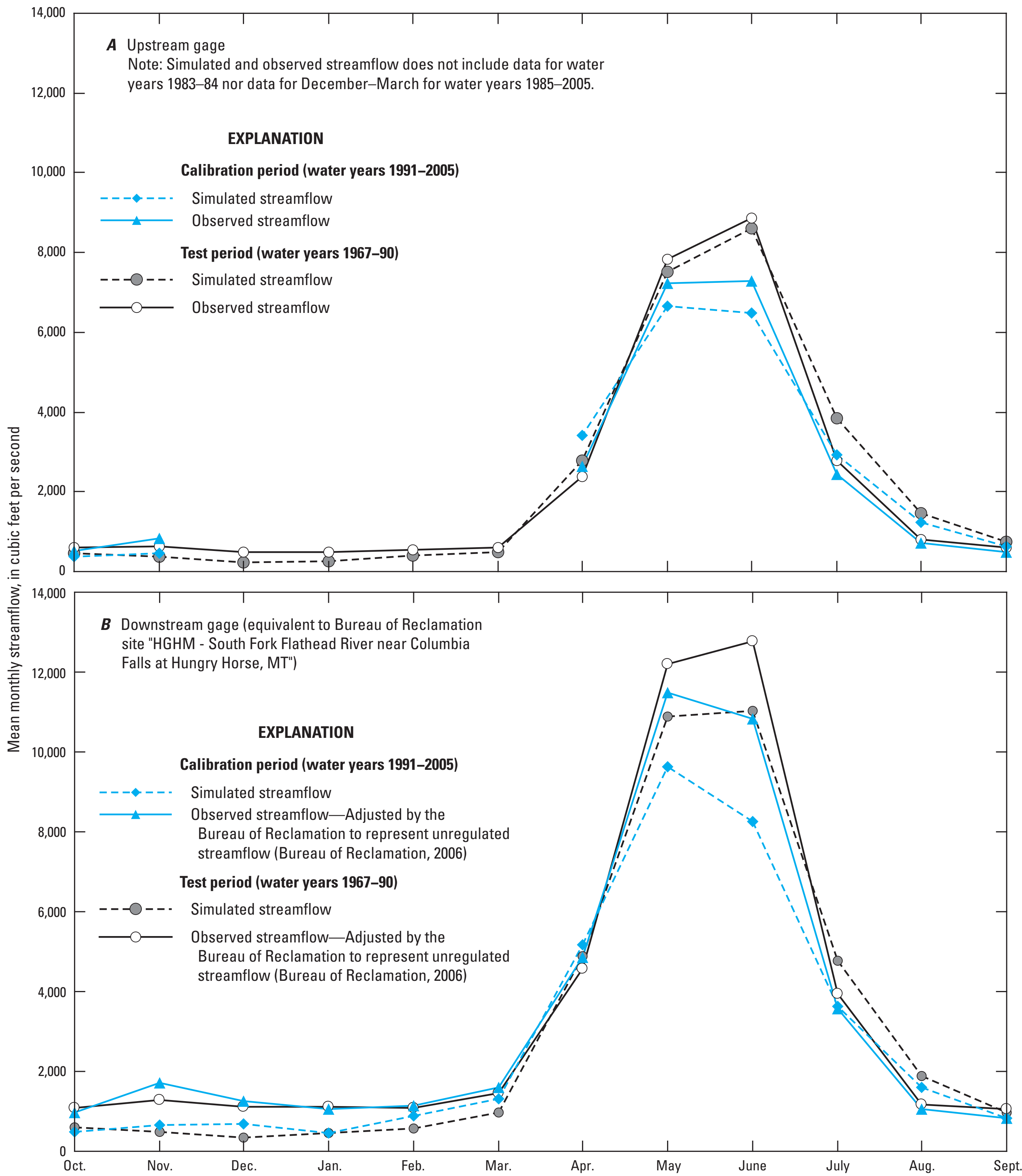


Figure 7. Simulated and observed mean monthly streamflow for the model calibration and test periods. *A*, Upstream gage: South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. *B*, Downstream gage: South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir.

elevations of HRUs 1 and 2 are 4,439 ft and 4,843 ft (above NAVD 88) respectively. Emery Creek represents one point within the basin, whereas the area of HRU 1 is 10 mi^2 and the area of HRU 2 is 12 mi^2.

SWE data measured on or close to the first of each month (fig. 14*B*) at the NRCS Spotted Bear snow-course station south of Hungry Horse Reservoir and near HRUs 41 and 44 (13B02; Natural Resources Conservation Service, 2008; fig. 6) were compared to simulated SWE at HRUs 41 and 44. The observed SWE typically was within 3 in. of the simulated SWE at HRU 41 and typically was 4 to 10 in. higher than the simulated SWE at HRU 44 (fig. 14*B*). The elevation of the Spotted Bear snow-course station could be expected to receive more snow because at 7,000 ft (above NAVD 88), it is higher than the average elevations of HRUs 41 and 44 (5,230 ft and 5,170 ft above NAVD 88, respectively). However, the snow-course station represents one point within the basin, whereas the area of HRU 41 is 21 mi^2 and the area of HRU 44 is 34 mi^2.

Model Calibration Using Alternate Parameter Files

Hydrologic computer models are simplified representations of very complex physical conditions and processes. The spatial and time-series data used in the models are coarse approximations of the physical attributes of the basin and the climate conditions that affect streamflow. Because of the complexity of the physical processes and the coarseness of the data, one model simulation with parameters values from one parameter file might not satisfactorily replicate all hydrologic processes within a basin throughout the year. Model calibration, however, can involve creating alternate parameter files that are better suited to represent, for example, the hydrologic processes in a basin at different times of the year or for wet and dry years (Bevin, 2006).

Additional calibrations were performed for different periods to develop four alternate parameter files (table 7). These alternate calibrations were necessary because the primary-parameter file discussed in the section titled “Model Calibration–Development of the Primary-Parameter File” was developed to represent, as well as possible, the study period (water years 1967–2005), but the data set for the study period contains years with above-normal streamflow and years with below-normal streamflow and a period (water years 1991–2005) in which precipitation and air-temperature data are available for a greater number of stations. The four alternate parameter files were developed by calibrating for a recent period (water years 1991–2005), a historical period (water years 1967–90), a wet period (water years 1989–97), and a dry period (water years 1998–2005). The wet and dry periods were selected on the basis of higher and lower, respectively, annual mean streamflow relative to the annual mean streamflow for the study period. The calibration procedures used to develop each of the alternate parameter files (table 7) were similar to those discussed in the section “Model Calibration–Development of the Primary-Parameter File.” For a given period, a single parameter file can be used to simulate a single streamflow value for each day of simulation, or all five parameter files can be used to simulate a range of streamflow values for each day of simulation.

During the calibration to develop the alternate parameter files, the values of cecn_coef, gwflow_coef, soil_moist_max, and soil_rechr_max (table 3) changed the most. Cecn_coef is an energy coefficient used in the module (snowcomp, table 1) that initiates development, accumulation, and depletion of the snowpack; the value of this parameter was 19.7 in the primary-parameter file and parameter values ranged from 4.8 to 19.9 in the alternate-parameter files. Gwflow_coef is used in the module (gwflow, table 1) that computes the groundwater flow contributions to streamflow; the value of this parameter was 0.02 in the primary-parameter file and parameter values ranged from 0.00175 to 0.00228 in the alternate-parameter files. Values for soil_moist_max and soil_rechr_max (used in the soil-moisture accounting module, smbal, that computes infiltration and evapotranspiration; table 1) varied for each HRU. The average soil_moist_max parameter value was 9.84 in. for the primary-parameter file and the average parameter values ranged from 2.83 to 4.20 in. for the alternate-parameter files. The average soil_rechr_max parameter value was 3.00 for the primary-parameter file and the average parameter values ranged from 0.916 to 3.75 in. for the alternative-parameter files.

Observed annual mean streamflow and annual mean streamflow simulated using the four alternate-parameter files, as well as from the primary-parameter file, are shown in figure 15. Simulated streamflow resulting from the recent parameter file is not shown for water years 1967–86 because the parameter file lacks information for water years 1967–86 and therefore cannot be used during that period. The different parameter files result in a range of simulated annual mean streamflow values each year. Where these values are more simlar, as shown by a narrower range or narrower blue-shaded band (fig. 15), there is less uncertainty in the results. More uncertainty is evident at the downstream gage than at the upstream gage, as shown by the wider range (blue shading) in figure 15*B* relative to that in figure 15*A*.

Percentage differences between simulated and observed annual mean streamflow were calculated for both gages; overestimated streamflow values result in positive percentage differences, underestimated streamflow values result in negative percentage differences, and the range in percentage differences is represented by the blue shading in figure 16. In general, streamflow tended to be overestimated at the upstream gage and underestimated at the downstream gage. At the upstream gage, all or part of the range is within 20 percent for all but 5 water years: water year 1972 (underestimated by 29–40 percent) and water years 1978, 1988, 1993, and 1995 (overestimated by 23–47 percent). At the downstream gage, all or part of the range is within 20 percent for every year but water year 1972 (underestimated by 37–47 percent). Therefore,

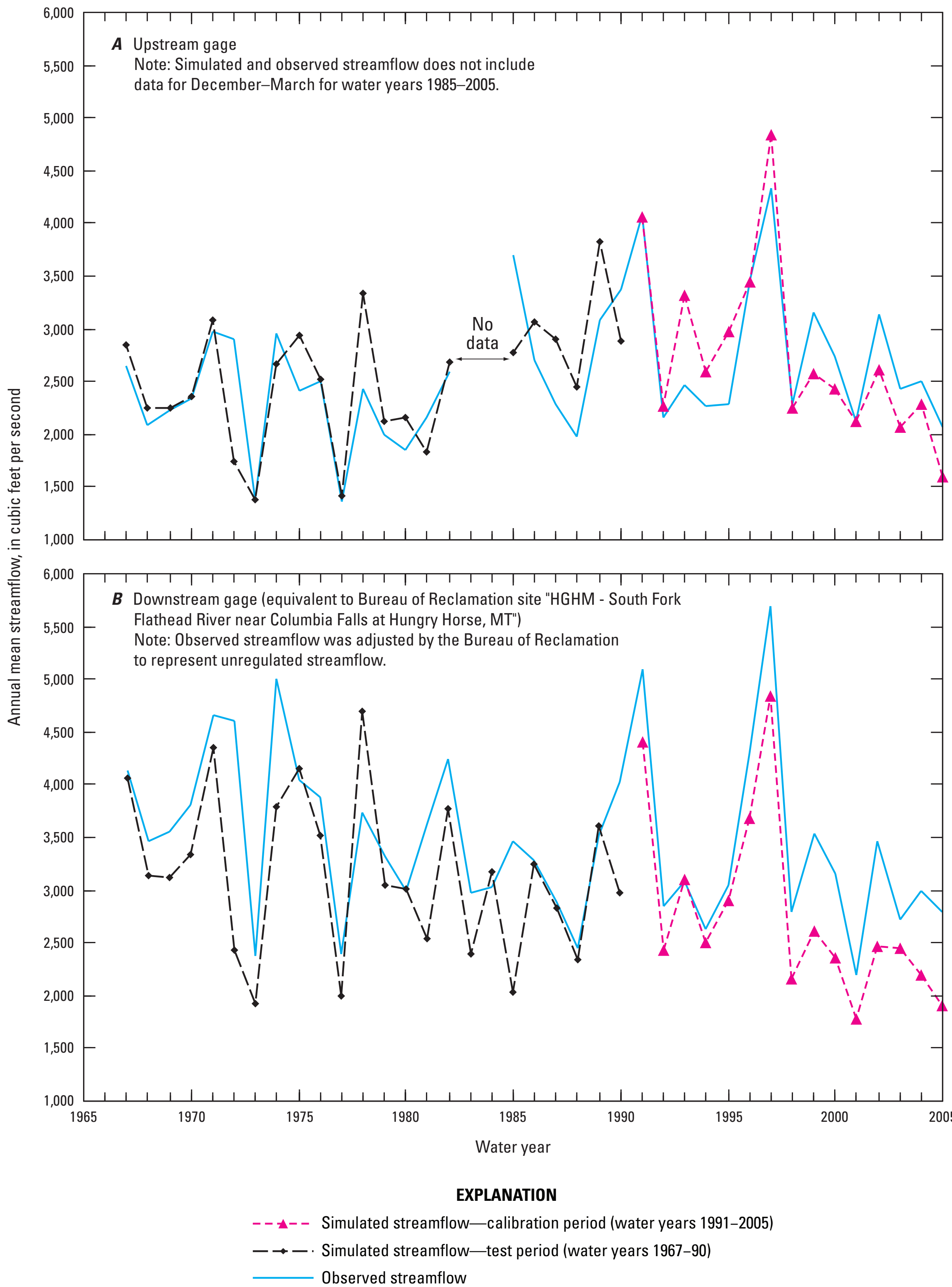


Figure 8. Simulated and observed annual mean streamflow for the calibration and test periods. *A*, Upstream gage: South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. *B*, Downstream gage: South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir.

Table 6. Simulated (primary-parameter file) and observed annual mean streamflow for the study period.

[Upstream gage, South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. Downstream gage, South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir (equivalent to Bureau of Reclamation site "HGHM - South Fork Flathead River near Columbia Falls at Hungry Horse, MT.") The observed streamflow data for this gage were adjusted to represent unregulated streamflow (Bureau of Reclamation, 2006). Percent error is equal to (simulated minus observed) divided by observed: negative percent errors indicate simulations underestimated; positive percent errors indicate simulations overestimated. Abbreviation: ft^3/s, cubic feet per second. Symbol: --, no data]

Water year	Annual mean streamflow at upstream gage			Annual mean streamflow at downstream gage		
	Simulated (ft^3/s)	Observed (ft^3/s)	Percent error	Simulated (ft^3/s)	Observed (ft^3/s)	Percent error
1967	2,840	2,650	7.2	4,070	4,140	-1.7
1968	2,240	2,090	7.2	3,140	3,480	-10
1969	2,250	2,230	.90	3,130	3,560	-12
1970	2,370	2,350	.85	3,340	3,810	-12
1971	3,090	2,970	4.0	4,370	4,660	-6.2
1972	1,740	2,890	-40	2,450	4,610	-47
1973	1,380	1,380	.00	1,930	2,390	-19
1974	2,670	2,950	-9.5	3,790	5,020	-25
1975	2,950	2,410	22	4,150	4,050	2.5
1976	2,520	2,510	.40	3,530	3,900	-9.5
1977	1,420	1,370	3.6	2,020	2,400	-16
1978	3,330	2,430	37	4,690	3,750	25
1979	2,110	1,990	6.0	3,050	3,330	-8.4
1980	2,160	1,840	17	3,020	3,010	.33
1981	1,830	2,160	-15	2,550	3,630	-30
1982	2,690	2,590	3.9	3,780	4,250	-11
1983	--	--	--	2,410	2,990	-19
1984	--	--	--	3,180	3,040	4.6
1985	2,770 [1]	[1]3,700	-25	2,050	3,480	-41
1986	3,060 [1]	[1]2,700	13	3,260	3,300	-1.2
1987	2,910 [1]	[1]2,280	28	2,840	2,890	-1.7
1988	2,440 [1]	[1]1,970	24	2,360	2,460	-4.1
1989	3,830 [1]	[1]3,080	24	3,610	3,530	2.3
1990	2,880 [1]	[1]3,370	-15	2,990	4,030	-26
1991	4,060 [1]	[1]4,090	-.73	4,410	5,100	-14
1992	2,270 [1]	[1]2,160	5.1	2,440	2,850	-14
1993	3,330 [1]	[1]2,470	35	3,110	3,090	.65
1994	2,590 [1]	[1]2,270	14	2,520	2,640	-4.5
1995	2,970 [1]	[1]2,290	30	2,920	3,070	-4.9
1996	3,440 [1]	[1]3,460	-.58	3,690	4,300	-14
1997	4,830 [1]	[1]4,330	12	4,840	5,700	-15
1998	2,250 [1]	[1]2,280	-1.3	2,170	2,800	-23
1999	2,580 [1]	[1]3,150	-18	2,630	3,550	-26
2000	2,430 [1]	[1]2,740	-11	2,370	3,170	-25
2001	2,120 [1]	[1]2,120	.00	1,790	2,210	-19
2002	2,620 [1]	[1]3,130	-16	2,490	3,470	-28
2003	2,070 [1]	[1]2,440	-15	2,460	2,740	-10
2004	2,280 [1]	[1]2,500	-8.8	2,210	3,000	-26
2005	1,590 [1]	[1]2,060	-23	1,920	2,810	-32

[1] As of water year 1985, no winter (December–March) streamflow data are available for this gage. Because December–March tend to be low-flow months, annual mean streamflows from water year 1985 to 2005 are higher than they would be if data for winter streamflows were included. For consistency with observed data, simulated annual mean streamflow values for water year 1985–2005 also do not include December–March streamflow data.

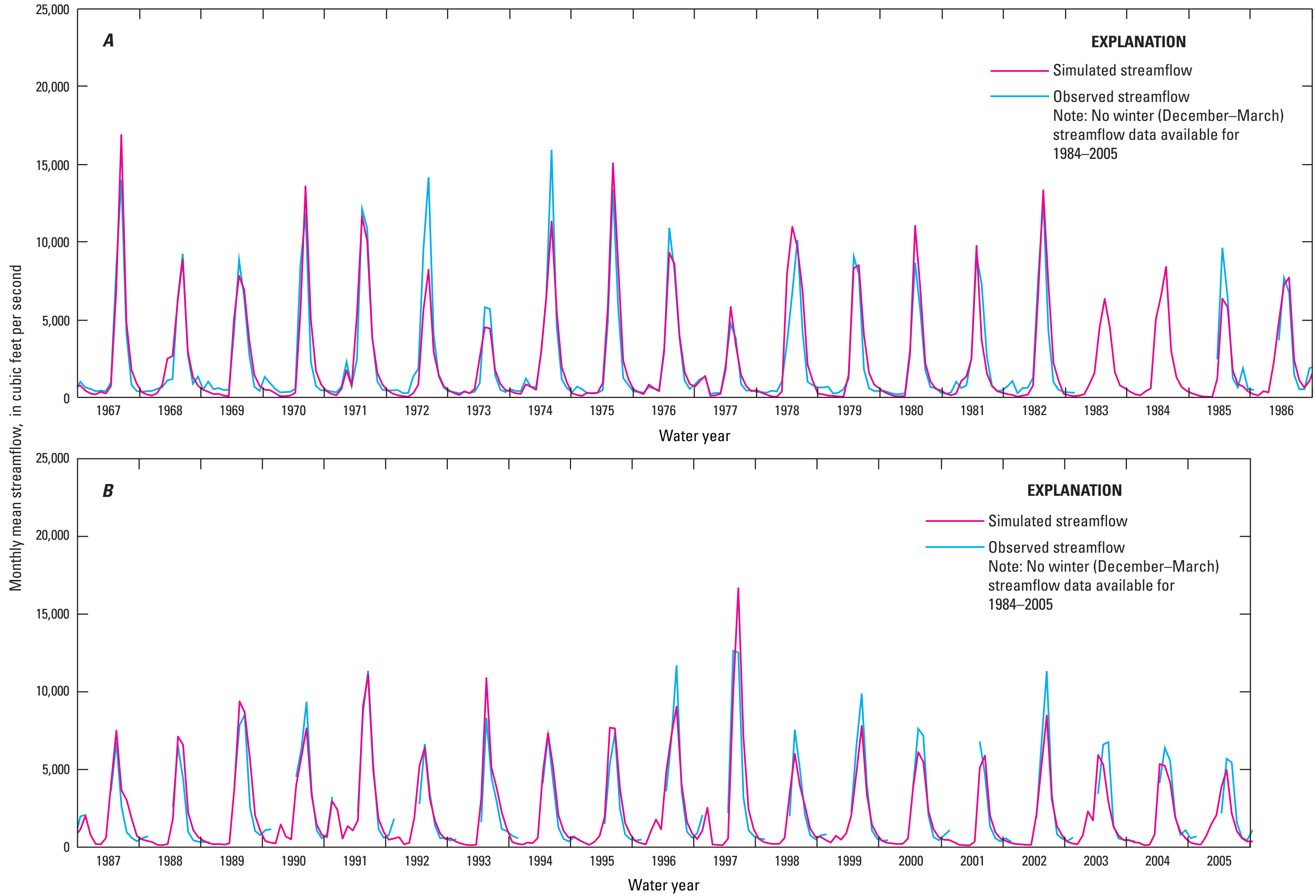


Figure 9. Simulated and observed monthly mean streamflow at the upstream gage: South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. *A*, Water years 1967–86. *B*, Water years 1987–2005.

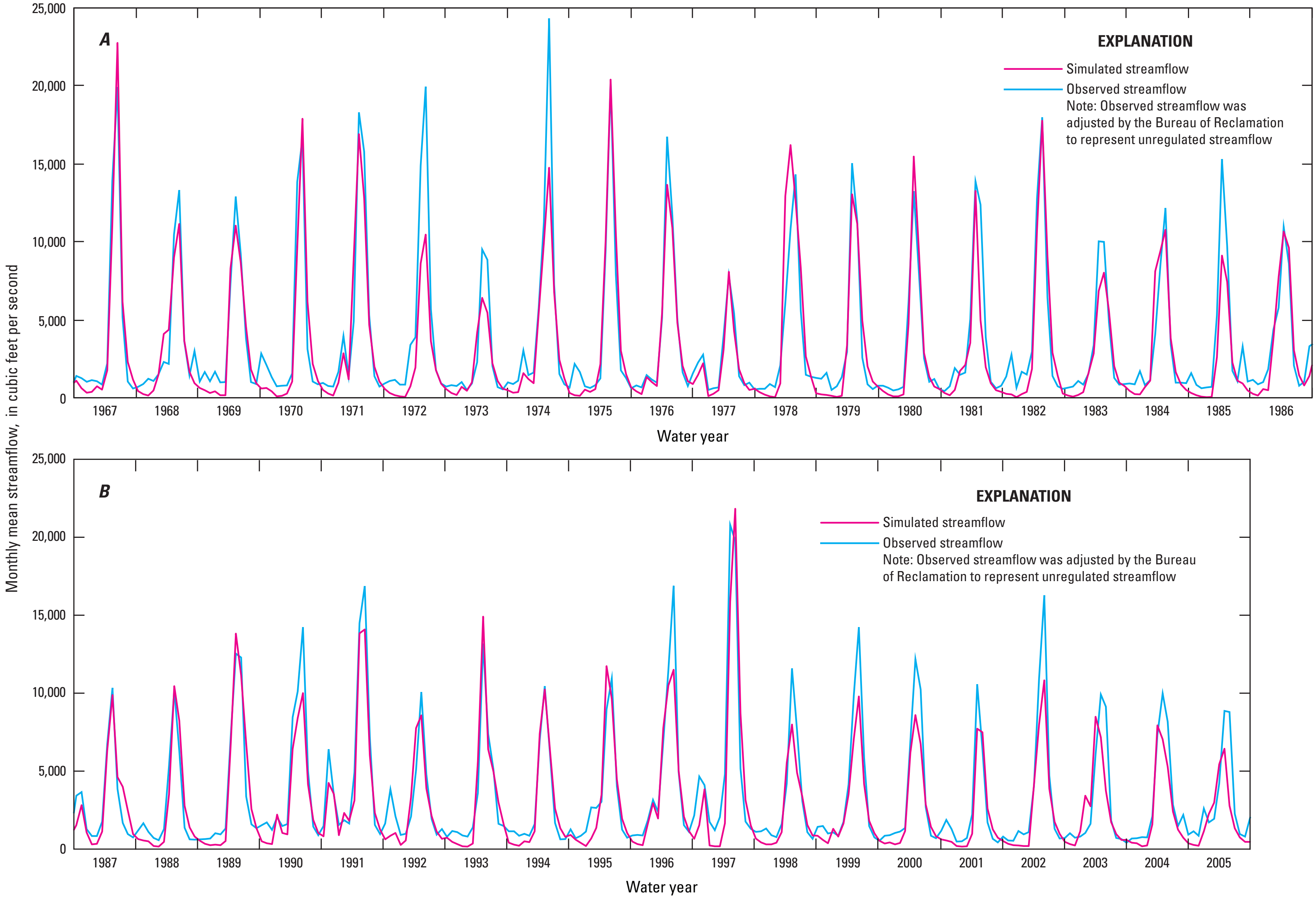


Figure 10. Simulated and observed monthly mean streamflow at the downstream gage: South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir. *A*, Water years 1967–86. *B*, Water years 1987–2005. This gage is equivalent to Bureau of Reclamation site “HGHM - South Fork Flathead River near Columbia Falls at Hungry Horse, MT” downstream from Hungry Horse Reservoir.

when all the parameter files are used, simulated flow can differ from observed flow by more than 20 percent for some years.

Potential Uses and Limitations of the Model

The PRMS model developed for the South Fork Flathead River Basin can be used to estimate possible future streamflow scenarios. Initial model simulations can be based on historical data, and then time-series data files containing projected precipitation and air-temperature data can be used to simulate future ensembles of streamflow (one set of simulated streamflow data for each time-series data file containing projected precipitation and air temperature). For each data file of projected precipitation and air temperature, a single parameter file can be used to simulate a single streamflow value for each day of simulation, or all five parameter files can be used to simulate a range of streamflow values for each day of simulation.

The model is a mathematical representation of the physical conditions and processes in the South Fork Flathead River Basin. Potential errors include errors in the mathematical representation of the physical conditions and processes (model errors); errors in the precipitation, air temperature, streamflow, SR, PE, and SCA data (time-series data errors); errors in the distribution of the time-series data to the HRUs (time-series data interpolation errors); and errors associated with the values of the model parameters (parameter errors).

The model was calibrated to daily mean and mean monthly unregulated streamflow at the upstream gage and to mean monthly unregulated streamflow at the downstream gage. Streamflow from subbasins on each side of Hungry Horse Reservoir also are simulated by the model, but because no data were available for calibration at those locations, the uncertainties associated with the model results at those locations are unknown. Losses due to evaporation from the Hungry Horse Reservoir were not included in the simulations. The model was not calibrated to extremely high or low daily streamflow, nor was it created to simulate storm events (storm events can be better simulated with air temperature and precipitation data at hourly or minute intervals). The parameter values for soils, land cover, and forest type do not reflect changes caused by periodic forest fires. The precipitation and air-temperature data used in the model represent only a few points in and near the South Fork Flathead River Basin; some error is introduced when the precipitation and air-temperature data are distributed to HRUs within the basin.

Calibration and test results (fig. 11) showed that some observed runoff events were not simulated by the model, primarily due to insufficient amounts of data in the basin. Simulated mean annual and mean April–July streamflow values differed from observed values by 0 to 17 percent. Simulated August monthly mean streamflow was as much as 84 percent higher than observed monthly mean streamflow. These differences could be due to the static nature of the parameters, to errors in the way the model distributes the precipitation and air-temperature data to the basin, or to the other errors discussed in preceding paragraphs in this section.

The simulated snowpack accumulated to 90–100 percent SCA earlier in the season than the observed snowpack, both before and after calibration. This overestimated snowpack corresponded with underestimated streamflow during October–February (fig. 7). This overestimation of fall–winter SCA and thus the underestimation of fall–winter mean monthly streamflow could be due to unreliable results produced by the regression equations that were used to distribute air-temperatures from the climate stations to the HRUs for those months. The discrepancies also could be due to incorrect values for other parameters, such as the settings that control temperatures at which precipitation falls as snow instead of rain.

Summary

The U.S. Geological Survey, in cooperation with the Bureau of Reclamation (Reclamation), developed a precipitation-runoff model for the South Fork Flathead River Basin in northwestern Montana. The Precipitation-Runoff Modeling System was used to simulate daily mean unregulated streamflow upstream and downstream from Hungry Horse Reservoir. Two input files are required to run the model. The time-series data file contains daily precipitation data and daily minimum and maximum air-temperature data from climate stations in and near the South Fork Flathead River Basin. The parameter file contains values of parameters that describe the basin topography, the flow network, the distribution of the precipitation and temperature data, and the hydrologic characteristics of the basin soils and vegetation.

The model was calibrated automatically by using the computer program **L**et **U**s **Ca**librate (LUCA). A primary-parameter file was created for simulating streamflow during water years 1967–2005. For this primary-parameter file, the model was calibrated for water years 1991–2005. This calibration was further refined using snow-covered area data for water years 2001–05. The model then was tested for water years 1967–90. Streamflow simulated by the model was calibrated against mean monthly and daily mean unregulated streamflow at the gage upstream from Hungry Horse Reservoir, and against mean monthly unregulated streamflow calculated by the Bureau of Reclamation for the gage downstream from the reservoir. Calibration also included basin mean-monthly solar radiation and potential evapotranspiration and daily snapshots of basin snow-covered area.

Simulated streamflow generally was in better agreement with observed streamflow at the upstream gage than at the downstream gage. Upstream from the reservoir, simulated mean annual streamflow was within 0.0 percent of observed mean annual streamflow for the calibration period and was about 2 percent higher than observed mean annual streamflow

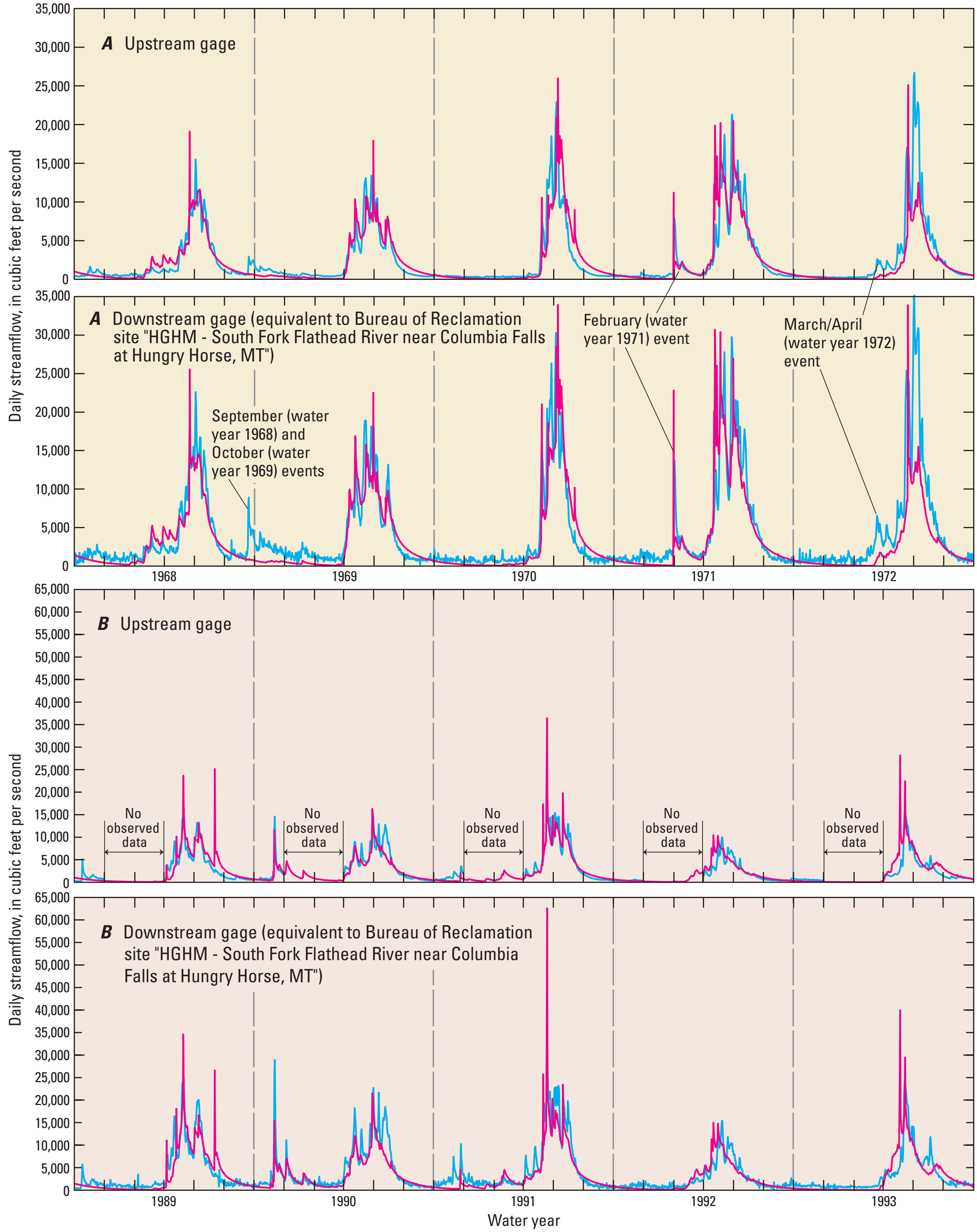


Figure 11. Simulated and observed daily mean streamflow for the upstream gage, South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir, and the downstream gage, South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir. *A*, Water years 1968–72. *B*, Water years 1989–93. *C*, Water years 2001–05. Observed streamflow at the downstream gage was adjusted by the Bureau of Reclamation (2006) to represent unregulated streamflow.

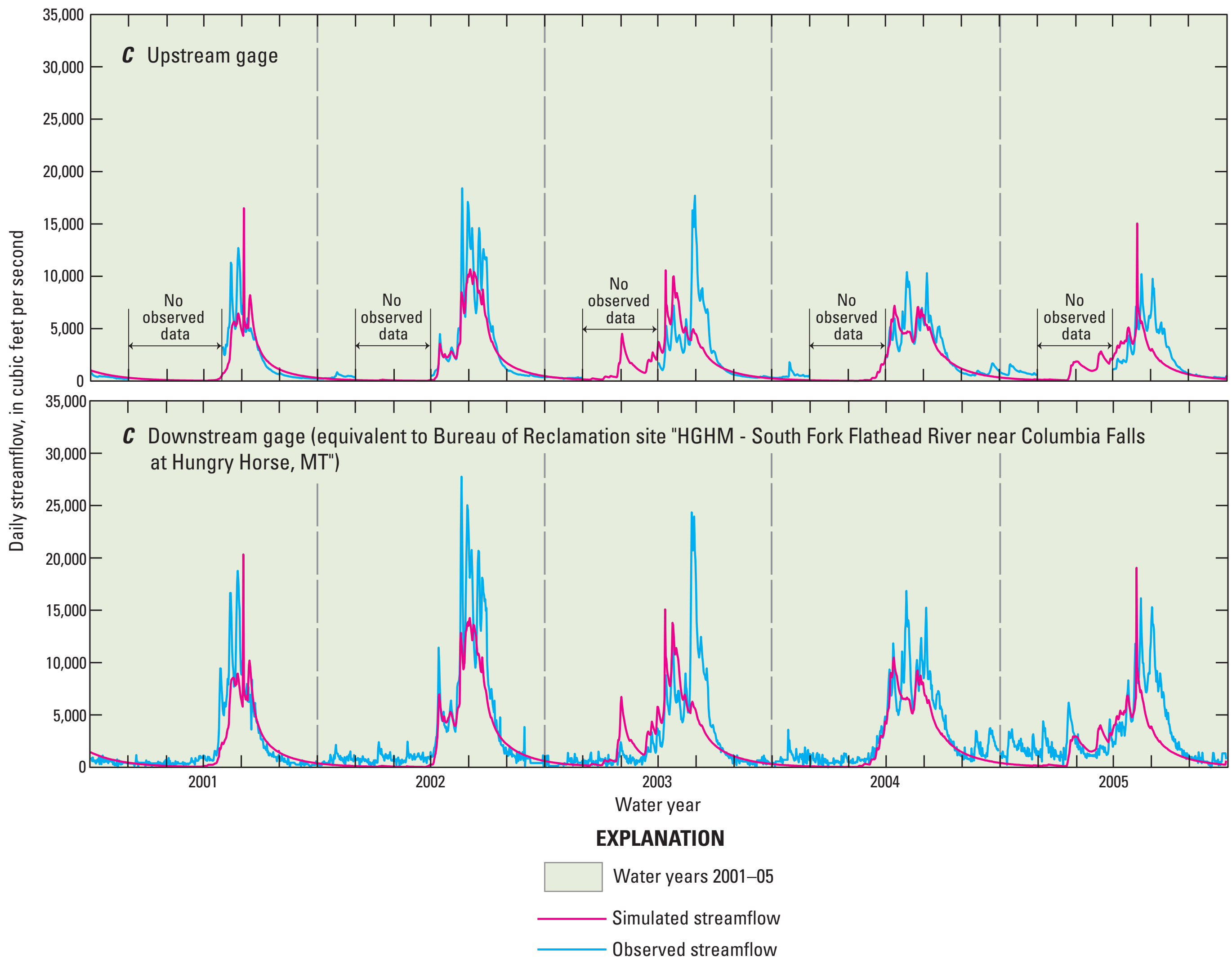


Figure 11. Simulated and observed daily mean streamflow for the upstream gage, South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir, and the downstream gage, South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir. *A*, Water years 1968–72. *B*, Water years 1989–93. *C*, Water years 2001–05. Observed streamflow at the downstream gage was adjusted by the Bureau of Reclamation (2006) to represent unregulated streamflow.—Continued

for the test period. Simulated mean April–July streamflow upstream from the reservoir was about 1 percent lower than observed streamflow for the calibration period and about 4 percent higher than observed for the test period. Downstream from the reservoir, simulated mean annual streamflow was 17 percent lower than observed streamflow for the calibration period and 12 percent lower than observed streamflow for the test period. Simulated mean April–July streamflow downstream from the reservoir was 13 percent lower than observed streamflow for the calibration period and 6 percent lower than observed streamflow for the test period.

Calibrating the model to solar radiation (SR), potential evapotranspiration (PE), and snow-covered area (SCA) improved the model representation of evapotranspiration, snow accumulation, and snowmelt processes. Simulated basin mean monthly SR values for both the calibration and test periods were within 9 percent of observed values except during the month of December (28 percent different). Simulated basin PE values for both the calibration and test periods were within 10 percent of observed values except during the months of January (100 percent different) and February (13 percent different). The larger percent errors in simulated potential evaporation occurred in the winter months when observed PE values were very small; in January the observed value was 0.000 inches and in February the observed value was 0.009 inches. Simulated start of melting of the snowpack occurred at about the same time as observed start of melting. The simulated snowpack accumulated to 90–100 percent snow-covered

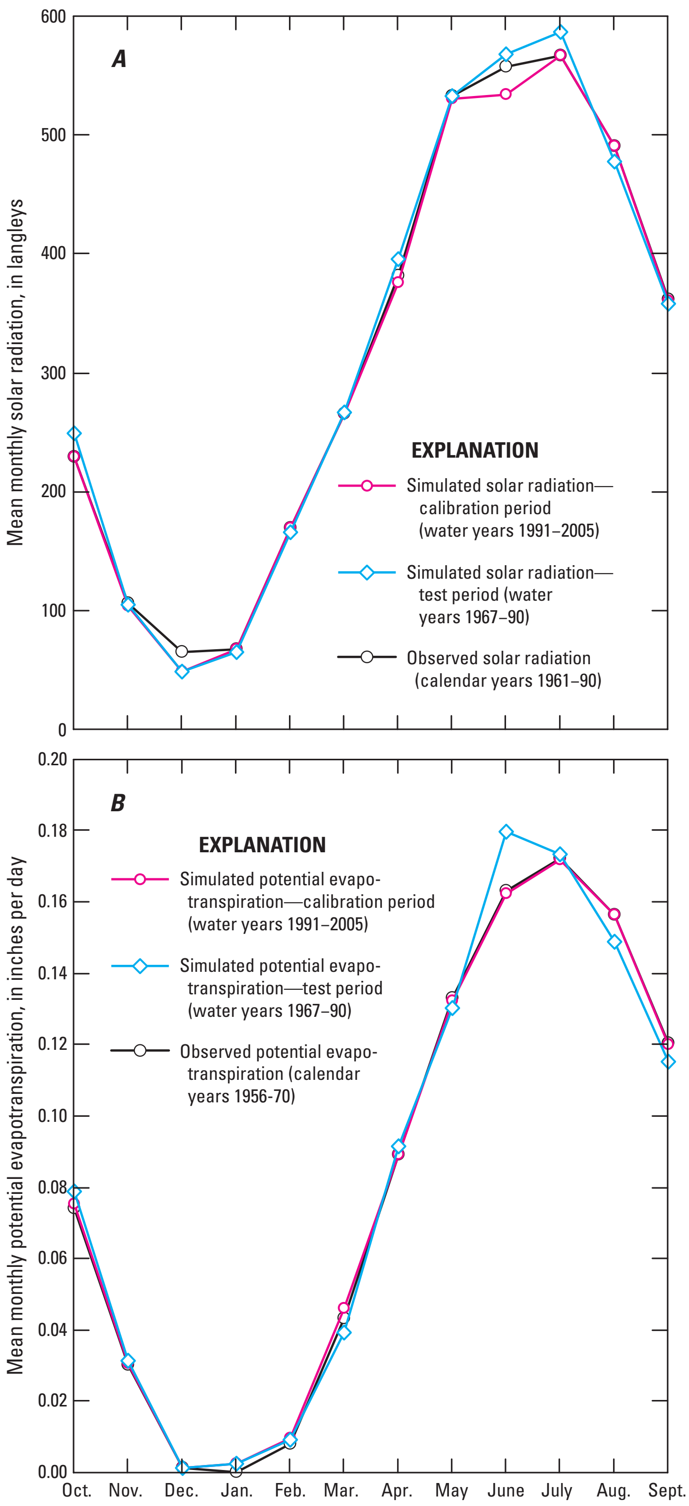


Figure 12. Simulated and observed climate variables for the South Fork Flathead River Basin, Mont. *A*, Mean monthly solar radiation. *B*, Mean monthly potential evapotranspiration.

area 1 to 3 months earlier than observed snowpack. This overestimated snowpack during the winter corresponded to underestimated streamflow during the same time period.

In addition to the primary-parameter file, four other parameter files were created: for a “recent” period (1991–2005), a historical period (1967–90), a “wet” period (1989–97), and a “dry” period (1998–2005). For each data file of projected precipitation and air temperature, a single parameter file can be used to simulate a single streamflow value for each day of simulation, or all five parameter files can be used to simulate a range of streamflow values for each day of simulation.

The model can be used to estimate possible future streamflow scenarios. Initial model simulations can be based on historical data, and then time-series data files containing projected precipitation and air-temperature data can be used to simulate future ensembles of streamflow (one set of simulated streamflow data for each time-series data file containing projected precipitation and air temperature). The user also can run the model with different combinations of parameters files and time-series files to simulate ranges of daily mean streamflow values.

The model has several limitations. It was calibrated to daily mean and mean monthly unregulated streamflow at the upstream gage and to mean monthly unregulated streamflow at the downstream gage. Streamflow from subbasins on the east and west sides of Hungry Horse Reservoir also is simulated by the model, but because no data were available for calibration at those locations, the uncertainty and quality of the model results at those locations are unknown. Losses due to evaporation from Hungry Horse Reservoir were not included in the simulations. The model was not calibrated to extremely high or low streamflow and was not created to simulate storm events. The parameter values for soils, land cover, and forest type do not reflect changes caused by periodic forest fires. Some error is introduced to the model when precipitation and air-temperature data are distributed from the climate stations to hydrologic response units in the basin. Calibration and test results show that some observed runoff events are not simulated by the model, primarily due to insufficient amounts of data in the basin. Simulated August monthly mean streamflow was up to 84 percent higher than observed monthly mean streamflow.

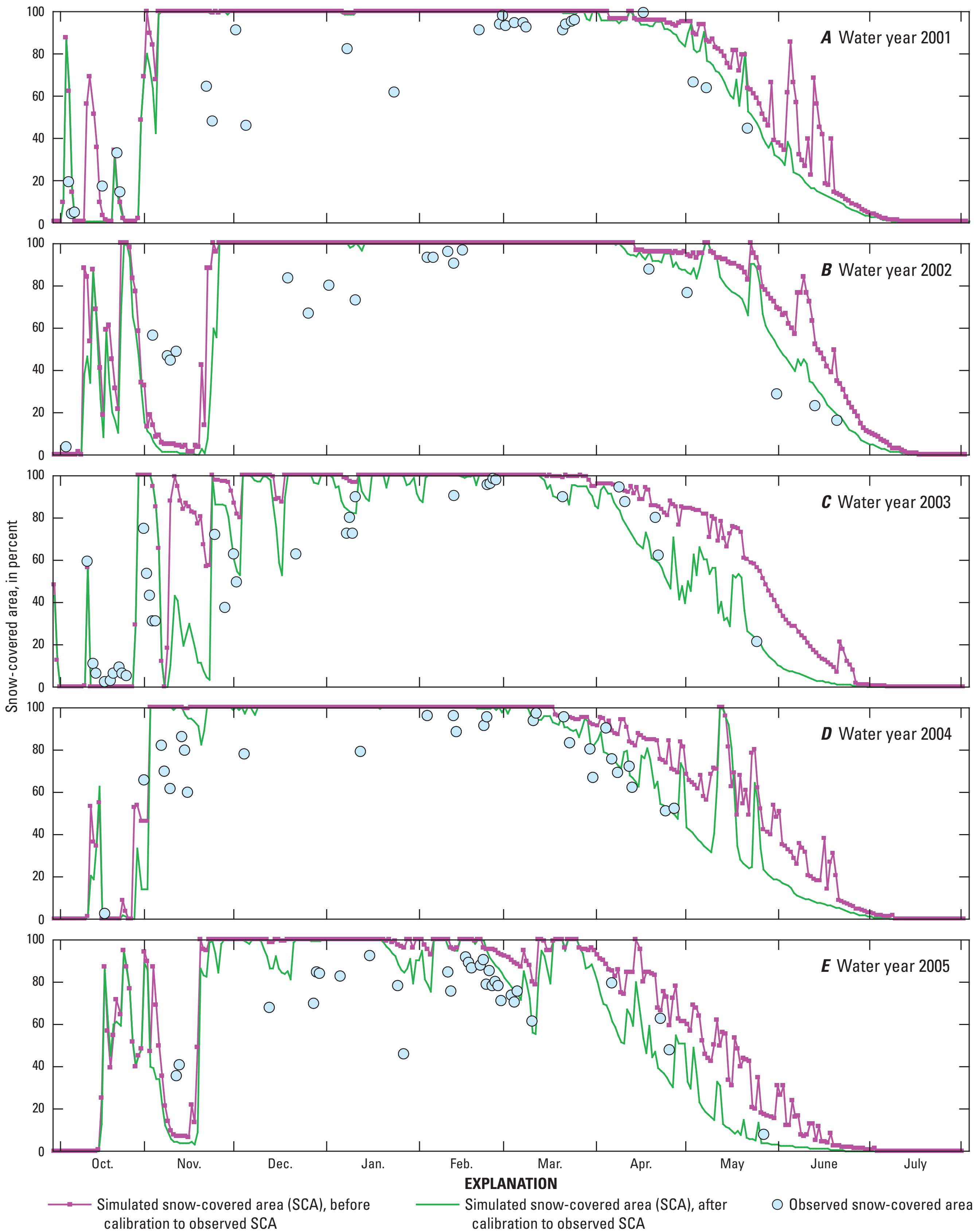


Figure 13. Simulated and observed snow-covered area for the South Fork Flathead River Basin, Mont. *A*, Water year 2001. *B*, Water year 2002. *C*, Water year 2003. *D*, Water year 2004. *E*, Water year 2005. Observed snow-covered area from Lauren E. Hay (U.S. Geological Survey, written commun., 2007) using methods described in Hay, Leavesley, and Clark (2006).

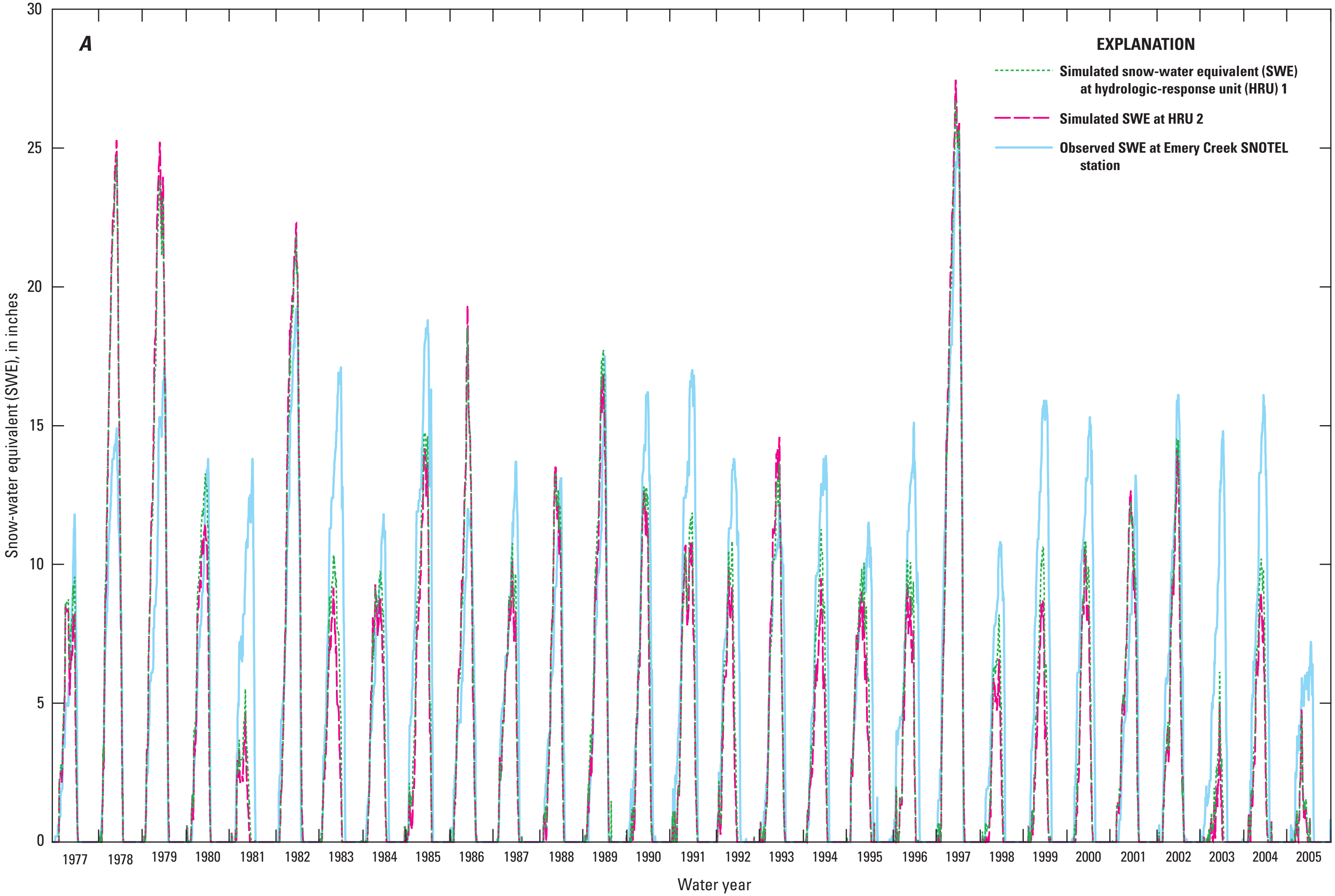


Figure 14. Simulated and observed snow-water equivalent (SWE) for selected locations in the South Fork Flathead River Basin, Mont., water years 1977–2005. *A*, Natural Resources Conservation Service (NRCS) Emery Creek Snowpack Telemetry (SNOTEL) station (13A24S; Natural Resources Conservation Service, 2006) and hydrologic response units 1 and 2. *B*, NRCS Spotted Bear snow-course station (13B02; Natural Resources Conservation Service, 2008) and hydrologic response units 41 and 44.

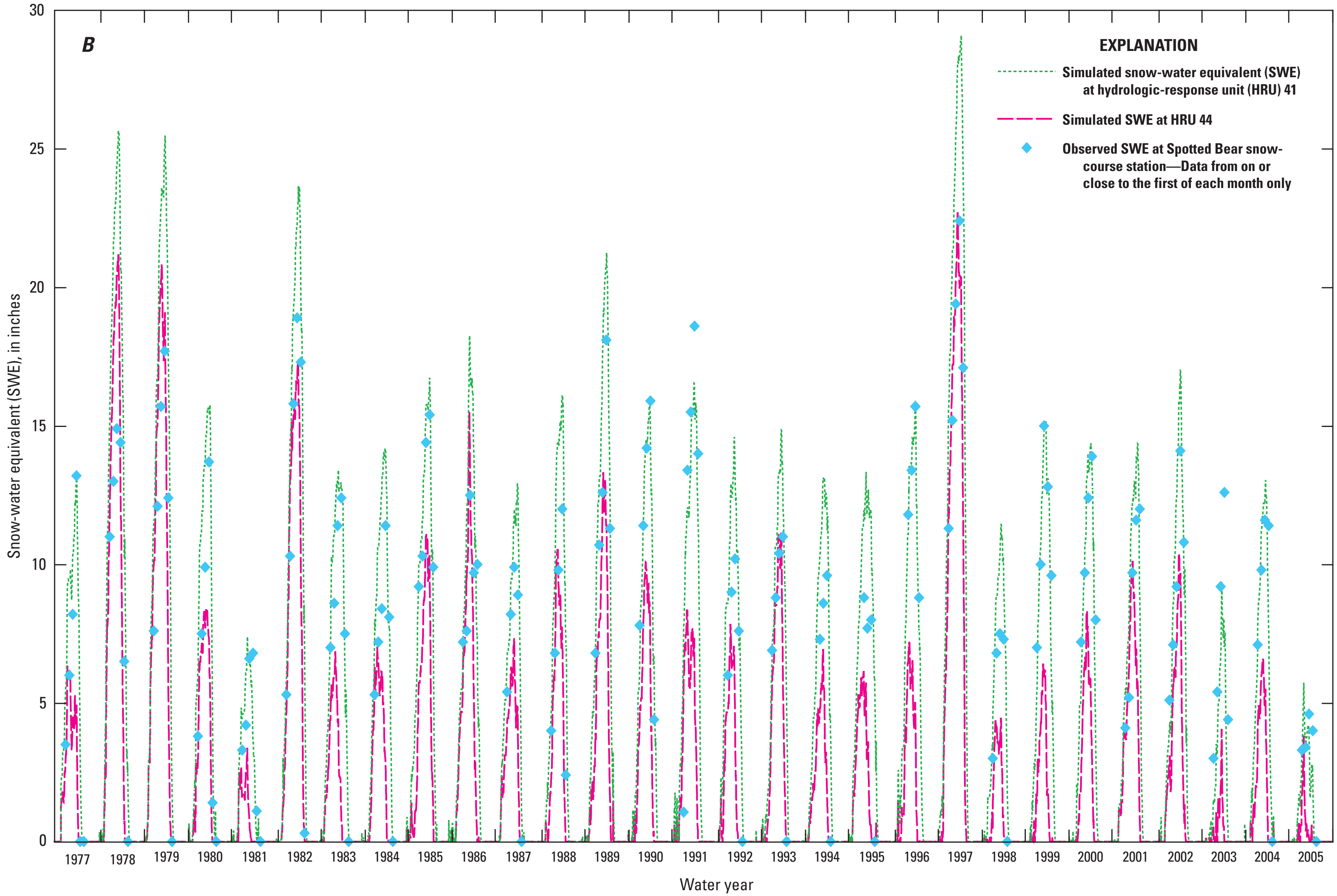


Figure 14. Simulated and observed snow-water equivalent (SWE) for selected locations in the South Fork Flathead River Basin, Mont., water years 1977–2005. *A*, Natural Resources Conservation Service (NRCS) Emery Creek Snowpack Telemetry (SNOTEL) station (13A24S; Natural Resources Conservation Service, 2006) and hydrologic response units 1 and 2. *B*, NRCS Spotted Bear snow-course station (13B02; Natural Resources Conservation Service, 2008) and hydrologic response units 41 and 44.—Continued

Table 7. Alternate parameter files developed for the precipitation-runoff model.

[Downstream gage, South Fork Flathead River near Columbia Falls, Mont. (12362500; equivalent to Bureau of Reclamation site "HGHM - South Fork Flathead River near Columbia Falls at Hungry Horse, MT"); upstream gage, South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800). The observed streamflow data for this gage were adjusted to represent unregulated streamflow (Bureau of Reclamation, 2006). Abbreviations: SR, solar radiation; PE, potential evapotranspiration]

Parameter-file name	Calibration period (water years)	Calibration targets
Recent period	1991–2005	Mean monthly SR. Mean monthly PE. Mean monthly streamflow at downstream gage. Mean monthly streamflow at upstream gage. Daily mean streamflow at upstream gage. Basin snow-covered area.
Historical period	1967–90	Mean monthly SR. Mean monthly PE. Mean monthly streamflow at downstream gage. Mean monthly streamflow at upstream gage. Daily mean streamflow at upstream gage.
Wet period[1]	1989–97	Mean monthly SR. Mean monthly PE. Mean monthly streamflow at downstream gage. Mean monthly streamflow at upstream gage. Daily mean streamflow at upstream gage.
Dry period[2]	1998–2005	Mean monthly SR. Mean monthly PE. Mean monthly streamflow at downstream gage. Mean monthly streamflow at upstream gage. Daily mean streamflow at upstream gage.

[1] Observed mean annual streamflow during this period is higher than the mean annual streamflow for the study period (water years 1967–2005).

[2] Observed mean annual streamflow during this period is lower than the mean annual streamflow for the study period (water years 1967–2005).

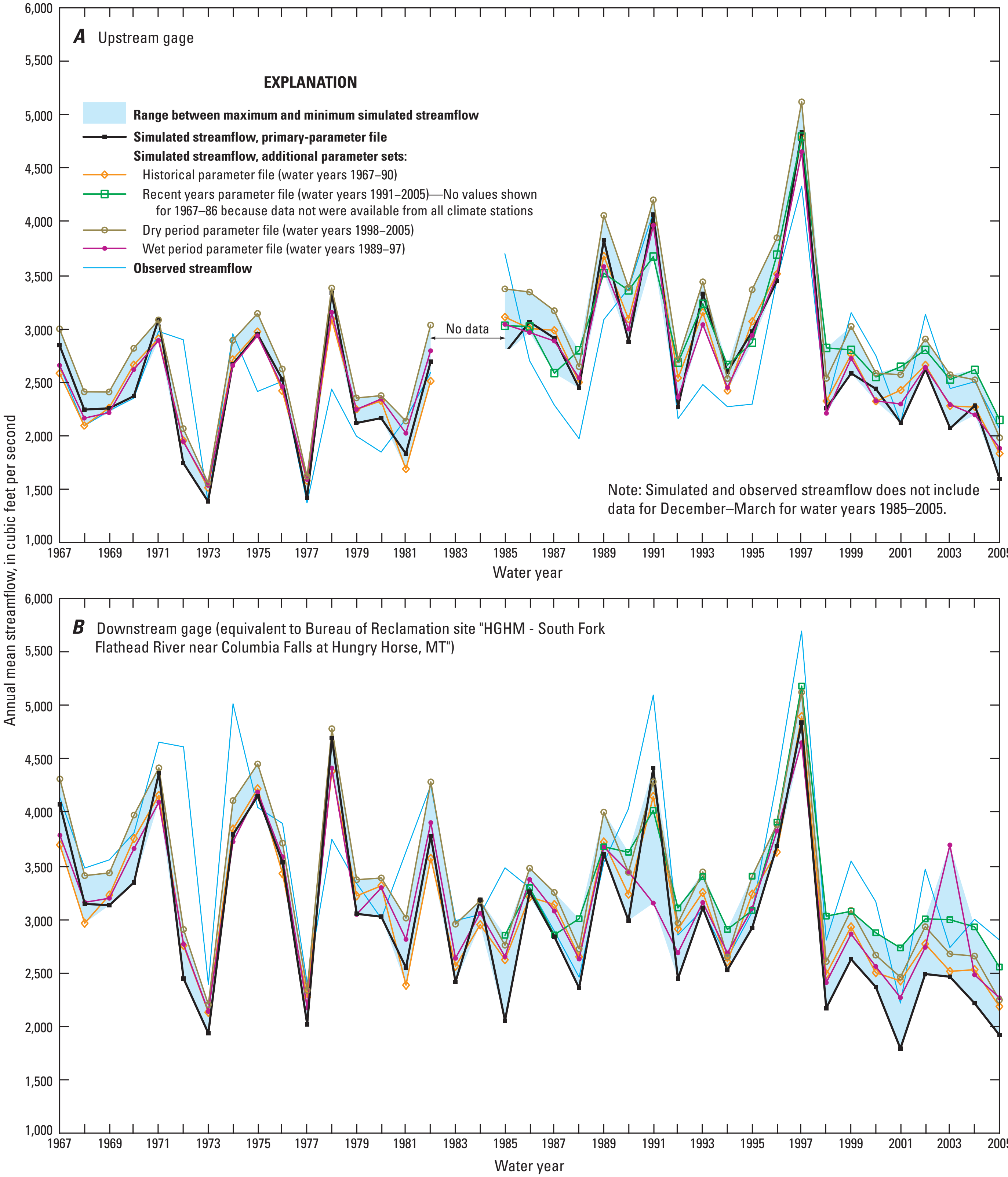


Figure 15. Simulated and observed annual mean streamflow for the primary and alternate parameter files used with the precipitation-runoff model, South Fork Flathead River Basin, Mont., water years 1967–2005. *A*, Upstream gage: South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. *B*, Downstream gage: South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir. Observed streamflow at the downstream gage was adjusted by the Bureau of Reclamation (2006) to represent unregulated streamflow.

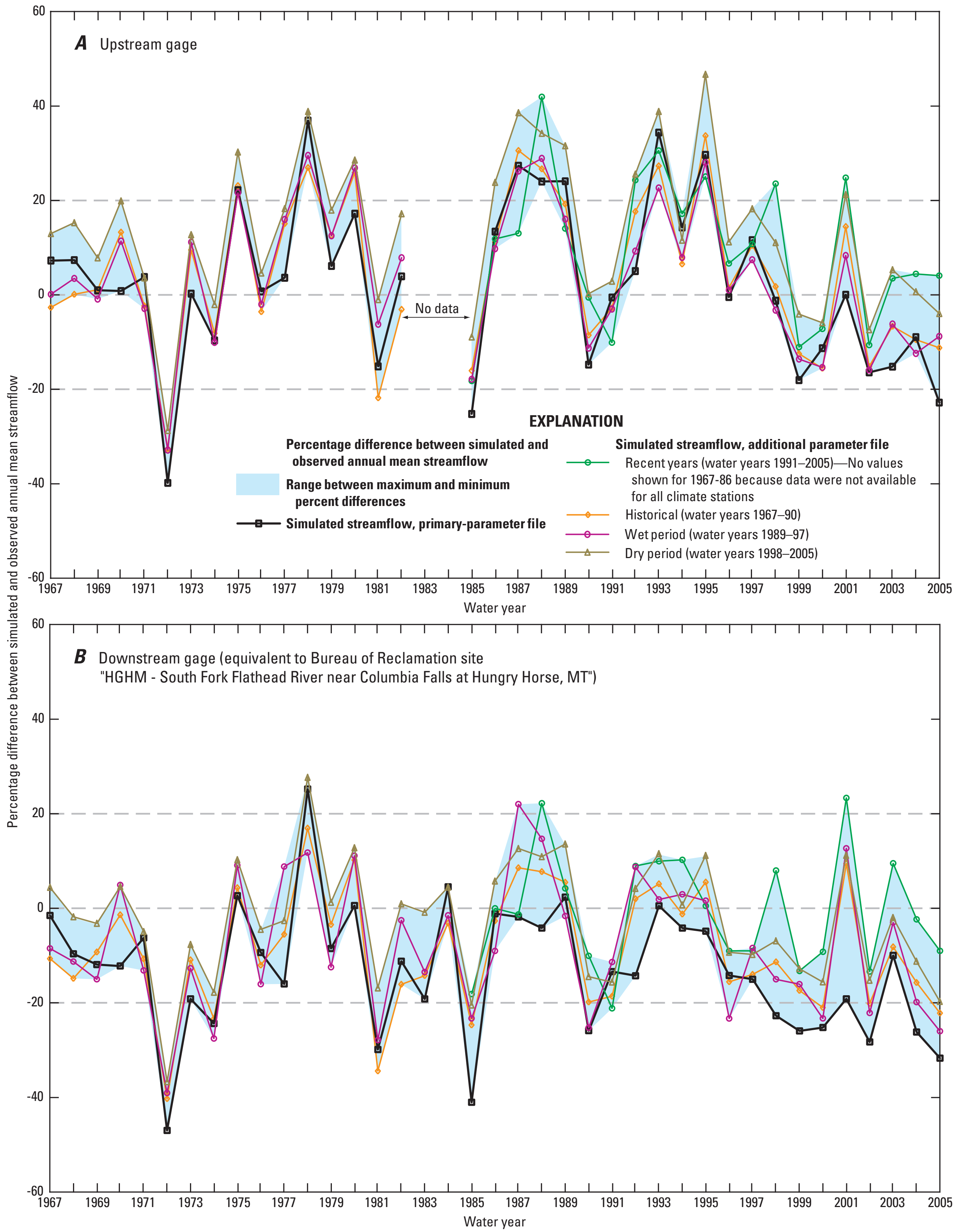


Figure 16. Percentage difference between simulated and observed annual mean streamflow for primary and alternate parameter files used with the precipitation-runoff model, South Fork Flathead River Basin, Mont., water years 1967–2005. *A*, Upstream gage: South Fork Flathead River above Twin Creek, near Hungry Horse, Mont. (12359800), upstream from Hungry Horse Reservoir. *B*, Downstream gage: South Fork Flathead River near Columbia Falls, Mont. (12362500), downstream from Hungry Horse Reservoir. Observed streamflow at the downstream gage was adjusted by the Bureau of Reclamation (2006) to represent unregulated streamflow.

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