PRECIPITATION-RUNOFF SIMULATIONS OF CURRENT AND NATURAL STREAMFLOW CONDITIONS IN THE METHOW RIVER BASIN, WASHINGTON

Water-Resources Investigations Report 03-4246

Prepared in cooperation with ***OKANOGAN COUNTY***

Photograph of Methow River, south of Winthrop, Washington facing north.
Photograph taken by Matthew Ely, U.S. Geological Survey, June 10, 2003.

U.S. DEPARTMENT OF THE INTERIOR
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Tacoma, Washington
2003

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, *Secretary*

U.S. GEOLOGICAL SURVEY
Charles G. Groat, *Director*

For additional information write to:

Director, Washington Water Science Center
U.S. Geological Survey
1201 Pacific Avenue – Suite 600
Tacoma, Washington 98402
http://wa.water.usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Building 810
Box 25286, Federal Center
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CONVERSION FACTORS AND DATUMS

CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile (ft^3/s)/mi	0.02832	cubic meter per second per mile
foot (ft)	0.3048	meter
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
inch per day (in/d)	25.4	millimeter per day
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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

°C=(°F-32)/1.8.

DATUMS

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). **Horizontal coordinate information** is referenced to the North American Datum of 1983 (NAD 83).

Precipitation-Runoff Simulations of Current and Natural Streamflow Conditions in the Methow River Basin, Washington

By D. Matthew Ely

ABSTRACT

Management of the water resources of the Methow River Basin is changing in response to the listing of three species of fish under the Endangered Species Act and the Washington State-legislated watershed-planning process. This report describes the construction and calibration of an enhanced precipitation-runoff model for the Methow River Basin and evaluates the model as a predictive tool for assessing the current and natural streamflow conditions.

This study builds upon a previous precipitation-runoff model for the Methow River Basin and validates the current model using a new, more extensive streamflow data network. The major enhancement was the simulation of current flow conditions with the addition of irrigation diversions, returns, and application. The Geographic Information System Weasel characterized the physical properties of the basin and the Modular Modeling System, using the Precipitation-Runoff Modeling System, simulated the hydrologic flow.

Streamflow was simulated for water years 1992–2001 to calibrate the model to measured streamflows. A sensitivity analysis was completed using nonlinear regression to determine hydrologic parameters pertinent to the modeling results. Simulated and measured streamflow generally showed close agreement, especially during spring runoff from snowmelt. Low-flow or baseflow periods, most restrictive to fish habitation, were simulated reasonably well yet possessed the most uncertainty. Simulations of annual mean streamflow as a percentage of measured annual mean streamflow for the 10-year calibration period at six of the seven streamflow-gaging stations ranged from -35.2 to +26.2 percent, with 65 percent of the simulated values within 15 percent. One station was intentionally calibrated to over-simulate discharge (simulated discharge greater than measured discharge) in order to compensate for observed channel losses not simulated by the model. Simulation of water years 1960-2001 demonstrated great variability in monthly streamflow statistics. The simulated mean monthly flows for 11 streamflow-gaging stations were an average of 2.5 percent higher for water years 1992-2001 than for the entire simulation period. If water year 2001, an extreme drought year, is omitted, simulated mean monthly flows for the 11 streamflow-gaging stations were an average of 9.0 percent higher than for the entire simulation period. The calibrated model also examined the effects of irrigation-canal seepage on streamflow. Irrigation-canal seepage contributed to streamflow throughout the year, with the greatest effect during the irrigation season.

INTRODUCTION

Management of the water resources of the Methow River Basin in eastern Washington is changing in response to the listing of three species of fish under the Endangered Species Act (ESA) and the Washington State-legislated watershed-planning process (Engrossed Substitute House Bill 2514). Water resources are used in the basin for human consumption and irrigation. Management options must be considered that minimize adverse effects on people but meet instream flow needs for fish. Diversions of water from the Methow River above existing and historical streamflow-gaging stations make it difficult to assess the natural streamflow conditions in the basin. To better estimate the effects of different management strategies throughout the basin prior to their implementation, a watershed model can be used to estimate both natural streamflow conditions and flows that could result from different management options. At present, such a management tool does not exist.

The U.S. Geological Survey (USGS), in cooperation with Okanogan County, began a study in October 2000 to evaluate natural streamflow for the Methow River and its tributaries. In the first phase of the study a basin-wide precipitation-runoff model for the watershed was constructed and calibrated to simulate daily natural streamflow at selected sites throughout the basin (Ely and Risley, 2001). The first phase discussed the limitations of accurately simulating natural streamflow, considering that locations where most data were measured (streamflow-gaging stations) were located below diversions and therefore did not represent the natural flow system. In the second phase, discussed in this report, an improved precipitation-runoff model is constructed and evaluated for its accuracy as a predictive tool for assessing current and natural streamflow conditions. This model builds upon the previous watershed model. The current model is validated using a new, more extensive streamflow data network. The major enhancement was the simulation of current flow conditions with the addition of irrigation application, diversions, and returns. Further refinement was accomplished through the use of more detailed soil and land-use data. A calibrated watershed model could provide a tool to assess the available water resources throughout the basin and simulate long-term time-series of the natural streamflow conditions.

In certain years, moisture availability is limited by climatic conditions and streamflow become severely reduced, resulting in dewatered reaches, winter icing, and higher summertime water temperatures (Washington Conservation Commission, 2000). If conditions are severe enough, the extent of dewatered reaches can expand, restricting access to habitat by fish, dewatering redds (nests where females deposit eggs), and stranding juvenile fish. Furthermore, it has been suggested that human alteration of the basin exacerbates naturally limiting conditions (Washington Conservation Commission, 2000). These actions could include construction of roads and dikes, conversion of riparian habitat to agriculture and residential development, and water diversions. For these reasons, periods of low streamflow, typical in late-summer months, are of primary interest and are the focus of this study.

The term “natural” streamflow refers to streamflow conditions that would exist if irrigation diversion take-outs and returns were not present. Natural streamflow is stressed in this report because surface water within the Methow River Basin is used extensively for agricultural irrigation. Through a system of irrigation canals, ranging from unlined to completely constructed of pipe, surface water is diverted from streams and spread over fields during the period from mid-April to early October. This practice dates back to the late 1800s and predates any formal streamflow-gaging measurements. Therefore, streamflow conditions that would exist if irrigation diversion take-outs and returns were not present are unknown.

To protect habitat for naturally producing salmonid populations, the National Marine Fisheries Service (NMFS) set minimum instream flow requirements for three tributaries to the Methow River: the Chewuch River, Early Winters Creek, and Wolf Creek (National Marine Fisheries Service, 2000a, b, c). Instream flow requirements resulted from the NMFS statement that biologic requirements for endangered and threatened fish species are "best expressed in terms of environmental factors that define flow, habitat quantity, and passage condition attributes necessary for survival and recovery of the species" (National Marine Fisheries Service, 2000a, b, c). Upper Columbia River steelhead, including the Methow River run, were listed under the ESA as "endangered" on August 18, 1997. Upper Columbia River spring-run Chinook salmon, including the Methow River run, were listed under the ESA as "endangered" on March 24, 1999. Bull trout in the Methow River were listed under the ESA as “threatened” on June 10, 1998.

Different methods were used to determine flow requirements for the three tributaries, including analysis of limited flow data and the Instream Flow Incremental Methodology (IFIM) (Caldwell and Catterson, 1992). The IFIM, described in detail by Bovee (1982), is a tool used to determine the relation between fish habitat and streamflow. The Chewuch River has flow requirements based on the IFIM that vary for each 15-day period between April 1 and October 16. The minimum instream flow requirement for Early Winters Creek is 35 cubic feet per second (ft^3/s), based on the IFIM and limited streamflow data and agreed upon by the Early Winters Ditch Company and the U.S. Forest Service. Wolf Creek has a minimum of 8 ft^3/s based on a report by Mullan and others (1992) and limited streamflow data. When flows in these streams decrease to the minimums set by the NMFS, selected irrigation canals are shut down.

Purpose and Scope

The purpose of this report is to document a tool that can be used to simulate streamflow conditions in the Methow River Basin. This report (1) describes the construction and calibration of the Methow River Basin watershed model, (2) evaluates the accuracy of the model as a predictive tool for assessing the current and natural streamflow conditions, and (3) discusses the limitations of the model. Time-series data for the study included streamflow data from 13 streamflow-gaging stations for water years 1960–2001 and climate data for water years 1959–2001. (A water year is the 12-month period beginning on October 1 of the previous year and ending on September 30.) The model was calibrated for water years 1992-2001 using streamflow data from 7 streamflow-gaging stations. The calibrated model was used to simulate streamflow outside of the period of record at 11 gaging stations for water years 1960-2001, and to examine the contribution of irrigation-canal seepage to streamflow at 2 gaging stations.

Description of Study Area

The Methow River Basin occupies most of the western one-third of Okanogan County in north-central Washington State and covers an area of about 1,800 square miles (fig. 1). The basin is bordered on the west by the Cascade Range, on the east by the Okanogan River Basin, on the north by the Canadian border, and on the south by the Columbia River down to latitude 48°00′N. The Methow River originates in the Cascade Range and flows southeasterly for about 60 miles to the confluence with the Columbia River near Pateros. The Methow River is formed by the confluence of the West Fork Methow River and Robinson Creek and is joined a short distance downstream by Lost River. Principal tributaries are the Chewuch and Twisp Rivers. The Chewuch River originates near the Canadian border and flows south for about 36 miles, joining the Methow River near Winthrop. The Twisp River originates high in the Cascade Range and flows easterly for about 27 miles to its confluence with the Methow River near the town of Twisp.

The population in the Methow River Basin was approximately 4,700 in 2000 (Washington State Office of Financial Management, 2002), with the majority concentrated within the Methow River valley between the towns of Mazama and Pateros. The largest towns are Twisp and Winthrop.

Topography in the Methow River Basin ranges from peaks reaching 8,950 feet above NGVD 29 along the Cascade crest down to 775 feet at the confluence of the Methow and Columbia Rivers near Pateros. Ridges rising to elevations of 7,000 feet above sea level and steep U-shaped canyons carved by glacial erosion dominate most of the study area, but in some areas, such as between Mazama and Carlton, the Methow River flows through broad valley bottoms with gentle relief.

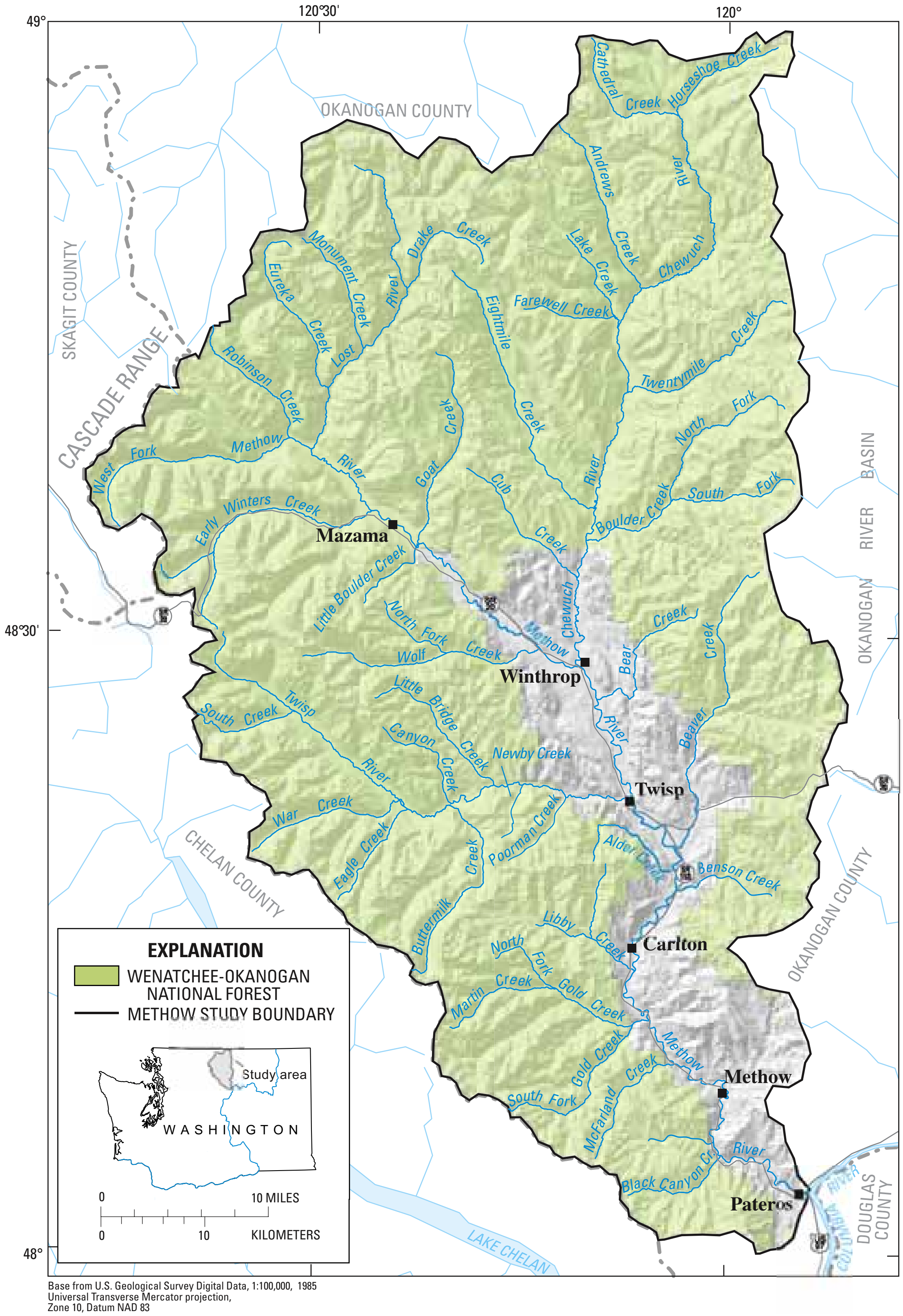


Figure 1. Location of the Methow River Basin study area, Washington.

Geology of the Methow River Basin is described in many reports, including Pitard (1958), Waitt (1972), Walters and Nassar (1974), and Barksdale (1975). A recent USGS study investigated the hydrogeology of the unconsolidated sediments of the Methow River Basin, and the brief summary that follows is taken largely from that work (Konrad and others, 2003).

The Methow River Basin is underlain by bedrock, which is exposed at the surface or is thinly covered by sediments almost everywhere except beneath the floors of the major valleys. The bedrock is of many different rock types with a wide range of ages. These rocks have been folded and faulted into a complex pattern (Walters and Nassar, 1974). Starting just south of Twisp and extending up the Methow River, the bedrock consists of sedimentary and volcanic rocks that have been downfaulted between large blocks of igneous and metamorphic rocks. These rocks are exposed over a 15- to 20-mile-wide expanse that extends about 35-40 miles northeast to southwest. Downriver of the sedimentary and volcanic rocks, the bedrock underlying the river is primarily igneous and metamorphic. The basin has been described as a graben (Barksdale, 1975) or a rift-block valley (Waitt, 1972). Shales, siltstones, sandstones, conglomerates, breccias, and tuffs are the major sedimentary and volcanic rocks present in the basin. Most of the igneous and metamorphic rocks are granite, gneiss, marble, and schist. The unconsolidated sediments that overlie the bedrock are mostly sands and gravels of glaciofluvial origin. Glacial till and glaciolacustrine silts and clays are also present, but are much less extensive than the sands and gravels.

The Methow River Basin was almost entirely covered by ice several times during the Pleistocene Epoch. As a result, upland areas were eroded and ultimately mantled with relatively thin glacial deposits, whereas thick accumulations of sand and gravel, along with some tills, silts, and clays, were deposited along the lower slopes and bottoms of the major valleys (Walters and Nassar, 1974). Although the glacial deposits at the surface originated from the ice-sheet glaciation that covered most of the basin, there are clear indicators of significant prior erosion from alpine glaciation (Waitt, 1972). The alpine glaciation is responsible for the wide, U-shaped cross-valley profiles of the Methow River valley upriver of Carlton and the Twisp River valley upriver of Little Bridge Creek (Waitt, 1972). Beneath parts of these U-shaped valleys, alpine glaciation apparently eroded the bedrock many hundreds of feet below the level of the bedrock immediately downriver. Alluvial and alpine and ice-sheet glacial sediments later filled these deep sections.

Coarse-grained materials, mostly sand and gravel, dominate the unconsolidated sediments beneath the main Methow River valley. These coarse-grained materials are highly transmissive and, where saturated, are the most productive aquifers in the basin. These materials included Quaternary alluvium deposited recently (Holocene) by river or glaciofluvial sediments that were deposited earlier by glaciers and rivers.

Minor amounts of silts, clays, and till occur within the mass of coarse-grained unconsolidated deposits. The fine-grained deposits are relatively poorly transmissive and locally act as confining units. Beneath some parts of the main Methow River valley, these confining units are nearly non-existent.

The alluvial aquifer extends from above Lost River continuously to around Black Canyon Creek, where bedrock is exposed along the river channel. Alluvial deposits along Lost River, Chewuch River, Twisp River, Beaver Creek, Benson Creek, and Libby Creek are contiguous with deposits along the Methow River.

The Methow River Basin also is an area of diverse climate with wide variations in temperature and precipitation. The high mountainous regions generally have the coldest temperatures and receive the greatest precipitation. More than 80 inches of precipitation falls each year near the crest of the Cascade Range. At low elevations, the climate becomes semi-arid. The valley floor near Pateros receives about 10 inches of precipitation per year. The eastern side of the basin receives considerably less annual precipitation than equal elevations on the western side. Therefore most snow, and thus spring runoff from snowmelt, originates near the Cascade crest. Average annual precipitation for the entire basin is about 32 inches per year (Walters and Nassar, 1974). Temperatures range from about 100°F (degrees Fahrenheit) to -20°F. Temperatures generally are highest in July and lowest in January.

Only small glaciers exist in this part of the North Cascades. Post and others (1971) report that the Methow River Basin contains 15 glaciers, ranging in size from 0.03 to 0.07 square mile. Total surface area of the glaciers equals about 0.54 square mile, only 0.03 percent of the total basin.

Seventy-five percent of the Methow River Basin is forested. Douglas fir (*Psuedotsuga menziesii*), lodgepole pine (*Pinus contorta*), and ponderosa pine (*Pinus ponderosa*) forests cover mid-elevation (2,000 to 5,000 feet) areas of the basin. Shrub-steppe communities are common below 4,000 feet and subalpine fir (*Abies lasiocarpa*), Pacific silver fir (*Abies amabilis*), mountain hemlock (*Tsuga mertensiana*), whitebark pine (*Pinus albicaulis*), and subalpine larch (*Larix lylli*) are common above 3,000 feet. Deciduous trees including black cottonwood (*Populus trichocarpa*) and aspen (*Populus tremuloides*) occupy valley bottoms and riparian areas. Vegetation is sparser and trees, shrubs, and grasses are smaller at high elevations. Most agricultural production occurs on the valley bottom and is limited to alfalfa and small orchards. Most of the Methow River Basin and all of its headwaters are in the Okanogan National Forest (fig. 1). Land use in the National Forest includes recreation, grazing, and timber harvesting. Historically, fire was the dominant landscape process influencing the structure, composition, and extent of vegetation communities in the Methow River Basin (Knott and others, 1998).

Acknowledgments

The author thanks the members of the Methow Basin Planning Unit for contributing knowledge of current and historical conditions in the basin, and Gregory H. Knott of the U.S. Bureau of Reclamation for his technical guidance.

ENHANCED PRECIPITATION-RUNOFF MODEL

The Modular Modeling System (MMS), developed by Leavesley and others (1996), is a framework for modeling that allows for the modularization of existing models and integration into MMS. Modularization allows the user to select appropriate algorithms or develop new algorithms to create an optimal model for the desired application. The Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983) was the computer-simulation model chosen for this study. PRMS is a physically based, distributed-parameter model designed to simulate precipitation and snowmelt runoff. Major advantages of this system include the ability to (1) simulate the moisture balance of each component of the hydrologic cycle, (2) account for heterogeneous physical characteristics of a basin, and (3) appropriately simulate both mountainous and flat areas.

PRMS and MMS have been used in numerous studies. PRMS was used to model watershed systems for Williams Draw and Bush Draw Basins, Jackson County, Colorado (Kuhn, 1989), the southern Yampa River Basin, Colorado (Parker and Norris, 1989), 11 small drainage basins in the Oregon Coast Range (Risley, 1994), the Willamette River Basin, Oregon (Laenen and Risley, 1997), the Lake Tahoe Basin, California and Nevada (Jeton, 1999a), and the Truckee River Basin, California and Nevada (Jeton, 1999b). MMS was used to model the San Juan River Basin, Colorado and New Mexico (Kuhn and others, 1998) and the Yakima River Basin, Washington (Mastin and Vaccaro, 2002b).

Model Description

The MMS modules used in the current study were similar to those used in the previous Methow River Basin simulation. A more complete description of the model modules is given in Ely and Risley (2001). An improved ground-water flow module and new modules to simulate the diversion, return, and application of irrigation water were used in the current model. Those modules are documented by Mastin and Vaccaro (2002a).

Delineation of Basin Physical Characteristics

The physical attributes of the basin were characterized in a format that could be readily used in the modeling process. Digital data exist that describe the topographic features, soils, land use, and vegetation. These spatial features determine, in large part, the quantity and movement of water throughout a basin, and subsequent steps in the modeling process will build upon this initial characterization.

The drainage network in the Methow River Basin (fig. 2) was delineated with the Geographic Information System (GIS) Weasel (Viger and others, 1998). The GIS Weasel is an interface for the treatment of spatial information used in watershed modeling and provides an accessible tool to delineate and characterize a watershed. The GIS Weasel uses standard ARC/INFO routines for delineation and therefore develops objective and reproducible results. Modeling Response Units (MRUs) are delineated to reflect spatially distributed attributes such as slope, aspect, elevation, soils, and vegetation, and to respond similarly to hydrologic inputs such as precipitation. Each MRU is a smaller polygon area of a subbasin on which these physical characteristics are assumed to be homogeneous. The GIS Weasel also delineates a drainage network and computes the connection between the MRU and possible stream locations. Accuracy of the characterization can be dependent upon the scale and quality of the digital input data, as well as on hydrologic judgment.

The initial input to the GIS Weasel to define topographic surfaces was a standard 100-foot (30-meter) USGS 7.5-minute digital elevation model (DEM) of the Methow River Basin, in ARC/GRID format. The 100-foot DEM contains regularly spaced cells, 100 feet on center, with elevation reported to the nearest 1 foot at each cell. A more detailed 30-foot (10-meter) DEM for the study area was not used because, given the large size of the basin, it would add additional computation time without significant gain in precision for the purpose of basin delineation. Because of the relatively large area of the study, the number of grid cells for the 100-foot DEM exceeded the maximum allowed by the GIS Weasel's parameterization process. The DEM grid was resampled to 150-foot (45-meter) intervals with no noticeable loss of precision.

A flow-accumulation surface is determined using the flow direction from the DEM to compute the number of cells upslope from each cell. A drainage network is extracted from the flow-accumulation surface by selecting points on the surface that drain, according to the flow-accumulation surface, an area equal to or greater than a user-specified threshold (Viger and others, 1998). This threshold represents the minimum upslope area needed to initiate a first-order link in the drainage network (Jenson and Domingue, 1988). In this study, a threshold of 4,500 cells, or 3.5 square miles, was chosen.

The GIS Weasel computed initial MRUs on the basis of the automatic two flow-plane process. With this feature, each side of the subbasin divided by the stream becomes a separate MRU. The MRUs were further delineated by using USGS streamflow-gaging station locations as the downstream outlet from which the drainage area was computed. To account for the effect of increasing precipitation in mountainous areas, elevation bands were incorporated at 1,000-foot intervals to subdivide any MRUs that may have spanned several of these intervals. Finally, all MRUs smaller than 1 square mile were dissolved into adjacent MRUs. This process resulted in 620 MRUs for the total Methow River Basin (fig. 2).

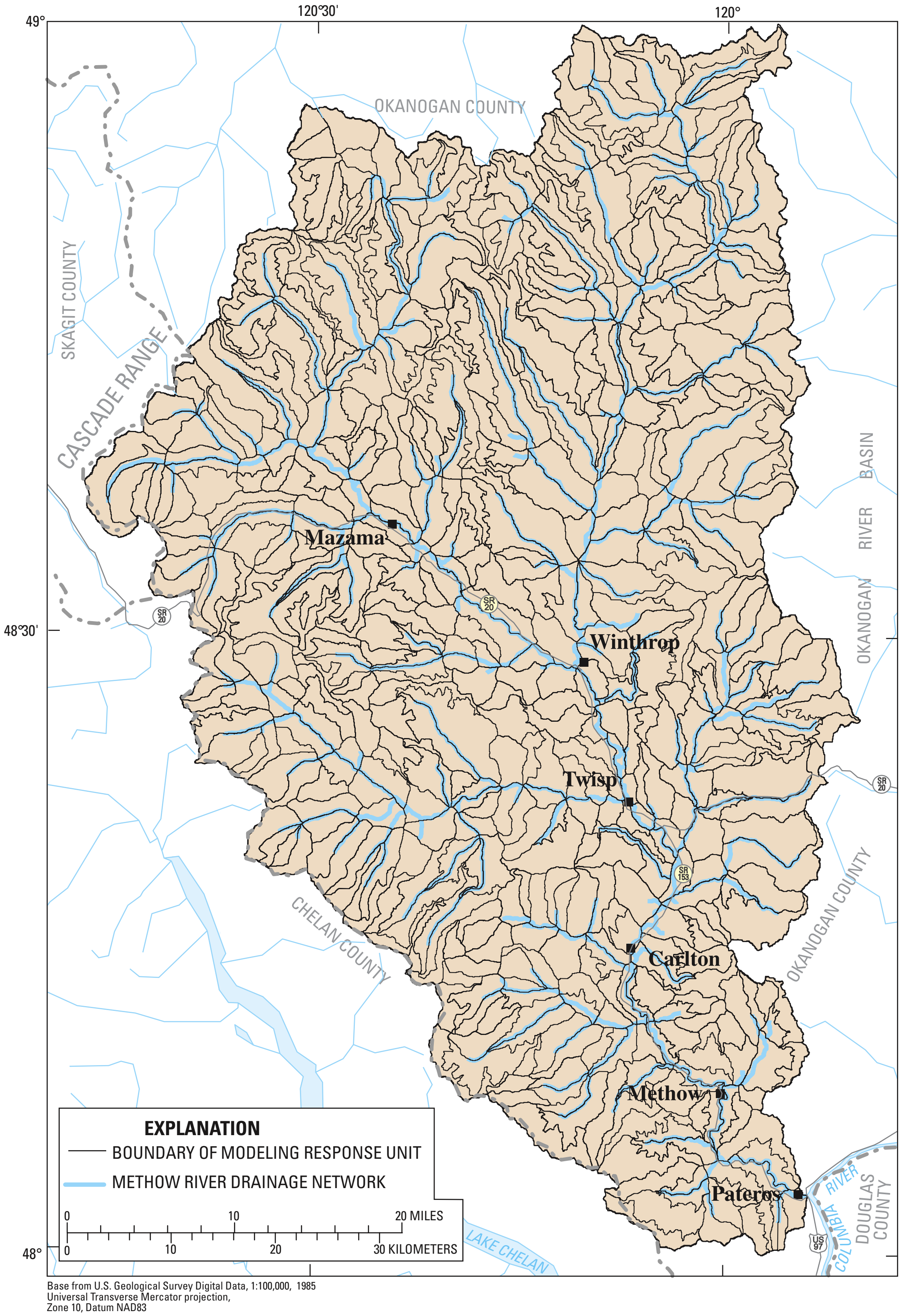


Figure 2. Drainage network and Modeling Response Units delineated for the precipitation-runoff model for the Methow River Basin, Washington.

Time-Series Data

Streamflow in the Methow River Basin was simulated using measured precipitation, air-temperature, and streamflow-discharge time-series data. The period of climate record used in model simulations was water years 1959-2001. Not all stations existed for the entire period of record. Precipitation and temperature modules employed a distance-weighted average approach. Periods of missing data from any station simply were not used in the calculation, so the missing data caused no problems in the simulation. Monthly mean precipitation ratios between climate stations and MRUs were calculated using estimates from the Parameter-estimation Regressions on Independent Slopes Model (PRISM) (Daly and others 1994; Daly and others 1997).

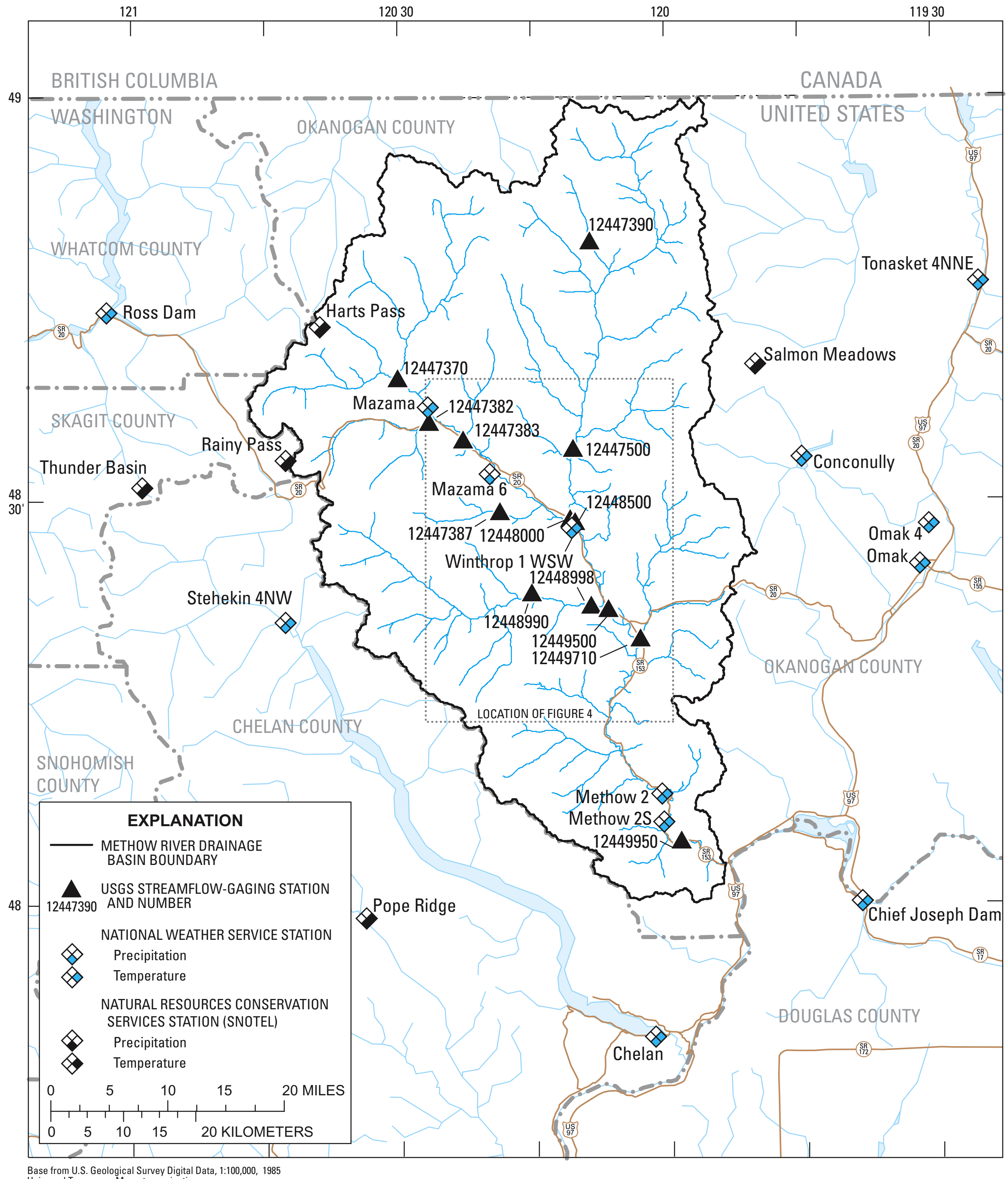
Precipitation

Daily precipitation totals used in the MMS model simulations were measured at precipitation gages located throughout the Methow River Basin and surrounding basins. Precipitation gages operated by the U.S. National Weather Service (NWS) and Snowpack Telemetry (SNOTEL) sites operated by the Natural Resources Conservation Service (NRCS) provided data from a total of 18 gages (fig. 3, table 1) with varying periods of record. The rain module requires mean monthly estimates of precipitation for each MRU to compute ratios between rain gage locations and the MRU. For this purpose, the PRISM model estimates (Daly and others 1994; Daly and others 1997) were used. Data input to the PRISM model consisted of mean monthly precipitation for the period 1961-90 from National Oceanic and Atmospheric Administration Cooperative sites, SNOTEL sites, and selected State network stations.

Table 1. Climate stations used in model simulations

[**Station name:** See figure 3 for locations; **Agency:** NWS, National Weather Service; NRCS, Natural Resources Conservation Service. **Daily data used in model:** ppt, precipitation; temp, temperature. **Latitude and longitude:** Degrees, minutes, seconds]

Station name	Agency	Daily data used in model	Latitude	Longitude	Elevation (feet above NGVD 29)	Period of record
Chelan	NWS	ppt, temp	47 50 00	120 02 00	1,120	July 1890 to present
Chief Joseph Dam	NWS	ppt, temp	48 00 00	119 39 00	820	Oct. 1949 to present
Conconully	NWS	ppt, temp	48 33 00	119 45 00	2,320	June 1948 to present
Mazama	NWS	ppt, temp	48 37 00	120 27 00	2,170	April 1950 to present
Mazama 6	NWS	ppt	48 32 00	120 20 00	1,960	June 1948 to Oct. 1976
Methow 2	NWS	ppt, temp	48 08 00	120 01 00	1,170	Aug. 1957 to June 1970
Methow 2S	NWS	ppt, temp	48 06 00	120 01 00	1,170	July 1970 to present
Omak	NWS	ppt, temp	48 25 00	119 32 00	851	Jan. 1931 to Dec. 1998
Omak 4	NWS	ppt, temp	48 28 00	119 31 00	1,301	Nov. 1980 to July 1991
Ross Dam	NWS	ppt, temp	48 44 00	121 03 00	1,236	Sept. 1960 to present
Stehekin 4 NW	NWS	ppt, temp	48 21 00	120 43 00	1,270	Jan. 1931 to present
Tonasket 4 NNE	NWS	ppt, temp	48 46 00	119 25 00	960	July 1984 to present
Winthrop 1 WSW	NWS	ppt, temp	48 28 00	120 11 00	1,755	Jan. 1931 to present
Harts Pass	NRCS	ppt, temp	48 43 00	120 39 00	6,500	Oct. 1981 to Oct. 1982, Oct. 1983 to present
Pope Ridge	NRCS	ppt, temp	47 59 00	120 34 00	3,580	Oct. 1981 to present
Rainy Pass	NRCS	ppt, temp	48 33 00	120 43 00	4,780	Oct. 1981 to present
Salmon Meadows	NRCS	ppt, temp	48 40 00	119 50 00	4,500	Oct. 1981 to Oct. 1982, Oct. 1983 to present
Thunder Basin	NRCS	ppt, temp	48 31 00	120 59 00	4,200	Oct. 1989 to present



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
Zone 10, Datum NAD83

Figure 3. Data-collection network used for the precipitation-runoff model for the Methow River Basin, Washington.

Air Temperature

Measured, daily, minimum, and maximum air-temperature data were collected by the NWS and the NRCS at 17 locations (fig. 3, table 1). To account for differences in elevation between the stations (table 1) and the basins, MMS adjusts the temperature data using a calculated lapse rate for every 1,000-foot increase in elevation.

Streamflow Discharge

Daily mean streamflow data were collected at 13 streamflow-gaging stations in the Methow River Basin (fig. 3, table 2), according to standardized techniques of the USGS (Rantz, 1982). The data obtained at a streamflow-gaging station include a continuous record of stage (water-surface elevation referenced to a gage datum), individual measurements of discharge, and observations of factors that may affect the relation between stage and discharge. The individual discharge measurements are then plotted against the stage and a stage-discharge relation curve is constructed. From these curves, discharges for any stage in the measured range can be approximated. The USGS rates the accuracy of its streamflow records on the basis of the stability of the stage-discharge relation and the quality of the measurements of stage and discharge. Accuracy levels of "good" indicate that 95 percent of the measurements are within 10 percent of the true values and "fair" indicate the measurements are within 15 percent.

Records of daily mean streamflow for Washington are available, by water year, in USGS Water-Data Reports. Streamflow data collected at streamflow-gaging stations are referred to as "measured" data throughout this report.

Table 2. Description of USGS streamflow-gaging stations, Methow River Basin, Washington

[**Station No.**: U.S. Geological Survey streamflow-gaging station; See figure 5 for locations. **Latitude and longitude:** Degrees, minutes, seconds. **Abbreviation:** mi^2, square mile]

Station No.	Station name	Latitude	Longitude	Period of record	Drainage area (mi^2)	Elevation (feet above NGVD 29)
12447370	Lost River near Mazama	48 39 19	120 30 18	Oct. 2000 to present	146	2,386
12447382	Early Winters Creek near Mazama	48 35 55	120 26 31	Oct. 2000 to present	80	2,180
12447383	Methow River above Goat Creek near Mazama	48 34 32	120 23 05	April 1991 to present	373	2,040
12447387	Wolf Creek below diversion near Winthrop	48 29 00	120 18 24	Oct. 2000 to present	32	2,660
12447390	Andrews Creek near Mazama	48 49 23	120 08 41	June 1968 to present	22	4,300
12447500	Chewuch River above Cub Creek near Winthrop	48 33 53	120 10 35	Oct. 2000 to present	466	1,980
12448000	Chewuch River near Winthrop	48 28 38	120 11 07	Oct. 1991 to present	525	1,736
12448500	Methow River at Winthrop	48 28 25	120 10 34	Aug. 1971 to June 1972, Nov. 1989 to present	1,007	1,718
12448990	Twisp River above Newby Creek near Twisp	48 22 51	120 15 38	Oct. 2000 to present	207	2,040
12448998	Twisp River near Twisp	48 22 12	120 08 51	May 1975 to Sept. 1979, Oct. 1989 to present	245	1,640
12449500	Methow River at Twisp	48 21 55	120 06 54	June 1919 to Sept. 1962 Apr. 1991 to present	1,301	1,580
12449710	Beaver Creek near Twisp	48 19 43	120 03 29	Oct. 2000 to Sept. 2001	110	1,540
12449950	Methow River near Pateros	48 04 39	119 59 02	Apr. 1959 to present	1,772	900

Irrigation Canal Discharge and Seepage

Konrad and others (2003) calculated aquifer recharge from irrigation-canal seepage in the Methow River Basin using a surface-water discharge balance and discharge measurements made in 14 irrigation systems. Discharge measurements were made at the upstream and downstream ends of 45 canal reaches comprising 31.6 miles, or approximately half of the total length of unlined irrigation canals, not including lateral canals, operating in the Methow River Basin during water year 2001. Measurements made by Klohn Leonoff, Inc. (1990) along an additional 9 reaches comprising 23.6 miles were also included in the recharge calculations. Measurement locations excluded large water users and spills from the irrigation canals, however the calculated difference between inflows and outflows along some reaches may have neglected small users. As a result, there may be a small upward bias in the estimates of recharge for some reaches. The mean seepage rate for each canal was calculated as the sum of the measured losses for each reach divided by the sum of canal-reach lengths. Reach lengths were calculated from digital raster graphics of 7.5-minute quadrangle maps (1:24,000 scale) using a GIS.

The mean seepage rate during water year 2001 from unlined irrigation canals was 2.0 (ft^3/s)/mi from May through August. Seepage rates are estimated to decline by approximately 50 percent in September because of the combined effects of subsurface saturation, reduction in the infiltration capacity of the canal beds from the accumulation of fine-grained materials, and lower diversion rates. Seepage estimates for individual irrigation canals varied from 1.6 to 6.2 (ft^3/s)/mi and, with the exception of one canal that had been excavated shortly before the seepage run, the standard deviation of seepage rates was 0.9 (ft^3/s)/mi.

Surface-water diversions for 16 irrigation canals (fig. 4) were simulated by removing streamflow from associated model nodes. Daily diversion rates (table 3) were selected from a range of reported values or determined from examining streamflow data near a diversion point. In general, the irrigation season was simulated as May 1–October 7. There are many small irrigation canals in the Beaver Creek subbasin. Those canals were simulated as one lumped canal (fig. 4). Many more irrigation canals exist in the Methow River Basin, but there is limited information concerning their operations. Most of the excluded canals divert small amounts of surface water, generally 2 ft^3/s or less.

Irrigation Application

Irrigation water was applied to MRUs at a constant rate of 0.2 inch per day for the period May 1 through October 7. The total amount of water for the 160-day period equaled 32.0 inches of water. This application rate was an average annual water requirement for alfalfa (Molenaar and others, 1952; James and others, 1982; Cline and Collins, 1992). MRUs were designated for irrigation application on the basis of an evaluation of land use from aerial photographs as part of the Washington State Department of Ecology's Methow Air Photo Assessment (MAPA) project.

Model Parameterization

Mathematically, parameters are defined as numerical constants used to determine variables. Variables are computed by equations during the simulation. PRMS has distributed and non-distributed parameters. Distributed parameters are attributed to each MRU and describe (1) physiographic characteristics such as area, slope, and aspect, (2) hydrologic processes within the MRU such as subsurface or ground-water flow, and (3) climatic input to the MRU such as precipitation and temperature adjustments. Non-distributed parameters are parameters held constant throughout the watershed, such as the Julian date to force snowpack depletion or the temperature that determines the form of precipitation. All MMS parameters are defined and discussed in depth by Leavesley and others (1983 and 1996). The distributed and non-distributed parameters for the precipitation-runoff model and their sources are listed in table 4.

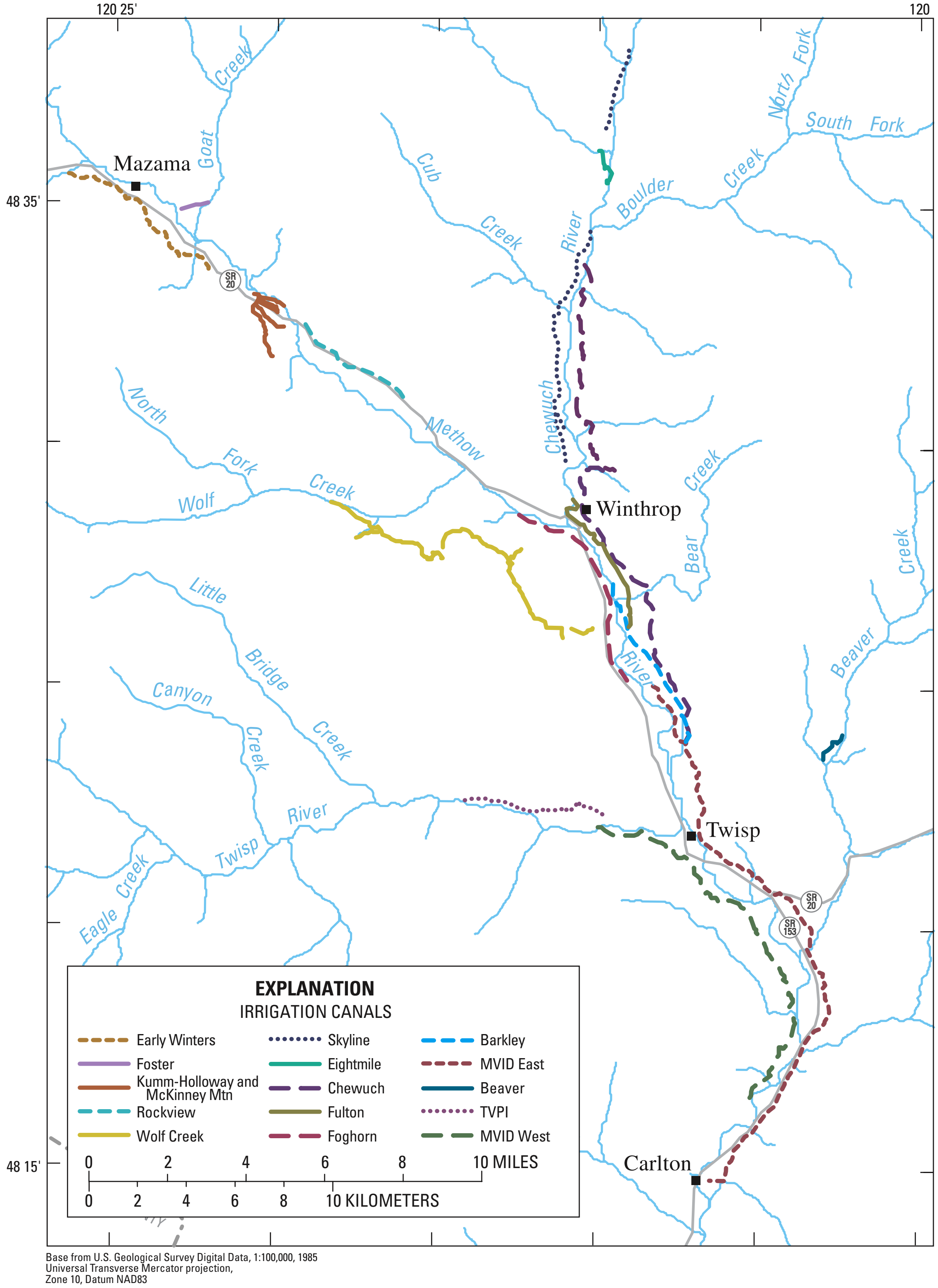


Figure 4. Irrigation canals used to simulate surface-water diversions for the precipitation-runoff model for the Methow River Basin, Washington.

Table 3. Simulated irrigation diversions

[**Abbreviations**: MVID, Methow Valley Irrigation District; TVPI, Twisp Valley Power and Irrigation; ft^3/s, cubic feet per second]

Month/ day	Daily diversion rate (ft^3/s)							
	Barkley	Beaver	Chewuch	Early Winters	Eightmile	Foghorn	Foster	Fulton
May 1–15	12	12	25	14	5	15	5	15
May 16–31	12	12	30	14	5	15	5	15
June 1–15	12	17	30	14	5	15	5	15
June 16–30	12	17	35	14	5	15	5	15
July 1–15	12	17	35	14	7	18	5	18
July 16–31	18	12	30	14	7	18	5	18
August 1–15	18	12	25	14	7	13	5	20
August 16–31	15	12	25	14	7	13	5	20
September 1–15	15	12	25	14	7	10	5	17
September 16–30	9	12	20	14	7	10	5	17
October 1-7	4.5	0	10	7	3.5	5	2.5	8.5
Month/ day	**Kumm-Holloway**	**McKinney Mountain**	**MVID East**	**MVID West**	**Rockview**	**Skyline**	**TVPI**	**Wolf Creek**
May 1–15	4.5	5	39	24	9	20	10	8
May 16–31	4.5	5	39	24	9	20	12	8
June 1–15	4.5	5	41	24	9	22	11	8
June 16–30	4.5	3	41	24	9	22	11	8
July 1–15	4.5	3	42	26	10	17	11	8
July 16–31	4.5	3	42	26	10	17	11	8
August 1–15	4.5	3	37	26	10	20	10	8
August 16–31	4.5	3	37	26	10	20	9	8
September 1–15	4.5	3	39	25	9	15	7	8
September 16–30	4.5	3	39	25	9	15	7	8
October 1-7	2.3	1.5	19.5	10	4.5	7.5	2.5	4

Parameters for the discrete spatial features of the study area were generated using the GIS Weasel. In addition to elevation, slope, and aspect, ancillary information concerning soils, land use and land cover, and vegetation were incorporated to assign further characteristics to each MRU. Digital soil data were obtained from a modified version of general soil maps from the State Soil Geographic Database (STATSGO; U.S. Department of Agriculture, 1994) and the Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, 2000). Parameters from the contiguous U.S. Forest Type Groups map and U.S. Forest Density map provided vegetation information (Zhu and Evans, 1992; Powell and others, 1998). The USGS, the University of Nebraska-Lincoln, and the European Commission's Joint Research Centre generated a 3,281-foot (1-kilometer) resolution database of global land-cover characteristics (Loveland and others, 1991; U.S. Geological Survey, 1992) for use in a wide range of environmental research and modeling applications. The land cover/land use grid used by the GIS Weasel is a composite of the global land cover, the MAPA land-use cover, and the Forest Type Group data listed above.

Table 4. Source of parameter values for distributed and (selected) nondistributed parameters for the Methow River Basin, Washington

[**GIS:** Data computed in geographic information system from digital data. **Computed:** Results from climatological data or other measured data. **Literature:** Obtained from Ely and Risley (2001) as estimated or empirical data. **Default value:** Parameters whose values are considered as provided by Leavesley and others (1983). **Calibration:** Parameters that have an initial value estimated from measured or published data and later adjusted during calibration. **Abbreviations:** MRU, Modeling Response Unit; ET, Evapotranspiration. –, no data available]

Model parameter	Description of parameter	Source				
		GIS-derived	Computed	Literature	Default value	Calibration
	Distributed (MRU-dependent) parameters					
CAREA_MAX	Maximum area contributing to surface runoff	–	X	–	–	–
COV_TYPE	Vegetation cover type	X	–	–	–	–
COVDEN_SUM	Vegetation cover density for summer	X	–	–	–	–
COVDEN_WIN	Vegetation cover density for winter	X	–	–	–	–
GWFLOW_COEF	Ground-water routing coefficient to obtain ground-water flow contribution to streamflow	–	–	–	–	X
GWSINK_COEF	Ground-water sink coefficient to compute seepage from each reservoir to ground-water sink	–	–	–	–	X
GWSTOR_INIT	Storage in each ground-water reservoir at beginning of simulation, in inches	–	–	–	–	X
HRU_AREA	MRU area, in acres	X	–	–	–	–
HRU_DEPLCRV	Index number for snowpack depletion curve		X	–	–	–
HRU_ELEV	Mean MRU elevation, in feet	X	–	–	–	–
HRU_GWRES	Index number for ground-water reservoir	X	–	–	–	–
HRU_PERCENT_IMPERV	MRU impervious area as decimal percent of total MRU area	X	–	–	–	–
HRU_RADPL	Index number of solar radiation plane	–	X	–	–	–
HRU_SLOPE	MRU slope in decimal percent, vertical feet/horizontal feet	X	–	–	–	–
HRU_SSRES	Index number of subsurface reservoir receiving excess water from soil zone	X	–	–	–	–
IMPERV_STOR_MAX	Maximum impervious retention storage for MRU, in inches	X	–	–	–	–
JH_COEF_HRU	Air-temperature coefficient used in Jensen Haise potential ET computations for each MRU, in degrees Fahrenheit	–	X	–	–	–
LOSS_DIV	Percentage of canal flow routed to specified MRU	–	X	–	–	–
PSTA_MON	Monthly factor to adjust measured precipitation from each climate station to each MRU	–	–	–	–	X
RAD_TRNCF	Transmission coefficient for short-wave radiation through winter canopy	–	X	–	–	–
RAIN_MON	Monthly factor to adjust measured precipitation (rain) to each MRU	–	–	–	–	X
SMIDX_COEF	Coefficient in nonlinear contributing area algorithm	X	–	–	–	–
SMIDX_EXP	Exponent in nonlinear contributing area algorithm	X	–	–	–	–
SNAREA_THRESH	Maximum snow-water equivalent below which snow-covered area depletion curve is applied	X	–	–	–	–
SNOW_INTCP	Snow-interception storage capacity for major vegetation type on MRU	X	–	–	–	–
SNOW_MON	Monthly factor to adjust measured precipitation (snow) to each MRU	–	–	–	–	X

Table 4. Source of parameter values for distributed and (selected) nondistributed parameters for the Methow River Basin, Washington *(Continued)*

[**GIS:** Data computed in geographic information system from digital data. **Computed:** Results from climatological data or other measured data. **Literature:** Obtained from Ely and Risley (2001) as estimated or empirical data. **Default value:** Parameters whose values are considered as provided by Leavesley and others (1983). **Calibration:** Parameters that have an initial value estimated from measured or published data and later adjusted during calibration. **Abbreviations:** MRU, Modeling Response Unit; ET, Evapotranspiration. –, no data available]

Model parameter	Description of parameter	Source				
		GIS-derived	Computed	Literature	Default value	Calibration
Distributed (MRU-dependent) parameters—*Continued*						
SNOWINFIL_MAX	Maximum infiltration rate for snowmelt, in inches per day	–	–	–	–	X
SOIL_MOIST_INIT	Initial value of available water in soil profile, in inches	X	–	–	–	–
SOIL_MOIST_MAX	Maximum available water-holding capacity of soil profile, in inches	–	–	–	–	X
SOIL_RECHR_INIT	Initial value for available water in soil recharge zone, in inches	X	–	–	–	–
SOIL_RECHR_MAX	Maximum value for available water in soil recharge zone, in inches	–	–	–	–	X
SOIL_TYPE	MRU soil type	X	–	–	–	–
SOIL2GW_MAX	Amount of soilwater excess for MRU that is routed directly to associated ground-water reservoir, in inches per day	–	–	–	–	X
SRAIN_INTCP	Summer interception storage capacity for major vegetation type on MRU, in inches	X	–	–	–	–
SSR2GW_RATE	Coefficient to route water from subsurface to ground-water reservoir	–	–	–	–	X
SSRCOEF_LIN	Linear subsurface routing coefficient to route subsurface storage to streamflow	–	–	–	–	X
SSRCOEF_SQ	Nonlinear subsurface routing coefficient to route subsurface storage to streamflow	–	–	–	–	X
TMAX_ADJ	MRU maximum temperature adjustment to MRU temperature based on slope and aspect of MRU, in degrees Fahrenheit	–	–	–	–	X
TMIN_ADJ	MRU minimum temperature adjustment to MRU temperature based on slope and aspect of MRU, in degrees Fahrenheit	–	–	–	–	X
TRANSP_BEG	Month to begin summing maximum temperature for each MRU; when sum is greater than or equal to TRANSP_TMAX, transpiration begins	–	–	X	–	–
TRANSP_END	Last month for transpiration computations	–	–	X	–	–
TRANSP_TMAX	Temperature index to determine specific date of start of transpiration period	–	–	–	X	–
WRAIN_INTCP	Winter rain-interception storage capacity for the major vegetation type on MRU, in inches	X	–	–	–	–

Table 4. Source of parameter values for distributed and (selected) nondistributed parameters for the Methow River Basin, Washington *(Continued)*

[**GIS:** Data computed in geographic information system from digital data. **Computed:** Results from climatological data or other measured data. **Literature:** Obtained from Ely and Risley (2001) as estimated or empirical data. **Default value:** Parameters whose values are considered as provided by Leavesley and others (1983). **Calibration:** Parameters that have an initial value estimated from measured or published data and later adjusted during calibration. **Abbreviations:** MRU, Modeling Response Unit; ET, Evapotranspiration. –, no data available]

Model parameter	Description of parameter	Source				
		GIS-derived	Computed	Litera-ture	Default value	Calibra-tion
	Selected non-distributed (basinwide) parameters					
	(Temperature/precipitation-dependent)					
ADJMIX_RAIN	Monthly factor to adjust rain proportion in mixed rain/snow event	–	–	–	–	X
JH_COEF	Monthly air-temperature coefficient used in Jensen-Haise potential ET computations	–	–	–	–	X
MELT_FORCE	Julian date to force snowpack to spring snowmelt	–	–	–	–	X
MELT_LOOK	Julian date to start looking for spring snowmelt	–	–	–	–	X
TMAX_ALLRAIN	Maximum temperature above which all precipitation is simulated as rain	–	–	–	–	X
TMAX_ALLSNOW	Maximum temperature below which all precipitation is simulated as snow	–	–	–	–	X
TMAX_LAPSE	Monthly maximum temperature lapse rate representing change in maximum temperature per 1,000 feet of elevation change for each month	–	–	X	–	–
TMIN_LAPSE	Monthly minimum temperature lapse rate representing change in minimum temperature per 1,000 feet of elevation change for each month	–	–	X	–	–

Model Calibration

The calibration phase of the modeling effort consisted of matching simulated and measured variables, such as streamflow and snow water equivalent. Calibration was accomplished using an ordered approach of manual trial and error.

Streamflow was simulated for water years 1992–2001 to calibrate the model to measured streamflows at the seven USGS streamflow-gaging stations operating for that period (fig. 5, table 2). Additional streamflow data were used for water years 2000–2001 from six other USGS streamflow-gaging stations established for this study. Initial estimates of the parameters were taken from values determined by the GIS Weasel, values calculated from the MMS algorithms, MMS algorithm default values, and parameter estimates used in the previous Methow River Basin watershed model (Ely and Risley, 2001) (table 4). The model was calibrated by adjusting several sensitive parameters within the acceptable range of known values. Most parameter adjustments were made to precipitation (rain_mon and snow_mon), temperature (tmax_adj), and the ground-water flow coefficient (gwflow_coef). These parameters were adjusted uniformly throughout a subbasin. Other parameters, including snowinfil_max, soil2gw_max, melt_force, melt_look, tmax_allrain, tmax_allsnow, ssr2gw_rate, and the monthly jh_coef, were altered to an acceptable estimate and applied throughout the entire Methow River Basin. Many more parameters could have been adjusted during calibration, but there were inadequate data to justify that approach and additional assumptions about the physical processes would be required.

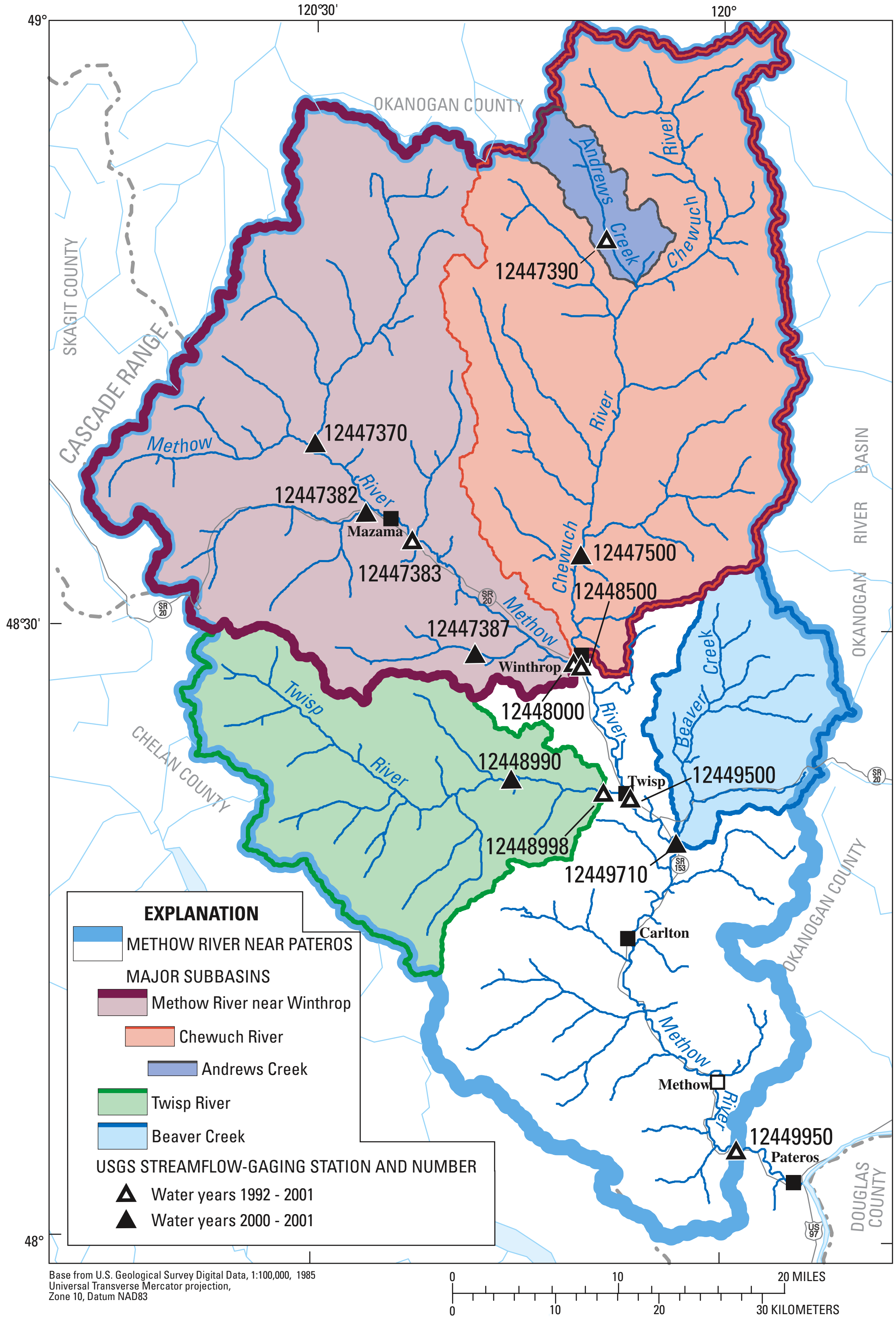


Figure 5. Major subbasins delineated for the precipitation-runoff model and periods of records for streamflow-gaging stations, Methow River Basin, Washington.

Simulated and measured streamflow have many similarities and generally show close agreement, especially during the spring runoff from snowmelt, as demonstrated by hydrographs of simulated and measured daily mean streamflows for four streamflow-gaging stations for water years 1995–2001 (fig. 6). Measured streamflow for April through June at the most downstream streamflow-gaging station (12449950, fig. 6*D*) averaged 66.2 percent of the total flow. Simulated streamflow for that period averaged 64.0 percent of the total flow. Because of the hydrologic complexities of the subbasins, the model simulations performed less well in capturing the magnitude and timing of short-term (1- to 3-day) peak flows during the spring and summer runoff. The model also tended to over-simulate (simulated discharge greater than measured discharge) fall and winter peak flows. The model did represent the baseflow periods of autumn through winter well. Measured streamflow for October through February at the most downstream streamflow-gaging station (12449950) averaged 12.4 percent of the total flow; simulated streamflow averaged 14.2 percent.

Precipitation in the Methow River Basin generally occurs as snowfall, and the amount of snowfall varies drastically throughout the basin. Increasing or decreasing the MRU PRISM value appropriately adjusted the ratio between the precipitation gage and the MRU. To match snowfall totals at the high elevations, monthly values used in the calculation of snowfall generally were increased from initial PRISM-estimated values. Monthly rainfall and snow amounts for low elevations were decreased from those values determined from PRISM data. Precipitation on MRUs located below Beaver Creek was lowered from initial PRISM-estimated values by as much as 50 percent. This procedure resulted in a simulated average annual precipitation for the basin of 32.6 inches per year for the calibration period.

After the annual streamflow totals were adjusted, the timing of flows was matched. Hydrographs of simulated and measured mean monthly streamflow for four streamflow-gaging stations, which include spring runoff of snowmelt and autumn/winter baseflows, demonstrate good agreement between the two (fig. 7).

The timing of the spring runoff and shape of the hydrograph during high flow was controlled largely by adjusting rain- and snow-rate adjustments and maximum-temperature. Temperature adjustments also affected the form of precipitation (snow versus rain) and evapotranspiration (ET). Potential and actual ET were calculated using the Jensen-Haise equation (Jensen and Haise, 1963). Potential and actual ET for the calibration period were 51.5 and 19.0 inches per year, respectively.

The recessionary limb of the hydrograph was affected by precipitation and temperature (as it affects snowmelt rates) and the subsurface and ground-water flow parameters. Flow algorithms in MMS move water to a ground-water reservoir from both a soil zone and a subsurface reservoir. Detailed explanations of these processes are given in Leavesley and others (1983). The ground-water flow coefficient proved to be an important parameter to estimate, having a great effect on the shape of the hydrograph during low-flow periods. The ground-water reservoir for each MRU was assigned a flow coefficient based on reasonable ranges and measured streamflow. MRUs located largely in the broader alluvial valley near the rivers were given high ground-water flow coefficients within an acceptable range and were adjusted to correctly shape the simulated hydrograph. The higher coefficient resulted in more ground-water discharge per area. The values given to the ground-water flow coefficients decreased with distance from the streams.

The irrigation diversion module required a diversion-loss parameter (loss_div), the percentage of the canal flow routed to a specified MRU. Field studies found that seepage rates vary throughout the irrigation season. Also, each irrigation canal loses water at different rates and rates vary along the length of an individual canal. Measured seepage rates were averaged for initial parameter values and a final seepage rate of 50 percent for each canal was chosen. Several irrigation canals have been lined or converted to pipes in recent years, eliminating any seepage loss. These changes were not incorporated in the simulations because the module does not allow time-varying values for loss_div. The changes mostly would affect water years 2000 and 2001. In response to NMFS biological opinions (National Marine Fisheries Service, 2000a and b), Early Winters and Wolf Creek ditches shut down early in the irrigation season during water years 2000 and 2001.

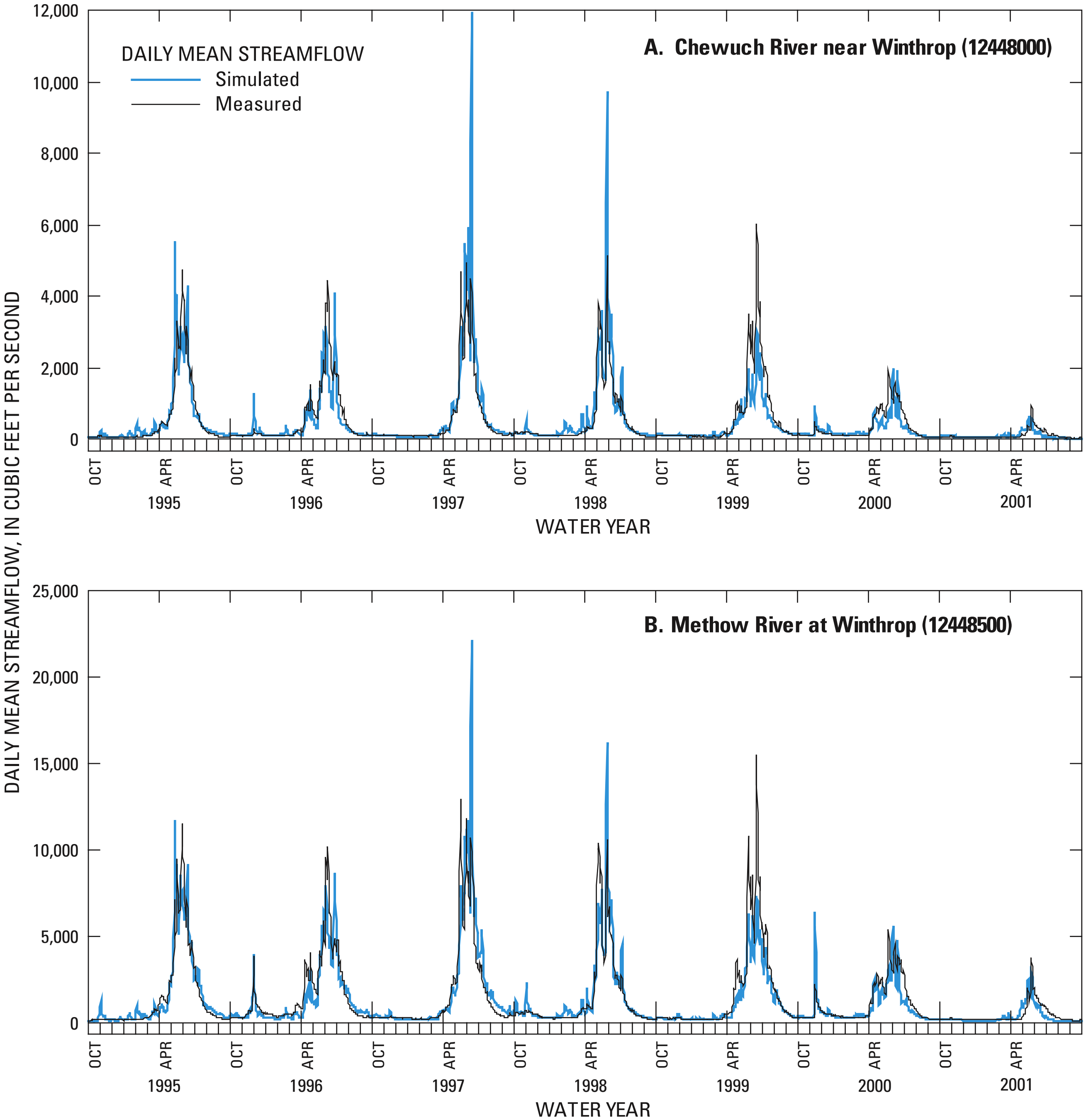


Figure 6. Simulated and measured daily mean streamflow for selected streamflow-gaging stations in the Methow River Basin, water years 1995-2001.

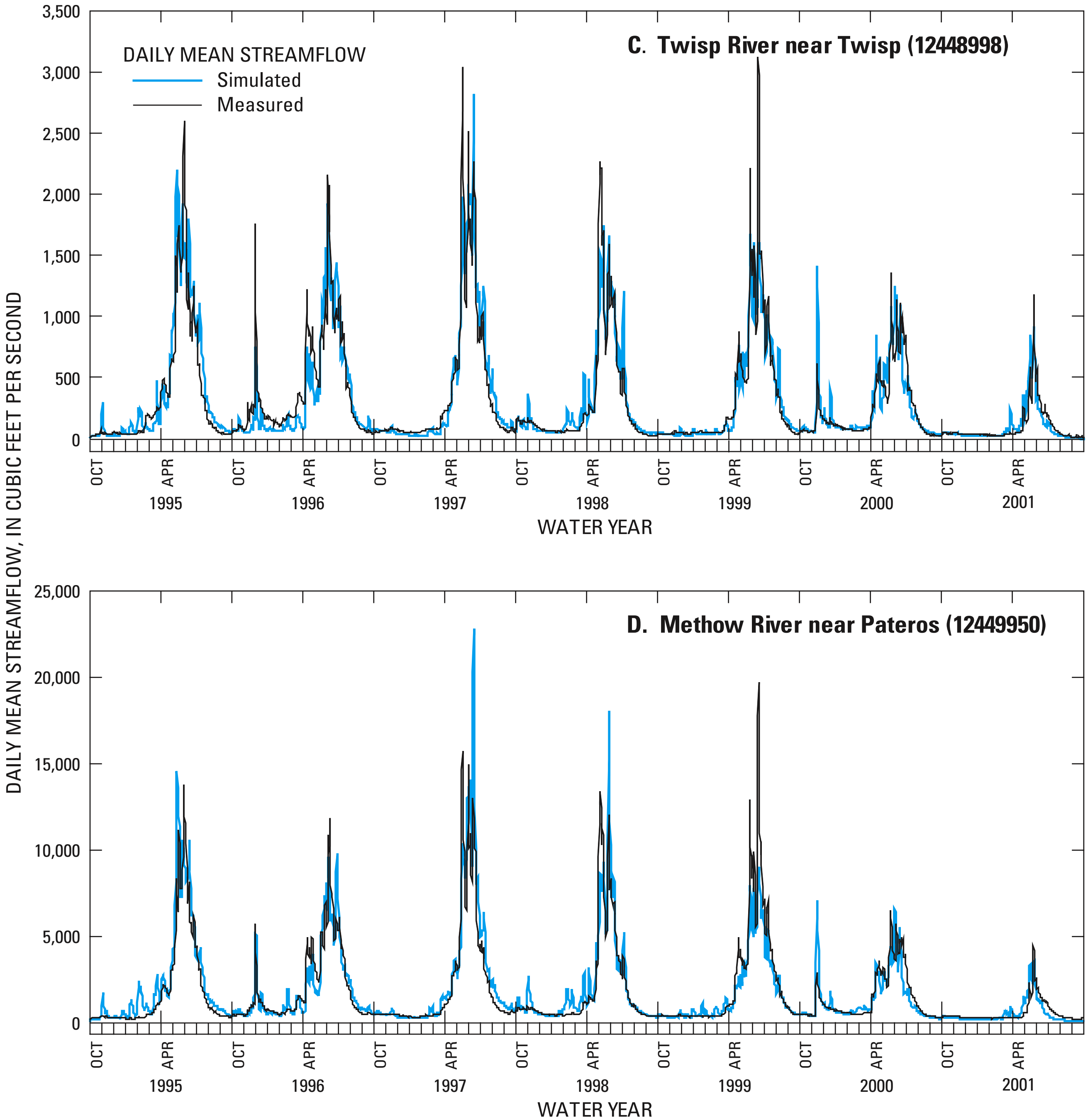


Figure 6. — *Continued.*

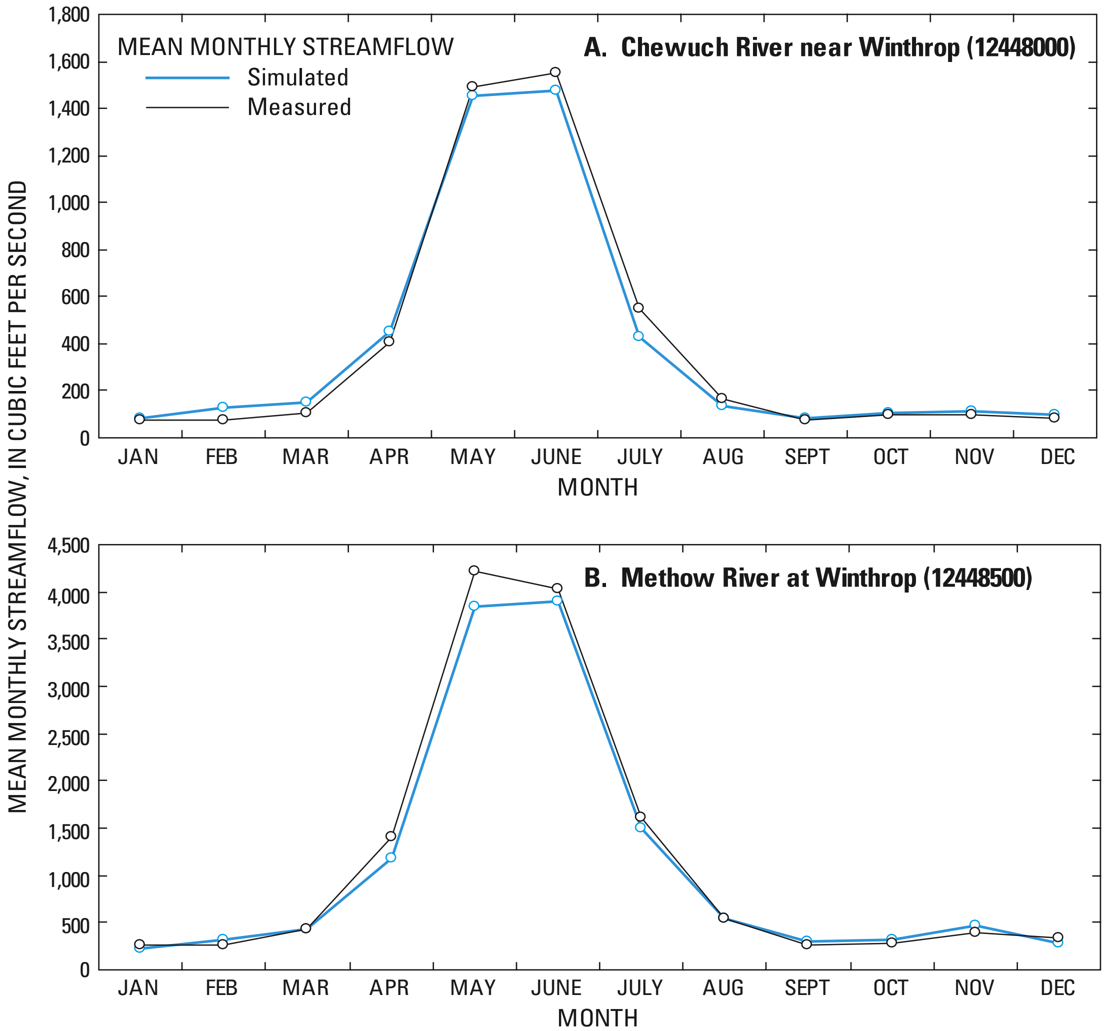


Figure 7. Simulated and measured mean monthly streamflow for selected streamflow-gaging stations in the Methow River Basin, Washington, water years 1992-2001.

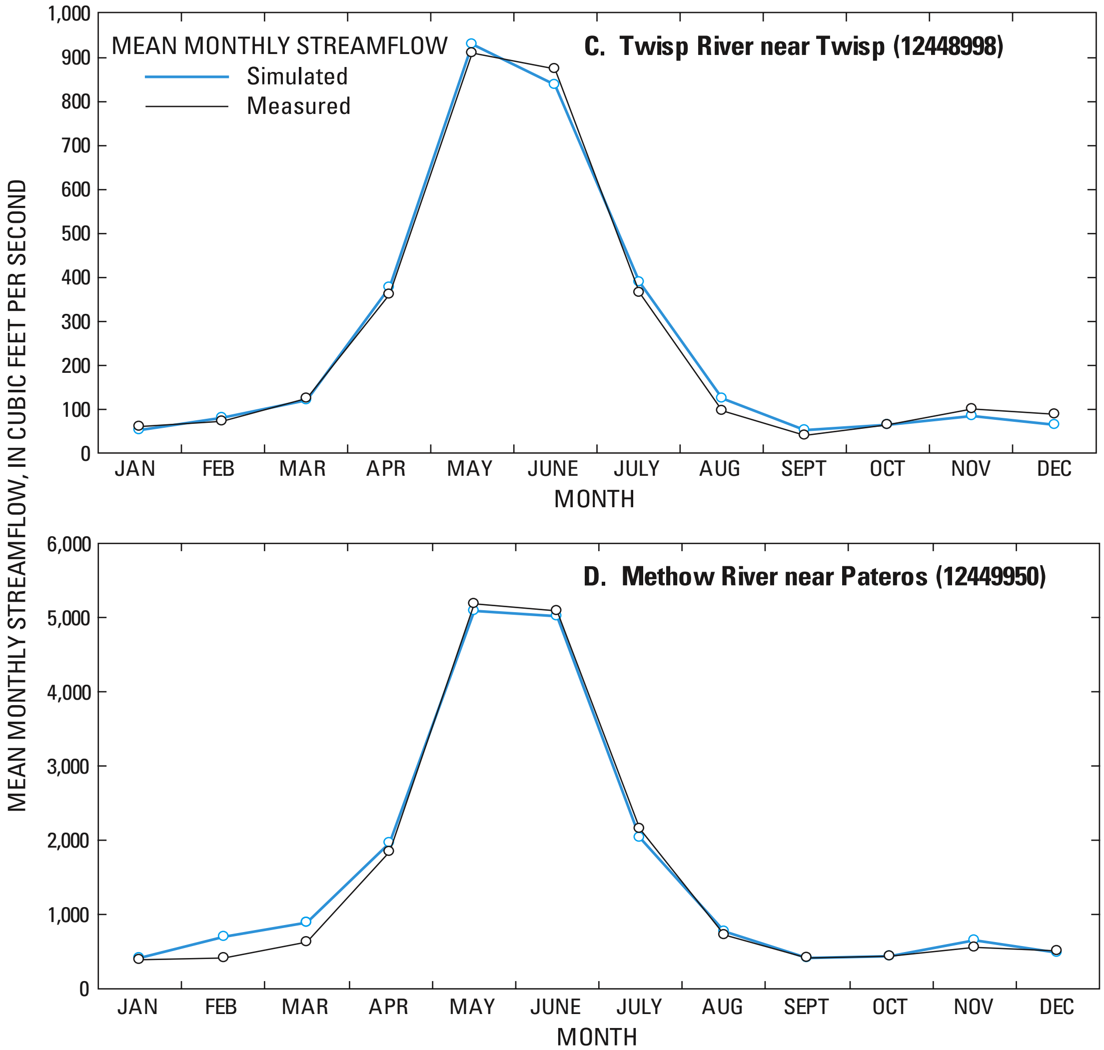


Figure 7. — *Continued.*

Parameter Sensitivities

A sensitivity analysis determines the extent to which a parameter value affects the simulated value, or, in this case, streamflow. This analysis provides a good indication of how parameter uncertainty will adversely affect predicted streamflow.

The computer program UCODE (Poeter and Hill, 1998), a universal inverse model using nonlinear regression, was applied with the MMS model to measure the amount of information provided by the streamflow data. A sensitivity analysis was completed to determine hydrologic parameters pertinent to the modeling results. The diagnostic statistics generated by UCODE used in this sensitivity analysis were the dimensionless scaled sensitivities and the composite scaled sensitivities. A complete discussion of these statistics is given by Hill (1998) and Poeter and Hill (1998). Dimensionless scaled sensitivities indicate the sensitivity of the simulated equivalent of each measurement (mean daily streamflow) to the parameter. The dimensionless scaled sensitivity, ss_{ij}, is calculated as (Hill, 1998):

$$ss_{ij} = \left(\frac{\partial y'_i}{\partial b_j}\right) b_j \omega_{ii}^{1/2} \qquad (1)$$

where

i identifies one of the observations;

j identifies one of the parameters;

y'_i is the simulated value associated with ith observations;

b_j is the jth estimated parameter;

$\frac{\partial y'_i}{\partial b_j}$ is the sensitivity of the simulated value associated with the ith observation with respect to the jth parameter and is evaluated at the final parameter values; and

ω_{ii} is the weight for the ith observation.

Composite scaled sensitivities (*CSS*) summarize all the sensitivities for one parameter. *CSS* is calculated for each parameter using the scaled sensitivities for all observations (here, the daily mean streamflow). Because they are dimensionless, *CSS* can be used to compare the amount of information provided by different types of parameters. Model results will be more sensitive to parameters with large *CSS* relative to those for other parameters. The *CSS* for the jth parameter, css_j, is calculated as (Hill, 1998):

$$CSS_j = \left[\frac{\sum_{i=1}^{ND} (ss_{ij}^{2})\big|_{\underline{b}}}{ND}\right]^{\frac{1}{2}} \qquad (2)$$

where *ND* is the number of observations being used in the regression, $\underline{b}$ is a vector that contains the parameter values at which the sensitivities are evaluated, and the quantity in parentheses equals the scaled sensitivities of equation 1.

CSS for 15 parameters were calculated for the final model, using daily mean streamflow for water years 1991-94 from streamflow-gaging stations 12448000 (Chewuch River near Winthrop), 12448998 (Twisp River near Twisp), and 124499500 (Methow River near Pateros) as the observations (fig. 8). The monthly air-temperature coefficient used in the Jensen-Haise potential ET computation was divided into six parameters: jh_coef1 represented January and February; jh_coef2 represented March; jh_coef 3 represented April and May; jh_coef 4 represented June – August; jh_coef 5 represented September and October; and jh_coef 6 represented November and December. CSS for tmax_allsnow, the maximum temperature below which all precipitation is simulated as snow, was the highest, jh_coef 3 and 4 the next highest. This jh_coef 3 and 4 result is expected because those parameters control ET during the spring and summer months. During periods when streamflow is dominated by ground-water flow (typically late summer through winter), the ground-water and subsurface flow parameters have a great effect on simulated streamflow.

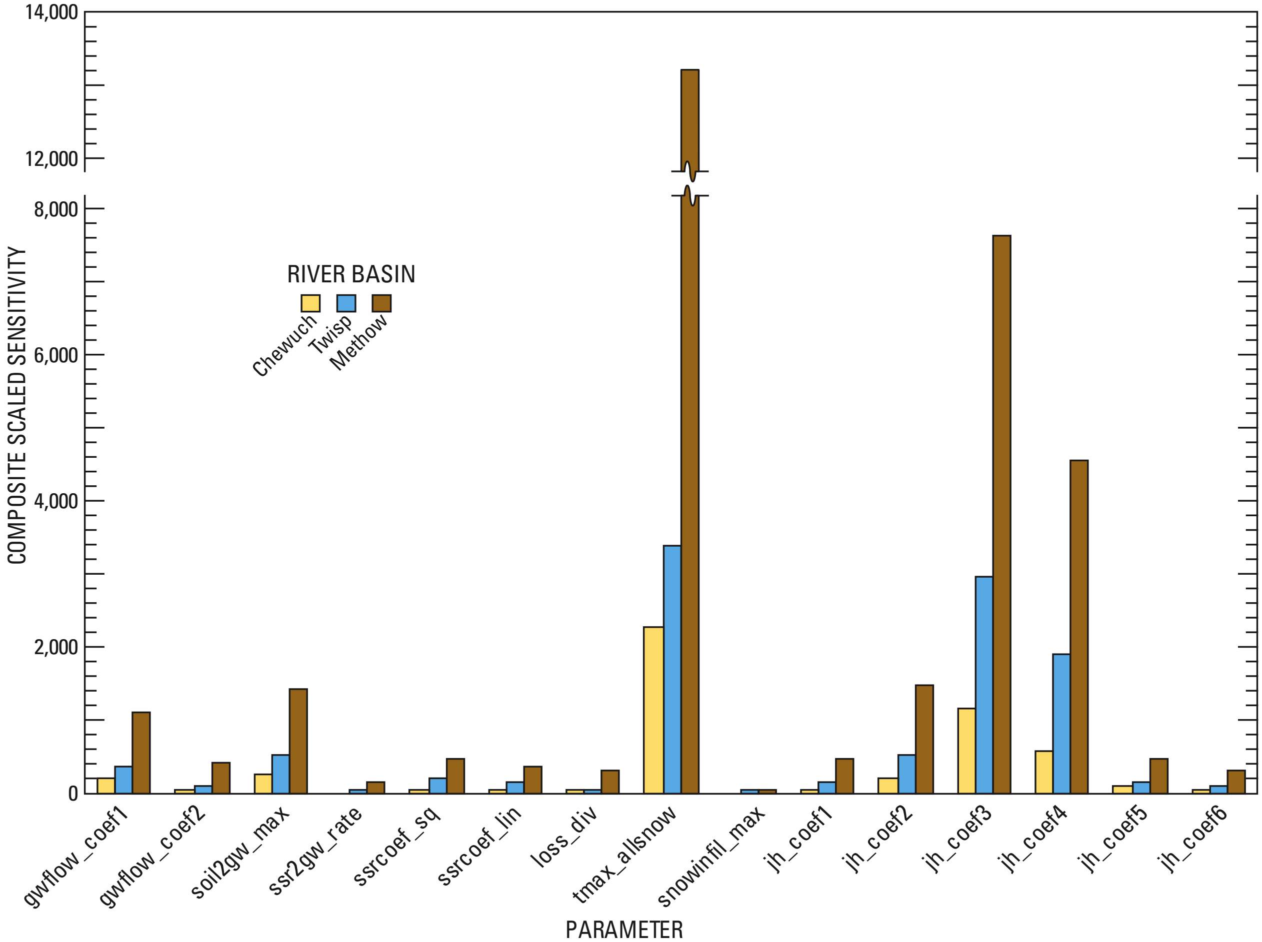


Figure 8. Composite scaled sensitivities for model parameters used in the precipitation-runoff model for the Twisp River Basin, the Chewuch River Basin, and the Methow River Basin, Washington.

Long-Term Simulations

The calibrated model can be used as a tool to simulate natural streamflows, streamflows at gaged streams for periods outside the measured streamflow record, and ungaged streams. This ability allows the examination of the system's hydrologic response to climatic conditions. Also, long-term means could differ significantly from those means produced from the shorter-term record of the streamflow-gaging stations. Annual, or even decadal, trends in streamflows would be more evident. To demonstrate the capability of simulating streamflow outside the streamflow-gaging record, water years 1960–2001 were simulated and monthly streamflow statistics generated for 11 streamflow-gaging stations (table 5). Standard deviations for the period of simulation were large, suggesting great variability in monthly streamflows. Mean monthly streamflows for water years 1992–2001 were compared with mean monthly streamflows for the simulation period 1960-2001. The simulated mean monthly streamflows for the 11 streamflow-gaging stations were an average of 2.5 percent higher for 1992–2001 than for the entire simulation period. If water year 2001, an extreme drought year, is omitted, simulated mean monthly streamflows for the 11 streamflow-gaging stations were an average of 9.0 percent higher than for the entire simulation period.

Table 5. Simulated minimum, maximum, mean monthly streamflows and standard deviations for the Methow River Basin, Washington, water years 1960-2001

[**Station No.**: U.S. Geological Survey streamflow gaging station;

Standard deviation: $\sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$. **Abbreviatons**: ft^3/s, cubic feet per second]

Station No.		Simulated monthly streamflow (ft^3/s)											
		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
12447370	Minimum	15.6	22.8	19.3	16.0	16.3	16.4	61.3	278.0	53.4	23.1	18.0	16.6
	Maximum	529.0	502.5	103.5	66.2	92.5	231.1	760.2	2,061.1	2,603.4	964.5	3,15.3	175.1
	Mean	78.5	92.2	41.5	36.9	42.8	61.4	326.1	1,025.4	888.2	288.1	78.1	50.1
	Standard deviation	105.8	98.4	19.9	13.5	18.3	36.9	181.7	399.6	539.1	250.7	68.1	28.3
12447382	Minimum	5.2	9.8	7.5	5.8	4.5	4.4	11.3	210.7	39.0	18.8	11.6	7.8
	Maximum	389.2	264.9	55.6	35.4	40.3	57.7	343.6	1,181.1	1,471.5	685.0	508.7	249.8
	Mean	58.4	55.3	23.2	18.0	18.4	20.4	140.8	627.0	589.2	295.9	133.5	65.3
	Standard deviation	71.7	57.4	13.0	8.4	9.0	12.7	93.6	205.0	278.0	177.7	124.5	61.6
12447383	Minimum	38.2	62.2	46.4	40.8	46.1	38.0	119.8	858.9	175.1	79.8	57.4	45.4
	Maximum	1,420.6	1,430.0	344.0	191.8	238.6	433.1	1,558.0	4,443.3	5,889.1	2,491.1	1,528.1	634.6
	Mean	228.6	273.6	123.5	101.9	114.1	141.5	670.0	2,391.6	2,173.7	913.4	349.7	192.6
	Standard deviation	274.8	278.5	63.4	40.8	55.6	76.9	363.6	829.3	1,133.1	636.8	326.7	135.7
12447387	Minimum	1.7	3.1	2.9	2.2	2.1	3.2	9.9	10.8	4.6	3.5	2.7	2.2
	Maximum	94.4	80.1	15.4	12.6	14.0	41.8	162.1	431.9	367.8	71.9	26.3	19.7
	Mean	14.5	14.8	7.0	5.9	6.4	8.5	79.7	179.3	78.8	22.1	12.9	10.4
	Standard deviation	17.5	14.8	3.3	2.6	2.9	6.9	39.5	86.9	74.0	14.9	5.1	3.7
12447390	Minimum	2.6	2.3	2.2	2.1	2.0	2.1	2.8	28.5	7.1	4.4	3.6	3.1
	Maximum	33.8	13.8	7.3	7.1	7.0	6.4	95.2	282.3	4,27.4	105.6	30.9	11.2
	Mean	5.6	5.1	4.0	3.9	4.0	4.0	27.6	154.8	116.0	32.1	9.7	5.8
	Standard deviation	4.7	2.7	1.1	1.1	1.2	1.3	24.9	60.5	90.6	28.1	5.1	1.8
12448000	Minimum	27.4	41.6	34.5	33.7	38.5	48.3	102.4	135.0	50.4	37.7	33.0	29.8
	Maximum	459.8	536.9	293.9	284.1	305.9	367.0	1,419.6	4,711.2	5,243.7	1,302.3	329.7	198.5
	Mean	104.8	131.0	97.3	92.9	124.5	154.7	528.4	1,711.1	1,233.8	357.2	162.5	110.3
	Standard deviation	75.4	115.4	63.1	57.3	71.0	77.4	307.7	966.7	1,095.2	270.1	71.3	42.8
12448500	Minimum	69.9	125.5	96.1	95.5	114.2	142.9	430.7	1,032.1	240.6	127.4	98.0	81.2
	Maximum	2,192.3	2,310.8	757.2	567.6	628.8	891.5	3,420.2	9,508.9	12,495.3	3,714.2	1,897.8	868.7
	Mean	380.2	473.1	271.6	243.7	311.0	398.1	1,454.2	4,601.5	3,691.2	1,362.4	561.0	337.1
	Standard deviation	409.7	447.5	156.6	123.3	154.7	175.2	721.8	1,930.3	2,427.2	925.8	403.0	177.9

Table 5. Simulated minimum, maximum, mean monthly streamflows and standard deviations for the Methow River Basin, Washington, water years 1960-2001 *(Continued)*

[**Station No.**: U.S. Geological Survey streamflow gaging station;

Standard deviation: $\sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$. **Abbreviatons**: ft³/s, cubic feet per second]

Station No.		Simulated monthly streamflow (ft³/s)											
		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
12448998	Minimum	18.7	22.4	17.3	16.0	21.3	36.1	131.7	287.5	95.3	42.4	27.8	20.8
	Maximum	499.0	752.2	219.5	199.2	192.1	278.4	946.6	2,252.0	2,137.1	801.5	365.2	169.4
	Mean	78.6	105.6	62.7	64.3	78.3	110.5	450.1	1,079.8	867.3	313.2	114.4	64.7
	Standard deviation	85.2	126.6	47.5	44.4	42.7	59.1	178.2	384.9	475.2	226.3	69.3	32.3
12449500	Minimum	88.7	150.6	117.4	125.3	154.9	250.8	575.2	1,329.4	338.7	170.6	126.5	102.5
	Maximum	2,718.6	3,138.7	1,030.1	858.2	926.0	1,196.3	4,437.3	11,931.6	14,766.9	4,439.5	2,151.0	1,015.6
	Mean	464.1	597.9	360.9	340.5	446.9	580.1	1,968.9	5,726.9	4,601.8	1,699.3	687.3	409.0
	Standard deviation	493.8	582.0	224.0	192.1	218.1	249.2	899.0	2,324.5	2,892.4	1,153.3	468.5	210.6
12449710	Minimum	0.7	3.5	2.7	3.4	3.4	2.6	2.1	2.0	1.4	1.1	1.0	0.8
	Maximum	35.3	132.9	70.5	89.2	131.2	170.9	371.8	579.9	203.4	92.1	35.0	26.5
	Mean	14.4	20.0	19.1	24.0	42.6	65.6	140.1	130.5	50.0	26.8	18.4	14.0
	Standard deviation	8.1	24.0	16.8	21.0	28.7	37.4	101.4	117.4	45.6	16.2	9.1	6.9
12449950	Minimum	90.5	170.6	130.8	148.9	169.7	290.4	598.5	1,381.5	353.9	177.1	131.5	106.4
	Maximum	2,843.1	3,324.4	1,429.4	1,274.1	1,400.6	1,956.4	5,006.7	12,738.9	15,380.3	4,678.2	2,267.8	1,094.3
	Mean	506.6	676.4	442.4	453.0	629.1	832.0	2,280.8	6,002.3	4,847.2	1,826.6	757.9	455.9
	Standard deviation	508.4	640.2	294.1	287.1	324.9	386.4	1,006.0	2,497.6	3,018.6	1,220.4	499.5	228.8

The calibrated model can also be used to examine the effects of irrigation-canal seepage on streamflow. Konrad and others (2003) report that ground-water discharge contributes a substantial portion (33 to 96 percent) of baseflow in the Methow and Twisp Rivers. Field studies have shown that 50 percent or more of canal discharge can be returned to the ground-water system through canal seepage. To examine the contribution of irrigation-canal seepage to streamflow, two scenarios were simulated for irrigation canals diverting water from the Chewuch and Twisp Rivers. The first scenario returned 50 percent of the diverted water to the ground-water system. The second scenario returned none of the diverted water to the ground-water system, representing a system of lined irrigation canals. The difference in daily mean streamflow from the two scenarios (fig. 9) shows an increasing gain in streamflow throughout the irrigation season (May 1–October 7). When the canals are shut down after October 7, the net gain begins to decrease, but remains throughout the year. The effect on Chewuch River streamflow is greater because of the greater amount of diverted flow (fig. 9*A*).

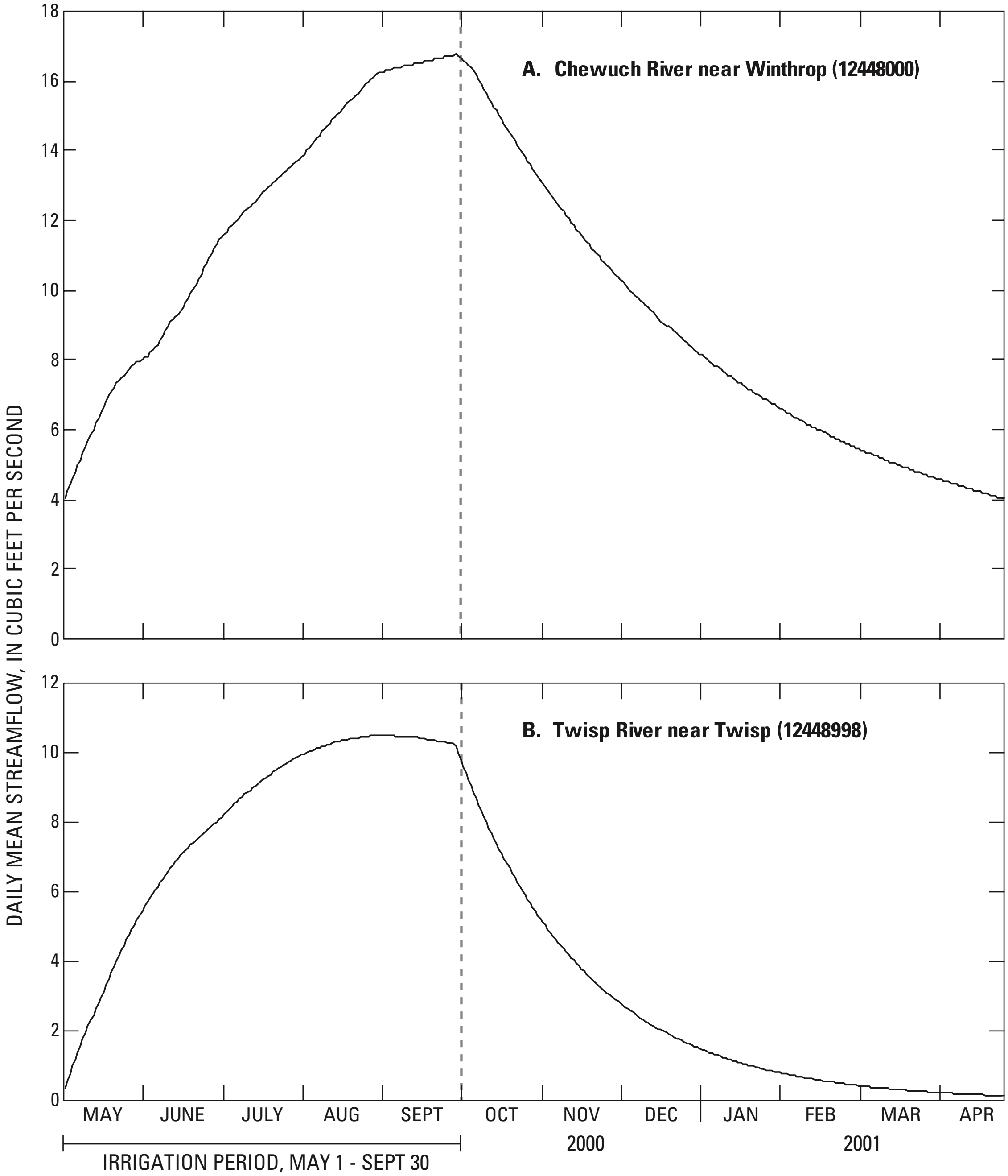


Figure 9. Mean daily difference between contributions of irrigation-canal seepage to streamflow in the Chewuch and Twisp Rivers, May 2000-April 2001, simulated by the precipitation-runoff model using two scenarios: 50-percent returned seepage and zero-percent returned seepage.

Analysis of Simulation Limitations

All modeling studies contain errors. Certain approximations and simplifications must be made to simulate the actual flow systems. Errors in precipitation-runoff modeling typically are caused by a combination of inadequate input data, inadequate representation of the physical processes by the algorithms of the model, and inadequate parameter estimation during the calibration procedure (Troutman, 1985). A lack of understanding about some aspects of the natural flow system accounts for much of the error. As a result, model-predicted values must be used with caution, in consideration of simulation error.

Mean annual streamflow totals for simulated and measured streamflow for 1992-2001 varied considerably during many of the water years, and there was no well-defined pattern or bias in the results (table 6). Simulated and measured mean annual streamflow for the 10-year period matched closely for all calibration points with the exception of station 12447383, Methow River above Goat Creek, for which streamflow sometimes was over-simulated, mostly for the baseflow period of autumn and winter. A large amount of Methow River flow goes into the ground water above Goat Creek and then returns to the surface upstream of Winthrop (Caldwell and Catterson, 1992). The current model does not simulate channel losses and, therefore it does not correctly represent this ground water-surface water interaction. During the calibration process, streamflow was purposely simulated to exceed measured streamflow at the Methow River above Goat Creek. At the next downstream station on the Methow River (12448500), the cumulative annual streamflow is under-estimated by 5.5 percent. Simulations of the mean annual streamflow as a percentage of measured mean annual streamflow for the 10-year calibration period at six streamflow-gaging stations (12447383 was omitted for the reasons discussed) ranged from -35.2 to +26.2 percent, with 65 percent of the simulated values within 15 percent (table 6). For the 10-year simulation period, measured annual streamflow totals were highest for water years 1995, 1996, 1997, and 1999. Above-average measured annual flows during water years 1996 and 1999 were under-simulated at all streamflow-gaging stations, indicating that the current model is less effective at simulating high-flow conditions. The model performed reasonably well during low-flow years (table 6) and during typically low-flow months (table 7). These results were deemed acceptable, because the low-flow period is of primary interest in issues concerning fish habitat quality.

Parameter Error

Parameter error occurs when improper values are chosen during the calibration process. Various combinations of parameter values can achieve the desired reduction in residual error yet improperly represent the actual system. For example, an increase in ET or a decrease in precipitation would both result in lowered discharge at a node. Model fit was accomplished primarily with manual calibration, but nonlinear regression was used to measure the sensitivities for model parameters. With most watershed models, the most sensitive parameters will be those directly related to precipitation and temperature, as found in this study. Ground-water flow parameters had a large effect on the shape of the simulated hydrograph during low-flow periods. The uncertainty associated with the estimation of these parameter values propagates through to the model predictions.

Data Error

The MMS watershed model requires measured precipitation, temperature, and streamflow time-series data and physical characteristics of the basin. Precipitation volume is often the most important driving factor of the simulation, and it is often the most difficult to estimate. Precipitation records are point measurements, whereas the model requires input distributed throughout the study area. This study used 18 precipitation sites within and adjacent to the study area, and the measurements were extrapolated to estimate precipitation throughout the entire basin. Precipitation in the Methow River Basin varies widely. Mean elevation of an MRU can differ significantly from that of the closest rain gage, and the MRU can include a wide range of average precipitation. In addition to the problems with spatial distribution, much of the precipitation comes in the form of snowfall, which can be underestimated if the collection device is not protected from the wind. Catchment losses also occur for rain, but they are believed to be smaller than for snow.

Table 6. Simulated and measured mean annual streamflows, relative error, in percent, and bias, in percent, for water years 1992-2001

[**Station No.**: U.S. Geological Survey streamflow gaging station. See figure 5 for location. **Water year**: a water year begins on October 1 of the previous year and ends on September 30; **Abbreviation:** $(ft^3/s)/d$, cubic feet per second per day;
Bias: $\frac{\sum[(s-m)/m]}{N} \times 100$. Relative error: $(s - m)/m \times 100$, where s is simulated daily mean streamflow, in cubic feet per second; m is measured daily mean streamflow, in cubic feet per second; and N is number of measured values]

Station No.	Water year	Mean streamflow $(ft^3/s)/d$		Relative error (percent)	Bias (percent)
		Simulated	Measured		
[1]12447383	1992	447.7	405.5	10.4	
	1993	459.2	309.2	48.5	
	1994	387.0	286.4	35.1	
	1995	767.2	590.7	29.9	
	1996	776.6	690.3	12.5	
	1997	953.3	725.4	31.4	
	1998	706.5	589.9	19.8	
	1999	661.6	798.3	-17.1	
	2000	541.0	499.7	8.3	
	2001	242.1	147.4	64.2	
	Total	5,942.3	5,042.9	17.8	24.3
12447390	1992	22.1	22.1	0.1	
	1993	31.8	25.3	25.8	
	1994	20.2	28.4	-29.0	
	1995	41.7	40.7	2.5	
	1996	34.0	41.4	-17.8	
	1997	54.9	43.5	26.2	
	1998	46.3	37.2	24.7	
	1999	33.1	45.0	-26.5	
	2000	25.2	28.2	-10.7	
	2001	13.3	10.7	23.6	
	Total	322.6	322.4	0.0	1.9
12448000	1992	216.6	223.3	-3.0	
	1993	338.1	275.4	22.7	
	1994	220.1	281.6	-21.8	
	1995	565.9	527.6	7.3	
	1996	461.1	529.3	-12.9	
	1997	724.9	580.7	24.8	
	1998	627.3	511.1	22.7	
	1999	408.0	629.7	-35.2	
	2000	277.7	333.2	-16.7	
	2001	93.8	101.4	-7.5	
	Total	3,933.6	3,993.3	-1.5	-2.0
12448500	1992	741.2	869.3	-14.7	
	1993	870.8	814.5	6.9	
	1994	668.5	758.1	-11.8	
	1995	1,529.8	1,444.1	5.9	
	1996	1,402.3	1,570.4	-10.7	
	1997	1,878.3	1,639.6	14.6	
	1998	1,490.4	1,423.6	4.7	
	1999	1,217.1	1,728.9	-29.6	
	2000	927.9	1,067.0	-13.0	
	2001	369.4	427.2	-13.5	
	Total	11,095.6	11,742.7	-5.5	-6.1
12448998	1992	179.7	179.8	-0.1	
	1993	171.0	170.4	0.4	
	1994	156.5	151.9	3.1	
	1995	393.3	341.4	15.2	
	1996	346.4	409.5	-15.4	
	1997	395.4	384.9	2.7	
	1998	310.9	294.9	5.4	
	1999	324.0	344.0	-5.8	
	2000	262.3	248.2	5.7	
	2001	101.5	98.7	2.8	
	Total	2,641.2	2,623.7	0.7	1.4
12449500	1992	934.7	1033.8	-9.6	
	1993	1055.3	947.7	11.4	
	1994	834.2	901.3	-7.4	
	1995	1,985.1	1,752.4	13.3	
	1996	1,790.0	1,915.3	-6.5	
	1997	2,322.3	1,922.8	20.8	
	1998	1,840.4	1,670.9	10.1	
	1999	1,573.8	1,968.6	-20.1	
	2000	1,211.6	1,305.1	-7.2	
	2001	472.4	503.7	-6.2	
	Total	14,019.9	13,921.6	0.7	-0.1
12449950	1992	1,045.2	1,084.0	-3.6	
	1993	1,161.7	1,022.9	13.6	
	1994	924.2	963.0	-4.0	
	1995	2,312.6	1,854.1	24.7	
	1996	2,010.9	2,053.6	-2.1	
	1997	2,532.9	2,128.1	19.0	
	1998	2,074.0	1914.2	8.3	
	1999	1,775.4	2,251.0	-21.1	
	2000	1,361.2	1,439.3	-5.4	
	2001	512.2	572.5	-10.5	
	Total	1,5710.3	15,282.8	2.8	1.9

[1]Station 12447383 was intentionally oversimulated to compensate for channel losses not simulated by the model.

Table 7. Simulated and measured mean monthly streamflows, relative error, in percent, and bias, in percent, for low-flow periods, water years 1992-2001

[**Station No.**: U.S. Geological Survey streamflow gaging station. See figure 5 for location. **Water year**: a water year begins on October 1 of the previous year and ends on September 30; **Abbreviation:** $(ft^3/s)/d$, cubic feet per second per day;

Bias: $\frac{\sum[(s-m)/m]}{N} \times 100$. Relative error $(s - m)/m \times 100$, where s is simulated daily mean streamflow, in cubic feet per second; m is measured daily mean streamflow, in cubic feet per second; and N is number of measured values]

Station No.	Month	Mean streamflow $(ft^3/s)/d$		Relative error (percent)	Bias (percent)
		Simulated	Measured		
[1]12447383	September	198.5	37.7	427.2	
	October	175.6	30.7	471.0	
	November	277.1	107.1	158.8	
	December	130.7	79.1	65.2	
	Total	781.8	254.6	207.1	112.2
12447390	September	6.6	7.6	-12.5	
	October	4.6	6.4	-28.6	
	November	4.0	7.2	-44.8	
	December	3.3	5.7	-41.0	
	Total	18.5	26.9	-31.0	-12.7
12448000	September	82.5	75.6	9.1	
	October	102.6	96.3	6.6	
	November	115.9	101.6	14.1	
	December	100.2	84.6	18.5	
	Total	401.2	358.0	12.1	4.8
12448500	September	292.6	268.0	9.2	
	October	312.8	288.2	8.5	
	November	461.4	388.0	18.9	
	December	280.8	337.7	-16.9	
	Total	1,347.5	1,281.9	5.1	2.0
12448998	September	52.1	39.7	31.2	
	October	62.5	62.9	-0.7	
	November	85.8	99.7	-13.9	
	December	64.0	86.3	-25.9	
	Total	264.4	288.6	-8.4	-0.9
12449500	September	327.3	300.1	9.1	
	October	389.2	362.7	7.3	
	November	575.9	482.7	19.3	
	December	376.0	414.1	-9.2	
	Total	1,668.5	1,559.7	7.0	2.6
12449950	September	399.4	400.4	-0.2	
	October	434.3	438.1	-0.9	
	November	635.3	558.1	13.8	
	December	482.3	502.7	-4.0	
	Total	1,951.4	1,899.2	2.7	0.9

[1]Station 12447383 was intentionally oversimulated to compensate for channel losses not simulated by the model.

Temperature data can be the source of as much potential error as the rainfall data. Again, temperature is recorded as a point measurement and basin-wide distributed values must be estimated for each MRU. Differences of a few degrees can determine if precipitation is simulated as snow or rain or if an accumulated snowpack melts. Precipitation, combined with air temperature, determines both the cumulative annual streamflow and the basic shape of the simulated hydrograph.

In general, the DEM and the GIS Weasel represented the physical characteristics of the basin well. Even though the basin was delineated into 620 MRUs, however, approximations of slope and aspect were necessary. Coarse coverages of forest density, land use, and soils introduced error in sensitive parameters that determine ET, infiltration, and ground-water recharge.

Model Error

The precipitation-runoff algorithm cannot completely represent all physical processes of a basin. Determining whether a weakness in a simulation is attributable to input data error or model weakness is almost impossible in some cases. The nonlinear regression used in the sensitivity analysis helped to understand the possible effects of this uncertainty.

Ground-water flow is a dominant component of streamflow during autumn and winter months. These low-flow periods can limit accessible habitat to resident fish species, and therefore are a critical period to understand and accurately simulate. MMS is designed to simulate surface and shallow subsurface flow and simplifies ground-water flow much more than would a ground-water flow model. The current ground-water flow equations use few parameters and are not physically based. Separating the baseflow component from the total streamflow produced complex baseflow hydrographs that could not be reproduced by the standard parameter algorithm for ground-water flow used by PRMS.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey, in cooperation with Okanogan County, constructed and calibrated an enhanced precipitation-runoff model for the Methow River Basin in eastern Washington, and evaluated the model as a predictive tool for assessing the current and natural streamflow conditions. This effort was part of a larger study to evaluate streamflow conditions for the Methow River and its tributaries in eastern Washington, prompted in part by the listing of Upper Columbia River steelhead, including the Methow River run, and Upper Columbia River spring-run Chinook salmon, including the Methow River run, as "endangered" under the Endangered Species Act. Also, Bull trout in the Methow River were listed under the Endangered Species Act as "threatened." This new model builds upon the previous watershed model and the current model is validated using a new, more extensive streamflow data network. The major enhancement was the simulation of current streamflow conditions with the addition of irrigation diversions, returns, and application. Further refinement was accomplished through the use of more-detailed soil and land-use data. A calibrated watershed model provides a tool to assess the available water resources throughout the basin and simulate long-term time-series of natural streamflow conditions.

The Geographic Information System (GIS) Weasel was used to delineate subbasins and the drainage network. A 150-foot (45-meter) USGS 7.5-minute digital elevation model of the Methow River Basin was used to define topographic surfaces. The GIS Weasel delineated 620 modeling response units (MRU) based on slope, aspect, elevation, and flow planes. The parameterization component of the program then generated parameters for the MRUs, incorporating ancillary information concerning soils, land use and land cover, and vegetation.

Information from the GIS Weasel was used to construct and calibrate a computer-simulation model of current and natural streamflow conditions for the Methow River Basin. The Modular Modeling System (MMS), using the Precipitation-Runoff Modeling System, was the simulation model chosen for this study. Major advantages of this system include the ability to (1) simulate the moisture balance of each component of the hydrologic cycle, (2) account for heterogeneous physical characteristics of a basin, and (3) appropriately simulate both mountainous and flat areas. Model calibration was accomplished using measured precipitation, air-temperature, and streamflow time-series data.

Streamflow was simulated for water years 1992–2001 to calibrate the model to measured streamflows at seven USGS streamflow-gaging stations. Additional data for water years 2000-2001 from six other USGS streamflow-gaging stations were also used. Initial estimates of parameters were taken from values determined by the GIS Weasel, values calculated from the MMS algorithms, MMS algorithm default values, and parameter estimates used in the previous Methow River Basin watershed model. Most parameter adjustments were made to precipitation, temperature, and the ground-water flow coefficient.

Simulated and measured streamflow generally showed close agreement, especially for spring runoff and baseflows. Because of the hydrologic complexities of the subbasins, the model simulations were less accurate at capturing the magnitude and timing of short-term (1- to 3-day) peak flows. The model also tended to over-simulate (simulated discharge greater than measured discharge) fall and winter peak flows. One streamflow-gaging station location was intentionally calibrated to over-simulate discharge in order to compensate for observed channel losses not simulated by the model.

A sensitivity analysis determines the extent to which a parameter value affects the simulated value, or, in this case, streamflow. Composite scaled sensitivities summarize all the sensitivities for one parameter and can be used to compare the amount of information provided by different types of parameters. Parameters that control the form of precipitation and monthly air-temperature coefficients used to compute potential evapotranspiration were most important. During periods when streamflow is dominated by ground-water flow (typically late summer through winter), the ground-water and subsurface flow parameters had a great effect on simulated streamflow.

The calibrated model can be used as a tool to simulate natural streamflows, streamflows at gaged streams for periods outside the measured streamflow record, and ungaged streams. To demonstrate this ability, streamflow for water years 1960–2001 was simulated and monthly streamflow statistics generated. The simulated mean monthly flows for 11 streamflow-gaging stations were an average of 2.5 percent higher for water years 1992–2001 than for the entire simulation period. If water year 2001, an extreme drought year, is omitted, simulated mean monthly flows for the 11 streamflow-gaging stations were an average of 9.0 percent higher. The calibrated model also examined the effects of irrigation canal seepage on streamflow. Irrigation-canal seepage contributed to streamflow throughout the year, with the greatest effect during the irrigation season.

Mean annual streamflow for simulated and measured streamflow for 1992–2001 varied considerably during many water years. Simulated and measured mean annual streamflow for the 10-year period matched closely for all calibration points with the exception of station 12447383, Methow River above Goat Creek. Station 12447383 was intentionally over-simulated to compensate for channel losses not simulated by the model. Simulations of the mean annual streamflow as a percentage of measured mean annual streamflow for the 10-year calibration period at six streamflow-gaging stations ranged from -35.2 to +26.2 percent, with 65 percent of the simulated values within 15 percent.

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