Use of a Precipitation-Runoff Model to Simulate Natural Streamflow Conditions in the Methow River Basin, Washington

Prepared in cooperation with
Okanogan County

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 01-4198

science for a changing world

The Methow River below Boesel Fault. (Photograph by Dick Ewing. Used with permission.)

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By D. Matthew Ely and John C. Risley

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CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
	0.4047	hectare
	0.4047	square hectometer
	0.004047	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
	0.001233	cubic hectometer
cubic foot (ft^3)	28.32	cubic decimeter
	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	2.54	centimeter
	25.4	millimeter
inch per year	25.4	millimeter per year
mile (mi)	1.609k	kilometer
square miles	12.590	square kilometers

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:
°C = 5/9 × (°F - 32).

VERTICAL DATUM

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum *derived* from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

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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. Management options must be considered that minimize adverse effects on people but meet instream flow needs for fish. This report describes the construction and calibration of the Methow River Basin watershed model and evaluates the accuracy of the model as a predictive tool for assessing the natural instream flow conditions. The term “natural” instream flow is stressed because surface water within the Basin is used for agricultural irrigation through an extensive system of diversions.

The USGS Modular Modeling System was used for the watershed modeling component of the Methow River Basin study. The Geographic Information System Weasel characterized the physical properties of the basin, and the Precipitation-Runoff Modeling System simulated the natural streamflow. Natural streamflow conditions in the Basin were difficult to calibrate because six of the seven streamflow gaging stations are located below irrigation diversions and few streamflow measurements exist for the study area before the diversions were present. Therefore, limited records of natural streamflow conditions were available and estimations concerning some physical processes could not be quantified.

Streamflow was simulated for water years 1992-99 to calibrate the model to measured streamflows. Simulated and measured streamflow generally showed close agreement, especially during spring runoff from snowmelt. Low-flow periods, most restrictive to fish habitation, were simulated reasonably well, yet possessed the most uncertainty. Simulations of the total annual runoff as a percentage of measured annual runoff for the 8-year calibration period at seven gaging stations ranged from -33.7 to +30.5 percent with 70 percent of the simulated values within 16 percent. Simulation of water years 1959-99 demonstrated great variability in monthly streamflow statistics. The simulated mean monthly flows for the seven streamflow-gaging stations were an average of 11.5 percent higher for the calibration period (1992-99) than for the entire simulation period (1959-99).

INTRODUCTION

The Methow River Basin, located in north-central Washington in Okanogan County (**fig. 1**), is well-known for its natural beauty, wildlife, and outdoor recreation. Human activity and water appropriation, however, have affected streamflow and fish habitat throughout the Basin. At the most critical times of year, the amount of water necessary to preserve fish habitat and satisfy existing water rights could equal or exceed the amount of water naturally flowing in the stream (Washington State Department of Ecology, 1998). The Methow River and its tributaries are home to upper Columbia summer steelhead and spring Chinook salmon, which are both listed as endangered under the Endangered Species Act, and bull trout, which is listed as threatened. The Methow River Basin is currently one of many watersheds in Washington whose local citizens and governments have elected to coordinate with Tribes and State agencies to develop a watershed management plan, according to the guidelines outlined in the Watershed Management Act of 1998 (Washington State Engrossed Substitute House Bill 2514).

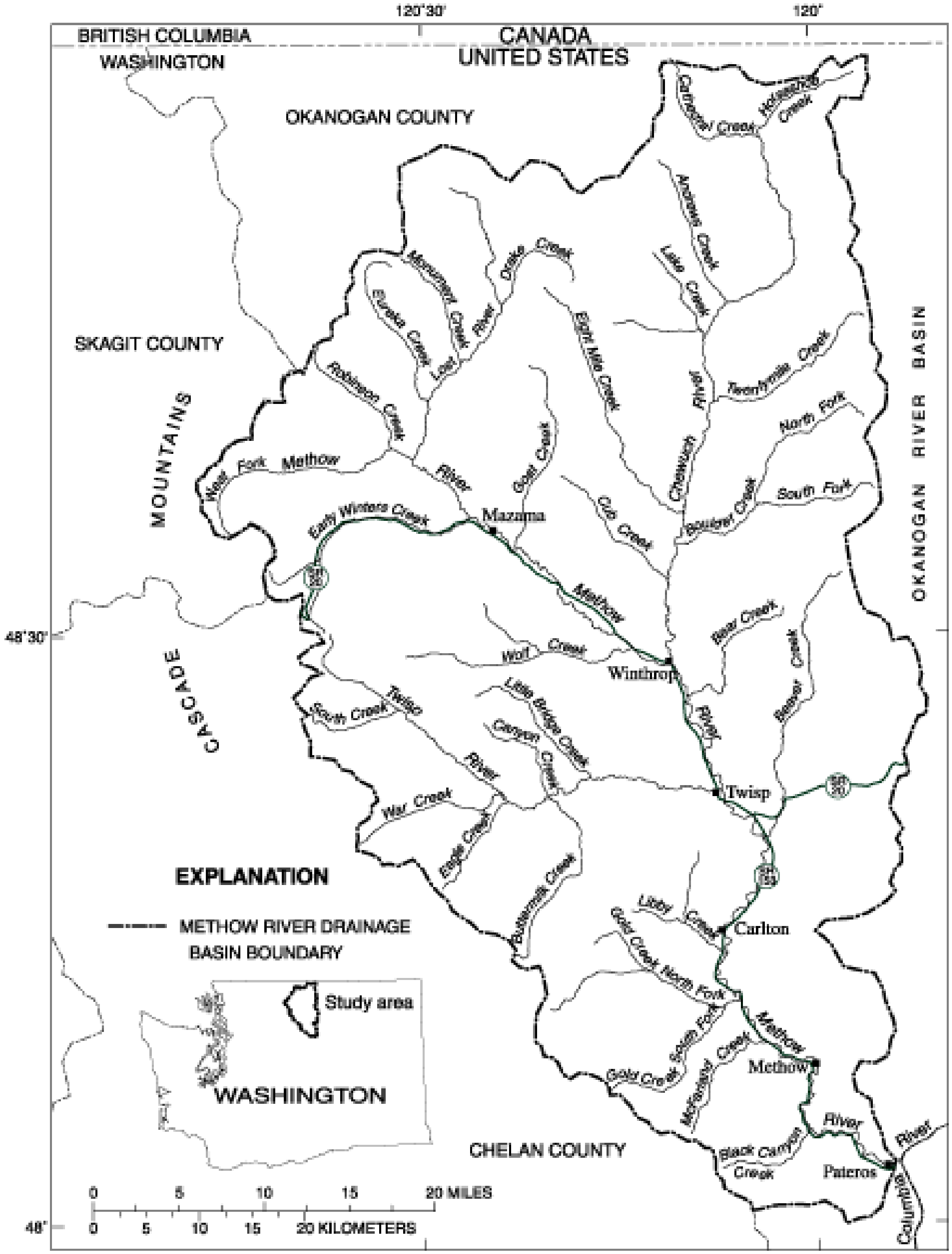

Figure 1. Location of the Methow River Basin, Washington

Naturally producing salmonid fish are important to Washington, both culturally and economically and their survival depends on the quality and quantity of fish habitat. In some years, water availability is limited by climatic conditions and instream flows become severely reduced, resulting in extensive dewatered reaches, winter icing, and high summertime water temperatures (Washington Conservation Commission, 2000). If conditions are severe enough, expansion of dewatered reaches will reduce habitat area, restrict access to the habitat by adult fish, dewater redds (nests where females deposit eggs), and strand juvenile fish. Furthermore, road building, conversion of riparian habitat to agriculture and residential development, diking, and water diversions could “further exacerbate the naturally limiting conditions in some portions of the Methow River Basin” (Washington Conservation Commission, 2000).

Streamflow in the Methow River and its tributaries has been diverted for irrigation since the late 1800s. This practice predates any formal system of water measurements and, as a result, natural streamflow conditions of the present or past are unknown. Currently, a system of canals, ranging from unlined to completely piped, diverts water from about mid-April to October. The net effect of this system on instream flows is unknown. The net effect may be a combination of the rates of diversion and return, the rate of water loss to the ground-water system from leaking canals, the degree of ground-water and streamflow interaction, and other factors.

The Washington State Department of Ecology is required to establish baseflows to protect and, where possible, enhance instream beneficial uses, including the protection of fish and wildlife habitat, recreation, and irrigation (Washington Conservation Commission, 2000). The development of instream-flow requirements considers many factors, including the hydrology of a stream and its natural variations in streamflow and baseflow over the course of time and the need for fish habitat (Washington State Department of Ecology, 1998). To protect habitat for naturally producing salmonids, the National Marine Fisheries Service (NMFS) sets minimum instream flow requirements. Currently, the NMFS has 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) which have resulted in the reduction or termination of diversions in those tributaries before the end of the regular irrigation season.

The U.S. Geological Survey (USGS) in cooperation with Okanogan County, Washington, began two studies in October 2000 to evaluate the net effect of the irrigation system of the Methow River Basin on streamflows. The first study focuses on understanding the unconsolidated ground-water system of the Basin and the interaction between ground water, leaking canals, and instream flows. The second study focuses on understanding the natural and modified streamflows for the Methow River and its main tributaries. This study is conducted in two phases. In Phase One (documented in this report), a basin-wide watershed model was constructed and calibrated to simulate daily natural streamflows at selected locations throughout the basin. In Phase Two, the model of Phase One will be improved to allow for the simulation of more complex hydrologic features such as streamflow diversions and returns. Findings from the ground-water study also will be considered. The model of Phase Two will be a tool that can be used to simulate the impact of different management options prior to their implementation.

Purpose and Scope

This report documents the development of a basin-wide watershed model and the ability of the model to accurately simulate natural streamflow conditions in the Methow River Basin (Phase One of the second study). The term "natural streamflow” refers to streamflow conditions that would exist if no surface water was diverted. The report discusses simulated daily streamflow for water years 1959-99, and focuses on simulated streamflow during low-flow periods, particularly late-summer and early-autumn months.

This report discusses the limitations of accurately simulating natural streamflow, considering that most streamflow-gaging stations are located below diversions and therefore do not measure natural streamflow with which to calibrate the model. The report also documents the assumptions made about interactions between ground- and surface-water and the uncertainties that result in simulated natural streamflow.

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 city of Twisp.

The population of the Methow River Basin is concentrated on the valley floor between Mazama and Pateros. U.S. Census data reported the permanent population at about 5,000 (U.S. Census Bureau, 2001). Additional seasonal population is about 1,200.

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

The geology of the Methow River Basin is described in many reports, including Pitard (1958), Waitt (1972), Walters and Nassar (1974), and Barksdale (1975). Bedrock, comprised primarily of granite, is exposed or thinly covered throughout the Basin except beneath or immediately adjacent to the valley floor. Major topographic features of the Basin were formed during the Pleistocene Epoch as glacial ice scoured and rounded upland areas. Thick deposits of clay, sand, and gravel cover the lower slopes and valley bottoms. These deposits form broad glaciofluvial terraces that account for most ground-water storage and flow in the Basin.

The Basin also is an area of diverse climate with wide variations in temperature and precipitation. The high mountainous regions generally receive the coldest temperatures and greatest precipitation. More than 80 inches of precipitation fall each year near the crest of the Cascade Range, which accumulates as snow from late autumn to early spring. At low altitudes, climate becomes semi-arid. The valley floor near Pateros receives about 10 inches of precipitation a year. The east side of the Basin receives considerably less annual precipitation than equal altitudes on the west side. 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) and temperatures range from about 100° F to -20° F. Temperatures generally are highest in July and lowest in January.

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

About 75 percent of the Basin is forested and the remainder is covered by grasslands, shrubs, irrigated crops, and bare rock. Intermediate altitudes are covered by Douglas fir, spruce, and lodgepole pine. Ponderosa pine inhabits low altitudes. Vegetation is sparser at high altitudes — smaller trees, shrubs, and grasses. Most agricultural production occurs in the valley bottom and is limited to alfalfa and small orchards.

Numerous studies were conducted to investigate the hydrology of the Methow River Basin. A summary of the general water resources is given in Walters and Nassar (1974). Sorlie (1975), Milhouse and others (1976), and Golder Associates (written commun., 2001) discuss water use, irrigation, surface-water/ground-water interaction, and the Methow River Basin water budget. Average monthly streamflows under natural conditions are estimated in Richardson (1976). Artim (1975) discusses ground water in the broad valley bottom from Mazama to Winthrop. Individual watershed analyses were conducted for the Chewuch River (U.S. Forest Service, 1994b), Twisp River (U.S. Forest Service, 1995), Upper Methow River (U.S. Forest Service, 1998), and Lower Methow River (U.S. Forest Service, 1999).

Acknowledgments

The authors thank the members of the Methow River Basin Planning Unit for contributing information about current and historical conditions in the Basin. We also thank Greg H. Knott and Jennifer A. Molesworth of the U.S. Forest Service for their technical guidance.

PRECIPITATION-RUNOFF MODEL

The USGS Modular Modeling System (MMS), developed by Leavesley and others (1996), was used for the watershed modeling component of the Methow River Basin study. MMS is an integrated system of computer software developed to provide a framework for the development and application of models to simulate a variety of hydrologic processes. Existing models can be modularized and brought 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 model incorporated into MMS for the simulation of natural streamflow conditions.

A Geographic Information Systems (GIS) interface, termed the GIS Weasel (Viger and others, 1998), is part of MMS. 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 watershed delineation and therefore develops more objective and reproducible results.

Precipitation-runoff models typically simulate the hydrologic response of a basin at the outlet to the precipitation that falls over the basin surface. The hydrologic response at a basin outlet represents a composite of numerous physical processes in that basin. The selection of a precipitation-runoff model for a study is based on the specific study objectives and the availability of data representing the climatic, hydrologic, and physical characteristics of the basin. PRMS has been 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).

Description of Simulation Model

The PRMS was the simulation model selected for this study. Major advantages of this model 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, (3) appropriately simulate both mountainous and flat areas, and (4) easily accept parameterization output from the GIS Weasel.

The PRMS is schematically diagrammed in figure 2 to show the components used in this study. A basin is conceptualized as an interconnected series of reservoirs whose collective output produces the total hydrologic response. These reservoirs include interception storage in the vegetation canopy, storage in the soil zone, subsurface storage between the surface of a basin and the water table, and ground-water storage. Subsurface flow (or interflow) is considered to be the relatively rapid movement of water from the unsaturated zone to a stream channel and typically accounts for 60 to 80 percent of total flow. Flow to a ground-water reservoir comes from a soil zone and a subsurface reservoir. The ground-water reservoir is considered the source of all baseflow. The movement of water from one reservoir to another is computed throughout the simulation. The application of the model for this study was run on a daily time step. The system inputs included daily precipitation and daily maximum and minimum air temperature. Streamflow at a basin outlet is the sum of surface, subsurface, and ground-water flows.

The heterogeneity of a basin is accounted for by Modeling Response Units (MRUs), formerly known as hydrologic response units, in MMS. Total flow from each MRU is computed and assigned to a user-specified node, which represents a stream location. A water balance from all MRUs contributing flow to a certain node is computed during each time step. Flows from each node are routed to the next user-specified node, with a time delay, to simulate surface-water flow.

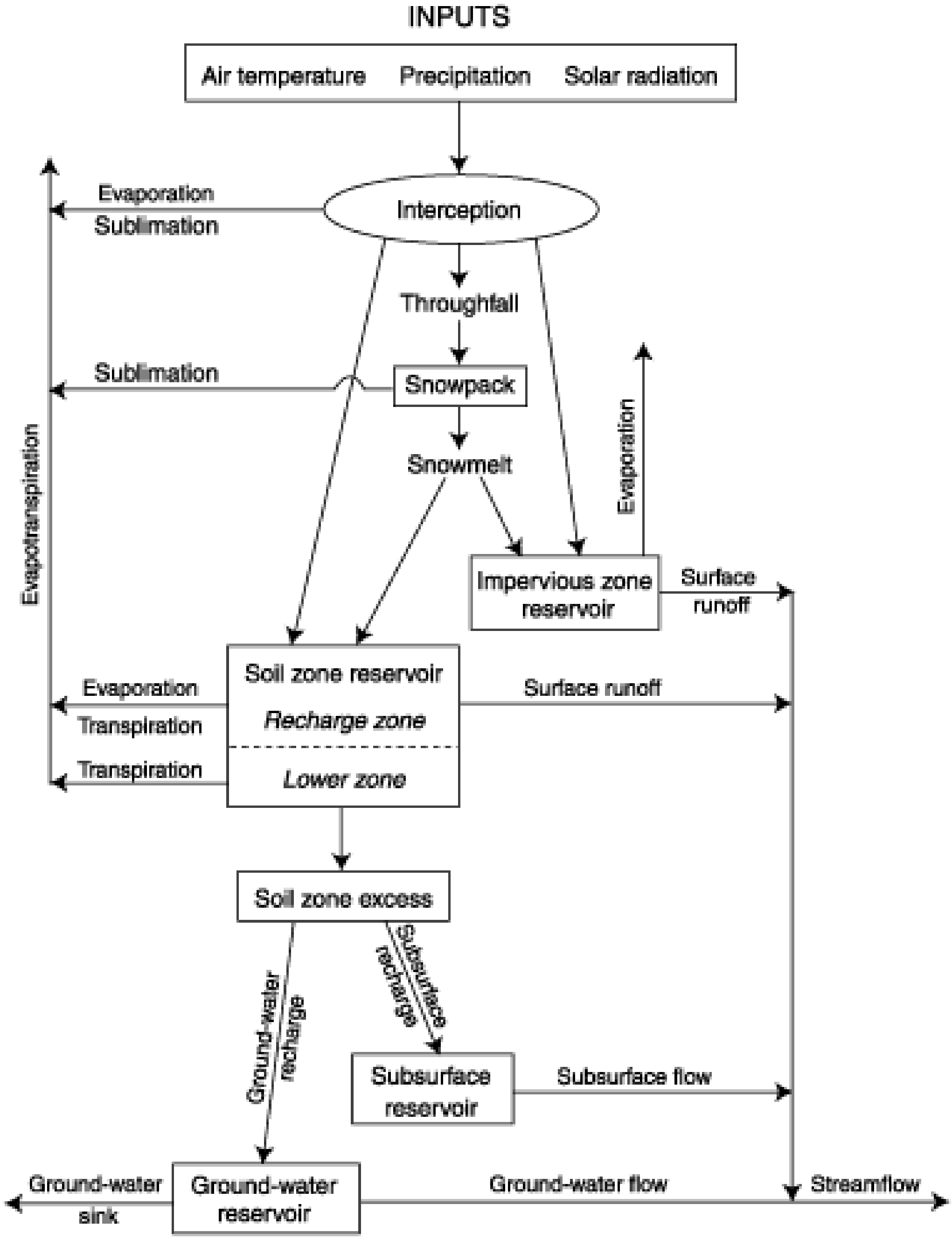

Figure 2. Precipitation-Runoff-Modeling System

Surface runoff and infiltration in the daily time step are computed using a variable source-area approach (Hewlett and Hibbert, 1967). Surface runoff is related to a dynamic source area that expands and contracts to rainfall characteristics, and to the capability of the soil mantle to store and transmit water (Troendle, 1985). As conditions become wetter, the proportion of precipitation diverted to surface runoff increases, while the portion that infiltrates to the soil zone and subsurface reservoirs decreases. Daily infiltration is computed as the net precipitation minus surface runoff. Precipitation retained on the land surface is modeled as surface-retention storage. Once the maximum retention storage is satisfied, excess water becomes surface runoff. When free of snow, the retention storage is depleted by evaporation.

Precipitation that falls through the crown canopy infiltrates the soil zone. This soil zone is conceptualized as a two-layer system. Moisture in the upper soil (or recharge) zone and in the lower soil zone is depleted through root uptake and seepage to lower zones. Evaporation also depletes the upper soil zone of moisture. The depths of the soil zones are defined on the basis of water-storage characteristics and the average rooting depth of the dominant vegetation.

Potential evapotranspiration (PET) losses were computed as a function of solar radiation and the number of cloudless days (Jensen and Haise, 1963). When soil moisture is nonlimiting, actual evapotranspiration (AET) equals PET. When soil moisture is limiting, AET is computed from PET to AET relations for soil types as a function of the ratio of current available water in the soil profile to the maximum available water holding capacity of the soil profile (Zahner, 1967).

In the Methow River Basin, snow accumulation and subsequent melting produces the vast majority of runoff in the spring and summer months. Accurate simulation of this yearly cycle is essential for proper agreement between modeled and measured runoff. The simulation model contains a snow module to simulate the initiation, accumulation, and depletion of a snowpack in each MRU. The snow routine requires computed daily shortwave radiation.

Soil water in excess of field capacity first satisfies the ground-water reservoir based on a user-specified recharge rate. When average moisture exceeds this daily rate, excess soil water goes to the subsurface reservoir. Soil water in excess of field capacity drains to subsurface and ground-water reservoirs. Excess moisture in the subsurface reservoir either percolates to a ground-water reservoir or flows to a discharge point above the water table. Seepage to the ground-water reservoir is computed first from the soil zone, then as a function of a recharge rate coefficient and the volume of water in the subsurface reservoir.

A hydrologically similar watershed model in the nearby Yakima River Basin produced initial results suggesting that some changes to the original PRMS modules were needed (M.C. Mastin and J.J. Vaccaro, U.S. Geological Survey, written commun., 2001). Specifically, Mastin and Vaccaro made improvements in the method for distributing daily weather variables to MRUs to better reflect large spatial variations and to account for missing or erroneous data. Other changes were made to account for runoff from glacial melt, to allow for minimum ground-water storage in a subbasin, and to add a groundmelt component to the snow accumulation and ablation module. All these modifications were made to existing PRMS modules. A simplified flow-accumulation and flow-routing module was modified from an existing module developed by the U.S. Bureau of Reclamation (USBR) (T. Ryan, U.S. Bureau of Reclamation, written commun., 1996). The module changes are described in detail below.

The precipitation distribution module was changed so that data from all precipitation sites were used to interpolate a daily value using a simple inverse distance-weighting technique. This precipitation distribution method reduces sensitivity to missing or bad data. The daily precipitation at a site is first weighted by the inverse square of the distance between the site and the MRU centroid and is then further corrected by the ratio of the mean monthly precipitation of the MRU to the mean monthly precipitation of the site. After interpolating all daily values from all precipitation sites, an average value is calculated for the MRU. The method and computer code are from Bauer and Vaccaro (1987) except that mean monthly precipitation values are used instead of mean annual precipitation values.

Daily minimum and maximum air temperatures were distributed to the MRUs based on the inverse distance-weighting method of Bauer and Vaccaro (1987). First, daily minimum and maximum lapse rates were estimated for the Yakima Basin by (1) calculating daily rates for the period 1952-94 using all daily temperature data, and (2) estimating a value after analyzing the lowest 5 percent and highest 5 percent of the values for each month (M.C. Mastin and J.J. Vaccaro, U.S. Geological Survey, written commun., 2001). These same lapse rates were used in this study. Next, the MRU daily minimum and maximum temperatures were computed from an average of the inverse distance-weighted temperature values from each temperature station's recorded value and the basin lapse rate.

A simple glacier-melt function was added to the surface-runoff module to account for glacier-supplied streamflow during the warm months. For a glacier MRU, glacier melt is calculated when there is no snow cover and the average air temperature is above a user-defined base temperature (32° F in this study). Melt is equal to the difference between the air temperature and the base temperature multiplied by a glacier-melt coefficient. This glacier-melt is added to the surface-runoff component.

A groundmelt component (Anderson, 1976) was added to the snow accumulation and ablation module to simulate runoff after a snowmelt event. The additional groundmelt component supplies much of the water needed to support low flows during times when a basin is snow-covered. The groundmelt is added to the upper part of the MRU soil zone.

A simple reach-routing module was added that allows the runoff to be accumulated at points called nodes. Each defined node has a user-specified MRU, ground-water reservoir, and subsurface reservoir contributing to it. These runoff components are accumulated at the node and then routed to the next downstream node using a standard Muskingham routing equation (Linsley and others, 1982). The equation requires a storage coefficient that approximates an average traveltime, in hours, and a routing weighting-factor that adjusts the attenuation of a flood wave. An existing USBR module (called FIXROUTE) contained all but the reach-routing feature; that module used a user-input time lag for each reach between an upstream and downstream node. This routing module allowed streamflow statistics to be generated at the outlet of subbasins and then accumulated downstream. Streamflow could be examined on a basin or subbasin scale without the need to delineate and parameterize separate models.

Time-Series Data

Calibration of the various subbasins within the Methow River Basin was accomplished using measured precipitation, air-temperature, and discharge data for water years 1992-99. The period of climate station record used in model simulations spanned water years 1959-99. Not all stations existed for the entire period of record. Rain and temperature modules used a distance-weighted average approach to estimate missing data and avoid problems in the simulations. Monthly mean precipitation ratios between climate stations and MRUs were calculated from the Parameter-estimation Regressions on Independent Slopes Model (PRISM) estimates (Daly and others 1994; 1997).

Precipitation

Daily precipitation totals used in the model simulations were collected from rain gages located throughout the Methow River Basin and surrounding basins. Rain 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 precipitation 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; 1997) were used. PRISM data are 1961-90 mean monthly precipitation from National Oceanic and Atmospheric Administration Cooperative sites, SNOTEL sites, and selected state network stations. Short-term stations supplemented data-sparse areas.

Figure 3. Location of data-collection network in the Methow River Basin, Washington

Table 1. Climate stations used in model simulations

[NWS, National Weather Service; NRCS Natural Resources Conservation Service]

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

Air Temperature

Daily minimum and maximum air-temperature data were collected by the NWS and the NRCS. The location names and altitudes of the air-temperature stations used for the simulations are shown in **figure 3** and **table 1**. To account for differences in altitude between the stations and MRUs, MMS adjusts the temperature data using a user-defined calculated lapse rate for every 1,000-foot increase in altitude.

Discharge

Daily mean streamflow data were collected at seven gaging stations in the Methow River Basin (**fig. 3**, **table 2**), according to standardized techniques of the USGS (Rantz, 1982). Summarized records of streamflow are available in USGS annual data reports.

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

[USGS Station No.: Locations are shown in figure 3. Latitude and longitude are given in degrees, minutes, seconds. USGS, U.S. Geological Survey; WA, Washington; mi^2, square mile]

Station No.	Station Name	Latitude	Longitude	Period of Record	Drainage Area (mi^2)	Altitude (feet above sea level)
12447383	Methow River above Goat Creek near Mazama	48 34 32	120 23 05	April 1991 to present	373	2,040
12447390	Andrews Creek near Mazama	48 49 23	120 08 41	June 1968 to present	22	4,300
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
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
12449950	Methow River near Pateros	48 04 39	119 59 02	Apr. 1959 to present	1,772	900

Delineation of Basin Physical Characteristics

Subbasins and the drainage network in the Methow River Basin were delineated with the GIS Weasel (Viger and others, 1998). MRUs are delineated in a manner that reflects spatially distributed attributes such as slope, aspect, elevation, soils, and vegetation, and which respond similarly to hydrologic inputs such as precipitation. Each MRU is a smaller area of a subbasin in 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 depend on the scale and quality of the digital input data, as well as hydrologic judgment.

A standard 100-foot (30-meter) USGS 7.5 minute digital elevation model (DEM) of the Methow Basin, in ARC/GRID format, was used to define topographic surfaces and provided the initial input to the GIS Weasel. The 100-foot DEM contains regularly spaced cells, 100 feet on center with elevation reported to the nearest 1 foot at each cell. The extremely steep slopes of the Methow Basin allowed the 100-foot DEM to provide accurate topographic representations. A more detailed 30-foot (10-meter) DEM was available for the study area but was not used because the size of the Basin added additional computation time at that resolution 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 exceeded the maximum allowed by the GIS Weasel's parameterization process. To resolve this problem, the DEM grid was resampled to 150-foot (45-meter) intervals with no noticeable loss of quality.

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 drainage network of the study area is shown in **figure 4**.

The GIS Weasel was used to compute initial MRUs based on slope and aspect (**figs. 5** and **6**). USGS gaging station locations were used as the downstream outlet from which the drainage area was computed. Further subdividing was accomplished with the automatic two flow-plane process. With this feature, each side of the subbasin divided by the stream becomes a separate MRU. To account for the orographic effect of increasing precipitation, elevation bands were incorporated at 2,000-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 607 MRUs for the entire Methow River Basin (**fig. 7**).

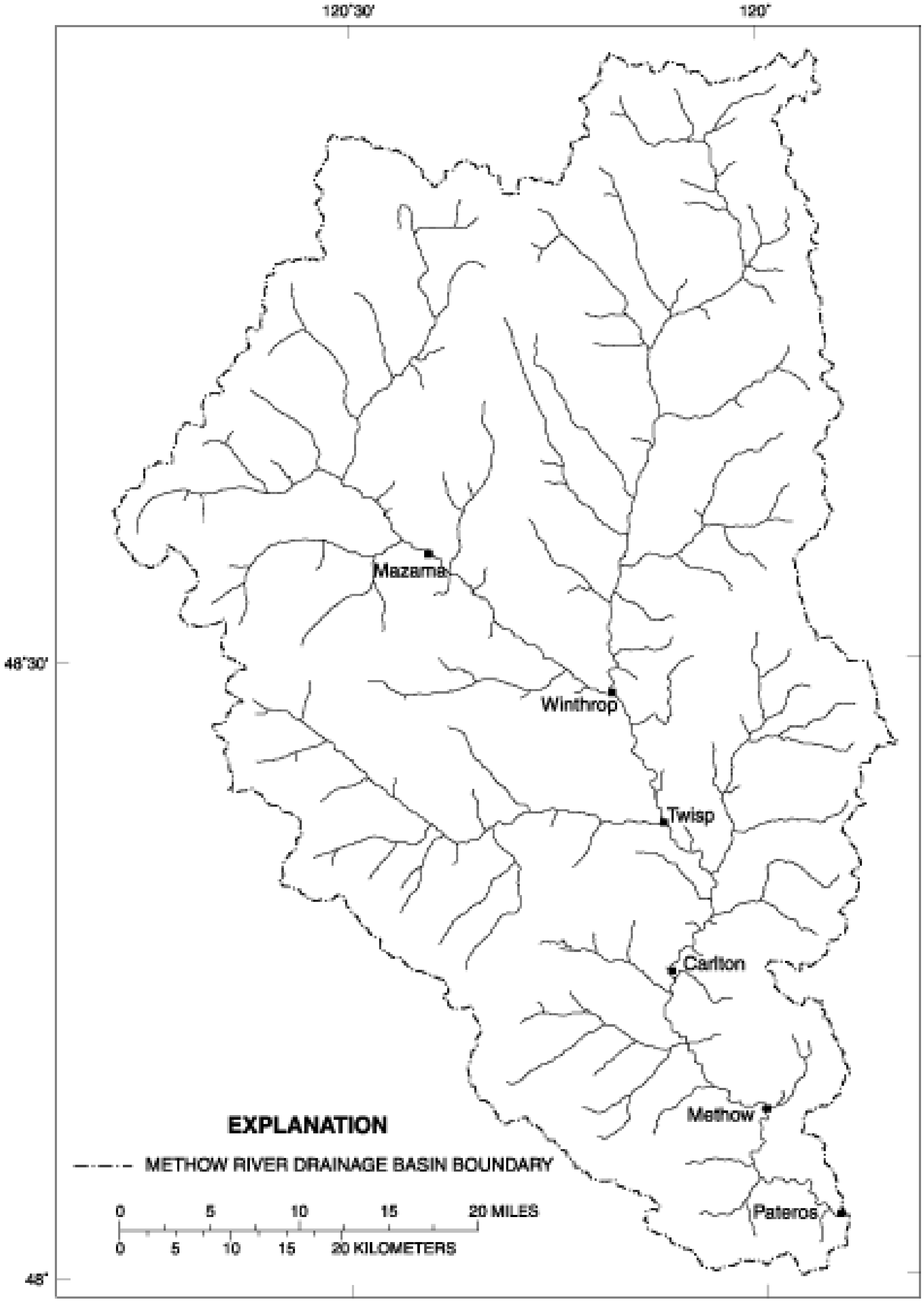

Figure 4. Drainage network defined for the Methow River Basin, Washington, with a minimum flow accumulation area of 3.5 square miles using GIS Weasel

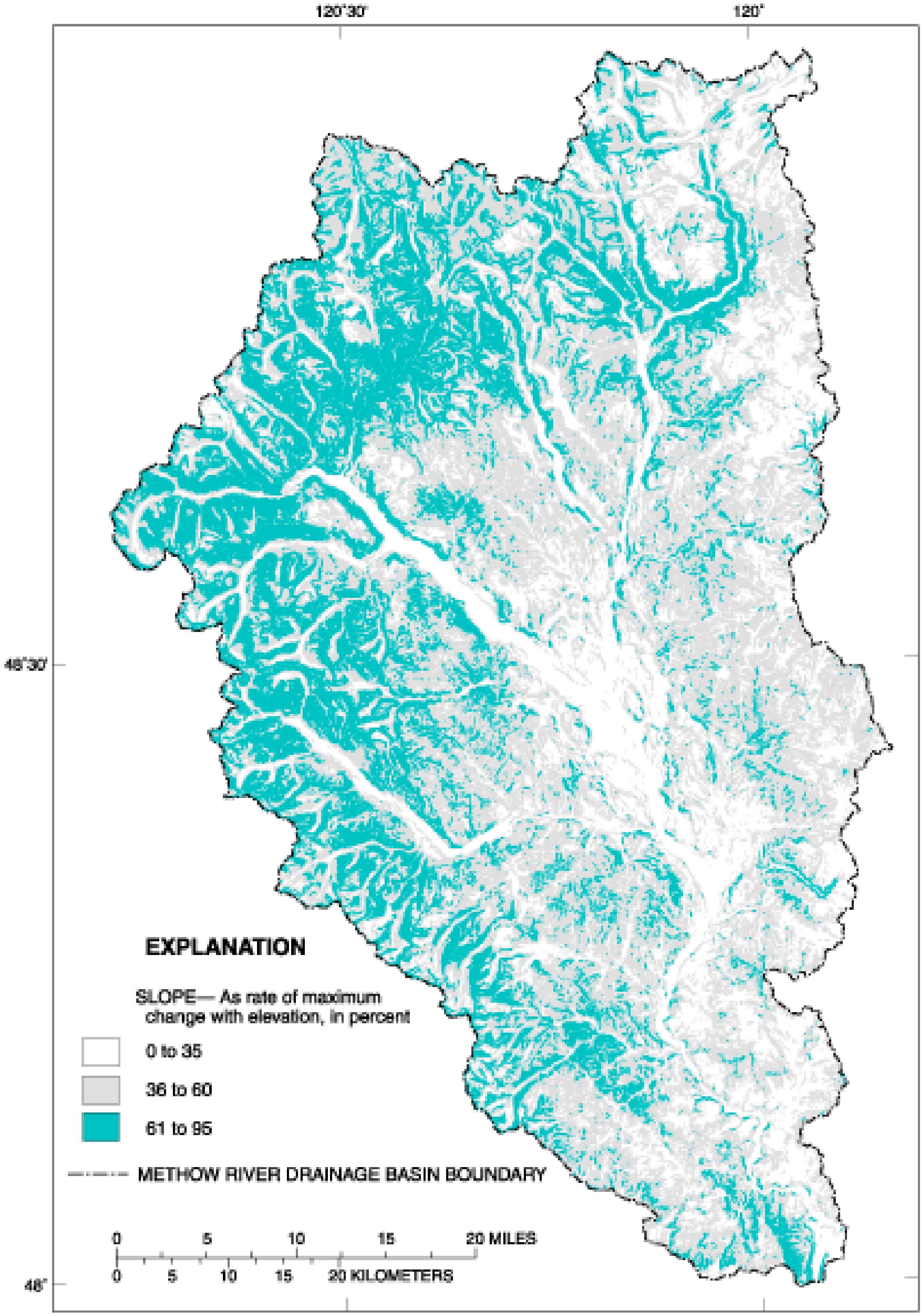

Figure 5. Generalized slope of the Methow River Basin, Washington, delineated using GIS Weasel

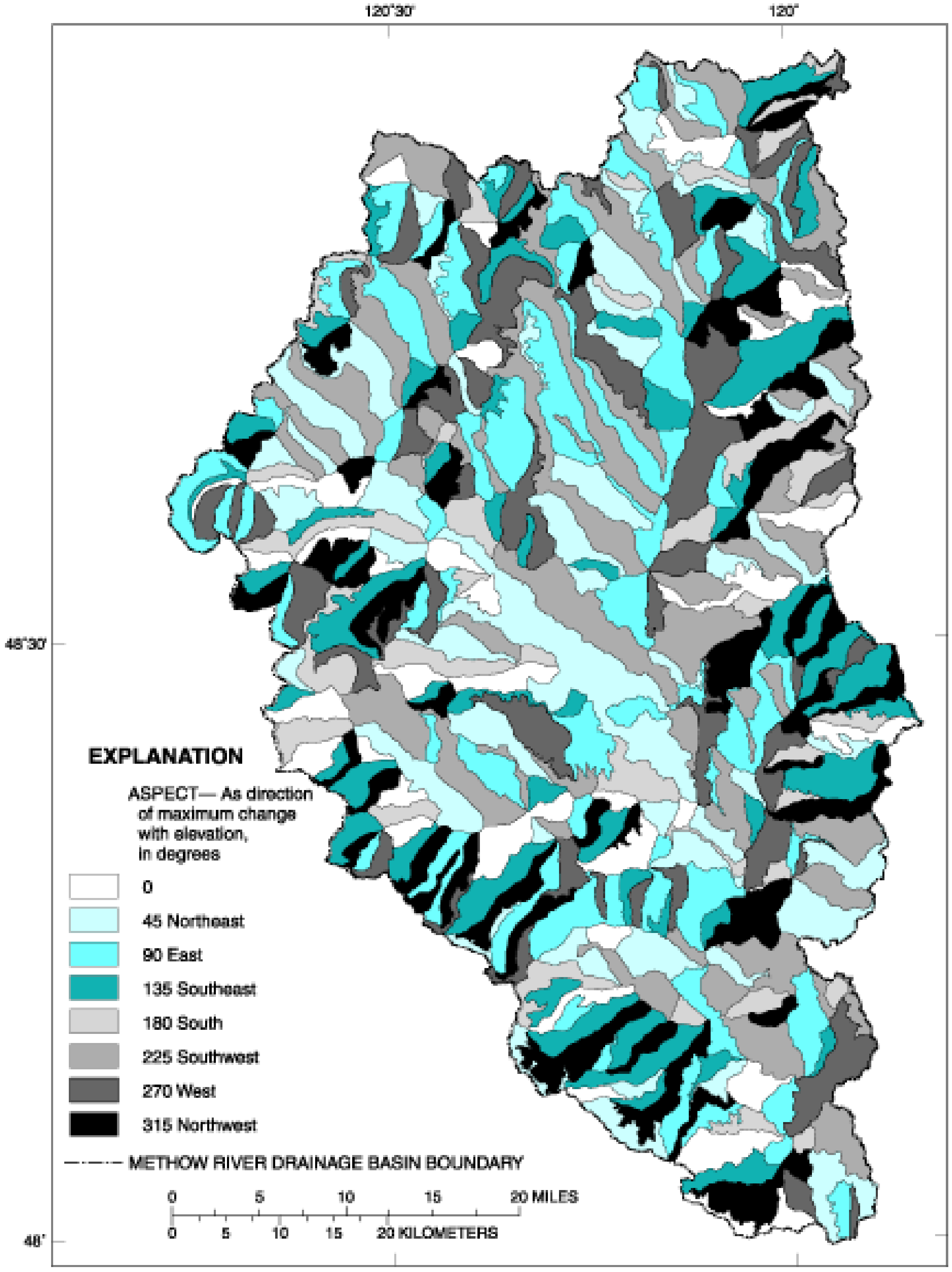

Figure 6. Generalized aspect of the Methow River Basin, Washington, delineated using GIS Weasel

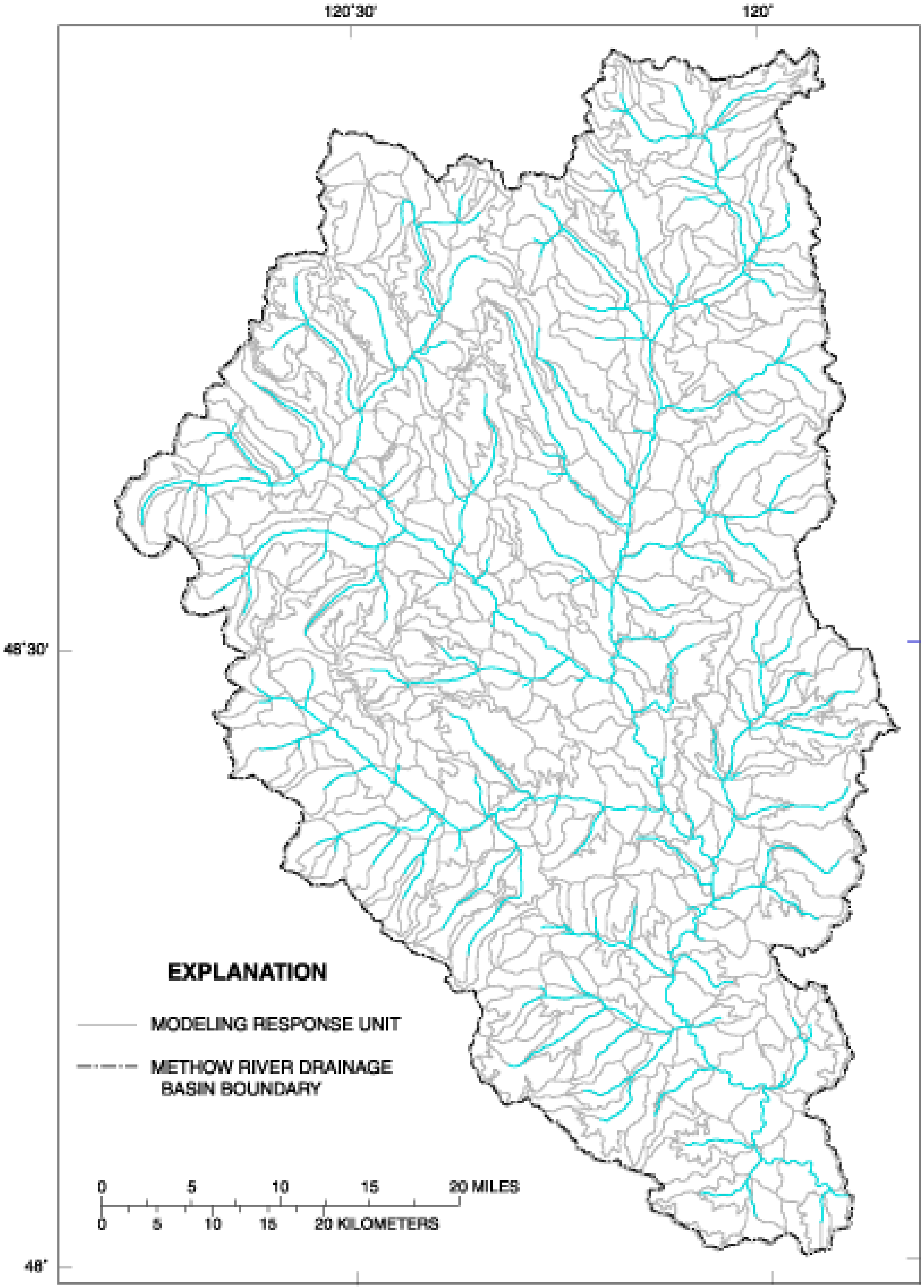

Figure 7. Location of Modeling Response Units in the Methow River Basin, Washington, delineated using GIS Weasel

Parameterization of Basin Physical Characteristics

Initial parameters for the discrete spatial features of the study area were generated using the GIS Weasel. Mathematically, parameters are defined as numerical constants in equations used to compute variables during the simulation. In addition to elevation, slope, and aspect, ancillary information concerning soils, land use and cover, and vegetation were incorporated to assign further characteristics to each MRU. Digital soil data were obtained from a modified version of the State Soil Geographic Database (STATSGO) general soil maps (U.S. Department of Agriculture, 1994), which were made by generalizing detailed state soil survey data. The GIS Weasel used the soil properties provided by STATSGO but further simplified the soil to two different soil textures (**fig. 8**). Parameters from the contiguous U.S. Forest Type Groups map and U.S. Forest Density map provided vegetation information (Powell others, 1998; Zhu and Evans, 1992). The USGS, the University of Nebraska-Lincoln, and the European Commission's Joint Research Centre generated a 3,281-foot (1-kilometer) resolution global land cover characteristics database (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 (**fig. 9**) used by the GIS Weasel is a composite of this global land cover and the Forest Type Group data listed above.

The parameters not initially calculated or estimated by the GIS Weasel were the ground-water recession coefficients, monthly coefficients in regression equations that relate the difference between daily maximum and minimum air temperature to cloud cover, the monthly precipitation values for the MRUs and the weather sites, the flow-routing parameters for the simple reach-routing module, and the monthly minimum and maximum air-temperature lapse rates. These parameters and the methods of computation are discussed in following sections.

Calibration of Simulation Model

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. Automated calibration, or optimization, was used in the adjustment of two subsurface reservoir routing coefficients. The optimization of these two parameters for three basins is accomplished by minimizing the errors between simulated and measured streamflow data. All MMS parameters are defined and discussed in depth by Leavesley and others (1983) and Leavesley and others (1996).

As stated previously, one basic difficulty existed in calibrating natural streamflow conditions in the Methow River Basin. All streamflow-gaging stations with the exception of Andrews Creek (12447390) are below irrigation diversions and no historical records exist for the study area prior to the diversions . Certain assumptions concerning the flow system can be made, however. First, diversions remove water directly from the stream channel, and therefore the effect is seen immediately in the streamflow record. At the end of the irrigation season, as diversions are shut down, a response in the system also will be evident. Second, ground-water flow from irrigation recharge and leaking irrigation canals may return to surface-water flows, but in a delayed fashion. Finally, some of the diverted water is lost to evapotranspiration above what would have been lost in the river, thereby decreasing available return flows. It is expected that the net effect of diversions modifies streamflows from the natural conditions but the difference between natural flows and "irrigated" flows is unknown. Assumptions can be made concerning the effects of diversions on the flow system but these cannot be quantified at this stage of the study.

Streamflow was simulated for water years 1992-99 to calibrate the model to measured streamflows at the seven USGS gaging stations. This 8-year period was selected because it was the only time when all USGS gaging stations had streamflow records.

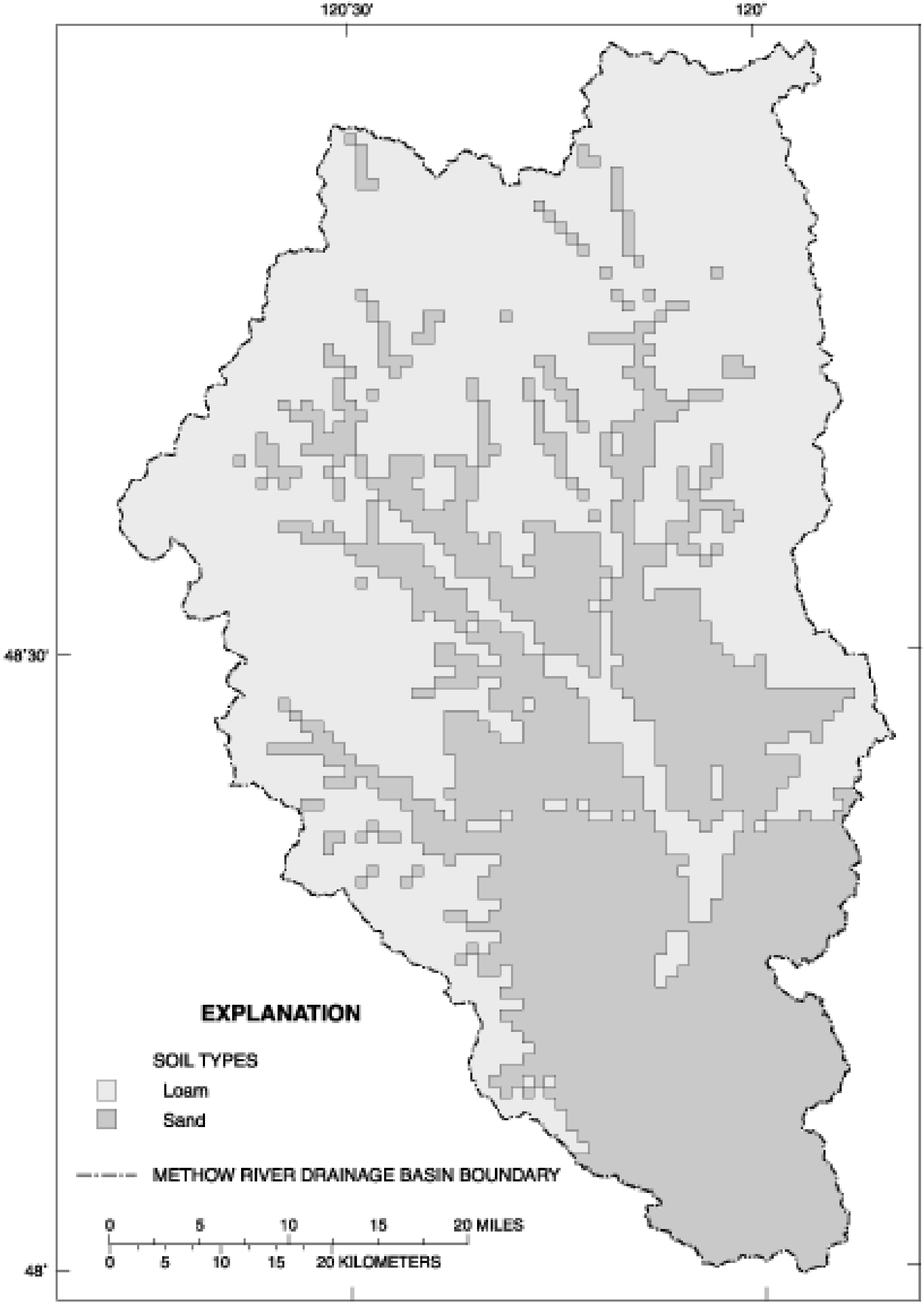

Figure 8. Simplified soil grid of the Methow River Basin, Washington, generated from the State Soil Geographic Database and the GIS Weasel

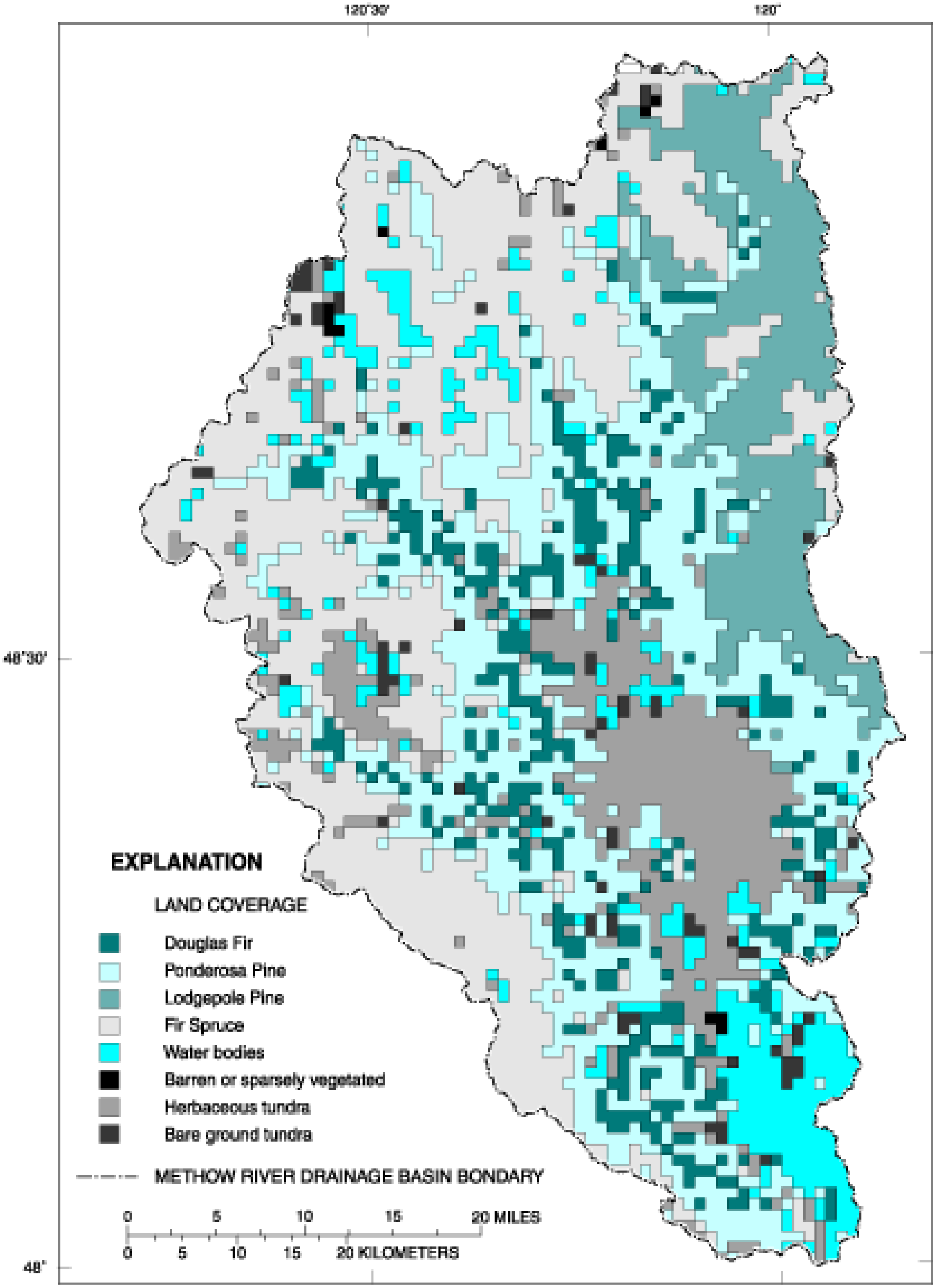

Figure 9. Land use and vegetation in the Methow River Basin, Washington, delineated using the GIS Weasel

Values determined by the GIS Weasel, values calculated and set by the MMS algorithms, and parameter estimates used in the hydrologically similar Yakima River Basin watershed model all provided initial estimates of parameters. 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), minimum ground-water storage (gwstor_min), 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, temperature lapse rates, gwstor_init, transp_begin, transp_end, and jh_coef_hru, 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 about the physical processes to justify that approach.

Simulated and measured daily mean streamflows from four selected streamflow-gaging stations for water years 1992-99 are shown in **figure 10**. Locations of the modeled subbasins are shown in **figure 11**. Simulated and measured streamflows have many similarities and generally show close agreement, especially during spring runoff from snowmelt. Measured streamflow for April through June at the most downstream streamflow-gaging station (12449950) averaged 67.3 percent of the total flow. Simulated streamflow for that period averaged 67.8 percent of the total flow. Due to 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) autumn and winter peak flows for the most downstream gaging station (**fig. 10*D***). The model did represent the baseflow periods of autumn and winter well. Measured streamflow for August through October at the most downstream gaging station (12449950) averaged 8.8 percent of the total flow; simulated streamflow averaged 6.8 percent.

Precipitation in the Methow River Basin generally occurs as snowfall. To match snowfall totals at the high altitudes, monthly PRISM values used in the calculation of snowfall generally were increased, as much as 25 percent for the Andrews Creek subbasin. The location of the Andrews Creek subbasin is shown in **figure 11**. Monthly rainfall amounts and snow for lower elevations were decreased from those values determined from PRISM data. Precipitation on MRUs in the lower Methow River Basin was lowered by as much as 50 percent. Increasing or decreasing the MRU PRISM value appropriately adjusted the ratio between the precipitation gage and the MRU. This procedure resulted in annual precipitation totals within reported ranges.

Minimum ground-water storage (gwstor_min) was set at 0.0 for all MRUs except those directly above streamflow-gaging station 12448500, Methow River below the Chewuch River. Initial simulated baseflow at this station was considerably lower than measured. By increasing the minimum ground-water storage (gwstor_min) to 0.05 inch for these MRUs, flows in the winter months were increased.

The final parameter used to adjust cumulative streamflow totals was an evapotranspiration coefficient. The procedure is one developed by Jensen and Haise (1963). Potential evapotranspiration (*PET*) (inches/day) is computed by:

$$PET = CTS(\mathrm{MO}) * (TAVF - CTX) * RIN \qquad (1)$$

where

CTS is a coefficient for the month (MO),
$TAVF$ is the daily mean air temperature (°F),
CTX is an MRU air-temperature coefficient, and
RIN is a daily solar radiation expressed in inches of evaporation potential.

For all MRUs, except those at the highest elevations, jh_coef_hru (or CTX) was reduced by 25 percent, thus increasing PET for the MRU and reducing simulated streamflow. Farnsworth and Thompson (1982) reported a PET value of 51.87 inches per year for Yakima, Washington, for the period of 1956-70. The simulated PET value in this study for the Methow River Basin was 50.04 inches per year for the simulation period of 1958-70.

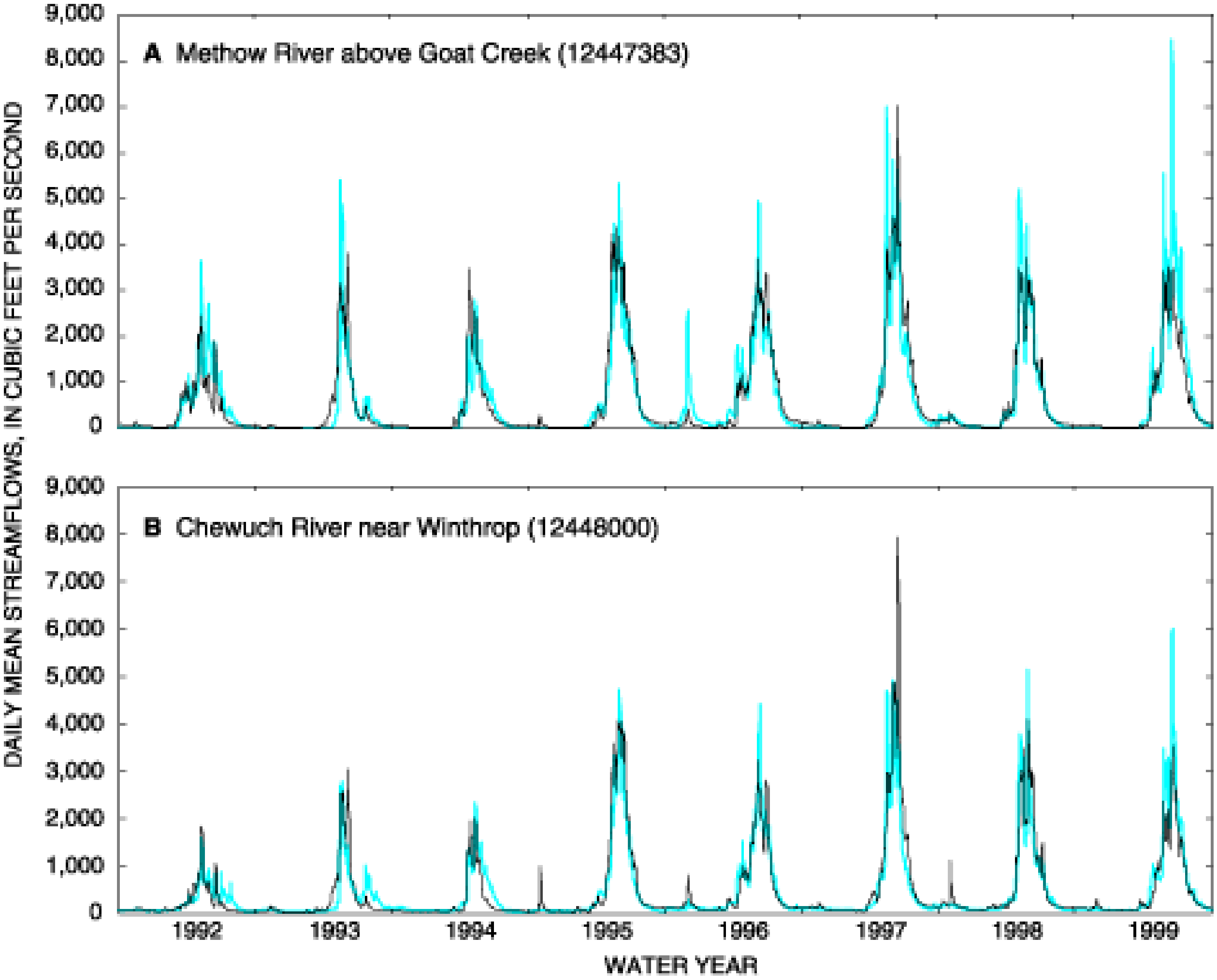

Figure 10. Simulated and measured daily mean streamflow for selected streamflow-gaging stations, Methow River Basin, Washington, water years 1992-99

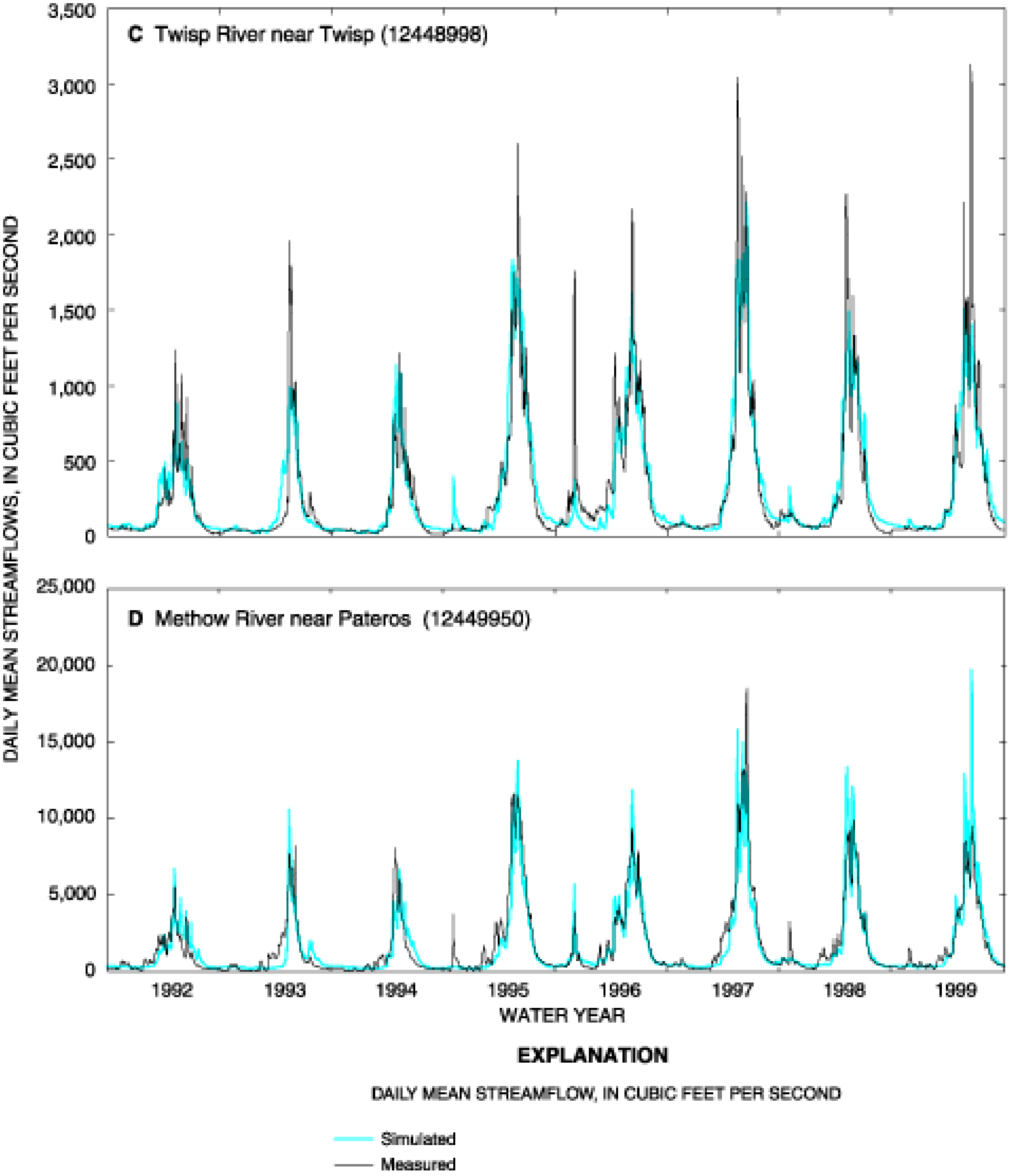

Figure 10. Simulated and measured daily mean streamflow for selected streamflow-gaging stations, Methow River Basin, Washington, water years 1992-99—*Continued*

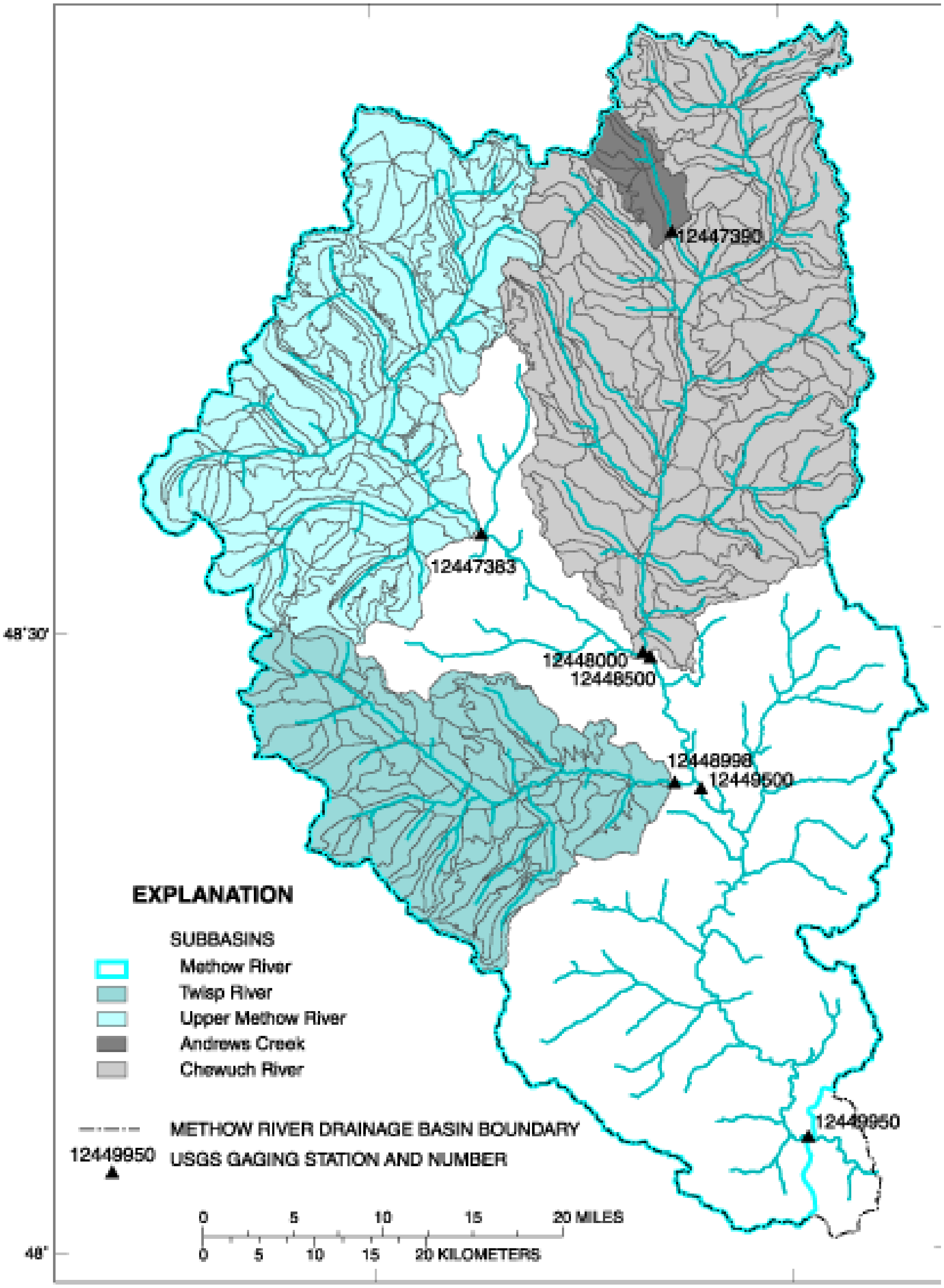

Figure 11. Location of major subbasins in the Methow River Basin, Washington, delineated using GIS Weasel

One of the major goals of this study was to better understand mean monthly flows at certain stream locations. After the model was adjusted to match measured annual streamflow totals, the timing of flows was matched. Simulated and measured mean monthly streamflow for four selected stream-gaging stations is shown in **figure 12**. Because diverted water, some of which is transported out of the subbasin of origin, was not considered in this phase of the study, some difference between simulated and measured mean monthly streamflow is expected. The general shapes of the graphs, which include winter baseflows and spring runoff from snowmelt, show good agreement. In two of the graphs, the Methow River above Goat Creek (12447383) (**fig. 12*A***) and the Chewuch River (12448000) (**fig. 12*B***), simulated streamflows for September and October (1992-99) are greater than measured streamflows.

The possibility exists that the model does not adequately represent all hydrologic processes at these locations or that water diversion during these months decreases flows beyond what may return from canal leakage and irrigation. The streamflow records for the Chewuch River (calendar year 1995) and Twisp River (calendar year 1992) indicate that when diversions were shut off at the beginning of October, the measured mean daily flow increased by the amount that is generally diverted (**fig. 13*A* and 13*B***). Rain increased later in October and November and the simulated and measured daily streamflow match more closely.

The timing of the spring runoff and shape of the hydrograph during high flow were controlled largely by adjustments in precipitation rates and maximum air temperature. Temperature adjustments also affected the form of precipitation (snow versus rain) and evapotranspiration. The recessionary limb of the hydrograph was affected by precipitation and air temperature (as it affects snowmelt rates), but also 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 system is conceptualized as a linear reservoir and is assumed to be the source of all baseflow (BAS). BAS expressed in acre-inches is computed by:

$$BAS = GWFLOW\_COEF * GW \qquad (2)$$

where

$GWFLOW\_COEF$	is	the reservoir routing coefficient, and
GW	is	the ground-water reservoir storage, in acre-inches

The ground-water flow coefficient proved to be an important parameter to estimate because it has a large effect on the shape of the streamflow 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 higher flow coefficients within an acceptable range and adjusted to match the shape of the simulated and measured hydrographs. The higher coefficient resulted in more ground-water discharge per unit area. The values given to the ground-water coefficients decreased with distance from the streams.

The rate of outflow from the subsurface reservoir was matched in three subbasins, Andrews Creek, Twisp River, and Chewuch River (**fig. 11**), by optimizing the routing coefficients, ssrcoef_sq and ssrcoef_lin, using the Rosenbrock process in MMS (Rosenbrock, 1960). The rate of movement to a ground-water reservoir from a subsurface reservoir was adjusted by a daily recharge coefficient (ssr2gw_rate). The model proved to be less sensitive to this parameter, resulting in a single value for the entire basin.

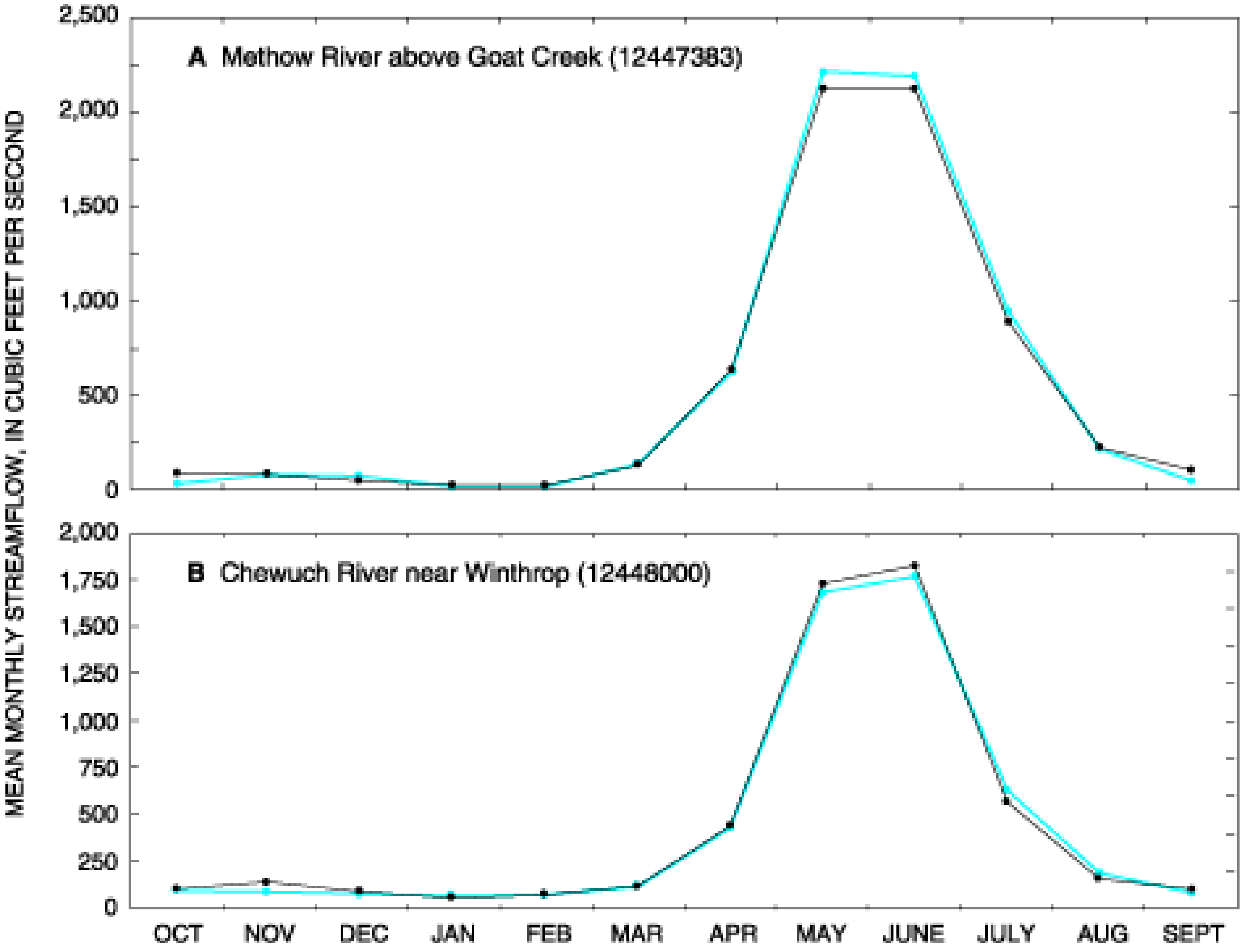

Figure 12. Simulated and measured mean monthly streamflow for selected streamflow-gaging stations, Methow River Basin, Washington, water years 1992-99

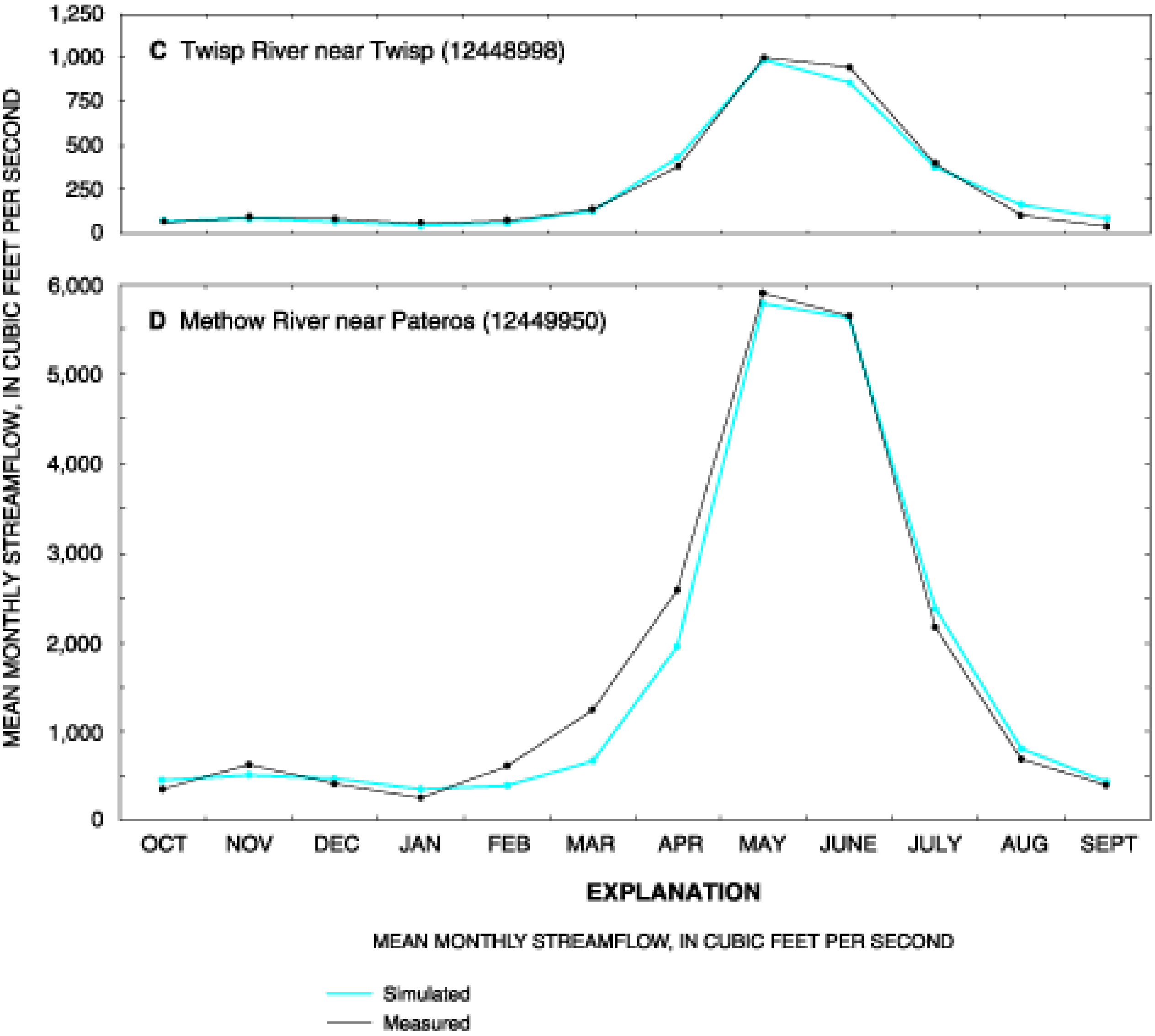

Figure 12. Simulated and measured mean monthly streamflow for selected streamflow-gaging stations, Methow River Basin, Washington, water years 1992-99—*Continued*

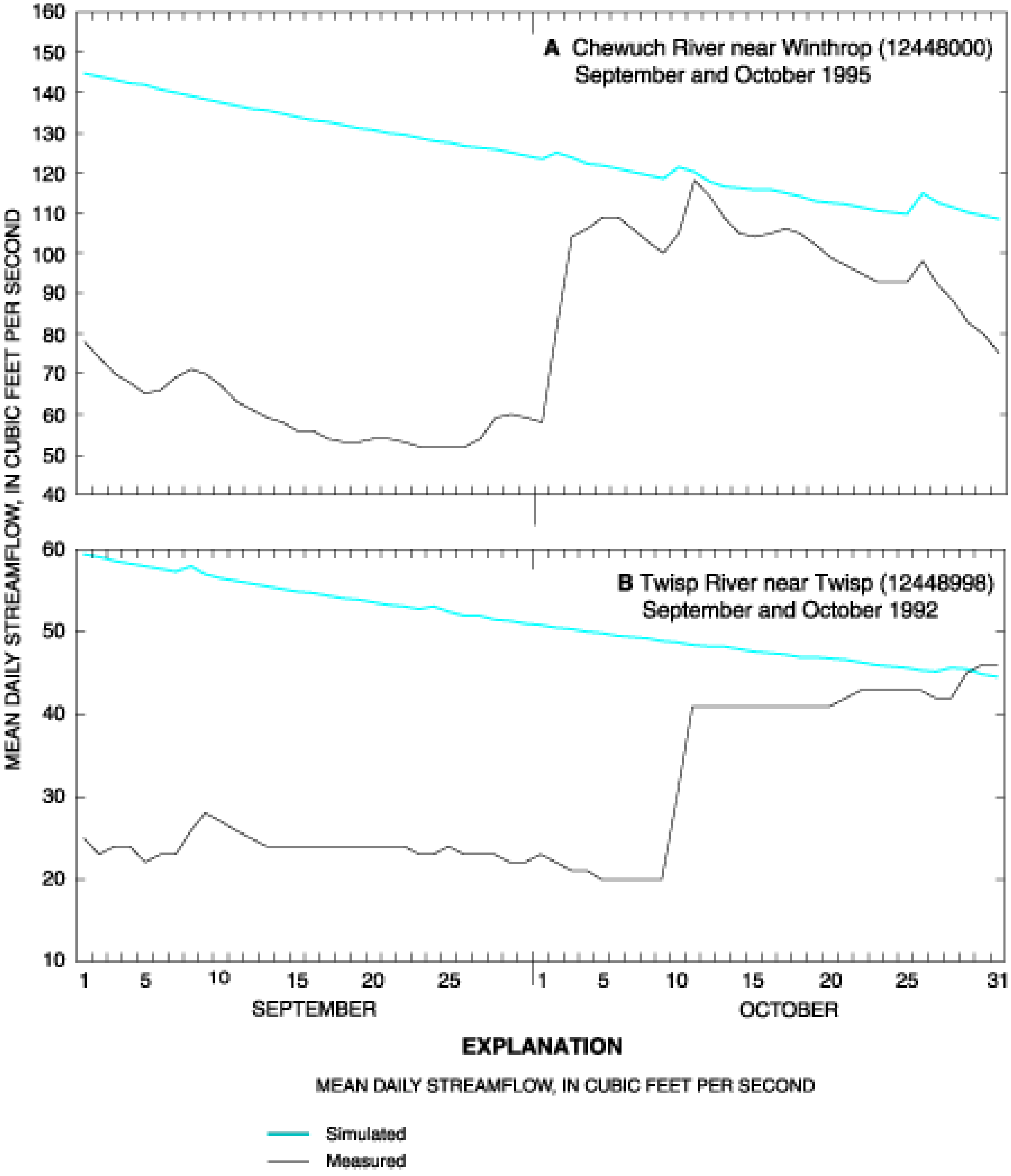

Figure 13. Simulated and measured mean daily streamflow for selected streamflow-gaging stations, Methow River Basin, Washington, calendar years 1992 and 1995

Long-Term Model Simulation

The calibrated model can be used as a tool to simulate flows at ungaged streams or flows at gaged streams for periods outside the historical record. This ability allows the examination of the system's hydrologic response to climatic conditions. For example, long-term mean streamflows could differ significantly from means computed from the shorter-term record of the stream gages. Annual, or even decadal, trends in streamflows would be more evident. To demonstrate the capability of simulating streamflow outside the gaging record and at ungaged streams, water years 1959-99 were simulated and monthly streamflow statistics generated for the seven gage locations and two biologically important ungaged tributaries, Early Winters Creek and Wolf Creek (**table 3**). Standard deviations for the period of simulation were relatively large, suggesting great variability in monthly flows. To demonstrate this point, mean monthly flows for the calibration period (1992-99) were compared to mean monthly flows for the entire simulation period (1959-99). The simulated mean monthly flows for the seven streamflow-gaging stations were an average of 11.5 percent higher for the calibration period than for the entire simulation period.

Analysis of Errors in the Simulation

All modeling studies contain errors. Certain approximations and simplifications must be made to simulate the actual flow systems. Precipitation-runoff modeling errors 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). Lack of understanding about some aspects of the natural flow system, coupled with only one streamflow-gaging station demonstrating the natural flow system (above irrigation diversions), accounts for much of the error. As a result, model-predicted values must be used with caution in consideration of simulation error.

Annual runoff totals for simulated and measured streamflow varied considerably during many of the water years, yet there was no definite pattern or bias in the results for the entire calibration period (**table 4**). Simulations of the total annual runoff as a percentage of measured annual runoff for the 8-year calibration period at seven gaging stations ranged from –33.7 to +30.5 percent with 70 percent of the simulated values within 16 percent. For the 8-year simulation period, measured annual runoff totals were highest for water years 1995, 1996, 1997, and 1999. Water years 1996 and 1999, with above-average measured annual flows, were under-simulated at all gaging stations, indicating that the current model is less effective at simulating high-flow conditions. The model performed reasonably well during low-flow years. These results were deemed acceptable because the major interest for biological importance is in these low-flow years. Simulated and measured annual runoff for the 8-year period matched closely for all calibration points with the exception of station 12448500, Methow River at Winthrop. The under-simulation occurred mostly in the baseflow period of autumn and winter. A significant amount of Methow River streamflow enters the ground-water system above Goat Creek and then returns to the river upstream of Winthrop (Caldwell and Catterson, 1992). The current model does not simulate channel losses and, therefore, it is not correctly representing this ground-water/surface-water interaction. At the next downstream station (12449500) on the Methow River, the simulated deficit is made up and simulated streamflows closely match the measured annual runoff.

Data Error

The PRMS watershed model requires measured rainfall, air-temperature, and streamflow time-series data, and physical characteristics of the basin. Rainfall volume is often the most important driving factor of the simulation and it is often the most difficult to estimate. Rainfall 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. The mean elevation of an MRU can differ significantly from that of the closest precipitation gage and the MRU area can span a wide range of average precipitation. Rainfall data indicate a large variation over relatively short distances. In addition to errors introduced by spatially distributing precipitation, error is also introduced regarding the type of precipitation (rain versus snow). Usually, precipitation collection devices are subject to catchment losses that are believed to be smaller for rain than for snow. These measurement and interpolation factors introduce error to the simulation.

Air-temperature data can be the source of as much potential error as the precipitation data. Again, air 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 runoff 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 with the delineation of 607 MRUs, however, approximations of slope and aspect were necessary. Coarse coverages of forest density, land use, and soils introduced error in sensitive parameters such as evapotranspiration and soil recharge.

Model Error

The precipitation-runoff algorithm cannot completely represent all physical processes of a basin. Determining if a weakness in a simulation is attributable to input data error or model shortcomings is almost impossible in some cases. This issue is further complicated by the fact that the vast majority of the streamflows measured in the study area are affected by human activity. A more rigorous method of model calibration, such as automated nonlinear regression, might help to constrain some of the uncertainty. However, use of these techniques was not within the scope of this study.

Ground-water flow is a dominant component of streamflow during late summer-autumn months. These low-flow periods can limit the habitat of fish and, therefore, are a critical period to understand and simulate accurately. PRMS 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 of PRMS use few parameters and are not physically based. Simple hydrograph separation indicates that one value for the rate of ground-water flow is insufficient. The methodology for routing water between ground-water reservoirs is currently non-existent and probably accounts for some differences in measured and simulated flows.

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 evapotranspiration or a decrease in precipitation would both result in a lower simulated discharge at a node. With all watershed models, the most sensitive parameters will be those directly related to precipitation and air temperature. Ground-water flow parameters had a large effect on the shape of the simulated hydrograph during low-flow periods. Model fit was accomplished primarily with manual calibration and this method does not provide statistical insight into observation sensitivity to parameters or correlation between parameters. Uncertainty of parameters is therefore not quantified.

Table 3. Simulated minimum, maximum, and mean monthly streamflows and standard deviations for the Methow River Basin, Washington, water years 1959–99

[Standard deviation: $\sqrt{\frac{n\sum x^2 - (\sum x)^2}{n(n-1)}}$]

Station No.		**MONTHLY STREAMFLOWS, IN CUBIC FEET PER SECOND**											
		OCT	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUNE**	**JULY**	**AUG**	**SEPT**
12447390	Minimum	1.2	1.1	1.0	0.9	0.8	0.8	1.5	32.5	4.2	1.7	1.5	1.4
	Maximum	31.0	7.6	3.0	2.6	2.4	2.2	76.6	251.8	427.6	133.6	34.4	16.0
	Mean	4.1	2.9	2.0	1.8	1.7	1.6	25.5	135.5	136.4	33.0	5.0	3.3
	Standard deviation	4.8	1.4	0.5	0.4	0.3	20.9	48.8	92.4	38.1	14.4	5.6	2.3
12448000	Minimum	14.8	45.1	35.0	20.9	17.7	21.8	65.0	93.2	30.3	22.8	19.8	17.4
	Maximum	589.4	524.4	225.5	92.2	131.5	183.8	1,040.1	3,673.3	5,584.2	1,148.5	313.3	292.3
	Mean	126.2	163.5	79.4	54.5	58.6	100.3	425.1	1,691.4	1,351.5	303.7	110.0	95.0
	Standard deviation	106.8	114.2	38.4	19.10	22.2	37.6	202.7	822.6	1,161.6	301.1	55.3	46.9
12448998	Minimum	32.4	38.7	33.6	32.4	28.9	39.6	148.2	279.7	116.4	52.2	42.2	36.7
	Maximum	245.6	300.8	148.1	74.8	112.3	285.4	794.5	2,017.8	2,522.8	739.6	340.1	133.0
	Mean	77.7	101.7	68.1	48.0	52.5	107.4	464.4	991.8	833.7	283.1	118.1	78.1
	Standard deviation	35.6	59.1	27.3	11.0	17.2	47.5	152.3	385.8	470.3	182.5	67.6	24.9
12447383	Minimum	29.1	45.4	32.2	17.1	14.9	19.3	134.2	677.4	146.1	54.5	40.3	33.0
	Maximum	605.9	480.7	121.0	57.7	117.4	543.8	1,712.3	4,556.1	6,298.9	2,533.8	1,281.8	306.0
	Mean	116.8	116.1	53.3	37.1	38.9	102.8	840.7	2,439.9	1,982.5	642.5	205.3	108.0
	Standard deviation	97.6	85.6	18.0	8.6	19.0	103.4	409.0	796.5	1,191.5	616.3	255.5	61.8
12448500	Minimum	56.7	108.1	86.0	61.7	72.6	130.7	499.1	839.0	200.8	94.7	75.0	63.9
	Maximum	1,509.8	1,362.7	456.3	184.3	381.6	999.6	3,324.8	9,053.7	13,607.0	3,643.9	1,721.1	690.7
	Mean	307.2	382.9	170.5	118.7	169.7	381.3	1,689.7	4,708.2	3,694.9	1,060.4	365.5	238.7
	Standard deviation	265.5	269.8	74.8	32.8	78.8	182.0	696.2	1,797.2	2,616.2	985.8	327.6	117.9

Table 3. Simulated minimum, maximum, and mean monthly streamflows and standard deviations for the Methow River Basin, Washington, water years 1959–99 — *Continued*

Station No.	MONTHLY STREAMFLOWS, IN CUBIC FEET PER SECOND												
		OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
12449500	Minimum	89.2	155.5	127.4	102.5	115.2	265.5	641.8	1128.3	319.6	147.7	117.8	101.1
	Maximum	1,833.0	1,814.5	716.3	318.7	631.1	1,325.7	4,098.8	10,830.7	16,258.7	4,434.3	1,950.1	838.4
	Mean	401.5	541.6	273.9	181.6	277.6	601.4	2,196.4	5,729.4	4,571.4	1,363.2	492.3	323.4
	Standard deviation	316.5	367.7	125.9	52.0	121.9	241.1	823.6	2,170.5	3,090.4	1,168.0	388.0	143.3
12449950	Minimum	91.3	169.3	149.5	118.3	129.4	275.0	642.8	1,172.3	331.0	151.8	120.6	103.6
	Maximum	2,096.6	2,239.8	1,218.6	566.8	1,107.9	2,307.7	4,871.1	11,583.7	17,052.5	4,714.0	2,121.4	900.6
	Mean	482.8	751.3	394.3	253.7	465.6	1,077.9	2,672.1	6,099.4	4,861.4	1,486.7	553.0	364.9
	Standard deviation	398.7	519.5	228.8	105.0	228.9	454.8	981.2	2,350.0	3,260.7	1,239.3	419.0	159.0
Early Winters	Minimum	14.7	13.6	12.7	11.9	11.2	12.6	17.5	112.1	24.7	19.3	17.5	16.1
	Maximum	127.9	58.1	29.5	26.3	32.0	70.7	401.2	1,020.9	1,367.6	538.2	306.4	68.3
	Mean	32.1	26.9	21.2	18.9	17.8	22.1	191.7	547.1	406.5	121.6	47.7	31.4
	Standard deviation	17.9	8.0	3.4	2.8	3.4	14.2	98.6	178.2	266.0	133.5	55.6	10.8
Wolf	Minimum	0.6	1.1	0.3	0.1	0.0	0.2	41.2	20.2	5.6	2.7	1.5	0.8
	Maximum	51.9	47.7	5.6	2.0	27.0	78.9	242.0	495.5	542.2	185.8	76.6	24.0
	Mean	9.8	10.2	1.8	0.7	2.0	15.3	128.9	192.4	122.7	38.8	14.5	7.1
	Standard deviation	10.0	9.2	1.3	0.4	4.7	18.1	49.7	93.4	93.8	38.2	14.8	4.8

Table 4. Simulated and measured mean annual streamflows, simulated streamflow as a percentage of measured, and bias for water years 1992–99

[**Difference**: [(SIM–OBS)/OBS] × 100. **Bias**: as a percentage of mean measured runoff = 100 × SUM{[(S–O)/O]/N} for all 0>0.0. ft^3/s, cubic foot per second]

Station No.	Water year	Mean annual streamflow (ft^3/s)		Difference between simulated and measured as percentage of measured	Bias (percent)
		Simulated	Measured		
12447383	1992	343.8	405.5	-15.2	
	1993	374.1	309.2	21.0	
	1994	337.6	286.4	17.9	
	1995	685.5	590.7	16.0	
	1996	655.7	690.3	-5.0	
	1997	821.5	725.4	13.2	
	1998	586.7	589.9	-0.5	
	1999	603.0	798.3	-24.5	
Total		4,407.9	4,395.8	0.3	2.9
12447390	1992	19.7	22.1	-10.8	
	1993	27.1	25.3	7.1	
	1994	18.8	28.4	-33.7	
	1995	42.9	40.7	5.4	
	1996	34.2	41.4	-17.3	
	1997	50.5	43.5	15.9	
	1998	43.9	37.2	18.2	
	1999	35.7	45.0	-20.6	
Total		272.8	283.5	-3.8	-4.5
12448000	1992	199.6	223.3	-10.6	
	1993	299.5	275.4	8.7	
	1994	217.3	281.6	-22.8	
	1995	622.6	527.6	18.0	
	1996	494.6	529.3	-6.6	
	1997	735.5	580.7	26.7	
	1998	565.1	511.1	10.6	
	1999	500.8	629.7	-20.5	
Total		3,635.0	3,558.7	2.1	0.4
12448500	1992	659.4	869.3	-24.1	
	1993	782.7	814.5	-3.9	
	1994	651.0	758.1	-14.1	
	1995	1,559.7	1,444.1	8.0	
	1996	1,366.2	1,570.4	-13.0	
	1997	1,808.2	1,639.6	10.3	
	1998	1,361.8	1,423.6	-4.3	
	1999	1,303.9	1,728.9	-24.6	
Total		9,492.9	10,248.5	-7.4	-8.2

Table 4. Simulated and measured mean annual streamflows, simulated streamflow as a percentage of measured, and bias for water years 1992–99—*Continued*

Station No.	Water year	Mean annual streamflow (ft^3/s)		Difference between simulated and measured as percentage of measured	Bias (percent)
		Simulated	Measured		
12448998	1992	183.7	179.8	2.2	
	1993	167.2	170.4	-1.8	
	1994	164.4	151.9	8.2	
	1995	378.4	341.4	10.9	
	1996	337.5	409.5	-17.6	
	1997	395.7	384.9	2.8	
	1998	315.3	294.9	6.9	
	1999	332.8	344.0	-3.3	
Total		2,275.0	2,276.7	-0.1	1.0
12449500	1992	868.0	1,033.8	-16.0	
	1993	976.4	947.7	3.0	
	1994	832.2	901.3	-7.7	
	1995	2,008.6	1,752.4	14.6	
	1996	1,759.7	1,915.3	-8.1	
	1997	2,277.8	1,922.8	18.5	
	1998	1,718.2	1,670.9	2.8	
	1999	1,678.7	1,968.6	-14.7	
Tota..............1		12,119.7	12,112.8	0.1	-1.0
12449950	1992	1,000.6	1,084.0	-7.7	
	1993	1,144.0	1,022.9	11.8	
	1994	952.3	963.0	-1.1	
	1995	2,420.4	1,854.1	30.5	
	1996	2,041.2	2,053.6	-0.6	
	1997	2,631.6	2,128.1	23.7	
	1998	1,955.6	1,914.2	2.2	
	1999	1,927.9	2,251.0	-14.4	
Total		14,073.5	13,271.0	6.0	5.6

PLANNED WORK AND FUTURE STUDIES

The next phase of the current study will improve the watershed model by simulating more complex hydrologic features such as streamflow diversions and returns and by considering findings from the concurrent ground-water study. Inverse modeling using non-linear regression will be used to better construct and calibrate these simulations and to provide a more rigorous sensitivity analysis. The Phase Two model will be calibrated and validated to newly measured streamflow- and diversion-discharge measurements collected through the 2001 irrigation season and the historical record of streamflow that includes the effects of diversions. If additional streamflow and diversion data are collected in future years, the model calibration can be further improved.

The Phase Two watershed model will be a user-friendly tool that can be used to simulate the impact on streamflow of different watershed-management options prior to their implementation. A special case that can be simulated includes summers without diversions and returns. Because the Phase Two model will be better calibrated than the current Phase One model, the special-case simulation would provide natural streamflows for the period of the climate record (1959 to the present) with greater reliability than natural streamflows simulated with the current model.

The calibrations of the Phase Two and possible other models will be improved if the current data sets continue to be expanded to include future years with different climatic and water-use conditions. Useful data to be measured include streamflow discharge, irrigation-canal diversion and return discharge, irrigation-canal leakage, rates of streamflow losses and gains to and from the ground-water system, respectively, climate variables, land- and water-use, and water levels in the ground-water system.

SUMMARY AND CONCLUSIONS

A study was conducted in cooperation with Okanogan County to evaluate natural streamflows for the Methow River and its tributaries. The need for this study was due in part to 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.” In an effort to focus on habitat conditions to sustain naturally producing salmonid populations, the National Marine Fisheries Service set instream flow requirements for three tributaries to the Methow River: the Chewuch River, Early Winters Creek, and Wolf Creek. Irrigation diversions from the river above existing and historical streamflow-gaging stations make it difficult to assess the natural streamflow conditions in the Basin. A calibrated watershed model could properly assess the available water resources throughout the Basin and provide guidance as to the natural streamflow conditions.

Delineation of subbasins and the drainage network was accomplished with the Geographic Information System (GIS) Weasel. 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 607 modeling response units (MRUs) 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 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, (3) appropriately simulate both mountainous and flat areas, and (4) easily accept parameterization output from the GIS Weasel. Additionally, the system was recently applied and calibrated to a nearby, hydrologically similar watershed, the Yakima River Basin. Calibration of the various subbasins within the Methow River Basin was accomplished by using measured precipitation and air-temperature data as model input and by matching simulated and measured streamflows. Precipitation and air-temperature modules used a distance-weighted average approach to estimate missing data and avoid problems in the simulations. Monthly mean precipitation ratios between climate stations and MRUs were calculated from Parameter estimation Regressions on Independent Slopes Model (PRISM) estimates.

Streamflow was simulated for water years 1992-99 to calibrate the model to measured streamflows at the seven USGS gaging stations. Values determined by the GIS Weasel, values calculated and set by MMS algorithms, and parameter estimates used in the hydrologically similar Yakima River watershed basin model all provided initial estimates of parameters. Most parameter adjustments were related to precipitation, air temperature, minimum ground-water storage, and the ground-water flow coefficient.

Difficulty existed in calibrating natural streamflow conditions in the Methow River Basin because all streamflow-gaging stations, with the exception of Andrews Creek (12447390), are located below irrigation diversions and few historical records exist for the study area prior to the diversions. Certain assumptions were made about the flow system. Simulated and measured streamflow generally showed close agreement, especially for spring runoff from snowmelt and low-flow conditions. The model simulations were less accurate capturing the magnitude and timing of short-term (1 to 3-day) peak flows. Annual water totals for simulated and measured streamflow varied considerably during many of the water years but total annual runoff for the 8-year period matched closely for all calibration points with the exception of station 12448500, Methow River at Winthrop. Simulated mean monthly September and October streamflow for two gaging stations, the Methow River above Goat Creek (12447383) and the Chewuch River (12448000), were greater than measured flows.

The calibrated model can be used as a tool to simulate flows at ungaged streams or flows at gaged streams for periods outside the historical record. To demonstrate this ability, the period of water years 1959-99 was simulated and monthly streamflow statistics generated.

Certain approximations and simplifications must be made to simulate actual flow systems. Lack of understanding about some aspects of the natural flow system, coupled with only one streamflow-gaging station that measures natural streamflow (above irrigation diversions), accounts for much of the error in simulated results. Additional sources of error are data error, model error, and errors in the estimated parameter values. As a result, model-predicted values must be used with caution in consideration of simulation error.

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