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

Watershed Models for Decision Support in the Yakima River Basin, Washington

Open-File Report 02-404

A contribution of the **Watershed and River System Management Program**
A joint program of the **U.S. Geological Survey** and **U.S. Bureau of Reclamation**

USGS
science for a changing world

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Watershed Models for Decision Support in the Yakima River Basin, Washington

By M. C. Mastin and J. J. Vaccaro

U.S. GEOLOGICAL SURVEY

Open-File Report 02-404

Tacoma, Washington
2002

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
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.2832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	2.54	millimeter
mile (mi)	1.609	kilometer
pound	0.4536	kilogram
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (^{o}F) may be converted to degrees Celsius (^{o}C) as follows:

$$^{o}C=(^{o}F-32)/1.8.$$

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.

Watershed Models for Decision Support in the Yakima River Basin, Washington

by M.C. Mastin and J.J. Vaccaro

ABSTRACT

A Decision Support System (DSS) is being developed by the U.S. Geological Survey and the Bureau of Reclamation as part of a long-term project, the Watershed and River Systems Management Program. The goal of the program is to apply the DSS to U.S. Bureau of Reclamation projects in the western United States. The DSS was applied to the Reclamations's Yakima Project in the Yakima River Basin in eastern Washington. An important component of the DSS is the physical hydrology modeling. For the application to the Yakima River Basin, the physical hydrology component consisted of constructing four watershed models using the U.S. Geological Survey's Precipitation-Runoff Modeling System within the Modular Modeling System. The implementation of these models is described.

To facilitate calibration of the models, mean annual streamflow also was estimated for ungaged subbasins. The models were calibrated for water years 1950-94 and tested for water years 1995-98. The integration of the models in the DSS for real-time water-management operations using an interface termed the Object User Interface is also described. The models were incorporated in the DSS for use in long-term to short-term planning and have been used in a real-time operational mode since water year 1999.

INTRODUCTION

Competition among water-resource users in many basins in the western United States has resulted in a need for retrospective analyses of watersheds and river systems for long-term planning using long-length records as well as near real-time assessments of water availability and use. Coupling hydrologic and water-management models can provide a means for these assessments, with substantial benefits for water-resource planning and operation.

The U.S. Geological Survey (USGS) and the U.S. Bureau of Reclamation (USBR) are working collaboratively on a long-term program termed the Watershed and River Systems Management Program (WARSMP). The goals are to (1) couple watershed and river-reach models that simulate the physical hydrology with routing and reservoir management models that account for water availability and use, and (2) apply them to USBR projects in the western United States. The coupling provides a database-centered decision support system (DSS) (fig. 1) for use by WARSMP and other projects. The program also supports the development of the models and necessary software tools for the coupling and use of the models (U.S. Geological Survey, 1998).

The program has applied the DSS to the Yakima River Basin, located in eastern Washington (fig. 2) to provide tools for improving the management of water in the basin. Issues of many western States are common to the basin. These issues include Indian treaty rights, historical water rights, potential over-appropriation of water, reservoir and irrigation development, increasing demand for wildlife and anadromous and resident fish, water quality of the streams and ground water, and the interaction of ground water and streamflow.

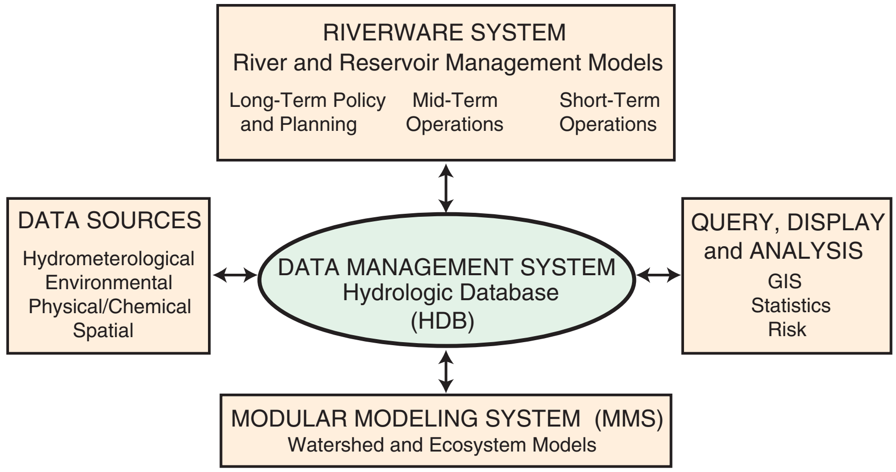

Figure 1. A database-centered Decision Support System.

The surface water in the Yakima River Basin is also under adjudication, and the amount of surface water that may be available for appropriation is not known. New demands are being met by ground-water sources that compound the issues. These demands may be met by changes in the way water resources are allocated and used. An integrated understanding of surface-water resources is needed in order to effectively implement most water-resources management strategies in the basin. On-going activities in the basin for enhancement of fisheries, obtaining additional water for agriculture, and meeting rules implemented under the Endangered Species Act for salmonid fish, which have been either listed or are proposed for listing, all need to be assessed within a consistent framework, which the DSS can provide.

Purpose and Scope

This report describes (1) the methods used to estimate mean annual streamflow for ungaged subbasins and the stream channel network to provide a data set of natural and unregulated streamflow for calibrating and testing the watershed models; (2) the construction, calibration, and testing of the four watershed models for the Yakima River Basin; and (3) the integration and use of the four watershed models in the DDS.

The four models included 51 subbasins in the Yakima Basin that produce 95 percent of the streamflow in the basin and are relatively unaffected by irrigation activities. The models were calibrated using mean annual streamflow data for water years 1950-94 and tested for streamflow data for water years 1995-98.

A Database-Centered System

The models in the DSS are coupled through a common database, termed the hydrologic database (HDB) for WARSMP. In the DSS, output from one model can be written to the HDB for use as input to another model. The HDB also links data sources and ancillary tools such as a geographical information system (GIS), statistical analysis, and data query and display capabilities that are part of the DDS. The coupling, interaction, and other capabilities in the DSS allow for improved assessments of long-term planning and policy decisions, in addition to the major program thrust of improving short-term and mid-term water-management operations of USBR projects, and in particular the Yakima Project. The HDB will also become the data-repository and management system for the data collected by the USBR's Yakima Project Office when it replaces the existing HYDROMET system.

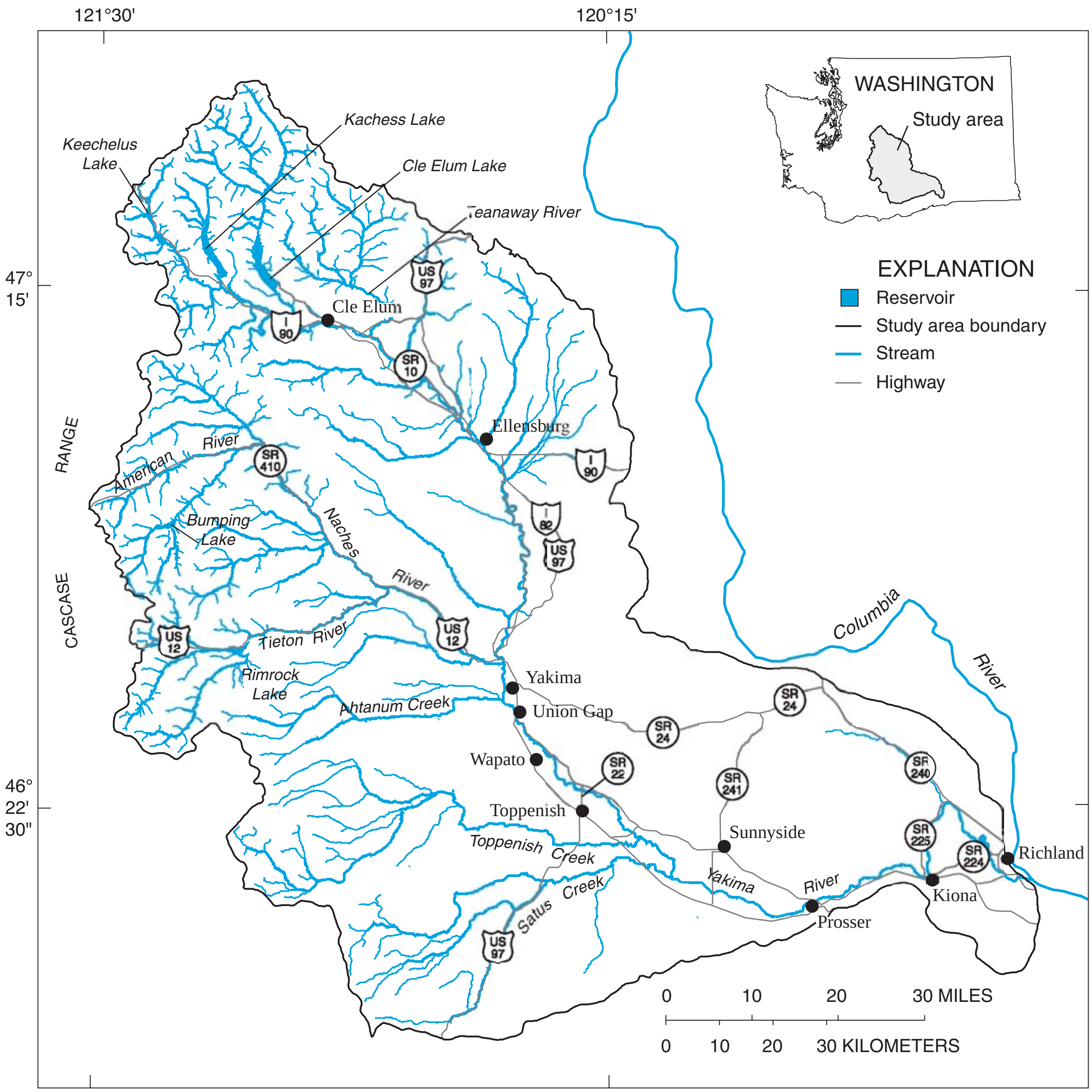

Figure 2. Location of the Yakima River Basin, Washington.

The Modular Modeling System

The USGS Modular Modeling System (MMS) was used for the watershed modeling component of this study. MMS is an integrated system of computer software developed to provide a framework for the development and application of numerical models to simulate a variety of water, energy, and biogeochemical processes (Leavesley and others, 1996). MMS's three major components—pre-process, model, and post-process (fig. 3)—all include graphical user interfaces (GUIs) and data-management interfaces (DMIs). The model component has the capability for optimization (Opt), sensitivity analysis (Sens), and ensemble streamflow prediction (ESP) (fig. 3). The model component for this study was the USGS Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983); the physical process modules for PRMS are contained in the Module Library (fig. 3).

Description of Study Area

The Yakima River Basin has a drainage area of 6,200 mi^2 and produces a mean annual unregulated runoff of 5,600 ft^3/s (about 4,055,000 acre-feet) and a regulated runoff of 3,600 ft^3/s (about 2,607,00 acre-feet). Unregulated runoff was calculated from observed runoff that was adjusted to reflect unregulated conditions. There are eight major rivers and numerous smaller streams in the Yakima River Basin.

The headwaters are on the humid east slope of the Cascade Range, where the mean annual precipitation is more than 100 inches. The basin ends at the confluence of the Yakima and Columbia Rivers in the low-lying, arid part of the basin, which receives 6 inches of precipitation per year. Most of the precipitation falls during the winter in the form of snow in the mountains. The mean annual precipitation over the entire basin is 27 inches (about 12,000 ft^3/s or 8.7 million acre-feet). The spatial pattern of mean annual precipitation resembles the pattern of the basin's highly variable topography. Altitudes in the basin range from 400 to nearly 8,000 feet above sea level.

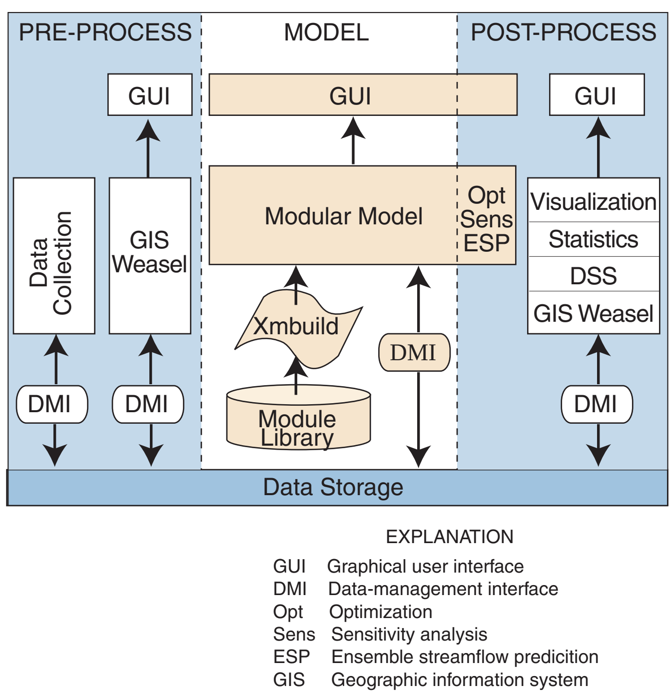

Figure 3. Components of the Modular Modeling System.

Agriculture is the principal economic activity in the basin. The average annual water demand is 2,590,000 acre-feet. Most of the demand is for irrigation of about 500,000 acres in the low-lying semiarid-to-arid parts of the basin, and the difference between unregulated and regulated streamflow indicates that the irrigation of crops (crop water use, evaporative losses) consumptively uses about 1.4 million acre-feet of water. The demand is partially met by storage of water in the five USBR reservoirs, which can store 1,065,400 acre-feet; the capacity of the reservoirs ranges from 33,700 to 436,900 acre feet. About 86,000 acre-feet of the demand is met by ground-water withdrawals from the major aquifers underlying the basin. The major management point for USBR, where flows are closely monitored for instream flow limits and forecasted to determine the total water supply available for upcoming irrigation seasons, is at the streamflow gaging site at the Yakima River near Parker; this site is considered the dividing line between the upper (mean annual precipitation of 7 to 100 inches) and lower (mean annual precipitation of 6 to 45 inches) halves of the Yakima River Basin. Some 45 percent of the surface water diverted for irrigation eventually is returned to the river system as either surface water or ground water, but at varying time lags. During the low-flow period, these return flows account for some 75 percent of the water in the lower river basin.

Basin and Subbasin Delineation

A GIS interface, termed the GIS Weasel (Leavesley and others, 1997), facilitated both model construction and watershed analysis. The primary data input to the GIS Weasel was a digital elevation model (DEM) composed of square grid cells of 208 feet on a side (about 1 acre). The GIS Weasel used the cell data to delineate the Yakima River Basin and the modeled subbasins; subbasin boundaries were defined with an acceptable degree of accuracy using the 208-foot-sized cells. Based on locations of streamflow gages, outlets of ungaged watersheds, and USBR water-management points, 59 subbasins were defined (fig. 4). Fifty-one of those subbasins were grouped into four watershed modeling units.

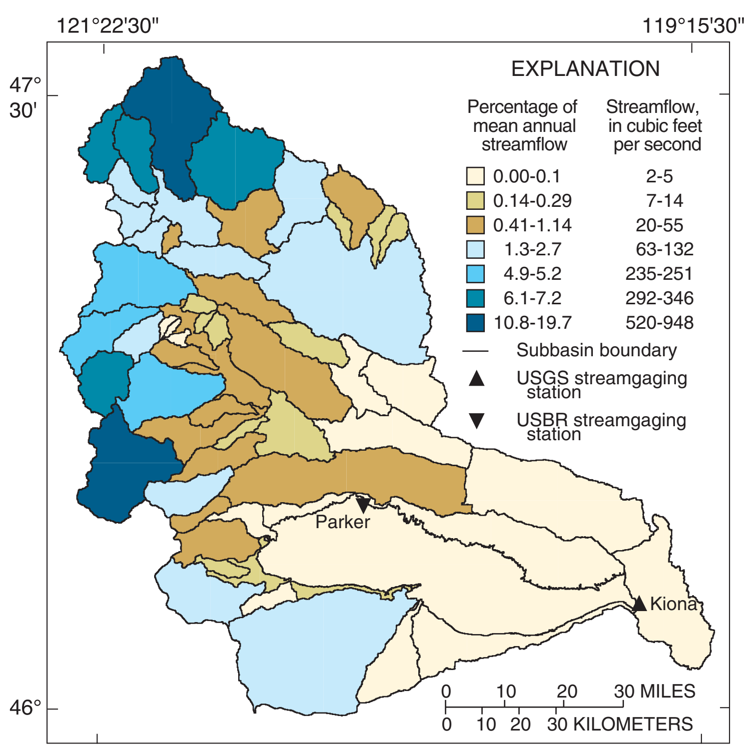

Figure 4. Mean annual streamflow and percentage of mean annual streamflow calculated by the U.S. Bureau of Reclamation (USBR) for the Yakima River near Parker site for the 59 subbasins in the Yakima River Basin, Washington.

Data Sources and Information

Various watershed, meteorologic, and streamflow characteristics are needed to construct and calibrate the watershed models. In addition to the GIS data layer for the DEM, data layers for soils (U.S. Department of Agriculture, 1994), land cover/land use (U.S. Geological Survey, 1992; see Loveland and others, 1991; Cassidy, 1997), a forest-cover type and a forest-density (Zhu and Evans, 1992; Powell and others, 1998), simplified surficial geology (Fuhrer and others, 1998), and mean annual and monthly precipitation (Daly and others, 1994) were obtained to aid in the initial parameter estimates and to help in basin assessment. All data layers were established as a 208-foot-square GIS grid that was consistent with the DEM. A GIS layer of the major hydrometeorological sites in the basin was established jointly with USBR.

Daily precipitation and minimum and maximum air temperature data were obtained from Hydrosphere Data Products (1993), U.S. Department of Agriculture (1998), and USBR. Missing values in the daily weather data were filled in and all records were extended (if needed) by correlation with nearby stations to create a common base period of water years 1950-98. Snow-course and daily snow-pillow data (SNOTEL) were obtained from U.S. Department of Agriculture (1998). The snow-pillow data began between water years 1978 and 1983 except for one site, which began in water year 1991.

Daily values of natural streamflow were compiled from the databases of the USGS (Washington District Office) and USBR (Yakima Project Office). Monthly values of estimates of unregulated streamflow for seven sites on the Yakima River, one site on the Natches River, and one site on a small creek in the upper Yakima River Basin described were provided by Robert Larson (U.S. Bureau of Reclamation, written commun., 1994).

ESTIMATING MEAN ANNUAL STREAMFLOW

Operational models need to be calibrated by adjusting parameters until a reasonable match is obtained between streamflow calculated by the model (“calculated” streamflows) and observed natural or unregulated streamflows (“observed/estimated” streamflows). In the Yakima River Basin, daily values of streamflow are available for only eight subbasins: observed values of natural streamflow are available for three subbasins, and the USBR has estimated daily unregulated streamflow for the five subbasins whose outflow is controlled by the five major reservoirs in the basin. In addition to the daily values, monthly unregulated values have been estimated by the USBR at nine sites—seven on the main stem of the Yakima River, one on the Naches River, and one on a smaller creek in the headwaters of the upper Yakima River. Monthly mean streamflow for the Toppenish Creek near Fort Simcoe was estimated for water years 1950-84 and compiled from gaged data from 1984-94 (Kale Gullett, Wapato Irrigation District, written commun., 1999).

If an ungaged subbasin was sufficiently similar to a gaged subbasin, a synthetic time-series of annual streamflow values was estimated, based on the streamflow estimated by regression and observed mean annual streamflow values. For example, the ratio of the estimated ungaged mean annual streamflow to gaged mean annual streamflow values is multiplied by the annual streamflow values of the gaged subbasin, producing a synthetic time-series of annual streamflow values for the ungaged subbasin (herein called regression/ratio-derived values). This annual time-series can be further disaggregated to monthly values using the same technique. Such time-series provide additional information for model calibration.

Estimates of mean annual streamflow along the stream network for selected locations also are useful for testing the reasonableness of the modeled-calculated streamflow. For selected stream network locations, the model-calculated mean annual streamflow values for upstream subbasins were summed within MMS and compared with the mean annual streamflow value at the location on the stream network. The spatial distribution of mean annual streamflow also can be used as an aid in resource management, for example, identification of stream reaches that may have been historically good for salmonid habitat.

Estimates for Ungaged Basins

Three regression equations were used initially to estimate mean annual streamflow for ungaged subbasins. Two equations were developed by Nelson (1991) using data for a 22-year period (1956-77) as part of the Columbia Plateau regional aquifer system analysis (Vaccaro, 2000). These two equations use mean annual precipitation to calculate mean annual streamflow in terms of unit streamflow in inches per year. One equation is for areas with a mean annual precipitation of less than or equal to 17.9 inches and the other for areas with a mean annual precipitation greater than 17.9 inches. These two equations were applied to the 12 ungaged subbasins in the lower basin below the stream-gaging site on the Yakima River near Parker. The third equation was developed as part of WARSMP by comparing mean annual streamflow with the amount of area within elevation zones weighted by mean annual precipitation. The equation calculates mean annual streamflow values representative for a 48-year base period (1947-94) that includes extended wet (1947-76) and dry (1977-94) periods. It was applied to the 45 ungaged subbasins in the upper basin, upstream of the Parker gage site.

The WARSMP equation uses the area within zones as the predictor variables. The zones were defined by a grid of effective altitudes calculated by multiplying a cell's altitude by the ratio of mean annual precipitation to a mean annual precipitation of 100 inches. The ranges of the zones were 0-1000 (area1), 1000-1500 (area2), 1500-2000 (area3), 2000-2500 (area4), 2500-3000 (area5), 3000-3500 (area6), 3500-4000 (area7), and greater than 4000 feet (area8). The precipitation weighting of altitude allows for two locations at the same altitude but with different mean annual precipitation values to have different effective altitudes. The predictor variable accounts for some of the effects of altitude on hydrology and the spatial variations in mean annual precipitation with altitude (in the study area mean annual precipitation may vary by as much as 80 inches for the same altitude). The importance of accounting for these variations in the Cascade Range was described as early as 1970 by Gladwell (1970).

To obtain zone information for every subbasin, the 208-foot-cell DEM data first were multiplied by the mean annual precipitation values (Daly and others, 1994) that were gridded in GIS using the same 208-foot cell size as the DEM, and then divided by 100. For each subbasin, the number of cells in a zone were accumulated and then converted to an area for each zone present in a subbasin.

The WARSMP equation was developed using the area predictor variable and the 48-year mean annual streamflow values of all of the gaged subbasins. For subbasins that were not gaged for the full 48 years, the partial-period mean annual streamflow value was adjusted to the 1947-94 base period. An adjusted value for a partial-period subbasin was obtained by calculating, and then averaging, the ratios of the 48-year mean annual streamflow to the partial-period mean annual streamflow for the subbasins with a complete period of record. This average value was then multiplied by the partial-period value. The WARSMP equation was significant at less than the 0.01 level, and had an *r*-squared value of greater than 0.95 and a standard error of estimate of 62 ft^3/s. The equation is:

$$\begin{aligned}\text{Mean annual streamflow} &= (17.62 \times \text{area1}) \\ &+ (-11.27 \times \text{area2}) \\ &+ (8.06 \times \text{area3}) + 2.53 \times \text{area4}) \\ &+ (-9.222 \times \text{area5} + (20.481 \times \text{area6}) \\ &+ (-9.77 \times \text{area7}) + (13.86 \times \text{area8}), \qquad (1)\end{aligned}$$

where area1-area8 are the areas, in square miles, in the zones defined above and mean annual streamflow is in cubic feet per second.

The WARSMP equation was applied to the 45 ungaged subbasins upstream of the Parker gage site. For five of the nine USBR river sites with estimated unregulated monthly values (one on the Naches River and four on the main-stem Yakima River), the mean annual streamflow values for the upstream subbasins contributing to a site were added and compared with the USBR's value. Subbasin or contributing subbasin values also were compared with the historical natural or estimated unregulated mean annual streamflow (base-period adjusted) of Parker and Storey (1916). Based on the comparisons, some values were adjusted so that the summations at the five sites or at the Parker and Storeys' locations were within about 5 percent. Values for 11 subbasins were adjusted less than about 15 percent. For one small subbasin with a drainage area of 17.3 mi^2, the mean annual streamflow was increased by 40 percent, from 10 to 14 ft^3/s. At the Parker gage site, USBR's estimated mean annual streamflow is 4,808 ft^3/s, and the sum of the contributing subbasins is 4,857 ft^3/s.

Two subbasins below Parker have been gaged (1910-23) and have a combined mean annual streamflow, adjusted to the base period, of about 130 ft^3/s. These two subbasins account for most of the streamflow generated in the lower basin. The other 12 ungaged subbasins below Yakima River near Parker were assigned values using Nelson's equations. These values were not adjusted based on the main-stem mean annual streamflow values because of the lack of historical mean annual streamflow data in the more semiarid to arid lower basin, which has a mean annual precipitation of about 11.5 inches.

The mean annual streamflow values for all subbasins were then compared to subbasin characteristics—such as drainage area, mean basin altitude, and mean annual precipitation—and to the ratio of mean annual streamflow to mean annual precipitation (the percentage of precipitation that ultimately becomes streamflow). This comparison was done to assess if a subbasin was producing significantly more or less streamflow than other subbasins with similar characteristics. Minor adjustments, on the order of 1 to 5 percent, were made to mean annual streamflow values for a few subbasins based on this comparison.

For the stream gaging site nearest the mouth of the Yakima River (Yakima River at Kiona), USBR has estimated the unregulated mean annual streamflow at 5,582 ft^3/s (Robert Larson, Bureau of Reclamation, written commun., 1994), and the sum of the subbasin values is 5,138 ft^3/s, a difference of 444 ft^3/s (8 percent). The spatial distribution of mean annual streamflow for the 59 subbasins is shown as a range in values and as a percentage of USBR's mean annual streamflow for the Yakima River near Parker (fig. 4). The subbasin values range from about 2 to 950 ft^3/s, and the nine subbasins with mean annual streamflow values of more than 290 ft^3/s produce about 63 percent of the streamflow in the basin. The 51 subbasins for which the PRMS models are being constructed produce more than 95 percent of the streamflow in the basin.

Estimates for the Stream Channel Network

Estimates of mean annual streamflow for the stream channel network in the basin were based on the subbasin values of mean annual streamflow (fig. 4) and on Nelson's (1991) equations. First, a stream network was defined for the basin wherever the drainage area for a stream cell was equal to or greater than 0.47 mi^2, using the GIS Weasel and the input DEM (fig. 5). The network does not necessarily match the actual stream network due to the coarse resolution of the DEM, but in most instances it closely approximates the mapped stream network.

Mean annual streamflow values were calculated for each 208-foot cell in the basin using Nelson's (1991) equations and the mean annual precipitation data. For each subbasin, the cell values were adjusted by dividing each cell value by the sum of cell values, and then multiplying by the previously estimated or observed subbasin mean annual streamflow value; this adjustment constrains the sum at a subbasin outflow point to be equal to the estimated or observed subbasin mean annual streamflow value. Accumulating the mean annual streamflow values for the cells in a downslope-downstream direction using GIS produced a basin-wide distribution of accumulated mean annual streamflow.

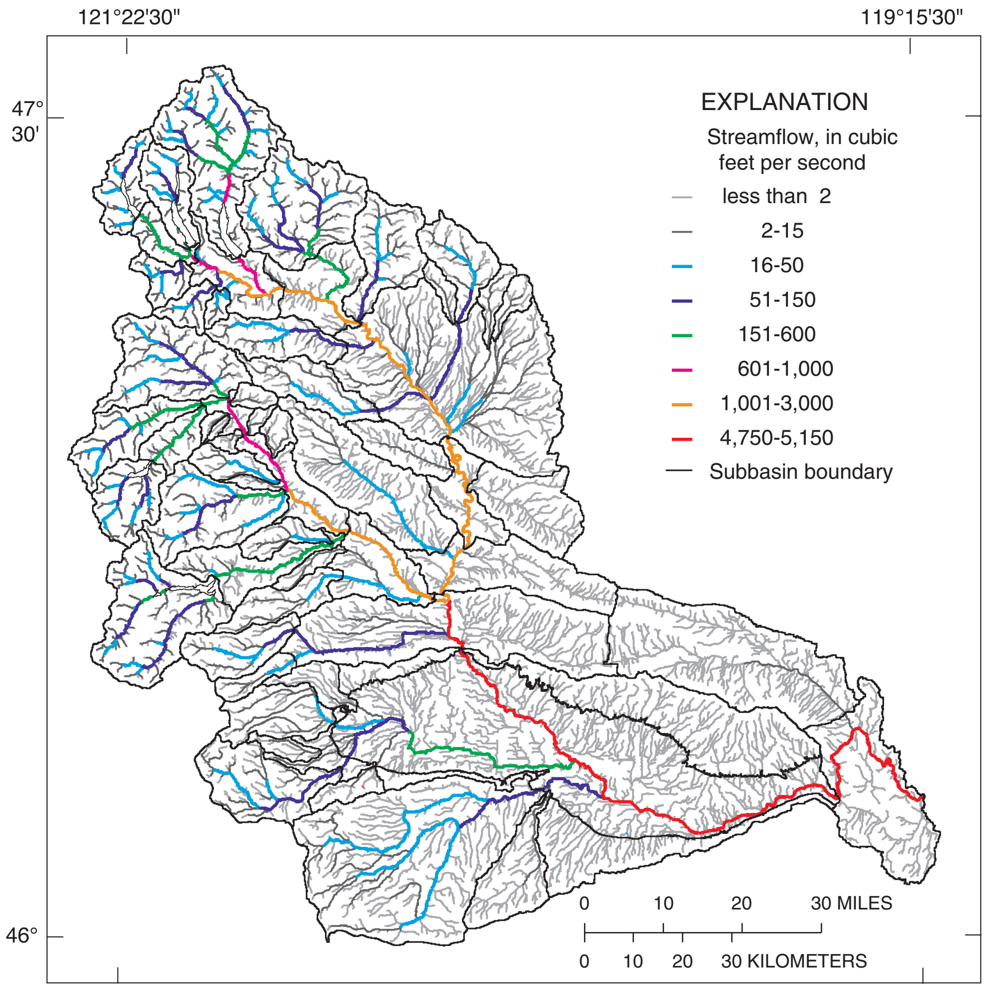

Figure 5. Distribution of estimated mean annual streamflow along the stream channel network in the Yakima River Basin, Washington.

The accumulated values along the stream channel network (fig. 5) were then obtained from this distribution, and the values represent, depending on location, natural streamflow, unregulated streamflow, or some combination of the two. The values do not account for variations in streamflow along the network due to ground water, but do account for the total ground-water contribution to the basin's streamflow. Regional pre-development ground-water discharge for the upper and the lower parts of the basin have been estimated to be about 185 ft^3/s and 45 ft^3/s, respectively (Hansen and others, 1994).

CONSTRUCTION OF WATERSHED MODELS USING THE MODULAR MODELING SYSTEM

Four watershed models for calculating daily unregulated streamflow were constructed for 51 subbasins in the Yakima River Basin, of which all but two are non-agricultural. Forty-one are located in the upper part of the basin and 10 are located in the lower basin. The PRMS models allow for the spatial distribution of hydrologic-model parameters by partitioning or characterizing a subbasin into hydrologic response units.

The GIS Weasel was used to partition each subbasin into modeling response units (MRUs), which for this study are equivalent to hydrologic response units. The first partitioning used a two-flow plane division method where the stream network is divided into stream links at each confluence, and each stream link defines a subbasin. Each subbasin is then divided into two units, one on either side of the stream link. Further partitioning was based on the precipitation-altitude zones described earlier in the section “Estimates for Ungaged Basins” and on soil characteristics.

Of the 1,209 MRUs defined for the Yakima Basin, 1,110 are in areas covered by the four models. The 99 MRUs that are not in the four models are all in the low-lying dry agricultural areas and contribute less than 2 percent of the total streamflow. Watershed models were constructed for the following four areas (fig. 6):

- Naches modeling unit —the watershed upstream of the stream-gaging station Naches River at Naches plus four unregulated subbasins;
- Upper Yakima modeling unit —the watershed upstream of the stream-gaging station Yakima River at Horlick plus seven unregulated subbasins;
- Toppenish/Satus modeling unit—the watershed upstream of the irrigation canals within the Toppenish and Satus Creek watersheds; and
- Yakima Canyon modeling unit —the part of the watershed that directly contributes to or abuts what is called the Yakima Canyon along the Yakima River.

The modeling and hydrologic characteristics of the four watershed models are summarized in table 1 and location of the meteorological and streamflow sites is shown on figure 6.

The four modeled areas have a total area of 3,663 mi^2. These areas were selected because they account for more than 95 percent of the streamflow in the Yakima Basin, contain the five major reservoirs managed by the USBR, and, with two exceptions, are relatively unaffected by diversions and irrigation. The two exceptions are the Wenas Creek subbasin in the Yakima Canyon model, which contains a small reservoir used for irrigation of lands in the lower part of the subbasin, and the subbasin that is in the river canyon itself, which contains small parcels of irrigated lands. Each model can be operated individually using MMS, or all four models can be operated conjunctively within the DSS.

A daily water balance is computed for each MRU and the streamflow values for the MRUs are summed by subbasin and by river management nodes. As is described in the section “Integrating the Models in the Decision Support System for Real-Time Operations,” the summations (accumulations) can be passed to and stored in the HDB for use by RiverWare, the river and reservoir management model component of the DSS (Fulp and others, 1995). RiverWare is a general purpose, interactive model-building tool used to develop water-distribution models for operations, scheduling, and planning. RiverWare is being applied by USBR’s analysts and operators.

Table 1. Modeling and hydrologic characteristics of the four watershed models used in the Yakima River Basin, Washington

[MRU=modeling response unit; mi^2=square miles]

Watershed model	Number of subbasins	Number of MRUs	Number of temperature stations	Number of precipitation stations	Drainage area (mi^2)	Mean annual precipitation (inches)
Naches	20	363	12	12	1,100	43
Upper Yakima	17	404	14	12	1,130	53
Toppenish/Satus	10	242	8	8	1,027	17
Yakima Canyon	4	101	7	5	406	21

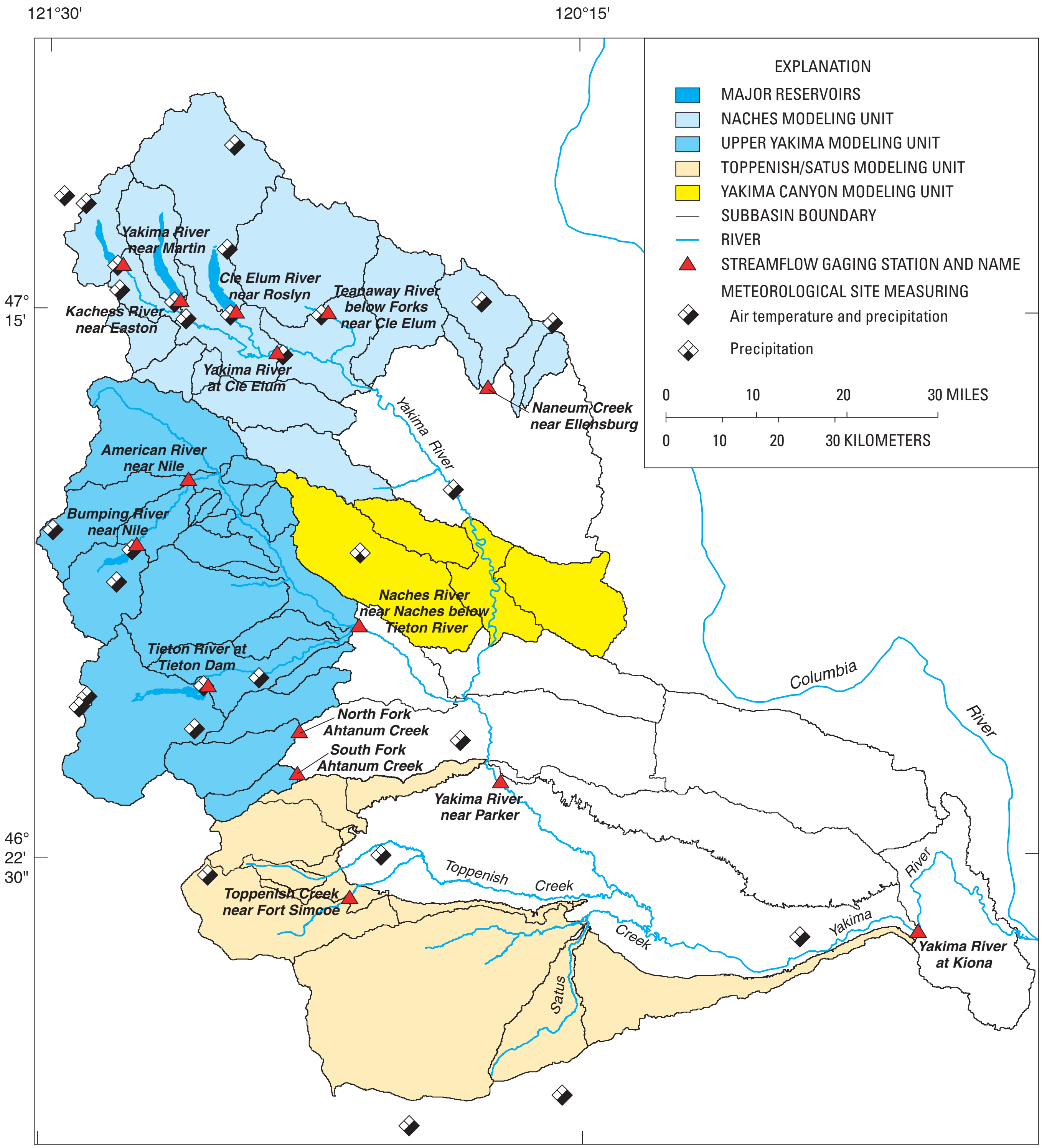

Figure 6. Location of the four watershed modeling areas in the Yakima River Basin, Washington, and of the meteorological and streamflow sites with data used for calibrating and testing the models.

Changes to the Precipitation-Runoff Modeling System Model

Results produced from the initial models, constructed with the standard PRMS modules, suggested that some changes to modules would be beneficial. In particular, the method for distributing daily weather to the MRUs could be improved to better reflect the large spatial variations in daily weather. Also, in a real-time operational mode, missing or erroneous data at one or more weather sites may cause problems because the standard PRMS module uses a method of assigning a single weather site to a MRU. Algorithms to account for the runoff processes of glacier melt and the water budget of lakes, which are not explicitly accounted for in PRMS, were added because of the presence of glaciers and large water reservoirs in the Yakima River Basin Other, minor changes in modules included allowing for a minimum ground-water storage in a subbasin in the ground-water module, adding a groundmelt component to the snow accumulation and ablation module, and adding a simplified flow-accumulation and flow-routing module. Except for the latter module, all changes were made to existing PRMS modules. The flow-routing module was modified from an existing module developed by the USBR for operations in another project (Ryan, 1996). The modules that were changed are documented in Mastin and Vaccaro (2002); the documentation follows the MMS standard documentation and uses existing MMS module documentation for all but the flow-routing module. The module changes are described in more detail below.

The precipitation distribution module was changed so that data from all the precipitation sites are used to interpolate a daily value to a MRU using a simple inverse distance-weighting technique. This method of precipitation distribution is robust because it is less sensitive to missing or bad daily data at a site. Previously, the data from a precipitation site were assigned to an MRU and a factor was applied to adjust the site data on a monthly basis for rain and snow. In the changed module, the daily precipitation at a site is first weighted by the inverse square of the distance between the site and the centroid of the MRU, and is further corrected by the ratio of the mean monthly precipitation of the MRU to the mean monthly precipitation at the site. After interpolating all daily values from the weather sites to a MRU, an average value is calculated for the MRU. New model parameters are the x, y coordinates and mean monthly precipitation (for both rain and snow) of the MRUs and the weather sites. The method and computer code are from Bauer and Vaccaro (1987), except that mean monthly precipitation values for MRUs are used instead of the mean annual precipitation values used in the technique of Bauer and Vaccaro. Using mean monthly values improves on the accuracy and provides spatially distributed mean monthly values (Daly and others, 1994). In addition, adjustments to the mean monthly precipitation parameter values can account for gage-catch deficiency (recorded precipitation as a percentage of true precipitation) and snow-depth variations due to winds or topography, and allows the model to more easily obtain a match of calculated and observed streamflow by increasing or decreasing the monthly values to better approximate the true water budget.

Daily minimum and maximum air temperatures are also distributed to the MRUs on the basis of the inverse distance-weighting interpolation from Bauer and Vaccaro (1987). Previously, the PRMS temperature distribution module assigned the data for a temperature site to a MRU and adjusted the temperature on the basis of a lapse rate calculated using two user-defined sites and an adjustment factor for the MRU. In the modified temperature module, daily minimum and maximum lapse rates first are computed for the basin using averages of calculated lapse rates between all sites. These daily rates are constrained by user inputs of monthly minimum and maximum lapse rates for both minimum and maximum temperature—a total of 48 values. For example, the calculated daily minimum lapse rate is not allowed to exceed an upper or lower limit. This constraint was added because bad or missing data in the real-time operational mode can lead to erroneous calculated daily lapse rates. Next, daily minimum and maximum temperatures for the MRU are computed from an average of the inverse distance-weighted temperature values computed from each temperature station's observed value and the basin lapse rate.

The glaciers in two of the subbasins supply streamflow during the warm months. A simple glacier-melt function was added to the existing surface-runoff module to account for this streamflow. For a MRU with a glacier, glacier melt is calculated when there is no snow cover and the average air temperature is above a specified base temperature. Melt is equal to the difference between the air temperature and a base temperature, multiplied by a glacier-melt coefficient. There is no provision for the glacier to change volume or area; that is, the glacier melt is only temperature dependent. The base temperature was set at 32 degrees Fahrenheit and the coefficient was set at 0.004 inch per day (from Bauer and Vaccaro, 1990). This melt adds a new source of water to a subbasin with a glacier, and the melt goes directly to the surface-runoff component of the water budget and thus to the total streamflow.

Each of the five reservoirs was delineated as an MRU with the reservoir at the mouth of a subbasin. A new soil type representing water-covered areas was added to the soil-moisture balance module. For this soil type, the actual evapotranspiration is set equal to potential evapotranspiration, and for this study the surface runoff was set equal to zero. Consequently, all outflow from the MRU is derived from the PRMS subsurface-flow (SSF) and ground-water flow (GWF) reservoirs. Parameters are set such that the total available water capacity of the soil and recharge zones defined for PRMS are made equal and set to 27 inches, and land-cover parameters are made to represent bare ground. Twenty-seven inches approximates the annual potential evapotranspiration, and using 27-inch soil zones generally keeps the simulated soil-water content above 0.0. Thus, water is available for both evapotranspiration and streamflow for these lake MRUs. The only change made to the PRMS soil-moisture balance module was adding a soil type that set the actual equal to the potential evapotranspiration (adding two lines of code to the existing PRMS module). All other aspects described above are part of the standard parameterization in PRMS. Although simple, this method makes improved estimates of the water budget of a lake, compared to those from the standard soil moisture module.

Many east-slope streams in the central to southern Cascade Range have a winter low-flow period with flows that are larger than the late summer-early fall low flows. These higher low flows generally occur after a snowmelt event. This type of flow could not be sustained adequately during simulations with the available PRMS modules, so a groundmelt component (Anderson, 1976) was added to the snow accumulation and ablation module in order to supply the needed simulated runoff. The additional groundmelt component, set at 0 to 0.05 inch per day (Anderson, 1976), supplies much of the water needed to support these low flows during times when a subbasin is snow covered. The groundmelt, calculated for each MRU, goes to the upper part of the soil zone.

A simple reach-routing module, MODFLOW, was added that allows the runoff to be accumulated at points called nodes. Each defined node has user-specified MRUs, GWF reservoirs, and SSF reservoirs contributing to it. After all components of runoff (surface, subsurface, and ground water) are accumulated at the nodes, the runoff is then routed from the most upstream node to downstream nodes using a standard Muskingham routing equation (Linsley and others, 1982). This equation only requires two parameters—a storage coefficient that approximates an average traveltime, in hours, and a routing weighting-factor that adjusts the attenuation of a flood wave. The existing PRMS did not have a module for accumulating and routing, but an existing USBR module (called FIXROUTE), which MODFLOW was based on, contained all but the reach-routing feature; that module used a user-input time lag for each reach between an upstream and downstream node.

Initial Model-Parameter Estimation

PRMS requires many parameters for constructing a model. The types of parameters include single values, monthly values, and values for the SSF reservoirs, GWF reservoirs, and MRUs. A single value generally relates to a parameter needed by one of the physical process modules, such as the emissivity of snow used in the snow accumulation and ablation module. An example of a monthly parameter is a coefficient used in the evapotranspiration calculations. SSF parameters are needed for each SSF reservoir defined. For each of the models, a SSF reservoir was defined for each MRU. Parameters for the SSF would include coefficients for routing SSF to surface runoff and to the GWF reservoir.

The important parameter for a GWF reservoir is the recession coefficient. MRU parameters include average altitude, slope, and aspect, the land-cover density, summer and winter interception capacity of the foliar cover, and total available water capacity in the soil root zone. The parameters are fully described by Leavesley and others (1983, 1996).

A GWF reservoir was defined for each subbasin in each model, with the following exceptions: for the Naches model, two GWF reservoirs per subbasin were defined for five subbasins; for the Yakima Canyon model, two GWF reservoirs per subbasin were defined for two subbasins; and for the Toppenish/Satus model, a second GWF reservoir was defined for one subbasin to simulate relatively constant baseflows that persist throughout the summer and early fall.

In MMS, each parameter has a default value. In lieu of using all default values, the parameter-estimating part of the GIS Weasel was used to estimate spatially distributed parameters. This part of the GIS Weasel is a robust method that uses input GIS information and built-in tabulation or equation procedures to identify parameters. For example, each MRU needs a parameter for the snow computations that identifies a transfer coefficient for the amount of solar radiation that reaches the ground during winter. This parameter can range from about 0.10 for thickly forested areas to 1.0 for grasslands, and is also a function of slope and aspect. Based on GIS data for foliar-cover density, type of land-cover, slope, and aspect, the GIS Weasel estimates a value. Thus, in place of the single default value (0.5), a realistic range of values is estimated for the models. The only parameters initially estimated or calculated outside of the GIS Weasel were the GWF 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 (representing more of a calculation rather than an estimation); the flow-routing parameters for the simple reach-routing module, and the monthly minimum and maximum lapse rates that were initially estimated by (1) calculating daily rates for the period 1952-1994 using all the daily temperature data, and (2) estimating a value after analyzing the lowest 5 percent and highest 5 percent of the values for each month.

Model Calibration and Testing

The Naches and upper Yakima models initially were calibrated by examining the match between the daily observed/estimated and calculated streamflow for the subbasins with observed or estimated daily streamflow for the period 1950-94; there were no available daily streamflow values for the other two models for the 1950-94 period. Indeed, only the stream-gaging station at American River near Nile had observed daily values of natural streamflow for the complete calibration period. The North and South Fork Ahtanum Creek subbasins had data for water years 1950-78, and Naneum Creek had daily data for 1957-78. In addition, daily unregulated streamflow values were estimated by USBR for the five reservoir sites, monthly streamflow values were estimated by USBR for the calibration period of the nine sites previously discussed, and monthly streamflow values were available for Toppenish Creek as previously discussed.

For the gaged subbasins, the following parameters were adjusted in the calibration process. Calibration mainly focused on the recession coefficients for the GWF reservoir, partitioning of water between the surface, subsurface, and ground-water contributions to subbasin outflow, air temperature for defining snow events, the spatial distribution of monthly precipitation, maximum snowmelt infiltration rate (which affects the calculated winter streamflow peaks during extensive rain-on-snow events), and maximum amount of water on a MRU transferred directly to a GWF reservoir.

The comparison of observed/estimated and calculated unregulated streamflow during model calibration was done concurrently with a comparison between snow-water equivalent at snow-course and SNOTEL sites and snow-water equivalent for the MRU that contained the site. The SNOTEL data are used as a check of simulated snow-water equivalent for the MRUs containing snow-pillow sites. There are six snow-pillow sites for the Upper Yakima and Naches models and two sites for the Toppenish/Satus model. Generally, the timing of the start of snow and end of snow on ground was examined first, and then the daily times series of snow-water equivalent at SNOTEL sites or available snow-water equivalent at snow-course sites were compared.

In addition, GIS data sets (maps) showing the snow-pack extent and water equivalent were obtained for selected periods from the National Operational Hydrologic Remote Sensing Center (National Weather Service, National Oceanographic and Atmospheric Administration: http://www.nohrsc.nws.gov/). Data sets for the basin were extracted from the larger spatial data set, and the snow-water equivalent was plotted and compared with the model-calculated water equivalent for an additional, spatial check on the simulations. The comparison showed reasonable matches.

For ungaged subbasins, the model parameters that changed during the calibration process described above initially were set to the calibrated parameters for gaged subbasins with similar characteristics. Simulated mean annual values from the ungaged subbasins then were compared with the regression/ratio-derived values and appropriate adjustments were made to the parameters. For the smaller creeks in the Naches model, parameters were considered acceptable if the calculated and regression derived values were in the same range. For example, if the regression/ratio-derived mean annual streamflow was 4 ft^3/s and the model calculated a value of 9 ft^3/s, this was considered acceptable because both values are in the same general range. In addition, the sum of the differences between mean annual streamflow of the calculated and regression/ratio-derived values is much less than the measurement error for the total streamflow for the Naches River Basin. However, all of the calculated streamflow values for these smaller creeks are larger than the regression/ratio-derived values, suggesting that a downward adjustment in the MRU values of monthly precipitation may be needed. Results from the operation of the models in the real-time mode will be assessed over a several-year period, at which time these adjustments will be made if calculated streamflow from the Naches River Basin is consistently larger than the estimated unregulated streamflow. During calibration, model parameters for the ungaged subbasins did not change much from those directly derived using the GIS Weasel.

The partitioning of total streamflow between surface runoff, SSF, and GWF is an important component for understanding the hydrology of the basin, and is a function of the geologic setting. The partitioning also acts as a further check on the model results because it is based on the known hydrogeologic setting. In a previous study for the Oregon Coast Range, typified by a wet climate and thickly forested basins composed of loamy soils overlying fine-grained geologic rock units, streamflow was partitioned as 0.5-1 percent surface runoff, 74 percent SSF, and 25 percent GWF (Risley, 1994). For the Willamette River Basin in Oregon, there is more variation in partitioning because of a greater variety of geologic materials composing the basin: 1-3 percent surface runoff, 49-75 percent SSF, and 20-49 percent GWF (John Risley, U.S. Geological Survey, written commun., 2000). For this study, on a mean annual basis, streamflow was partitioned by the models as 1-9 percent surface runoff, 15-86 percent SSF, and 10-84 percent GWF. The large range in values reflects the variety of geologic units and climatic regimes. Generally, the parts of the basin underlain by sedimentary rock materials had a smaller GWF component and a larger SSF component, and the subbasins underlain by fractured basalts had a larger GWF component with a correspondingly smaller SSF component. The variations in contributions correspond to the overall hydrology of the Cascade Range and the Yakima River Basin. For example, in the drier subbasins underlain by basalts, ground water contributed the largest percentage to total streamflow, which corresponds to the fact that the basalts have a higher infiltration rate than either sedimentary or granitic/metamorphic rock materials and that the total streamflow in these predominantly semiarid subbasins is dominated by ground water. In addition, in wetter years the SSF component composes a larger part of the total streamflow than on average and in drier years the GWF component composes a larger part—as much as 89 percent for the drier years with few major rainfall events. Again, these variations correspond to what is understood about the overall basin hydrology and add further confidence in the model results.

The calculated partitioning of streamflow contributions for the American and Tieton Rivers in the Naches River Basin for a wet (water-year 1976) and a dry (water-year 1977) year show many of the aspects described above (fig. 7, table 2). The differences between the subbasins are derived from differences in rock type, and the differences within a basin are derived from the two different climatic regimes for 1976 and 1977. In addition, the larger value for the surface-runoff component in the Tieton River subbasin is due to the presence of glaciers; for the dry year much of the total streamflow for the Tieton River during the summer is calculated to be glacier melt, which, as described earlier, becomes surface runoff.

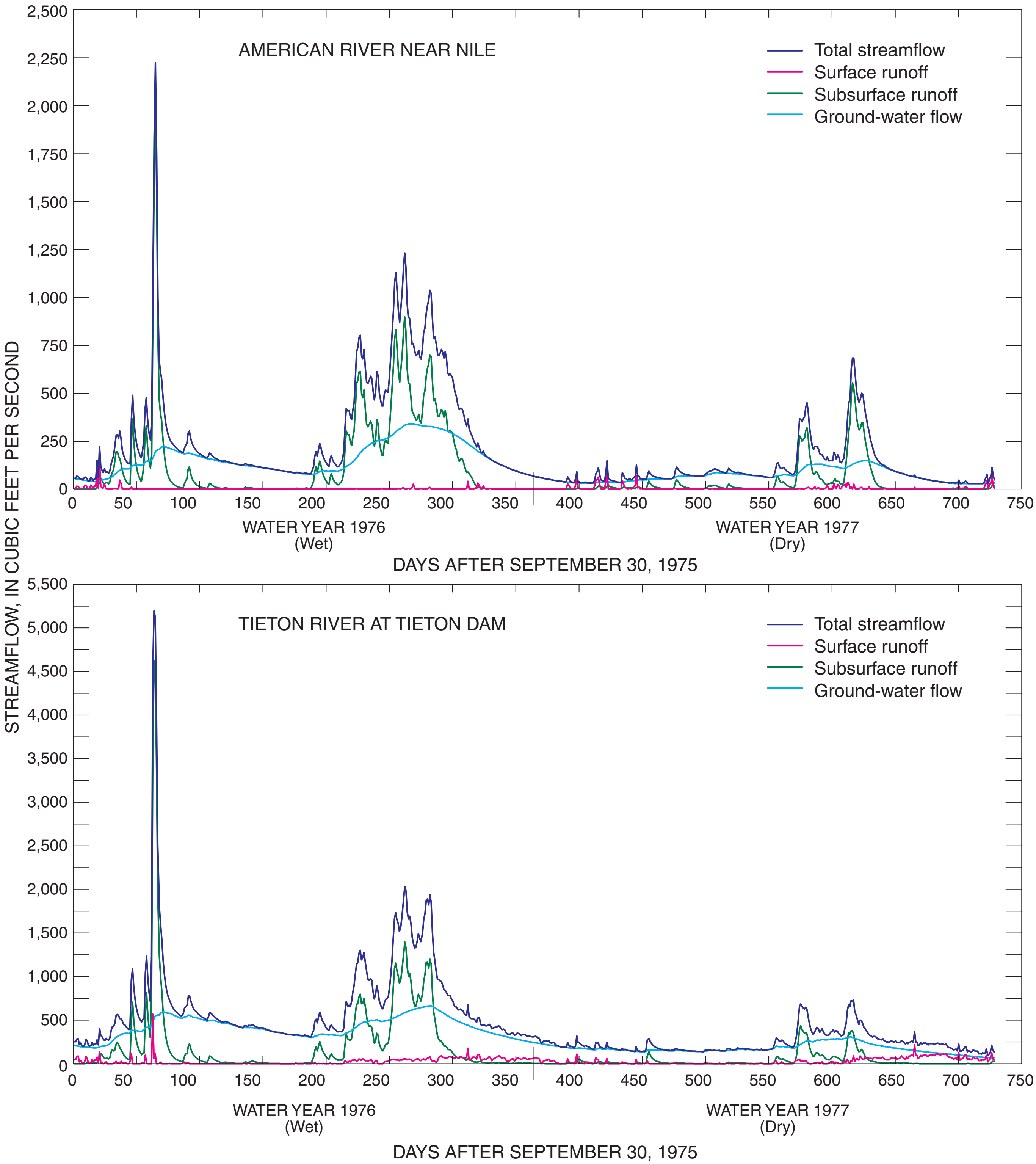

Figure 7. Partition of total streamflow by the watershed model into surface runoff, subsurface runoff, and ground-water flow for a wet and a dry year at the American River near Nile, and Tieton River below Tieton Dam in the Yakima River Basin, Washington.

Table 2. Calculated streamflow partition to total streamflow for water years 1976 and 1977 for the American River near Nile and the Tieton River at Tieton Dam, Naches River Basin, in the Yakima River Basin, Washington

[Water year 1976 is representative of a wet year and water year 1977 is representative of a dry year. Because of rounding, percent values may not total 100 percent]

Stream-gaging station name	Streamflow as a percentage of total			Total runoff (inches)
	Surface runoff	Subsurface runoff	Ground-water flow	
WATER YEAR 1976 (wet)				
American River near Nile	0.7	48.6	50.8	54.3
Tieton River at Tieton Dam	3.9	35.6	60.4	50.9
WATER YEAR 1977 (dry)				
American River near Nile	3.8	32.4	63.8	18.1
Tieton River at Tieton Dam	12.2	14.4	73.4	17.2

The comparison of mean monthly and annual observed/estimated and calculated streamflow are presented (table 3, at back of report) for 35 streamflow sites for the calibration period of water years 1950-94. The observed/estimated values in table 3 represent gaged values of natural flow, estimated unregulated values, and regression/ratio-derived values. The percent error of the calculated mean annual discharge from the observed annual discharge ranged from -7.4 percent to +177.1 percent, with two-thirds of the values within a range of -8 percent to +10 percent. The sites with the large percentage errors are all small watersheds with small absolute errors. For example, the Lost Creek subbasin, with a drainage area of 7 mi^2, had the largest percent error, +177.1 percent, but the difference between the calculated mean annual streamflow (12.5 ft^3/s) and the observed mean annual streamflow (4.5 $ft^{3/}$s) is only 8.0 ft^3/s or only 0.46 percent of the mean annual streamflow at the mouth of the Naches River Basin modeling unit at Naches River near Naches. As discussed above, the model calibration for these small creeks with regression/ratio-derived estimates of mean annual streamflow was based on capturing the general range in streamflow and not actual values, and the results for these creeks will be reassessed after several years of operating in a real-time mode.

The calibrated models were then operated for the testing period, water years 1995-98, with the same model parameters used during calibration. Calculated streamflow values were compared with the available observed values to check whether ranges of error for the testing period were similar to ranges of error for the calibration period. There were only 11 sites with observed discharge data available for the testing period (table 3). Comparisons of mean annual discharge with calculated mean annual discharges show a range of percent errors from -27.4 to +25.2 percent, with two-thirds of the values with a range of percent error from -7.2 to +9 percent.

Some of the bias and errors of the models can be seen in plots of the mean monthly streamflow data (fig. 8). Despite efforts during the calibration process to eliminate the bias, there are some problems associated with timing and volume of rain-on-snow peaks. Generally, these problems interact to yield higher calculated values than observed in October through December and, which would sometimes be balanced with smaller values than observed during May through June (for some sites, in July) because the water in the simulated snow pack was lost earlier in the October-December period to runoff. However, the timing of the snowmelt peak was reasonably simulated in the larger subbasins and for the downstream mainstem nodes.

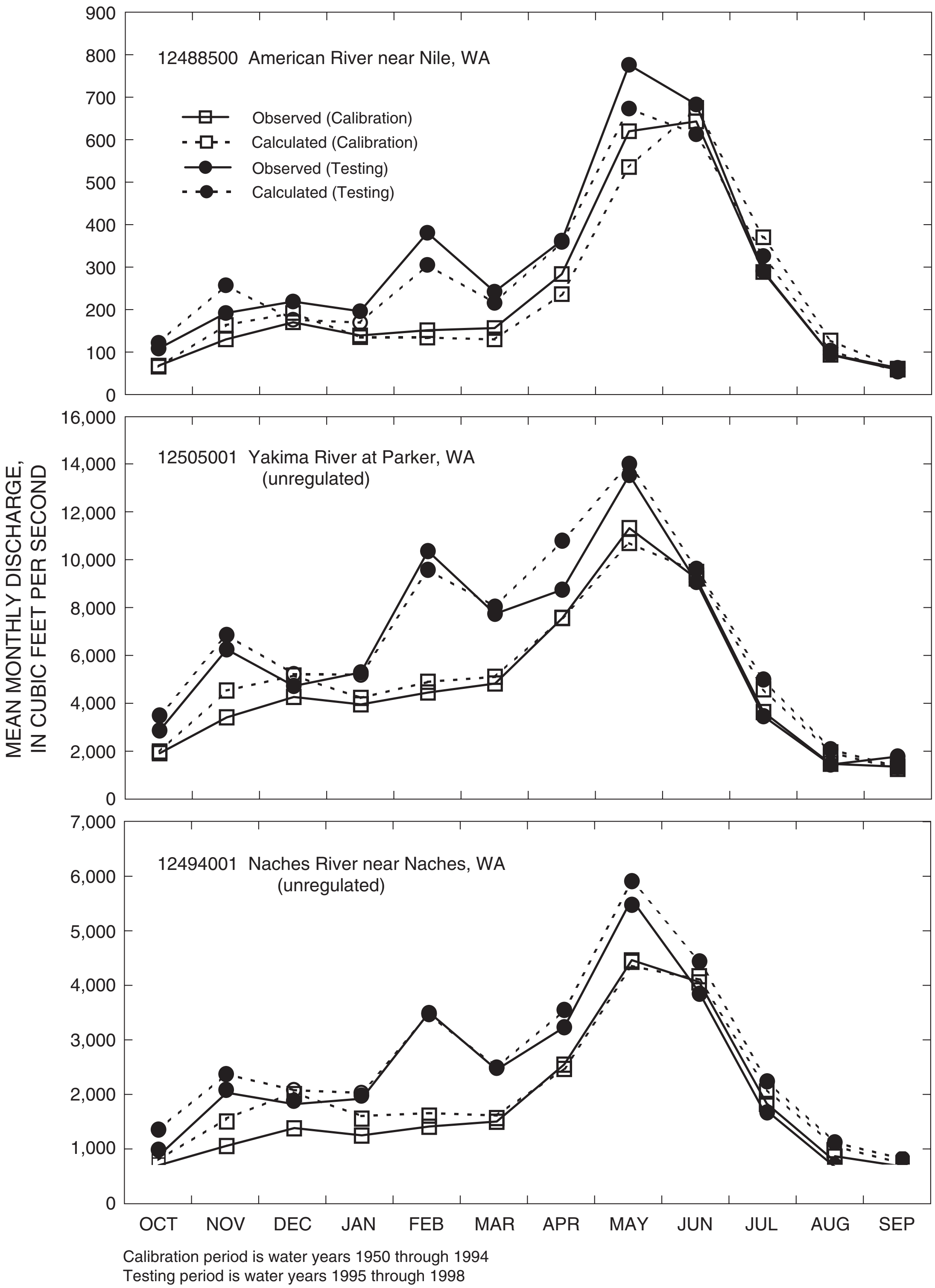

Figure 8. Observed and calculated mean monthly streamflow for the watershed-model calibration and testing periods for selected sites in the Yakima River Basin, Washington.

Observed and model-calculated values (water years 1956-65) for the Naches River Basin modeling unit are shown as a MMS screen image of run-time graphics (fig. 9) for the Tieton River at Tieton Dam (the largest subbasin in the Naches River Basin and represented as estimated unregulated values), the American River near Nile (the longest record of natural streamflow in the basin), and the South Fork Ahtanum Creek at Conrad Ranch (a drier part of the basin that is underlain by basalts). As can be seen, calculated values may be too large in one subbasin and too small in another probably because the true spatial variations in precipitation and temperature have not been captured. For this 1956-65 period, only one weather site (at Rimrock Dam) was operating in these three subbasins, therefore the match between observed and calculated values is reasonable considering that the daily spatial distribution of weather for this period is based on that weather site.

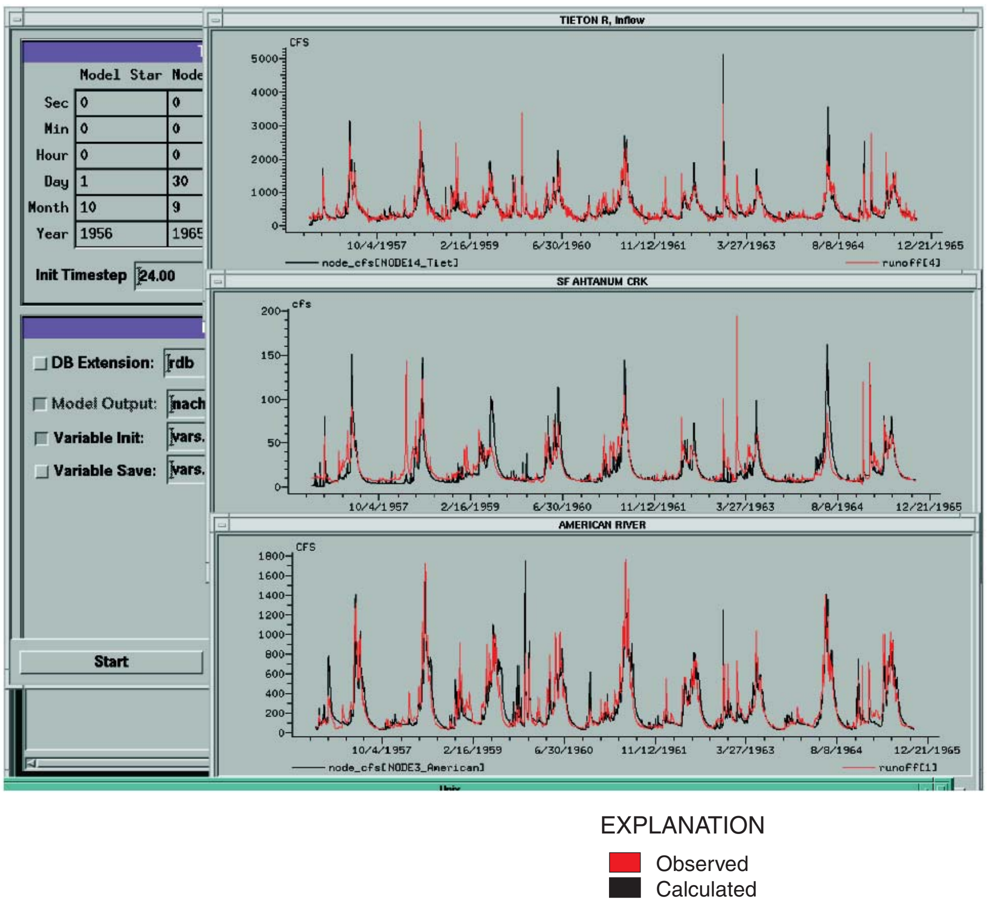

Figure 9. Hydrographs from the Naches River Basin modeling unit of observed and calculated daily streamflow for water years 1956-65 for Tieton River below Tieton Dam, the American River near Nile, and the South Fork Ahtanum Creek at Conrad Ranch in the Yakima River Basin, Washington.

The calculated daily values for all ungaged subbasins and the stream nodes, together with the observed/estimated daily values, for the 1950-98 period provide a long data series (49 years) that can be used for assessment of long-term reservoir management planning and policy decisions. These values will be stored in the HDB for statistical analysis and for input into RiverWare. The values thus provide the ability to do planning in a daily mode with streamflow values that are consistent with each other and represent a full spatial data series, which was not previously available. Having streamflow data at a daily time step is important because releases from the reservoirs for irrigation demands generally do not commence until the unregulated streams can no longer meet demand (this time is called the storage control date, which generally occurs in mid to late June). Thus, how the flows in these subbasins and at stream nodes have varied over time and how they may affect changes in reservoir operations can now be fully assessed in a consistent manner.

INTEGRATING THE MODELS IN THE DECISION SUPPORT SYSTEM FOR REAL-TIME OPERATIONS

The four MMS watershed models were incorporated into the DSS by linking them through an interface, termed the Object User Interface or OUI (Steven L. Markstrom, U.S. Geological Survey, written commun., 1999), which is a Java/XML™ software-language-based interface. The OUI can display spatial and time-series information, update data files, initiate model simulations, and pass data to the HDB.

Background

The Yakima River Basin OUI can update the data-input files for the four MMS models either through a direct connection to the HDB for the USBR's OUI residing on a computer in Yakima or through the Internet for remote users such as the USGS or other USBR locations. After the data files have been updated with the most current real-time daily values of air temperature, precipitation, and streamflow, the OUI can initiate a model run from the last modeled date to the current date using the variable values from the end of the last model run. For a complete run, the OUI runs each model and then routes the output from the nodes (subbasins and stream) of the four watershed models downstream to 13 OUI nodes. Similar to the four models, most of the nodes in OUI are USBR management points or other points of interest. The calculated values at any node (model or OUI) then can be displayed graphically and(or) passed to the HDB for analysis using RiverWare or statistical analysis. This same technique can also be used to operate the models for a particular historical period; for example, 1972-78.

In the operational mode, the data-input files from water year 1999 to present are based on real-time data in the HDB, some of which may be missing or in error (herein called missing). For example, the Naches model was calibrated using precipitation data from 12 weather sites, but on some days the current data-input file for this model has as many as 11 sites with missing precipitation data. Although the missing data are accounted for in the precipitation distribution module, the spatial distribution of precipitation may be in error for days with a large amount of missing data. Generally, even with the missing data, the model results are still reasonable. The results from using real-time data for water-years 1999 and 2000 in the Naches model for the American River and the Bumping River (equivalent to the inflow to the Bumping Lake reservoir) are shown in a screen image from MMS (fig. 10); the vertical red lines extending down to the x-axis in the graphs indicate seven streamflow values that are missing from the real-time observed data.

An Ensemble Streamflow Prediction (ESP) capability is provided in both the MMS and in the OUI. The ESP capability provides probabilistic information for planning of mid-term water-management operations (2 weeks to 8 months lead time). To initiate an ESP run, the user can define the start and end dates for the ESP run. The models are then operated for these dates using the historical climate time series, in this study the historical climate time period is 1950-2000 as of the year 2000, and initial conditions calculated from the model run that ends on the ESP start date. For example, on April 1 the data-input files can be updated through March 31; next, the models are run from the last model end date through March 31, and then the ESP ensemble can be completed for April 1 through September 30 (the actual start and end dates of the ESP run are user defined with defaults given).

Figure 10. Real-time observed and calculated daily streamflow values for the American and Bumping Rivers in the Yakima River Basin, Washington.

The resulting ensemble of 51 hydrographs of April 1-September 30 daily streamflow values for each model and OUI node (a total of 76 nodes) are stored for analysis; these 51 hydrographs (also called traces) represent probabilistic forecasts based on historical climate and calculated using the PRMS physical hydrology model. Because each node represents accumulated upstream streamflow that is forced by a climate regime that may vary by subbasin, the actual years for an exceedance-probability trace may vary by location. For example, if the climatic regime in 1956 produced the 10-percent exceedance probability for an upper headwater reservoir inflow, it may have produced a 20-percent exceedance value at the downstream Yakima River near Parker node because other headwater streams may have produced 30-percent exceedance values for 1956. Thus, if a system operator needs to analyze how the system might be operated for a 10-percent exceedance-probability value at a downstream location (node), the analysis may include exceedance-probability values for individual upstream reservoir locations that may differ from each other and they also may not be the 10-percent exceedance for any of the reservoir locations.

The ESP output can be selected in the OUI and the results for a particular node or site selected. For the selected site, the hydrographs (volume or peak) for the 51 years are ranked by exceedance probabilities, and any one or many of these hydrographs can be displayed. These traces can be analyzed and selected traces or a trace, such as the 50-percentile hydrograph, can be passed to the HDB for further analysis, which may be done statistically or with RiverWare.

Examples of Using the Object User Interface in Real-Time Operations

Examples of the various capabilities of the Yakima River Basin OUI in the real-time mode are shown through a series of OUI screen images. First, information can be displayed in the map or display part of the main OUI window. The outline of the basin and the location of the precipitation sites used to drive the Naches River Basin modeling unit are shown as an example (fig. 11). In this case, the precipitation sites have been activated, displayed, and opened for query. With this option, a site on the screen can be selected and the input data plotted. This option can be selected to examine the newest real-time data to determine its reasonableness.

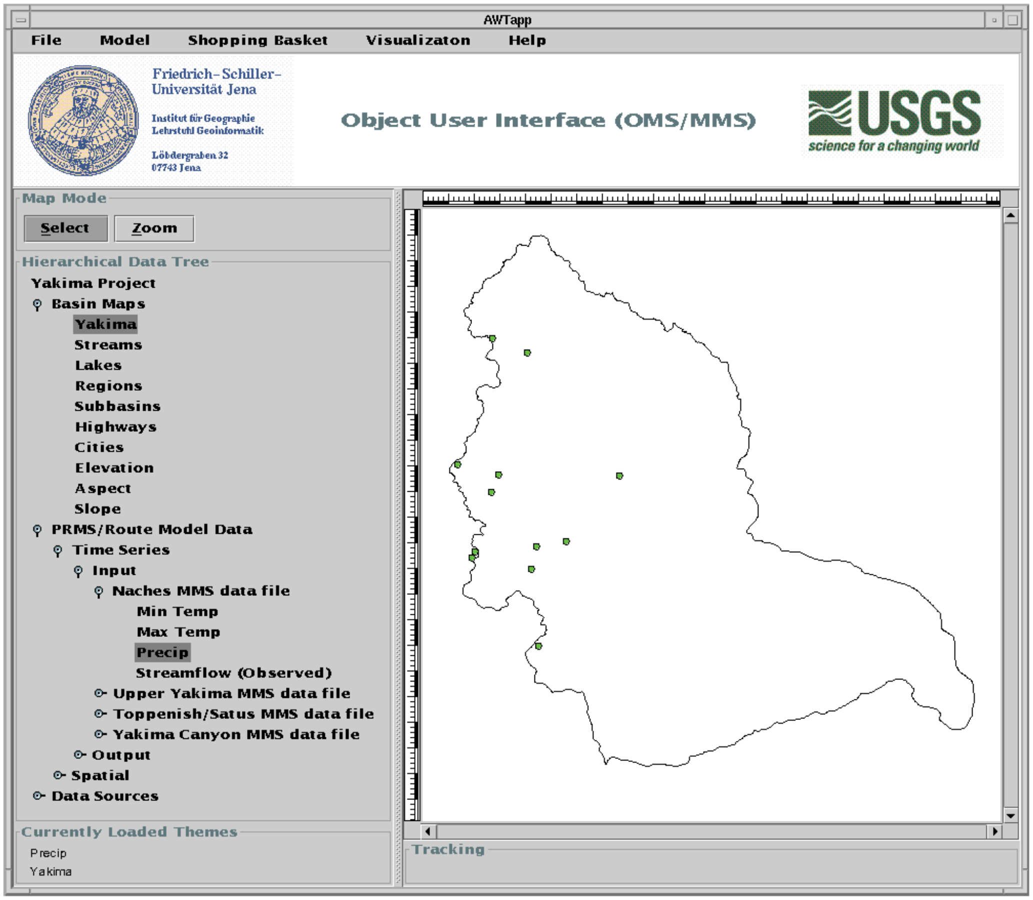

Figure 11. Input display of Yakima River Basin boundary and location of precipitation sites used for the Naches watershed model in the Yakima River Basin, Washington.

The ESP run item then can be selected from the Model drop-down menu. From the MMS PRMS/Routing ESP Run window the data input files for the four models can be updated by selecting the Input DMI tag (fig. 12). When this tag is selected, the window shows the start and end dates of the current data files and lists query start and end dates, in this case from 11/21/2000 to 11/28/2000; these dates can be modified by the user. Updating the input files by selecting the Update the MMS Data File button occurs through a password-protected connection to the HDB. After the files have been updated, the data can be examined as described above or the Run ESP tag selected. Selecting this tag opens the Run PRMS/Routing ESP Analysis window (fig. 13), which is also part of the main MMS PRMS/Routing ESP Run window. This window shows both the previous initialization and ESP forecast start and end dates, and displays editable lines for initializing and running an ESP simulation any dates within the range of the data input files can be selected. Selecting the Run ESP line starts the initialization of the models and the ESP runs. After the models have finished running, the Output DMI tag can be selected for passing data to the HDB or this window closed by selecting DONE.

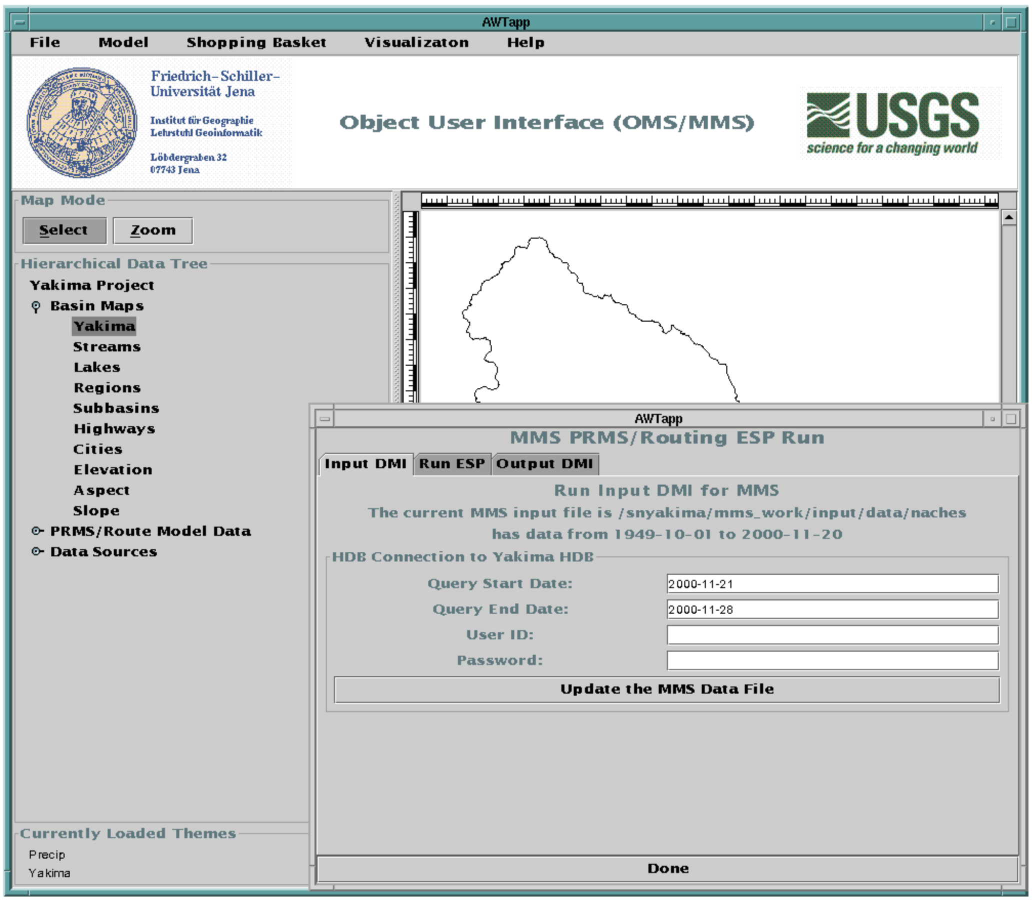

Figure 12. The Input DMI tag of the MMS PRMS/Routing ESP Run window for updating data-input files for the watershed models.

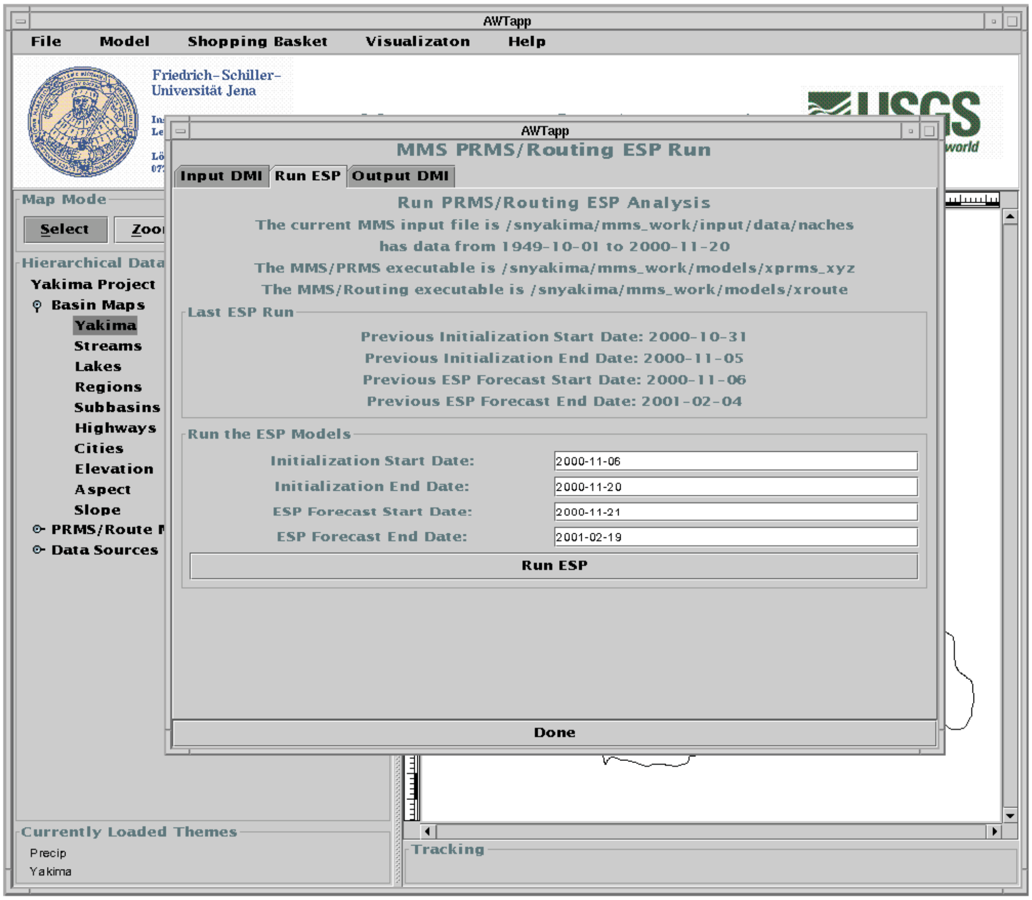

Figure 13. The RUN ESP tag of the MMS PRMS/Routing ESP Run window for initiating an Ensemble Streamflow Prediction simulation.

The ESP results are displayed by turning on, from the main OUI window, the PRMS/Route Model Data switch, followed by the Time Series switch, which is then followed by turning on the Output switch (fig. 14). The PRMS ESP Accumulated Discharge is selected and activated, and the nodes that have ESP output are displayed for querying in the display window (fig. 14). After a site is selected (querying), the Forecast Trace window opens and the exceedance probabilities associated with the 51 years are listed, sorted from lowest to highest (fig. 15). Selecting several exceedance probabilities, in this case the 44th through 56th, results in the display of the traces, and the explanation for the selected ESP traces is listed on the right hand side; the selected traces are also ordered from lowest (higher flows) to highest (lower flows) exceedance probabilities by year (fig. 15). These traces can be analyzed visually or can be written to the HDB for further analysis. The Forecast Trace window can then be closed or be set aside and another site selected and traces displayed. The information in this new window can then be compared visually with that in the previous Forecast Trace window. When finished, the DONE item is selected in the Forecast Trace window and then the quit item from the File menu is selected to close OUI.

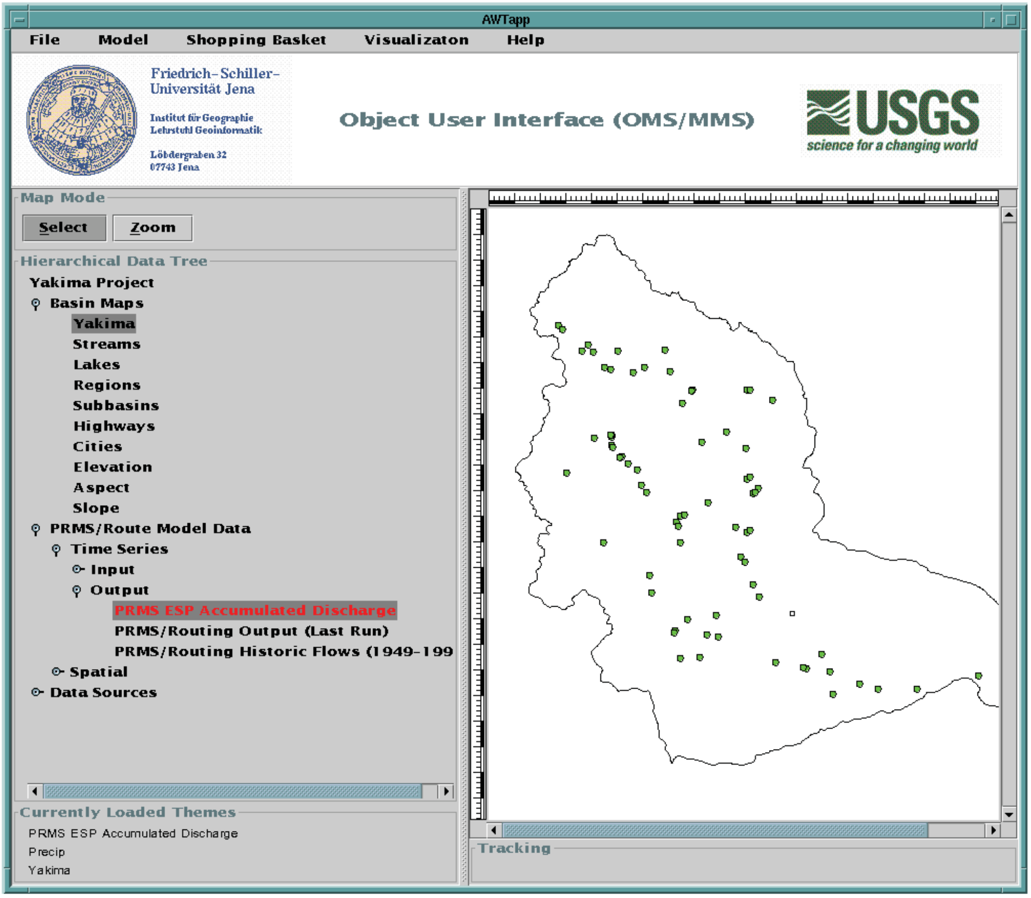

Figure 14. Display of Ensemble Streamflow Prediction output nodes after turning on selected switches and selecting type of output.

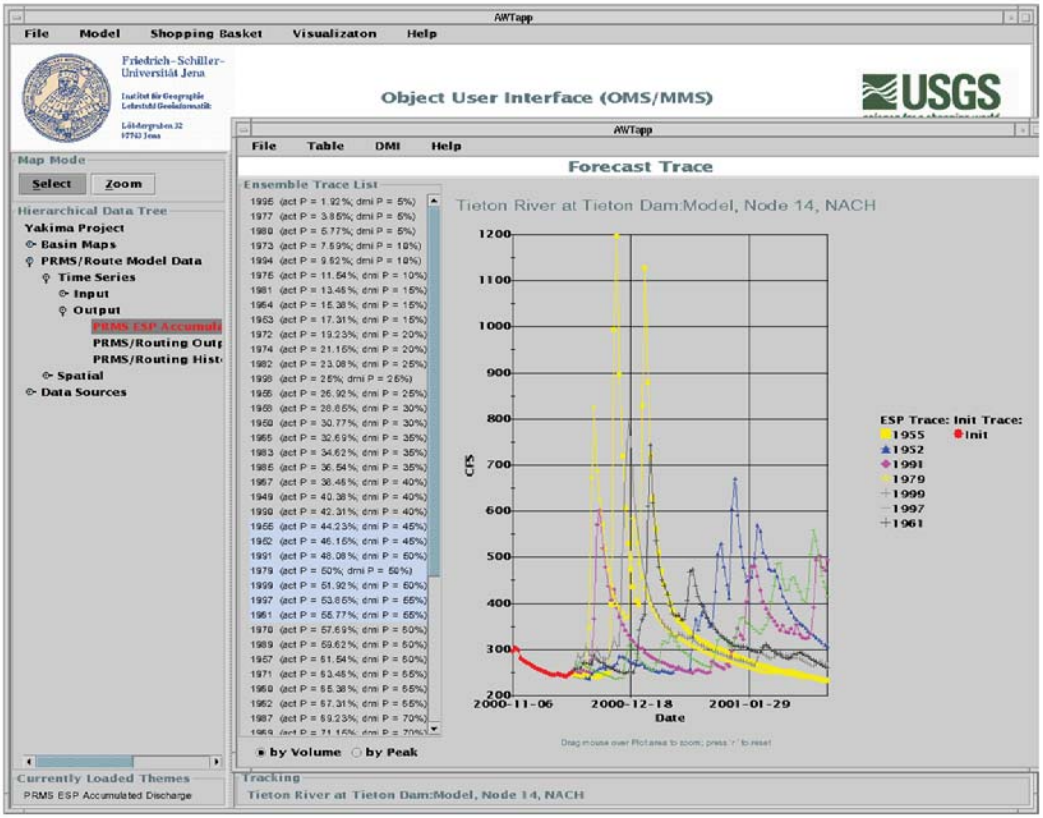

Figure 15. The Forecast Trace window and plot of hydrographs for the site (node) selected from the display of Ensemble Streamflow Prediction output nodes.

SUMMARY

The U.S. Geological Survey (USGS) and the Bureau of Reclamation (USBR) are working collaboratively on a long-term program, termed the Watershed and River Systems Management Program. The goals are to (1) couple watershed and river-reach models that simulate the physical hydrology with routing and reservoir management models that account for water availability and use, and (2) apply the coupled models to USBR projects in the western United States. The coupling provides a Decision Support System. The program has applied the Decision Support System to the USBR's Yakima Project in the Yakima River Basin that is located in eastern Washington; the Yakima River Basin has a drainage area of 6,200 mi^2 and produces a mean annual unregulated runoff (adjusted for regulation) of 5,600 ft^3/s and a regulated runoff of 3,600 ft^3/s.

As part of the application of the Decision Support System, four watershed models were constructed, calibrated, and tested; these models form the major physical hydrology component of the Yakima River Basin's Decision Support System. The models were constructed using the USGS Precipitation-Runoff Modeling System watershed model that is a part of the Modular Modeling System, and were integrated in the Decision Support System using the Object User Interface developed by the USGS. Model calibration and testing were completed using the Modular Modeling System.

The basin and 59 subbasins first were delineated using the GIS Weasel, an interface for the treatment of spatial information in modeling. Four areas containing 51 subbasins with a total area of 3,663 mi^2 were selected for constructing models. These modeled areas produce about 95 percent of the streamflow in the basin and are relatively unaffected by irrigation activities. The GIS Weasel was used to subdivide each subbasin and to provide initial estimates of most of the model parameters. Selected model parameters were adjusted during the calibration of the models for the 45-year period 1950-94. The models were calibrated to daily values of observed or estimated unregulated streamflow for 11 subbasins that produce more than 70 percent of the streamflow in the basin; not all of the 11 subbasins had daily values available for the complete period. The models also were calibrated to estimated natural or unregulated monthly, annual, or mean annual values for the other 41 subbasins and for selected sites along the mainstem of the river system. The estimated values were provided by the USBR or were developed as part of this study using regression equations and the ratios of regression-derived values to observed values. The four watershed models then were tested using data for 1995-98. The results from the calibration and testing showed that the models calculate reasonable values of streamflow. Since the 1999 water year, the models have been operated using real-time hydrometeorological data.

The models were integrated in the Decision Support System using the Object User Interface developed by the USGS. The Object User Interface can display information, update data files, initiate model simulations, and pass data to the Yakima Project's Hydrologic Database. The Object User Interface provides capabilities to display the input or output time-series data visually for analysis. The Modular Modeling System's Ensemble Streamflow Prediction capability also is provided in the Object User Interface. For any watershed model or Object User Interface-defined site or node, the Ensemble Streamflow Prediction output is ordered by exceedance probabilities, and selected years can be displayed as hydrographs, and in turn, daily values for selected exceedance-probability hydrographs can be passed to the Hydrologic Database.

The calculated daily values for all ungaged subbasins and the stream nodes, together with the observed estimated daily values, for the complete 1950-98 period provide a long (49 years) data series that can be used for assessment of long-term planning and policy decisions for water management. The values are stored in the Hydrologic Database for statistical analysis and for input into RiverWare. The values provide the ability to plan basin operations in a daily or monthly mode with streamflow values that are consistent with each other and represent a full spatial data series, which was not previously available. The integration of the models in the Decision Support System using the Object User Interface provides the framework for mid- to short-term operations and planning.

REFERENCES

Anderson, E.A., 1976, A point energy and mass balance model of snow cover: NOAA Technical Report NWS 19, Silver Springs, Md., U.S. Dept. of Commerce, 150 p.

Bauer, H.H., and Vaccaro, J.J., 1987, Documentation of a deep percolation model for estimating ground-water recharge: U.S. Geological Survey Open-File Report 86-536, 180 p.

——— 1990, Estimates of ground-water recharge to the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho, for predevelopment and current land-use conditions: U.S. Geological Survey Water-Resources Investigations Report 88-4108, 37 p., 2 pls.

Cassidy, K.M., 1997, Washington State land cover manual: Metadata and data dictionary. *in* Cassidy, K.M., Grue, C.E., Smith, M.R., and Dvornich, K.M., eds., Washington State Gap Analysis Final Report, Supplement A: Washington Cooperative Fish and Wildlife Research Unit, Seattle, University of Washington, 94 p.

Daly, Chris, Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological precipitation over mountainous terrain: Journal of Applied Meteorology, v. 33, p. 140-158.

Daly, C. and Taylor, G.H., 1998, 1961-90 mean annual and monthly precipitation maps for the conterminous United States, Oregon Climate Center, at URL http://www.ocs.orst.edu/pub/maps/Precipitation/prism_ppt.README)

Fuhrer, G.J., Cain, D.J., McKenzie, S.W., Rinella, J.G., Crawford, J.K., Skach, K.A., and Hornberger, M. I., 1998, Surface-water-quality assessment of the Yakima River Basin in Washington—Spatial and temporal distribution of trace elements in water, sediment, and aquatic biota, 1987-91: U.S. Geological Survey Water-Supply Paper 2354-A, 186 p.

Fulp, T.J., Vickers, W.B., Williams, B., and King, D.L., 1995, Decision support for water resources management in the Colorado River region: *in* Ahuja, L., Leppert, J., Rojas, K., and Seely, E.(eds.), Workshop on computer applications in water management: Fort Collins, CO., Colorado Water Resources Research Institute, Information Series No. 79, p. 24-27.

Gladwell, J.S., 1970, Runoff generation in western Washington as a function of precipitation and watershed characteristics: Washington State University, Bulletin 319, College of Engineering, Research Division, R.L. Albrook Hydraulic Lab, 341 p.

Hansen, A.J., Vaccaro, J.J., and Bauer, H.H., 1994, Ground-water flow simulation of the Columbia Plateau regional aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4178, 101 p., 15 sheets.

Hydrosphere Data Products, 1993, Climate data, TD 3200 Summary of the Day Cooperative Observer Network, User Manual: Boulder, CO., Hydrosphere Data Products, 113 p.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system—users manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p.

Leavesley, G.H., Restrepo, P.J., Markstrom, S.L., Dixon, M., and Stannard, L.G., 1996, The modular modeling system (MMS)—user's manual: U.S. Geological Survey Open-File Report 96-151, 142 p.

Leavesley, G.H., Viger, R.J., Markstrom, S.L., and Brewer, M.S., 1997, A modular approach to integrating environmental modeling and GIS: *in* Proceedings of 15th IMACS World Congress on Scientific Computation, Modelling, and Applied Mathematics: Berlin, Germany.

Linsley, R.K, Kohler, M.A., and Paulhus, J.L., 1982, Hydrology for Engineers, 3rd ed.: New York, New York, McGraw-Hill Book Company, 578 p.

Loveland, T.R., Merchant, J., Ohlen, D.O., and Brown, J., 1991, Development of a land cover characteristic data base for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 57, no. 11, p. 1453-1463.

Mastin, M.C., and Vaccaro J.J., 2002, Documentation of precipitation runoff modeling system modules for the modular modeling system modified for the watershed and river systems management program: U.S. Geological Survey Open-File Report 02-362, on-line on the World Wide Web, accessed December 9, 2002, at URL <http://water.usgs.gov/pubs/of/ofr02362/>.

National Oceanic and Atmospheric Administration, 2002, National Weather Service, National Operational Hydrologic Remote Sensing Center, on-line on the World Wide Web, accessed July 1, 2002, at URL <http://www.nohrsc.nws.gov/>.

Nelson, L.M., 1991, Surface-water resources for the Columbia Plateau, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Resources Investigations Report 88-4105, 4 sheets.

Parker, G.L., and Storey, F.B., 1916, Water power of the Cascade Range, Part III—Yakima River Basin: U.S. Geological Survey Water-Supply Paper 369, 169 p., 20 pls.

Powell, D.S., Faulkner, J.L., Darr, David, Zhu, Zhiliang, and MacCleery, D.W., 1998, Forest resources of the United States, 1992. Gen. Tech. Report. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 132 p.

Risley, J.C., 1994, Use of a precipitation-runoff model for simulating effects of forest management on streamflow in 11 small drainage basins, Oregon Coast Range: U.S. Geological Survey Water-Resources Investigations Report 93-4181, 61 p.

Ryan, Thomas, 1996, Global climate change response program: Development and application of a physically based distributed parameter rainfall runoff model in the Gunnison river basin: United States Department of Interior, Bureau of Reclamation, 64 p.

U. S. Department of Agriculture, 1994, State Soil Geographic (STATSGO) Data Base: Data Use information, Soil Conservation Service, National Cartography and GIS Center, Fort Worth, Texas. (obtained from Earth System Science Center, The Pennsylvania State University, at URL http://dbwww.essc.psu.edu/dbtop/amer_n/us_nw/wa/data/soilprop/statsgo/doc.html)

U.S. Department of Agriculture, 1998, Natural Resources Conservation Center, Historical SNOTEL and snow course data, at URL http://www.wa.nrcs.usda.gov/snow/data_reports.htm)

U. S. Geological Survey, 1992, 1990 Conterminous U.S. Land Cover Characteristics Data Set CD-ROM, EROS Data Center, National Mapping Division, Sioux Falls, South Dakota.

U.S. Geological Survey, 1998, Watershed and River Systems Management Program: Application to the Yakima River Basin, Washington: U.S. Geological Survey Fact Sheet 037-98.

Vaccaro, J.J., 2000, Summary of the Columbia Plateau regional aquifer-system analysis, Washington, Oregon, and Idaho: U.S. Geological Survey Professional Paper 1413-A, 51 p.

Zhu, Zhiliang, and Evans, L. D., 1992, Mapping midsouth forest distributions: Journal of Forestry, v. 90, no. 12, p. 27-30.

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington

[**Stream-gaging station**: Numbers ending in “1” indicate stations with unregulated or regression-derived (estimated values at ungaged sites) streamflow values representing observed values. **Calibration**: Water years 1950-94. **Testing**: Water years 1995-98; testing period results are provided only at sites where observed streamflows were available. **Observed/Estimated**: Observed unregulated streamflow at a gaging site or observed regulated streamflow with corrections for regulation. **Percent error** = [(*C* − *O*)/*O*] × 100, where *C* is calculated runoff and *O* is observed/estimated runoff; percent error calculated before streamflows were rounded. **(P)**: Part of the observed record was estimated by regression. Streamflow values are in cubic feet per second]

American River near Nile, Stream-gaging station No. 12488500

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	68.2	129.9	170.1	139.3	151.4	156.5	283.7
Calculated 45-year average streamflow	63.7	162.1	190.6	133.7	133.0	129.0	232.1
Percent error	-6.7	24.8	12.1	-4.1	-12.1	-17.6	-18.2

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	619.9	643.1	288.4	93.7	58.6	233.6
Calculated 45-year average streamflow	533.0	668.0	364.6	124.4	60.3	233.1
Percent error	-14.0	3.9	26.4	32.8	3.0	-0.2

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	108.4	192.0	219.2	196.2	380.8	242.2	362.6
Calculated 4-year average streamflow	121.3	257.0	176.1	169.6	305.2	210.4	354.9
Percent error	11.9	33.8	-19.7	-13.6	-19.9	-13.1	-2.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	776.0	682.8	290.8	94.1	63.0	300.0
Calculated 4-year average streamflow	670.9	607.8	319.4	101.4	53.1	278.5
Percent error	-13.6	-11.0	9.8	7.7	-15.7	-7.2

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Big Creek, Stream-gaging station No. 12474001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	33.1	67.8	114.8	102.5	109.4	105.6	155.3
Calculated 45-year average streamflow	32.8	104.1	112.9	85.2	93.2	96.9	156.1
Percent error	-1.1	53.7	-1.7	-16.8	-14.8	-8.2	0.5

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	193.4	99.2	26.6	13.9	14.9	86.4
Calculated 45-year average streamflow	170.4	113.4	40.4	20.6	14.1	86.5
Percent error	-11.9	14.4	52.2	47.5	-5.2	0.2

Bumping River near Nile, unregulated, Stream-gaging station No. 12488001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	103.0	220.6	262.3	211.9	208.4	184.2	303.1
Calculated 45-year average streamflow	116.3	260.3	249.6	144.5	139.2	154.2	292.7
Percent error	12.9	18.0	-4.8	-31.8	-33.2	-16.3	-3.4

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	700.1	762.9	343.6	107.5	74.8	290.2
Calculated 45-year average streamflow	750.0	778.2	348.5	99.9	72.9	284.2
Percent error	7.1	2.0	1.4	-7.1	-2.5	-2.1

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	181.2	402.2	304.5	295.2	504.2	299.0	374.0
Calculated 4-year average streamflow	233.1	373.1	202.2	199.6	348.0	232.9	424.9
Percent error	28.6	-7.2	-33.6	-32.4	-31.0	-22.1	13.6

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	823.2	723.0	286.8	98.2	90.2	365.0
Calculated 4-year average streamflow	920.8	802.9	368.8	100.7	89.3	357.6
Percent error	11.8	11.0	28.6	2.4	-1.0	-2.0

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Cabin Creek, Stream-gaging station No. 12475001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	46.6	116.7	195.5	174.6	167.6	139.0	216.9
Calculated 45-year average streamflow	65.7	161.7	162.6	126.7	134.7	142.2	239.2
Percent error	40.9	38.6	-16.8	-27.5	-19.6	2.3	10.3

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	292.1	146.8	42.2	16.1	19.8	130.8
Calculated 45-year average streamflow	262.3	169.7	60.5	30.1	23.6	131.4
Percent error	-10.2	15.6	43.2	87.0	18.7	0.4

Cle Elum River near Roslyn, unregulated, Stream-gaging station No. 12479001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	379.3	761.4	762.9	616.6	601.0	606.7	1,204.5
Calculated 45-year average streamflow	488.2	1,065.8	928.6	686.9	824.9	853.9	1,280.1
Percent error	28.7	40.0	21.7	11.4	37.3	40.7	6.3

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	2,372.0	2,284.1	1,082.6	391.0	245.1	942.4
Calculated 45-year average streamflow	1,884.5	2,044.6	1,078.4	350.9	219.4	974.7
Percent error	-20.6	-10.5	-0.4	-10.3	-10.5	3.4

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	653.8	1,409.2	709.2	677.0	1,222.5	949.8	1,395.2
Calculated 4-year average streamflow	947.7	1,328.1	603.5	669.9	1,308.8	1,229.7	1,746.9
Percent error	45.0	-5.8	-14.9	-1.1	7.1	29.5	25.2

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	2,704.2	2,136.5	1,042.0	359.5	203.5	1,121.8
Calculated 4-year average streamflow	2,421.1	2,342.6	1,446.3	424.4	234.2	1,222.6
Percent error	-10.5	9.6	38.8	18.0	15.1	9.0

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Devil Creek near mouth, Stream-gaging station No. 12488801

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	1.2	2.3	3.0	2.4	2.6	2.6	4.8
Calculated 45-year average streamflow	1.3	7.6	14.4	11.7	11.9	10.7	17.7
Percent error	10.7	226.0	382.8	376.6	354.7	304.7	268.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	10.4	10.9	4.9	1.6	1.1	4.0
Calculated 45-year average streamflow	20.9	9.3	3.8	1.6	0.8	9.3
Percent error	100.5	-14.5	-22.7	5.7	-29.6	131.2

Gold Creek at/near mouth, Stream-gaging station No. 12488911

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	2.2	4.1	5.3	4.3	4.7	4.8	8.5
Calculated 45-year average streamflow	1.8	8.9	15.7	13.6	14.1	12.8	24.0
Percent error	-18.5	117.0	197.3	214.8	199.6	167.4	182.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	18.7	19.5	8.9	2.8	1.7	7.1
Calculated 45-year average streamflow	24.7	9.4	4.3	2.0	1.1	11.0
Percent error	31.9	-52.1	-51.6	-27.2	-36.1	54.6

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Kachess River near Easton, unregulated, Stream-gaging station No. 12476001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	130.2	309.3	338.6	288.9	274.3	255.2	442.8
Calculated 45-year average streamflow	170.3	367.9	306.1	237.8	284.4	317.9	485.6
Percent error	30.8	18.9	-9.6	-17.7	3.7	24.5	9.7

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	687.4	551.3	205.5	56.4	55.3	299.6
Calculated 45-year average streamflow	563.8	495.3	248.3	94.5	60.3	302.3
Percent error	-18.0	-10.2	20.8	68.4	9.1	0.9

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	264.2	536.0	302.5	328.2	486.2	369.0	514.2
Calculated 4-year average streamflow	365.9	531.9	249.2	300.2	566.0	510.4	607.3
Percent error	38.5	-0.8	-17.6	-8.6	16.4	38.3	18.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	796.2	468.0	189.8	64.0	87.0	367.0
Calculated 4-year average streamflow	582.4	381.2	172.4	63.5	35.3	362.1
Percent error	-26.9	-18.6	-9.1	-0.9	-59.4	-1.3

Little Creek, Stream-gaging station No. 12477601

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	11.2	26.4	44.5	39.8	38.7	32.6	51.9
Calculated 45-year average streamflow	13.4	40.6	43.8	36.4	39.2	39.6	55.7
Percent error	19.8	54.3	-1.6	-8.7	1.4	21.2	7.4

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	67.9	33.7	9.8	3.8	4.8	30.4
Calculated 45-year average streamflow	58.8	40.8	16.1	7.8	5.3	33.0
Percent error	-13.4	21.0	64.9	106.1	9.2	8.6

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Little Naches River near Cliffdell, Stream-gaging station No. 12487200

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow (P)	67.8	130.8	180.2	157.8	183.5	199.9	386.1
Calculated 45-year average streamflow	87.3	240.4	314.8	233.4	228.3	203.9	424.7
Percent error	28.7	83.8	74.7	47.9	24.4	2.0	10.0

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow (P)	696.8	607.3	247.2	81.8	56.2	249.3
Calculated 45-year average streamflow	849.6	551.3	183.7	61.2	34.3	284.5
Percent error	21.9	-9.2	-25.7	-25.1	-38.9	14.1

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	84.8	189.5	230.8	316.5	410.8	401.2	571.5
Calculated 4-year average streamflow	214.6	434.7	297.2	283.2	554.8	335.6	585.8
Percent error	153.2	129.4	28.8	-10.5	35.1	-16.4	2.5

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	630.8	508.2	141.5	61.2	43.5	299.2
Calculated 4-year average streamflow	1,010.7	533.6	177.2	49.0	34.9	374.6
Percent error	60.2	5.0	25.2	-20.0	-19.9	25.2

Lost Creek, Stream-gaging station No. 12488921

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	1.3	2.5	3.5	2.8	3.0	3.1	5.4
Calculated 45-year average streamflow	2.0	9.8	19.0	16.0	16.2	14.0	24.1
Percent error	48.6	287.9	449.4	477.2	448.3	359.1	346.4

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	11.9	12.4	5.5	1.8	1.1	4.5
Calculated 45-year average streamflow	29.9	12.3	4.5	1.8	0.8	12.5
Percent error	151.4	-0.2	-18.4	-1.0	-27.6	177.1

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Manastash Creek, Stream-gaging station No. 12483501

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	14.4	31.2	40.5	38.6	42.4	52.6	99.9
Calculated 45-year average streamflow	13.0	14.6	27.9	29.0	43.4	69.6	112.4
Percent error	-9.7	-53.3	-31.2	-25.1	2.4	32.4	12.5

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	154.0	101.5	32.7	12.9	9.9	52.6
Calculated 45-year average streamflow	145.1	88.9	48.8	30.5	19.5	53.6
Percent error	-5.8	-12.4	49.2	136.6	97.5	2.0

Milk Creek, Stream-gaging station No. 12488701

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	3.4	6.4	8.3	6.8	7.3	7.4	13.4
Calculated 45-year average streamflow	3.0	16.5	30.3	24.4	25.2	22.7	37.7
Percent error	-10.2	157.4	263.6	259.1	243.1	207.4	182.3

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	29.3	30.6	13.7	4.4	2.9	11.1
Calculated 45-year average streamflow	46.5	20.3	8.6	3.9	1.9	20.1
Percent error	58.6	-33.8	-37.1	-11.2	-33.8	80.2

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Naches River near Naches, Stream-gaging station No. 12494001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	560.2	996.4	1,321.1	1,186.2	1,348.5	1,439.8	2,487.2
Calculated 45-year average streamflow	641.1	1,431.5	1,933.2	1,486.9	1,542.1	1,498.3	2,384.5
Percent error	14.4	43.7	46.3	25.3	14.4	4.1	-4.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	4,400.4	3,995.9	1,767.6	721.2	532.4	1,729.5
Calculated 45-year average streamflow	4,350.2	4,071.7	1,969.7	907.0	579.6	1,899.9
Percent error	-1.1	1.9	11.4	25.8	8.9	9.9

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	849.0	1,996.0	1,786.5	1,886.5	3,467.2	2,416.8	3,195.2
Calculated 4-year average streamflow	1,232.1	2,294.2	1,990.8	1,938.0	3,445.3	2,400.9	3,507.6
Percent error	45.1	14.9	11.4	2.7	-0.6	-0.7	9.8

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	5,541.0	3,835.5	1,563.8	543.8	505.2	2,298.8
Calculated 4-year average streamflow	5,974.4	4,424.0	2,131.4	978.2	670.1	2,575.8
Percent error	7.8	15.3	36.3	79.9	32.6	12.1

Naneum Creek near Ellensburg, Stream-gaging station No. 12483800

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow (P)	16.9	22.0	25.8	25.3	34.5	46.5	87.5
Calculated 45-year average streamflow	23.6	23.3	32.9	29.3	33.3	42.5	80.9
Percent error	39.5	5.8	27.5	15.8	-3.3	-8.5	-7.6

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow (P)	182.7	129.9	45.6	23.4	16.7	54.8
Calculated 45-year average streamflow	141.0	101.2	61.0	42.9	31.8	53.7
Percent error	-22.8	-22.1	33.8	83.0	90.1	-1.9

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

North Fork Ahtanum Creek near Tampico, Stream-gaging station No. 12500500

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow (P)	19.7	26.2	36.5	38.2	53.0	69.7	125.2
Calculated 45-year average streamflow	16.1	17.8	41.3	48.3	57.5	63.1	119.5
Percent error	-18.0	-32.1	13.1	26.4	8.5	-9.6	-4.5

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow (P)	200.1	170.2	61.0	26.9	20.2	70.6
Calculated 45-year average streamflow	202.4	160.9	50.8	27.8	20.6	68.8
Percent error	1.1	-5.4	-16.8	3.1	1.6	-2.5

North Fork Cowichee Creek, Stream-gaging station No. 12494051

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	2.6	3.2	4.4	5.4	7.5	9.8	13.5
Calculated 45-year average streamflow	2.8	6.5	18.0	19.0	22.0	22.8	27.5
Percent error	7.2	105.5	304.2	252.0	194.2	131.7	103.2

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	17.5	16.2	6.3	3.5	2.8	7.7
Calculated 45-year average streamflow	13.6	9.3	6.5	4.5	3.2	12.9
Percent error	-22.3	-42.3	3.3	29.5	15.4	67.3

Nile Creek near mouth, Stream-gaging station No. 12489071

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	8.2	16.9	23.0	19.6	22.6	26.1	50.2
Calculated 45-year average streamflow	5.7	26.3	58.2	48.9	49.9	44.8	58.7
Percent error	-31.4	56.1	153.1	149.9	121.2	71.7	16.9

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	87.1	77.8	33.1	10.7	7.1	31.9
Calculated 45-year average streamflow	91.8	83.4	36.1	15.2	7.3	43.8
Percent error	5.4	7.2	9.1	42.4	3.7	37.5

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Oak Creek at mouth, Stream-gaging station No. 12492901

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	5.6	11.8	15.2	12.5	13.7	14.4	25.5
Calculated 45-year average streamflow	3.0	19.1	52.1	47.5	50.6	49.0	60.1
Percent error	-46.5	61.8	242.3	280.8	269.9	241.2	136.2

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	54.0	53.1	23.9	7.5	4.8	20.2
Calculated 45-year average streamflow	68.7	35.7	14.9	6.8	3.3	34.2
Percent error	27.2	-32.9	-37.4	-8.2	-30.9	69.5

Rattlesnake Creek, Stream-gaging station No. 12489201

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	49.4	123.8	177.0	156.8	210.5	272.1	503.7
Calculated 45-year average streamflow	70.7	174.7	217.6	164.6	185.3	185.9	317.0
Percent error	43.0	41.1	23.0	4.9	-12.0	-31.7	-37.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	718.7	397.7	122.7	74.5	57.8	238.7
Calculated 45-year average streamflow	532.2	407.2	198.7	120.5	78.6	221.1
Percent error	-25.9	2.4	61.9	61.7	35.9	-7.4

Rock Creek at mouth, Stream-gaging station No. 12489061

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	4.1	7.8	10.1	8.3	9.2	9.8	17.5
Calculated 45-year average streamflow	3.1	17.3	36.3	28.1	27.8	28.0	41.8
Percent error	-24.6	120.9	260.3	237.2	200.4	184.6	139.3

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	36.9	36.2	16.2	5.5	3.5	13.8
Calculated 45-year average streamflow	52.8	21.3	9.9	4.8	2.6	22.8
Percent error	43.2	-41.2	-39.0	-13.2	-26.4	65.6

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

South Fork Ahtanum Creek at Conrad Ranch near Tampico, Stream-gaging station No. 12400000

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow (P)	6.9	8.5	11.9	14.4	19.9	26.2	36.1
Calculated 45-year average streamflow	7.3	7.4	12.8	13.3	15.7	17.6	29.7
Percent error	6.0	-12.2	8.3	-7.6	-21.2	-32.9	-17.7

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow (P)	46.5	43.2	16.7	9.3	7.5	20.6
Calculated 45-year average streamflow	49.3	46.5	17.1	9.5	7.8	19.5
Percent error	5.9	7.9	2.0	1.8	3.7	-5.3

South Fork Cowichee Creek,Stream-gaging station No. 12494061

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	11.3	13.8	19.3	23.4	32.5	42.8	58.9
Calculated 45-year average streamflow	10.6	18.0	59.5	61.1	70.4	77.0	94.9
Percent error	-6.4	30.4	207.5	160.9	116.7	79.9	61.3

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	75.9	70.3	27.3	15.2	12.2	33.6
Calculated 45-year average streamflow	83.4	54.5	32.3	21.2	14.2	49.6
Percent error	10.0	-22.6	18.4	39.1	16.5	47.9

Swamp Creek near mouth, Stream-gaging station No. 12488901

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	0.9	1.6	2.2	1.8	2.0	2.0	3.6
Calculated 45-year average streamflow	0.8	5.1	10.4	7.9	7.9	7.5	9.7
Percent error	-13.3	212.6	368.6	330.8	297.5	273.9	164.9

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	8.0	8.3	3.7	1.3	0.9	3.1
Calculated 45-year average streamflow	13.6	7.4	3.0	1.4	0.7	6.3
Percent error	68.7	-11.4	-18.5	4.6	-27.3	104.6

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Swauk Creek near Cle Elum, Stream-gaging station No. 12481001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	23.6	51.0	66.1	63.0	69.2	85.8	163.0
Calculated 45-year average streamflow	13.3	23.7	50.7	58.7	87.3	123.8	209.8
Percent error	-43.7	-53.6	-23.3	-7.0	26.1	44.2	28.7

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	252.0	166.2	53.6	21.2	16.2	85.9
Calculated 45-year average streamflow	229.1	120.2	62.0	33.2	19.1	85.8
Percent error	-9.1	-27.7	15.8	56.8	18.4	-0.1

Taneum Creek near Thorp, Stream-gaging station No. 12400001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	20.5	51.2	67.7	64.8	70.2	87.3	166.4
Calculated 45-year average streamflow	16.9	37.4	59.2	53.6	65.2	83.9	150.8
Percent error	-17.7	-26.9	-12.5	-17.4	-7.1	-3.9	-9.4

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	246.4	159.2	50.2	17.4	13.1	84.5
Calculated 45-year average streamflow	226.3	172.8	85.0	44.8	24.5	85.1
Percent error	-8.1	8.6	69.4	157.2	87.4	0.6

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Teanaway River below Forks, Stream-gaging station No. 12480000

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	54.5	192.7	301.4	300.2	313.0	411.9	809.1
Calculated 45-year average streamflow	91.8	331.2	333.1	213.7	294.9	407.9	765.8
Percent error	68.5	71.9	10.5	-28.8	-5.8	-1.0	-5.4

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	955.4	518.5	129.8	32.2	24.2	337.5
Calculated 45-year average streamflow	974.2	607.3	161.2	42.4	31.6	354.1
Percent error	2.0	17.1	24.2	31.6	30.8	4.9

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	87.5	378.5	289.2	463.5	907.8	700.0	992.0
Calculated 4-year average streamflow	170.7	607.4	247.9	173.8	475.0	651.3	1,301.1
Percent error	95.1	60.5	-14.3	-62.5	-47.7	-7.0	31.2

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	1,107.8	416.2	95.0	30.2	22.8	457.5
Calculated 4-year average streamflow	1,376.7	499.5	180.1	45.8	33.0	478.7
Percent error	24.3	20.0	89.6	51.2	45.2	4.6

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Tieton River at Tieton Dam, unregulated, Stream-gaging station No. 12491501

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	243.0	347.6	434.9	385.6	402.9	386.3	580.8
Calculated 45-year average streamflow	240.3	374.2	454.4	337.7	334.8	319.5	500.9
Percent error	-1.1	7.6	4.5	-12.4	-16.9	-17.3	-13.8

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	1,036.3	1,118.2	646.4	343.0	266.2	516.1
Calculated 45-year average streamflow	990.6	1,199.2	628.0	372.6	258.2	501.2
Percent error	-4.4	7.3	-2.8	8.6	-3.0	-2.9

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	362.5	638.0	547.5	551.8	925.8	568.2	692.0
Calculated 4-year average streamflow	398.1	535.7	467.1	435.4	706.0	536.4	827.3
Percent error	9.8	-16.0	-14.7	-21.1	-23.7	-5.6	19.5

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	1,288.8	1,143.2	706.2	353.8	303.0	673.5
Calculated 4-year average streamflow	1,592.7	1,443.4	748.8	434.4	307.9	702.3
Percent error	23.6	26.3	6.0	22.8	1.6	4.3

Toppenish Creek near Fort Simcoe, Stream-gaging station No. 12506000

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	24.4	42.2	71.3	106.9	140.7	159.9	222.9
Calculated 45-year average streamflow	20.5	27.2	78.2	109.1	151.2	185.8	225.2
Percent error	-16.1	-35.6	9.7	2.1	7.5	16.2	1.1

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	171.3	61.2	27.8	20.1	19.8	88.6
Calculated 45-year average streamflow	166.8	72.7	40.2	29.9	24.0	93.9
Percent error	-2.6	18.8	44.6	48.6	21.3	5.9

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Yakima River at Cle Elum, unregulated, Stream-gaging station No. 12479501

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	911.5	1,850.6	2,041.6	1,737.0	1,713.8	1,665.5	2,981.0
Calculated 45-year average streamflow	1,130.8	2,506.9	2,259.5	1,748.1	2,064.5	2,189.6	3,239.8
Percent error	24.1	35.5	10.7	0.6	20.5	31.5	8.7

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	4,884.2	4,067.9	1,754.5	713.6	565.6	2,073.2
Calculated 45-year average streamflow	4,065.1	3,767.0	1,881.6	690.0	457.6	2,163.8
Percent error	-16.8	-7.4	7.2	-3.3	-19.1	4.4

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	1,844.2	3,606.8	2,133.2	2,465.5	4,066.2	3,671.2	5,591.2
Calculated 4-year average streamflow	2,211.5	3,490.1	1,823.2	1,971.7	3,725.9	3,334.6	4,109.8
Percent error	19.9	-3.2	-14.5	-20.0	-8.4	-9.2	-26.5

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	8,016.0	5,328.5	3,343.5	2,482.0	1,116.0	3,638.8
Calculated 4-year average streamflow	4,556.2	3,517.4	2,009.8	675.6	395.5	2,641.5
Percent error	-43.2	-34.0	-39.9	-72.8	-64.6	-27.4

Yakima River near Easton, unregulated, Stream-gaging station No. 12477001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	444.8	962.7	1,075.2	894.4	860.2	788.3	1,357.7
Calculated 45-year average streamflow	542.4	1,113.4	963.0	761.3	873.8	933.0	1,462.1
Percent error	21.9	15.7	-10.4	-14.9	1.6	18.4	7.7

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	2,073.9	1,532.6	590.8	208.0	212.6	915.8
Calculated 45-year average streamflow	1,716.8	1,399.5	664.8	272.1	195.9	906.9
Percent error	-17.2	-8.7	12.5	30.8	-7.9	-1.0

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Yakima River at Kiona, unregulated, Stream-gaging station No. 12510501

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	2,666.2	3,985.2	5,109.2	5,004.8	5,639.6	6,237.2	8,853.5
Calculated 45-year average streamflow	1,936.8	4,487.9	5,486.5	4,782.6	5,700.0	6,042.3	8,328.4
Percent error	-27.4	12.6	7.4	-4.4	1.1	-3.1	-5.9

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	12,114.7	9,764.1	3,730.8	1,595.3	1,906.4	5,543.1
Calculated 45-year average streamflow	11,230.9	9986.6	4,917.3	2,134.2	1,350.7	5,524.8
Percent error	-7.3	2.3	31.8	33.8	-29.1	-0.3

Yakima River near Martin, unregulated, Stream-gaging station No. 12474501

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	196.9	402.5	389.3	325.9	299.1	267.5	472.6
Calculated 45-year average streamflow	230.7	394.0	299.6	231.6	266.5	280.1	502.0
Percent error	17.2	-2.1	-23.0	-28.9	-10.9	4.7	6.2

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	743.7	616.0	251.6	84.4	93.6	345.2
Calculated 45-year average streamflow	686.1	610.8	308.1	121.2	90.6	334.9
Percent error	-7.7	-0.8	22.5	43.6	-3.2	-3.0

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	354.5	623.2	315.5	357.5	521.8	371.8	541.8
Calculated 4-year average streamflow	433.6	532.6	215.2	270.8	523.9	496.9	680.4
Percent error	22.3	-14.5	-31.8	-24.3	0.4	33.7	25.6

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	828.8	473.8	193.8	84.2	83.2	396.0
Calculated 4-year average streamflow	706.4	445.7	210.2	84.3	61.0	387.0
Percent error	-14.8	-5.9	8.5	0.0	-26.7	-2.3

Table 3. Mean monthly and annual observed/estimated and calculated streamflow, and the percent error for the calibration and testing periods of the four watershed models for the Yakima River Basin, Washington—*Continued*

Yakima River near Parker, unregulated, Stream-gaging station No. 12505001

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	1,908.5	3,407.3	4,261.7	3,949.8	4,443.2	4,820.6	7,556.6
Calculated 45-year average streamflow	1,949.3	4,503.7	5,109.2	4,144.7	4,822.1	5,061.5	7,528.2
Percent error	2.1	32.2	19.9	4.9	8.5	5.0	-0.4

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	11,317.5	9,211.2	3,628.8	1,467.4	1,350.3	4,772.3
Calculated 45-year average streamflow	10,696.7	9,460.8	4,554.1	1,941.4	1,249.1	5,080.2
Percent error	-5.5	2.7	25.5	32.3	-7.5	6.5

TESTING

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 4-year average streamflow	2,859.5	6,248.8	4,718.5	5,287.5	10,355.5	7,736.2	8,744.5
Calculated 4-year average streamflow	3,465.3	6,830.4	5,166.8	5,039.9	9,384.6	7,941.2	10,746.0
Percent error	21.2	9.3	9.5	-4.7	-9.4	2.6	22.9

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 4-year average streamflow	13,537.8	9,065.5	3,457.8	1,435.8	1,773.2	6,268.5
Calculated 4-year average streamflow	14,020.8	9,591.8	4,969.2	2,071.7	1,327.6	6,690.5
Percent error	3.6	5.8	43.7	44.3	-25.1	6.7

Yakima River at Umtanum, unregulated, Stream-gaging station No. 12484501

CALIBRATION

	OCT	NOV	DEC	JAN	FEB	MAR	APR
Observed/estimated 45-year average streamflow	1,209.0	2,205.4	2,610.3	2,373.1	2,608.2	2,823.2	4,587.6
Calculated 45-year average streamflow	1,294.8	2,986.1	2,889.2	2,270.4	2,805.2	3,148.5	4,753.9
Percent error	7.1	35.4	10.7	-4.3	7.6	11.5	3.6

	MAY	JUNE	JULY	AUG	SEP	ANNUAL
Observed/estimated 45-year average streamflow	6,595.9	5,089.7	2,008.8	915.2	852.5	2,820.6
Calculated 45-year average streamflow	5,939.4	4,987.3	2,382.5	929.1	609.4	2,912.4
Percent error	-10.0	-2.0	18.6	1.5	-28.5	3.3

Mastin and Vaccaro

Watershed Models for Decision Support in the Yakima River Basin, Washington

USGS-OFR 02-404

Printed on recycled paper