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Watershed Models for Decision Support for Inflows to Potholes Reservoir, Washington

Scientific Investigations Report 2009–5081

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

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Watershed Models for Decision Support for Inflows to Potholes Reservoir, Washington

By Mark C. Mastin

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
centimeter (cm)	0.3937	inch (in)

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

$$°F=(1.8×°C)+32.$$

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

$$°C=(°F-32)/1.8.$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Datums

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

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

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

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Abbreviations and Acronyms

actP	actual probability
AET	actual evapotranspiration
CBP	Columbia Basin Project
CFGI	Continuous Frozen Ground Index
CM	creek mile
DA	drainage area
DEM	digital elevation model
DMI	data-management interfaces
DSS	decision support system
ENSO	El Niño Southern Oscillation
ESP	ensemble streamflow prediction
ET	evapotranspiration
GIS	geographical information system
GUI	graphical-user interface
HDB	hydrologic database
MMS	Modular Modeling System
MRU	Model Response Unit
NDVI	Normalized Difference Vegetation Index
NINO	El Niño
NWS	National Weather Service
OUI	Object User Interface
PDO	Pacific Decadal Ocillation
PET	potential evapotranspiration
PRMS	Precipitation-Runoff Modeling System
SEE	standard error of estimate
STATSGO	State Soil Geographic Database
USGS	U.S. Geological Survey
WARSMP	Watershed and River Systems Management Program
WY	water year
XML	eXtensible Markup Language

Watershed Models for Decision Support for Inflows to Potholes Reservoir Basin, Washington

By Mark C. Mastin

Abstract

A set of watershed models for four basins (Crab Creek, Rocky Ford Creek, Rocky Coulee, and Lind Coulee), draining into Potholes Reservoir in east-central Washington, was developed as part of a decision support system to aid the U.S. Department of the Interior, Bureau of Reclamation, in managing water resources in east-central Washington State. The project is part of the U.S. Geological Survey (USGS) and Bureau of Reclamation collaborative Watershed and River Systems Management Program. A conceptual model of hydrology is outlined for the study area that highlights the significant processes that are important to accurately simulate discharge under a wide range of conditions. The conceptual model identified the following factors as significant for accurate discharge simulations: (1) influence of frozen ground on peak discharge, (2) evaporation and groundwater flow as major pathways in the system, (3) channel losses, and (4) influence of irrigation practices on reducing or increasing discharge.

The Modular Modeling System was used to create a watershed model for the four study basins by combining standard Precipitation Runoff Modeling System modules with modified modules from a previous study and newly modified modules. The model proved unreliable in simulating peak-flow discharge because the index used to track frozen ground conditions was not reliable. Mean monthly and mean annual discharges were more reliable when simulated. Data from seven USGS streamflow-gaging stations were used to compare with simulated discharge for model calibration and evaluation. Mean annual differences between simulated and observed discharge varied from 1.2 to 13.8 percent for all stations used in the comparisons except one station on a regional groundwater discharge stream. Two thirds of the mean monthly percent differences between the simulated mean and the observed mean discharge for these six stations were between -20 and 240 percent, or in absolute terms, between -0.8 and 11 cubic feet per second.

A graphical user interface was developed for the user to easily run the model, make runoff forecasts, and evaluate the results. The models; however, are not reliable for managing short-term operations because of their demonstrated inability to match individual storm peaks and individual monthly discharge values. Short-term forecasting may be improved with real-time monitoring of the extent of frozen ground and the snow-water equivalent in the basin. Despite the unreliability of the models for short-term runoff forecasts, they are useful in providing long-term, time-series discharge data where no observed data exist.

Introduction

As population and development increase in the West and the demand for instream flows for fish and other aquatic wildlife also increases, water supplies are becoming limited. Water managers require detailed accounting and efficient management of water from all sources.

The Bureau of Reclamation (Reclamation) manages the Columbia Basin Project (CBP; fig. 1), a multipurpose project providing hydropower, recreation, irrigation, and flood protection. A principal feature of the project is Grand Coulee Dam on the Columbia River, the largest concrete structure in the United States. Behind the dam is Franklin D. Roosevelt Lake. Water to irrigate about one-half million acres in the CBP area is pumped from the lake up to Banks Lake for distribution via the Main Canal to the East Low Canal and to the West Canal. Return flows from irrigation, plus natural flows from Crab Creek, Rocky Ford Creek, Rocky Coulee, and Lind Coulee, feed Potholes Reservoir either directly or through Moses Lake. The management of the diverted water from the Columbia River is fairly straightforward because the amount of water pumped into Banks Lake and released to the Main Canal for irrigation distribution is known and the supply is available to meet present irrigation demands.

An unknown factor in the management of the inflows to Potholes Reservoir is the natural inflow of water from creeks and coulees. With a forecast of the natural inflow volumes to Potholes Reservoir made just prior to the runoff season (typically February through May), Reclamation could manage more efficiently the early season filling of Potholes Reservoir by reducing the amount of water diverted from the Columbia River during years when Crab Creek, Rocky Ford Creek, Rocky Coulee, and Lind Coulee runoff is greater than average. If a large flood on this natural system can be predicted, diverted water could be managed so that the capacities of Potholes Reservoir, Moses Lake, and the canal system are not exceeded. Long-term simulation of the natural inflows to Potholes Reservoir could be useful in planning various water-management activities, especially when and where observed discharge data are not available.

Figure 1. Streamflow-gaging stations, Columbia Basin Project, and study area boundaries in the Potholes Reservoir basin, Washington.

Since 1995, the U.S. Geological Survey (USGS) and Reclamation have worked collaboratively on a Watershed and River Systems Management Program (WARSMP). Program goals are to (1) create a database-centered Decision Support System (DSS; fig. 2) by coupling watershed and river-reach models that simulate the physical hydrology with routing and reservoir management models that account for water availability and use; (2) support the development of the models and necessary software tools; and (3) apply the DSS to Reclamation projects in the Western United States.

The WARSMP applied the DSS to the Potholes Reservoir basin in east-central Washington (fig. 1) and part of Reclamation's CBP to provide tools to improve the efficiency of water use in the basin, augment the length of the observed streamflow record with simulated record, and forecast runoff volumes and timing of unregulated flows in Crab Creek, Rocky Ford Creek, Rocky Coulee, and Lind Coulee. No public forecasts for runoff currently are being made in these basins.

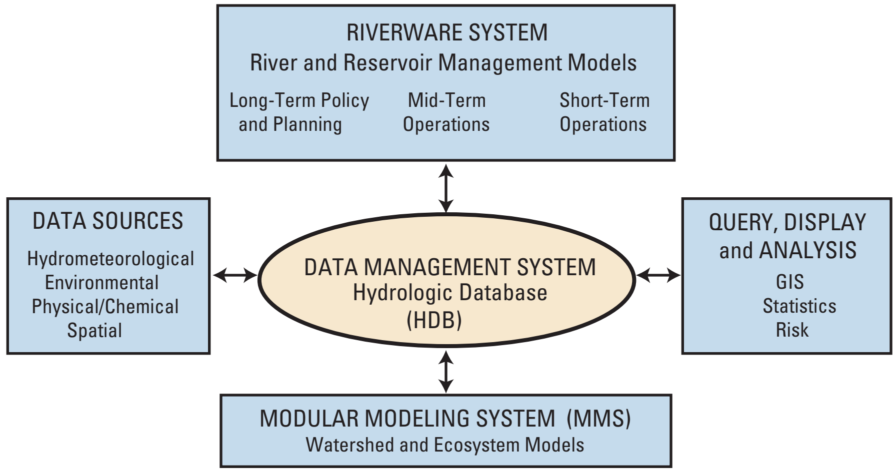


Figure 2. Database-centered Decision Support System.

Purpose and Scope

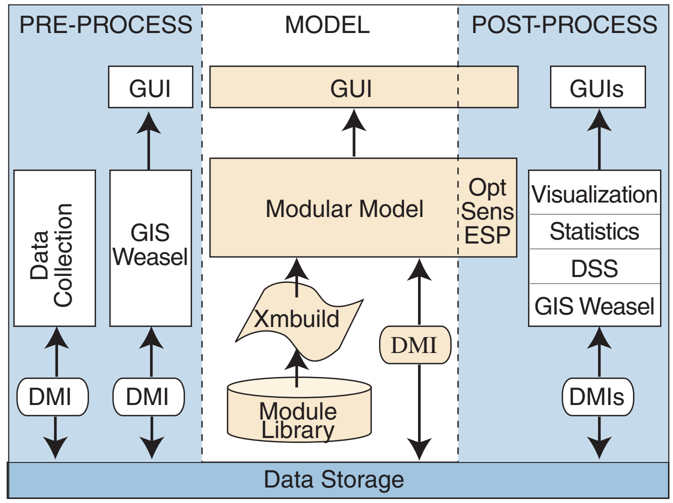
This purpose of this report is to describe the (1) conceptual hydrology model of the unregulated inflows to Potholes Reservoir; (2) watershed model and Modular Modeling System (MMS) used to simulate the hydrology of the study area; (3) construction, calibration, and evaluation of the watershed model for the three model units; and (4) integration of the watershed models into a DSS. Three watershed models were created to simulate hydrology in four basins of interest. One model covers Crab Creek and Rocky Ford Creek upstream of Potholes Reservoir, and two models cover Rocky Coulee and Lind Coulee separately. The models were calibrated with observed meteorological and discharge data from water years 1950 through 2004 and were evaluated by running the watershed models with two subsets of the weather-station input data—one subset is real-time station data that will be used for forecasting operations and the other subset is used to extend the observed discharge record because the weather record extends further into the past than the streamflow record. The term "water year" means a 12-month period beginning on October 1 and ending September 30 of the water year. The observed runoff data and simulated runoff data from the calibrated model were compared and evaluated. A primary reason for the development of the watershed models is to make forecasts of natural runoff volumes for an upcoming runoff season (generally March through June). These forecasts then will be input into Reclamation's RiverWare model that will simulate water imports, irrigation, and return flows in the CBP system. The simulated runoff also will be used in long-term planning to extend runoff records at streamflow-gaging stations beyond the period of observation or to completely simulate records at ungaged sites.

Database-Centered Decision Support System

The WARSMP model for a DSS involves the coupling of a watershed model (MMS) and a river-management model (RiverWare) through a common database—the hydrologic database (HDB). 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 DSS (fig. 2). The many links between information sources along with the tools provided by the DSS can facilitate long-term planning and policy decisions as well as short- and medium-term water-management operation of Reclamation projects such as the CBP.

Modular Modeling System

The MMS is a software package that provides a framework to modelers for the development and application of numerical models to simulate a variety of water, energy, and biogeochemical processes (Leavesley and others, 1996). Several modules representing rainfall-runoff processes were combined within MMS to develop the watershed model that was applied to the study basin. Each of the modules is a FORTRAN-coded program designed to simulate a separate physical process. Graphical-user interfaces (GUIs) and data-management interfaces (DMIs) allow users to access and use the preprocess, model, and post process components of MMS (fig. 3). The MMS framework provides the capability for optimization, sensitivity analysis, and forecasting through Ensemble Streamflow Prediction—a procedure documented by Day (1985). The watershed model used for this study was based on the USGS Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983). The model was compiled from three groups of modules: (1) a standard set of PRMS modules, (2) modified modules developed from a previous WARSMP project in the Yakima River Basin (Mastin and Vaccaro, 2002a), and (3) new modules developed for this study.



EXPLANATION

GUI Graphical user interface
DMI Data-management interface
Opt Optimization
Sens Sensitivity analysis
ESP Ensemble streamflow prediction
GIS Geographic Information system

Figure 3. Components of the Modular Modeling System.

Description of the Study Area

The study area (fig. 1) is in east-central Washington State and includes the basins of Crab Creek above Potholes Reservoir, upstream of the USGS streamflow-gaging station on Crab Creek near Moses Lake (12467000); Rocky Ford Creek; Rocky Coulee; and Lind Coulee, upstream of the USGS streamflow-gaging station on Lind Coulee Wasteway at SR17 near Warden (12471400). All these creeks drain into Potholes Reservoir either directly or through Moses Lake and then eventually to the Columbia River through lower Crab Creek or as return flows from irrigated lands south of Potholes Reservoir.

The study area is within the physiographic province of the Columbia River Plateau. The plateau, one of the largest flood basalts in the world, covers 63,000 mi^2 in Washington, Idaho, and Oregon. These flood basalts were sculpted at the end of the last ice age by a series of massive floods called the Missoula Floods, or the "Bretz Floods," named after J.H. Bretz who first proposed the Missoula Flood theory to explain an intricate network of channels and coulees known as the channeled scablands (McKee, 1972). Viewed from the ground, the pattern of channels is subtle. Channels often are dry and either covered in sagebrush or bare with exposed basalt bedrock. Most of the study area is underlain by the Wanapum Basalt Formation varying in thickness from about 200 ft in the northwest part of the study area to about 600 ft near Potholes Reservoir (Hansen and others, 1994). Many exposed areas of the basalt are at the surface in the northern and eastern sections of the study area and large areas of thin layers of Quaternary sediments cover the basalt in the southern and western sections of the study area (Drost and Whiteman, 1986).

No distinct mountain ranges in the basins exist and relief generally is gradual. Elevation varies from 3,049 ft on the top of Hanning Butte on the northeast corner of the Crab Creek basin and slopes downward toward the southwest to 1,039 ft at Potholes Reservoir (fig. 4).

The study area is in a rain shadow on the east side of the Cascade Range, with only enough moisture to sustain a shrub-steppe grassland under natural conditions—vegetation such as sagebrush, rabbitbrush, bitterbrush, bunchgrass, and cheatgrass. As one proceeds eastward through the study area, average annual precipitation gradually increases from about 7 to 16 in. (figs. 5 and 6). Most precipitation, often as snow, falls during the winter months (fig. 6). Localized summer convective rainstorms bring moisture during the warm season, when it is most needed for agriculture. Dryland wheat farming is common in the northern and eastern parts of the Crab Creek

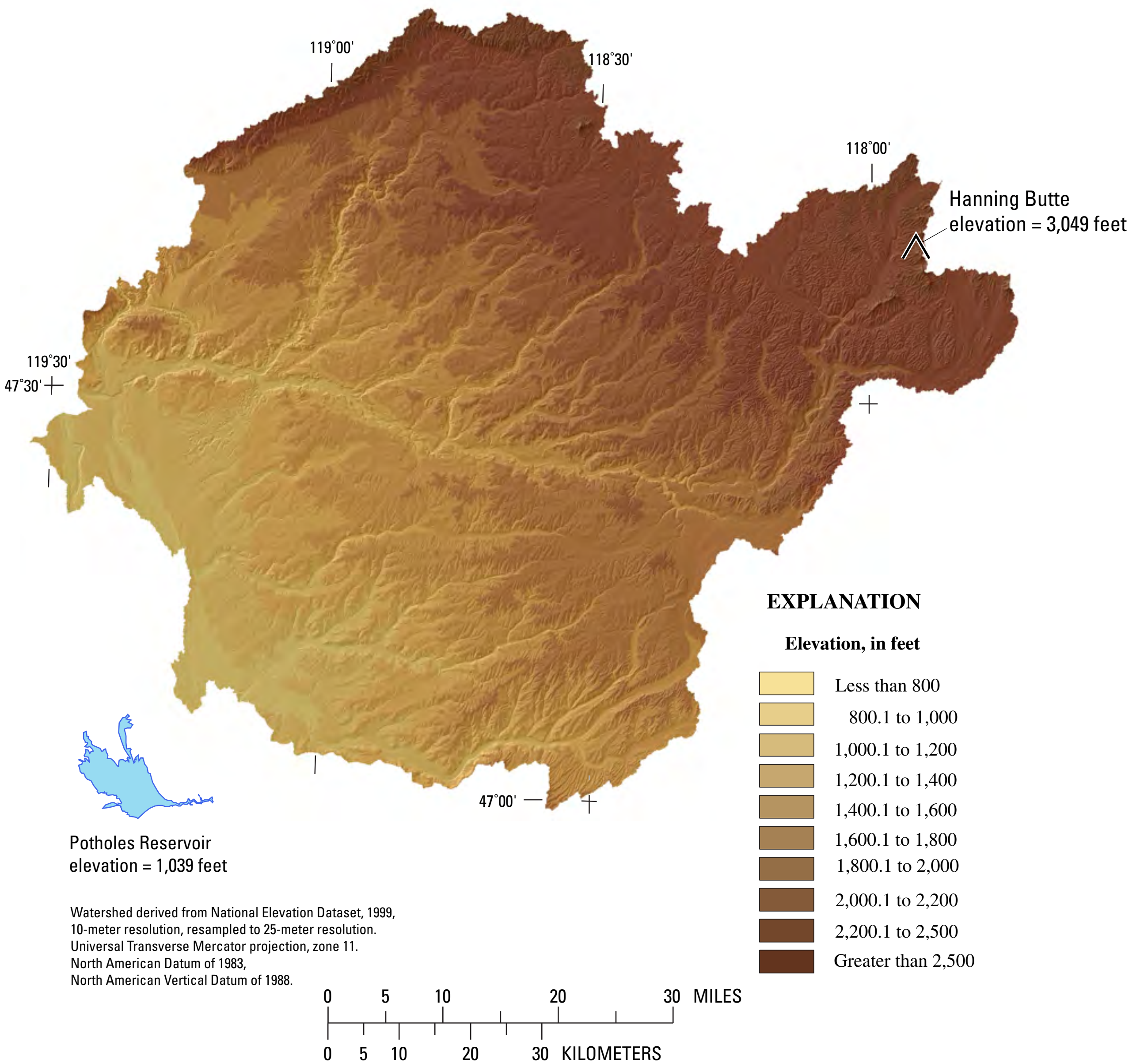


Figure 4. Study area near Potholes Reservoir, east-central Washington. (Source: U.S. Geological Survey, 2002, National Elevation Dataset.)

basin, but precipitation only marginally supports this type of farming. In eastern Washington, 12–17 in. of precipitation define the intermediate zone for dryland farming, which often requires fields to remain fallow in summer to allow the soil to accumulate extra moisture (Donovan, 2000). In the creek valleys and in the lower parts of the study area, irrigation primarily is from surface water provided by the CBP, which is managed by Reclamation within the project boundaries (generally west or downslope from the East Low Canal; fig. 1). Outside the project boundaries, irrigation is available from groundwater pumpage. Various orchards and field crops such as alfalfa, corn, and potatoes along with livestock operations are in the irrigated regions of the study area.

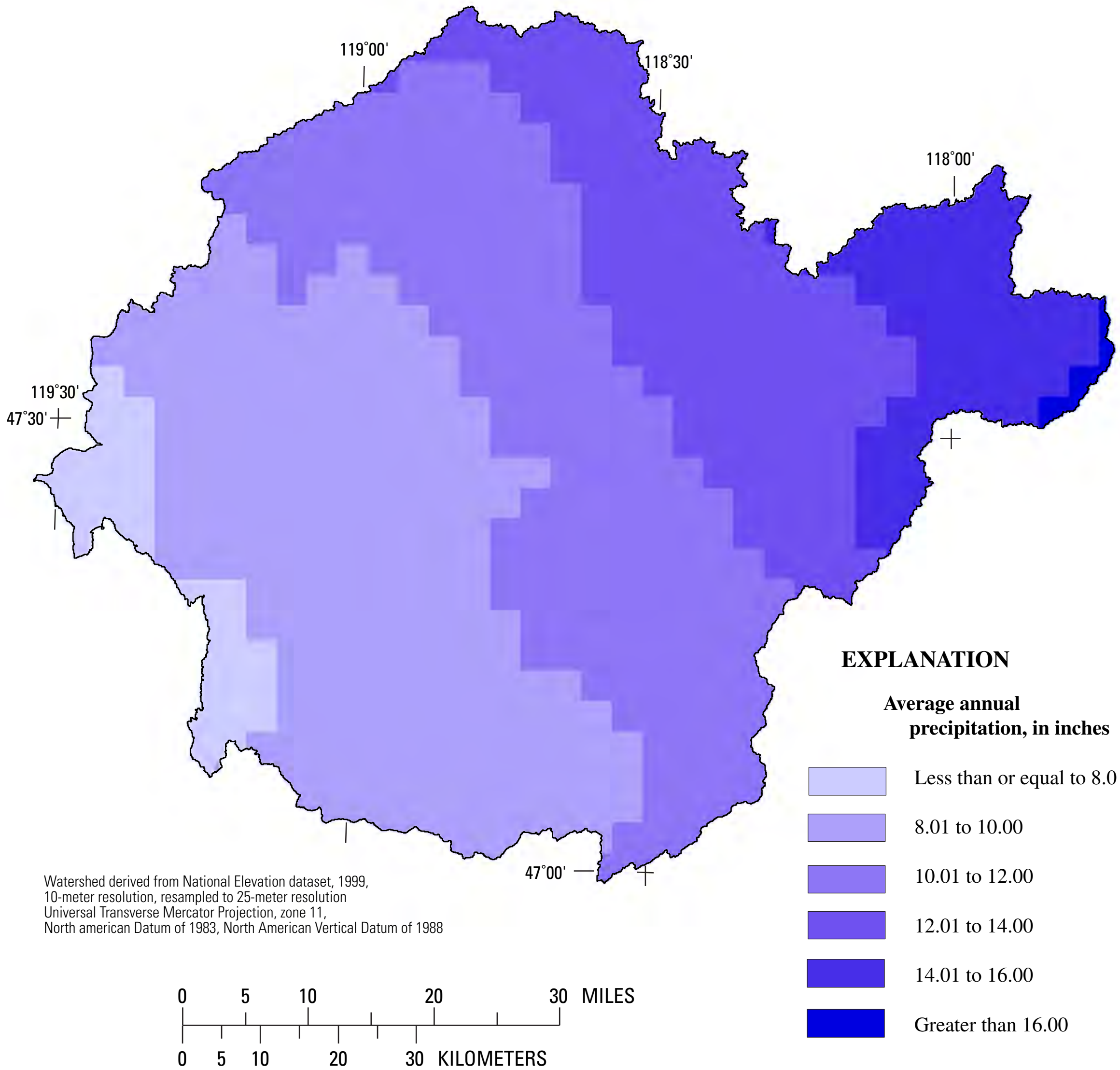


Figure 5. Average annual precipitation during 1961–90 in the Potholes Reservoir basin, Washington. (Source: Daly and Taylor [1998].)

Patterns of runoff contrast dramatically throughout the study area and show how different hydrological and irrigation processes can affect the volume and timing of water in the stream channels. Groundwater processes are indicated by the many springs in the area and by creek names such as Sinking Creek. Rocky Ford Creek is an example of a stream receiving almost all of its flow from groundwater. A mean monthly hydrograph of its observed discharge at USGS streamflow-gaging station number 12470500 (fig. 7) indicates a constant flow varying only from 60 to 90 ft^3/s throughout the year in a watershed with a surface-water drainage area of only 12 mi^2. The streamflow-gaging station at Crab Creek near Moses Lake (USGS station number 12467000, fig. 1) has more than twice the contributing area of the upstream gaging station, Crab Creek at Irby (USGS station number 12465000), but less flow during January through April. This discrepancy is especially true during the early runoff season, which begins in January when a wetting-up process of the channel downstream of

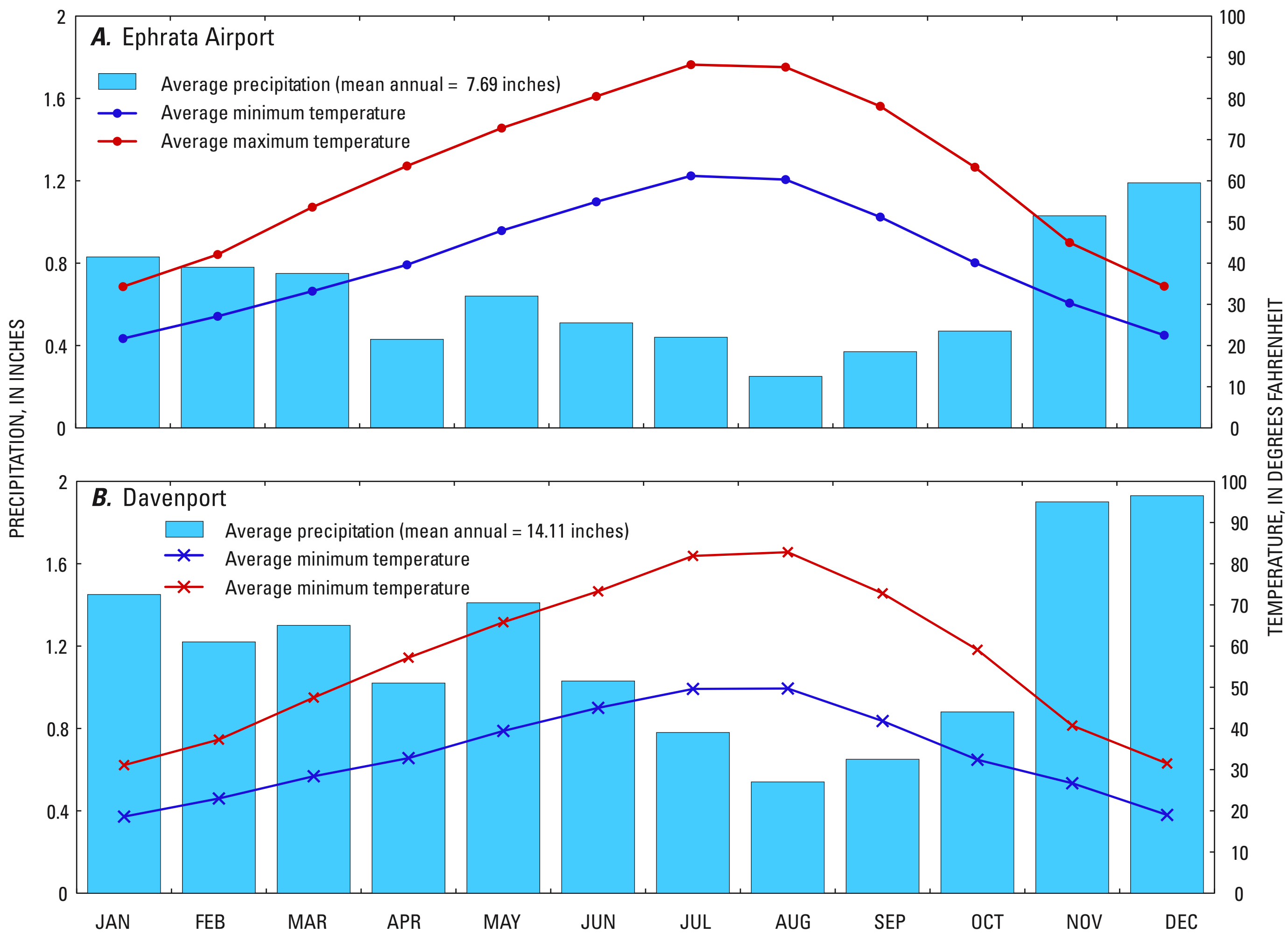


Figure 6. Average monthly precipitation, and minimum and maximum temperatures at (*A*) Ephrata Airport and (*B*) Davenport, Washington, 1971 through 2000. (Source: Western Regional Climate Center [2006b].)

Irby takes place and much of the runoff is lost to the surface aquifer or stored in several small lakes. Later in the irrigation season, return flows running off the fields irrigated by the CBP sustain the summer and fall flows at Crab Creek near Moses Lake. The streamflow-gaging station at Crab Creek at Irby is upstream of the Columbia River Basin irrigation boundaries (fig. 1) and receives far less return flows from irrigation.

Figure 8 shows mean monthly discharge at three streamflow-gaging stations in the Lind Coulee Basin (fig. 1). Of these, the streamflow-gaging station on Farrier Coulee near Schrag (USGS station number 12471279) is outside the CBP and is dry most of the year. Occasional rainstorms or snowmelt may generate some flow, but no flow is common at this gaging station throughout the year. Both Lind Coulee gaging stations are within the CBP boundaries and receive irrigation return flows that can sustain flow throughout most of the year; upstream of the CBP, the coulee is often dry. The streamflow-gaging station at the Lind Coulee Wasteway at Highway 17 (USGS station number 12471400, fig. 1) also receives wasteway water (water that comes directly from a main irrigation canal) from the East Low Canal through the Weber Wasteway, which explains the high flows at this station during January through March when flows are low at the streamflow-gaging station at Lind Coulee near Warden.

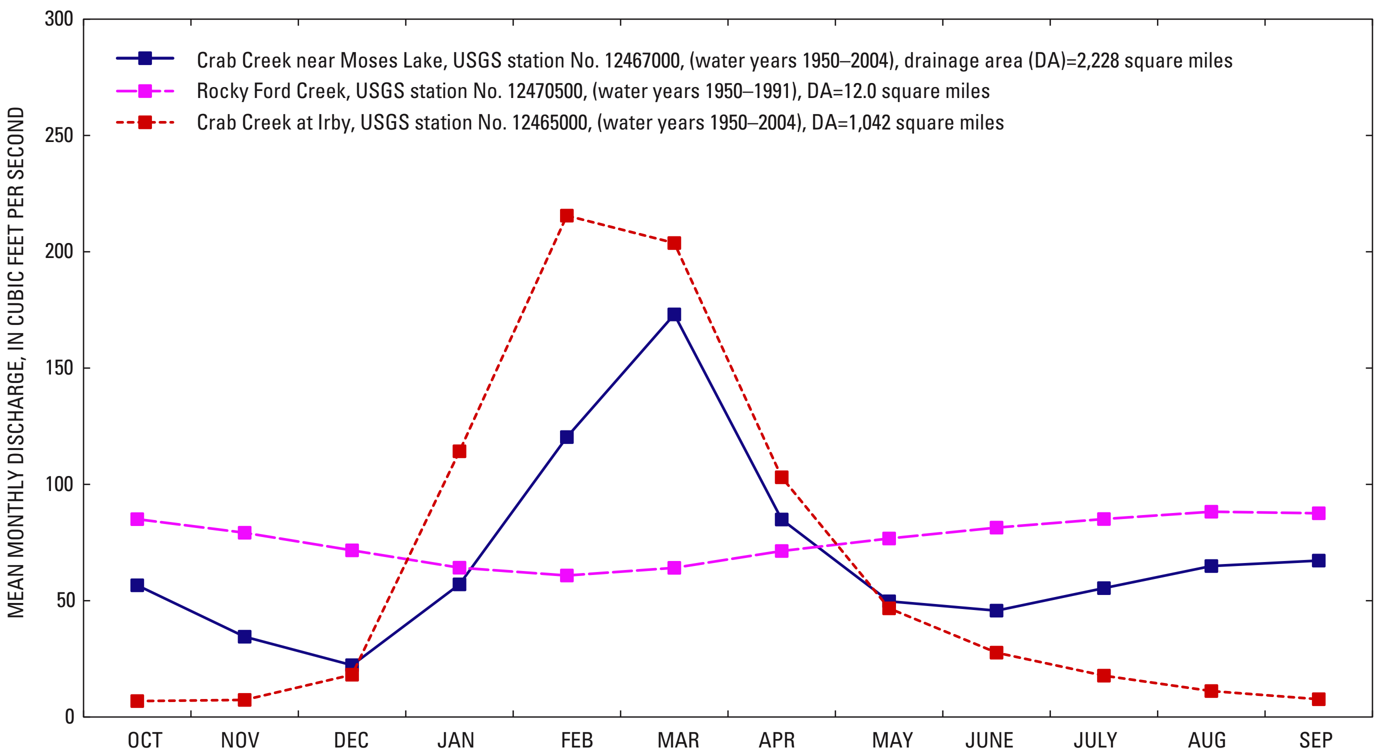


Figure 7. Mean monthly discharge at two Crab Creek streamflow-gaging stations and one Rocky Ford Creek streamflow-gaging station for indicated periods, Potholes Reservoir basin, Washington.

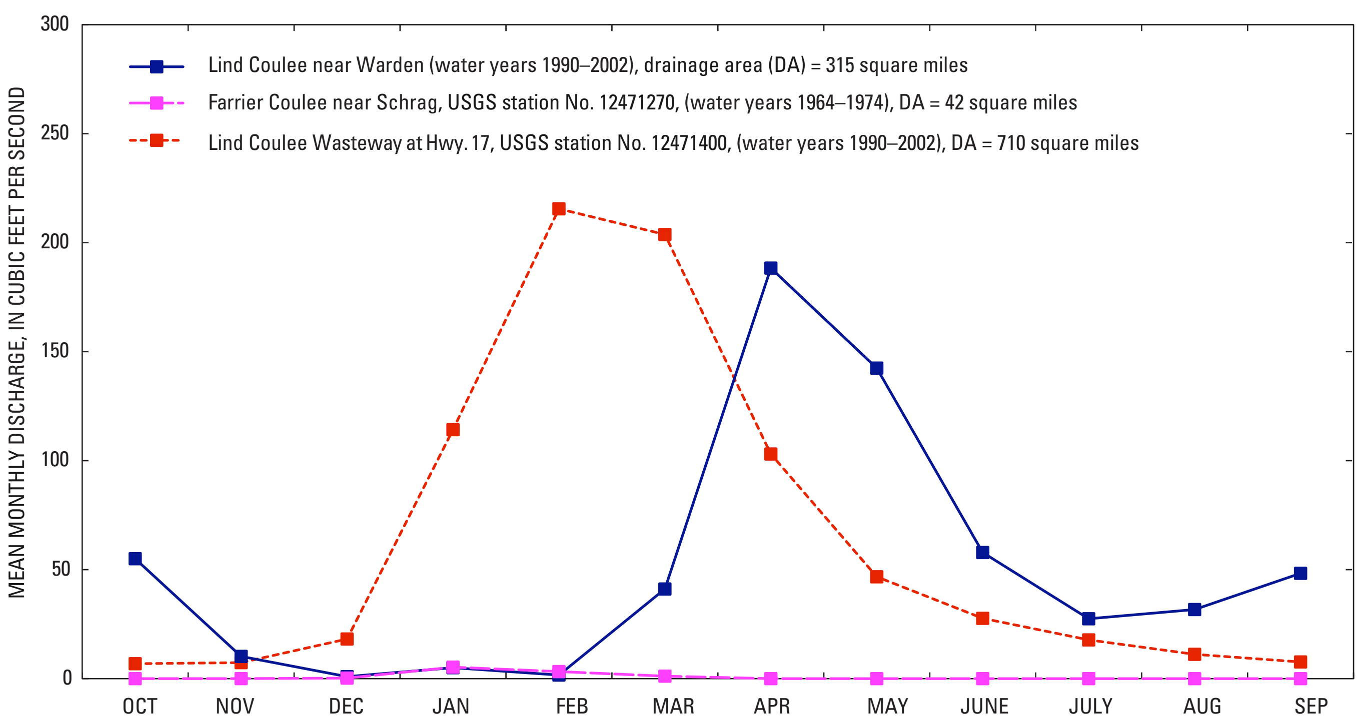


Figure 8. Mean monthly discharge at three streamflow-gaging stations in the Lind Coulee basin for indicated periods, Potholes Reservoir basin, Washington.

Conceptual Model of Hydrology

The conceptual model presented here outlines the significant hydrologic processes for the study area and describes the pathways, fluxes, and storage of water within the system. These processes are part of the water cycle, beginning with precipitation falling on the surface and continuing to a point where water leaves the basin. Processes vary in importance with the goals of the study and the physical features of the study area. For this study, the significant hydrologic processes were quite different from those in mountain headwater areas where similar models have been applied previously in Washington (Mastin and Vaccaro, 2002b; Ely, 2003). The processes that strongly influence stream hydrology in this study area are: (1) peak-flow generation when soils are frozen, (2) evaporation from the land, especially during the warm season, (3) regional groundwater flow patterns, (4) seasonal seepage losses and gains in channels, and (5) irrigation withdrawals and return flows including wastewater returns.

Frozen Ground

During winter, air temperatures commonly drop below freezing and soils begin to freeze. Soil insulates itself from cold air temperatures during the winter, and generally, soil temperature increases with depth during this season (fig. 9). Snow cover also insulates the soil, but the timing of the snowfall is critical. If soils are frozen prior to a snowstorm, snowfall may keep the soil frozen throughout the winter—if the snow falls and then the temperatures drop, the snow cover may prevent frozen-ground conditions (figs. 9 and 10). For example, figure 9 shows that a late-December snowfall generated snowcover that prevented frozen-ground conditions throughout the remainder of the winter. Intense soil freezing can make the soil impenetrable to rain or snowmelt. In these cases, any rain or snowmelt becomes surface runoff and can cause significant flooding.

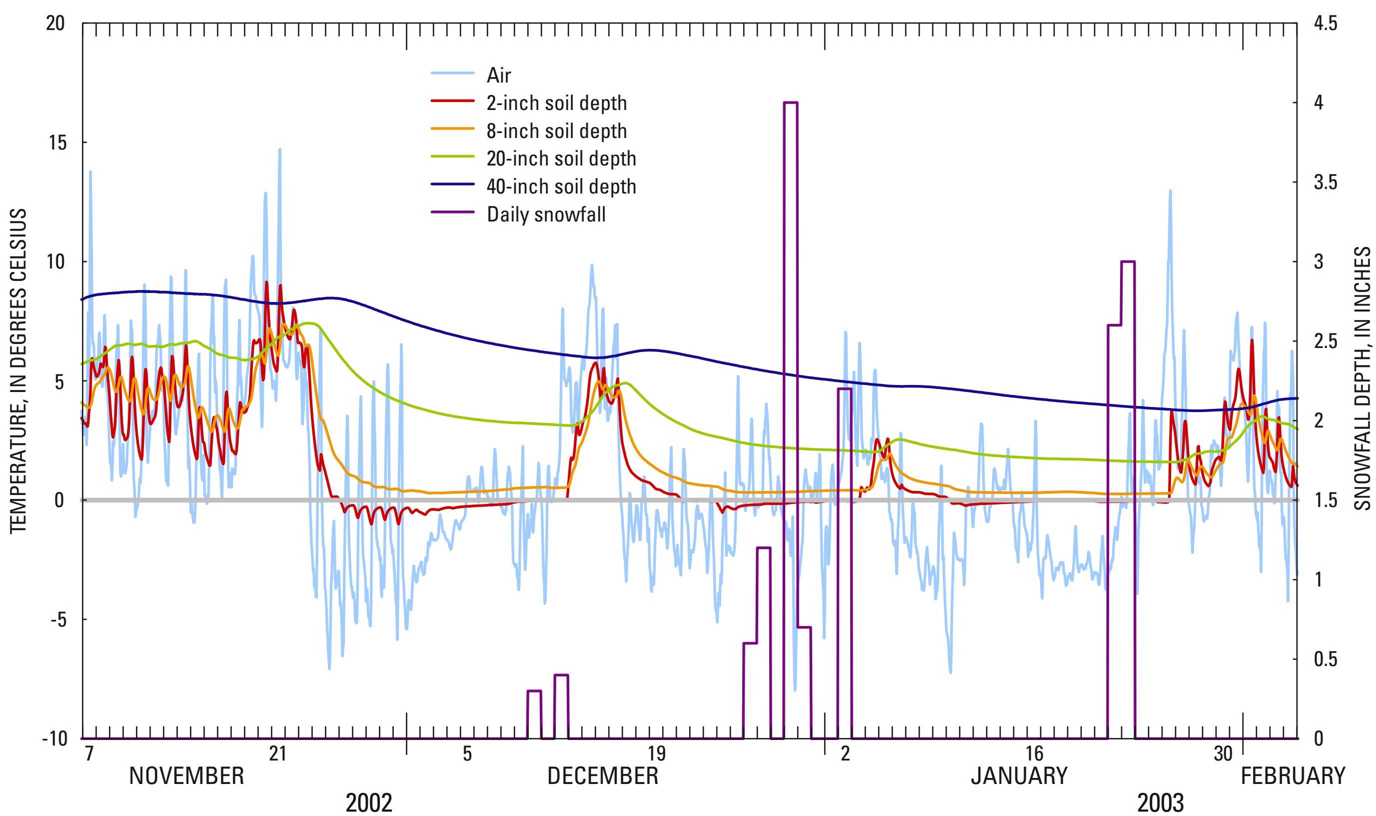


Figure 9. Hourly air and soil temperature, and daily snowfall for part of winter 2002–03 at Davenport, Washington. (Source: Temperature data collected by U.S. Geological Survey and daily snowfall data reported by the U.S. Department of Commerce, 2002–03.)

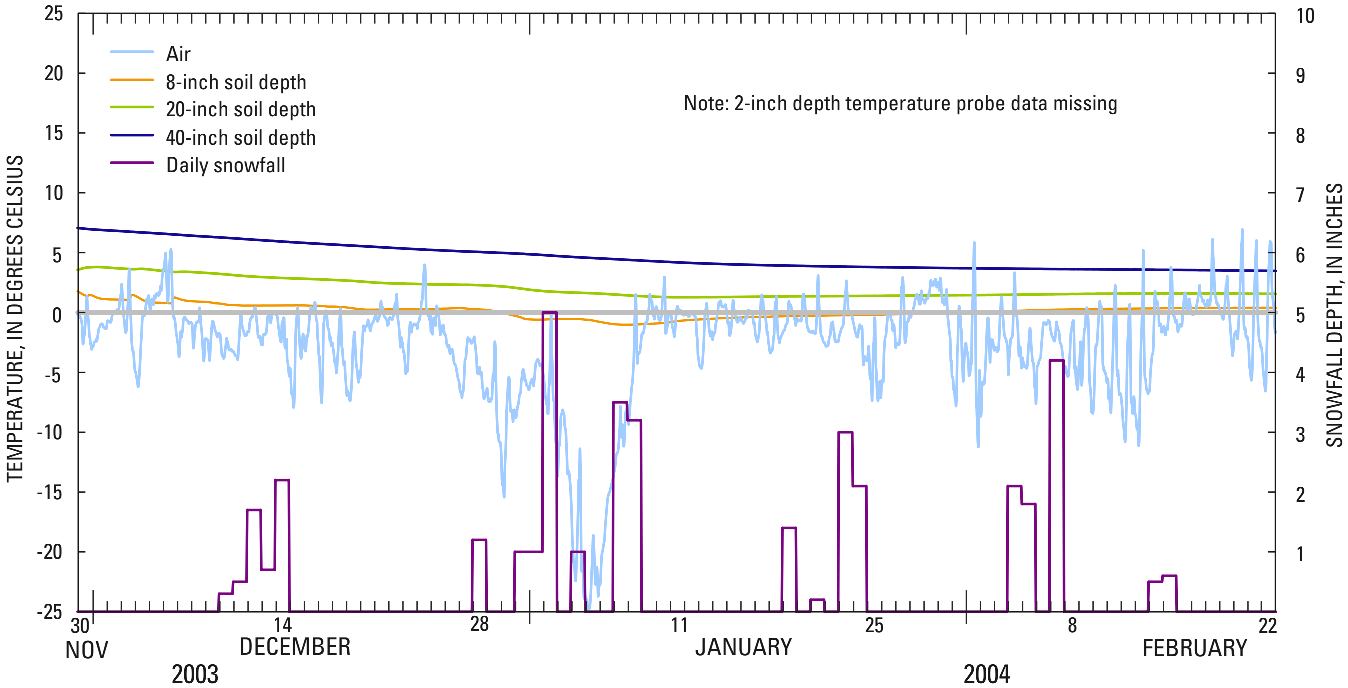


Figure 10. Hourly air and soil temperature, and daily snowfall for part of winter 2003–04 at Davenport, Washington. (Source: Temperature data collected by U.S. Geological Survey and daily snowfall data reported by the U.S. Department of Commerce, 2003–04.)

Figure 11 shows dramatically different discharge hydrographs for the Crab Creek at Irby streamflow-gaging station—one for the peak-of-record discharge in water year 1957 and one for water year 2004 that occurred during the same month as the 1957 peak. Snow-water equivalent data were available to estimate the volume of water contained in snow in the basin prior to both peaks; almost twice the volume of snow-water equivalent was measured in upper Crab Creek basin snowpack during water year 2004 than during water year 1957 prior to the peak. Similar 2-day totals of rainfall were reported in water year 2004 and water year 1957 prior to the peak. Why was there a difference in peak discharges? Don Miller (Bureau of Reclamation, written commun., September 25, 1957) described the situation leading up to the February 1957 flood:

> Examination of temperature records for stations in the basin shows that from February 18 to noon of February 23, 1957, temperatures did not exceed 32°F. Furthermore, at Davenport, minimum temperatures did not exceed 32°F during the period December 22 to February 23, and maximum temperatures exceeded 32°F only 21 days within the 62-day period cited. All reports of the February 1957 flood cite the fact that the ground was frozen solidly at the beginning of the runoff period.

Air temperatures at the beginning of water year 2004 were relatively mild. A sharp drop in the air temperatures occurred at the beginning of calendar year 2004, but an existing snowpack insulated the soil from the cold air temperatures and little change was measured in soil temperatures (fig. 10). When the rain came and the snow melted, much of the excess water infiltrated into the soil because the soil was not frozen during the February 19, 2004, which generated the peak-of-the-year discharge event. This event resulted in an instantaneous peak discharge of only 380 ft^3/s, despite similar water availability for runoff as the February 27, 1957, a peak-of-record discharge event, which resulted in an instantaneous peak of 8,370 ft^3/s at the same gaging station.

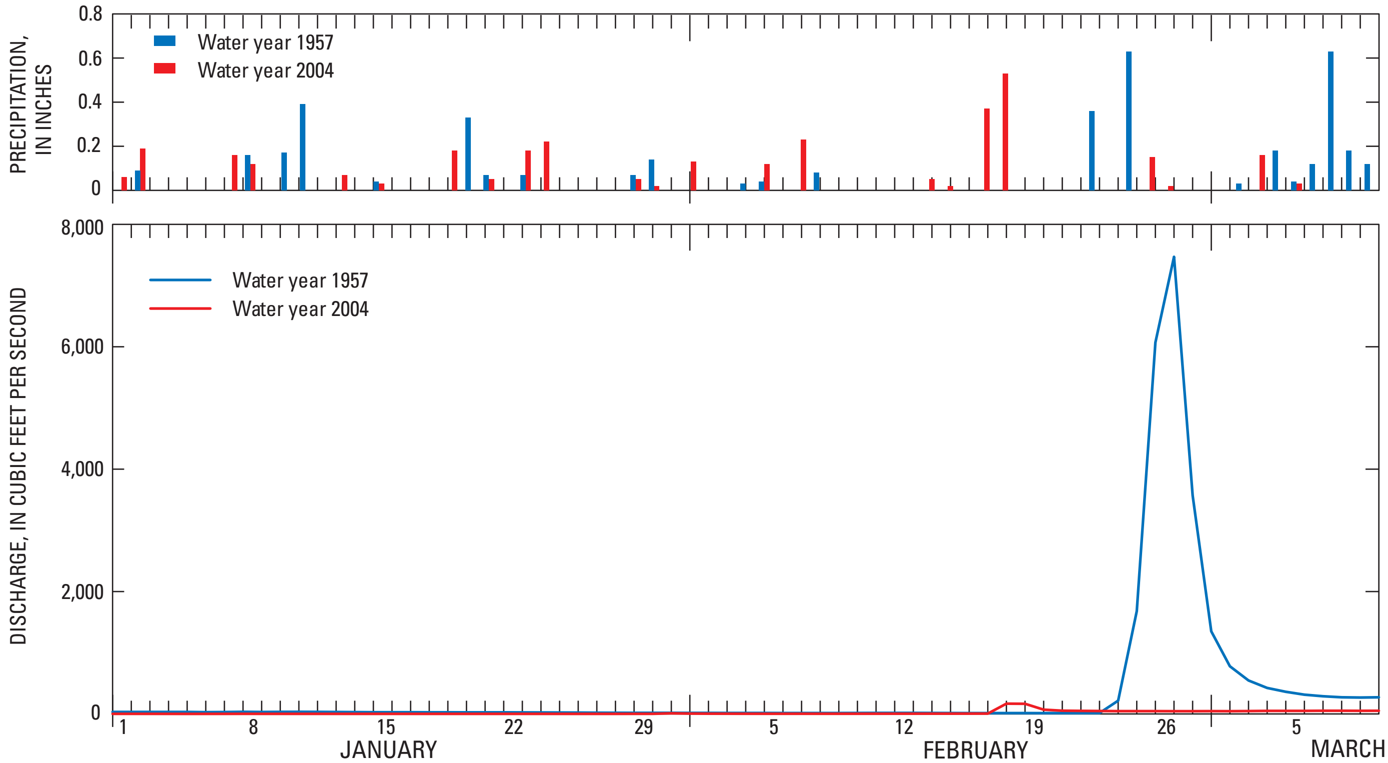


Figure 11. Precipitation and daily discharge for the USGS streamflow-gaging station at Crab Creek at Irby, Washington, from January 1 to March 10, water years 1957 and 2004.

Evapotranspiration

Evaporation is an important pathway for water in the study basin, especially during the summer months when demand for water is highest. The simulation of evaporation is often approached by first calculating the potential evapotranspiration (PET) and then evaluating actual evapotranspiration (AET), a value that includes evaporation directly from water bodies, water in the soil, water intercepted by vegetation, and transpiration from vegetation. In the center of the study area, Reclamation maintains an Agrimet (a Pacific Northwest Cooperative Agricultural Weather Network) site near Odessa (station code ODSW) that computes evapotranspiration (ET) from meteorological data collected at the site (fig. 12). Agrimet uses the Kimberly-Penman ET model developed by the U.S. Department of Agriculture, Kimberly, Idaho, with alfalfa as the reference crop (Wright, 1982) to compute what effectively represents PET for the site. PET is highest in the summer, when precipitation is low, resulting in a large moisture deficit during the growing season that must be supplied by irrigation in order to grow crops (fig. 12). When the water budget is computed for average monthly conditions, the calculations show no surplus water available for runoff on non-irrigated soils with about 3 in. or more of water capacity. The timing and volume of runoff partially is governed by the amount of moisture in the soil relative to its capacity, and soil moisture is affected directly by AET. AET is nearly equal to PET within the irrigated lands and wetland areas. With greater than 50 in. of PET in the basin and less than 12 in. of precipitation, AET becomes one of the most significant variables in the water budget.

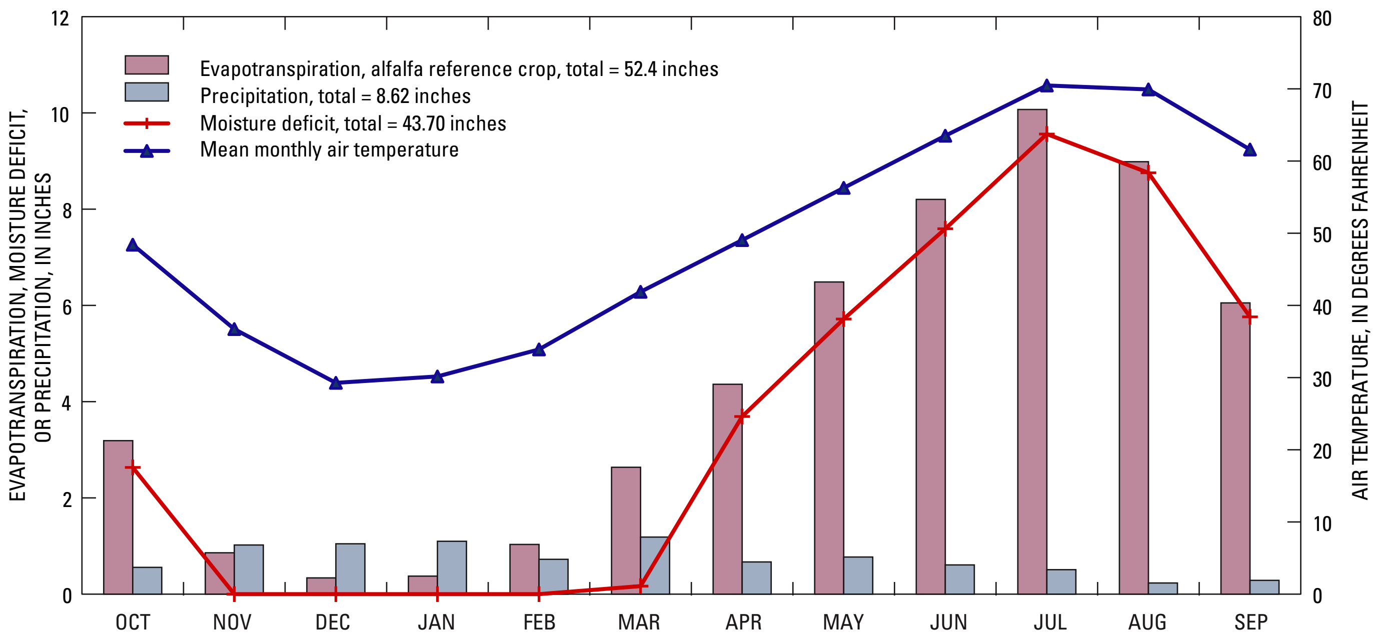


Figure 12. Average evapotranspiration, precipitation, moisture deficit, and mean monthly air temperature at Agrimet site ODSW, Odessa, Washington, water years 1986–2004. (Source: U.S. Department of Interior, Bureau of Reclamation, Agrimet: accessed August 15, 2006, at http://www.usbr.gov/pn/agrimet/. Moisture deficit was computed for a Stratford soil with a total available water capacity of 3.8 inches and assumes zero soil moisture in October.)

Groundwater Flow

For a watershed study, if all the groundwater recharge and discharge occurs within subbasins defined by surface-water divides, the groundwater flow process generally can be defined easily and simulated with a watershed model. However, regional groundwater flow that crosses surface-water divides, as is the case in this study area, can complicate a watershed study and make it difficult to simulate the proper timing and amounts of groundwater contributions to the runoff. Previous studies on regional groundwater hydrology (Hansen and others, 1994; Bauer and Hansen, 2000) provided the regional-flow patterns and this information, combined with the locations of springs from topographic maps, helped define the principal areas of groundwater discharge.

Regional Flow

Hansen and others (1994) simulated an average steady-state condition for groundwater levels in the region from spring 1983 through spring 1985. General groundwater flow directions can be inferred to be perpendicular to water-level contours and from higher to lower water levels. Simulated groundwater levels in the Wanapum unit (fig. 13), the predominant hydrogeologic unit in the study area, indicate that the predominant direction of groundwater flow tends to be from the northeast to the southwest, following surface topography. The major groundwater discharge surface features are in the southwest part of the study area, which include the Gloyd Seeps Wildlife Area and Rocky Ford Creek. Despite its small contributing surface drainage area (DA), Rocky Ford Creek as measured at streamflow-gaging station 12470500 (fig. 1) discharged more annually (75.7 ft^3/s, DA=12 mi^2) than Crab Creek measured either at the station at Irby (62.8 ft^3/s, DA=1,042 mi^2) or at the station near Moses Lake (71.9 ft^3/s, DA=2,228 mi^2), for water years 1952 through 1991. Regional groundwater flow processes that transport water across surface-drainage boundaries are the dominant flow process for many streams such as Rocky Ford Creek. Although it is difficult to simulate these processes with a watershed model, a general knowledge of the flow direction and discharge points helps in routing groundwater flows to the correct locations and approximating the total volumes.

Springs

Springs are groundwater discharge points and many springs are in the study area. To field inventory these springs and estimate their discharge is beyond the scope of this study. Instead, USGS 7.5 minute topographic maps covering the study area were used to locate and inventory most of the springs (fig. 13); however, this method does not provide an indication of discharge rates. Springs provide specific areas of groundwater discharge that can sustain streamflow channels well after rain and snowmelt events.

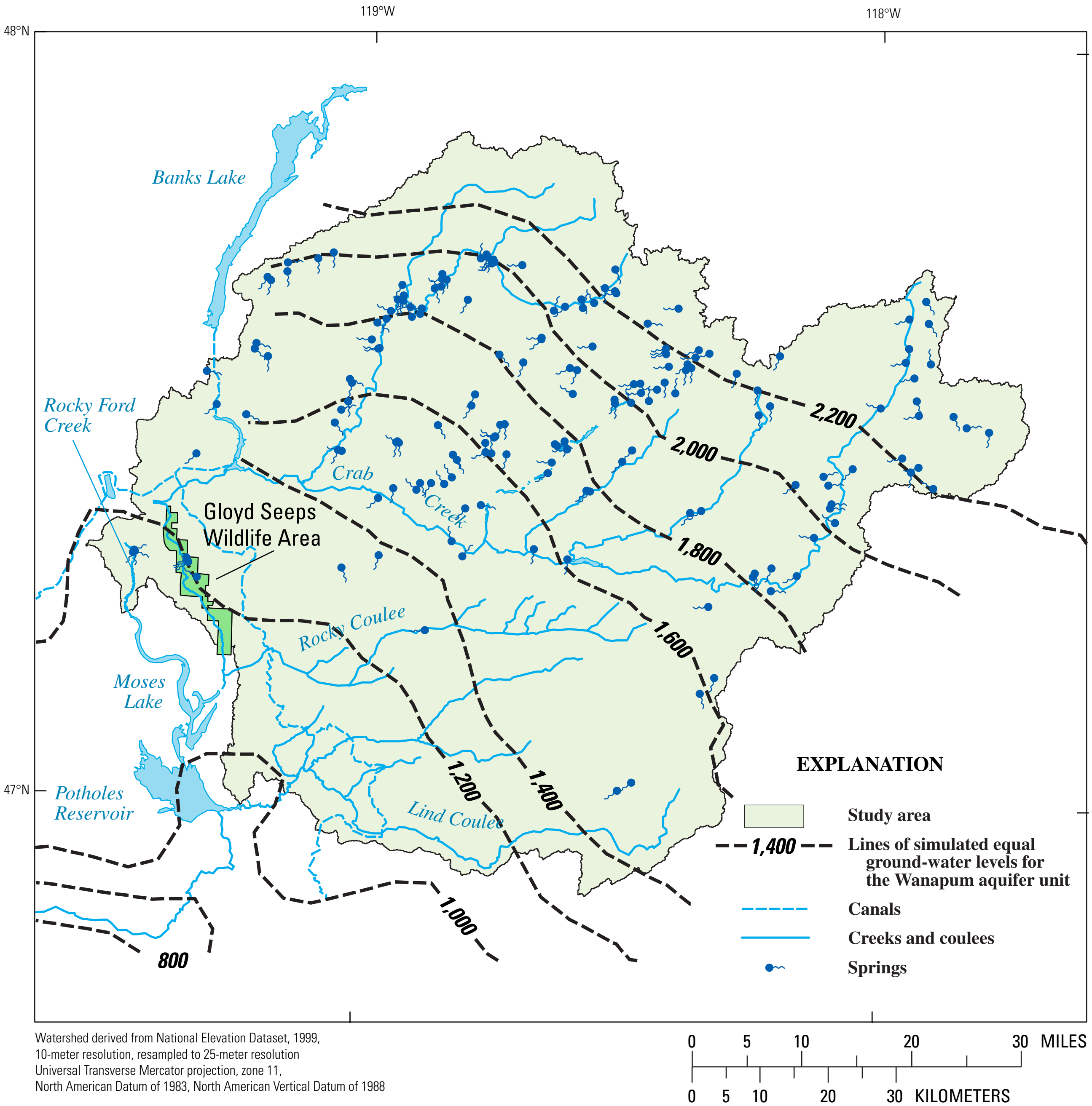


Figure 13. Simulated groundwater levels in the Wanapum aquifer unit and location of springs in the upper Crab Creek, Rocky Ford Creek, Rocky Coulee, and Lind Coulee drainage basins, Washington. (Source: Hansen and others [1994], plate 12, map c; U.S. Geological Survey [variously dated], 7.5 minute topographic maps.)

Channel Gains and Losses

Most streamflow channels in the study area have low gradients and contain low flows or no flow during much of the year. Two channel-flow processes are important in the study area: (1) the channel losses-and-gains process, and (2) the wetting-up process during the spring-runoff season when certain reaches lose all or most of their water to channel-connected ponds or lakes and to the shallow groundwater system until a threshold volume is reached. After the threshold is reached, channel losses are reduced. Presumably, the water recharges a local surface aquifer until the water table intersects with streamflow channels, and local instream ponds and lakes that have drawn down over the autumn and winter seasons.

Channel losses and gains are evident in most of the channel reaches throughout the study area. The results of two seepage runs (discharge measurements made at many places in a basin over a short period) on May 20–22 and September 8–10, 2003, for Crab Creek are listed in table 1. Large channel gains from groundwater discharge were at the highest and lowest reaches of Crab Creek between creek mile (CM) 145.1 and CM 137.3 and between CM 66.9 and CM 65.6—channel losses generally were at other locations. These channel losses are important sources of recharge to the groundwater system and often make the difference between a downgradient reach being perennial or being dry most of the year.

A comparison of the hydrograph measured at the streamflow-gaging station at Crab Creek at Irby with the hydrograph for its downstream station, Crab Creek near Moses Lake, indicates that the pattern of streamflow varies with the season (fig. 14). Early in the calendar year after the runoff season begins, flows at Crab Creek at Irby are much greater than those measured at the streamflow-gaging station at Crab Creek near Moses Lake, which indicates almost no response in its discharge hydrograph despite large flow increases upstream. Local hydrologists have described this dramatic channel loss early in the season as a "wetting-up" process of recharging the local, shallow aquifer below the channel (P. J. O'Callaghan, Bureau of Reclamation, oral commun., 2005). The hydrograph shows that after a certain volume of runoff has flowed past Crab Creek at Irby, Crab Creek near Moses Lake becomes more responsive and often exceeds the flow at Crab Creek at Irby. This wetting-up process seems to require a threshold amount of runoff volume before the downstream gaging station becomes responsive to the flows recorded upstream. For the reaches below Crab Creek at Irby, the threshold cumulative runoff volume is about 20,000 acre-ft measured beginning January 1 (fig. 14). As the aquifer becomes saturated, channel losses decrease to zero or near zero. Also, a part of the process includes the filling of in-channel lakes on Crab Creek in the spring before water can begin to flow downstream.

Table 1. Results from discharge measurements at Crab Creek upstream of Moses Lake, some tributaries, and several irrigation returns in the Potholes Reservoir basin, Washington, May and September 2003.

[Creek mile of irrigation returns is at the confluence of the return with Crab Creek. **Abbreviations:** e, estimated discharge; ft^3/s, cubic foot per second; ºC, degrees Celsius; µS/cm, microsiemens per centimeter; N, north; S, south; E, east; W, west; NE, northeast; NW, northwest; SE, southeast; SW, southwest; sec., section, T, township; R, range; –, no data]

Creek mile	Stream	Location	Measured discharge (ft^3/s)	Date	Gain (+) or loss (-)	Water temperature (ºC)	Specific conductance (µS/cm)
		May 20–22, 2003					
145.1	Crab Creek	SE¼NE¼ sec. 22, T.21N., R.36E., at State Route 23 near Sprague	20.0	05-21	–	12.1	361
137.3	Crab Creek	Gaging station at Rocky Ford Road near Ritzville (12464770)	39.2	05-21	+19.2	11.5	367
142.7	Coal Creek	Gaging station at Mohler (12464800)	2.16	05-21	–	14.5	600
127.8	Coal Creek	NW¼NW¼ sec. 6, T.21N., R.34E., above railroad bridge crossing near Odessa	0.44	05-21	-1.72	16.8	447
125.8	**Confluence of Coal Creek and Crab Creek**						
125.4	Crab Creek	SE¼SW¼ sec. 12, T.21N., R.33.E., downstream of Sylvan Lake near Odessa (12464810)	29.9	05-21	-9.7	14.8	407
111.5	Crab Creek	Gaging station at Irby (12465000)	27.3	05-21	-2.6	12.3	456
103.5	Crab Creek	SE¼SE¼ sec. 12, T.22N., R.30E., at Marlin	6.93	05-22	-20.4	16.2	449
96.9	Crab Creek	NE¼SW¼ sec. 12, T.22N., R.29E, above Wilson Creek near Wilson Creek	0.00	05-22	-6.93	–	–
119.6	Wilson Creek	Gaging station below Corbett Draw near Almira (12465400)	8.68	05-21	–	14.4	475
97.7	Wilson Creek	SW¼NW¼ sec. 6, T.22N., R.30E., at discontinued gaging station at Wilson Creek (12465500)	0.00	05-21	-8.68	–	–
96.6	**Confluence of Wilson Creek and Crab Creek**						
91.1	Crab Creek	SW¼NE¼ sec. 6, T.22N., R.29E., above Brook Lake near Stratford	0.00	05-21	0.00	–	–
87.2	Crab Creek	NE¼NE¼ sec. 10, T.22N., R.28E., at Stratford Road at Stratford	0.00	05-21	0.00	–	–

Table 1. Results from discharge measurements at Crab Creek upstream of Moses Lake, some tributaries, and several irrigation returns in the Potholes Reservoir basin, Washington, May and September 2003.—Continued

[Creek mile of irrigation returns is at the confluence of the return with Crab Creek. **Abbreviations:** e, estimated discharge; ft^3/s, cubic foot per second; ºC, degrees Celsius; µs/cm, microsiemens per centimeter; N, north; S, south; E, east; W, west; NE, northeast; NW, northwest; SE, southeast; SW, southwest; sec., section, T, township; R, range; –, no data]

Creek mile	Stream	Location	Measured discharge (ft^3/s)	Date	Gain (+) or loss (-)	Water temperature (°C)	Specific conductance (µS/cm)
			May 20–22, 2003—Continued				
80.35	Irrigation return	SW¼SE¼ sec. 23, T.22N., R.27E., W3EWW on Road 20 NE near Adrian	[1]0.086	05-21	–	[1]16.1	1,140
80.3	Crab Creek	NE¼NE¼ sec. 26, T.22N., R.27E., at Road 20 NE near Adrian	0.009	05-21	-0.08	20.8	134
77.8	Irrigation return	Center of SE¼ sec. 35, T.22N., R.27E., W3W1WW above Willow Lake near Soap Lake	[1]0.004(e)	05-21	–	[1]19.4	[1]140
74.7	Crab Creek	SW¼NW¼ sec. 18, T.21N., R.28E., below Willow Lake near Ephrata	0.00	05-21	-0.005	–	–
74.7	Irrigation return	SW¼NW¼ sec. 18, T.21N., R.28E., below Willow Lake near Ephrata	0.077	05-21	–	22.2	412
67.3	Irrigation return	SE¼SE¼ sec. 9, T.20N., R.28E., EL16GWW on Road 10 NE near Moses Lake	4.59	05-22	–	14.7	137
66.9	Crab Creek	NE¼SW¼ sec. 10, T.20N., R.28E., above Road 10 NE at Gloyd	0.00	05-20	- 4.67	–	–
66.6	Irrigation return	NE¼SW¼ sec. 10, T.20N., R.28E., East Low Return above Road 10 NE, west of Stratford Road	[1]30.6	05-21	–	[1]14.1	[1]376
66.4	Irrigation return	NE¼NW¼ sec. 14, T.20N., R.28E., DE214 below Road 10 NE, east of Stratford Road	[1]7.51	05-21	–	[1]16.1	[1]345
66.4	Irrigation return	NW¼SW¼ sec. 11, T.20N., R.28E., East Low Return above Road 10 NE, east of Stratford Road	[1]3.13	05-21	–	[1]16.0	[1]382
65.6	Crab Creek	NE¼SE¼ sec.15, T.20N., R.28E., at Stratford Road near Moses Lake	20.9	05-22	-20.3	14.9	415
63.2	Irrigation return	SW¼SW¼ sec. 25, T.20N., R.28E., DE217 on Road 7 NE, east of Stratford Road	[1]0.591	05-20	–	[1]19.6	[1]565
63.0	Crab Creek	Gaging Station near Moses Lake (12467000)	27.8	05-22	+6.31	14.8	435
			September 8–10, 2003				
145.1	Crab Creek	SE¼NE¼ sec. 22, T.21N., R.36E., at State Route 23 near Sprague	1.96	09-09	--	8.9	358
137.3	Crab Creek	Gaging station at Rocky Ford Road near Ritzville (12464770)	10.6	09-09	+8.6	12.7	371
142.7	Coal Creek	Gaging station at Mohler (12464800)	0.22	09-09	–	12.8	462
145.1	Crab Creek	SE¼NE¼ sec. 22, T.21N., R.36E., at State Route 23 near Sprague	1.96	09-09	--	8.9	358
137.3	Crab Creek	Gaging station at Rocky Ford Road near Ritzville (12464770)	10.6	09-09	+8.6	12.7	371
142.7	Coal Creek	Gaging station at Mohler (12464800)	0.22	09-09	–	12.8	462
127.8	Coal Creek	NW¼NW¼ sec. 6, T.21N., R.34E., above railroad bridge crossing near Odessa	0.00	09-09	-0.22	–	–
125.8	**Confluence of Coal Creek and Crab Creek**						
125.4	Crab Creek	SE¼SW¼ sec. 12, T.21N., R.33.E., downstream of Sylvan Lake near Odessa (12464810)	0.00	09-09	-10.6	–	–

Table 1. Results from discharge measurements at Crab Creek upstream of Moses Lake, some tributaries, and several irrigation returns in the Potholes Reservoir basin, Washington, May and September 2003.—Continued

[Creek mile of irrigation returns is at the confluence of the return with Crab Creek. **Abbreviations:** e, estimated discharge; ft^3/s, cubic foot per second; ºC, degrees Celsius; µs/cm, microsiemens per centimeter; N, north; S, south; E, east; W, west; NE, northeast; NW, northwest; SE, southeast; SW, southwest; sec., section, T, township; R, range; –, no data]

Creek mile	Stream	Location	Measured discharge (ft^3/s)	Date	Gain (+) or loss (-)	Water temperature (ºC)	Specific conductance (µS/cm)
		September 8–10, 2003—Continued					
111.5	Crab Creek	Gaging station at Irby (12465000)	4.60	09-09	+4.6	16.2	485
103.5	Crab Creek	SE¼SE¼ sec. 12, T.22N., R.30E., at Marlin	0.00	09-09	-4.6	–	–
96.9	Crab Creek	NE¼SW¼ sec. 12, T.22N., R.29E, above Wilson Creek near Wilson Creek	0.00	09-09	0.00	–	–
119.6	Wilson Ck.	Gaging station below Corbett Draw near Almira (12465400)	1.84	09-10	–	11.4	639
97.7	Wilson Ck.	SW¼NW¼ sec. 6, T.22N., R.30E., at discontinued gaging station at Wilson Creek (12465500)	0.00	09-09	-1.84	–	–
96.6	**Confluence of Wilson Creek and Crab Creek**						
91.1	Crab Creek	SW¼NE¼ sec. 6, T.22N., R.29E., above Brook Lake near Stratford	0.00	09-09	0.00	–	–
87.2	Crab Creek	NE¼NE¼ sec. 10, T.22N., R.28E., at Stratford Road at Stratford	0.00	09-09	0.00	–	–
80.35	Irrigation return	SW¼SE¼ sec. 23, T.22N., R.27E., W3EWW on Road 20 NE near Adrian	[1]2.57	09-09	–	[1]16.7	[1]140
80.3	Crab Creek	NE¼NE¼ sec. 26, T.22N., R.27E., at Road 20 NE near Adrian	0.024	09-09	[3]	20.5	134
77.8	Irrigation return	Center of SE¼ sec. 35, T.22N., R.27E., W3W1WW above Willow Lake near Soap Lake	[2]1.98	09-09	–	[1]13.7	[1]96.7
74.7	Crab Creek	SW¼NW¼ sec. 18, T.21N., R.28E., below Willow Lake near Ephrata	0.00	09-09	-2.00	–	–
74.7	Irrigation return	SW¼NW¼ sec. 18, T.21N., R.28E., below Willow Lake near Ephrata	2.35	09-09	–	16.2	702
67.3	Irrigation return	SE¼SE¼ sec. 9, T.20N., R.28E., EL16GWW on Road 10 NE near Moses Lake	[1]4.42	09-08	–	19.3	133
66.9	Crab Creek	NE¼SW¼ sec. 10, T.20N., R.28E., above Road 10 NE at Gloyd	0.00	09-09	-6.77	–	–
66.6	Irrigation return	NE¼SW¼ sec. 10, T.20N., R.28E., East Low Return above Road 10 NE, west of Stratford Road	[1]43.0	09-09	–	[1]13.2	[1]501
66.4	Irrigation return	NE¼NW¼ sec. 14, T.20N., R.28E., DE214 below Road 10 NE, east of Stratford Road	[1]5.44	09-09	–	[1]14.3	[1]522
66.4	Irrigation return	NW¼SW¼ sec. 11, T.20N., R.28E., East Low Return above Road 10 NE, east of Stratford Road	[1]6.19	09-09	–	[1]14.2	[1]377
65.6	Crab Creek	NE¼SE¼ sec.15, T.20N., R.28E., at Stratford Road near Moses Lake	30.1	09-09	-24.5	15.4	451
63.2	Irrigation return	SW¼SW¼ sec. 25, T.20N., R.28E., DE217 on Road 7 NE, east of Stratford Road	[1]4.29	09-09	–	[1]14.8	[1]621
63.0	Crab Creek	Gaging Station near Moses Lake (12467000)	54.6	09-10	+20.2	12.1	555

[1]Measurement or estimate made by Patrick Pope, Bureau of Reclamation, Ephrata, Washington.

[2]Discharge determined from weir rating.

[3]Just prior to the discharge measurement at Crab Creek at Road 20 NE, near Adrian, the irrigation return W3EWW on Road 20 NE near Adrian was shut down to near zero flow.

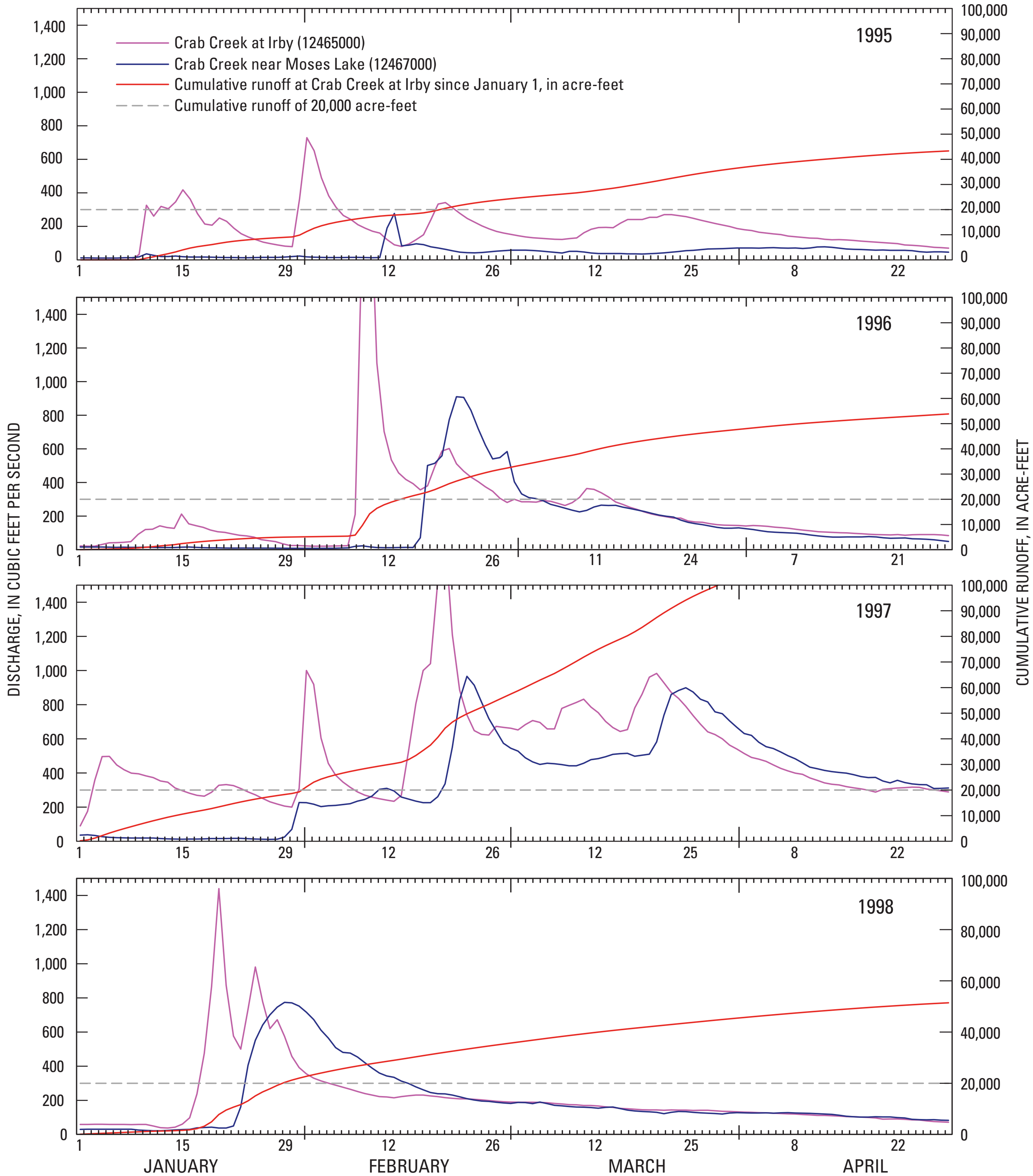


Figure 14. Discharge at Crab Creek at Irby, Crab Creek near Moses Lake, and cumulative runoff volume at Crab Creek at Irby, in the Potholes Reservoir basin, Washington, January through April during water years 1995–98.

Irrigation

The CBP currently irrigates 620,000 acres with farmland deliveries of about 3.7 acre-ft/acre or about 2,294,000 acre-ft of water. Total return flow to Potholes Reservoir is estimated at 640,000 acre-ft or an annual mean discharge of 884 ft^3/s (Montgomery Water Group, 2003). Much of the return flow to Potholes Reservoir is through drains that flow into the natural stream channels. The hydrograph (fig. 7) for mean monthly discharge measured at the streamflow-gaging station at Crab Creek at Irby (upstream of the irrigation areas within the CBP) shows that flow continues to recede in June after peaking during the spring runoff season. However, after May, the hydrograph measured at the streamflow-gaging station at Crab Creek near Moses Lake begins to rise for the remainder of the water year, as irrigation return flow becomes the major part of the flow. In the study area, irrigated CBP land totals 77,400 acres, which is downgradient and generally west of the East Low Canal.

Outside the CBP boundaries, water for irrigation is pumped from wells. Cline and Knadle (1990) estimated that a total of 33,270 acre-ft was pumped in 1984 in the Crab Creek basin upstream of the Crab Creek at Irby gaging station. The water came mostly from two basalt units, the Grande-Ronde (12,900 acre-ft) and the Wanapum Units (9,370 acre-ft). Hansen and others (1994, table 9) estimated that groundwater pumping decreased the streamflow discharge at Crab Creek at Irby by 38.2 ft^3/s between predevelopment conditions and the simulated 1983–85 time-average conditions. If pumpage is assumed to occur only during the irrigation season, April through September, the monthly decrease in discharge would average 76.2 ft^3/s for this 6-month period.

Generalizations about the Study Area

The description of the conceptual model does not include all the hydrologic processes that operate in the study area, but it does include those that are common in the study area and many other basins in Washington. Six generalizations make up the conceptual hydrologic model that guides the development and calibration of the runoff simulation model for the study area.

1. The hydrologic processes common in most watersheds in Washington, such as precipitation distribution, snow accumulation and melt, interception, infiltration, shallow-subsurface flow, and other processes are important in the study area and must be considered in any hydrologic simulation.

2. The timing and volume of peak flows can be strongly affected by frozen ground in the basin by reducing soil infiltration and routing most water available for runoff overland. This results in flashy and much greater peak-flow discharge. Because snow cover can be an insulating factor, snow cover established after a deep freeze may keep the soils frozen and snow cover established before a deep freeze may keep the soil unfrozen by shielding it from cold air temperatures.

3. A significant part of water provided by precipitation to the land surface in the study area is lost through evaporation and transpiration, leaving little water available for runoff—especially during the summer season. To simulate AET and PET accurately, soil moisture also must be simulated accurately when computing water available for runoff.

4. Regional groundwater flow crosses surface-water flow boundaries and is a significant source of streamflow in several reaches in the study area. Mapped locations of springs and seeps provide a simple method of identifying groundwater discharge sites and reaches that can maintain flows that otherwise would be dry soon after rain or snowmelt ends.

5. Many reaches in the study area are either losing or gaining water through channel losses or groundwater discharge, respectively. Certain reaches require a threshold flow volume during spring to “wet up” the channel before significant outflow can occur.

6. Within the CBP, imported surface water supplies most of the irrigation needs and irrigation return flows become an increasing part of the total flow in the natural channels as the irrigation season progresses. Groundwater supplies the irrigation water on irrigated farmland outside the CBP boundaries. Although a direct link between a particular groundwater withdrawal and a surface-water flow is difficult to demonstrate for specific reaches in the study area, it is likely that withdrawals from shallow wells are reducing flows in the creeks and coulees.

Simulation of Runoff

The hydrologic generalizations summarized in the previous section were incorporated into a numerical model that simulates the runoff as a function of hydrologic processes in the study basin. MMS provides the capability to pick and choose combinations of computer code or modules that best represent the hydrologic system that is being simulated. The numerical model chosen to simulate the hydrologic processes in the study area is based on the PRMS model (Leavesley and others, 1983) with updated modules developed for the Yakima WARSMP project (Mastin and Vaccaro, 2002a, b), and enhanced with new modules developed for this investigation. All the modules for this investigation have been written in FORTRAN and compiled and linked with the MMS XMBUILD utility program. The output from XMBUILD is an executable file designed to run on a UNIX platform, and it includes a built-in user interface (fig. 15). The modules

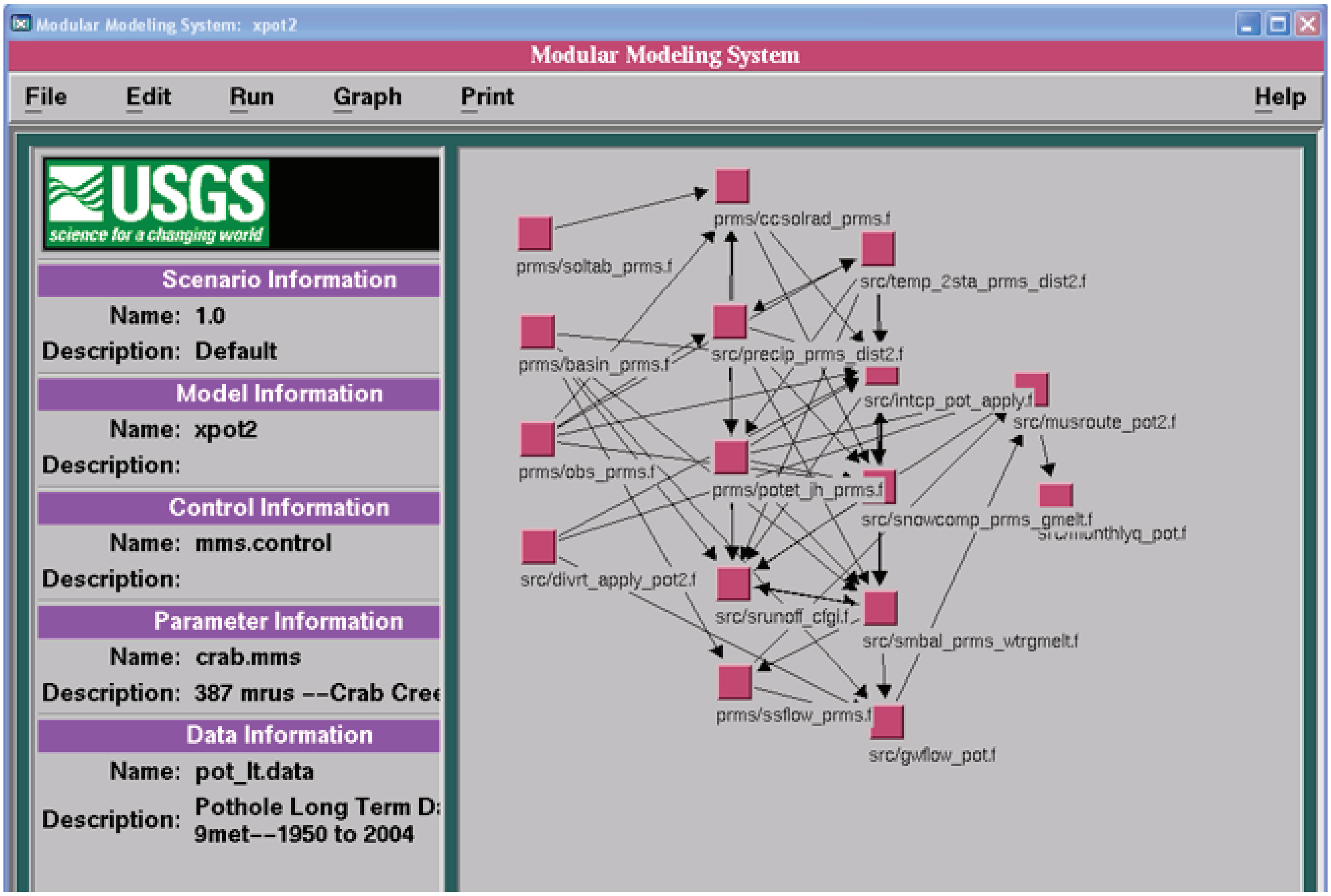


Figure 15. Opening screen of the Modular Modeling System user interface for the xpot2 watershed simulation model. (Red boxes on the right panel are the modules that were compiled and linked to build the executable file.)

were later compiled using a Windows compiler to create a Windows-compatible executable file with the same name. For this investigation, the executable file is call xpot2.exe, which can simulate runoff for each of the three watershed models developed for the study area simply by changing the parameter file. The data file contains time-series data of precipitation and air temperature and is common to all three models. Generally, modules represent a particular hydrologic process but they can be modified to add functionality to the model.

Description of the Numerical Model

The PRMS model is a continuous, distributed model that simulates runoff for individual land segments. The watershed is divided into many land segments and the segments are grouped into Model Response Units (MRUs) that have similar runoff responses to precipitation, temperature, and solar radiation inputs. A daily water budget is computed for each MRU that accounts for user-supplied inputs, the various surface and subsurface reservoirs, and the flow paths (fig. 16). See the users' manual for a more complete discussion of the model (Leavesley and others, 1983).

Modular Modeling System Modules Developed for the Yakima Watershed and River Systems Management Program Project

The Yakima WARSMP project modified several original PRMS modules. The modified modules, which are used in this investigation, are precipitation (precip_prms_dist2.f), temperature (temp_2sta_prms_dist2.f), snow (snowcomp_prms_gmelt.f), and soil moisture (smbal_prms_wtrgmelt.f). Mastin and Vaccaro (2002a) provide complete descriptions of each module and the model code.

The precipitation and temperature modules incorporate all the input values from all the weather stations to calculate precipitation and temperature values for each MRU using inverse distance-weighting techniques. The original PRMS model simply assigned one weather station and an adjustment factor to distribute precipitation and temperature to each MRU. Both modified modules overcome a real-time forecasting problem, present in the original modules, because they can compute valid results even when one or more weather stations report missing data or erroneous values that are outside of user-supplied limits.

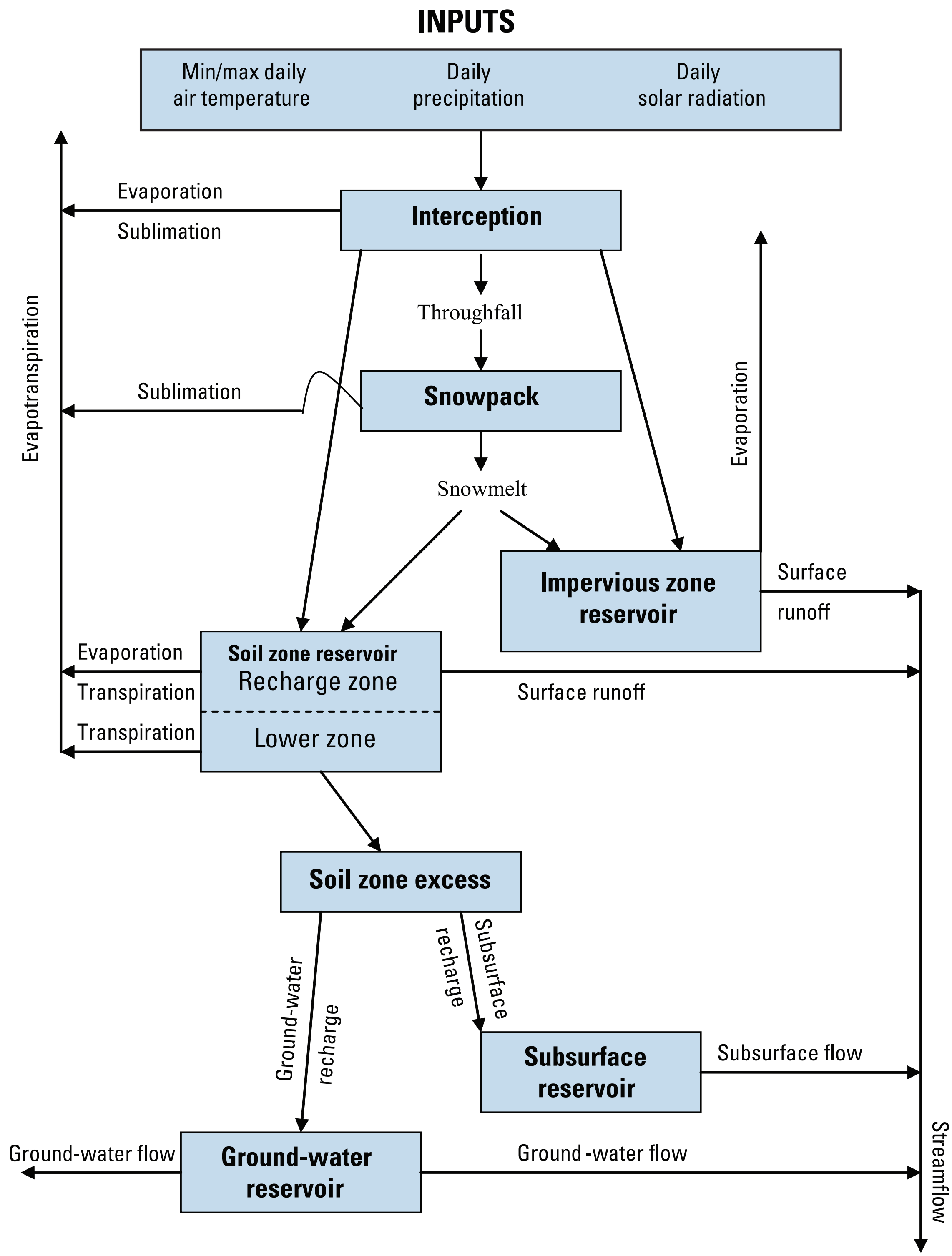


Figure 16. Water flow paths and reservoirs for a Model Response Unit computed by the Precipitation Runoff Modeling System numerical watershed model.

The following model parameters are needed to compute a precipitation value for each MRU: (1) coordinates of the center of each MRU and each precipitation station and (2) the mean monthly precipitation for each MRU and each precipitation station. For each MRU, each daily precipitation input from each station is weighted first by using a simple inverse distance-weighting technique and second by multiplying the result with the ratio of the mean monthly precipitation of the MRU to the mean monthly precipitation of the station. The daily value for the MRU is the average of each weighted value computed for each precipitation station with a valid input.

Daily minimum and maximum air temperatures also are distributed to each MRU by an inverse distance-weighting technique and by considering the effects of elevation. First, a basinwide daily minimum and maximum air-temperature lapse rate is computed from the average of all the lapse rates computed from temperatures measured at each weather station. Lapse rates are the rates of change in temperature with change in elevation. If the computed lapse rate is outside a user-defined, monthly varying range of lapse rates, it reverts to a default lapse rate. Second, the module computes the MRU minimum and maximum air temperatures as the average of inverse-distance weighted minimum and maximum weather-station temperatures multiplied by the appropriate temperature lapse rate and the elevation difference between the MRU and the weather station.

The modified snow module added a ground-melt component to the original PRMS snow module, which provides up to 0.05 in. additional snowmelt water to the soil zone per day. This additional component simulates a snowmelt process observed at experimental watersheds in the West (U.S. Army Corps of Engineers, 1956) that can sustain winter low flows when the air temperatures are below freezing.

The modified soil-moisture module altered the original PRMS by including a soil type for lakes and ponds, and setting the AET equal to PET for an MRU identified with that soil type. The modified module also incorporates any additional moisture input to the soil from ground melt.

New Modules

Five new modules were created for this investigation by modifying existing modules. Four of the existing modules were developed for the Yakima WARSMP (Mastin and Vaccaro, 2002a) and the fifth was an original PRMS module (Leavesly and others, 1983). The new modules are:

1. gwfow_pot.f, which allows the routing irrigation-diversion losses to a user-specified groundwater reservoir—this module modifies module gwflow_prms_min darcy.f (Mastin and Vaccaro, 2002a);

2. musroute_pot2f, which allows the simulation of channel losses and a "wetting-up" channel process—this module modifies modules musroute_prms_divretrn.f (Mastin and Vaccaro, 2002a);

3. intcp_pot_apply.f, which allows the simulation of irrigation applications with time series in cubic feet per second rather than inches—this module modifies module intcp_prms_apply.f (Mastin and Vaccaro, 2002a);

4. divrt_apply_pot2f, which allows the simulation of irrigation applications with time series in cubic feet per second rather than inches—this module modifies module divrt_apply.prms.f (Mastin and Vaccaro, 2002a); and

5. srunoff_cfgi.f, which simulates frozen ground with a frozen-ground index and channels all simulated runoff through the surface flowpath when frozen-ground conditions are indicated—this module modifies module srunoff_smidx_prms.f (Leavesley and others, 1983).

Groundwater outflow in the original PRMS model simply flowed out of a simulated reservoir to the stream or to a groundwater sink representing a deep aquifer. In module gwflow_prms_min_darcy.f, groundwater outflow may flow to a down-slope groundwater reservoir linked to a separate MRU. This gives the modeler the ability to redirect groundwater flow to known groundwater discharge points that may be outside the basin where the recharge originated. The rate of flow is determined by the elevation differences of the MRU and the average of the user-supplied groundwater routing coefficients for each MRU. For this investigation, the module was modified by adding the capability to simulate irrigation diversion losses as a percentage of the total diversion limited to a maximum amount, and assigning those losses to user-specified groundwater reservoirs.

Flow routing, channel losses, and the wetting-up process are simulated by new module musroute_pot2.f. In this module, channel reaches are represented by nodes at either end of the reach, and the channel network is defined by specifying the downstream node for each node as well as the final node. Discharge is calculated at each node and is available for display or output to files. Flow routing is computed using the Muskingum method (Linsley and others, 1982, p. 275), which is unchanged from the previously published musroute_prms.f module described by Mastin and Vaccaro (2002a). Surface runoff, subsurface flow, and groundwater flow from the MRUs are directed to nodes and then routed downstream. The modified module also routes return flows, if present. Where channel losses are known to occur, the module allows the modeler to simulate losses as a percentage of total flow up to a user-selected maximum amount. Channel losses are simulated as water lost to deep recharge, and thus water lost from the water-budget calculations and any runoff contributions.

The wetting-up process is simulated by defining a threshold volume or "dead storage" in the reach that must be met before outflow occurs. The dead storage is depleted by AET at the PET rate, and in application in this investigation, this generally would empty the reach before the spring melt begins.

Module intrcp_pot_apply.f simulates the interception of precipitation by vegetation and the application of irrigation. Irrigation is added to any precipitation that might be occurring, and if the irrigation type is identified as sprinkler irrigation, interception by vegetation is simulated. This module works together with module divrt_apply_pot2.f that reads user-provided time-series inputs of diversions, irrigation applications, and return flows in units of cubic feet per second and either subtracts the flows from a node in the case of a diversion or adds flows to a node in the case of a return flow. Note that the capabilities of simulating irrigation applications, diversion of water for irrigation, canal losses in diversion canals, and return flows were incorporated into the model but were not used in this study. Instead, the RiverWare water-management model that is part of the DSS will simulate these processes. The capabilities were added to the model to make them available if they are needed at a later time.

The srunoff_smidx_prms.f module was modified to simulate runoff from frozen ground with a Continuous Frozen Ground Index (CFGI). The CFGI was developed at the National Weather Service Northwest River Forecast Center by Molnau and Bissel (1983). The index also was described by Larson and others (2002) in the following equation:

$$CFGI_i = A*CFGI_{i-1} - T*e^{(-0.4*K*D)}, \qquad (1)$$

where

$CFGI_i$ is Continuous Frozen Ground Index on day i, dimensionless and , ≥ 0;

$CFGI_{i-1}$ is Continuous Frozen Ground Index on day i, minus 1, dimensionless and ≥ 0;

T is mean daily air temperature, in degrees Celsius;

A is daily decay coefficient, dimensionless;

e is the base of the natural logarithm;

K is snow reduction coefficient in centimeters^{-1} (0.5 cm^{-1} for T greater than 0°C and 0.08 cm^{-1} for T less than 0°C; and

D is depth of snow on the ground, in centimeters.

In the model, CFGI is set to zero at the start of the simulation unless a previous value has been stored and saved in a variable file. Once the index reaches a user-defined threshold (parameter cfgi_thrshld in the module), all simulated liquid water at the land surface of that MRU becomes surface runoff. CFGI only increases when the mean daily air temperature (T) is below 0°C. Increasing snow-cover depth (D) tends to reduce any increase in CFGI up to a certain depth when no increase in CFGI is possible. The user can adjust the daily rate of decay of the CFGI value by adjusting model parameter cfgi_decay (A in eq. 1).

Construction of Models

Three separate watershed models were constructed for the study area—the Crab Creek Model Unit, the Lind Coulee Model Unit, and the Rocky Coulee Model Unit. Each watershed model uses the same MMS model with the same set of modules, but each model has a different set of parameter values. The initial construction of the three watershed models was done with the GIS Weasel, a GIS tool developed through WARSMP that has GIS macros specifically designed to compute parameters for the PRMS model (Viger and others, 1998). Using the GIS Weasel, MRUs were delineated, MRU index numbers were renumbered into continuous sequences by subbasin, and initial model parameters were generated. PRMS requires many parameters for constructing a model and Weasel is designed to estimate most of them. However, many parameters still need to be computed outside of the GIS Weasel, especially for the new, nonstandard modules.

GIS Weasel

The primary input to the GIS Weasel is a digital elevation model (DEM) of the study area. A DEM with a 25-meter cell spacing was resampled for the study area from a 10-meter DEM from the National Elevation Dataset (U.S. Geological Survey, 2008). The GIS Weasel used this DEM to define the surface-water drainage boundaries and stream channels, partition each of the three model units—Crab Creek, Rocky Coulee, and Lind Coulee—into MRUs, and compute initial model-parameter values. The three resulting model units are shown in figure 17.

The pour point or the lowest point that Weasel uses to define the watershed was set at the mouths of the creek for Rocky Ford Creek (part of the Crab Creek Model Unit) and for Rocky Coulee. The pour point for Crab Creek was set at the USGS streamflow-gaging station at Crab Creek near Moses Lake (12467000) and for Lind Coulee it was set at the streamflow-gaging station at Lind Coulee Wasteway at SR 17 near Warden (12471400). The upstream point for a stream was defined as the point where the accumulated drainage area equaled 3.5 mi^2, a point that provided a reasonable definition of the drainage network. The first partitioning of MRUs used the two flow-plane division method where an MRU is defined on either side of a stream link. A stream link is the stream reach between two confluences or from the upstream stream endpoint to the first confluence. A second partitioning was made to include the irrigated blocks of land within the CBP and the basin boundaries defined as irrigation blocks or lateral basins—administrative units of land used by Reclamation to supply irrigation water (Roger Sonnichsen, Bureau of Reclamation, written commun., 2003).

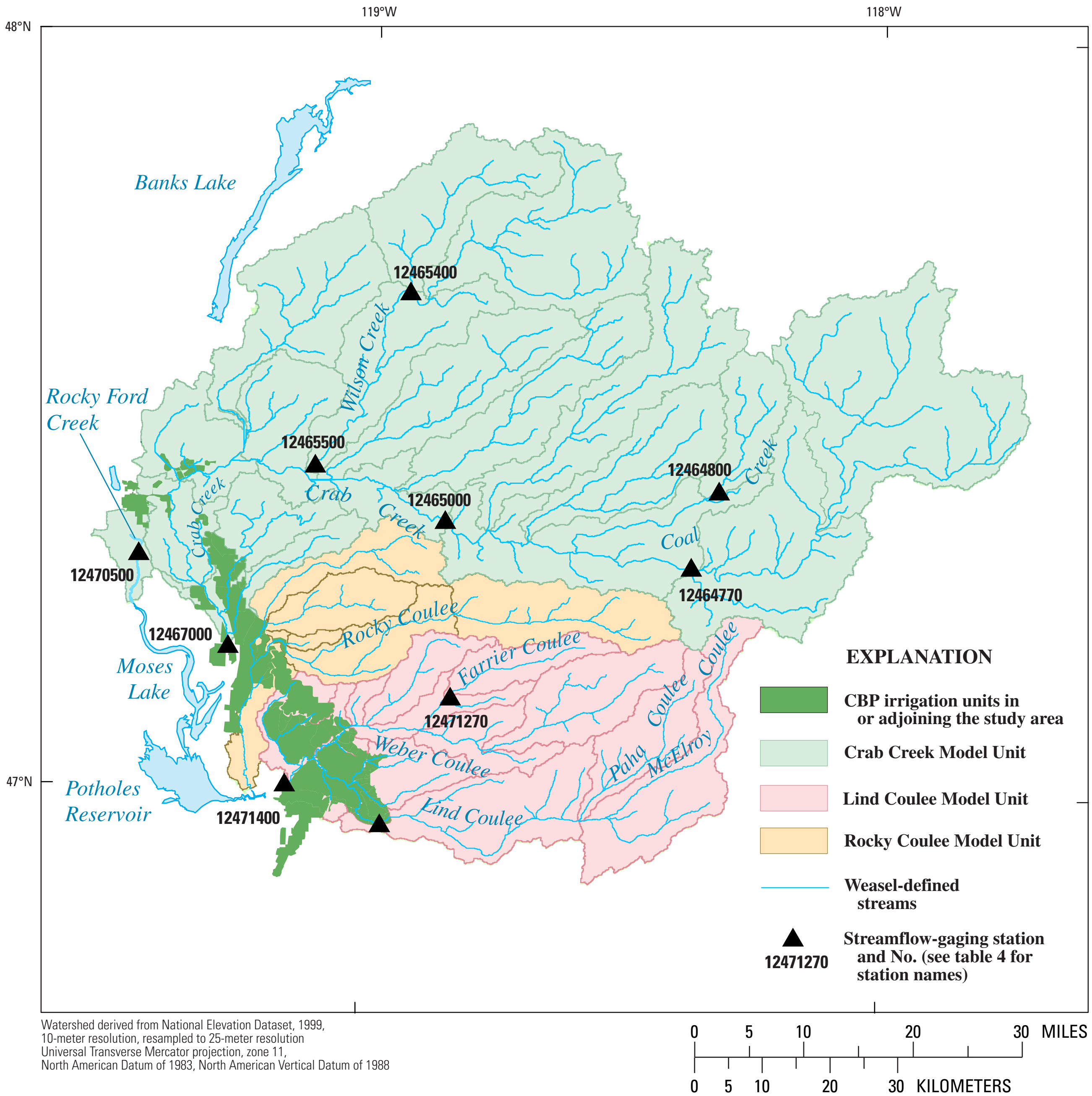


Figure 17. Subbasins and streams defined for the three model units and irrigation units in the Potholes Reservoir basin, Washington.

Each model unit was subdivided into major subbasins at major stream confluences or at streamflow-gaging stations, and the MRU index numbers (unique identifier for each MRU) were renumbered so that subbasins would have consecutive numbers. However, some editing of subbasin boundaries and MRUs after the fact sometimes created a separate series of consecutive numbers in the subbasins (fig. 17 and 19, table 2). A separate groundwater reservoir and subsurface reservoir was assigned to each MRU and each was indexed with the same index number as the MRU index number.

After defining the drainage and MRU boundaries, the Weasel computes a set of initial parameters for each MRU based on the DEM and the National GIS datasets that are packaged with the Weasel program. These datasets include: the 1-km gridded soil data of the State Soil Geographic Database (STATSGO, U.S. Department of Agriculture, 1994), the 1-km gridded land cover of the USGS Global Land Cover Characterization (Loveland and others, 2000), and the 1-km gridded forest cover and density produce by the Forest Service (U.S. Department of Agriculture, 1992). Though many years have passed since the datasets were compiled, no substantial changes have taken place in the watershed.

Table 2. Drainage areas, subbasins, model response units, and irrigated land in the Columbia Basin Project by model unit in the Potholes Reservoir basin, Washington.

[**Acronym:** MRU, model response unit]

Model unit	Drainage area (acres)	Number of subbasins	Number of MRUs	Irrigated land (acres)
Crab Creek	1,464,651	20	387	16,780
Rocky Coulee	213,804	7	76	13,846
Lind Coulee	460,086	10	165	46,739

Parameter Estimation Outside of Weasel

After a set of initial model parameters was generated by the GIS Weasel, other additional model parameters were needed and some initial model parameters had to be revised based on calculations outside of Weasel. These parameters are the groundwater reservoir outflow parameters, location and monthly mean precipitation parameters for the MRUs and weather stations, monthly coefficients for PET calculations, flow-routing parameters, vegetation density and interception parameters, and monthly regression coefficients for an equation that relates temperature to cloud cover that is then used to estimate daily incoming solar radiation.

Groundwater reservoir outflow can be directed to the channel, to other groundwater reservoirs that are lower in elevation, or to a deep-aquifer sink (removed from any runoff contribution). Initially, groundwater reservoirs near springs (fig. 13) and near the mouth of a subbasin had their outflows directed to the stream. Remaining groundwater outflows were routed to nearby, lower groundwater reservoirs in the same subbasin. The rate of outflow from a groundwater reservoir is a function of its current storage and a recession coefficient, or in the case of flow between two reservoirs, it is the average of the two recession coefficients. The recession coefficient can be estimated from observed streamflow records following a procedure described by Leavesley and others (1983, p. 33). The initial recession coefficient used in all three models was 0.0086 days^{-1}. This coefficient was computed using 53 years of September flows from the observed records for the USGS streamflow-gaging station at Crab Creek at Irby (12465000).

The new precipitation and temperature modules that use elevation and distance functions to distribute the observed values require elevation, and northing and easting for each MRU and each weather station. Elevation was determined from the DEM, and northing and easting, in meters in UTM 11 coordinates for the MRU centroid, were determined with GIS software. The monthly mean precipitation parameters for the MRUs were determined from the 1961–90 means reported in the PRISM model (Daly and others, 1997) using GIS techniques. Weather station monthly mean precipitation parameters were derived from observed data for the same period. Values of mean annual precipitation at weather stations were compared with PRISM values at the same locations for 1961–90. Only one site had a difference of 0.6 in. and the remainder of the sites had differences of 0.3 in. or less and little bias was evident.

Simulated PET is calculated using the Jensen-Haise procedure. The monthly MRU air-temperature coefficients for the Jensen-Haise algorithm were calculated according to equations described by Leavesley and others (1983, p. 21–22). In his equations the mean monthly minimum and maximum air-temperature data are used, and for this study, the means for the weather station at Odessa, Washington, 1948–2005 (Western Regional Climate Center, 2006a) were used. The watershed model was run using the original calculated monthly air temperature coefficients (jh_coef) and the simulated PET for the MRU containing the Odessa Agrimet site (MRU 4) was compared with the computed ET from observed weather data at the Odessa Agrimet site (fig. 18). In subsequent model runs, the monthly air temperature coefficients were multiplied by 1.7 to improve the fit with computed ET values.

The streamflow network is simulated with the module musroute_pot2.f by defining: (1) the network of flow-routing nodes, (2) which MRU runoff output goes to which node, and (3) the downstream node that receives flow from a particular node. For each node, a storage coefficient and routing coefficient are specified to compute flow delay and attenuation between nodes. Model parameters define which nodes receive outflows from each MRU and each subsurface and groundwater reservoir. Nodes generally were positioned at streamflow-gaging locations and at the mouths of subbasins (fig. 19) because the accumulated runoff from MRUs and upstream nodes is captured at a node and then runoff can be displayed or exported to files and compared with observed

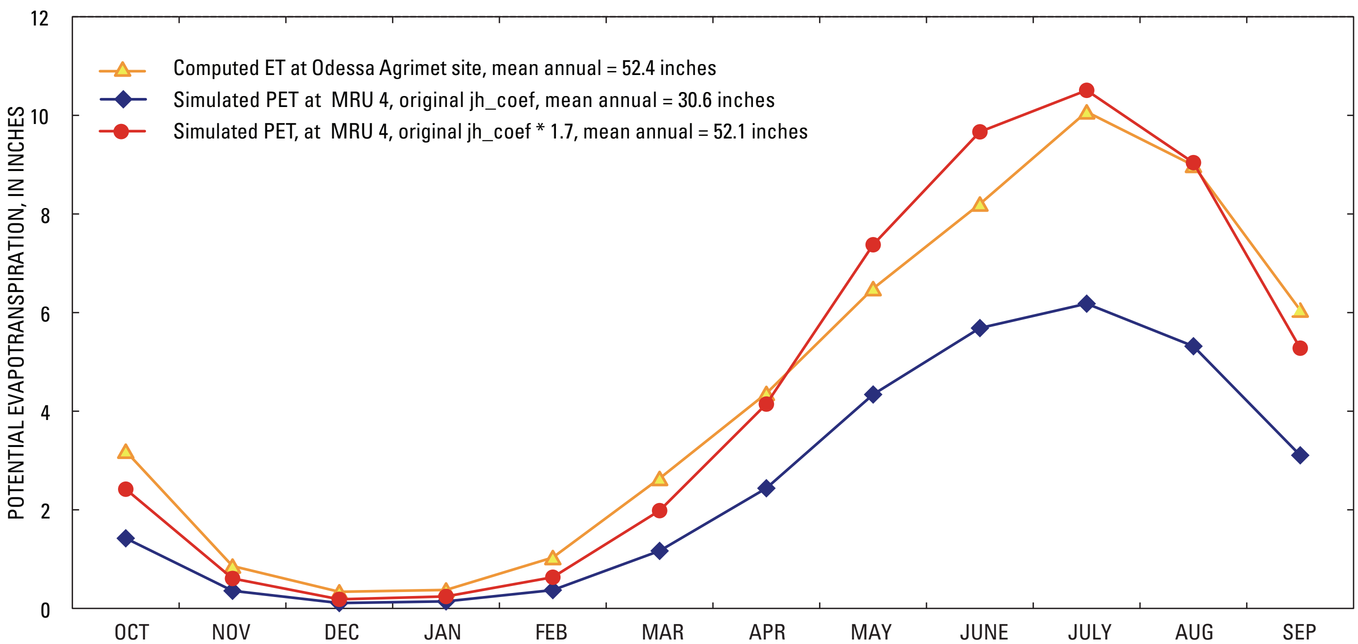


Figure 18. Computed mean monthly evapotranspiration (ET) at the Odessa Agrimet site, water years 1986–2004 and simulated potential evapotranspiration (PET) for model response unit 4 in the Rocky Coulee Model with originally calculated monthly air temperature coefficients and adjusted coefficients, Potholes Reservoir basin, Washington.

data. Nodes 6, 12, 13, and 17 in the Crab Creek model were defined as "reservoir type" reaches (the reach represented by a node is the reach extending from that node upstream to the next node) to allow the channel-loss and wetting-up processes to be activated and controlled with the user-supplied parameters.

In nonforested areas, the GIS Weasel computes vegetation cover and density parameters using the Global Land Cover Characterization at a 1-km resolution grid (Loveland and others, 2000). To improve accuracy, two alternative datasets were used and processed using GIS techniques external to the Weasel. First, the National Land Cover Dataset, version 2.0 gridded at a 30-m resolution (U.S. Geological Survey, 1992) was used to define the vegetation cover in the study area as shrubland, pasture/hay, small grains, or fallow land. A value of 0.12 in. of snow-interception capacity for shrubland vegetation cover and a value of 0.06 in. for the other vegetation covers were used in the model. Summer and winter rain-interception capacity was half the snow-interception capacity. Second, part of a national coverage of the Normalized Difference Vegetation Index (NDVI) at a 1-km resolution grid, compiled from data recorded by the Advanced Very High Resolution Radiometer satellite sensor and averaged for 2004 (U.S. Geological Survey Center for Earth and Resources Observation and Science, 2004), was used to estimate percent cover of the vegetation.

The NDVI has been used to monitor vegetation condition or "greenness" as an estimate of leaf area in forest studies (Franklin and Dickson, 2001) or as an estimate of plant cover and phytomass (Washington-Allen and others, 2006). A study to estimate the plant cover within the study area was outside the scope of work for this study, but Connelly and others (2004, figs. 5–10) report the percentage of plant cover of sagebrush in the sage-grouse habitat of the Western United States to range from near 0 to 53 percent. NDVI values in the study area ranged from 119 to 151. In light of the typical range of the percent cover for sagebrush landscapes, the values of percent cover used in the study area were computed as the NDVI value minus 100.

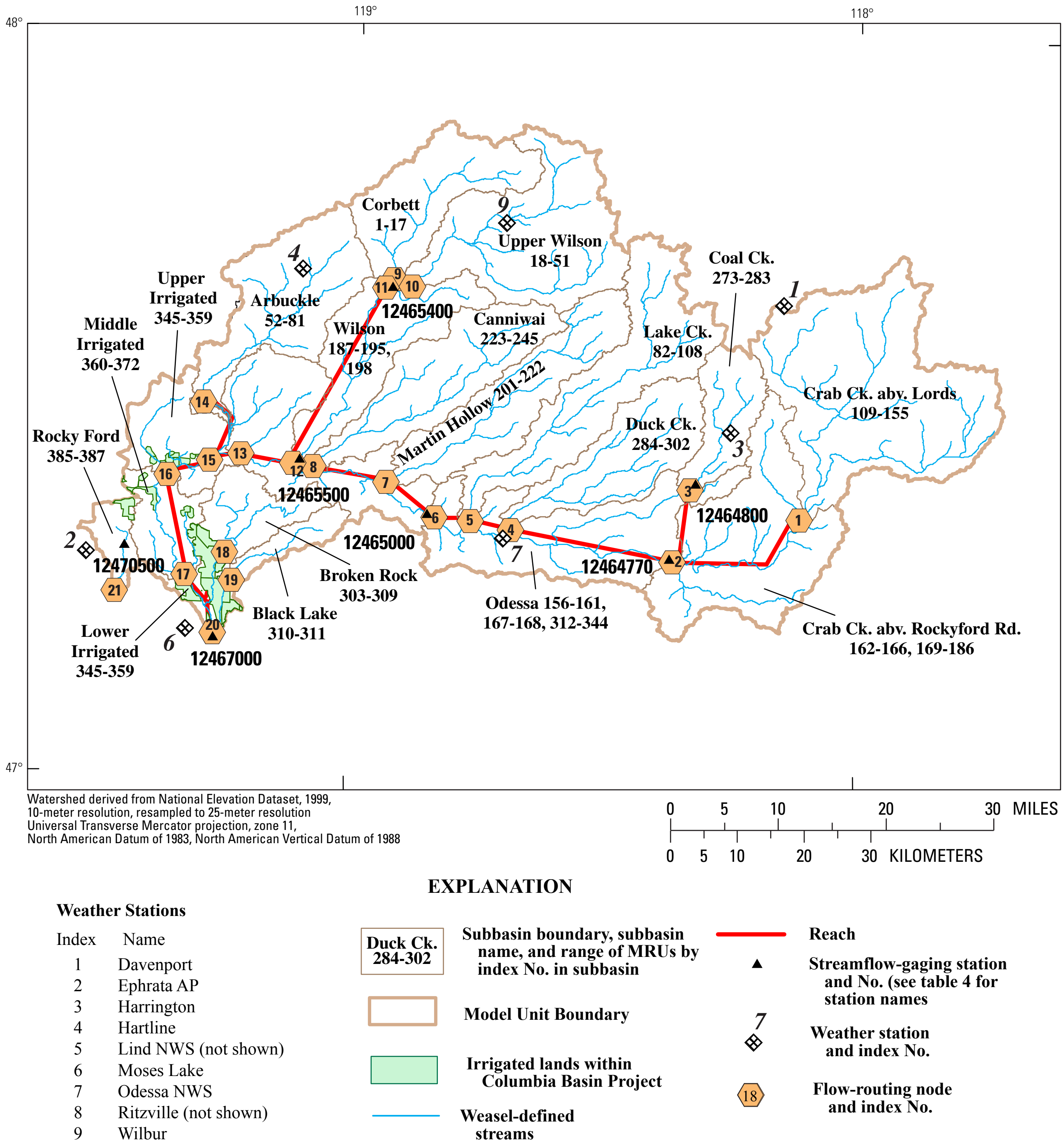


Figure 19. Model response units (MRUs), meteorological input, and flow-routing map for the Crab Creek model unit in the Potholes Reservoir basin, Washington.

Calibration and Evaluation of Numerical Model

Not all parameters in the numerical watershed model can be measured directly, and therefore, the model's parameters must be adjusted or calibrated in an effort to obtain a good match between the simulated and observed runoff. All of the streamflow-gaging stations in the CBP are affected by irrigation diversions, applications, and returns. Without accurate and extensive sets of time-series data of diversions, applications, and returns, the model cannot simulate accurately the flows in the CBP. The primary objective of the watershed model is to simulate natural runoff in the study area to use as input to the water-management model RiverWare. RiverWare would then use the detailed information on irrigation use in the CBP along with the simulated natural runoff to closely simulate the runoff affected by irrigation. A secondary objective is to use the watershed model in long-term planning as well as for operational forecasts of water supply for the runoff season. With these two objectives in mind, the primary statistics used in calibration were the differences between the annual and monthly mean simulated and observed runoff at streamflow-gaging stations outside of the CBP. Less effort was made in trying to minimize the error in instantaneous peak discharges and daily minimum flows. During the calibration process, efforts were made to match the hydrograph shape at both daily and annual scales to provide some assurance that the hydrologic processes were being simulated correctly.

Available Data

Daily minimum and maximum air-temperature and daily precipitation data are needed as input to run the watershed model. Observed discharge data are necessary for calibration and error analysis of the model. To forecast runoff volumes, real-time meteorological data are needed for simulations. For these purposes, real time is defined as availability of daily values up to the day previous of the current day. Weather stations may not have real-time capabilities but have a long-term record of meteorological data that is useful for long-term simulations, and in contrast; real-time streamflow-gaging stations may have only a short period of record but recent data are useful for forecast simulations. In consideration of the availability of input data from the weather-station sites, and the need for a sufficiently long record that contains a good sample of the variety of hydrologic-runoff events that characterize the hydrology of the study area, water year 1950 was selected as the starting year for the long-term simulations.

Table 3 lists the weather stations used for long-term and forecast simulations and figure 19 shows the long-term weather station locations. Data for Agrimet stations Lind and Odessa are available in real time via Reclamation's Hydromet satellite and radio telemetry, and online database system. These stations have a relatively short period of record, but they conveniently substitute with consistent data for the long-term National Weather Service (NWS) stations Lind and Odessa whose data are not available in real time for forecast simulations. Hartline, an NWS station in the northwest corner

Table 3. Weather stations used as input for long-term and real-time simulations in the Potholes Reservoir basin, Washington.

[The term "water year" means a 12-month period beginning on October 1 and ending September 30 of the water year. **Abbreviations:** deg., degrees; min., minutes; sec, seconds; N, north; W, west; NWS, National Weather Service]

Weather station	Latitude (deg. min. sec.)	Longitude (deg. min. sec.)	Station operator	Used for long-term simulation and (or) real-time simulation	Period of record since 1949 (water year)
Davenport	N 47 39 00	W 118 08 00	NWS	Long term/real time	1950 to current
Dry Falls	N 47 36 51	W 119 17 57	Hydromet	Real time	February 1997 to current
Ephrata AP[1]	N 47 18 27	W 119 30 57	NWS	Long term/real time	1950 to current
Harrington	N 47 29 00	W 118 15 00	NWS	Long term	1950 to current
Hartline	N 47 41 00	W 119 06 00	NWS	Long term	1950 to current
Lind NWS	N 47 00 00	W 118 35 00	NWS	Long term	1950 to current
Lind Agrimet	N 46 52 02	W 118 44 22	Agrimet	Real time	September 1983 to current
Moses Lake	N 47 11 35	W 119 18 48	NWS	Long term/real time	1950 to January 1987; January 1993 to current
Odessa NWS	N 47 19 00	W 118 42 00	NWS	Long term	1950 to current
Odessa Agrimet	N 47 18 32	W 118 52 43	Agrimet	Real time	June 1984 to current
Ritzville	N 47 07 00	W 118 22 00	NWS	Long term/real time	1950 to current
Wilbur	N 47 45 00	W 118 40 00	NWS	Long term	1950 to current

[1] Ephrata AP record was estimated for October 1, 1949, to November 30, 1949, based on linear regression with nearby Ephrata record data.

of the Crab Creek model unit, has a long-term period of record, but there is no real-time access to its data, so Dry Falls, a Hydromet station outside of the model unit about 10 mi to the west of Hartline, is substituted for forecasting simulations.

Listed in table 4 and shown in figure 17 are the streamflow-gaging station used in the calibration and their periods of record. Gaging stations Lind Coulee Wasteway at SR 17 near Warden (12471400) and Crab Creek near Moses Lake (12467000) are downstream of the CBP irrigated lands and canals, and receive a large amount of wastewater from the major canals and return flows from irrigation that cannot be separated easily from natural runoff. Therefore, data from these gaging stations have limited use in model calibration during the irrigation season. Outside of the CBP, a large amount of groundwater pumpage exists that can affect creek flows, especially the flow at the USGS streamflow-gaging station at Crab Creek at Irby. As described in the conceptual model section, a rough estimate of the reduction in runoff due to pumpage was made using the estimates by Hanson and others (1994). Comparisons of simulated and observed discharge at this site were made with the unadjusted and with the adjusted flows for the observed discharge assuming that the reduction due to pumpage is applied during the irrigation season (April through September).

Table 4. Streamflow-gaging stations used for calibration of the watershed models in the Potholes Reservoir basin, Washington.

[**Abbreviations:** USGS, U.S. Geological Survey; Reclamation, Bureau of Reclamation; –, not applicable]

Streamflow-gaging station name	USGS gaging-station No.	Station operator	Period of record since 1949 (water years)
Crab Creek at Rocky Ford Road near Ritzville	12464770	USGS	[1]1993–1995, [1]1997–2004
Coal Creek at Mohler	12464800	USGS	1964–1974, 2003–2005
Crab Creek at Irby	12465000	USGS	1950–2005
Wilson Creek below Corbett Draw, near Almira	12465400	USGS	1952–1973, 2003–2005
Wilson Creek at Wilson Creek	12465500	USGS	1952–1973
Crab Creek near Moses Lake[2]	12467000	USGS	1950–2005
Rocky Ford Creek near Ephrata	12470500	USGS	1950–1991
Farrier Coulee near Schrag	12471270	USGS	1964–1974
Lind Coulee Wasteway at SR17 near Warden[2]	12471400	USGS/ Reclamation	1990–2001
Lind Coulee near Warden 1	–	Reclamation	1990–2002

[1]Includes some partial water-year record.

[2]Spring-autumn flow heavily influenced by irrigation and canal return flows.

Parameter Adjustment

Comparisons of simulated and observed discharge were made after trial model runs run for the period of water years 1950 through 2004 and parameters were adjusted to improve the match between the simulated and observed hydrographs. This section discusses some of the more significant parameters that were adjusted during the calibration process.

Peak-discharge simulation is highly sensitive to parameters cfgi_decay and cfgi_thrshld, which control simulated frozen-ground conditions. The Rosenbrock optimization utility within the MMS user interface was used to optimize these parameters for peak-discharge values. The optimization produced a value of 137 for cfgi_thrshld and 0.97 for the cfgi_decay, and these were used as the final parameter values. Molnau and Bissel (1983) used a threshold CFGI value of 83 and a daily decay coefficient (A in eq. 1) of 0.97 based on their analysis of four streamflow sites in the Columbia River Basin. Figure 20 shows the sensitivity of the CFGI threshold parameter for several floods in water years 1956 and 1957 (including the peak of record). The model was run two times and the only difference was the value of cfgi_thrshld. Once cfgi_thrshld is exceeded, the simulated peak flows are much higher (fig. 20*A*) than when the threshold is not exceeded (fig. 20*B*). Note that the plotted CFGI value is for only one MRU in the basin, and although it may not have exceeded the threshold in that MRU, it may have exceeded the threshold in other MRUs that drain to Crab Creek at Irby. In this example, on February 18, 1956, 111 of the 168 MRUs that contributed simulated runoff to Crab Creek at Irby equaled or exceed a CFGI value of 137 but no MRUs exceeded a CFGI value of 200. This is why the simulated February 1956 peak flood is so much larger in figure 20*A* than in figure 20*B*, even though the CFGI threshold was not exceeded for MRU 146 in scenarios represented by either graph.

The parameters for channel losses, storage, and simulation of the wetting-up process were important in calibrating the flows in Crab Creek. No parameter could be measured directly in the field without significant effort, so they were estimated from seepage-run data, streamflow-gaging station data, or maps where possible. The parameters were refined until a reasonable fit was achieved between observed and simulated discharge. The channel-loss parameters dead_vol, channel_sink_threshld, and channel_sink_pct were estimated from seepage-run data or, for reaches between two streamflow-gaging stations, estimates were made from observed runoff data. For example, flow lost between gaging stations Crab Creek at Rocky Ford Road near Ritzville and Crab Creek at Irby (reach 6) averaged 28 percent for 9 years

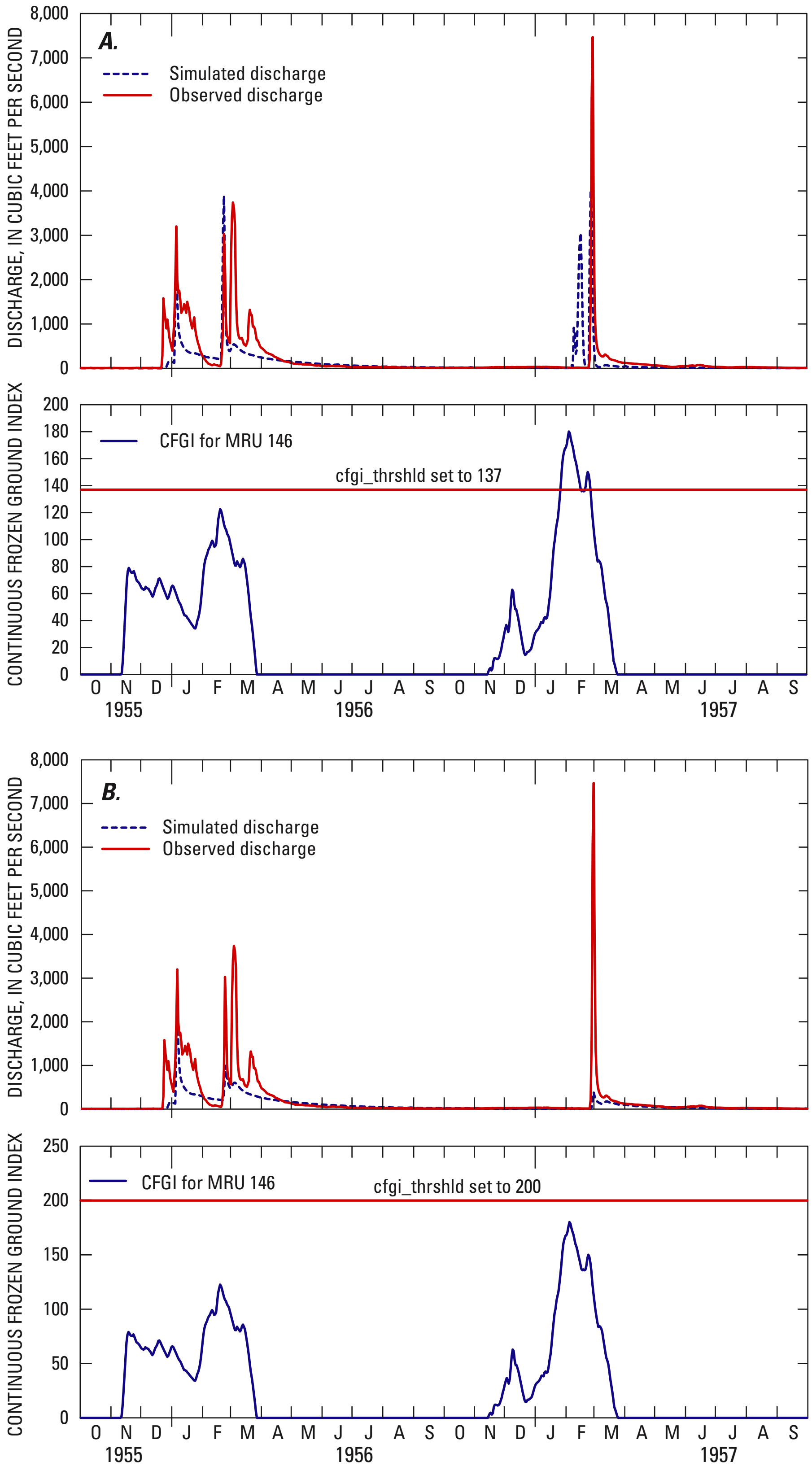


Figure 20. Simulated and observed discharge for Crab Creek at Irby and Continuous Frozen Ground Index (CFGI) at a model response unit (MRU) near Davenport, Washington, water years 1956–57.

(water years 1994, 1995, 1998–2004) between April 1 and August 31 whenever the discharge was less than or equal to 50 ft^3/s (parameter channel_sink_thrshld is set to 50 for reach 6 in the model). Dead storage was computed in a similar manner for this same reach by calculating the runoff volume beginning October 1 of the water year until flow at the downstream station (Crab Creek at Irby in this example) exceeded the flow at the upstream station. The average dead storage computed from these 9 years of data for reach 6 was 5,955 acre-ft. However, because the calculation does not include channel losses, the dead storage parameter (dead_vol) was reduced to 2,000 acre-ft by trial and error with many simulation runs and comparing the observed and simulation runoff hydrographs. Reach area, in acres (parameter reach_area), was computed by multiplying the channel length (measured on topographic maps) by an estimated channel width of 20 ft (approximate width in full channels measured during discharge measurements for the seepage run) and then adding any lake or wetland areas measured from the maps. Related parameters used in the final calibration are listed in table 5.

Groundwater flow and discharge patterns dominate the hydrology of the region except during times of flooding. Although the numerical model primarily is a watershed model, approximate simulation of the groundwater flow is critical to obtain comparable simulated and observed monthly and annual runoff totals. In the Crab Creek model, the simulated groundwater outflow from groundwater reservoirs for individual MRUs not near the mouth of subbasins or near springs was routed to other MRU groundwater reservoirs and eventually into Rocky Ford Creek. This simulated flow represents regional groundwater flow to the creek. The amount of simulated groundwater routed to Rocky Ford Creek was adjusted to obtain comparable simulated and observed annual runoff totals at the streamflow-gaging stations at Crab Creek and not Rocky Ford Creek. As a result, the mean annual simulated runoff is only 55.3 percent of the observed runoff at Rocky Ford Creek. Presumably, Rocky Ford Creek receives regional groundwater inflow from outside the study area, which adds to the flow generated within the study area. It was beyond the scope of this project to incorporate a regional groundwater flow model to more accurately simulate the flows in Rocky Ford Creek.

The percentage of area represented by the MRUs contributing groundwater to Rocky Ford Creek is 39.6 percent of the total area in the Crab Creek model unit. The parameter gwsink_coef was set to 0.5 or 1.0 on 32 of the 387 MRUs to simulate a loss of 50 or 100 percent, respectively, of the groundwater flow for that MRU from the model unit. The remainder of the MRUs in the Crab Creek model unit had a gwsink_coef value of 0.0. The MRUs with a positive gwsink_coef value in this model unit that were on the margins of the watershed where the regional groundwater flow as reported by Hansen and others (1994) indicated that groundwater flow would be lost to the system and not contribute flow to lower Crab Creek. In the Lind model unit, MRUs upgradient of the three seepage-run sites that were dry for both seepage runs (Lind Coulee at Roxboro, Farrier Coulee near Schrag, and Weber Coulee near Schrag, fig. 1) were given a gwsink_coef value of 1.0 except for those MRUs contributing to two springs in the Paha Coulee and McElroy Coulee subbasins (fig. 17).

Table 5. Channel-storage and loss parameters used in the final calibration for indicated flow-routing nodes for the Crab Creek model unit in the Potholes Reservoir basin, Washington.

[See figure 19 for location of nodes. Parameters apply to the reach upstream of the indicated node]

Channel-loss, storage, or volume parameter	Flow-routing nodes						
	6	12	13	15	16	17	20
channel_sink_pct[1]	0.28	0.5	0.3	0.7	0.2	0.7	0.7
channel_sink_thrshld[2]	50	50	50	100	50	100	100
dead_vol[3]	2,000	200	50	10,000	50	10,000	15,000
deep_sink_pct[4]	0.2	0.4	0.1	0.5	0.2	0.2	0.2
reach_area[5]	660	60	15	950	10	290	1,200

[1]Node discharge is reduced by this decimal percentage and routed to dead storage.

[2]Threshold used to calculate channel losses in reservoir node types, in cubic feet per second.

[3]Volume in a reach that needs to be filled before flow leaves the node, in acre-feet. Volume is reduced by evaporation.

[4]Decimal percentage that dead storage is reduced. Water is considered to go to deep groundwater (lost to the model).

[5]Parameter used to calculate evaporation to reduce dead-storage volume, in acres.

The simulated rate of groundwater discharge to the stream was controlled by the groundwater recession coefficient (parameter gwflow_coef), which initially was calculated as 0.0086 $days^{-1}$ based on the flows recorded by the streamflow-gaging station at Crab Creek at Irby. Comparison of the regression limbs of the simulated and observed discharge hydrographs indicated that the parameter should be changed to 0.015 $days^{-1}$ for all MRUs contributing to streams within the same subbasin. The gwflow_coef value for MRUs contributing to regional groundwater flow (flow leaving the subbasin where it originated) was set at 0.001 $days^{-1}$ to simulate more delayed outflows from the groundwater reservoirs.

After the initial calibrations, the simulated runoff was significantly more than the observed runoff in the upper watersheds of the Crab Creek Model Unit. To reduce the simulated runoff, the snow_mon and rain_mon values (average monthly precipitation values) for the MRUs upstream of the streamflow-gaging stations at Crab Creek at Irby gaging and Wilson Creek near Almira were reduced by 10 percent.

Several parameters were adjusted in the calibration process that affected the response of peak runoff to rainfall and snowmelt. These included the rate of ground melt of the snowpack (parameter groundmelt)—set to 0.02 inches per day in the Corbett, Upper Wilson, and Coal Creek subbasins (fig. 19) and zero inches per day elsewhere. Peak runoff commonly occurs in response to a rapid melting of the snowpack, and simulated peak runoff is sensitive to the parameter that governs the rate of infiltration of snowmelt into the soil (parameter snowinfil_max). The Rosenbrock optimization utility within the MMS user interface was used to optimize this parameter by isolating the optimization to only observed and simulated runoff for Coal Creek from January through June. The optimized parameter value for snowinfil_max was 0.766 inches per day for water years 1963 through 1974 and 0.489 inches per day for water years 2003 through 2004. This parameter was set to 0.6 inches per day and used for all the MRUs in the three models. Parameter soil2gw_max controls the amount of soil-moisture excess that flows into the groundwater reservoir, a less responsive flowpath to rainfall, and the calibrated values ranged from 0.3 to 0.8 inches per day throughout the model units. Parameter smidx_coef influences the amount of surface runoff that occurs. It was set to 0.003 in the Corbett, Upper Wilson, and Farrier Coulee subbasins (fig. 17 and 19) and 0.001 elsewhere. Whether precipitation fell as snow or rain was important in determining the timing of when the moisture input would become runoff. A major parameter that determines whether precipitation is snow or rain is tmax_allsnow (if the maximum daily temperature is below this value, the precipitation is snow). It influences the responsiveness of the runoff hydrograph to precipitation inputs, and it was set to 36°F in the final model.

The time of travel (parameter K_coef) and the attenuation of the flood hydrograph (parameter x_coef) from one node to the next downstream node are controlled by the flow-routing parameters. K_coef values were estimated from reach length and, in some cases, from observed flow data and ranged from 1 to 24 hours. Parameter x_coef can range from 0.0 to 0.5. Reach 21 and 22 in the Crab Creek Model Unit had x_coef values of 0.5, but the remainder of the reaches in all three model units had values of 0.2.

Other parameters were adjusted, but generally were not as significant as the parameters mentioned above. Parameters such as soil type, soil_moist_max, soil_rechr_max, psta_xlong, psta_ylat, and cov_type had some metric to compute their value; therefore, they generally were not adjusted in the calibration process. Many of these parameters were estimated by the GIS Weasel using GIS information and built-in tabulations or equations.

Comparisons of Simulated and Observed Runoff

Observed and simulated discharge hydrographs were compared for model calibration and for model evaluation. A table of the simulation results for annual peak discharges was also compiled to highlight the unreliability of the model to accurately simulate a random peak discharge. Hydrographs of monthly observed and simulated mean monthly discharge were plotted for seven streamflow sites for the available record during the calibration period and at four sites for the available record during the model-evaluation period. These graphics were instrumental in the calibration of the models and were used to minimize the mean monthly and mean annual errors. Error analysis for mean monthly and annual values as well as statistics descriptive of the errors for individual months and years were compiled for each of the observed streamflow-gaging stations upstream of the CBP boundaries for the calibration and model evaluation.

Peak-Flow Simulations

Close matches of observed and simulated peak discharges were difficult to obtain consistently at any of the sites. Before the model had the capability of simulating runoff under frozen-ground conditions, several large observed peaks were grossly undersimulated (simulated discharge is less than observed discharge). An example of a grossly undersimulated, frozen-ground generated peak is shown in figure 20*B* for Crab Creek at Irby. The model dramatically undersimulated the peak of record because frozen-ground conditions were not simulated. By simulating discharge under frozen-ground conditions, the simulation of the peak of record at the streamflow-gaging station at Crab Creek at Irby was improved significantly (fig. 20*A*). However, the CFGI method of simulating frozen ground is sensitive to the index value, which can cause dramatic oversimulation (simulated discharge is greater than observed discharge) when the index value exceeds the threshold and frozen ground did not exist or the extent was limited (fig. 21). Note in figure 21 that there is no runoff response to snowfall in the simulated or observed hydrograph and little response to rainfall except in the simulated hydrograph when the CFGI threshold was exceeded. Figure 22 also shows the sensitivity of runoff to frozen ground and the infiltration of snowmelt water for two annual-peak events in the simulated and observed discharge at the streamflow-gaging station at Coal Creek at Mohler. The two annual peaks had similar moisture volumes available for runoff. In both peak simulations the model seems to simulate the build-up and melt of the snowpack reasonably well at the time of the peak discharge (fig. 22*B*), and both peaks had similar 3-day precipitation totals recorded at Davenport (0.68 in. January 30–February 1, 2003; and 0.90 in. January 16–January 18, 2004). The soil temperatures recorded at the Odessa Agrimet site indicate no frozen ground for the 2003 annual peak and minimal frozen ground during the 2004 annual peak. The CFGI value for the representative MRU never reached the CFGI threshold. The observed responses to precipitation and snowmelt were quite different for each water year and the watershed model was unable to simulate the same differences. The model clearly missed the process that triggered a large peak-flow response for the 2004 peak.

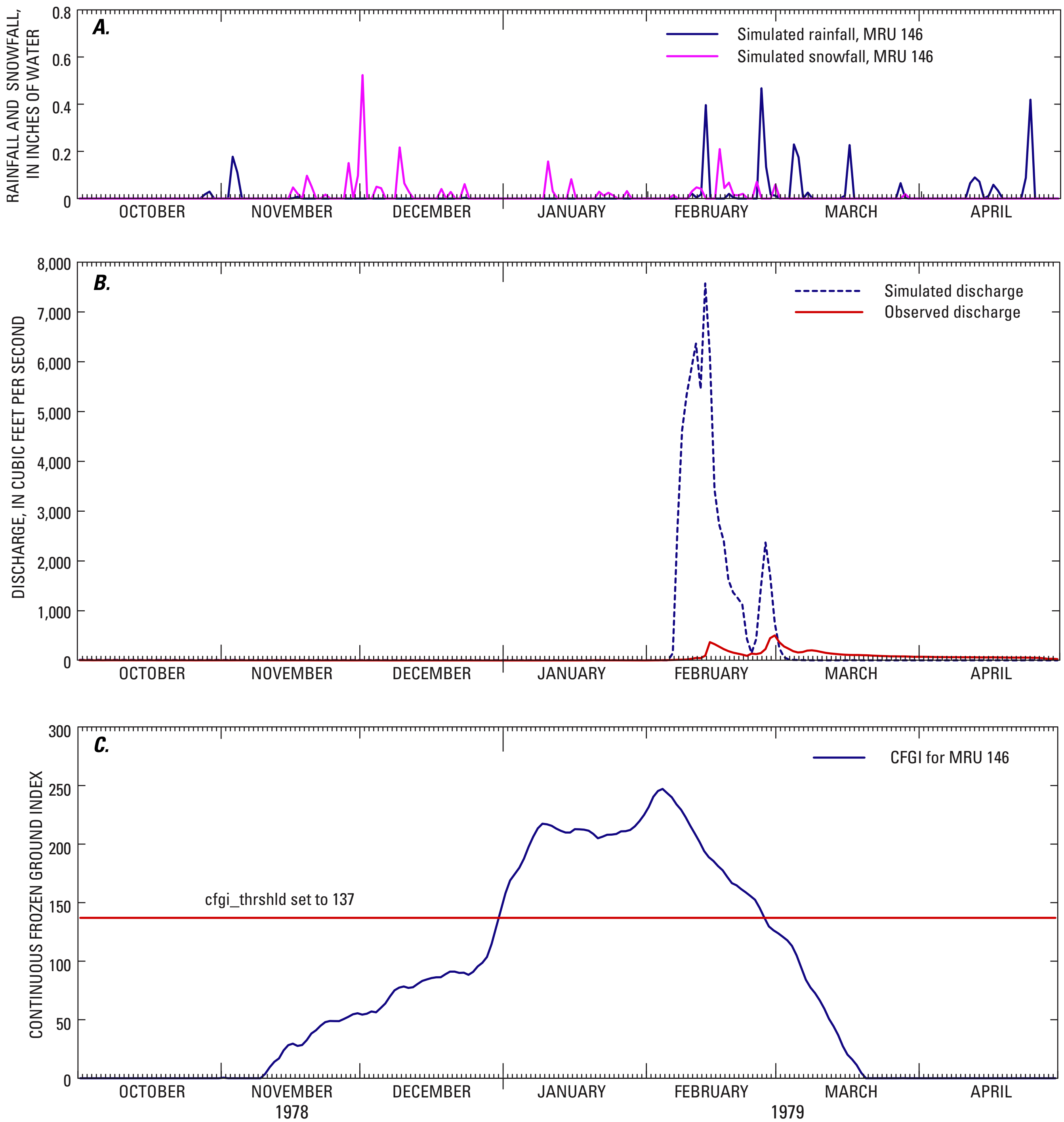


Figure 21. (*A*) Simulated rainfall and snowfall at model response unit (MRU) 146 near Davenport; (*B*) simulated and observed discharge for Crab Creek at Irby; and (*C*) Continuous Frozen Ground Index (CFGI) and threshold at MRU 146, Potholes Reservoir basin, Washington.

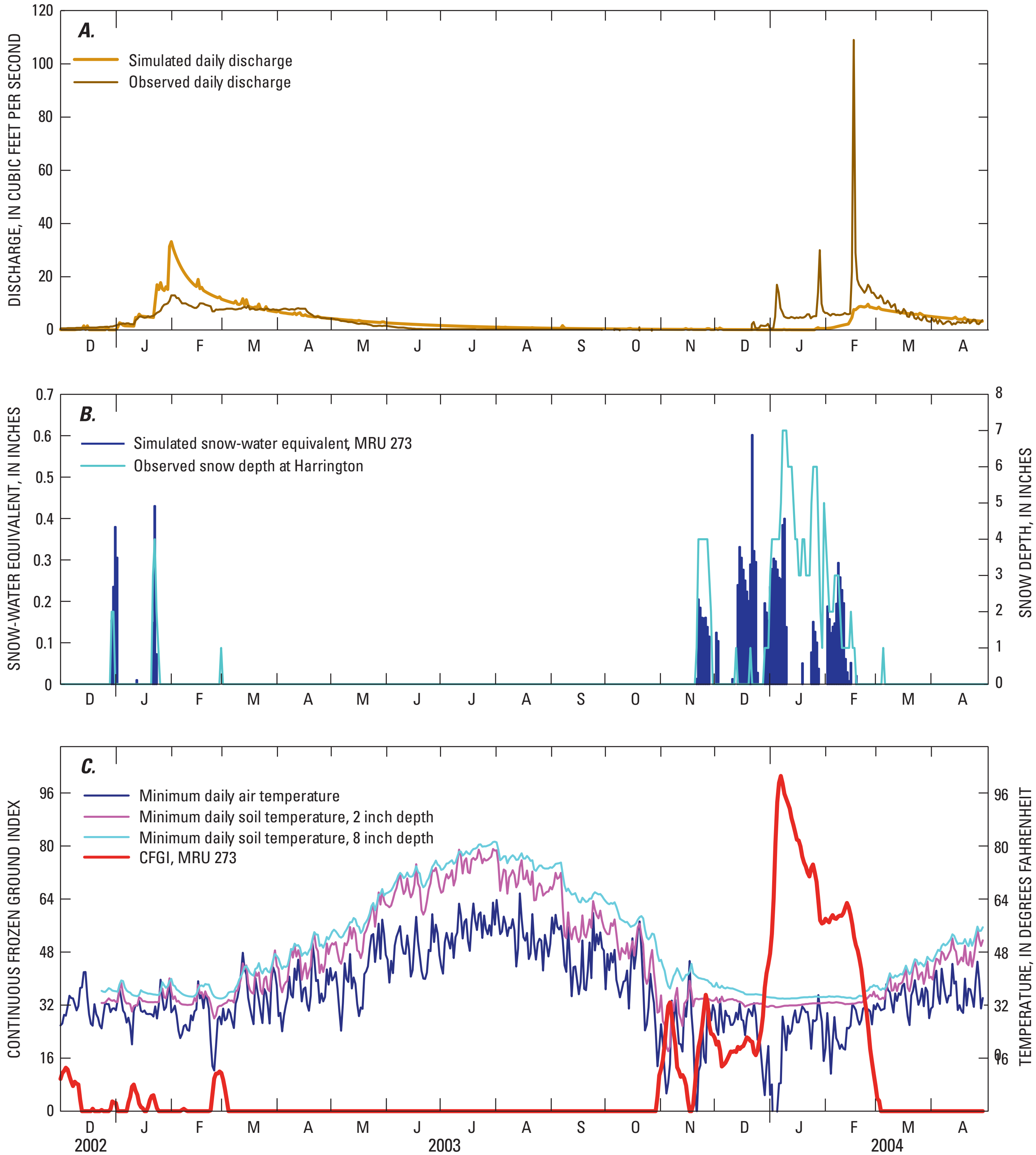


Figure 22. Simulated and observed discharge for Coal Creek at Mohler, Washington, for (*A*) annual peak discharges in water years 2003 and 2004; (*B*) simulated snow-water equivalent for model response unit (MRU) 273 in the Coal Creek basin and observed snow depth at Harrington, Washington; and (*C*) observed air and soil temperatures at the Odessa Agrimet site and Continuous Frozen Ground Index (CFGI) for MRU 273. (Observed snow depth at Ritzville was substituted for missing snow depth at Harrington for February 2004.)

Comparisons of the annual daily peak discharge and the 5-day simulated and observed runoff for the annual peak discharge at four of the streamflow-gaging stations in the Crab Creek Model Unit (table 6) indicate that the model provides poor, unreliable peak simulations most of the time and negative bias, which means it tends to undersimulate the peak discharges. Despite efforts to improve the model results, the runoff in the basin seems quite sensitive to the degree of frozen ground in the basin and the amount of snowmelt available for runoff. As a result, the model was unable to consistently capture the correct runoff response to these conditions. The negative bias partially is explained by improperly simulated timing of the peak runoff. To mitigate for this effect, 5-day runoff values were compared in addition to the annual daily peak value. For all but one gaging station listed in table 6, the percent bias is slightly less for the 5-day runoff values.

Mean Monthly Hydrographs

The daily-simulated runoff from the calibrated model was averaged by month over the time period that observed data was available at the seven sites in the study area for which there is minimal influence of agricultural diversions and returns. Figures 23 and 24 show the comparison of the mean monthly values and table 7 lists the results and some statistical analysis.

The plot for Crab Creek at Irby hydrographs (fig. 23) shows an additional time-series hydrograph of mean monthly discharge that represents the observed discharge plus the estimated reduction in streamflow due to groundwater pumpage. This reason for this reduction is discussed earlier in the conceptual model section about irrigation. We would expect that shallow pumping in the Crab Creek Basin would decrease the natural runoff. This additional hydrograph

Table 6. Comparison of simulated and observed annual daily peak discharge and five-day runoff at six streamflow-gaging stations in the Potholes Reservoir basin, Washington.

[Periods of record are shown in table 4. **Abbreviations:** ft^3/s, cubic feet per second; RMSE, Root Mean Square Error. **Definition of terms:** RMSE, average = SQRT{SUM[$(S\text{-}O)^2/N$]}; RMSE, percent = 100 × SQRT{SUM[$((S\text{-}O)/O)^2/N$]}; *S*, simulated daily mean discharge, cubic feet per second or cubic feet per second-days; *O*, observed daily mean discharge, in cubic feet per second or cubic feet per second-days; *N*, number of values in the sample; Bias, average = SUM[(S-O)/N]; Bias, percent = 100 x SUM{[(S-O)/O)/N]}; Standard Error of Estimate, average = [N/(N-1)] x SQRT[(RMSE, average)^2 – (Bias, average)^2]; Standard Error of Estimate, percent = [N/(N-1)] x SQRT[(RMSE, percent)^2 – (Bias, percent)^2]]

Streamflow-gaging station	Number of peaks	Annual daily peak discharge (ft^3/s)					
		RMSE		Bias		Standard error of estimate	
		Average	Percent	Average	Percent	Average	Percent
Crab Creek at Rocky Ford Road, near Ritzville	11	868.3	64.94	-480.2	-46.94	795.8	71.43
Coal Creek at Mohler	14	233.3	120.39	-88.6	-39.89	232.4	129.65
Crab Creek at Irby	55	1,582.7	85.72	-748.7	-36.18	1,420.2	87.31
Wilson Creek below Corbett Draw, near Almira	9	499.7	82.40	-308.3	-54.64	442.4	92.70
Wilson Creek at Wilson Creek[1]	16	1,528.6	89.34	-1,152.0	-85.34	1,071.8	28.21
Farrier Coulee near Schrag[1]	5	189.8	83.89	-111.4	-76.69	192.1	42.51
Five-day runoff[2]							
Crab Creek at Rocky Ford Road, near Ritzville	11	1,820.0	68.72	-961.2	-27.63	1700.0	75.59
Coal Creek at Mohler	14	559.9	95.65	-232.2	-25.78	548.6	103.01
Crab Creek at Irby	55	4,283.2	89.42	-17,845.2	-21.30	3,983.7	91.08
Wilson Creek below Corbett Draw, near Almira	9	1,230.7	77.36	-759.8	-40.80	1,089.2	87.03
Wilson Creek at Wilson Creek[1]	16	2,522.2	111.25	-2,042.2	-59.11	1,578.9	100.54
Farrier Coulee near Schrag[1]	5	493.3	505.04	-27.9	167.09	615.6	595.75

[1]Years with simulated or observed annual daily peaks of zero discharge are not included in the analysis.
[2]Sum of the runoff on the day of annual peak plus the runoff 2 days before and after the peak, in cubic feet per second-days.

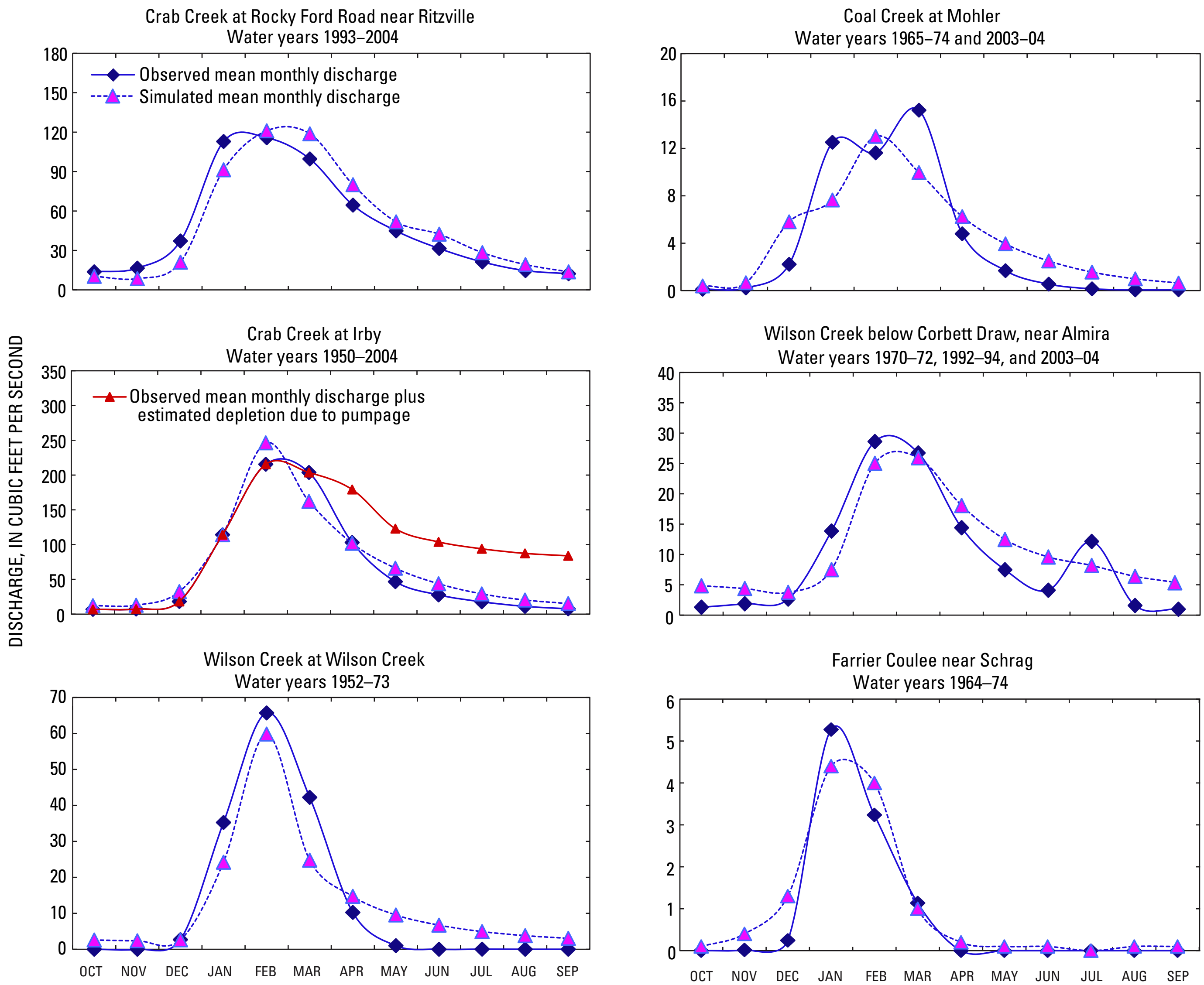


Figure 23. Observed and simulated mean monthly discharge at six streamflow-gaging stations in the Potholes Reservoir basin, Washington.

represents a closer approximation to the expected natural runoff than the unadjusted observed discharge hydrograph. The mean monthly simulated discharge generally fell in between the unadjusted observed mean monthly discharge and the observed discharge with the added estimated pumpage.

The calibration hydrographs of Rocky Ford Creek (fig. 24) indicate a significant undersimulation throughout the year, a -36.4 percent difference for the mean annual discharge, and a contrary pattern of runoff—simulated runoff is greatest in the early spring when observed runoff is lowest. As discussed earlier, Rocky Ford Creek receives most of its flow from springs, which are part of a regional groundwater flow system that extends beyond the study area boundaries. The watershed model does not accurately simulate the complex regional groundwater processes because groundwater originating outside the study area was not included in the model. The focus of the calibration was to try to match the discharge at the other six streamflow-gaging stations that received a majority of their runoff from localized groundwater and surface-water sources. Groundwater generated within the study area thought to recharge the regional groundwater system upgradient of Rocky Ford Creek was directed to the creek. The deficit of groundwater contributions to the simulated flow at Rocky Ford Creek likely represents flow from outside the study area. Correction of the errors in the timing and volume of the simulated discharge would require a regional groundwater model, which is beyond the scope of this project.

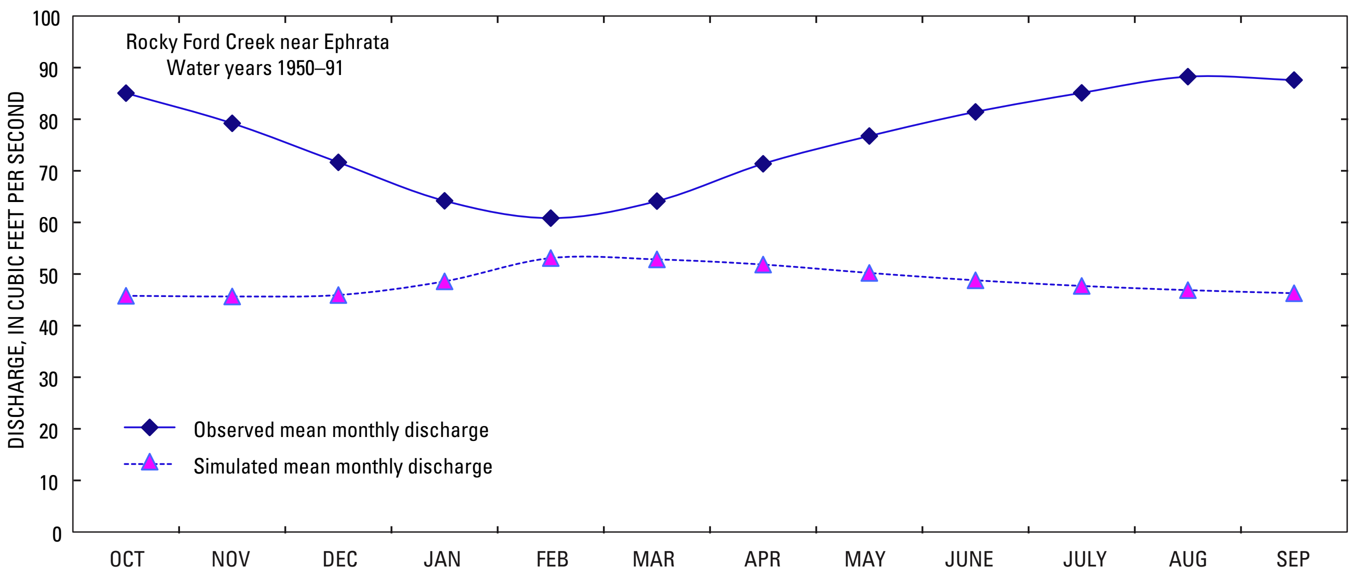


Figure 24. Observed and simulated mean monthly discharge at the streamflow-gaging station at Rocky Ford Creek near Ephrata, Washington, water years 1950–91.

The six other streamflow-gaging stations (fig. 23 and table 7) indicate a reasonably good match between the simulated and observed mean monthly and mean annual discharges. Differences between simulated and observed mean annual discharge ranged from 1.2 to 13.8 percent of observed values with a difference of 10 percent or less for five of the six sites (table 7). The model tended to oversimulate the discharge during the summer and early fall months except for the July runoff at Wilson Creek below Corbett Draw where discharge was undersimulated. Local pumping of water for irrigation probably reduces the observed discharge during the summer and early fall months and thereby increases the error because these effects are not simulated. Two thirds of the differences between the mean monthly simulated and observed discharge were between -20 and 240 percent of observed values or, in absolute terms, between -0.8 and 11 ft^3/s.

The remaining four statistics listed in table 7 compare the individual monthly and annual values for the calibration period:

1. Bias is the average of the differences, accounting for the sign of the difference, and indicates whether the model is oversimulating or undersimulating discharge;

2. Standard error of estimate (SEE) is the standard deviation of the differences after accounting for the bias. If the differences are distributed normally and little or no bias is present, then two-thirds of all the differences will be less than or equal to the SEE;

3. R^2 is a measure of the strength of the correlation between the observed and simulated monthly mean and annual mean discharges; and

4. Nash-Sutcliffe efficiency (E) statistic (Nash and Sutcliffe, 1970) is a measure of the model fit. A perfect fit would have an E value equal to 1. If E equals zero, the model fit is no better than estimating the discharge value with the observed mean, and if E is less than zero, the model simulation is worse than simply estimating a discharge using the observed mean.

Farrier Coulee and Rocky Ford Creek had E values less than zero for the annual discharges, indicating that the observed annual mean would be a better estimator of flow than the models. Although percent differences for the mean of the calibration period were small, a wide range of simulation success is indicated for individual months or years. Coal Creek, for example, had a mean annual percent difference of only 7.5 percent; however, the SEE was 3.13 ft^3/s for a mean discharge of 4.1 ft^3/s and the E value of 0.02 indicates little advantage of using the model over simply using the observed annual mean (table 7). Results for Crab Creek at Rocky Ford Road and Crab Creek at Irby were better with an annual E value of 0.56 and 0.40, respectively, and a SEE of 19.58 and 42.61 ft^3/s, respectively. Some individual months at these two sites did have negative E values, indicating a failure of the model to adequately simulate the discharge.

Table 7. Comparison of observed and simulated mean monthly and water-year discharges for the calibration period for seven streamflow-gaging stations for the indicated water years in the Potholes Reservoir basin, Washington.

[**Abbreviations:** SEE, standard error of estimate; *S*, simulated monthly mean or annual discharge in cubic feet per second; *O*, observed monthly mean or annual discharge in cubic feet per second; $\bar{O}$, mean of monthly means or annual means; *N*, number of monthly mean or annual values; RMSE, Root Mean Square Error; RMSE = SQRT$\{\sum[(S\text{-}O)^2/N]\}$; $\sigma^2_{observed}$, $\sum[(O-\bar{O})^2]/(N-1)$; σ^2_{error}, $\sum\{[(S\text{-}O)-\text{average}(S\text{-}O)]^2\}/(N-1)$; ft^3/s, cubic foot per second; --, unable to compute statistic because of division by zero]

Discharge or statistic	October	November	December	January	February	March	April	May	June	July	August	September	Water year
Crab Creek at Rocky Ford Road near Ritzville, water years 1993–2004													
Observed mean discharge (ft^3/s)	13.7	16.5	37.2	112.9	115.7	99.6	64.5	44.9	31.5	21.3	14.7	12.3	47.7
Simulated mean discharge (ft^3/s)	10.3	8.6	21.1	91.4	121.0	118.7	80.0	51.8	42.4	28.3	19.3	13.7	48.2
Percent difference[1]	-25.0	-48.2	-43.4	-19.1	4.6	19.2	24.1	15.4	34.7	33.2	31.4	11.6	1.2
[2]Bias	-3.43	-7.96	-16.13	-21.53	5.32	19.12	15.55	6.89	10.92	7.05	4.60	1.43	0.58
[3]SEE	2.98	4.32	25.66	131.07	76.98	38.51	31.14	20.74	19.41	14.77	10.42	6.12	19.58
[4]R^2	0.84	0.85	0.84	0.19	0.44	0.81	0.70	0.64	0.79	0.73	0.67	0.72	0.67
[5]Nash-Sutcliffe efficiency, *E*	0.80	0.76	0.72	0.11	0.32	0.71	0.11	-0.03	0.07	-1.06	-2.07	-0.28	0.56
Coal Creek at Mohler; water years 1964–74 and 2003–04													
Observed mean discharge (ft^3/s)	0.1	0.2	2.2	12.5	11.6	15.2	4.8	1.7	0.5	0.2	0.1	0.1	4.1
Simulated mean discharge (ft^3/s)	0.39	0.66	5.81	7.65	13.02	9.96	6.25	3.95	2.50	1.56	0.99	0.64	4.39
Percent difference[1]	240.0	196.6	161.5	-38.9	12.0	-34.6	30.3	134.5	357.7	941.0	1,473.2	764.6	7.5
[2]Bias	0.28	0.44	3.59	-4.87	1.39	-5.26	1.45	2.26	1.95	1.41	0.93	0.56	0.31
[3]SEE	0.30	1.20	8.91	17.52	8.52	23.40	2.31	2.26	1.80	1.14	0.73	0.46	3.13
[4]R^2	0.01	0.02	0.62	0.20	0.50	0.38	0.75	0.48	0.03	0.03	0.00	0.00	0.40
[5]Nash-Sutcliffe efficiency, *E*	-6.47	-64.21	-2.91	-0.24	0.45	0.27	0.63	-3.42	-36.24	-94.11	-47.30	-14.37	0.02
Crab Creek at Irby; water years 1950–2004													
Observed mean discharge (ft^3/s)	6.8	7.3	18.2	114.2	215.5	203.7	103.0	46.7	27.7	17.8	11.2	7.7	64.2
Simulated mean discharge (ft^3/s)	12.2	12.8	32.4	114.2	246.4	162.1	101.9	66.1	43.7	29.1	20.3	15.2	70.3
Percent difference[1]	78.2	74.3	78.2	0.00	14.3	-20.4	-1.1	41.5	58.0	63.8	81.9	98.5	9.5
[2]Bias	-0.17	-0.22	-0.23	-0.25	1.33	-11.21	-0.43	0.19	-0.03	-0.05	-0.16	-0.17	-0.98
[3]SEE	7.44	14.53	86.54	185.95	332.46	176.24	51.80	36.63	29.04	19.14	14.03	10.52	42.61
[4]R^2	0.44	0.02	0.00	0.36	0.14	0.46	0.65	0.65	0.50	0.53	0.40	0.40	0.47
[5]Nash-Sutcliffe efficiency, *E*	0.22	-2.07	-2.89	0.22	-2.05	0.45	0.63	0.25	-0.60	-1.04	-1.20	-0.75	0.40
Wilson Creek below Corbett Draw, near Almira; water years 1970–72, 1992–94, and 2003–04													
Observed mean discharge (ft^3/s)	1.3	1.9	2.6	13.9	28.6	26.7	14.4	7.5	4.1	12.1	1.6	1.0	9.5
Simulated mean discharge (ft^3/s)	4.8	4.4	3.7	7.5	25.0	25.9	18.1	12.5	9.6	8.2	6.4	5.3	10.9
Percent difference[1]	272.1	134.7	41.4	-45.9	-12.6	-2.9	25.4	66.8	133.7	-32.6	302.3	448.9	13.8
[2]Bias	3.70	2.30	0.46	-12.96	-13.08	-40.50	-6.45	3.53	5.61	-4.27	4.30	4.40	1.48
[3]SEE	4.14	2.54	1.21	0.00	45.39	103.48	37.03	11.96	9.19	21.08	6.08	5.38	11.55
[4]R^2	0.91	0.76	0.93	0.45	0.86	0.02	0.05	0.32	0.24	0.64	0.35	0.17	0.33
[5]Nash-Sutcliffe efficiency, *E*	-2.66	-0.46	0.70	0.10	0.70	0.20	-0.04	-0.40	-4.28	0.40	-6.36	-4.07	0.27

Table 7. Comparison of observed and simulated mean monthly and water-year discharges for the calibration period for seven streamflow-gaging stations for the indicated water years in the Potholes Reservoir basin, Washington.—Continued

[**Abbreviations:** SEE, standard error of estimate; *S*, simulated monthly mean or annual discharge in cubic feet per second; *O*, observed monthly mean or annual discharge in cubic feet per second; $\bar{O}$, mean of monthly means or annual means; *N*, number of monthly mean or annual values; RMSE, Root Mean Square Error; RMSE = SQRT$\{\sum [(S\text{-}O)^2/N]\}$; $\sigma^2_{observed}$, $\sum[(O\text{-}\bar{O})^2]/(N\text{-}1)$; σ^2_{error}, $\sum\{[(S\text{-}O)\text{-average}(S\text{-}O)]^2\}/(N\text{-}1)$; ft^3/s, cubic foot per second; --, unable to compute statistic because of division by zero]

Discharge or statistic	October	November	December	January	February	March	April	May	June	July	August	September	Water year
Wilson Creek at Wilson Creek; water years 1952–73													
Observed mean discharge (ft^3/s)	0.0	0.0	2.7	35.2	65.7	42.2	10.2	1.0	0.0	0.0	0.0	0.0	12.8
Simulated mean discharge (ft^3/s)	2.6	2.4	2.6	24.2	59.8	24.8	14.7	9.5	6.7	4.9	3.8	3.0	13.0
Percent difference[1]	–	–	-2.7	-31.4	-8.9	-41.3	43.7	853.6	–	17933.3	–	–	1.3
[2]Bias	2.58	2.36	-0.07	-11.05	-5.86	-17.46	4.48	8.54	6.70	4.89	3.79	3.04	0.17
[3]SEE	1.66	1.19	12.04	53.33	108.67	69.28	18.48	8.33	5.64	4.06	2.92	2.21	11.55
[4]R^2	–	–	0.01	0.78	0.07	0.32	0.40	0.14	–	0.05	–	–	0.50
[5]Nash-Sutcliffe efficiency, *E*	–	–	-0.10	0.72	-0.34	0.26	0.40	-4.62	–	-959.20	–	–	0.48
Farrier Coulee near Schrag; water years 1964–74													
Observed mean discharge (ft^3/s)	0.0	0.0	0.2	5.3	3.2	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.8
Simulated mean discharge (ft^3/s)	0.1	0.4	1.3	4.4	4	1	0.2	0.1	0.1	0	0.1	0.1	0.9
Percent difference[1]	–	2,100.0	429.6	-16.6	23.6	-12.0	–	–	–	–	–	–	10.0
[2]Bias	0.13	0.41	0.88	-1.69	0.79	-0.11	0.21	0.12	0.12	0.03	0.04	0.05	0.08
[3]SEE	0.12	0.34	2.56	15.64	3.48	4.46	0.20	0.12	0.09	0.05	0.07	0.07	1.62
[4]R^2	–	0.61	0.02	0.01	0.88	0.00	–	–	–	–	–	–	0.06
[5]Nash-Sutcliffe efficiency, *E*	–	-28.40	-8.77	-1.03	0.88	-0.27	–	–	–	–	–	–	-0.47
Rocky Ford Creek near Ephrata; water years 1950–91													
Observed mean discharge (ft^3/s)	85.1	79.2	71.6	64.2	60.8	64.1	71.4	76.7	81.4	85.1	88.2	87.6	76.4
Simulated mean discharge (ft^3/s)	45.8	45.7	45.9	48.6	53.1	52.8	51.8	50.2	48.8	47.7	46.9	46.3	48.6
Percent difference[1]	-46.2	-42.4	-35.9	-24.3	-12.7	-17.6	-27.4	-34.6	-40.1	-44.0	-46.9	-47.2	-36.4
[2]Bias	-39.28	-33.55	-25.72	-15.61	-7.74	-11.29	-19.53	-26.53	-32.63	-37.42	-41.37	-41.31	-27.78
[3]SEE	18.68	17.30	16.94	17.74	18.37	27.80	36.40	35.11	28.96	25.77	22.00	19.39	21.79
[4]R^2	0.13	0.13	0.08	0.05	0.23	0.11	0.17	0.18	0.08	0.09	0.15	0.17	0.20
[5]Nash-Sutcliffe efficiency, *E*	-0.43	-0.48	-0.65	-0.96	-0.38	-0.20	-0.14	-0.16	-0.19	-0.23	-0.28	-0.37	-0.33

[1]Percent difference = ((simulated mean – observed mean) / observed mean) * 100; calculations were made before the averages were rounded.

[2]Bias = $\sum[(S\text{-}O)/N]$.

[3]SEE = $[N/(N\text{-}1)]$ * SQRT($RMSE^2$ - $Bias^2$).

[4]R^2 = coefficient of determination.

[5]Nash-Sutcliffe efficiency, $E = 1\text{-}(\sigma^2_{error}/\sigma^2_{observed})$.

Model Evaluation

Model evaluation was designed to test the model as it would be used for its primary purposes, which is to use it in a real-time forecast mode to predict the runoff volumes for an upcoming runoff season and to extend the record of observed discharge. Two tests were made for this evaluation by running the calibrated model with (1) a slightly reduced and slightly different set of weather-station inputs (as it will be run for forecast purposes) and (2) a much-reduced set of weather-station inputs (necessary for extending the discharge record at the streamflow-gaging station at Crab Creek at Irby). The simulation results from these two model runs were compared with the observed discharges and the error was determined for evaluation of the model. The error also was compared with the error generated by the calibrated model with the full set of historical weather-station inputs to determine how much the reduced sets of input data affect the simulation accuracy.

Forecast Evaluation

To use the model for forecasting, the input data must be obtained in real time and the model must be run to obtain the current state of the variables. The set of real-time weather stations is different and includes fewer stations (seven) than the set of long-term stations used to simulate the historical period (nine stations; table 3). Once the current state of the variables has been computed, the MMS ensemble streamflow prediction (ESP) capability can be employed to make a forecast of runoff for the period of interest—usually the runoff season—by using the results of model runs generated from historical weather data. ESP is a method that first runs the model from some time in the past (usually at least a couple of years) to the current time and saves all the current variable values. It then uses the long-term time series of weather data inputs to make an ensemble of model runs. The ensemble of model runs includes a model run for each year or for selected years beginning at the current date and running through a period selected by the user (the forecast period). The output from the ensemble is summarized by peak discharge or total runoff volume and arranged in order from highest to lowest. Using this ordered list of ensemble values, the probability of the forecast peak or volume being equaled or exceeded in the forecast period can be estimated.

The calibration results provided a sense of the accuracy and bias of the model's simulation of monthly mean discharges for the historical period with a full set of weather-station inputs, but the accuracy of the forecast using a different set of fewer weather-station inputs was unknown. The set of parameters derived through the model-calibration process was modified for the new set of weather stations by adjusting the station elevation parameter (tsta_elev), the station location parameters (psta_xlong, psta_ylat, tsta_xlong, and tsta_ylat), and the station mean monthly precipitation values (psta_mon). The psta_mon parameters are based on the mean monthly precipitation during the period 1961–99. Because some real-time stations were not in operation during this period, psta_mon parameters for those stations were estimated by multiplying psta_mon parameters for a nearby long-term station by the ratio of total precipitation at the real-time station to the total at the long-term station during overlapping periods of record.

The shortest period of record for all the real-time stations was for the Dry Falls station with its first complete record beginning in water year 1998. As a result, the evaluation model was run for water years 1998–2005. A "lingering moderate to severe" drought was experienced in the Pacific Northwest during water year 2005 (Le Compte, 2005; National Oceanic and Atmospheric Administration, 2005). The observed runoff volume at the streamflow-gaging site at Crab Creek at Irby for water year 2005 was the third lowest since 1950. The simulation results for the model-evaluation period show that with the exception of Wilson Creek below Corbett Draw, near Almira, the model performed in a similar manner as for the calibration model runs (fig. 25; table 8). The model substantially oversimulated the winter runoff in water year 2003 at the two upper Crab Creek stations and at Wilson Creek. Only 3 years of record were available for Wilson Creek for comparison; therefore, the 1 year of poor simulation in 2003 had a marked influence on the comparison statistics for this site.

Simulated runoff at the streamflow-gaging stations at Wilson and Coal Creeks for the available observed data for the evaluation period is shown in figure 26. The watershed model results for Wilson Creek greatly oversimulates discharge for the 2003 water-year peak and, generally, oversimulates discharge throughout the evaluation period (water years 2003 and 2004). It should be noted, however, that the model with the reduced number of weather data input sites (evaluation model) closely matched the model with the full number of weather data input sites (calibration model). For Coal Creek, the simulated discharge closely matched the observed discharge for the 2003 water year, but completely missed a sharp peak in 2004. The sharp, high observed peak in 2004 with little precipitation (0.9 in. recorded at Davenport for the 2-day period before the peak) indicates that frozen ground was limiting the infiltration of water, making the water immediately available for runoff; however, the Wilson Creek hydrograph showed little response to the precipitation, indicating that the soils in the Wilson Creek watershed were not frozen to the extent that they were frozen in the Coal Creek watershed. This is an example of the model's inability to simulate peak-flow events in the basin accurately and consistently. This pattern is consistent with the peak-flow error analysis discussed earlier that indicates the model is unreliable in simulating individual peaks, thereby making it unsuitable for short-term forecasts such as forecasting the impact of an impending storm. However, the evaluation simulated hydrographs are similar to the calibration simulated hydrographs.

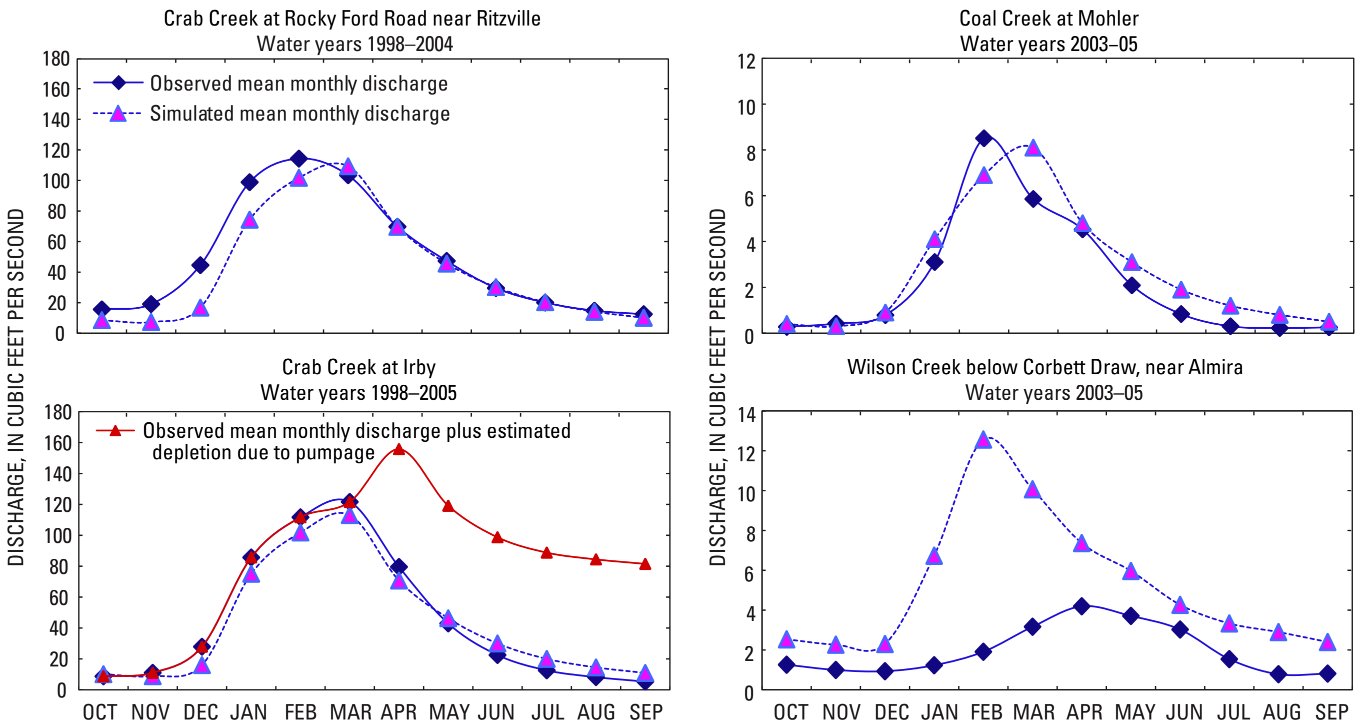


Figure 25. Model evaluation hydrographs of observed and simulated mean monthly discharge at four streamflow-gaging stations using a subset of the total number of weather-station inputs for indicated water years, Potholes Reservoir basin, Washington.

Table 8. Comparison of observed and simulated mean monthly and mean water-year discharges for model evaluation for four streamflow-gaging stations for the indicated water years, Potholes Reservoir basin, Washington.

[**Abbreviations:** ft^3/s, cubic foot per second]

Discharge or statistic	October	November	December	January	February	March	April	May	June	July	August	September	Water year
Crab Creek at Rocky Ford Road near Ritzville, water years 1998–2004													
Observed mean discharge (ft^3/s)	15.6	19.1	44.6	99.1	114.6	103.6	69.9	47.4	29.6	20.1	14.8	12.4	48.9
Simulated mean discharge (ft^3/s)	8.5	7.3	16.8	74.5	101.9	109.6	69.8	45.7	30.2	20.3	14.1	10.1	42.1
Percent difference[1]	-45.5	-61.6	-62.4	-24.8	-11.0	5.7	-0.1	-3.6	2.0	1.0	-4.8	-18.5	-13.9
Coal Creek at Mohler; water years 2003–05													
Observed mean discharge (ft^3/s)	0.3	0.4	0.8	3.1	8.5	5.9	4.5	2.1	0.8	0.3	0.2	0.3	2.2
Simulated mean discharge (ft^3/s)	0.40	0.30	0.90	4.10	6.90	8.10	4.80	3.10	1.90	1.20	0.80	0.50	2.70
Percent difference[1]	46.3	-28.6	14.4	32.1	-18.9	38.3	6.0	48.6	128.0	300.0	258.2	97.4	20.9
Crab Creek at Irby; water years 1998–2005													
Observed mean discharge (ft^3/s)	8.7	11.0	27.9	85.7	111.7	121.6	79.6	42.9	22.5	12.6	8.2	5.3	44.5
Simulated mean discharge (ft^3/s)	10.1	8.8	16	75.1	101.8	113.1	70.7	46.3	30	20	14.5	10.9	42.8
Percent difference[1]	16.0	-20.0	-42.6	-12.3	-8.8	-7.0	-11.1	7.9	33.3	59.0	76.9	106.0	-3.7
Observed mean discharge plus estimated depletion due to pumpage (April through September) (ft^3/s)	8.7	11.0	27.9	85.7	111.7	121.6	155.8	119.1	98.7	88.8	84.4	81.5	82.7
Wilson Creek below Corbett Draw, near Almira; water years 1970–72, 1992–94, and 2003–04													
Observed mean discharge (ft^3/s)	1.3	1.0	0.9	1.2	1.9	3.2	4.2	3.7	3.0	1.5	0.8	0.8	2.0
Simulated mean discharge (ft^3/s)	2.5	2.3	2.3	6.7	12.6	10.1	7.4	6.0	4.3	3.3	2.9	2.4	5.2
Percent difference[1]	101.1	127.4	146.4	445.9	557.9	217.9	75.7	60.8	41.0	116.5	270.2	195.1	163.6

[1]Percent difference = ((simulated mean – observed mean) / observed mean) * 100; calculations were made before the averages were rounded.

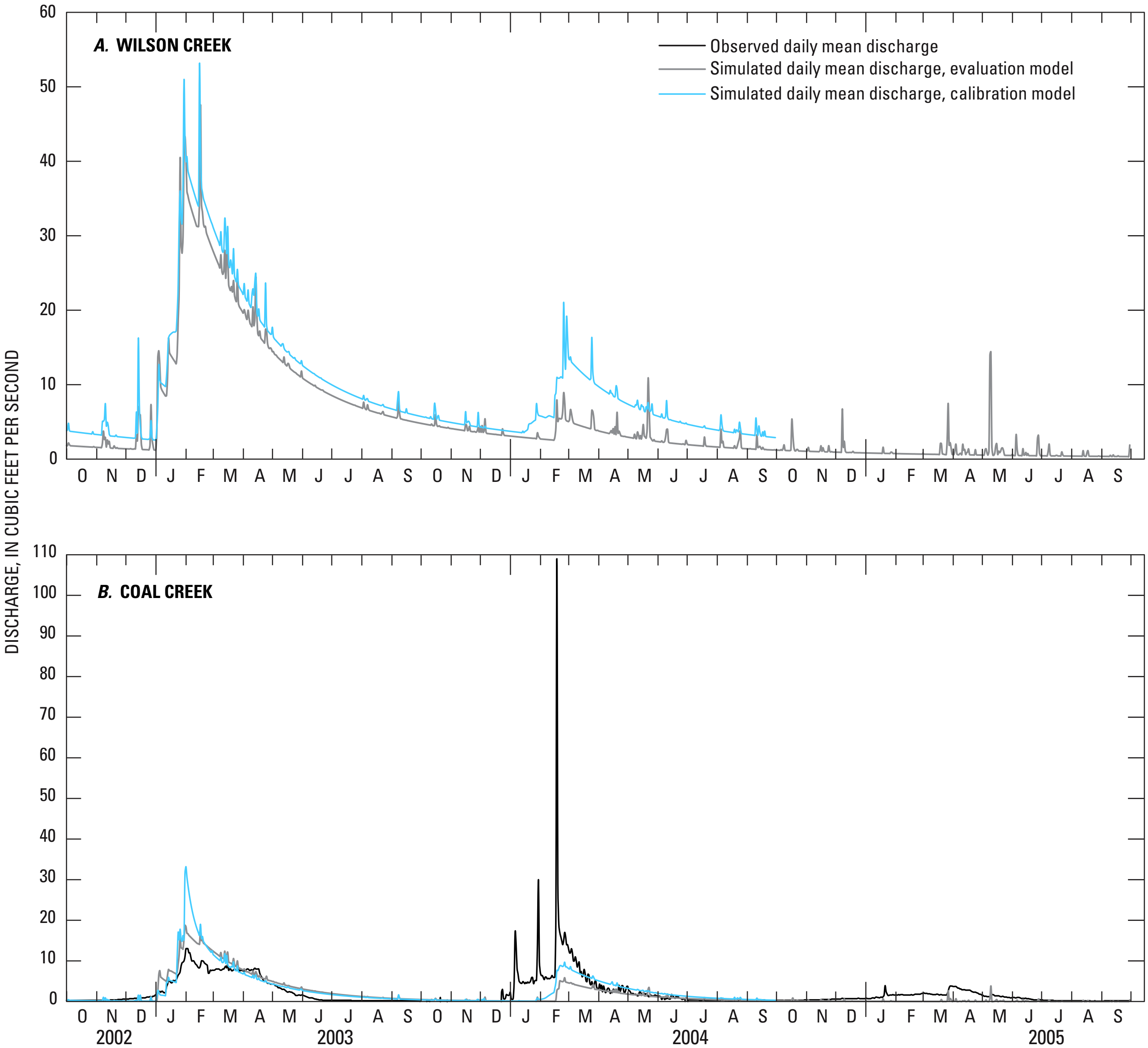


Figure 26. Observed and simulated hydrographs for the calibration and evaluation model runs for Wilson Creek below Corbett Draw, near Almira, and Coal Creek at Mohler, Washington, water years 2003–05. (Simulated runoff not available for water year 2005 for the calibration model runs.)

Crab Creek at Irby Record Extension

Reclamation expressed interest in simulating the discharge record at the streamflow gaging station at Crab Creek at Irby for water years 1928–42 so that it is compatible with other stream gages in the region for a current study they are conducting. The period of record at this gaging station begins in water year 1943 and continues to the present (2008). For water years 1928–31, only one weather station (Wilbur, table 3) was in operation in the basin and for water years 1932–48 only three weather stations (Wilbur, Ephrata AP, and Lind NWS, table 3) were in operation. The model could generate a discharge record for this period (1928-42), but an evaluation was needed to determine how well the model would perform with a much reduced set of input data.

The calibrated model was run with only three weather-station inputs and the results showed a similar pattern of mean monthly discharge during the calibration period, water years 1950-2004, as the calibrated model run with nine weather-station inputs. The main difference was that slightly more discharge was simulated in spring with the three-station model (fig. 27). The model with three weather-station inputs oversimulated the observed discharge by 22.8 percent annually compared with 9.5 percent for the model with nine weather-station inputs (table 9). The three-station model did a little better for the period 1943–2004, only oversimulating the annual mean by 19.9 percent. The watershed model does not simulate the effects of groundwater pumpage. If the estimate by Hansen and others (1994) of the annual depletion of Crab Creek flows by groundwater pumpage (38.2 ft^3/s) is accurate, the annual discharge simulated by the calibrated model with only three weather-station inputs would be 23.1 percent less than the observed discharge (1950–2004) plus the estimated reduction in discharge due to pumpage. Despite the uncertainty in the effects of pumpage on discharge, it is reasonably certain that if pumpage ceased, discharge would be greater and, therefore, a moderate oversimulation of discharge by the three-station model would be closer to the natural runoff volume.

Table 9. Comparison of observed and simulated mean monthly and water-year discharges for indicated water years at the streamflow gaging station at Crab Creek at Irby, Washington.

[**Abbreviation:** ft^3/s, cubic foot per second]

Discharge or statistic	October	November	December	January	February	March	April	May	June	July	August	September	Water year
Water years 1950–2004													
Observed mean discharge (ft^3/s)	6.8	7.3	18.2	114.2	215.5	203.7	103.0	46.7	27.7	17.8	11.2	7.7	64.2
Simulated mean discharge (ft^3/s) with calibrated model with nine weather station inputs	12.2	12.8	32.4	114.2	246.4	162.1	101.9	66.1	43.7	29.1	20.3	15.2	70.3
Percent difference[1]	78.2	74.3	78.2	0.0	14.3	-20.4	-1.1	41.5	58.0	63.8	81.9	98.5	9.5
Simulated mean discharge (ft^3/s) with calibrated model with three weather station inputs	14.5	17.8	25.1	97.5	233.8	219.2	129.7	83.0	55.2	36.9	25.3	18.5	78.8
Percent difference[1]	111.9	142.2	38.1	-14.6	8.5	7.6	25.9	77.6	99.5	107.5	126.9	141.7	22.8
Water years 1943–2004													
Observed mean discharge (ft^3/s)	7.6	7.8	18.1	105.1	220.0	200.0	102.4	49.1	35.1	19.9	12.6	8.7	64.7
Simulated mean discharge (ft^3/s) with calibrated model with three weather station inputs	14.6	17.2	23.8	91.4	237.6	214.4	127.8	81.9	54.4	36.3	24.9	18.3	77.6
Percent difference[1]	92.4	119.8	31.3	-13.1	8.0	7.2	24.7	67.0	55.0	82.2	98.2	110.2	19.9

[1]Percent difference = ((simulated mean – observed mean) / observed mean) * 100; calculations were made before the averages were rounded.

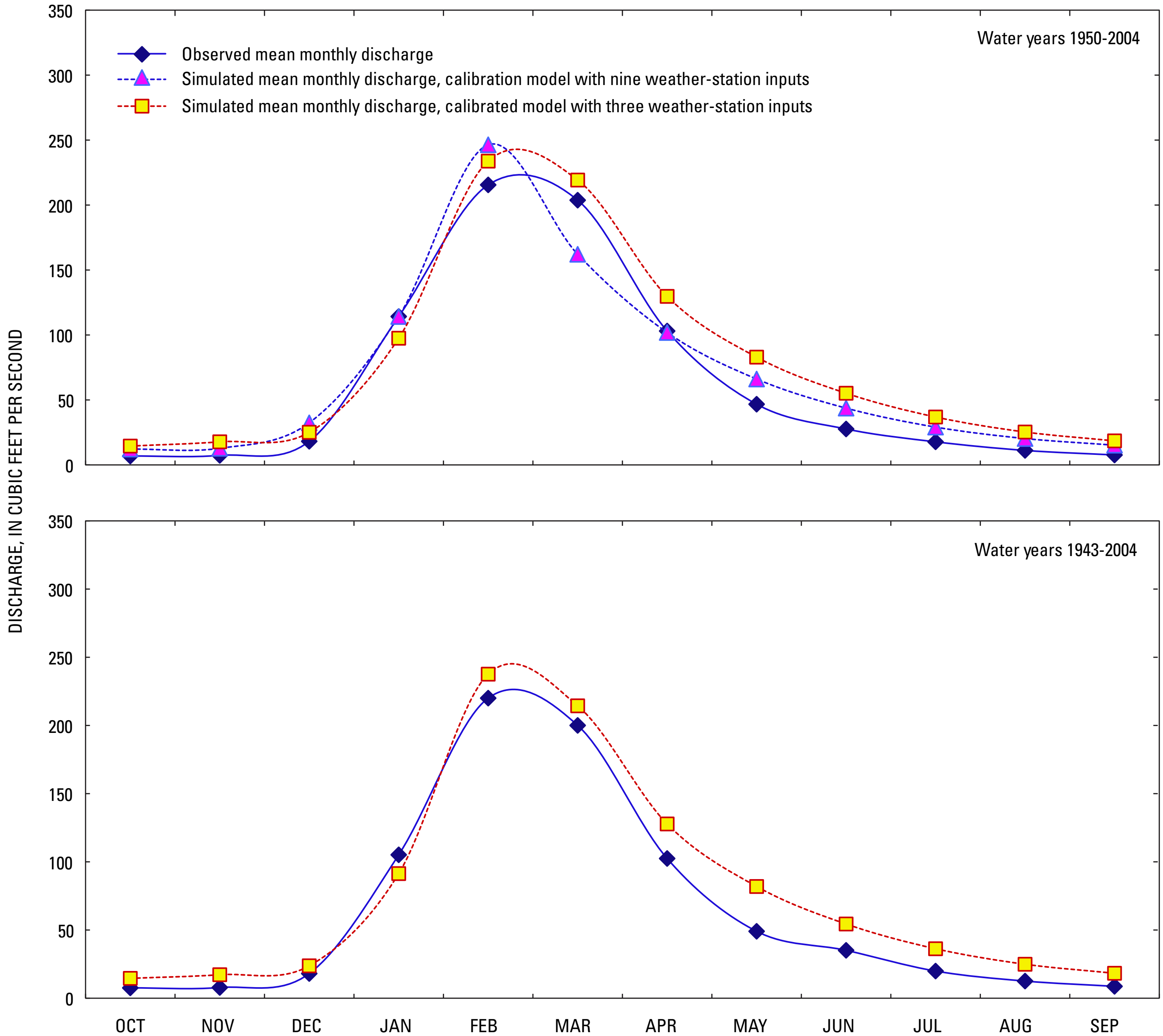


Figure 27. Observed and simulated mean monthly discharge for indicated water years at the streamflow-gaging station at Crab Creek at Irby, Washington.

Sources of Error

Three sources of error generally are associated with a numerical watershed model that involves physical-process representation, model parameterization, and data precision and accuracy. Model error is the error associated with incorrectly representing physical hydrologic processes with numerical algorithms. Parameter error involves selecting incorrect parameter values for the numerical algorithms. Data error is the error associated with the weather-station input data and includes the accuracy of the data and adequacy of weather stations.

Large differences in peak discharge were shown to be dependent on whether or not the ground was frozen. The runoff process is highly sensitive to frozen-ground conditions. Many of the grossly oversimulated and undersimulated peak discharges were a result of the model's failure to simulate the extent of frozen ground or to simulate frozen-ground conditions when they did not exist (model error). The results indicated that a relatively simple frozen-ground index reduced the error, but a more physically based algorithm of frozen ground may be needed to improve the model and may be the best opportunity to make improvements to the model. If the model is used for short-term forecasting of runoff, the model would not be reliable in forecasting a peak flow without additional user input or close monitoring. If the soils in the basin could be assessed as being frozen or not frozen during the short-term forecast period, and the CFGI value in the model could be monitored and altered if needed so that the model was simulating frozen or unfrozen conditions correctly, the reliability of the model to accurately simulate peak discharges would increase dramatically.

Also, in a basin like the Crab Creek Basin where regional groundwater flow processes often dominate the generation of streamflow discharge, the numerical watershed model had difficulty simulating the lag times in groundwater flow to the stream and accounting for regional groundwater inflow from outside the basin boundaries. This difficulty was evident in the simulation of Rocky Ford Creek where the seasonal pattern of flow was not duplicated nor was the total volume of groundwater from the upper basin adequate to simulate the observed runoff volumes. The simulation of streamflow in Rocky Ford Creek was not a priority in the project objectives. The relatively constant flows in Rocky Ford Creek could be more accurately forecasted from observed historical monthly mean discharges than from a model trying to simulate the complex groundwater hydrology that dominates the flow in this creek.

The idea of correctly calibrating all the parameters in the model (more than 55,000 in the Crab Creek model) was unrealistic, and it was presumed that parameter error would be the largest source of error. However, most parameters were defined by the GIS Weasel, optimization procedures were sometimes used to estimate the best parameter values, and a set of hydrologic generalizations were known about the study area that could be used to constrain the parameter values. With an infinite number of possibilities, there is no doubt that a better set of parameters could be found; however, after the initial calibration runs much effort was spent adjusting the parameters without significant improvement in the simulation results. Therefore, unless some significant parameter was overlooked, there is no indication that further adjustment of parameters would result in substantial improvement of the model.

The climate of the study area has limited spatial variability, which eliminates the need for a greater number of weather-station inputs to reduce the third source of error, data error. The model evaluation tested the effects of reducing or slightly altering the location of weather-station inputs and some minor changes were detected. When data input was changed from nine weather stations to three, the simulated annual runoff volumes at Crab Creek at Irby showed about a 12 percent difference, but the shape of the mean monthly hydrographs remained similar. The error due to weather-data input is important, but probably is not as significant as the errors due to the inability of the model's algorithms to consistently simulate the hydrologic processes in the basin.

Water Budget

The water budget is a basin average of the amount of water that falls as precipitation and then follows the various flowpaths simulated by the model—the sum of inputs, outputs, and changes in storage. Flow paths at the MRU scale are between surface and subsurface reservoirs, and at the regional scale are between stream channels and the groundwater system. By tallying the amounts of runoff through each simulated flowpath, the importance of each path and the hydrologic processes can be compared. The budget is divided into two parts. One budget balances basin-averaged precipitation with basin-averaged runoff and evapotranspiration (in inches) near the land surface and runoff in the subsurface (table 10). The second part of the budget is the stream-channel and groundwater budget that balances the stream channel discharge against water flowing in groundwater flowpaths, groundwater sinks, and MRU runoff outputs (table 10).

Most of the precipitation is lost to evapotranspiration (interception ET losses plus AET), which varies from 84.0 to 90.7 percent of the total precipitation. This leaves on average only 0.90 in. (Lind Coulee) to 1.74 in. (Crab Creek) for contribution to runoff. Most water available for runoff (80.8–86.2 percent) follows the groundwater flowpath. Although the surface-runoff flowpath is used only occasionally during intense rainstorms or frozen-ground conditions, it is the next most important flowpath. The subsurface pathway contributes minimal amounts of runoff.

Table 10. Average annual water budget for three model units simulating runoff into Potholes Reservoir, Washington, water years 1950–2004.

[**Model response unit budget: Balance** equals Precipitation – Interception ET Loss – Actual ET – Surface runoff–Subsurface runoff – Flow to groundwater – Change in storage. **Stream channel and groundwater budget: Balance** equals Streamflow + Channel losses + Change in groundwater storage – Groundwater sink – Surface runoff – Subsurface runoff – Groundwater flow to stream. **Change in storage** equals sum of the change in soil moisture, subsurface reservoir, and interception. **Groundwater sink:** Groundwater lost to regional groundwater that does not contribute to local streamflow. **Abbreviation:** ET, evapotranspiration]

Model unit	Model response unit budget, in inches							
	Precipitation	Interception ET loss	Actual ET	Surface runoff	Subsurface runoff	Flow to groundwater	Change in storage	Balance
Crab Creek	10.872	0.589	8.546	0.157	0.082	1.498	0.001	0.000
Rocky Coulee	8.972	0.557	7.544	0.121	0.025	0.724	0.001	0.000
Lind Coulee	9.639	0.536	8.202	0.164	0.009	0.730	0.002	-0.001

Model unit	Stream-channel and groundwater budget, in inches							
	Streamflow	Channel losses	Groundwater sink	Surface runoff	Subsurface runoff	Groundwater flow to stream	Change in groundwater storage	Balance
Crab Creek	0.599	0.606	0.480	0.157	0.082	0.967	0.480	-0.001
Rocky Coulee	0.638	0.000	0.233	0.121	0.025	0.492	0.233	0.000
Lind Coulee	0.368	0.000	0.391	0.164	0.009	0.198	0.391	-0.003

Potential simulated runoff to the groundwater system or to the stream channel does not always make it to the mouth of the streams or model outlets. Some water available for runoff may be lost to the regional groundwater system through channel losses or direct losses from the MRUs (groundwater sinks). In the Crab Creek model, channel losses are greater than the amount of discharge at the mouths of Crab Creek and Rocky Ford Creek (model outlets) and the groundwater sink losses from the MRUs are about 80 percent of the discharge at the model outlets (listed as streamflow in table 10). The Lind Coulee and Rocky Coulee models did not use the channel-loss options during the calibration process, but data indicate they do lose a substantial amount of the water available for runoff through the groundwater sink. The dominant pathways for water in the system generally were simulated as would be expected from the conceptual model for hydrology in the study area discussed earlier.

Integrating Watershed Models Into a User Interface for Real-Time Forecasting

The three watershed models were linked together through an Object User Interface (OUI; Steve Markstrom, U.S. Geological Survey, written commun., 2004) in a similar manner described by Mastin and Vaccaro (2002b) for the Yakima River basin. This linking allows a user to easily display input and output data and make runoff forecasts for up to 1 year. Four principal operations are performed by the OUI: (1) make single runs of the three models, (2) run an ESP utility to make forecasts of runoff for an upcoming season, (3) provide output in HDB format or ASCII files, and (4) provide graphical displays of input and output data.

These principal operations are initiated from one simple point-and-click graphical interface. They allow user access to all functions needed to make forecasts and long-term planning model runs (except for the retrieval of real-time data that currently is accomplished outside of OUI using a script program), assess the input data or current state of the model, and provide input to the water-management model RiverWare. The Potholes DSS uses a newer version of the OUI than the one used for the Yakima DSS. The newer version allows the user access to the traditional MMS user interface and provides the ability to adjust model parameters.

The OUI is a Java-compiled program that is highly configurable through a control file that is a text file written in the eXtensible Markup Language (XML). The OUI can be run by either Unix or Windows operating systems. Examples of the various capabilities of the Potholes Project OUI are shown through a series of OUI screen images (figs. 28–36).

Opening Screen

After opening the OUI, the user is provided a series of maps that can be opened for display and queried for attributes of the theme map. These maps are stored as ESRI-formatted shape files for point, line, or polygon features and ESRI-formatted ASCII grid files for raster features in subdirectories below the root directory from which the OUI is initiated.

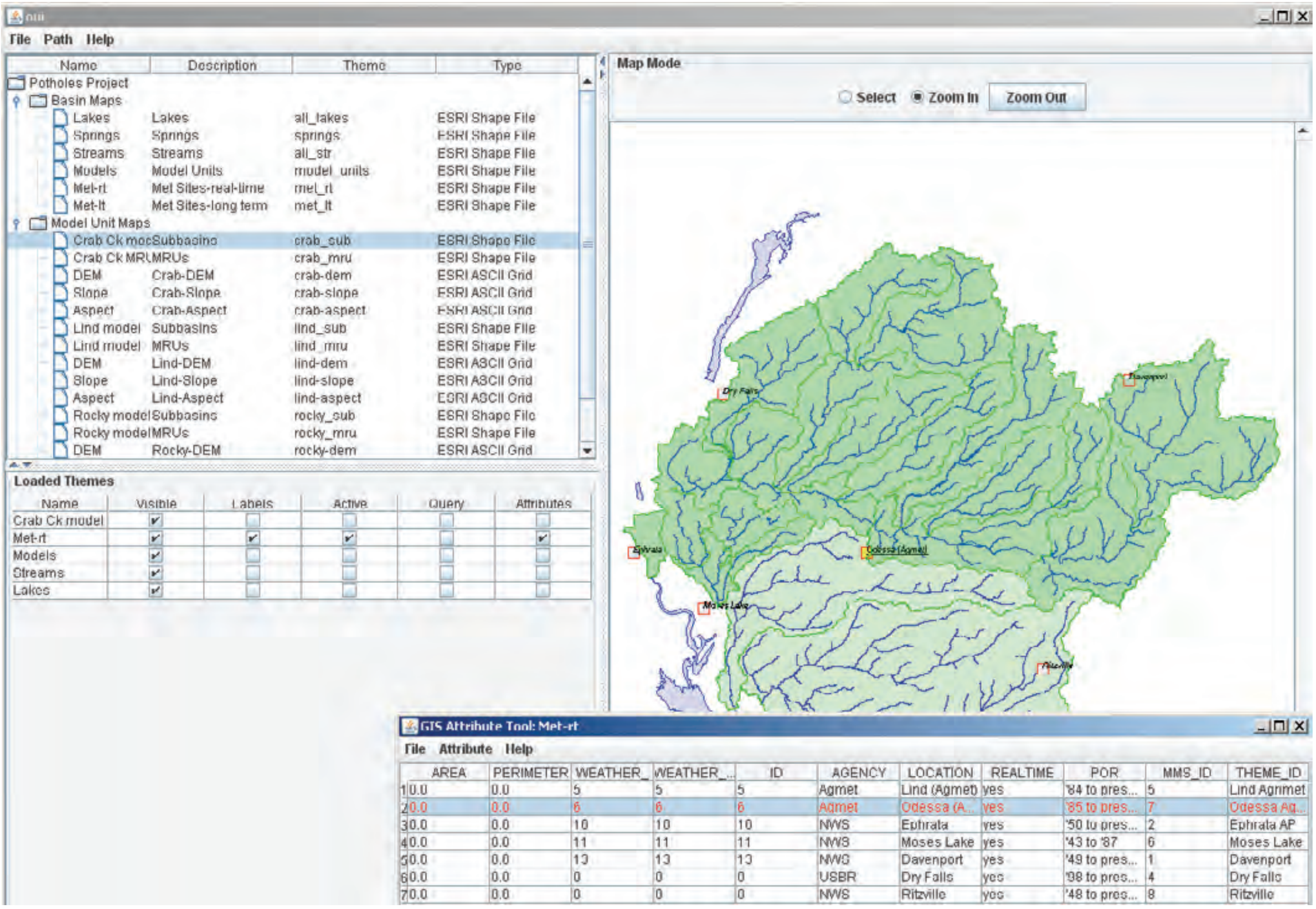


Figure 28. Potholes Project OUI showing the list of basin and model unit maps (upper left panel), the selected map themes (lower left panel, "Loaded Themes"), the display map (right panel, "Map Mode"), and a pop-up window showing the attributes of the Met-rt theme (below display map panel, "Edit Attributes of Theme Met-rt").

Figure 28 shows the opening screen and the five themes (Crab Creek modeling subbasins, real-time weather stations, model units, streams, and lakes) that have been loaded by the OUI (see lower left panel, Loaded Themes). The real-time weather stations point coverage, Met-rt, has been activated and the Odessa station has been selected in the "Map Mode" panel. When a point in the Met-rt coverage is selected, the pop-up window "Edit Attributes of Theme Met-rt" appears (see fig. 28 in the bottom of the Map Mode panel). This window provides attribute data for the coverage and highlights the selected point. The text headings in the upper left panel represent the hierarchical tree structure or the Project Tree starting from highest to lowest level: Potholes Project, Basin Maps, Model Unit Maps, and Models and Data. The tree structure is defined in the project XML file (fig. 28).

Data Retrieval

To perform a seasonal forecast of runoff using ESP, hydrologic-process variables simulated for each MRU need to be updated to reflect current conditions. Examples of such variables include snowpack water-equivalent and soil-moisture content. Updating of the model to current conditions requires input of real-time daily air temperature and precipitation data. Reclamation created a script that retrieves NWS data and Reclamation hydrologic data maintained on its real-time database (Hydromet). The script reformats the downloaded data into MMS format. This data is appended to the last input-data file before the current forecast model run is made.

Time-Series Graphs

The OUI includes utilities to make time-series graphs. Any time-series data—including but not limited to weather-station data, and observed and simulated discharge—can be viewed in a graph (fig. 29). For example, by first clicking on the "Models & Data" toggle switch (fig. 28) and then the "Single Run" toggle switch, a tree-node name "Single Run Model Output" becomes visible. Right clicking on this node and then the "Load" tab will load the theme in the Map Mode panel. The theme must be activated to select a station.

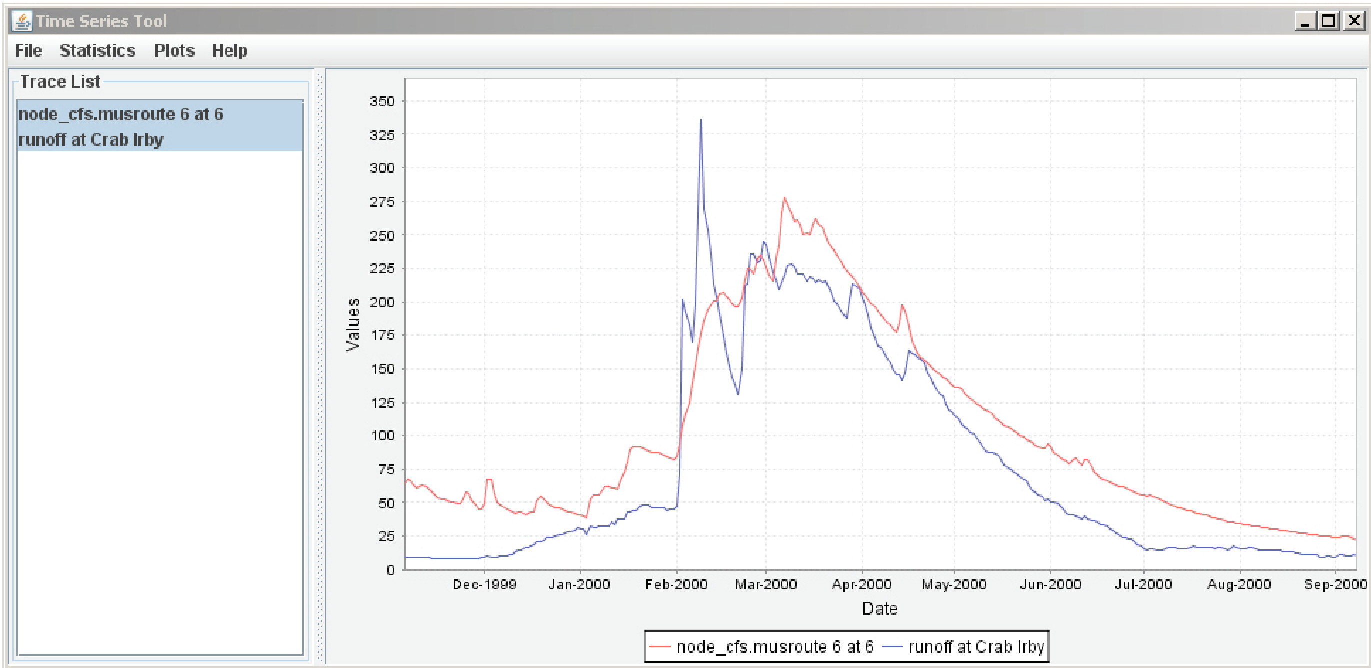


Figure 29. Hydrograph of simulated discharge ("node_cfs.musroute 6 at 6," red line) and observed discharge ("runoff at Crab Irby," blue line) for Crab Creek at Irby, Washington, for the time indicated as displayed in the Time Series Tool window of the Potholes Project OUI.

To do this the "Active" check box for this theme in the Loaded Theme panel must be checked. Once activated, the "Select" tool can be used to click on a point and a Time Series Tool window is generated that allows the user to plot the available record and zoom into periods of interest (fig. 29).

Single Model Runs

Under the "Models & Data" tree node (fig. 28) is a "Single Run" tree node that can be activated to make a single model run for each of the three models. Model runs are initiated with a right mouse click on the tree node name. A pop-up menu window (fig. 30) allows the user to enter the model-run start and end dates, and begin the model run. For each model run, output is stored in ASCII files called "statvar" files, which contain one row of data for each day of simulation. Each row contains a time stamp followed by a listing of simulated discharges at preselected routing nodes. An attribute in the shape file that is displayed under the Single Run Model Output tree node lists the order of the discharge values in each row of data in the statvar file. This information allows the OUI to correctly parse the statvar file for a user-selected site and export simulated discharges or make a time-series plot for one or more nodes of interest.

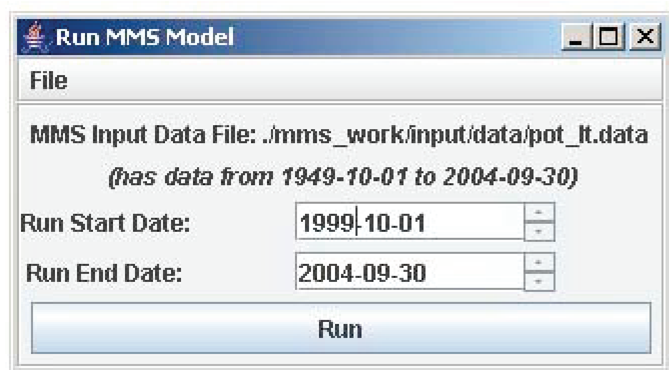


Figure 30. Screen capture from Potholes Project OUI of the single model run pop-up window requesting the user to enter the Run Start Date and Run End Date of the model run.

ESP Model Runs

Under the "Models & Data" tree node (fig. 28) is a second model run option, the "ESP Run" tree node, which allows the user to initiate an ESP model run. By right clicking on this tree node a pop-up window appears (fig. 31), which is similar to the pop-up for the "Single Run" option (fig. 30).

The start and end dates for an ESP model run define the forecast period, which usually extends from the last day when near-real-time input data are available to the last day of the runoff season that the user is interested in simulating. After entering the forecast dates and initiating the ESP model run by clicking the “Run” button, an initial model run simulates the 3 years prior to the “Forecast Start Date” (2004-02-01 in the example shown in fig. 31). The simulated values at the end of this 3-year period are then used as the starting values of the ESP model runs for the forecast period. The ESP model runs simulate the requested forecast period multiple times, using the model inputs of each year in the real-time input data file. For the Potholes Project, this means that a completed ESP run consists of 58 simulations of the forecast period, using input data from water years 1950–2007.

Figures 32, 33, and 34 show the results of an ESP model run for the Crab Creek at Irby station. Figure 32 shows the simulated discharge for the initial, 3-year model run that generates the starting variables for the ESP model runs (in red) and the forecasted February through July discharge that has a 50 percent exceedance probability based on discharge volume for the forecast period (in blue). The 50 percent exceedance probability was determined by ranking the simulated runoff volume for the forecast period of each of the 55 ESP runs (called traces). In this example, data from 1962 generated the 50 percent exceedance probability as shown in the upper left scroll window that lists all 55 ranked ESP traces (1962 actP = 50; actP stands for actual probability). The ESP traces also can be ranked by peak discharge or water year with the set of buttons in the left center of the tool in the “Rank By” box. The DMIs allow the output to be downloaded directly into the HDB, but this feature has not been implemented in the Potholes Project OUI. When the ESP model run is made, output files of the simulated discharge, one for each year, are generated in the oui/potholes/mms_work/output/esp directory. At this time, the Potholes DSS will use these files directly as input to the RiverWare model rather than using the HDB and DMIs.

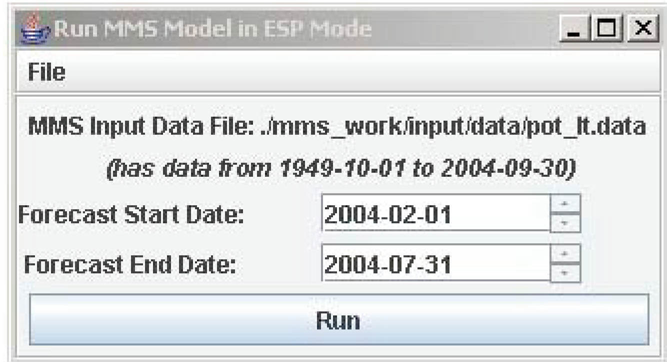


Figure 31. Potholes Project OUI of the ESP model run pop-up window requesting the user to enter the Run Start Date and Run End Date of the model run.

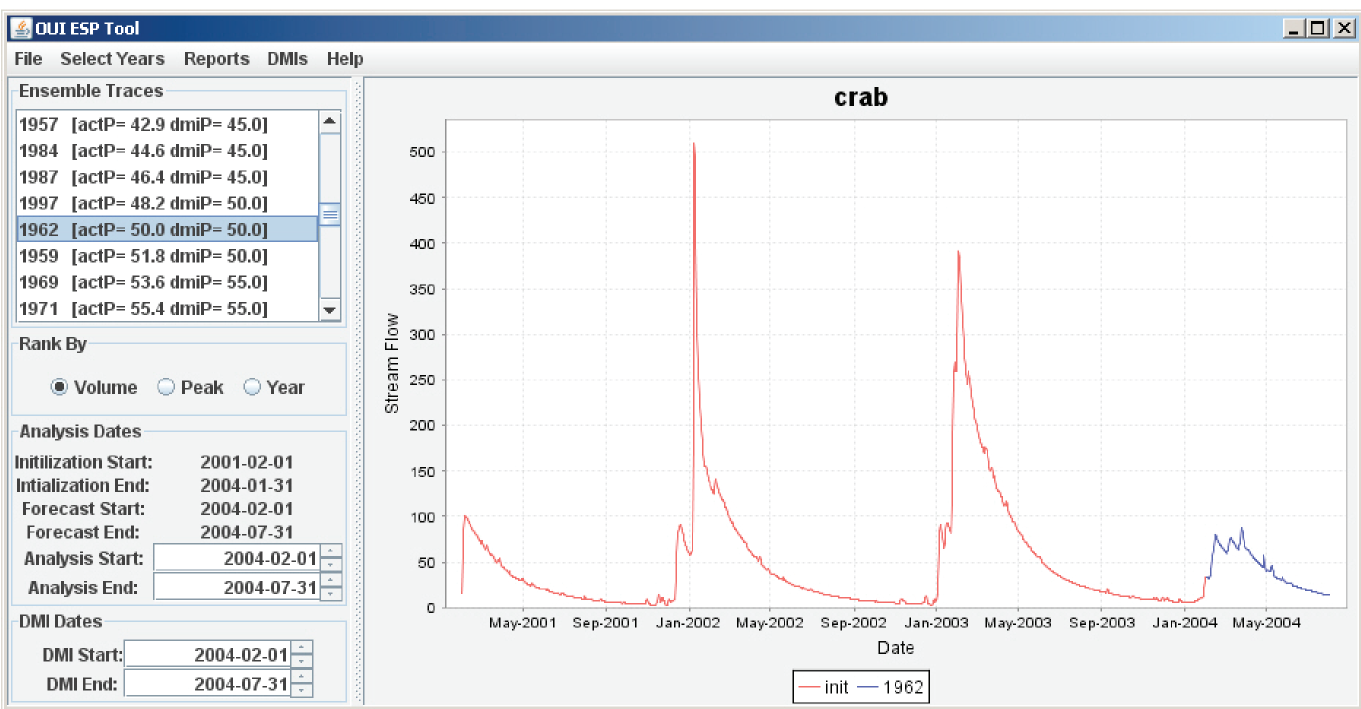


Figure 32. Potholes Project OUI for the OUI ESP Tool window showing a hydrograph of the initial model run (init, in red) and the 1962 ESP run trace (in blue), which has a 50 percent exceedance probability based on runoff volume for Crab Creek at Irby, Washington for the forecast period. The Data Management Interface (DMI) feature for exporting data has not been implemented in the Potholes Project OUI.

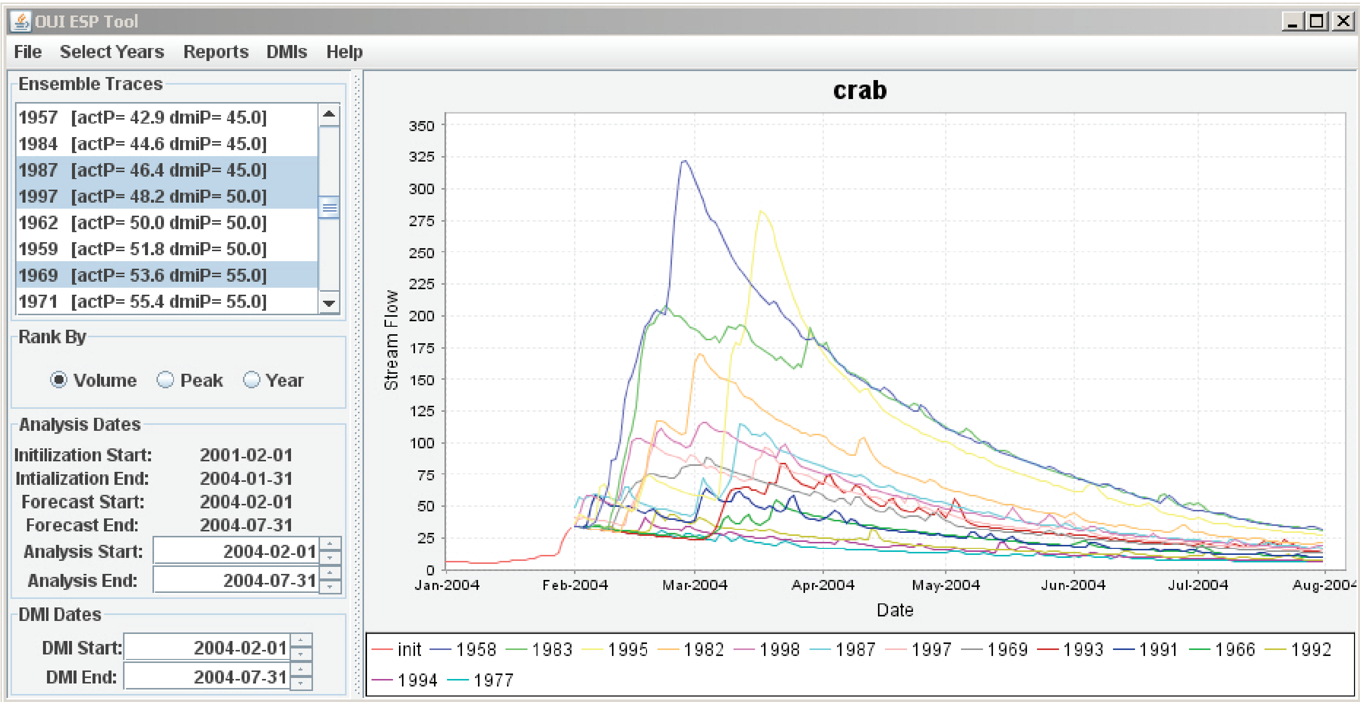
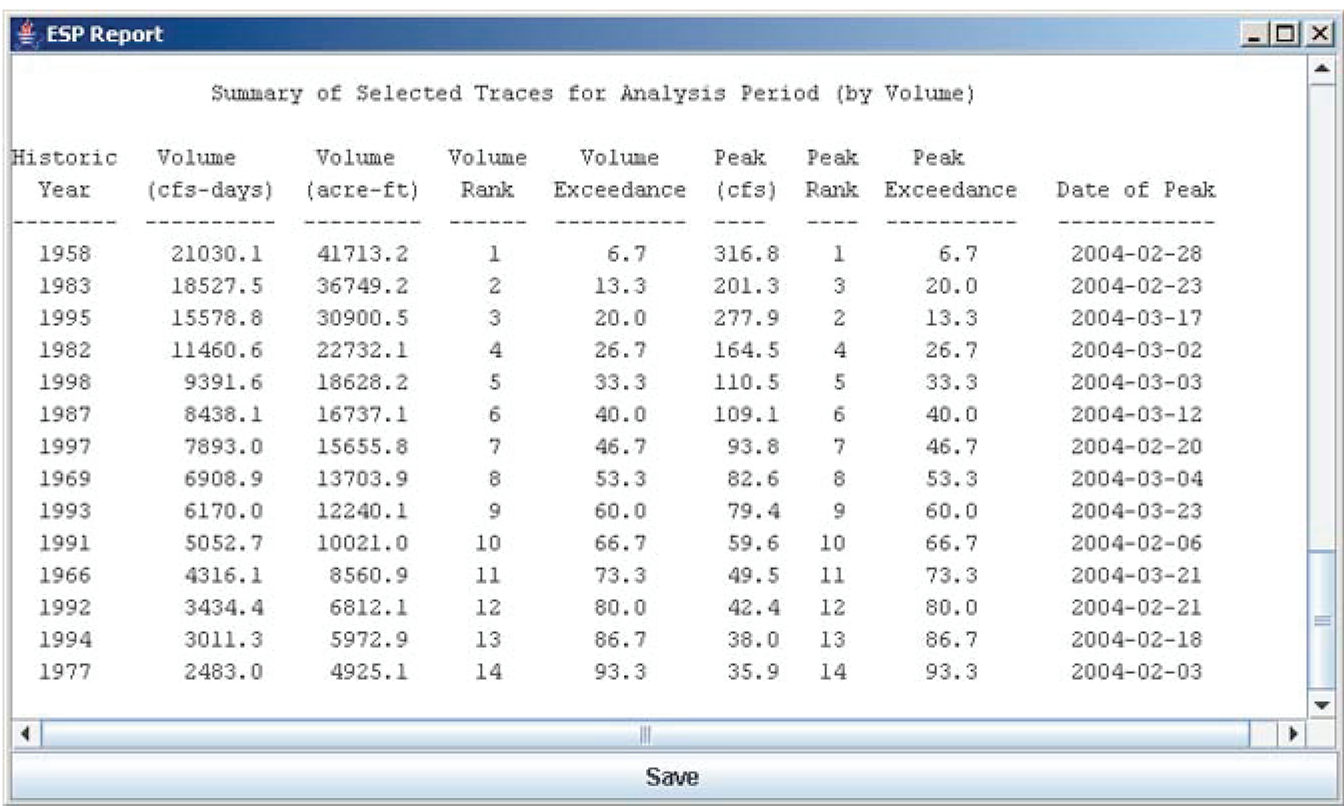


Figure 33. Potholes Project OUI for the OUI ESP Tool window showing the initial model run (init) and the ensemble of traces for the "El Niño" years ranked by runoff volume for the indicated forecast period for Crab Creek at Irby, Washington.


ESP Report

Summary of Selected Traces for Analysis Period (by Volume)

Historic Year	Volume (cfs-days)	Volume (acre-ft)	Volume Rank	Volume Exceedance	Peak (cfs)	Peak Rank	Peak Exceedance	Date of Peak
1958	21030.1	41713.2	1	6.7	316.8	1	6.7	2004-02-28
1983	18527.5	36749.2	2	13.3	201.3	3	20.0	2004-02-23
1995	15578.8	30900.5	3	20.0	277.9	2	13.3	2004-03-17
1982	11460.6	22732.1	4	26.7	164.5	4	26.7	2004-03-02
1998	9391.6	18628.2	5	33.3	110.5	5	33.3	2004-03-03
1987	8438.1	16737.1	6	40.0	109.1	6	40.0	2004-03-12
1997	7893.0	15655.8	7	46.7	93.8	7	46.7	2004-02-20
1969	6908.9	13703.9	8	53.3	82.6	8	53.3	2004-03-04
1993	6170.0	12240.1	9	60.0	79.4	9	60.0	2004-03-23
1991	5052.7	10021.0	10	66.7	59.6	10	66.7	2004-02-06
1966	4316.1	8560.9	11	73.3	49.5	11	73.3	2004-03-21
1992	3434.4	6812.1	12	80.0	42.4	12	80.0	2004-02-21
1994	3011.3	5972.9	13	86.7	38.0	13	86.7	2004-02-18
1977	2483.0	4925.1	14	93.3	35.9	14	93.3	2004-02-03

Save

Figure 34. Potholes Project OUI showing part of the ESP Report window that includes the years, volumes, ranks, and exceedance probabilities for the "El Niño" traces for forecast period February 1 through July 31.

Figure 33 shows the same window as figure 32, but a set of traces were selected for display of the forecast period only. The tail end of the initial model run (red line) can be seen, and 1 day after it ends selected traces from the ESP model run begin. Input that generated the traces was selected automatically using the "Select Years" drop-down menu list. In this example, the drop-down menu item "El Niño (Water Year NINO 3.4, SSTs > 0.5)" was selected. (NINO 3.4 refers to the region in the Pacific Ocean bounded from 120°W to 170°W longitude and from 5°S to 5°N latitude, and SSTs greater than 0.5 refers to mean sea surface temperatures greater than 0.5 degrees Celsius above normal in the NINO 3.4 area for the water year.) Other predetermined groupings of the traces include La Niña (Water Year NINO 3.4, SST < -0.5), ENSO Neutral, PDO > 0.5, PDO < -0.5, and PDO Neutral. PDO (Pacific Decadal Ocillation) is an El Niño-like pattern of Pacific Region climate that uses an index defined as the leading principal component of North Pacific Ocean monthly sea surface temperature north of 20 degrees latitude (Mantua and Hare, 2002).

A traditional ESP model run uses all the water years available in a record and its results are automatically compiled in an ESP report. Figure 34 shows part of an ESP report that is generated from the "Reports" drop-down menu. Volume of runoff, peak discharge, rankings, and exceedance probability information is given for all ESP traces and a separate listing is given for selected years. In this report example, figure 34 shows that the El Niño criteria fit 14 of all 55 water years.

MMS Model Runs

The final model run option under the "Models & Data" tree node is the "MMS Runs." Under this tree node are three model-run options that initiate the MMS GUI with specific parameter, data, and control files for each watershed model (fig. 35). The MMS GUI provides the user the option of a different interface to run the models and the ability to change model parameters. Figure 36 is an example of the parameter editing window where parameters for the nhru (number of hydrologic response units—the same as model response units) dimension for the Crab Creek watershed model can be changed. It allows all the parameters related to the 386 MRUs in the crab_final.mms parameter file to be edited and saved in a new file with a different name. Other sets of parameters can be edited, such as monthly parameters when the "nmonths" node in the left panel of this window is selected. Multidimensional parameters also are available for editing such as the snow_mon parameter, which has one value for each month and for each MRU. This parameter is accessed by opening the nhru,nmonths node in the left panel of the window and clicking on the snow_mon node name. More information on how to work with the MMS GUI can be found in the MMS user's manual (Leavesley and others, 1996).

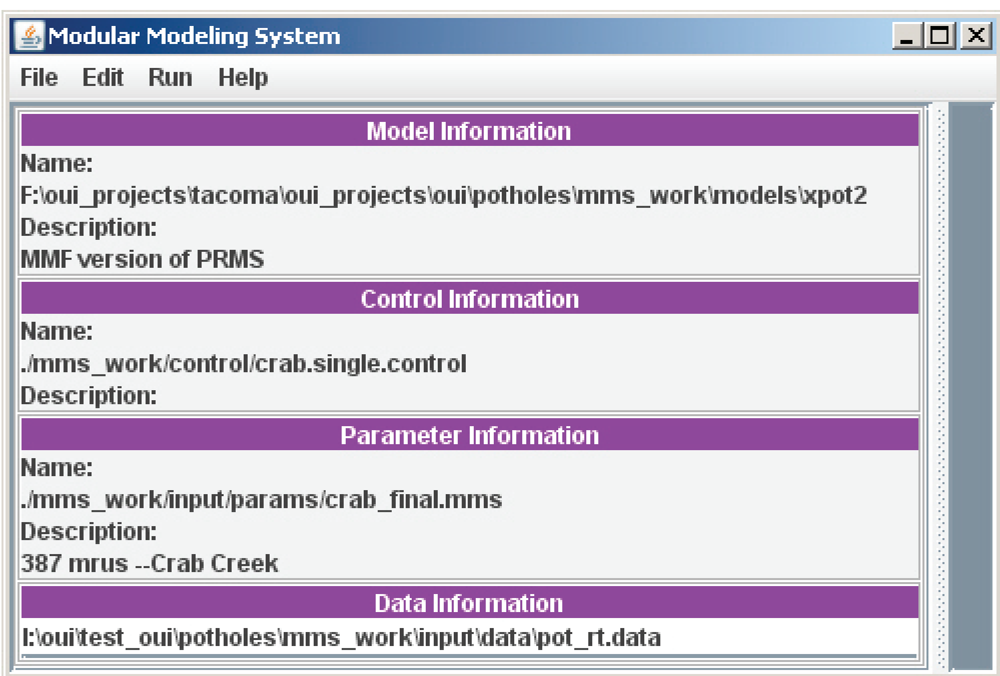


Figure 35. Potholes Project showing the opening screen of the MMS GUI and the control, parameter, and data files for the Crab Creek Watershed model.

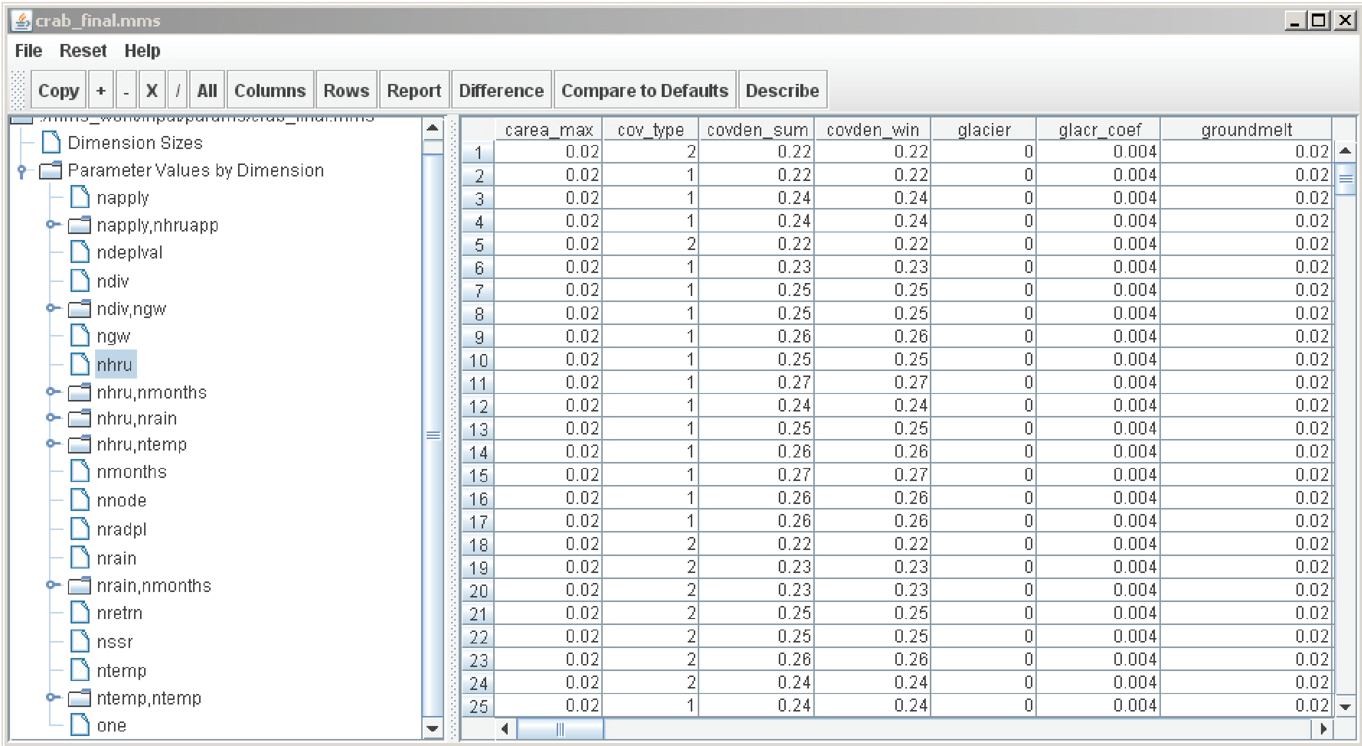


Figure 36. Potholes Project OUI showing the parameter editing window of the MMS GUI. Listed are some of the parameters for the nhru (number of hydrologic response units—the same as model response units) dimension for the Crab Creek Watershed model.

Summary

The U.S. Geological Survey (USGS) and Bureau of Reclamation (Reclamation) are collaboratively working on the Watershed and River Systems Management Program (WARSMP) to couple watershed and river-management models and then apply them to Reclamation projects in the western United States. The coupling provides a decision support system (DSS). One such DSS was applied to Reclamation's water-management project in east-central Washington. As part of this DSS, three watershed models were constructed for four drainage basins providing inflow to Potholes Reservoir: Crab Creek, Rocky Ford Creek, Rocky Coulee, and Lind Coulee.

Beyond the typical hydrologic processes that occur in most basins in Washington, five other processes were identified that occur in the study area.

1. Frozen ground can have a significant influence on peak runoff causing runoff peaks more than an order of magnitude greater than they would be without frozen ground.

2. Precipitation is limited in the basin, which can only marginally support dry-land farming, and evaporation is the major pathway for moisture once it falls to the ground; therefore, accurate simulation of evaporation is critical for accurate simulation of runoff.

3. Most remaining moisture that becomes runoff follows groundwater pathways that cross surface-water boundaries.

4. Channel losses can significantly reduce available water downstream and are especially significant in certain reaches during the spring when a "wetting up" process diverts channel flow to recharge of the shallow aquifer or in-channel lakes.

5. Irrigation practices can decrease runoff in drainage areas where groundwater is pumped for irrigation and increase runoff in drainage areas where surface water that is used for irrigation returns to the stream through channels, wasteways, and groundwater flowpaths.

The watershed models were constructed using hydrologic-process modules from the USGS Precipitation-Runoff Modeling System (PRMS). Some PRMS modules were modified for a previous WARSMP basin (the Yakima River basin), and some for this study. The hydrologic-process modules were integrated into a watershed model using the Modular Modeling System (MMS), and integrated into a DSS using the OUI developed by the USGS. The modified PRMS modules included a surface-runoff module modified to incorporate a continuous frozen-ground index that simulates frozen-ground conditions by routing all water available for runoff through surface-water flowpaths once a threshold-index value has been reached. The groundwater module was modified to allow groundwater to be routed across surface-water drainage boundaries and thereby simulate regional groundwater flow. The flow-routing module created for the Yakima River basin WARSMP was modified to simulate channel wetting-up and channel-loss processes. The watershed model compiled from these modules was calibrated and evaluated against observed runoff data.

The GIS Weasel, a collection of GIS macros specifically designed to process spatial information for watershed processes and compute many of the initial parameters for the PRMS model, delineated the 3 model units and the 37 subbasins within a drainage area of 2.14 million acres. These subbasins then were divided into 628 model response units, which are units of homogeneous hydrologic response to precipitation, solar radiation, and air temperature inputs. Data input files for water years 1950–2004 (the model calibration period) were compiled and selected model parameters were adjusted to match simulated runoff with observed, unregulated runoff where available. The model was evaluated as a forecast tool by using a different (smaller) set of weather stations. A separate evaluation examined the ability of the model to simulate discharges at the streamflow-gaging station at Crab Creek at Irby, in order to extend the record for that station. Results from the two evaluation models were compared with observed runoff and with runoff simulated using the complete set of weather-station data as input. No substantial differences in runoff were found between the long-term calibration model with the full number of weather-station inputs and the models with subsets or different weather-station inputs.

The models proved to be unreliable with respect to simulating runoff from frozen ground. The continuous frozen-ground index value did not always correctly indicate frozen ground and when it was in error, the model could significantly undersimulate or oversimulate the observed peak discharge. Root-mean-square errors of simulated annual peak discharges ranged from 65 to 505 percent. For these reasons, the models are not considered reliable for short-term forecasts without knowing the frozen ground conditions ahead of time and adjusting the continuous frozen-ground index value in the model if needed. Comparisons of the mean monthly and mean annual runoff were more reliable. Simulated mean annual discharge for the period of observed discharge differed by 1.2–13.8 percent from the observed discharge, except for Rocky Ford Creek, which was undersimulated by 36.4 percent. Rocky Ford Creek is an area of regional groundwater discharge and is thought to receive groundwater flow from outside the basin. This flow component is not simulated by the model. The simulated mean monthly discharge hydrograph at other sites generally followed the shape of the observed mean monthly discharge hydrograph. Two thirds of the percent differences between the simulated and observed mean monthly discharge was between -20 percent and 240 percent or, in absolute terms, between -0.8 and 11 ft^3/s.

The Nash-Sutcliffe efficiency values for the models indicated some success of the models' ability to simulate annual flows in Crab Creek on an annual basis. The efficiency values also indicated that the model failed to improve runoff estimation over a simple estimation of flow from the observed mean for some individual months at the two Crab Creek sites and for most of the year in Farrier Coulee and Rocky Ford Creek.

Despite efforts to incorporate the significant flow processes in the simulation models, the results indicate that the complex hydrologic processes in the basin are still too much of a challenge to allow accurate and reliable short-term simulation of runoff with current models. The models demonstrated some success in simulating discharges. In the absence of other models, the ones used in this investigation can assist water-management planners by providing long-term, time-series discharge data where no observed data exist—with the expectation of providing mean monthly and annual discharge values within the percent errors shown in this report. The models are not reliable for managing short-term operations because of their demonstrated inability to match individual storm peaks and individual monthly discharge values. Short-term forecasting may be improved with real-time monitoring of the extent of frozen ground and the snow-water equivalent in the basin. Future investigations should focus on incorporating real-time frozen-ground conditions and snow-water equivalent into the model, and then evaluate the improvements that are gained.

The simulated daily discharge values were stored at all the routing nodes in the models for water years 1950–2004. These values can be used for long-term planning as input into the water-management model RiverWare that was constructed for the basins by Reclamation. The Potholes DSS provides the ability to plan basin operations in a daily or monthly mode with discharge values that are consistent with each other and represent a full spatial data series, which was not previously available. The OUI allows users to view all the data, update the data files with real-time data, and make forecasts for midterm operations and long-term planning.

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