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Real-Time Flood Alert and Simulation of River Flood Discharges in the Puyallup River Basin, Washington

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Real-Time Flood Alert and Simulation of River Flood Discharges in the Puyallup River Basin, Washington

By M.C. Mastin

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Charles S. Groat
Director

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per hour	25.4	millimeter per hour
inch per year	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
mile (mi)	1.609	kilometer
mile per hour (m/h)	1.609	kilometer per hour
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS—Continued

Temperature: To convert temperature given in this report in degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation: °C = 5/9(°F-32).

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

Elevation: In this report, "elevation" is measured in feet above sea level.

ABBREVIATIONS

ADAPS	Automated Data Processing System
CROHMS	Columbia River Operations Hydromet Management System
DEM	Digital elevation model
GIS	Geographic information system
NAP	Normal annual precipitation
NOHRSC	National Operational Hydrologic Remote Sensing Center
NRCS	National Resources Conservation Services
NWS	National Weather Service
PC	Personal computer
PCRI	Pierce County River Improvement
SEE	Standard error of estimate
SSARR	Streamflow Synthesis and Reservoir Regulation model
SWE	Snow-water equivalent
USACOE	U.S. Army Corps of Engineers
WAR	Water available for runoff
WATSTORE	National Water Data Storage and Retrieval System

REAL-TIME FLOOD ALERT AND SIMULATION OF RIVER FLOOD DISCHARGES IN THE PUYALLUP RIVER BASIN, WASHINGTON

By M. C. Mastin

ABSTRACT

The U.S. Geological Survey, in cooperation with Pierce County, Washington, has developed an operational tool called the Puyallup Flood-Alert System to alert users of impending floods. The system acquires real-time meteorological and hydrological data to make real-time flood simulations of discharge in the major rivers of the Puyallup River Basin and provides a flood-alert computer display. The system consists of a network of U.S. Geological Survey-operated river discharge and stage, precipitation, and temperature gages; a numerical watershed runoff and streamflow-routing model; and a computer interface. A snowband version of the Streamflow Synthesis and Reservoir Regulation (SSARR) numerical model is the heart of the system that makes real-time and forecast simulations based on real-time data from the gaging network and precipitation and temperature forecasted by the National Weather Service.

The watershed model was calibrated against observed peak discharge and runoff volumes from five subbasins during four storms in water years 1995 and 1996 and validated with similar data from four storms in the 1996 and 1997 water years. Two-thirds of the simulated peak discharges for the calibration storms were within 36 percent of the observed peak discharges, and two-thirds of the 5-day runoff volumes were within 17 percent of observed runoff volumes. For the validation storms, the corresponding values were 30 percent and 24 percent, respectively.

SSARRMENU, a customized user interface for the Puyallup Flood-Alert System, is the central software that provides a graphical display of flood-alerts and model input and output, makes retrievals of hydrologic and meteorological data from the U. S. Geological Survey computer, and initiates simulations by SSARR. With SSARRMENU operating on its computer, Pierce County has an increased ability to evaluate current and near-future floods and to efficiently allocate its resources to potential trouble spots.

INTRODUCTION

Flooding on the Puyallup River and its major tributaries threatens people and property as the river weaves through increasingly urban areas from the western foothills of the Cascade Range to Puget Sound in the City of Tacoma (fig. 1). Most of the basin lies within Pierce County, and Pierce County River Improvement or PCRI (also known as the Water Programs Rivers Division), an agency of Pierce County Public Works and Utilities, has primary responsibility for floodplain management and maintaining the flood-control levees of the major rivers in the basin. The agency monitors river levels and weather forecasts closely during the rainy season (November through March) and allocates its resources in response to current and imminent flooding. To allocate its resources efficiently for impending flooding, the agency needed a monitoring and predictive tool to assess the size and timing of peak flows at critical locations.

The U.S. Geological Survey (USGS), in cooperation with PCRI, has developed a real-time flood-alert tool that personnel of PCRI can operate on their computers using real-time data gathered at USGS-operated gaging stations and quantitative temperature and precipitation forecasts made by the National Weather Service (NWS). This real-time flood-alert tool, an operational system called the "Puyallup Flood-Alert System," provides graphic and tabular information on current river discharges and stages in the Puyallup River Basin, simulated river discharges and stages, as well as 2-day river forecasts based on meteorological forecasts by the Seattle NWS office. Two versions of the software that provides users an interface to the system were developed—one runs on a MS-DOS[TM] or Windows 3.1[TM] operating system and one runs on a Windows NT[TM] operating system.
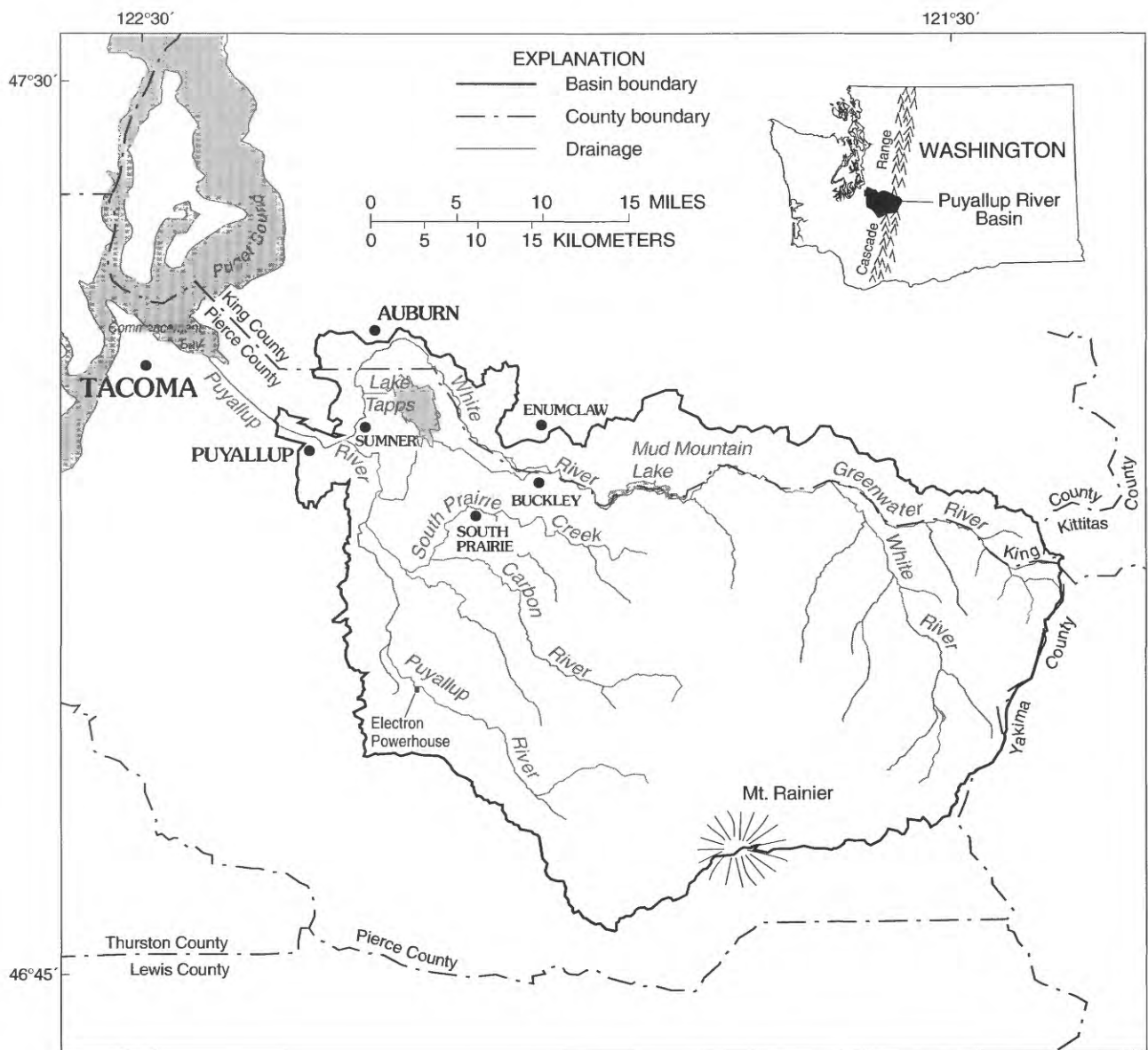
Figure 1. Study area showing the Puyallup River, its major tributaries, and its basin boundaries.

Purpose and Scope

This report describes (1) a conceptual model based on the main hydrologic and meteorologic influences on major floods in the Puyallup River Basin, (2) a numerical watershed and flow-routing model to simulate flooding in the Puyallup River and major tributaries, (3) the sensitivity of the model to various inputs and parameters, (4) an evaluation of the simulation model results, and (5) an operational system that provides real-time transfer of observed and forecasted meteorological and river data, real-time simulation of river discharges and stage, and real-time displays of observed and simulated meteorological and river data.

Before this work started, many streamgaging stations provided information via satellite telemetry to the USGS office and then via telephone to the PCRI. During the investigation, the USGS-operated hydrometeorological network was upgraded, and a meteorological site in the Puyallup River Basin was added to provide a more dense network of telemetered precipitation and temperature data. The Streamflow Synthesis and Reservoir Regulation (SSARR) model, a numerical model for simulating watershed runoff and streamflow routing, was calibrated to four observed peak flows during the 1995-96 water years and validated to four storms in the 1996-97 water years.

The Puyallup Flood-Alert System (fig. 2) is composed of the validated SSARR model that incorporates all the available telemetered meteorological and discharge data for the basin, the data base for observed and simulated data, and the compiled FORTRAN90 program SSARRMENU. SSARRMENU provides a graphical interface to the SSARR model so that users can make model runs and review the results with pull-down menus, dialog boxes, and a "point-and-click" map display.

Acknowledgments

The author wishes to acknowledge the NWS's River Forecast Center in Portland, Oreg., for its assistance with using the SSARR model and the PCRI for providing feedback on the design of the operational system.

DESCRIPTION OF STUDY AREA AND DATA-COLLECTION NETWORK

The study area is the Puyallup River Basin upstream of the streamgaging station Puyallup River at Puyallup (station number 12101500), located 6.6 miles upstream from the river's mouth at Commencement Bay. This area encompasses 948 square miles and ranges in elevation from near sea level to 14,410 feet at the peak of Mt. Rainier. The basin lies west of the Cascade Range and southeast of the City of Tacoma and constitutes most of eastern Pierce County and part of southeastern King County (fig. 1). Warm dry summers and cool wet winters are characteristic of the basin's climate. Storms, usually from the west or southwest, are typically large frontal storms of low intensity and long duration. Precipitation generally increases with elevation west of the Cascade divide, but is also influenced by storm tracks and local topography. The flood season coincides with the rainy season (table 1), generally from November to March.

The major streams that make up the Puyallup River System include the White River and its major tributary, the Greenwater River, which drain the northern and eastern part of the basin; the Carbon River and its major tributary, South Prairie Creek, which drain the central part of basin; and the main stem of the Puyallup River, which drains the southern part of the basin (fig. 1). Mud Mountain Dam, on the White River, is operated by the Army Corps of Engineers (USACOE) for flood control and forms Mud Mountain Lake, with a storage capacity of 106,000 acre-feet. Six miles downstream from Mud Mountain Dam at river mile 24.3, water is diverted from the White River by the White River Canal, which feeds Lake Tapps, and eventually is returned to the White River at river mile 3.6. Lake Tapps, operated by Puget Power for hydroelectricity, has a storage capacity of 46,600 acre-feet, and the canal has a capacity of about 2,000 cubic feet per second (ft^3/s). On the Puyallup River, Puget Power diverts water up to 400 ft^3/s through a flume at river mile 41.8 to the Electron Powerhouse and returns the water to the river at river mile 31.2, 4.8 miles upstream of the Puyallup River near Orting stream gage (fig. 1). There is negligible water storage capacity at the Electron Powerhouse
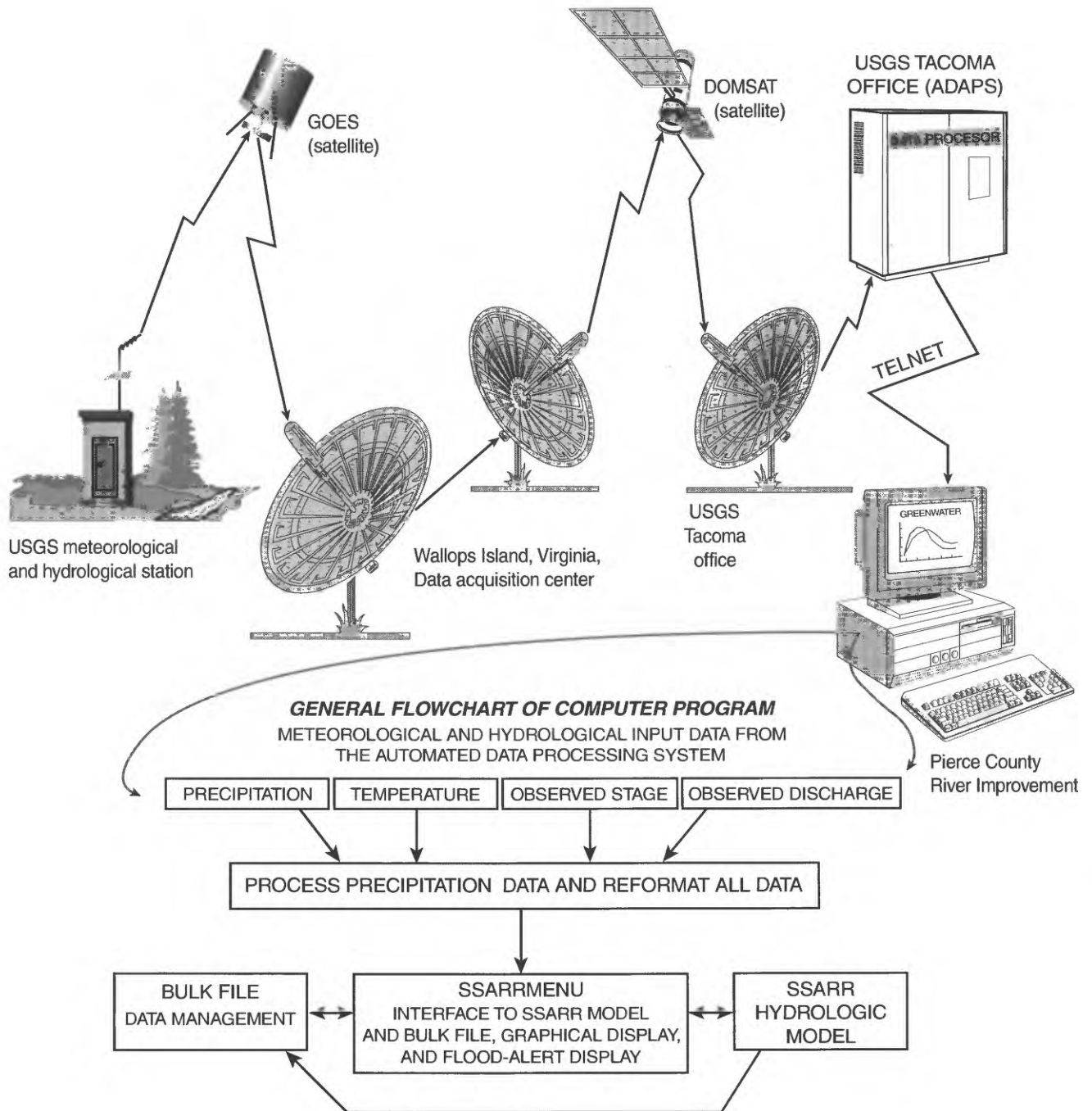
Figure 2. Generalized flowpath of hydrological and meteorological data from the gage sites to the Pierce County River Improvement office and within the computer for the Puyallup Flood Alert System.

Table 1. Normal monthly and annual precipitation, base period 1961–90, for selected National Weather Service stations in or near the Puyallup River Basin, Washington (see figure 5 for station locations)

	Precipitation, in inches			
	Rainier Paradise RNGER, elevation 5,427 feet above sea level	Longmire Rainier National Park Service, elevation 2,762 feet above sea level	Mud Mountain, elevation 1,308 feet above sea level	McMillin Reservoir, elevation 579 feet above sea level
October	9.03	6.72	4.57	3.38
November	17.20	11.52	7.55	6.00
December	18.38	12.51	6.93	5.89
January	18.32	13.31	7.13	5.72
February	13.71	9.16	5.16	4.37
March	11.97	7.33	5.05	4.05
April	8.42	5.59	4.91	3.14
May	5.18	4.13	4.28	2.38
June	3.76	3.70	3.73	2.16
July	1.95	1.67	1.89	1.06
August	2.79	2.34	2.48	1.50
September	4.96	4.25	3.36	2.12
Annual	115.64	82.23	57.04	41.77

The land cover in the upper basin is mostly forests, and timber harvesting by clear-cutting is common. In the lower elevations the landscape varies from rural, low-density land uses such as dairy farming and residential to the high-density urbanized areas near Puyallup near the mouth of the river.

The data-collection network consists of 15 stream gages, 7 rain gages, 8 air-temperature sites, and 1 snow pillow (fig. 3). As a part of this study, the Buck Creek meteorological site was established; air-temperature probes and rain gages were added to the South Prairie Creek, White River Canal, and Greenwater stream gages; and the Greenwater stream gage was upgraded from a seasonal (June to October) to a year-round streamflow gage with satellite telemetry. Each of the streamflow gages is on a 15-minute recording cycle that transmits the data via satellites to the USGS office in Tacoma every four hours in a normal (non-flood) mode or every 15 minutes in an alert mode. Precipitation and temperature are measured either every 15 minutes or every hour and transmitted via satellite telemetry. Because only the Buck Creek and White River Canal precipitation gages are heated, data collected at the other sites while snow is falling are not considered reliable. An auxiliary meteorological site at the Nevan-McCullough Seed Orchard, established in 1995 and operated for the 1995 and 1996 water years, included two heated precipitation gages (one shielded and one not shielded), an air-temperature probe, and an anemometer

(to record wind velocity and direction). Because this site does not have real-time telemetry, it is not used in the operational system.

CONCEPTUAL MODEL OF FLOODING

The conceptual model in this investigation is simply a collection of the important hydrological and meteorological factors related to the recent large flood events in the Puyallup River Basin. (The term "flooding," as used here and elsewhere in the report, refers to high flow discharges and high flow stages and not to areas inundated by floods.) The conceptual model is the framework for the numerical model selection and the focus of the calibration and validation efforts used in this investigation. The conceptual model is based on the largest floods since 1965 and selected observed meteorological data for representative stations. After data were reviewed and initial simulations were made, it was apparent that the distribution of water available for runoff (rain and snowmelt) is a chief factor in the conceptual model of flooding in the Puyallup River Basin. While accounting for soil moisture and its effect on runoff is an important factor in the conceptual model, precise understanding of many other runoff processes is less important. For example, the flow path that runoff takes to the stream channel, the influence on ground-water interaction, or the location in the soil profile where moisture is being stored needs little attention. Also, the data to describe such runoff characteristics or processes are generally not available.

EXPLANATION

USGS Station Number | Station Name

——————— Puyallup River Basin boundary

- - - - - - - - - - Subbasin boundary and name
CARBON

△ Stream gage reporting stage and discharge

△ Stream gage reporting stage only

❄ Snow pillow site

◆ Meteorological site recording precipitation and temperature

◇ Stream gage recording precipitation and temperature

USGS Station Number	Station Name
12092000	Puyallup River near Electron
12093500	Puyallup River near Orting
12094000	Carbon River near Fairfax
12095000	South Prairie Creek at South Prairie
12095600	Carbon River near Fairfax
12096500	Puyallup River at Alderton
12097500	Greenwater River at Greenwater
12097850	White River below Clearwater River near Buckley
12098000	Mud Mountain Lake near Buckley
12098500	White River near Buckley
12099000	White River Canal at Buckley
12100000	White River at Buckley
12100496	White River near Auburn
12101000	Lake Tapps near Sumner
12101100	Lake Tapps Diversion near Dieringer
12101105	White River at Williams Bridge at Sumner
12101500	Puyallup River at Puyallup
470118121330800	Buck Creek Camp meterological site near Greenwater
465216121312601	Cayuse Pass snow course
470418121351200	Nevan-McCullough Seed Orchard meteorological site near Greenwater

Figure 3. Streamflow and meteorological network of U.S. Geological Survey-operated gages in the Puyallup River Basin, Washington.

Flood History

Several long-term stream gages in the basin provide a good history of floods on rivers in the Puyallup River Basin since the 1930's (table 2). Although Mud Mountain Dam has regulated flood flows on the White River and the lower Puyallup River since its completion in 1942, the 1934 peak flow, the largest recorded at the Puyallup River at Puyallup, was unregulated. The other stations listed in table 2 are all upstream of major regulation.

Other notable floods include the record 1978 peak flow in the Greenwater River, which was almost twice the discharge of the second largest peak flow—clearly a significantly large flood in the record. The 1996 peak flows, all during February 8–9, 1996, are ranked number one or two at all the stations listed in table 2, and because they occurred during the model calibration and validation period of this study (water years 1994-97), they provided an excellent opportunity to calibrate the numerical model to a significantly large flood. If the November 28, 1995, peaks had not been exceeded by the February 1996 peak flows, they would have ranked in the 10 highest recorded annual peaks at all but the Puyallup River at Puyallup gage sites. On the other end of the scale, 1994 peak flows ranked last or near last for all the stations listed. Although the 1994 peak flows occurred during the model calibration and validation period, they do not provide useful data for testing the model and, therefore, were not used. The other floods during the data-collection period of this study lie in the midrange of the ranked floods.

Meteorological Conditions Related to Flooding

Comparing meteorological data associated with the largest recorded floods reveals some important aspects of flooding in the Puyallup River Basin (table 3). It is correct to assume that flooding is related to precipitation, but in the Puyallup River Basin the relation is not straightforward. As seen in table 3, precipitation amounts do not correlate well with the peak discharges. For the eight largest floods, 1-day precipitation at the Rainier Paradise RNGER station varied from 2.60 inches to 7.76 inches, and 5-day precipitation varied from 6.87 to 17.53 inches. For reference, the precipitation total with a 10-year, 24-hour precipitation frequency for this station is about 6.2 inches (U.S. Department of Commerce, 1973). (The 10-year, 24-hour precipitation frequency is the average amount of rainfall over a 24-hour period that is exceeded on average once every 10 years.)

The most likely explanation for this lack of a strong correlation between rainfall total and peak discharge is that the runoff during floods with low precipitation totals was augmented with snowmelt. In basins of western Oregon (similar to the Puyallup River Basin), a transient snow zone, the zone of transition between precipitation as rain and precipitation as snow, is from 1,150 to 3,610 feet (350 to 1,100 meters) above sea level (Harr, 1986 . By this definition, the transient snow zone of the Puyallup River Basin takes up 38.8 percent of the drainage area. Therefore, depending on the extent of snow in the basin and the freezing levels during a storm, rain-on-snow events in the Puyallup River Basin may contribute significantly to runoff from snowmelt. Floods with relatively low precipitation amounts at the Paradise (elevation 5,427 feet) and Longmire (elevation 2,762 feet) stations generally had high snowmelt index values and relatively high temperatures (table 3). (The snowmelt index described in table 3 is a simple indicator of snowmelt during storms based on reported observed snow on the ground at NWS stations). By contrast, the lower elevation stations Mud Mountain Dam (elevation 1,308 feet) and McMillin Reservoir (elevation 579 feet) did not show any addition of snowmelt to runoff (index = 0), although the available data are sparse. Maximum surface air temperatures were above freezing for all the floods (table 3). The 1996 flood, the largest flood in table 2, had high snowmelt, temperatures, and precipitation totals—a sure recipe for big floods.

Schermerhorn (1967, p.707) stated, "The [spatial] variation in annual precipitation in western Oregon and Washington is greater than anywhere else in the contiguous 48 states," and, indeed, in the Puyallup River Basin large variations in precipitation often occur over short distances due primarily to differences in elevation. Precipitation normally increases with increased elevation, as can be seen, with few exceptions, by relating storm precipitation totals and Normal Annual Precipitation ("NAP" is the term used by the National Weather Service in its climatological data reports; NAP is the same as the mean annual precipitation over a specified period or "base period") to elevations for the four stations in table 3. The NAP at McMillin Reservoir (elevation 579 feet) is only 36 percent of NAP at Rainier Paradise (elevation 5,427 feet). 35 miles away. While this is usually true for annual totals, individual storm precipitation totals at lower elevations may exceed those at higher elevations due to short-term variations in atmospheric circulation patterns, winds, and temperatures in combination with the topography of the basin.

Table 2. Ten largest annual peak discharges (ranks 1 through 10) for selected stations in the Puyallup River Basin, Washington, and the annual peak flows* used during the model calibration and validation period of this study (1994-97 water years)

[USGS, U.S. Geological Survey; M/D, month/day; ft³/s, cubic feet per second]

Puyallup River at Puyallup
USGS Station Number 12101500
Record: 1914–97
83 years of annual peak-flow data

Rank	Water year	Date (M/D)	Discharge (ft³/s)
1	1934	12/10	57,000
2	1996	02/09	*46,700
3	1990	01/09	44,800
4	1987	11/24	43,800
5	1991	11/24	41,900
6	1965	01/29	41,500
7	1978	12/02	40,600
8	1918	12/18	40,500
9	1935	10/25	39,500
10	1933	11/13	37,800
35	1997	01/01	*22,800
49	1995	02/19	*19,200
79	1994	03/03	*9,040

Greenwater River at Greenwater
USGS Station Number 12097500
Record: 1912, 1930–78, 1993–97
53 years of annual peak-flow data

Rank	Water year	Date (M/D)	Discharge (ft³/s)
1	1978	12/02	10,500
2	1996	02/08	*5,900
3	1960	11/22	5,360
4	1965	01/29	5,090
5	1947	12/11	5,000
6	1934	12/09	4,140
7	1976	12/02	4,140
8	1912	11/19	2,800
9	1971	01/31	2,260
10	1956	12/12	2,230
21	1997	01/01	*1,510
27	1995	02/20	*1,330
54	1994	01/14	*574

South Prairie Creek at South Prairie
USGS Station Number 12095000
Record: 1950–79, 1988–97
40 years of annual peak-flow data

Rank	Water year	Date (M/D)	Discharge (ft³/s)
1	1996	02/08	*8,170
2	1956	12/11	6,850
3	1965	01/29	6,400
4	1990	01/09	5,930
5	1954	12/09	5,470
6	1991	02/19	5,390
7	1975	01/18	5,020
8	1976	12/02	4,380
9	1974	01/16	4,310
10	1960	11/20	3,900
14	1997	01/01	*3,490
23	1995	02/19	*2,680
36	1994	03/03	*1,500

Carbon River near Fairfax
USGS Station Number 12094000
Record: 1930–78, 1991–97
56 years of annual peak-flow data

Rank	Water year	Date (M/D)	Discharge (ft³/s)
1	1991	11/24	13,000
2	1996	02/08	*12,000
3	1934	12/09	11,000
4	1978	12/01	10,000
5	1960	11/23	9,970
6	1968	12/25	7,480
7	1976	12/01	7,460
8	1975	01/18	7,320
9	1974	01/15	7,180
10	1933	11/13	7,100
23	1995	10/31	*4,900
29	1997	11/27	*4,480
56	1994	03/03	*1,100

Puyallup River near Orting
USGS Station Number 12093500
Record: 1932–97
66 years of annual peak-flow data

Rank	Water year	Date (M/D)	Discharge (ft³/s)
1	1996	02/08	*18,300
2	1963	11/20	15,300
3	1960	11/22	12,900
4	1934	12/10	12,800
5	1965	01/29	12,200
6	1956	12/11	12,100
7	1978	12/02	12,100
8	1933	11/13	11,800
9	1990	01/09	11,600
10	1947	12/11	11,200
21	1997	01/01	*8,460
36	1995	10/31	*5,890
66	1994	03/03	*1,830

Table 3. Meteorological conditions at four National Weather Service stations for the eight largest floods since since 1965 at the U.S. Geological Survey gaging station Puyallup River at Puyallup, Washington

[NAP, normal annual precipitation in inches; --, not reported]

Rainier Paradise RNGER — Elevation, 5,427 feet above sea level — NAP 115.64 inches

Flood Date of peak	Discharge and rank[1]	1-day precipitation[2]	5-day precipitation[3]	Percent NAP[4]	Snowmelt index[5]	Maximum/minimum temperature[6]
02-09-96	48,200 (2)	7.43	17.53	15.2	32	42/21
01-09-90	44,800 (3)	3.14	8.99	7.8	14	39/26
11-24-86	43,800 (4)	5.49	14.65	12.7	23.5	40/22
11-24-90	41,900 (5)	5.72	12.65	10.9	19	42/32
01-29-65	41,500 (6)	4.50	12.55	10.9	25	35/30
12-02-77	40,600 (7)	7.76	15.66	13.5	4.8	40/32
01-25-84	37,100 (12)	2.98	11.60	10.0	11	36/26
02-24-86	34,400 (17)	2.60	6.87	5.9	20.5	42/25

Longmire Rainier National Park Service — Elevation, 2,762 feet above sea level — NAP, 82.23 inches

Flood Date of peak	1-day precipitation[2]	5-day precipitation[3]	Percent NAP[4]	Snowmelt index[5]	Maximum/minimum temperature[6]
02-09-96	2.50	11.21	13.6	9	44/27
01-09-90	2.55	8.19	10.0	4	45/33
11-24-86	2.61	8.16	9.9	4.5	43/33
11-24-90	1.76	4.89	5.9	10.5	45/36
01-29-65	4.27	11.66	14.2	16	34/34
12-02-77	7.63	11.61	14.1	0	38/32
01-25-84	3.55	10.19	12.4	2.5	42/33
02-24-86	3.10	7.21	8.8	5	42/25

Mud Mountain Dam — Elevation, 1,308 feet above sea level — NAP 57.04 inches

Flood Date of peak	Discharge and rank[1]	1-day precipitation[2]	5-day precipitation[3]	Percent NAP[4]	Snowmelt index[5]	Maximum/minimum temperature[6]
02-09-96	48,200 (2)	1.96	7.57	13.3	0	55/34
01-09-90	44,800 (3)	2.52	5.37	9.4	--	53/40
11-24-86	43,800 (4)	4.67	8.19	14.4	--	57/31
11-24-90	41,900 (5)	1.75	3.13	5.5	0	56/44
01-29-65	41,500 (6)	3.46	5.67	9.9	0	48/41
12-02-77	40,600 (7)	1.29	2.57	4.5	--	52/46
01-25-84	37,100 (12)	2.59	4.92	8.6	--	52/40
02-24-86	34,400 (17)	1.70	3.07	5.4	--	66/48

McMillin Reservoir — Elevation, 579 feet above sea level — NAP, 41.77 inches

Flood Date of peak	1-day precipitation[2]	5-day precipitation[3]	Percent NAP[4]	Snowmelt index[5]	Maximum/minimum temperature[6]
02-09-96	2.72	5.20	12.4	0	54/47
01-09-90	2.40	4.79	11.5	--	53/43
11-24-86	3.52	5.75	13.8	--	54/35
11-24-90	1.65	3.15	7.5	--	55/51
01-29-65	1.34	3.25	7.8	0	50/43
12-02-77	0.93	1.75	4.2	0	53/48
01-25-84	1.90	3.02	7.2	--	52/42
02-24-86	1.00	2.20	5.3	0	58/50

[1]Peak discharge in cubic feet per second recorded at the U.S. Geological Survey gaging station Puyallup River at Puyallup, Wash., and the rank among the annual peak discharges for the period of record (1914-97).

[2]1-day total precipitation for the peak date (U.S. Department of Commerce, 1965-96).

[3]5-day total precipitation beginning 4 days before the peak date and ending on the peak date (U.S. Department of Commerce, 1965-96).

[4]5-day precipitation total as a percent of normal annual precipitation, base period 1961-90 (U.S. Department of Commerce, 1995).

[5]Snowmelt index, S_m, is computed as follows: $S_m = S_{i,\,3\ days\ before\ peak} - S_{i,\,peak\ date} + S_{f,\,3\text{-}day\ total}$, where S_i is the observed snow on ground and S_f is the observed snowfall, all in inches (U.S. Department of Commerce, 1965-96).

[6]Maximum and minimum temperature in degrees Fahrenheit.

Several floods listed in table 3 can be characterized as high-elevation or low-elevation precipitation events. The December 1977 flood could be characterized as a high-elevation precipitation event because the 5-day precipitation as a percentage of NAP is greater at the two higher elevation stations in table 3 (13.5 and 14.1 percent) than at the two lower elevation stations (4.5 and 4.2 percent). In contrast, the November 1986 flood could be called a low-elevation precipitation event because the NAP percentages for the 5-day precipitation totals for the two lower elevation stations are higher than any others listed, while the NAP percentages for the two high-elevation stations are ranked among the lowest two peaks listed.

The dates of the annual peak discharges in the Puyallup River Basin define a relatively short season from mid-November to early March for large floods (table 2). This is the season of the heaviest rains (table 1), and although November is a month of heavy rain, there is a lag time on the order of several weeks to months before major flooding normally occurs. The rains through early November must saturate the relatively dry soils before a large enough portion of the rainfall becomes runoff. This phenomenon can be seen by comparing runoff from two storms in October and December 1994 (fig. 4) with similar precipitation totals and intensities and similar above-freezing temperatures (no snowfall was recorded at the Rainier Longmire NWS weather station during either storm).
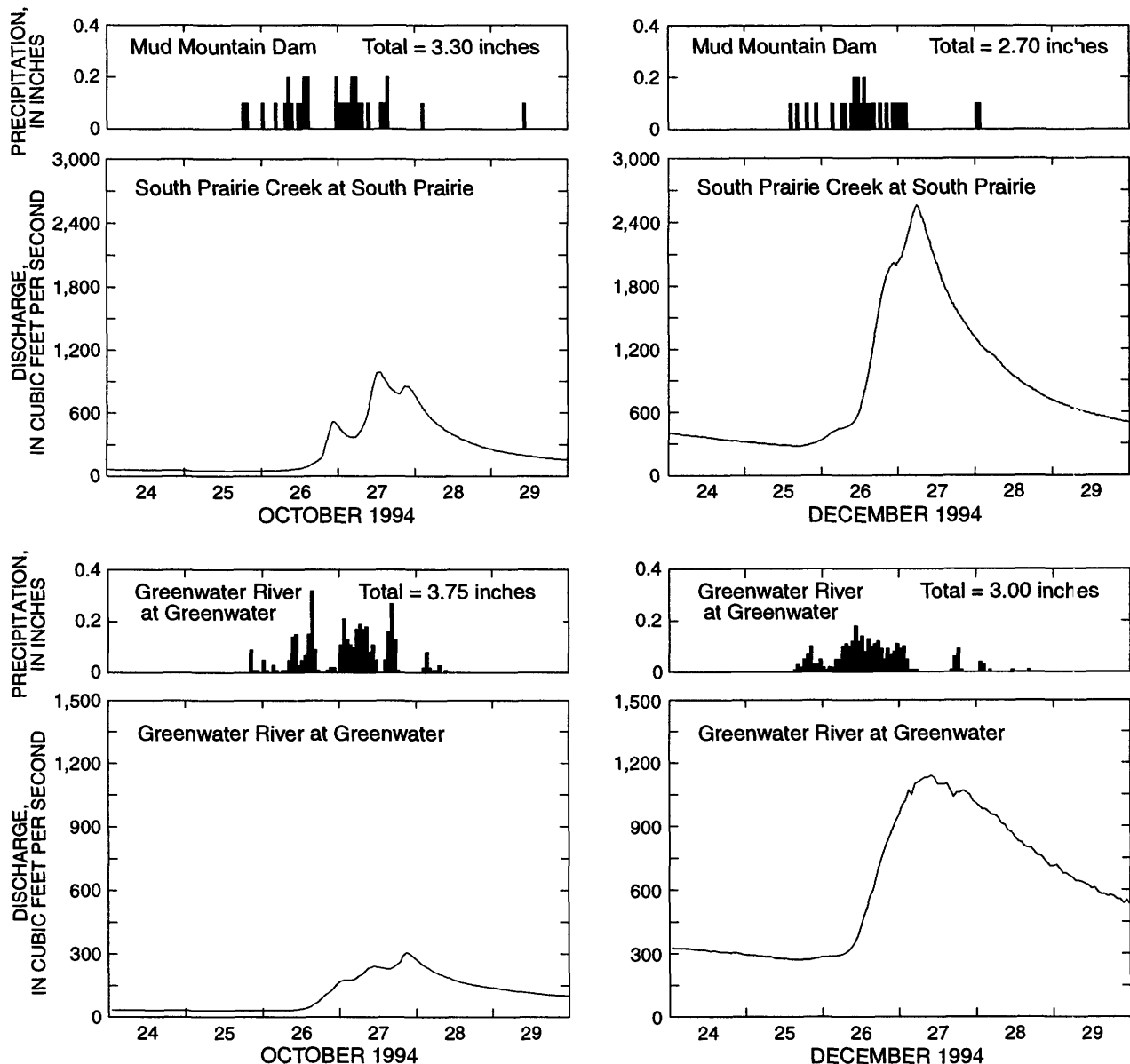

Figure 4. Comparison of runoff response to precipitation between an early fall and early winter storm at two gaging stations in the Puyallup River Basin, Washington.

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Although the December storm had 18 to 20 percent less precipitation than the October storm, the peak discharge was 2.6 to 3.7 times as large. Much of the rainfall in the October storm most likely infiltrated the ground and was stored in the soil, while during the December storm (after two more months of rain had saturated the soil) a larger fraction of the rainfall became runoff. Although snow is often present in the midelevation in the spring and perennial in the higher elevations, flooding due strictly to snowmelt has rarely produced major flooding, and as the chance for heavy rains diminishes in the spring, so does the chance for heavy flooding.

Generalizations about Flooding in the Puyallup River Basin

An examination of the meteorological conditions associated with large floods in the Puyallup River Basin has identified five important factors that define the basis for the conceptual model of how major floods are generated in the Puyallup River Basin:

1. Topography has a strong influence on precipitation; precipitation generally increasing as elevation increases.

2. Spatial patterns of precipitation totals of individual storms may vary considerably from the pattern defined by annual totals.

3. Flooding is primarily associated with storms bringing heavy rain to the basin, but snowmelt is an important contribution to flooding.

4. The extent of snow cover and the freezing level during a storm are important factors in the snowmelt contributions to runoff.

5. Most of the soil moisture storage capacity must be filled before heavy flooding can begin.

DESCRIPTION OF THE NUMERICAL MODEL

The Integrated-Snowband version of the SSARR model (U.S. Army Corps of Engineers, 1991) was used in this investigation for simulating river discharges and stages because of its ability to make real-time forecasts, its compatibility with the personal computers (PC's) in the PCRI computer system, its longtime use in the Pacific Northwest, its ability to simulate floods according to the conceptual model for flooding in the Puyallup River Basin described earlier, and its ability to route natural and regu-

lated flows through river channels and reservoirs. The SSARR model was developed by the U.S. Army Corps of Engineers (USACOE) for managing the Columbia River and has been used by the Northwest River Forecast Center of the NWS in Portland, Oreg., to make flood forecasts on many of the major rivers in the Pacific Northwest. The following is a brief description of the model, and the reader is referred to the SSARR user's manual (U.S. Army Corps of Engineers, 1991) for complete details of how the model works.

The SSARR Model

In the SSARR model, the modeled basin is divided into subbasins that drain to a network of storm reaches and reservoirs. The model simulates runoff by routing available water from rainfall and snowmelt from subbasins to streams and routes streamflow through the stream network. The model's characteristics, which are input data to the model that govern the simulation of runoff and routing, include such items as subbasin area, elevation, empirical coefficients that control infiltration, and tables relating stream channel or reservoir storage to outflow.

The SSARR model can store information about watershed and channel conditions, such as soil moisture and stream discharge, at the end of a simulation and start another simulation using these stored or modified conditions as initial conditions, thus allowing easy incorporation of real-time data as it is retrieved to make improved forecast results. The model also can adjust the simulated watershed runoff automatically to mimic the observed record by adjusting the inputs of precipitation, lapse rates, or temperature until the simulated record matches the observed record within specified tolerances.

The SSARR model also is appropriate for simulating peak discharges for the Puyallup River Basin because of (1) its continuous modeling in time (as opposed to event-based models) that accounts for antecedent soil moisture conditions and snow accumulation, (2) its temperature-index snowmelt algorithm (as opposed to energy-balance snowpack models that require more data input than is generally available), (3) its division of the watershed into elevation zones (snowbands) with corresponding division of precipitation (as rain or snow) and temperature according to defined precipitation-elevation curves and lapse rates, and (4) its distribution of water available for runoff into surface and subsurface flow paths as a function of soil moisture. A simple storage-routing equation computes the lengths of time (lag time) for water available for runoff to reach the stream for each of the flow

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components. The lag time defines the shape of the simulated hydrograph, which is adjusted through calibration to mimic the shape of the observed hydrograph. The SSARR model also simulates such other important hydrologic processes as interception, evapotranspiration, ripening of the snow pack, and groundmelt of the snow pack. The hydrologic parameters that govern the simulation of the hydrologic processes are the same throughout a subbasin, although precipitation and temperature inputs are adjusted differently for each snowband by user-defined precipitation-elevation relations and temperature lapse rates.

The NWS Northwest River Forecast Center has used a depletion version of the SSARR model to make routine flood forecasts on the Puyallup River. Many of the NWS depletion version's runoff parameters and flow-routing tables (outflow as a function of storage or stage) were used to construct the preliminary snowband SSARR model (a numerical model with uncalibrated parameters) for this investigation. The NWS depletion version was not used directly for several reasons (which are discussed further in the next paragraph): (1) The current network of precipitation and temperature gages within the basin provides a more accurate model than the network of region-wide gages used in the NWS model. (2) Many stations for which PCRI was interested in estimating discharge or stage during flood events are not represented in the NWS model. (3) The snowband version can continuously track current snow-water equivalent (SWE) in the basin's snowpack. (4) And the Columbia River Operation Hydromet Management System (CROHMS) network of gages used by the NWS is not generally available to county agencies, nor is it compatible with the PC version of the SSARR model.

The NWS SSARR depletion model used four subbasins, a 6-hour time step, one temperature station, and a set of regional precipitation stations, all outside the Puyallup River Basin. This investigation uses the SSARR Integrated Snowband model, with seven subbasins and four temperature stations and six precipitation stations located within the basin. The snowband model uses a 1-hour time step during storms (storm mode), and a 6-hour time step at other times (backup or nonstorm mode). However, when the model is used to forecast discharges, 6-hour time steps are used because forecasted temperature and precipitation are available only for 6-hour time steps. The 1-hour time step provides more definition of the storm hydrograph than a 6-hour time step, and it provides more flexibility to stop the model at specific times in anticipation of a subsequent model run. Although the snowband model used for this investigation uses considerably more input data than does the NWS model (the current

USGS-operated gage network of local meteorological gages instead of regional NWS gages) and greatly enhances the detail of the simulation model (seven subbasins instead of the four used by the NWS, and a 1-hour time step instead of a 6-hour time step), there is the disadvantage that the calibration and validation period is limited to the 1994-97 water years—the period during which the current gage network has existed.

Subdivision of the Puyallup River Basin into Subbasins and Elevation Zones

In the snowband model, the Puyallup River Basin is subdivided into 7 subbasins and 13 elevation zones (fig. 3 and table 4). Elevation zones are synonymous with the SSARR model term "snowbands." The subbasins are based on the topographic divides and locations of river confluences and stream gages. For example, the South Prairie subbasin is defined as the drainage basin upstream of the mouth of South Prairie Creek at the confluence with the Carbon River. Even though the stream gage South Prairie Creek at South Prairie (USGS station number 12095000) is located 5.9 miles upstream of the confluence, it is still representative of the outflow at the mouth because there are no major inflows between the gage and the mouth.

The Carbon subbasin is defined as the drainage basin upstream of the gage on the Carbon River near Fairfax (fig. 3) because this gage lies 16.1 miles upstream of the mouth and there are several significant inflows between the gage and the mouth. The upper White subbasin, the largest subbasin, is defined as the drainage basin upstream of the gage on the White River below Clearwater River near Buckley (fig. 3), excluding the Greenwater River drainage (the Greenwater subbasin). The upper White subbasin, which is more than twice as large as the second largest subbasin, is not subdivided into smaller units because there are no upstream gages at which to compare simulated runoff with observed runoff.

The elevation zones are subareas in each subbasin that encompass defined elevation boundaries. In the Puyallup River Basin model, the area between elevations 0 to 5,000 feet above sea level is divided into 10 zones equally spaced vertically at 500-foot intervals. The next zone is from 5,000 to 6,000 feet elevation; the next is from 6,000 to 8,000 feet elevation; and the last zone is everything above 8,000 feet elevation. The "contour intervals" of the elevation zones were configured in this manner to make the area within each zone approximately equal. The elevation zones were delineated using a digital elevation model

Table 4. Area of elevation zones by subbasin used in the Puyallup River Basin model, Washington

[--, no area in zone]

Zone number	Elevation range (feet above sea level)	Area, in square miles, for each elevation zone at each subbasin							Total area (square miles)[1]
		Greenwater	Upper White	Lower White	Upper Puyallup	Lower Puyallup	South Prairie	Carbon	
1	0 - 500	--	--	15.90	1.53	57.71	3.32	--	73.46
2	501 - 1,000	--	--	46.69	18.60	40.04	21.76	--	127.09
3	1,001 - 1,500	--	4.89	15.57	11.23	9.48	11.31	1.79	54.27
4	1,501 - 2,000	2.40	15.60	8.38	28.69	10.93	15.28	6.81	88.09
5	2,001 - 2,500	5.12	23.92	5.58	19.41	9.10	10.18	6.47	79.78
6	2,501 - 3,000	8.12	30.97	5.29	13.17	4.92	7.79	7.44	77.70
7	3,001 - 3,500	10.17	34.36	4.23	11.28	1.37	6.48	8.46	76.35
8	3,501 - 4,000	12.47	35.29	2.28	13.41	0.13	5.85	9.47	78.90
9	4,001 - 4,500	14.00	36.30	1.52	14.42	--	4.45	10.13	80.82
10	4,501 - 5,000	11.37	30.23	0.48	10.68	--	2.77	9.42	64.95
11	5,001 - 6,000	11.28	51.63	--	10.59	--	1.01	11.36	85.87
12	6,001 - 8,000	0.87	29.07	--	9.56	--	--	5.71	45.21
13	>8,000	--	6.46	--	6.06	--	--	2.90	15.42
TOTAL		75.80	298.72	105.92	168.63	128.68	90.20	79.96	947.91

[1]The Puyallup River Basin upstream of U.S. Geological Survey stream gage Puyallup River at Puyallup, Wash. (Station number 12101500).

(DEM) of regularly spaced elevation values with a 30-meter (98.4-foot) grid-cell resolution (Washington Department of National Resources, 1994) derived from 1:24,000 scaled topographic maps (U.S. Geological Survey, 1987). Geographic Information System (GIS) software was used to slice the individual subbasins into the 13 zones and calculate the areas. The elevation boundaries and the amount of area for each zone were coded into the Puyallup River Basin model to define the snowbands for each subbasin. The model uses this information to adjust the meteorological inputs (precipitation and temperature) to the midpoint elevation for each snowband and compute total volumes of runoff based on the area in each zone.

Computation of Subbasin Precipitation

Necessary input to the SSARR model includes a time series (a series of data values ordered in time) of precipitation associated with each subbasin. Since the precipitation record at a gage generally does not represent the average precipitation for a basin, a weighting factor is used to adjust the precipitation inputs. Although the model can adjust the input precipitation for each subbasin, for this investigation a separate time series for each subbasin was computed. The individual precipitation time series for each subbasin, P_{sub}, was calculated as a weighted average of two observed precipitation records:

$$P_{sub} = \frac{P_{sta1}\left(\frac{NAP_{sub}}{NAP_{sta1}}\right) + P_{sta2}\left(\frac{NAP_{sub}}{NAP_{sta2}}\right)}{2} \quad , (1)$$

where

P_{sta1} and P_{sta2} are the recorded precipitations at gaging stations 1 and 2, respectively;

NAP_{sub} is the normal annual precipitation for the subbasin; and

NAP_{sta1} and NAP_{sta2} are the normal annual precipitation for stations 1 and 2, respectively.

After all the gage records were reviewed for erroneous or missing data, the two gages within or nearest to each subbasin that had complete and accurate data for the period of a particular simulation were selected from the six available real-time USGS-operated rain gages. Table 5 shows the matrix used to select the precipitation record and the NAP values used in equation 1.

Table 5. Priority matrix for selecting two rain-gage records and normal annual precipitation used to compute a subbasin precipitation record, Puyallup River Basin, Washington

Priority Matrix

The first two rain gages listed in the rows below are selected for each subbasin. If a rain-gage record is determined to have missing or bad values, the next rain gage is selected.

Subbasin	Rain gages in order of priority for selection					
Greenwater	Greenwater	Buck Creek	Carbon	White River Canal	South Prairie	Electron
Upper White	Buck Creek	Greenwater	Carbon	White River Canal	South Prairie	Electron
Lower White	White River. Canal	South Prairie	Greenwater	Buck Creek	Carbon	Electron
South Prairie	South Prairie	Carbon	Electron	Carbon	Buck Creek	Greenwater
Upper Puyallup	Electron	Carbon	South Prairie	White River Canal	Buck Creek	Greenwater
Lower Puyallup	South Prairie	White River Canal	Carbon	Electron	Greenwater	Buck Creek
Carbon	Carbon	Electron	South Prairie	White River Canal	Buck Creek	Greenwater

Normal annual precipitation (NAP), in inches, for subbasins and rain gages, base period 1930-57

Subbasin	NAP	Rain gages	NAP
Greenwater	90.69	Greenwater	56.54
Upper White	79.43	Buck Creek	60.00
Lower White	54.47	Carbon	59.55
South Prairie	60.89	White River Canal	48.14
Upper Puyallup	83.17	South Prairie	43.49
Lower Puyallup	47.40	Electron	66.25
Carbon	90.47		

The subbasin NAP values were based on an isohyetal map of mean annual precipitation for the State of Washington (Soil Conservation Service, 1965). The isohyets were digitized and overlaid on the subbasin boundaries to compute the subbasin NAP (fig. 5).

Adjusting Meteorological Data Inputs for Elevation

After time series of subbasin precipitation were computed from station precipitation, the values were adjusted for midpoint elevations of each snowband within the subbasin. In a similar manner, time series of temperature values at specific stations were adjusted by lapse rates to midpoint elevations of subbasin snowbands.

As discussed earlier, precipitation generally increases as elevation increases, but significant error would result if a single linear equation were used to represent the elevation-precipitation relation for the entire Puyallup River Basin. Figure 6 shows the relation defined for the Puyallup River Basin as a whole and individually for each subbasin as calculated from the isohyetal map shown on figure 5. Local topography can cause the relations to vary

considerably from subbasin to subbasin. Several north-south ridges in the center of the Puyallup River Basin tend to create rain shadows, resulting in less than basin-average precipitation east of the ridges. For example, the north-south trending Dalles Ridge defines the western drainage divide of the upper Greenwater subbasin, resulting in a relation of decreased precipitation with increasing elevation above 5,000 feet. Data points defining each subbasin's unique relation between precipitation and elevation were coded into the subbasin's fixed model characteristics (ELP tables) and applied during every time step to adjust the precipitation inputs for each snowband.

To reduce the amount of data input, only four of the seven real-time temperature stations (fig. 3) (the Cayuse Pass snow pillow site records temperature) were used in the model. The three stations not used—Carbon River near Fairfax, White River Canal, and Greenwater River at Greenwater—were represented by nearby stations Buck Creek Camp and South Prairie Creek. The data for the four stations were applied to individual snowbands during model runs and used to compute a time series of temperature lapse rates. The lapse rates, in units of degrees Fahrenheit for each 1,000-foot range in elevation,

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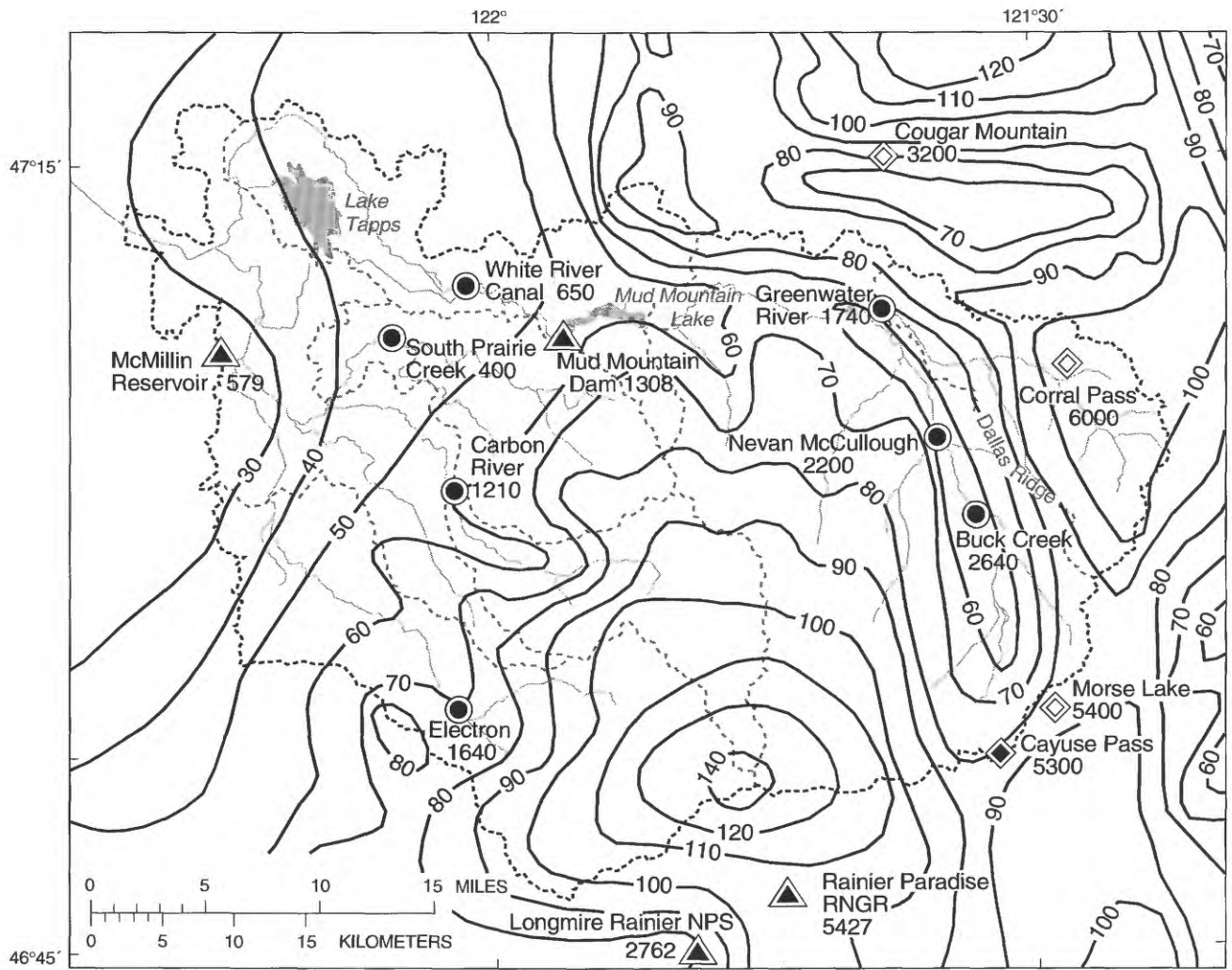
EXPLANATION

--------------	Puyallup River Basin boundary
--------------	Subbasin boundary
——100——	Line of equal mean annual precipitation (base period, 1930-57), in inches; interval, 10 inches (Natural Resource Conservation Service, March 1965)
▲ Rainier Paradise RNGR 5427	National Weather Service climate station with elevation, in feet
⦿ Electron 1640	U.S. Geological Survey-operated precipitaton and temperature gage with elevation, in feet
◈ Cayuse Pass 5300	U.S. Geological Survey-operated snow pillow and temperature gage with elevation, in feet
◇ Morse Lake 5400	Natural Resource Conservation Service-operated snow pillow with elevation, in feet

Figure 5. Weather stations and mean annual precipitation in the Puyallup River Basin, Washington.

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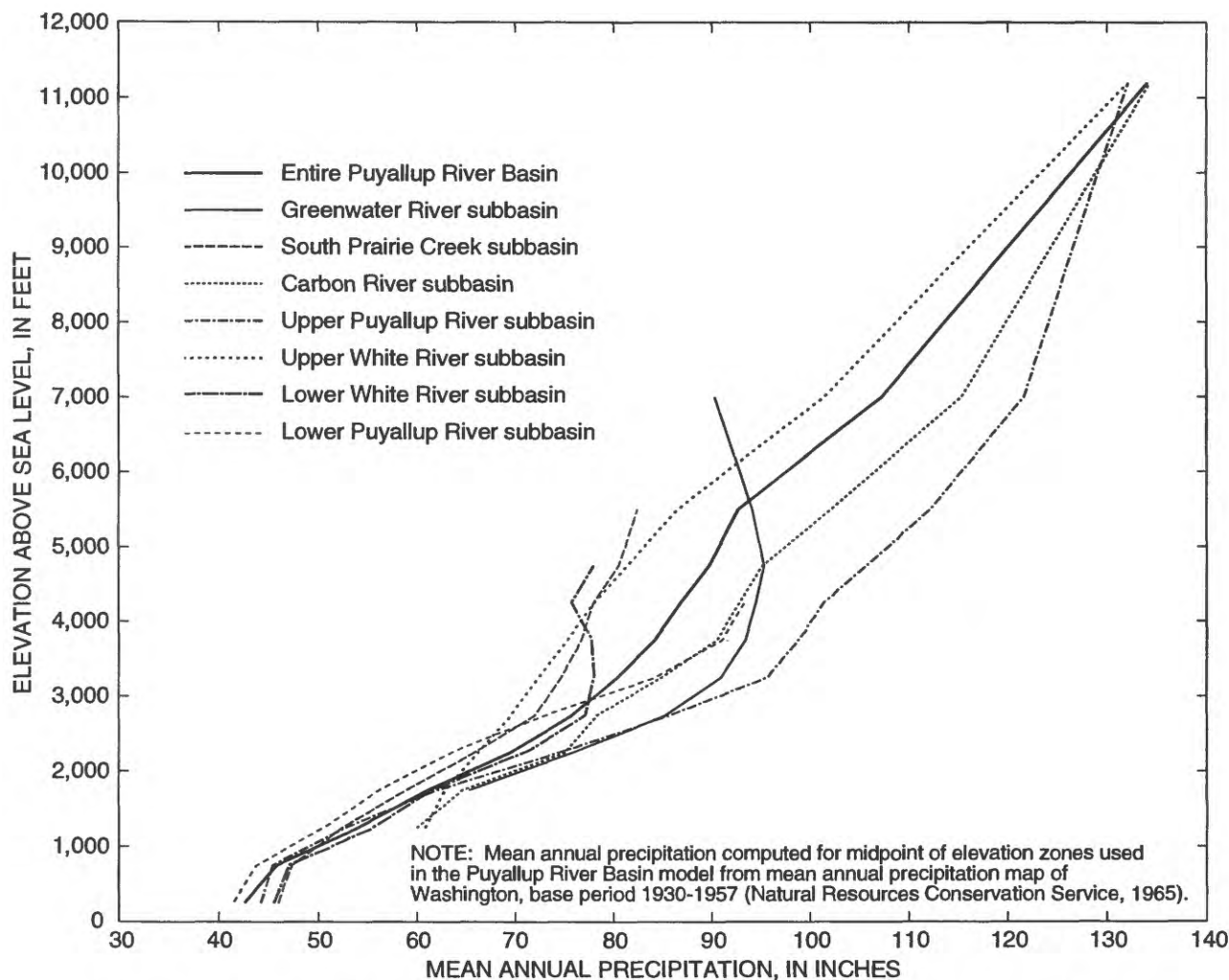
Figure 6. Mean annual precipitation as a function of elevation in the Puyallup River Basin and subbasins, Washington.

adjusted the station temperature values recorded at known elevations to the midpoint elevations of each snowband. Depending on the weather conditions, the lapse rate varied across the basin. If a temperature record for a specific time period contained bad or missing data, it was eliminated from the computations for that model run. A minimum of one good temperature record was needed to make a model run, and a minimum of two good temperature records was needed to compute a time series of lapse rates; otherwise, the default lapse rate value was used. Table 6 shows the priority matrix for determining which temperature records were selected for each subbasin.

Often a precipitation record was unusable for a particular model run because of missing or questionable data, and less often a temperature record was unusable. When this happened, the priority matrixes (table 5 and 6) were

used to compute estimates of meteorological inputs for each subbasin. Although model results would be different if all the records were available, it is typical of actual real-time operation of the model.

Runoff Simulation

The hydrologic parameters that govern the simulation of runoff of rain and snowmelt from each subbasin in the snowband version of the model were originally taken from the depletion version of the SSARR model used by the NWS Northwest River Forecast Center for real-time flood forecasting for the Puyallup River Basin (Chuck Orwig, Northwest River Forecast Center, National Weather Service, written commun., 1993). In the snowband version of the model, the South Prairie and Carbon subbasins

were initially assigned the same set of parameters as the Carbon subbasin in the NWS model; the Greenwater and upper White subbasins were assigned the same parameters as the NWS's Mud Mountain inflow subbasin; the lower White and lower Puyallup subbasins were assigned the same parameters as the NWS's Puyallup local subbasin; and the upper Puyallup subbasin was assigned the same parameters as the NWS's Orting subbasin. Values for these hydrologic parameters were changed slightly during calibration, which used data from the current network of USGS-operated precipitation stations for water years 1994–97. A listing of the final characteristics file, which contains the parameter values, is provided in the appendix of this report.

A flow chart of the computations for simulating runoff from individual snowbands by the SSARR Integrated Snowband model is shown on figure 7. Table 7 defines the parameters, tables, and indexes found in the characteristics file and shown in the flow chart. Runoff simulation from a snowband can be broadly grouped into three parts: (1) simulating snow accumulation and melt; (2) partitioning moisture input among surface, subsurface, and baseflow components of flow; and (3) routing runoff in separate flow paths. These are discussed briefly in the following sections.

Table 6. Priority matrixes for selecting a single temperature record and a pair of temperature records to compute subbasin snowband temperature and subbasin temperature lapse rates, Puyallup River Basin, Washington

Snowband-temperature record selection priority matrix

The first temperature station listed in the rows below is selected for each subbasin. If it is determined to have a missing or bad value, the next station is selected.

Subbasin	Temperature station in order of priority for selection			
Greenwater	Buck Creek	Cayuse Pass	Electron	South Prairie
Upper White	Buck Creek	Cayuse Pass	Electron	South Prairie
Lower White	South Prairie	Buck Creek	Cayuse Pass	Electron
South Prairie	South Prairie	Buck Creek	Cayuse Pass	Electron
Upper Puyallup	Electron	Buck Creek	Cayuse Pass	South Prairie
Lower Puyallup	South Prairie	Buck Creek	Cayuse Pass	Electron
Carbon	Electron	Buck Creek	Cayuse Pass	South Prairie

Temperature-lapse rate record pairs priority matrix

The first pair of temperature stations listed in the row below is selected for each subbasin. If one of the stations has missing or bad values, one of the next two station pairs is selected depending on which station was rejected.

| Subbasin	Temperature station pairs used to compute subbasin lapse rates	
Greenwater	Buck Creek-Cayuse Pass	South Prairie-Cayuse Pass or South Prairie-Buck Creek
Upper White	Buck Creek-Cayuse Pass	South Prairie-Cayuse Pass or South Prairie-Buck Creek
Lower White	South Prairie-Electron	Electron-Buck Creek or South Prairie-Buck Creek
South Prairie	South Prairie-Electron	Electron-Buck Creek or South Prairie-Buck Creek
Upper Puyallup	Electron-Cayuse Pass	South Prairie-Cayuse Pass or South Prairie-Buck Creek
Lower Puyallup	South Prairie-Electron	Electron-Buck Creek or South Prairie-Buck Creek
Carbon	Electron-Cayuse Pass	South Prairie-Cayuse Pass or South Prairie-Buck Creek
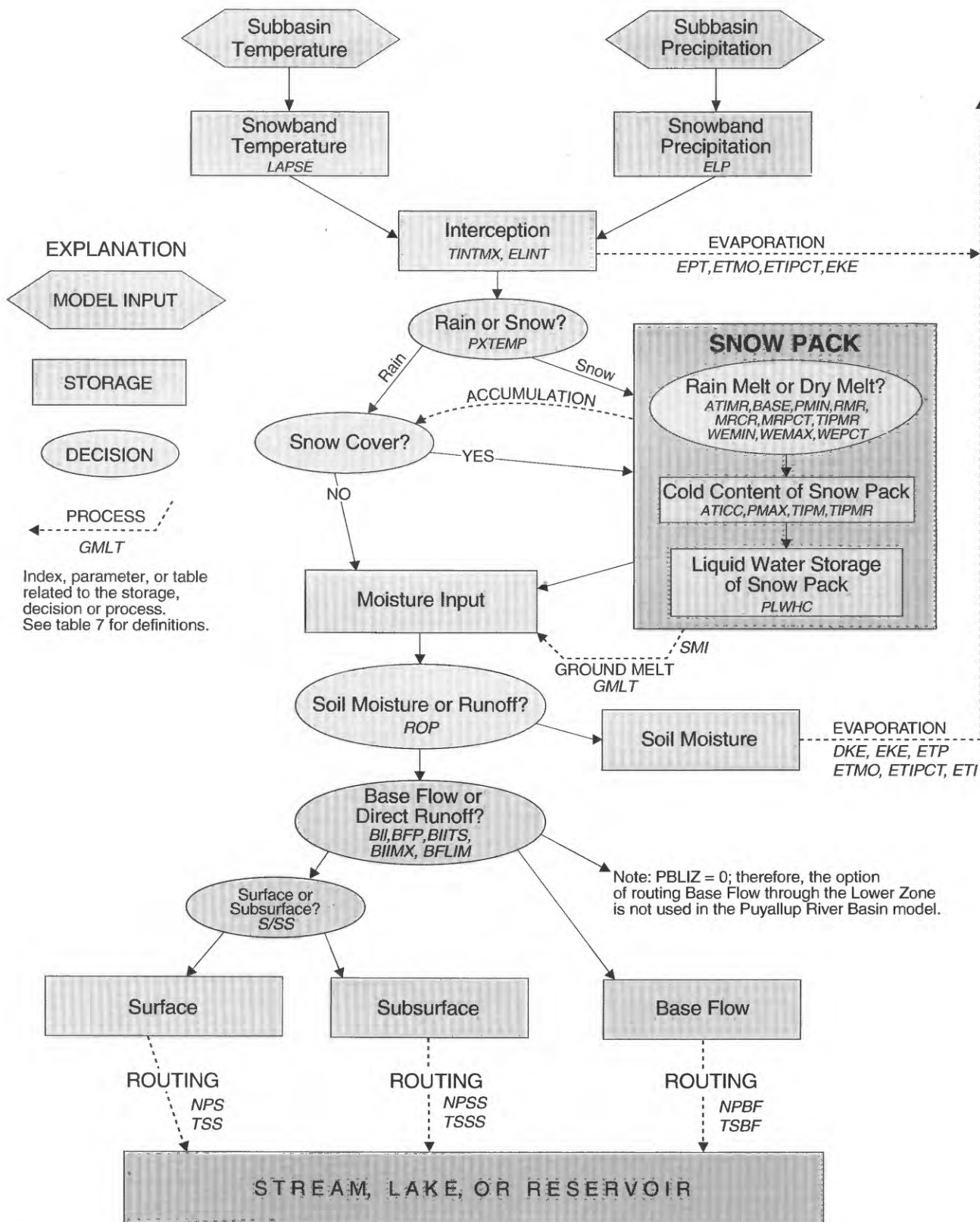
Figure 7. Flow chart of the simulated runoff from a snowband for the Puyallup River Basin model, Washington.

Table 7. Definitions of indexes, parameters, and tables used in the model characteristics file that define the hydrologic processes and parameters used in the Puyallup River Basin model, Washington

[PET, potential evapotranspiration, in inches; --, no default value]

Indexes	Definition	
ATICC	Index to the snow temperature near the surface, in degrees Fahrenheit, used to calculate snow pack cold content	
ATIMR	Temperature index, in degree days, used to determine snow pack dry-melt rates	
BII	Base flow infiltration index, in inches per 24 hours, used to partition runoff as direct flow or base flow	
ETI	Evapotranspiration index, in inches, used to compute PET	
SMI	Soil moisture index, in inches, an indicator of relative soil wetness used to partition moisture input into runoff or soil moisture.	

Parameters	Definition	Default value
BASE	Base temperature for snowmelt, in degrees Fahrenheit	32.0
BFLIM	Base flow input limit, in inches	--
BIIMX	BII maximum value, in inches	--
BIITS	Base flow infiltration time of storage, in hours	--
ELINT	Tree line elevation for interception, in feet	100,000
LAPSE	Subbasin temperature lapse rate, in degrees per 1,000 feet	3.3
NPS	Number of surface routing phases	--
NPSS	Number of subsurface routing phases	--
NPBF	Number of base flow routing phases	--
PBLIZ	Percent of baseflow input to lower zone (zero in Puyallup River model)	0.0
PLWHC	Liquid water holding capacity of snow as a percent of water equivalent of snowpack	0.03
PMIN	Minimum rain for rain melt to occur, in inches per hour	0.017
PMAX	Threshold precipitation rate, in inches per hour for the calculation of ATICC	0.0333
PXTEMP	Rain-freeze temperature, in degrees Fahrenheit	35.0
RMR	Snowmelt rate during a rain period, in inches per degree-day	0.074
SNETF	Ratio of evapotranspiration over snow that computed PET is reduced.	0.9
TINTMX	Maximum precipitation interception, in inches	0.2
TIPMR	"Die-away" coefficient used in the calculation of the ATIMR index	0.98
TIPM	"Die-away" coefficient used in the calculation of the ATICC index	0.84
TSS	Surface flow time of storage in hours	--
TSSS	Subsurface flow time of storage in hours	--
TSBF	Baseflow time of storage in hours	--
WEMIN	Minimum snow-water equivalent, in inches for unrestricted dry-melt of snow pack	2.0
WEMAX	Maximum snow-water equivalent, in inches for restricted dry-melt of snow pack	0.4
WEPCT	Percentage of snow-water equivalent per day below WEMIN that can be melted	60

Tables	Definition	
BFP	Percent of runoff to baseflow based on BII values	
DKE	Adjustment to PET or the ETI index when soil moisture becomes depleted.	
EKE	Adjustment to PET or the ETI index based on rainfall intensity	
ETIPCT	Elevation in feet versus percent effectiveness of ETI	
ELP	Elevation in feet of midpoint of snowband versus percent of subbasin precipitation applied to snowband	
ETMO	Percent effectiveness of ETI versus month	
ETP	Daily unadjusted PET based on air temperature	
GMLT	Groundmelt in inches per day versus month	
MRCR	ATIMR index versus dry-melt rate and cold rate	
MRPCT	Percent effectiveness of the snow pack dry-melt rate versus month	
ROP	SMI versus runoff percent of moisture input	
S/SS	Input to surface flow path in inches per hour versus input of direct runoff in inches per hour	

Snow Accumulation, Conditioning, and Melt

Because snowmelt contribution to runoff can be an important factor in floods, simulated contributions of snowmelt to runoff must be accounted for continuously. The depletion version of the SSARR model has an option of an energy-budget approach for simulating snowmelt, but such a data-intensive approach was not used. Instead, a temperature-index approach was chosen. Surface air temperature, which is strongly related to elevation and is the single most reliable index to snowmelt (Linsley and others, 1982, p. 253), is the sole index of energy exchange at the top of the snowpack used in the SSARR temperature-index algorithms.

Simulated snow accumulates at an even depth throughout an individual subbasin snowband when precipitation occurs if interception storage (TINTMX) has been satisfied and the temperature is below the rain-freeze temperature (PXTEMP). The simulated snowpack melts at the top by application of either a clear-weather melt equation or a rainy-weather melt rate (RMR) and at the bottom (groundmelt) at a rate that varies seasonally according to a table of monthly values (GMLT). Parameters and tables controlling simulated clear-weather melt and groundmelt are most important for correctly simulating the size of the snowpack, measured in inches of snow-water equivalent, before a storm, and the RMR is important in determining the contribution of snowmelt to runoff during a rain storm.

Melt water from the top of the snow pack must travel through the pack before becoming runoff. The snow pack "cold content" and "liquid water" deficits must be satisfied before melt water traveling through the snowpack is available for runoff. Satisfying these deficits is part of the snowpack conditioning and follows the same algorithms used by Anderson (1973) in his temperature-index, snow accumulation, and ablation model.

Partitioning Moisture Inputs

Liquid water from rain or snowmelt either increases soil moisture or becomes direct or baseflow runoff. The portion of liquid water that the model uses to increase soil moisture is a function of the simulated water already present in the soil, which is represented by the soil moisture index (SMI), in inches of water. As SMI increases, the percentage of moisture input available for runoff increases, and the percentage going to soil moisture decreases as defined in the runoff percentage table (ROP). Precipitation intensity may also influence the runoff percentages, but this option was not used in the Puyallup

River Basin model. Simulated water in soil moisture storage can only be depleted through evaporation. All of the liquid water input not going to soil moisture becomes runoff as either base flow, representing shallow to intermediate ground-water discharge, or direct runoff, representing surface or shallow subsurface runoff. A runoff pathway through deep ground water called "lower zone" in SSARR (U.S. Army Corps of Engineers, 1991, p. 23) is generally used to simulate the "long term" component of baseflow. This pathway was not used in the Puyallup River Basin model because the focus of the runoff simulations was on high flows, which are not significantly affected by long-term baseflow runoff. Similar to the ROP table, a base-flow percentage (BFP) table computes the percentage of available runoff that is base flow as a function of the base-flow infiltration index (BII). Other parameters define limits to the index (BIIMX), limits to the base flow runoff (BFLIM), and a time of storage delay (BIITS).

Simulated water not going to base flow or soil moisture becomes direct runoff and is partitioned as surface runoff (S) or subsurface runoff (SS). A table (S/SS) is provided to the program by the user to define the partitioning of available direct runoff as a function of the input rate in inches per hour. General guidelines for this relation are that (1) surface runoff is always at least 10 percent of the direct runoff and (2) the subsurface flow rate begins at zero, reaches a maximum rate when the rate of direct runoff is twice the maximum subsurface rate, and remains constant for increasing rates of direct runoff (U.S. Army Corps of Engineers, 1991, p. 24).

Routing of Surface, Subsurface, and Base Flow Runoff from Subbasins to Streams

The routing of available rainfall and snowmelt from the subbasins to streams represents delays in flow that naturally occur in the subbasin. Actual base flow will have delays on the order of weeks and months as water travels through the ground-water system, subsurface runoff will have delays of days or weeks, and surface runoff delays are generally measured in hours. The model uses a storage-routing technique that divides the water available for runoff into a specified number of increments of storage (phases) and applies a specified time of storage to the phases. Increasing the number of phases and time of storage will add longer delays to the outflow hydrograph from the subbasin, tending to attenuate the hydrograph. The partitioning of runoff into the three flow paths is computed in inches per hour and then converted to cubic feet per second based on the drainage area of the subbasin. The simulated outflow hydrograph from the subbasin can be

compared directly to the observed hydrograph recorded at a gage site if one is available. In the Puyallup River Basin model, comparisons between the observed and simulated subbasin outflow hydrographs are made for the Greenwater, Carbon, upper White (including flow from the Greenwater subbasin), upper Puyallup, and South Prairie subbasins. No comparisons are made with the two lower subbasins because there are no representative observed records of runoff from these subbasins.

Stream Network

For the purposes of modeling, a river system is represented by a network of one-dimensional channel reaches, lakes, reservoirs, and summary points (fig. 8). Subbasins generate runoff that becomes inflows to the network. All inflows to river reaches enter at their upstream ends, and all outputs exit through their downstream ends. The SSARR model uses *summing points* to add or subtract flows at junctions of *reaches*; *adjacent stations* to route stream flows through channels where flow is a specified function of the flow in another reach; *reservoirs* to simulate the effects of dams; and *balancing stations* where the flow is specified as the difference between outflows from two reaches or between an observed and a simulated outflow.

In the Puyallup River Basin model, diversions from the White River into the White River Canal are simulated by CANALA, an adjacent station, and CANALB, a summing point. The flow at CANALA is set equal to the flow at the White River Canal gage (USGS station number 12099000). During a forecast model run, estimates of the diversions are obtained from Puget Power, the utility that operates the canal, and supplied to the model as flows for White River Canal at Buckley. Summing point CANALB subtracts an amount of water from SUM2 equal to the flow specified for CANALA.

It is worth noting that discharge of the White River at the gage near Buckley (USGS station number 12098500) is not available in real time because the stage-discharge relation (rating) used to compute discharges from observed stage is not stable. However, the record is published and is generally considered fair to good after the rating is adjusted at the end of the water year using information gathered from discharge measurements made at the site. The operational system uses only the stage information at this site.

Flow In Channels and Reservoirs

The travel time through and the attenuation of peak discharges by river channels, lakes, and reservoirs can significantly influence the shape of downstream hydrographs. In the Puyallup River Basin model, flow routing begins with the inflow to Mud Mountain Lake on the White River, at the mouth of South Prairie Creek on the Carbon River, and near Orting (USGS station number 12093500) on the main stem of the Puyallup River. Routing continues downstream to near the mouth of the Puyallup River (USGS station number 12101500).

Flow routing in two of the channel reaches, REACH2 and REACH5, of the model is controlled by a storage-routing equation that routes the flow incrementally. In the routing equation, the shape of the outflow hydrograph from a channel reach is affected by the number of phases (increments) and the time of storage, both provided by the user. Increasing the number of phases will decrease the peak discharge and increase the time of storage, causing greater attenuation of the outflow hydrograph (U.S. Army Corps of Engineers, 1991, p. E-3). The user also provides values for the parameters n and KTS to determine a time of storage, T_s, for each phase:

$$T_s = \frac{KTS}{Q^n} \, , \qquad (2)$$

where

KTS is a coefficient determined by calibration,

Q is discharge, in cubic feet per second, and

n is a coefficient, usually between -1 and 1, also determined by calibration.

Larger values of KTS and smaller values of n tend to attenuate the discharge hydrograph. The User's Manual (U.S. Army Corps of Engineers, 1991, p. E-3 to E-9) provides typical values and tables to make initial estimates of the parameters that require a series of trial-and-error model runs to calibrate. Time of storage can also be provided as a table of discharges versus time of storage, as was done for reaches 1, 3, and 4. These tables were taken from the NWS Northwest River Forecast Center's Puyallup River Basin model (Chuck Orwig, National Weather Service, Northwest River Forecast Center, National Weather Service, written commun.,1993).
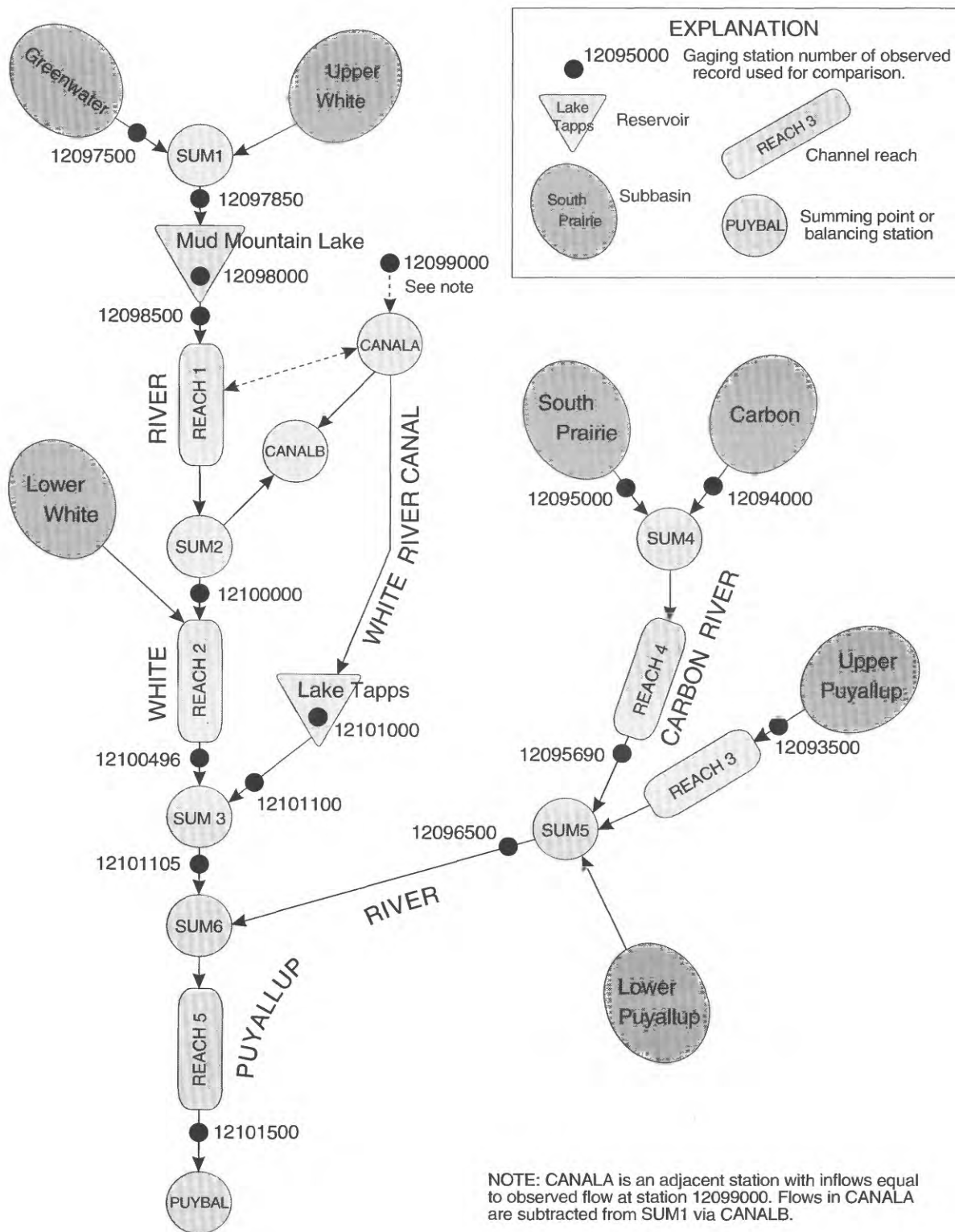
Figure 8. Schematic diagram of the network of subbasins, channel reaches, reservoirs, and summing points used in the Puyallup River Basin model, Washington.

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In the Puyallup River Basin model there are two reservoirs, Mud Mountain Lake and Lake Tapps, that can store water and affect flows. The Electron diversion has little storage capability and little effect on flows other than slight changes in timing, most notable during low flows when the travel time through the flume is less than through the natural channel reach. The diversion of water from the Puyallup River and through the Electron Powerhouse was ignored in the Puyallup River Basin model because of its small effect on flood flows in the river.

Routing through a reservoir is based on a user-provided table of discharge and storage for various levels of stage in the reservoir. Free-flow outflow is determined from the storage and relations between storage, stage, and discharge. Controls on the simulated outflow, however, may be made by specifying a time series of outflow discharges or reservoir stages. In the Puyallup River Basin model, simulated outflow from Lake Tapps equals observed discharge at Lake Tapps Diversion (station number 12101100); and simulated outflow from Mud Mountain Lake is computed using observed stage and a relation of lake stage to storage—simulated outflow equals the simulated inflow minus the change in storage. When lake stage is missing (possible during real-time applications), simulated outflow from Mud Mountain Lake equals the addition of the observed discharges of the White River at Buckley (USGS station number 12100000) and of the White River Canal at Buckley (USGS station number 12099000).

Generally, the controls on the simulated outflow are used. During forecast model runs, the outflows for Mud Mountain Dam, inflows to the White River Canal, and outflows for Lake Tapps must be estimated in order to use the controls on simulated outflow. There are times when controls should not be used for Mud Mountain Dam. With controls, the simulated flows from Mud Mountain Dam can be wildly unstable when there is little or no storage, which is common during nonflood conditions. If the simulated inflow is not enough to maintain specified outflows or lake stage, then negative outflows are computed to conserve mass. At these points in time, the outflow or stage often fluctuates dramatically from negative values to unreasonably large positive outflows. If this problem occurs, the model run can be rerun by specifying that the storage remains constant, which causes free flow to occur—outflow equals inflow.

The stage at several sites critical to PCRI operations is determined from simulated discharges and the stage-discharge relationships (ratings) at these sites. These sites include Puyallup River near Orting (12093500), Carbon

River at Orting (12095690), Puyallup River at Alderton (12096500), White River near Auburn (12100496), and Puyallup River at Puyallup (12101500).

Automated Adjustment of Simulated Runoff

The SSARR model can automatically adjust runoff simulations for individual subbasins to the observed record with the ADJUST command. The common use for this command is to make adjustments to the observed gage values of precipitation and and (or) temperature just prior to a forecast model run to make sure that certain initial conditions for the run, such as stream discharges, match the observed conditions at the last time step for which the observed data are available. By this method, much of the error that may have accumulated prior to the forecast model run is eliminated. These adjustments are not carried forward into the forecast simulations.

In the first step of the automated adjustment procedure, a time series of differences between simulated and observed discharges is computed. The model uses these differences and an attribution table (table ATTR1 in the Puyallup River Basin model) to estimate the error that potentially can be corrected by changing the available water for runoff at a particular time. The estimated correction E_i at time step i is computed as

$$
\begin{aligned}
E_i &= P_i(S_i - O_i) \\
&+ P_{i+1}(S_{i+1} - O_{i+1}) + ... \\
&+ P_{i+n}(S_{i+n} - O_{i+n})
\end{aligned} \qquad (3)
$$

where

P_i is the percent of total runoff for time, i, from the attribution table;

S_i is simulated discharge for time i;

O_i is observed discharge for time i; and

n is the number of time steps in the attribution table.

The attribution table (fig. 9) is analogous to a unit hydrograph that defines the amount of runoff in a basin over time for a given input of rainfall. The table, ATTR1, was generated from a simulated unit hydrograph for the South Prairie Creek Basin for a 24-hour period and is used for all the basins that use the ADJUST procedure.
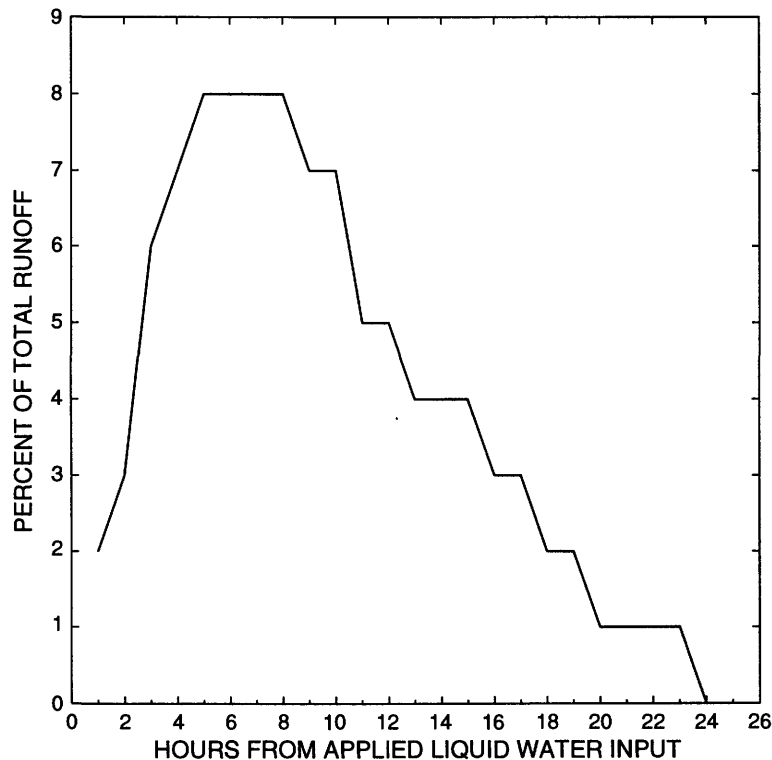
Figure 9. Simulated hourly subbasin runoff response to liquid water input defined by attribution table ATTR1 in the Puyallup River Basin model, Washington.

The next and final step in the adjustment procedure is to run a set of trial simulations in which lapse rate, temperature, and precipitation are adjusted by varying amounts. The first two are adjusted only if snow is present. The model will iterate a specified number of times (10 in the Puyallup River Basin model) or until a simulated discharge is within a specified range (5 percent of observed discharge for the Puyallup River Basin model). If the model has undersimulated runoff (observed is greater than simulated discharge) during a particular time period and snow is present in the snowband, the lapse rate is first lowered within specified increments (0.5°F per 1,000 feet elevation for the Puyallup River Basin model) to raise basin-averaged temperature and increase snowmelt and thus increase runoff. If more adjustment is needed to correct the undersimulation, temperature is increased by a specified increment (0.5°F for the Puyallup River Basin model), and finally if more adjustment is needed, precipitation is increased by a specified increment (0.2 inch for the Puyallup River model). The process is repeated until the maximum allowable number of trials have been made

or the error is within the specified tolerance. The trial with the smallest squared-error of differences between simulated and observed is chosen by the SSARR model as the final adjusted simulation.

In order for the ADJUST routine to work, a record of observed basin outflow is needed, which limits the application of the routine in the Puyallup River Basin model to the South Prairie, Greenwater, upper Puyallup, Carbon, and upper White subbasins. The observed record for the upper White subbasin is obtained by subtracting the observed flows at station number 12097500, Greenwater at Greenwater, from observed flows at station number 12097850, White River below Clearwater River.

A different process is used to adjust simulated outflow values for REACH5. At a "balancing" station called PUYBAL, the differences between outflows from REACH5 and the observed discharge of the Puyallup River at the Puyallup gage (PUYOBS) is computed (see fig. 8). Afterwards, the differences may be added to the inflow to REACH5.

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SIMULATION RESULTS

This section reports the results of simulations of eight of the largest storms that occurred during the calibration and validation period of this project (water years 1994 through 1997). The section also reports the results of several sensitivity analyses and comparisons of simulated and observed snow-water equivalent and precipitation, which are provided to give readers a feel for the various sources of errors and their relative magnitudes. This section begins by describing the guidelines used to attain the final calibrated SSARR model. They closely follow the methods used during real-time operation of the model, including making simulations using the latest observed data, generally 1 to 4 hours behind the current time. Forecast operation of the model uses forecasted input data to make 54-hour simulations with 6-hour time steps beginning at the end time of the most recent real-time simulation. The results of forecast simulations are not given in this report because the format, availability, and station location of the forecast data points have changed several times throughout this project.

Approach to Calibration and Validation of the Numerical Model

To attain the final set of model characteristics and tables, the investigation began with the characteristics and tables supplied by the NWS for its model of the Puyallup River Basin (preliminary model) and adjusted them as necessary to reduce simulation error (differences between the observed and simulated peak discharges and runoff volumes). Calibration is a trial-and-error process that involves adjusting parameter values until there is a reasonable agreement between simulated and observed streamflow hydrographs. For the snow-accumulating parameters not found in the NWS's depletion version of the SSARR model, default values were taken from the literature. Because streamflows at the mouths of the lower White and lower Puyallup subbasins were not gaged, parameters for these subbasins were assigned values similar to their nearby subbasins.

The procedures used for calibration and validation model runs were the same as those that are expected to be used for real-time simulations. Calibration and validation simulations were begun on the beginning of the water year, October 1, except for water year 1996, for which simulations were begun on September 20 to account for an unseasonably large amount of precipitation during the last week of September 1995. Initial conditions specified for the subbasins represented the relatively dry soil conditions at the end of summer in the Pacific Northwest. Initial conditions of the reaches were based on average October 1 streamflow discharges for water years 1990 to 1996.

Real-time model operation uses 1-hour time steps in a "storm" mode and 6-hour time steps when in a "backup" or "nonstorm" mode and for forecast model runs. For the calibration and validation model runs, simulations were run at a 6-hour time step until 4 days before the day of the peak recorded at the upper basin stream gages. (Sometimes the peak discharge occurred later at downstream gages because of regulation or travel time). The simulation was stopped at midnight and then restarted with a 1-hour time step (storm mode) and run for 8 days. If additional calibration peaks occurred in the water year, simulation restarted in backup mode until 4 days before the next calibration. During real-time operation, the model would generally be stopped at the last date when observed discharge was available just before a flood was expected to occur, and the automated adjustment procedures would be used to correct the simulated values to agree with the observed values. However, this was not done during calibration and validation because it would mask errors in the model that the calibration process is designed to correct.

Calibration of the flow routing in the reaches was limited to only two reaches, REACH2 and REACH5, because observed discharge records were available for upstream and downstream end points of only these two reaches. In most floods, the flow velocities are relatively high on the Puyallup River; therefore, the translation of the flood peak from the upstream end of a reach to the downstream end of a reach is usually less than several hours. Also, when floodwaters are contained within the river banks, channel storage has minimal attenuating effects on discharge peaks. Calibration of REACH2 and REACH5 was done with some of the highest available flows, which were all contained within the banks or levees of the river, so the differences between the upstream and downstream hydrographs were small compared to errors in the simulation of runoff from the watersheds. It should be noted that an actual large breach of a channel bank or levee will likely send flow into storage and increase the downstream travel time of the peak. All of the reach calibrations were made when the flow was entirely within the main channel; therefore, in the case of a channel bank or levee breach, the simulated downstream peak may be higher and occur sooner than the observed peak. Figure 10 shows observed flow at the White River at Buckley gage representing the upstream inflow to REACH2, observed flow at the White River near Auburn gage, which represents the outflow from REACH2, and simulated outflow from REACH2.
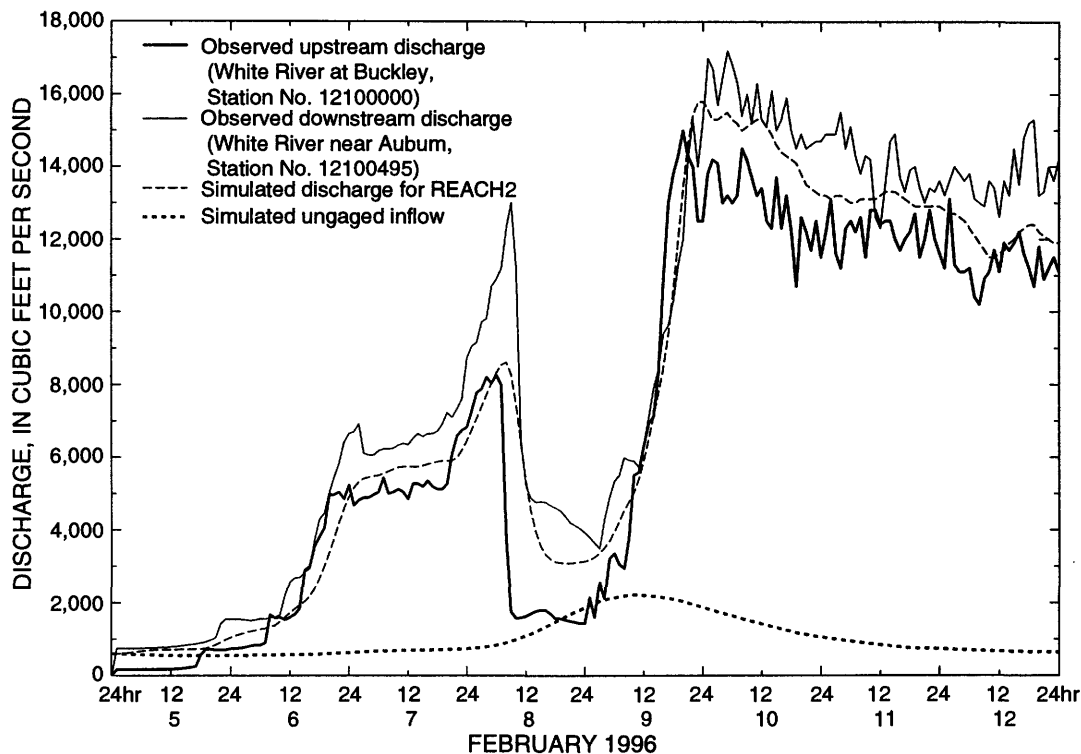
Figure 10. Simulated outflow discharge from REACH2 of the Puyallup River Basin model, simulated ungaged inflow to REACH2, observed upstream inflow to REACH2 at White River at Buckley, and observed outflow at White River near Auburn during February 5-12, 1996, Puyallup River Basin, Washington.

Simulated ungaged runoff from the lower White subbasin was added at the upstream end of REACH2 (fig. 8). The reach is 17 miles long but shows little attenuation of the hydrograph. No error analysis was performed on the reach calibrations.

Calibration and Validation of the Numerical Model

Four storms were selected for use in calibration. The first three occurred during the 1995 water year, and the fourth was the February 1996 storm, an exceptionally large event in the Puyallup River Basin. After a model was calibrated, the parameters were held constant and used to simulate runoff during four other storms designated as the validation period for the model. The validation storms included two 1996 water-year storms that occurred before the February 1996 peak and two storms in the 1997 water year.

Snow-water equivalent (SWE) data for the February 1996 storm were available from the National Operational Hydrologic Remote Sensing Center (NOHRSC) of the NWS. Adjustments of the snow-related parameters were made during a series of model runs (calibrations) to match the simulated SWE with the NOHRSC estimated SWE as well as possible. After these calibrations were made, these parameters were held constant throughout all the additional calibration and validation runs.

The model showed a strong seasonal bias to under-simulate storm runoff volume and peak discharges during late fall and early winter and to oversimulate these variables during late winter and early spring. The initial SMI at the beginning of the water year was increased, and the preliminary runoff percentage (ROP) tables were modified (fig. 11) to increase runoff early in the season and decrease it late in the season.
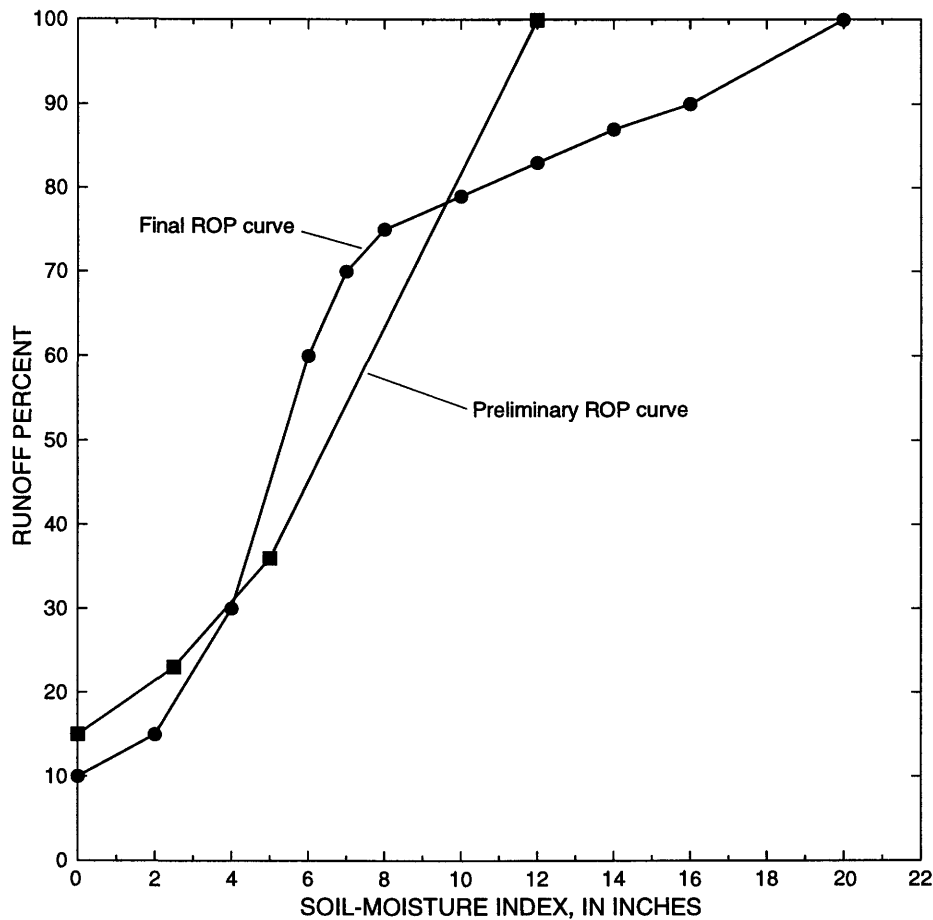
Figure 11. Preliminary and final runoff percentage (ROP) curves for the upper Puyallup subbasin in the Puyallup River Basin model, Washington.

The preliminary model used a precipitation adjustment weight of 100 percent (no adjustment) for all the subbasins. In the final model, the precipitation adjustment weight for the Carbon subbasin was increased to 120 percent because earlier model runs were consistently underestimating runoff. Conversely, because earlier model runs were consistently overestimating runoff from the South Prairie and Greenwater subbasins, in the final model, the precipitation adjustment weight for South Prairie subbasin was reduced to 85 percent and the weight for the Greenwater subbasin was reduced to 75 percent.

Comparison of Simulated Extent of Snow Cover with Observed Extent

Direct measures of SWE in the Puyallup River Basin are available for two sites with snow pillows: (1) Corral Pass, operated by the Natural Resources Conservation Service (data are usually gathered only from January to June), and (2) Cayuse Pass, operated by the USGS. With

data from only these two sites available, some form of indirect measurements of SWE was needed to evaluate the snowmelt contribution to runoff in order to calibrate the snow parameters in the watershed model. This was done for the February 1996 flood using gridded estimates of SWE obtained from the NOHRSC estimates. Estimates for February 1, 13, and 28, 1996, were obtained from the NOHRSC internet web site.

The SWE values from the NOHRCS web site were estimated by a "modified elevation detrending" method that uses satellite images of the extent of snow cover, a digital elevation model, and observations of SWE where they are available. Using all three sets of data, NOHRSC developed a linear relationship between elevation and SWE, and estimates of SWE were obtained for grid points at a spacing of approximately 0.4 mile (0.6 kilometer) (Hartman, Rost, and Anderson, 1996). In that paper the authors offer the following comment on their methodol-

ogy: "very little confidence should be placed on individual pixel [grid] values. However when integrated with [in] hydrologic basins, the results appear to be credible."

When NOHRSC estimates of SWE were compared with measured values of SWE at the Corral Pass site in the Puyallup River Basin and two other Natural Resources Conservation Service (NRSC)-operated sites in nearby basins (unfortunately, no usable data were available from the Cayuse Pass site for the February 1996 flood), there was reasonable agreement between estimated and measured values of SWE (table 8). In this comparison, the means of the NOHRSC estimates over representative areas, which varied in size from 2.5 to 12.1 square miles surrounding the snow-pillow sites, were used. Nine of the 12 NOHRSC estimates were within 3 inches of the observed values; however, all of the estimates were less than the observed values, with the largest difference (19.4 inches) occurring on February 13 for Corral Pass, the site at the highest elevation.

By use of GIS techniques, the subbasin total SWE and elevation-zone totals were computed from the basin-wide estimates of SWE from NOHRSC, thus allowing direct comparison with simulated results. SWE values simulated for subbasins are biased high in the high-elevation snowbands and biased low in the low-elevation snowbands, but are in reasonably close agreement with the NOHRSC esti-

mates in the midelevation snowbands (table 9). Of the five upper basins, the two lower elevation subbasins, South Prairie and Greenwater, generally had less simulated SWE than the NOHRSC estimates, while the higher elevation subbasins consistently had higher simulated SWE values. Simulated values on February 13, 5 days after the peak flooding, are almost all significantly larger than the NOHRSC estimates. Adjustment of the snow parameters, especially the snowmelt-rate-during-rainfall parameter, RMR, could have allowed more snow to melt and reduced the simulated February 13th SWE values. Several calibration runs were made to increase snowmelt, but they resulted in simulated peak discharges unreasonably larger than the observed values. Consequently, a value of RMR was chosen that compromised between errors of oversimulating peak discharges and of oversimulating snowmelt. Although there is an apparent bias of oversimulating SWE in the upper elevations and undersimulating SWE in the lower elevations, the final parameters were not adjusted to remove the bias because the same bias is indicated in the comparison of snow-pillow data and NOHRSC estimates (table 8), and attempts to correct the bias resulted in larger errors between observed and simulated peak discharges. Again, the values represent a balance of errors between SWE values and peak discharge values.

Table 8. Comparison of observed snow-pillow snow-water equivalent values and National Operational Hydrologic Remote Sensing Center estimates of snow-water equivalent at three sites in or near the Puyallup River Basin, Washington

[NOHRSC, National Operational Hydrologic Remote Sensing Center; NRCS, National Resource Conservation Service]

NRCS Station name (elevation, in feet above sea level)	February 1, 1996 Observed snow-water equivalent (inches)	NOHRSC[1] (inches)	February 6, 1996 Observed snow-water equivalent (inches)	NOHRSC[1] (inches)	February 13, 1996 Observed snow-water equivalent (inches)	NOHRSC[1] (inches)	February 28, 1996 Observed snow-water equivalent (inches)	NOHRSC[1] (inches)
Cougar Mountain (3,200)	10.9	9.5	12.6	11.3	9.5	4.7	9.1	7.3
Morse Lake (5,400)	31.2	29.7	36.6	33.8	38.1	35.6	43.8	41.1
Corral Pass (6,000)	21.1	8.8	23.5	21.4	24.7	5.3	27.5	26.4

[1]Mean value of snow-water equivalent estimates for a representative area surrounding the snow-pillow site.

Table 9. Snow-water equivalent for 5 upper basins and for all 13 elevation zones in the Puyallup River Basin, Washington, computed from National Operational Hydrologic Remote Sensing Center (NOHRSC) estimates and simulated by the Puyallup River Basin model, Washington, for 4 days in February 1996

Snow-water equivalent by subbasin, in inches

Subbasin	February 1, 1996 Esti-mated[1]	February 1, 1996 Simu-lated[2]	February 1, 1996 Diffe-rence[3]	February 6, 1996 Esti-mated[1]	February 6, 1996 Simu-lated[2]	February 6, 1996 Diffe-rence[3]	February 13, 1996 Esti-mated[1]	February 13, 1996 Simu-lated[2]	February 13, 1996 Diffe-rence[3]	February 28 1996 Esti-mated[1]	February 28 1996 Simu-lated[2]	February 28 1996 Diffe-rence[3]
Greenwater	10.0	7.3	-2.7	14.5	8.4	-6.1	6.6	7.6	+1.0	13.2	7.1	-6.1
Upper White	18.2	26.6	+8.4	19.9	28.8	+8.9	14.7	29.5	+14.8	22.8	30.6	+7.8
Upper Puyallup	15.5	20.5	+5.0	16.2	22.8	+6.6	10.4	24.4	+14.0	17.8	25.6	+7.8
Carbon	20.0	29.7	+9.7	21.1	33.6	+12.5	12.4	36.4	+24.0	23.8	37.7	+13.9
South Prairie	7.6	2.8	-4.8	6.0	3.2	-2.8	0.1	2.9	+2.8	5.5	3.3	-2.2

Snow-water equivalent by elevation, in inches

Midpoint elevation[4] (feet above sea level)	February 1, 1996 Esti-mated	February 1, 1996 Simu-lated[5]	February 1, 1996 Diffe-rence	February 6, 1996 Esti-mated	February 6, 1996 Simu-lated[5]	February 6, 1996 Diffe-rence	February 13, 1996 Esti-mated	February 13, 1996 Simu-lated[5]	February 13, 1996 Diffe-rence	February 28 1996 Esti-mated	February 28 1996 Simu-lated[5]	February 28 1996 Diffe-rence
250	0.8	0.0	-0.8	0.6	0.0	-0.6	0.0	0.0	0.0	0.0	0.0	0.0
750	1.5	0.2	-1.3	2.1	0.0	-2.1	0.0	0.0	0.0	0.0	0.0	0.0
1,250	3.4	1.4	-2.0	4.0	0.5	-3.5	0.0	0.0	0.0	0.3	0.2	-0.1
1,750	3.5	2.0	-1.5	3.3	1.4	-1.9	0.1	0.0	-0.1	1.4	0.5	-0.9
2,250	5.0	2.1	-2.9	3.2	1.7	-1.5	0.4	0.1	-0.3	3.6	0.8	-2.8
2,750	6.6	2.4	-4.2	6.4	2.5	-3.9	0.8	0.6	-0.2	7.4	1.1	-6.3
3,250	11.0	4.6	-6.4	9.1	6.4	-2.7	1.4	4.5	+3.1	12.8	4.0	-8.8
3,750	14.9	9.0	-5.9	14.6	11.8	-2.8	3.4	10.8	+7.4	17.7	10.6	-7.1
4,250	18.1	19.1	+1.0	18.6	22.8	+4.2	7.6	23.8	+16.2	22.6	24.6	+2.0
4,750	21.4	25.9	+4.5	23.8	29.9	+6.1	10.8	34.2	+23.4	27.8	35.7	+7.9
5,500	26.8	40.1	+13.3	31.9	44.4	+12.5	22.7	50.6	+27.9	35.2	56.6	+21.4
7,000	41.6	85.7	+44.1	50.1	91.1	+41.0	55.2	99.0	+43.8	51.6	90.2	+38.6
11,500	72.4	138.0	+65.6	78.9	103.4	+24.5	108.5	159.5	+51.0	85.1	146.5	+61.4

[1]National Operational Hydrologic Remote Sensing Center (NOHRSC) estimated snow-water equivalent data.

[2]Simulated snow-water equivalent from the Puyallup River Basin model.

[3]Difference between simulated and estimated snow-water equivalent values.

[4]Midpoint elevation of the elevation zones defined for the Puyallup River Basin model used in this investigation.

[5]Areally weighted average of snow-water equivalent in the elevation zones of five subbasins in the Puyallup River Basin model.

Comparison of Observed and Simulated Runoff

Although the upper White subbasin was not gaged directly, discharge from this subbasin for calibration was obtained by subtracting the discharge from the Greenwater subbasin (USGS station number 12097500) from the discharge of the White River below Clearwater River (USGS station number 12097850). Discharges of the White River at Buckley (USGS station number 12100000) and of the Puyallup River at Puyallup (USGS station number 12101500) are heavily regulated and, therefore, not used to calibrate runoff parameters. Calibration of the runoff parameters focused on the five gaged subbasins.

Many of the same patterns and magnitudes of errors seen for the calibration storms were also seen for the validation storms. Two-thirds of the simulated peak discharges were within 36 percent of the observed peak discharge for the calibration peaks and within 30 percent of the observed peak discharges for the validation peaks

(table 10). Two-thirds of the simulated runoff volumes for the five gaged subbasins were within 17 percent of the observed storm runoff volume for the calibration storms and within 24 percent of the observed storm runoff volume for the validation storms. Errors in simulating peak discharge can be attributed to either incorrectly simulating the amount of water available for runoff or incorrectly simulating the runoff process, or both. Simulated and observed storm runoff volumes were tabulated along with peak discharges in order to assess whether errors in peak discharge were due to incorrect simulation of runoff volume or incorrect runoff parameters.

Figure 12 shows the accuracy and bias of the simulated peak flow and runoff volume from the five gaged watersheds. More data points on each graph fall below the equivalence line, indicating a bias to undersimulate both runoff volume and peak discharge. However, the bias appears to decrease with increasing peak flow and runoff volume. The largest undersimulated flows occurred for the second calibration storm, November 29 to December 3, 1994, when the differences between simulated and observed runoff ranged from -8.1 to -70.3 percent (table 10). Even so, the shapes of the simulated hydrographs matched the shapes of the observed hydrographs for this storm fairly well (fig. 13). There simply was insufficient recorded precipitation to match the simulated runoff to the observed runoff no matter how much the model parameters were adjusted. The calibrated model simulated the largest peak (February 1996) well, closely matching the shape of the hydrograph and the peak (fig. 14).

The summation of errors (table 11) shows that the model tends to undersimulate peak discharge as measured by the bias. Bias is the average of the differences, either positive or negative, and indicates whether the model is oversimulating or undersimulating discharge. The bias is strongly seasonal, despite efforts to reduce the seasonal bias during the calibration process. For all the calibration and validation peaks for the five gaged subbasins, there is a -21.9 percent bias (-1,275 ft^3/s) for those peaks that occurred before January 1 of the water year and a +23.4 percent bias (842 ft^3/s) for those peaks after January 1. The standard error of estimate (SEE) is the standard deviation of the differences after accounting for the bias. If the differences were normally distributed and there were little or no bias, then about two-thirds of all the differences would be less than or equal to the SEE. Depending on the grouping of storms, values of SSE range from 16.6 to 40.1 percent (table 11).

Sources of Errors

This subsection discusses three possible reasons for the errors in simulated peak discharges and runoff volumes: (1) errors in the spatial distributions of temperature, precipitation, and SWE; (2) errors in the measurement and calculation of observed discharge; and (3) errors in the representation of the hydrologic runoff processes by the conceptual model and the SSARR model. It is difficult to quantify these errors, but some general comments about each type of error are made in this subsection, and three sensitivity tests on the effects of precipitation and temperature inputs and snow accumulation are described in the following subsection.

Four of the seven temperature stations provide temperature inputs to the real-time model. The model error due to these inputs was relatively small because the chosen stations rarely had missing or bad records and the accuracy of the measurements was adequate (the manufacturer's specifications state that measurements are accurate within 0.2°F, and regular field checks showed that the recorded temperatures generally were accurate within 0.5°F). Also the four chosen stations were adequate to define the lapse rates for most of the runoff-producing range in elevation. Lapse rates above 5,300 feet—the elevation of Cayuse Pass, the highest temperature station—may be in error, but the percentage of the area of the basin above 5,300 feet and especially above 8,000 feet is small and generally does not contribute much during winter storms because most of the precipitation is snow. Therefore, temperature errors in these high elevations probably do not contribute significantly to runoff volume or peak-discharge errors.

Precipitation inputs had a much larger potential to create errors in the simulations than did the temperature inputs. Six precipitation stations were available to provide precipitation inputs to the model. If all precipitation stations had acceptable records and were used, the precipitation network would represent a density of approximately one gage per 160 square miles, which may be inadequate. Also, experience has shown that it is common to have less than all of the six stations with acceptable records because many of the gages are unheated and, therefore, misreport actual precipitation during times of snowfall. Certainly, more precipitation gages located in the mid-to-upper elevations that are reliable during snowfall would provide a better measure of the true precipitation and most likely improve the accuracy of runoff simulations.

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Table 10. Observed and simulated storm runoff values per unit area and peak discharge of eight storms used for calibration and validation of the Puyallup River Basin model, Washington

[ft³/s, cubic feet per second]

Station number	Date of runoff period	Date of peak	Storm runoff volume[1] Observed (inches)	Simulated (inches)	Difference (inches)	Difference (percent)	Peak discharge Observed (ft³/s)	Simulated (ft³/s)	Difference (ft³/s)	Difference (percent)
12093500 Calibration				Puyallup River near Orting						
	10/30 - 11/3/94	10/31	1.75	1.52	-0.23	-13.1	5,890	4,420	-1,470	-25.0
	11/29 - 12/3/94	11/30	2.03	1.12	-0.91	-44.8	5,130	1,870	-3,260	-63.5
	02/18 - 22/95	02/19	2.32	2.30	-0.02	- 0.9	3,840	5,190	+1,350	+35.2
	02/07 - 11/96	02/08	7.38	7.08	-0.30	- 4.1	18,300	19,800	+1,500	+ 7.7
Validation										
	11/27 - 12/1/95	11/28	7.24	5.61	-1.63	-22.5	13,600	11,300	-2,300	-16.9
	01/06 - 10/96	01/07	3.55	2.12	-1.43	-40.3	5,700	4,470	-1,230	-21.6
	11/26 - 30/96	11/27	2.36	1.75	-0.61	-25.8	5,810	3,900	-1,910	-32.9
	12/29 - 1/2/97	01/01	4.95	3.77	-1.18	-23.8	8,240	8,240	0	0
12094000 Calibration				Carbon River near Fairfax						
	10/30 - 11/3/94	10/31	2.83	2.36	-0.47	-16.6	4,900	4,250	- 650	-13.3
	11/29 - 12/3/94	11/30	3.12	1.72	-1.40	-44.9	3,610	1,890	-1,720	-47.6
	02/18 - 22/95	02/19	4.12	4.87	+0.75	+18.2	4,700	5,920	+1,220	+26.0
	02/07 - 11/96	02/08	11.09	10.00	-1.09	- 9.8	12,000	13,100	+1,100	+ 9.2
Validation										
	11/27 - 12/1/95	11/28	10.66	8.81	-1.85	-17.4	10,100	7,090	-3,010	-29.8
	01/06 - 10/96	01/07	3.79	3.03	-0.76	-20.1	4,160	4,200	- 40	+ 1.0
	11/26 - 30/96	11/27	3.57	2.50	-1.07	-30.0	4,540	3,450	-1,090	-24.0
	12/29 - 1/2/97	01/01	6.04	6.38	+0.34	+ 5.6	4,440	5,010	+ 570	+12.8
12095000 Calibration				South Prairie Creek at South Prairie						
	10/30 - 11/3/94	10/31	0.99	1.26	+0.27	+27.3	1,400	1,390	- 10	- 0.7
	11/29 - 12/3/94	11/30	2.11	1.94	-0.17	- 8.1	2,560	1,880	- 680	-26.6
	02/18 - 22/95	02/19	2.44	2.74	+0.30	+12.3	2,680	2,940	+ 260	+ 9.7
	02/07 - 11/96	02/08	7.83	7.86	+0.03	+ 0.4	8,170	8,110	- 60	- 0.7
Validation										
	11/27 - 12/1/95	11/28	5.21	6.62	+1.41	+21.1	4,860	5,880	+1,020	+21.0
	01/06 - 10/96	01/07	1.96	2.54	+0.58	+29.6	1,820	2,740	+ 920	+50.5
	11/26 - 30/96	11/27	2.39	1.92	-0.47	-19.7	3,230	2,020	-1,210	-37.5
	12/29 - 1/2/97	01/01	4.99	4.40	-0.59	-11.8	2,810	3,540	+ 730	+26.0
12097500 Calibration				Greenwater River at Greenwater						
	10/30 - 11/3/94	10/31	0.80	0.73	-0.07	- 8.8	1,000	763	- 237	-23.7
	11/29 - 12/3/94	11/30	1.48	0.44	-1.04	-70.3	1,180	458	- 722	-61.2
	02/18 - 22/95	0219	1.96	2.15	+0.19	+ 9.7	1,330	2,260	+ 930	+69.9
	02/07 - 11/96	02/08	6.48	6.30	-0.18	- 2.8	5,900	5,660	- 240	- 4.1

Table 10. Observed and simulated storm runoff values per unit area and peak discharge of eight storms used for calibration and validation of the Puyallup River Basin model, Washington—Continued

Station number	Date of runoff period	Date of peak	Storm runoff volume[1] Observed (inches)	Simulated (inches)	Difference (inches)	Difference (percent)	Peak discharge Observed (ft³/s)	Simulated (ft³/s)	Difference (ft³/s)	Difference (percent)
12097500			Greenwater River at Greenwater--Continued							
Validation										
	11/27 - 12/1/95	11/28	7.12	5.15	-1.97	-27.7	4,240	3,740	- 500	-11.8
	01/06 - 10/96	01/07	1.79	1.73	-0.06	- 3.4	961	1,490	+ 529	+55.0
	11/26 - 30/96	11/27	1.11	1.24	+0.13	+11.7	850	1,320	+ 470	+55.3
	12/29 - 1/2/97	01/01	1.99	1.75	-0.24	-12.1	1,520	2,270	+ 750	+49.3
12097850			White River below Clearwater							
Calibration										
	10/30 - 11/3/94	10/31	1.19	1.00	-0.19	-16.0	7,380	6,840	- 540	- 7.3
	11/29 - 12/3/94	11/30	1.58	0.49	-1.09	-69.0	7,330	2,930	-4,400	-60 0
	02/18 - 22/95	02/19	2.09	2.11	+0.02	+ 1.0	7,600	13,100	+5,500	+72.4
Validation										
	11/27 - 12/1/95	11/28	4.70	5.09	+0.39	+ 8.3	20,500	18,500	-2,000	-11.7
	01/06 - 10/96	01/07	1.81	1.56	-0.25	-13.8	6,000	7,290	+1,290	+21.5
12100000			White River at Buckley							
Calibration										
	10/30 - 11/3/94	10/31	0.50	0.27	-0.23	-46.0	2,150	2,050	-100	- 4.7
	11/29 - 12/3/94	11/30	0.73	0.07	-0.66	-90.4	2,640	799	-1,841	-69.7
	02/18 - 22/95	02/?	0.87	0.69	-0.18	-20.7	2,860	2,840	-20	- 0 7
	02/07 - 11/96	02/10	3.16	3.09	-0.07	- 2.2	11,800	11,200	- 600	- 5.1
Validation										
	11/27 - 12/1/95	12/01	2.78	2.65	-0.13	- 4.7	13,700	11,600	-2,100	-15.3
	01/06 - 10/96	01/08	1.19	0.54	-0.65	-54.6	4,630	3,300	-1,330	-28 7
	11/26 - 30/96	11/29	0.73	0.60	-0.13	-17.8	3,040	3,510	360	+15.5
	12/29 - 1/2/97	12/31	2.70	1.26	-1.44	-53.3	9,480	8,990	-2,310	- 5.2
12101500			Puyallup River at Puyallup							
Calibration										
	10/30 - 11/3/94	10/31	1.20	1.06	-0.14	-11.7	13,400	11,100	-2,300	-17.2
	11/29 - 12/3/94	11/30	1.43	1.12	-0.31	-21.7	14,000	9,790	-4,210	-30 1
	02/18 - 22/95	02/19	1.95	2.01	+0.06	+ 3.1	19,200	16,800	-2,400	-12 5
	02/07 - 11/96	02/09	5.31	5.59	+0.28	+ 5.3	46,700	45,700	-1,000	- 2 1
Validation										
	11/27 - 12/1/95	11/28	3.76	4.94	+1.18	+31.4	32,600	35,900	+3,300	+10 1
	01/06 - 10/96	01/07	1.89	1.85	-0.04	- 2.1	13,000	16,600	+3,600	- 2.1
	11/26 - 30/96	11/28	1.62	1.64	+0.02	+1.2	17,000	14,700	-2,300	-13.5
	12/29 - 1/2/97	01/01	3.35	3.09	-0.26	- 7.8	22,800	26,700	+3,900	+17.1

[1]Storm runoff volumes are the 5-day total of daily streamflow volumes for the period of each storm divided by the drainage area

$RO = \dfrac{\text{cubic feet per second–days}}{DA} \times 0.03719$, where RO is runoff in inches, cubic feet per second–day is the 5-days total of mean daily discharges, and DA is the drainage area in square miles.
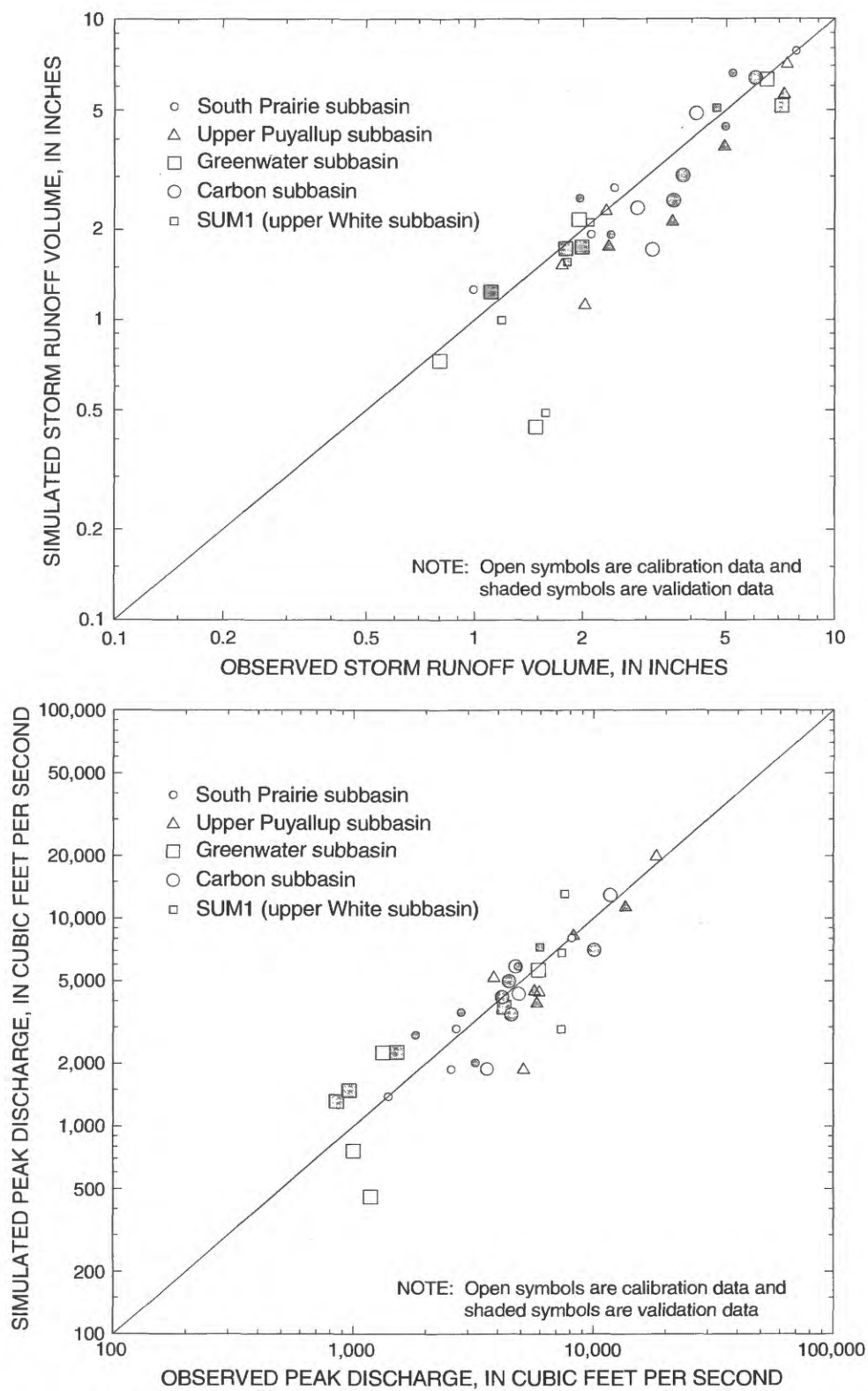
Figure 12. Observed and simulated storm runoff volumes and peak discharge for South Prairie, upper Puyallup, Greenwater, and Carbon subbasins and summation point SUM1, Washington.
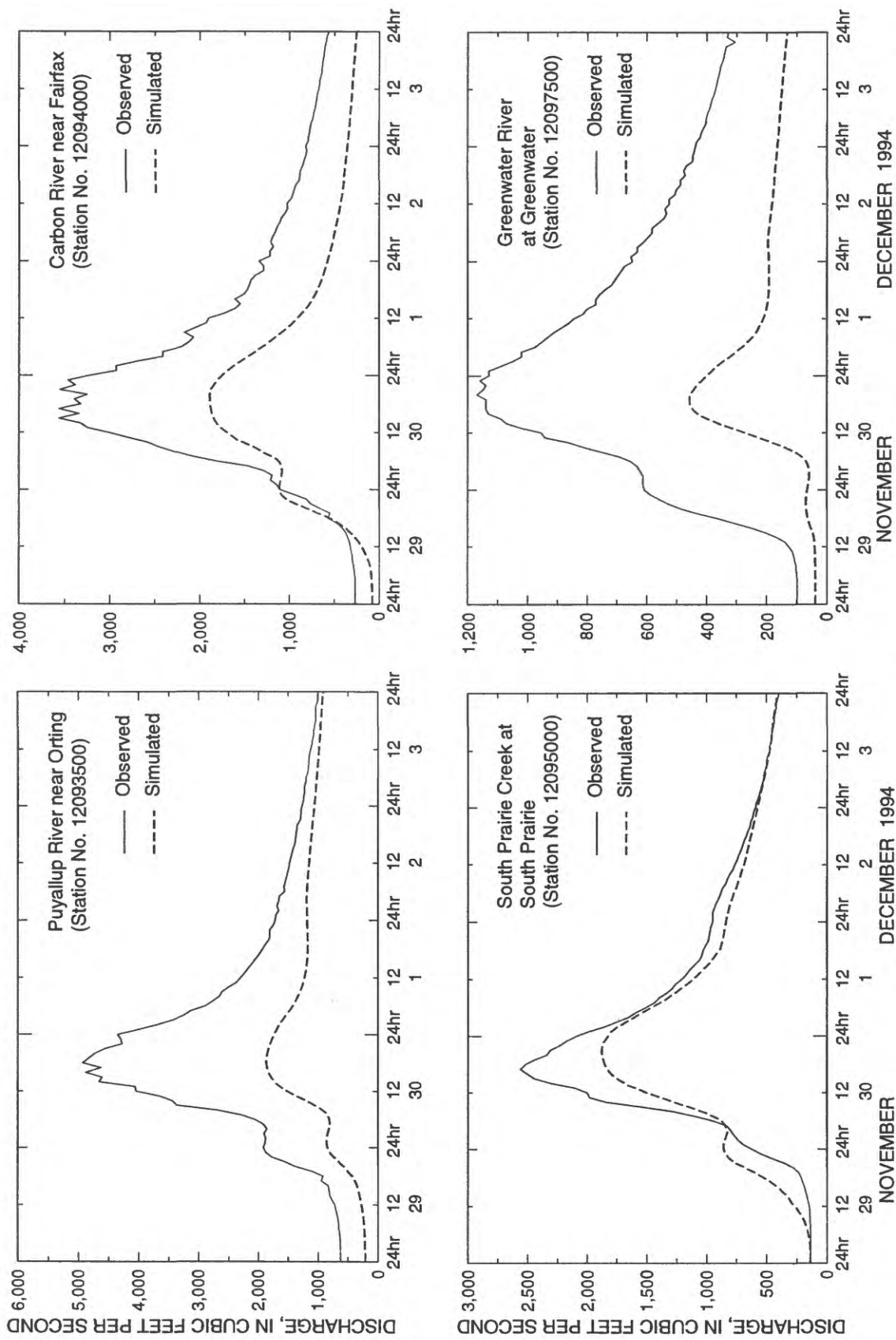
Figure 13. Observed and simulated discharge at Puyallup River near Orting, Carbon River near Fairfax, South Prairie Creek at South Prairie, and Greenwater River at Greenwater for the November 29 to December 3, 1994, storm, Puyallup River Basin, Washington.

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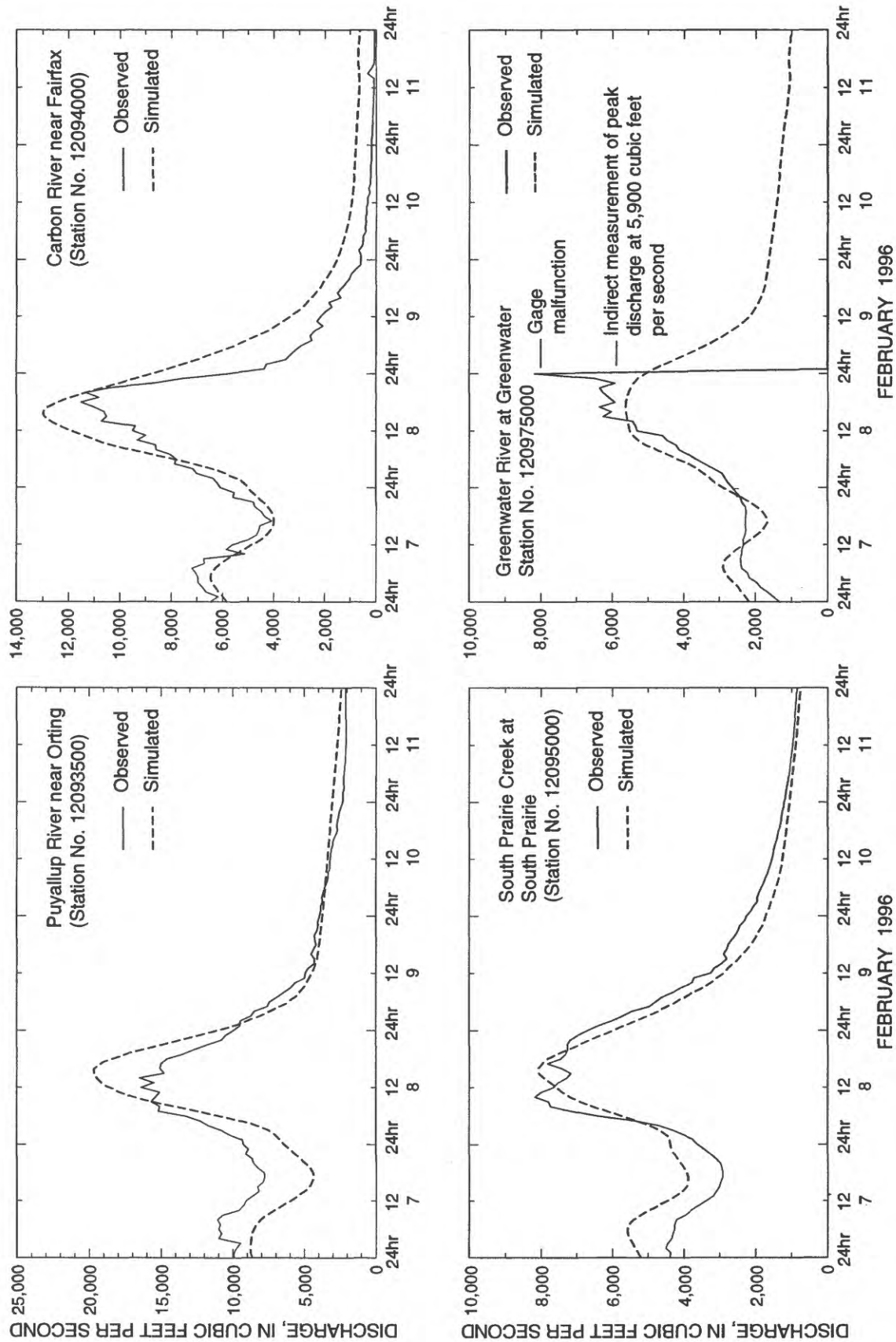
Figure 14. Observed and simulated discharge at Puyallup River near Orting, Carbon River near Fairfax, South Prairie Creek at South Prairie, and Greenwater River at Greenwater for the February 7-11, 1996, storm, Puyallup River Basin, Washington.

Table 11. Summation of errors of storm runoff and peak discharge for the five gaged subbasins in the Puyallup River Basin model, Washington

[RMSE, root mean square error; SEE, standard error of estimate]

	Storm runoff volume, in inches and (percent)		Peak discharge, in cubic feet per second and (percent)	
	Calibration	Validation	Calibration	Validation
Bias[1] (in percent)	-0.29 (-12.6)	-0.51 (-10.3)	-112 (-5.4)	-385 (6.0)
RMSE[2] (in percent)	0.63 (29.0)	1.02 (21.7)	1,985 (38.4)	1,331 (31.4)
SEE[3] (in percent)	0.59 (27.6)	0.94 (20.2)	2,092 (40.1)	1,349 (32.6)

	Storm runoff volume, in inches and (percent)		Peak discharge, in cubic feet per second and (percent)	
	Storms before January 1	Storms on or after January 1	Storms before January 1	Storms on or after January 1
Bias[1] (in percent)	-0.58 (-19.0)	-0.22 (-3.7)	-12.75 (-21.0)	842 (23.4)
RMSE[2] (in percent)	1.01 (32.3)	0.62 (16.1)	1,821 (35.3)	1,559 (35.0)
SEE[3] (in percent)	0.87 (27.6)	0.61 (16.6)	1,372 (29.2)	1,389 (27.6)

$$^1\text{Bias} = \sum_{i=1}^{n} \frac{S_i - O_i}{n} \; ; \; \text{Bias, percent} = \left[\sum_{i=1}^{n} \frac{\left(\frac{S_i - O_i}{O_i}\right)}{n}\right] \times 100$$

$$^2\text{RMSE} = \text{Root mean square error} = \sqrt{\sum_{i=1}^{n} \frac{(S_i - O_i)^2}{n}}$$

$$\text{RMSE, percent} = 100 \times \sqrt{\sum_{i=1}^{n} \frac{\left(\frac{S_i - O_i}{O_i}\right)^2}{n}}$$

$$^3\text{SEE} = \text{standard error of estimate} = \left(\frac{n}{n-1}\right) \times \sqrt{\text{RMSE}^2 - \text{BIAS}^2}$$

$$\text{SEE, percent} = \left(\frac{n}{n-1}\right) \times \sqrt{\text{RMSE, percent}^2 - \text{Bias, percent}^2} \; ,$$

where S is simulated value, O is observed value, and n is number of values.

Because precipitation varies greatly within 160-square-mile areas in the Puyallup River Basin, especially in the mid-to-upper elevations (fig. 5) where the fewest precipitation gages are located, there is the question whether snowband estimates of precipitation can be improved with additional precipitation gages. To answer this question, precipitation estimates for snowband 3 (2,000 to 2,500 feet above sea level) of the upper White subbasin were computed using three different pairs of gages. The second pair were farther apart than the first pair; and the third pair farther apart than the second pair. The snowband precipitation was estimated by the same method of calculating snowband precipitation used in the Puyallup River Basin model. The first pair of stations,

Nevan-McCullough and Buck Creek, are located only 3.6 miles apart in the same subbasin (fig. 3). The second pair of stations, Greenwater and Buck Creek, which are located 9.8 miles apart on either side of snowband 3, are the two default stations that the Puyallup Flood-Alert System uses to compute the precipitation for snowband 3. The final pair of stations, Greenwater and Electron, are located 25.6 miles apart at similar elevations but separated by several ridges and river valleys. Eight-day precipitation totals were calculated for six storms when data were available. The Nevan-McCullough gage lies in snowband 3 of the upper White subbasin. In this analysis it is assumed that the precipitation of the Nevan-McCullough gage is the true precipitation for snowband 3 of the upper White subbasin and that the precipitation data obtained from the various pairs represent precipitation amounts that would be obtained from a precipitation network containing fewer and fewer stations.

The range in differences from the measured totals at Nevan-McCullough (table 12) is an indication of the accuracy that would be expected from increasing the density of precipitation gages. As expected, the Nevan-McCullough and Buck Creek pair, a pair representing what might be considered a maximum density of precipitation stations to estimate snowband precipitation, has the smallest range of differences (about 27 percent). The Greenwater and Buck Creek pair has about double the range in differences despite the fact that they straddle the snowband relatively close to one another. The Greenwater and Electron pair, which represents a relatively sparse network of gages, shows a large range of values—about three times the range of the Nevan-McCullough and Buck Creek pair. The test suggests that the accuracy of precipitation estimates can be increased by increasing the number of precipitation gages in the basin.

How well individual gages measure precipitation also affects how well precipitation over an area can be estimated. The manufacturer of some of the tipping-bucket gages used in this study specifies an accuracy of measurement within 4 percent of the true value at a rainfall rate of 2.2 inches per hour. More intense rates of rainfall generally result in larger errors, but intensities of rainfall in the Puyallup River Valley rarely exceed 2.2 inches per hour—the 2-year, 6-hour maximum precipitation for the midelevations of the Puyallup River Basin is about 1.6 inches (U.S. Department of Commerce, 1973). Often, a bigger problem with precipitation gages is that wind reduces the catch efficiency of a rain gage. However, most of the precipitation gages in this study were sheltered from the wind by trees, so wind should not have had a large effect. Larson and Peck (1974) showed that wind can reduce

catch efficiency for rain about 1 percent for each mile per hour of wind velocity at the gage orifice. The reduction in catch efficiency of a shielded gage for snow is roughly double that for rain as wind increases, and of a non-shielded gage, it is more than triple. At the Nevan-McCullough site, a relatively windy location, paired heated tipping-bucket rain gages were placed side by side—one with an Alter shield and one without a shield. During 391 days of record, the shielded gage recorded 80.77 inches of precipitation while the unshielded gage recorded 79.15 inches, which is only 2.0 percent less.

Accurate simulation of SWE is dependent on accurate estimates of temperature and precipitation and correct calibration of the snow-related parameters. The errors in the simulated values of SWE are difficult to assess because there were little observed data available and the accuracy of the observed data was questionable. If more accurate observed SWE data were available, such as would be provided by a network of snow pillows within the basin or by improved and more frequent remote sensing of the basin, the calibration of the snow-related parameters probably could be improved. Also, if this observed data were available in real time, the simulated SWE values could be adjusted to agree with observed data just prior to a forecast model run. Improved simulation could be expected with the improved SWE estimates depending on the amount of snow-melt contributions to the flood.

Another possible source of error was the inaccuracy of the observed runoff volumes and peak discharges to which the models were calibrated. During floods, the accuracy of the observed streamflow record often is only fair (95 percent of the daily discharges are within 15 percent of the true discharge) to poor (daily mean discharges have less than fair accuracy) (Novak, 1985, p. 65). Because runoff volumes were computed from the mean daily discharges, the accuracy of these volumes probably is 15 percent or less. The errors in peak discharges obtained from gaging station records probably are greater than the error in mean daily discharges. Also, most of the peak-flow determinations for the February 8–9, 1996, flood were made indirectly and rated "fair"—indicating possible error in the range from 15 to 25 percent or greater (Benson and Dalrymple, 1967, p. 30).

The third source of error to be discussed is the deficiencies of the conceptual and SSARR models to represent the hydrologic process in the Puyallup River Basin. The model makes abstract, one-dimensional simplifications of the natural system in order to simulate runoff process using the limited amount of information describing the

watershed. Model error can be expected to increase with each simplification of the natural system, but this must be balanced against having too complex a model. Too much information may add little to accuracy, while at the same time add excessive data requirements and parameters that will overload a modeling system designed for real-time use. For this project, the SSARR model seems to have the appropriate balance of complexity and simplicity to efficiently simulate the runoff process according to the conceptual model outlined earlier. For example, a lot of detail is provided to adjust the precipitation input, a major source of error, to subdivisions (snowbands) of a subbasin based on precipitation-elevation relations—the dominant factor affecting precipitation amounts in the basin. On the other hand, the SSARR model is less rigorous than other available models in the details of the runoff process for different land types. For this project, even if a more "rigorous" model were needed, there is little discharge information available to calibrate the model according to different land types in the Puyallup River Basin. Also, this model deficiency is not crucial to the success of the simulations because the upper parts of the basin that contribute most to runoff consist of a relatively homogenous forested landscape or land type (although there are some differences in the degree of clearcutting). In addition, during major flood-producing storms in Western Washington, which are characterized by days and even weeks of preceding rain, the soils of all land types have generally reached or nearly reached their moisture holding capacity, and differences in peak runoff from different land types are less apparent.

Table 12. Observed storm precipitation totals at Nevan-McCullough Seed Orchard Meteorological site and estimated 8-day precipitation totals for snowband 3, subbasin UPWHT, calculated from three different pairs of precipitation stations

		Station pairs[1]								
		Nevan-McCullough and Buck Creek			Greenwater and Buck Creek			Greenwater and Electron		
		Esti-mated[4]	Difference[5]		Esti-mated[4]	Difference[5]		Esti-mated[4]	Difference[5]	
Storm number[2]	Ob-served[3]		(inches)	(percent)		(inches)	(percent)		(inches)	(percent)
1	6.67	6.72	+0.05	+ 0.78	6.51	-0.16	- 2.35	7.09	+0.42	+ 6.28
2	3.16	3.63	+0.47	+14.81	5.02	+1.86	+58.88	5.47	+2.31	+73.13
3	3.26	3.33	+0.73	+ 2.08	3.73	+0.47	+14.36	4.22	+0.96	+29.45
4	10.55	10.35	-0.20	- 1.90	10.69	+0.14	+ 1.34	14.21	+3.66	+34.70
5	2.70	2.38	-0.32	-11.97	2.86	+0.16	+ 5.95	3.80	+1.10	+40.85
6	8.81	9.35	+0.54	+ 6.12	9.44	+0.63	+ 7.16	11.38	+2.57	+29.22
	Range:		1.05	26.78		2.02	61.23		3.24	66.85

[1]Pair of stations used to estimate precipitation totals, full station names and number (in parenthesis) are listed below:
Greenwater—Greenwater River at Greenwater (12097500)
Buck Creek—Buck Creek Camp Meteorological Site near Greenwater (47011813121330800)
Electron—Puyallup River near Electron (12092000)
Nevan-McCullough—Nevan-McCullough Seed Orchard Meteorological site near Greenwater (470418121351200).

[2]The dates for the numbered storms are as follows:
Storm No. 1   10-27-94 to 11-03-94
Storm No. 2   10-26-94 to 12-03-94
Storm No. 3   02-15-95 to 02-22-95
Storm No. 4   11-25-95 to 12-02-95
Storm No. 5   01-04-96 to 01-11-96
Storm No. 6   02-05-96 to 02-12-96.

[3]Observed 8-day precipitation total, in inches, for the shielded rain gage at Nevan-McCullough Seed Orchard Meteorological site.

[4]Estimated precipitation total, in inches, computed by the Puyallup River Basin model using indicated pair of precipitation records.

[5]Difference between estimated and observed precipitation totals.

A goal of the project was to minimize model errors while providing an efficient operational system to make flood simulations on a real-time basis. The SSARR model proved to have the flexibility and the appropriate algorithms to simulate peak discharges with some bias for the eight storms and require only two time series inputs—precipitation and temperature. Given the errors outlined above, the greatest opportunity to reduce error in this project and other similar projects appears to be the addition of more precipitation gages in the basin, especially in the midelevations (approximately 2,000 to 4,000 feet above sea level), where high precipitation rates (70 to 90 inches per year) and the high potential for snowmelt contributions to flood runoff are important for producing floods.

Sensitivity Analysis of Precipitation and Temperature Inputs and Snow-water Equivalence on Simulated Discharge

Three groups of simulations were performed to evaluate the effects of using precipitation inputs from different precipitation stations, of using different numbers of temperature station inputs, and of the accuracy of simulated snow-water equivalence on simulated runoff volumes and peak discharge.

Influence of Precipitation Inputs on Simulated Results

Rain-gage records frequently contain missing data or faulty data. The operational system for the Puyallup River Basin model has been set up to function when precipitation records from some sites are missing or unusable; however, different combinations of precipitation data will produce different simulated discharges. A test was made to show the effects on simulated discharges using regional (NWS-operated stations—some are outside the basin boundaries) and local (USGS-operated stations—all within the basin boundaries) precipitation inputs and different groupings of precipitation inputs from different precipitation stations. The tests were made using data from the two largest flood-producing storms in the 1996 water year. Six different combinations of precipitation inputs were used to simulate six sets of peak discharges and 5-day runoff volumes from the four upper subbasins where runoff was observed during two storms (table 13). In these simulations, subbasin precipitation was computed using equation 1. Precipitation weights were not used to adjust the computed subbasin average precipitation.

The sensitivity analysis showed that simulated peak discharge can be extremely sensitive to the precipitation inputs. Simulations using different regional or local pairs of precipitation inputs produce broad ranges of peak discharges and runoff volumes. These ranges are of similar magnitude to the errors obtained using the calibrated model. These results underscore the importance of having complete precipitation records, a dense network of rain gages, and heated tipping-bucket rain gages (or another cold temperature, precipitation-recording system) in the snow zone. Upgrading unheated rain gages in the current network for the Puyallup River Basin, especially those gages in the higher elevations, would produce a system that can accurately record precipitation when it is snowing.

Influence of the Number of Temperature Inputs on Simulated Results

Early in this study it was decided that four temperature stations would be used for the real-time runoff simulations instead of the seven available temperature stations. The smaller number of stations would lessen the data-input and data-checking requirements, and the stations not used were within the elevation range of the four stations that were used. It was believed that the addition of more temperature information would not significantly improve the estimation of lapse rates or the temperature distribution. A test comparing the simulated runoff using different sets and numbers of temperature stations was conducted to show how the number of temperature inputs affects simulation results. The test used the two largest runoff-producing storms during the data-collection period—the November 1995 storm and the February 1996 storm. Four sets of model runs using data from four sets of temperature stations were made (table 14). The Carbon temperature station had too much missing record during both storms to be used in this test.

The results of the temperature station sensitivity test indicated that errors in simulated peak discharge and runoff volume are larger when two temperature records are used than when four are used. All the error totals for model runs using Input 3 and Input 4 (which used only two temperature stations) were larger than the errors for the calibrated model (Input 1) except for one runoff volume total using Input 4. Also the individual peak discharges and runoff volumes for model runs using Input 3 and Input 4 differed significantly from each other, indicating that the model is sensitive to the pair of stations chosen as well as to the number of stations. There are insufficient numbers of stations to evaluate the effect on model accu-

racy of increasing the number of temperature stations from four to six. However, the results in table 14 indicate that including more temperature stations would not significantly improve the accuracy of the calibrated model. While the results from Input 2 (six temperature stations used) showed some tendency to reduce the errors, the sum of the peak discharge errors for the February storm was about double the errors for the calibrated model.

Influence of Simulated Snow-water Equivalence on Simulated Runoff

An analysis of the importance of pre-storm SWE on simulated peak discharge and runoff volume was performed using data from only the February 1996 storm. The following three scenarios were tested: (1) assume zero SWE in the basin at the beginning of the day on February 5, 1996, the approximate beginning of the storm; (2) increase the simulated SWE in each elevation band by 30 percent on February 5; and (3) decrease the simulated SWE in each elevation band by 30 percent on February 5. To perform the tests, the calibrated watershed model was stopped on February 4 at midnight, and the SWE values were adjusted as described for the three scenarios. The model was restarted, run through the end of the day on February 8, and the results were compared with the results of calibrated model run (table 15).

The results of these simulations of one storm in which snowmelt probably had a greater than average contribution to runoff showed that decreasing SWE has a much larger effect than increasing SWE (table 15). Increasing SWE by 30 percent increased simulated runoff volume and peak discharge by only 1.2 percent or less. Decreasing SWE by 30 percent and 100 percent (zero SWE) decreased simulated runoff volume by up to 5.7 and 12.9 percent, respectively, and decreased peak discharge by up to 5.6 and 11.2 percent, respectively. The effect of simulated SWE on simulated runoff volumes and peak discharges may be different for other storms, especially those storms during which snowmelt is not a major contribution to runoff.

Model Limitations

Because of the time and data constraints of this project, many of the hydrologic scenarios that are possible in the Puyallup River Basin were not observed or simulated, so several major limitations of the model are summarized here.

1. Only four water years of data (1994–97), the time period that the current network of gages has operated, were used to select eight storms for calibration and validation of the model. With more observed data, a larger range of conditions would be available to calibrate and test the model. Storms that have different precipitation totals, different initial snow extents, different temperature regimes, and other such variables may result in errors that fall outside the range of errors experienced during this calibration and validation.

2. Only one storm, February 1996, had basin-wide estimates of snow-water equivalent available for calibration of the snow-related parameters; therefore, the calibration of these parameters was limited. Much more observed snow data or accurate estimates of snow-water equivalent would probably result in different and more reliable snow-related parameters for the simulation of snowmelt and accumulation.

3. The calibrations focused on two observed runoff statistics, peak-flow discharge and 5-day runoff volumes for major high-water events. Using the model to simulate baseflow or low flows or monthly and yearly water balances would not be valid within the error analysis provided. Glacial meltwater, which can comprise a major portion of summer flows, is not explicitly modeled.

4. The limited calibration of the river reaches was made with observed flows that were contained within the natural or man-made levees. The model cannot accurately simulate flows that breach levees, river banks, or dams.

5. No calibration or error analysis was done for the forecast model runs because the format, availability, and location of forecast points have changed several times throughout the life of this project. It has been shown that the accuracy and the number of precipitation inputs strongly influence the accuracy of the simulation of peak discharge and runoff volumes. The results of the real-time model using forecasted input data probably does not fall within the errors experienced during calibration and validation and would most likely have a larger range of errors.

Table 13. Simulated discharge at four upper Puyallup subbasins, Washington, for two storms in water year 1996 using different combinations of precipitation inputs

[Precipitation inputs were computed using the stations listed below and the method described in the text section "Computation of Subbasin Precipitation."]

Regional precipitation inputs
(National Weather Service-operated stations)[1]

| | Peak discharge, in cubic feet per second | | | | | Runoff volume per unit area, in inches | | | | |
| | | Simulated | | | Percent range[2] | | Simulated | | | Percent range[2] |
Subbasin	Observed	Input 1	Input 2	Input 3		Observed	Input 1	Input 2	Input 3	
Storm date: 11-27-95 to 12-01-95										
Upper Puyallup	13,600	8,740	8,280	12,200	28.8	7.24	4.28	5.11	5.07	11.5
Greenwater	4,240	6,160	6,390	8,230	48.8	6.19	5.95	7.63	7.38	27.1
Carbon	10,100	6,020	6,250	7,760	17.2	10.66	5.79	7.22	7.10	13.4
South Prairie	4,860	4,460	4,950	6,030	32.3	5.21	5.36	6.66	6.22	25.0
Storm date: 02-07-96 to 02-11-96										
Upper Puyallup	18,300	19,600	13,200	17,200	35.0	7.38	6.07	5.54	5.91	7.2
Greenwater	5,900	11,400	8,750	10,400	44.9	6.48	8.50	8.13	8.30	5.7
Carbon	12,000	10,800	8,420	9,740	19.8	11.33	7.33	7.06	7.08	2.4
South Prairie	8,170	9,270	7,290	8,150	24.2	7.83	7.80	7.26	7.73	6.9

Local precipitation inputs
(U.S. Geological Survey-operated stations)

| | Peak discharge, in cubic feet per second | | | | | Runoff volume per unit area, in inches | | | | |
| | | Simulated | | | Percent range[2] | | Simulated | | | Percent range[2] |
Subbasin	Observed	Input 4	Input 5	Input 6		Observed	Input 4	Input 5	Input 6	
Storm date: 11-27-95 to 12-01-95										
Upper Puyallup	13,600	7,780	11,300	7,320	29.3	7.24	5.54	5.60	5.09	7.0
Greenwater	4,240	5,290	5,510	4,960	13.0	6.19	6.70	7.74	7.00	16.8
Carbon	10,100	5,470	5,810	5,170	6.3	10.66	7.63	7.45	6.89	6.9
South Prairie	4,860	4,390	6,110	4,490	35.4	5.21	7.26	7.24	6.67	11.3
Storm date: 02-07-96 to 02-11-96										
Upper Puyallup	18,300	19,800	11,900	18,800	43.2	7.38	7.08	6.06	6.59	13.8
Greenwater	5,900	7,700	8,180	11,500	64.4	6.48	8.30	8.92	9.62	20.4
Carbon	12,000	11,000	7,540	10,800	28.8	11.33	8.56	7.37	8.32	10.5
South Prairie	8,170	9,610	6,650	9,390	33.5	7.83	9.05	8.10	8.60	12.1

[1]The normal annual precipitation, in inches, used in the computation for the National Weather Service-operated stations are shown below in parentheses:

    Input 1 = Seattle TCOMA WSCMO AP (37.6) and Mud Mountain Dam (53.16).
    Input 2 = Mud Mountain Dam and Snoqualmie Pass (103.16).
    Input 3 = Seattle TCOMA WSCMO AP and Snoqualmie Pass.
    Input 4 = Buck Creek, South Prairie, White River Canal, Electron, and Greenwater.
    Input 5 = Buck Creek and Electron, and
    Input 6 = Greenwater and South Prairie.

[2]Percent range is the range of percentages that are calculated by the following formula: $\dfrac{\text{simulated peak discharge}}{\text{observed peak discharge}} \times 100$.

Table 14. Simulated discharge at four upper Puyallup subbasins, Washington, for two storms in water year 1996 using different combinations of temperature inputs

Peak discharges

Simulated peak discharge, in cubic feet per second[1]

Subbasin	Observed discharge	[2]Input 1	Error[4]	[3]Input 2	Error[4]	[2]Input 3	Error[4]	[2]Input 4	Error[4]
Storm date: 11-27-95 to 12-01-95									
Upper Puyallup	13,600	11,300	2,300	12,200	1,400	9,830	3,770	10,300	3,300
Greenwater	4,240	3,710	530	4,290	50	2,930	1,320	4,470	230
Carbon	10,100	7,070	3,030	7,980	2,120	5,940	4,160	6,350	3,750
South Prairie	4,860	5,830	970	5,770	910	5,000	140	5,630	770
Sum of errors			6,830		4,480		9,380		8,050

Simulated peak discharge, in cubic feet per second[1]

Subbasin	Observed discharge	[2]Input 1	Error[4]	[3]Input 2	Error[4]	[2]Input 3	Error[4]	[2]Input 4	Error[4]
Storm date: 02-07-96 to 02-11-96[5]									
Upper Puyallup	18,300	19,800	1,500	21,100	2,800	15,200	3,100	23,300	5,000
Greenwater	5,900	5,660	240	5,740	160	2,050	3,850	6,200	300
Carbon	12,000	13,100	1,100	14,800	2,800	8,760	3,240	16,800	4,800
South Prairie	8,170	8,110	60	8,410	240	8,940	770	9,430	1,260
Sum of errors			2,900		6,000		10,960		11,360

Runoff volumes

Simulated storm runoff, in inches[1]

Subbasin	Observed runoff	[2]Input 1	Error[4]	[3]Input 2	Error[4]	[2]Input 3	Error[4]	[2]Input 4	Error[4]
Storm date: 11-27-95 to 12-01-95									
Upper Puyallup	7.24	5.60	1.64	5.81	1.43	5.31	1.93	5.43	1.81
Greenwater	7.12	5.13	1.99	5.51	1.61	4.64	2.48	5.61	1.51
Carbon	10.66	8.80	1.86	9.30	1.36	8.29	2.37	8.52	2.14
South Prairie	5.21	6.58	1.37	6.57	1.36	6.17	0.96	6.44	1.23
Sum of errors			6.86		5.76		7.74		6.68

Simulated storm runoff, in inches[1]

Subbasin	Observed runoff	[2]Input 1	Error[4]	[3]Input 2	Error[4]	[2]Input 3	Error[4]	[2]Input 4	Error[4]
Storm date: 02-07-96 to 02-11-96[5]									
Upper Puyallup	7.24	5.60	1.64	5.81	1.43	5.31	1.93	5.43	1.81
Greenwater	7.12	5.13	1.99	5.51	1.61	4.64	2.48	5.61	1.51
Carbon	10.66	8.80	1.86	9.30	1.36	8.29	2.37	8.52	2.14
South Prairie	5.21	6.58	1.37	6.57	1.36	6.17	0.96	6.44	1.23
Sum of errors			6.86		5.76		7.74		6.68

[1]Temperature stations used for the various input:
    Input 1 = Electron, Cayuse Pass, South Prairie, and Buck Creek (calibrated model),
    Input 2 = Electron, Cayuse Pass, South Prairie, Buck Creek, Greenwater, and White River Canal,
    Input 3 = Electron and Buck Creek, and
    Input 4 = South Prairie and Cayuse Pass.

[2]The matrixes that determine which pairs of temperature data sets to use to compute lapse rates and subbasin temperatures during a model run are defined in table 6 for input sets 1, 3, and 4.

[3]Input 2 used three temperature data sets to compute subbasin temperature using White River Canal as the third station for the upper Puyallup, South Prairie as the third station for the Carbon subbasin, and Greenwater as the third station for the Greenwater Basin.

[4] $Error = ABS(S - O)$,
where ABS is the absolute value, S is the simulated value, and O is the observed value.

[5]The Electron temperature data were not used during the February storm because of missing data and were substituted with either the South Prairie or the Buck Creek data.

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Table 15. Storm runoff and peak discharge for February 5–9, 1996, from four model runs that show the model's sensitivity to pre-storm snow-water equivalent for four upper subbasins in the Puyallup River Basin, Washington

[SWE, snow-water equivalent; RO, storm runoff per unit area; ft³/s, cubic feet per second]

Subbasin	Calibrated model[1]		Zero-SWE model[2]				Plus-30-percent model[3]				Minus-30-percent model[4]			
	5-day RO (inches)	Peak discharge (ft³/s)	5-day RO (inches)	Percent difference[5]	Peak discharge (ft³/s)	Percent difference[5]	5-day RO (inches)	Percent difference[5]	Peak discharge (ft³/s)	Percent difference[5]	5-day RO (inches)	Percent difference[5]	Peak discharge (ft³/s)	Percent difference[5]
Greenwater	6.26	5,620	6.13	(-2.1)	5,500	(-2.1)	6.33	(1.1)	5,670	(0.9)	6.26	(0.0)	5,550	(-1.2)
Upper Puyallup	7.02	19,700	6.27	(-10.7)	17,500	(-11.2)	7.04	(0.3)	19,800	(0.5)	6.76	(-3.7)	18,600	(-5.6)
Carbon	9.94	13,100	9.16	(-7.8)	12,300	(-6.1)	9.96	(0.2)	13,100	(0.0)	9.65	(-2.9)	12,800	(-2.3)
South Prairie	7.83	8,090	6.82	(-12.9)	7,290	(-9.9)	7.90	(0.9)	8,190	(1.2)	7.38	(-5.7)	7,650	(-5.4)

[1]Calibrated model refers to the results from the final calibration model.

[2]Zero-SWE model is the same as the calibrated model except that all snow-water equivalent values in all the elevation bands in the four subbasins were set to zero inches at the beginning of February 5, 1996, and then the model was run for 5 days.

[3]Plus-30-percent model is the same as the calibrated model except that all snow-water equivalent values in all the elevation bands in the four subbasins were increased by 30 percent at the beginning of February 5, 1996, and then the model was run for 5 days.

[4]Minus-30-percent model is the same as the calibrated model except that all snow-water equivalent values in all the elevation bands in the four subbasins were decreased by 30 percent at the beginning of February 5, 1996, and then the model was run for 5 days.

[5]Percent difference from the calibrated model's simulated value.

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REAL-TIME SIMULATION

A main objective of this project was to build an operational model and data processing system capable of being operated by PCRI's personnel and of making real-time simulations of flood discharges and stages in the Puyallup River Basin. This section provides an overview of the Puyallup Flood-Alert System, a description of the general procedure users would follow to make a simulation, and an example of a real-time simulation.

Overview of the Puyallup Flood-Alert System

The Puyallup Flood-Alert System is composed of three parts: (1) the network of hydrologic and meteorologic gages and the accompanying data-telemetry and data-management system; (2) the computer interface (SSARRMENU) between PCRI personnel and numerical model (SSARR); and (3) the SSARR model, including its data-management component—the BULK file.

The Flood-Alert System begins in the field at the streamflow and meteorological gaging stations that provide the raw data for the system. Precipitation, temperature, river stage, and river discharge data are relayed to the USGS office in Tacoma by satellite telemetry every 4 hours during normal conditions and once every 15 minutes during alert mode. Data are received and stored on the USGS Washington District computer network and managed by the USGS Automated Data Processing System (ADAPS). Next, the data are transferred via telephone lines to a PC in the PCRI office as WATSTORE-formatted (National Water Data Storage and Retrieval System) files (fig. 2).

The computer interface, SSARRMENU, has several functions. First, it reviews data for values that have exceeded predetermined threshold values (table 16) and displays flashing alert symbols on a map display of the Puyallup River Basin (fig. 15). Second, it provides graphs of the available hydrologic and meteorologic data at user-selected stations and of simulated values of river stage and discharge. Third, it allows users to initiate a data transfer from the ADAPS system to the BULK file located on the PC, reformatting the data from WATSTORE format to SSARR format. During this data transfer, records of subbasin precipitation are created from the user-selected station precipitation records. And finally, SSARRMENU is a user interface to the SSARR model enabling users to make model runs easily.

Table 16. Threshold values for alert status for the Puyallup Flood-Alert System, Washington

[ft^3/s, cubic feet per second]

Variable	Station name	Threshold value[1]	
Stage	White River near Auburn	80.0	feet
Stage	Puyallup River at Alderton	53.0	feet
Discharge	Puyallup River at Puyallup	17,000	ft^3/s
Discharge	Puyallup River near Orting	4,000	ft^3/s
Stage	Carbon River at Orting	27.0	feet
Discharge	Carbon River near Fairfax	3,500	ft^3/s
Discharge	White River below Clearwater River	7,090	ft^3/s
Lake stage	Mud Mountain Lake	1,092.0	feet
Stage	White River at Williams Bridge	47.80	feet
Discharge	South Prairie Creek	2,500	ft^3/s
Stage	White River near Buckley	7.10	feet
Discharge	Greenwater River at Greenwater	1,300	ft^3/s
24-hour precipitation	Buck Creek Meteorological Site	3.0	inches
6-hour precipitation	Buck Creek Meteorological Site	1.4	inches

[1]If this value is exceeded, the station is on alert.
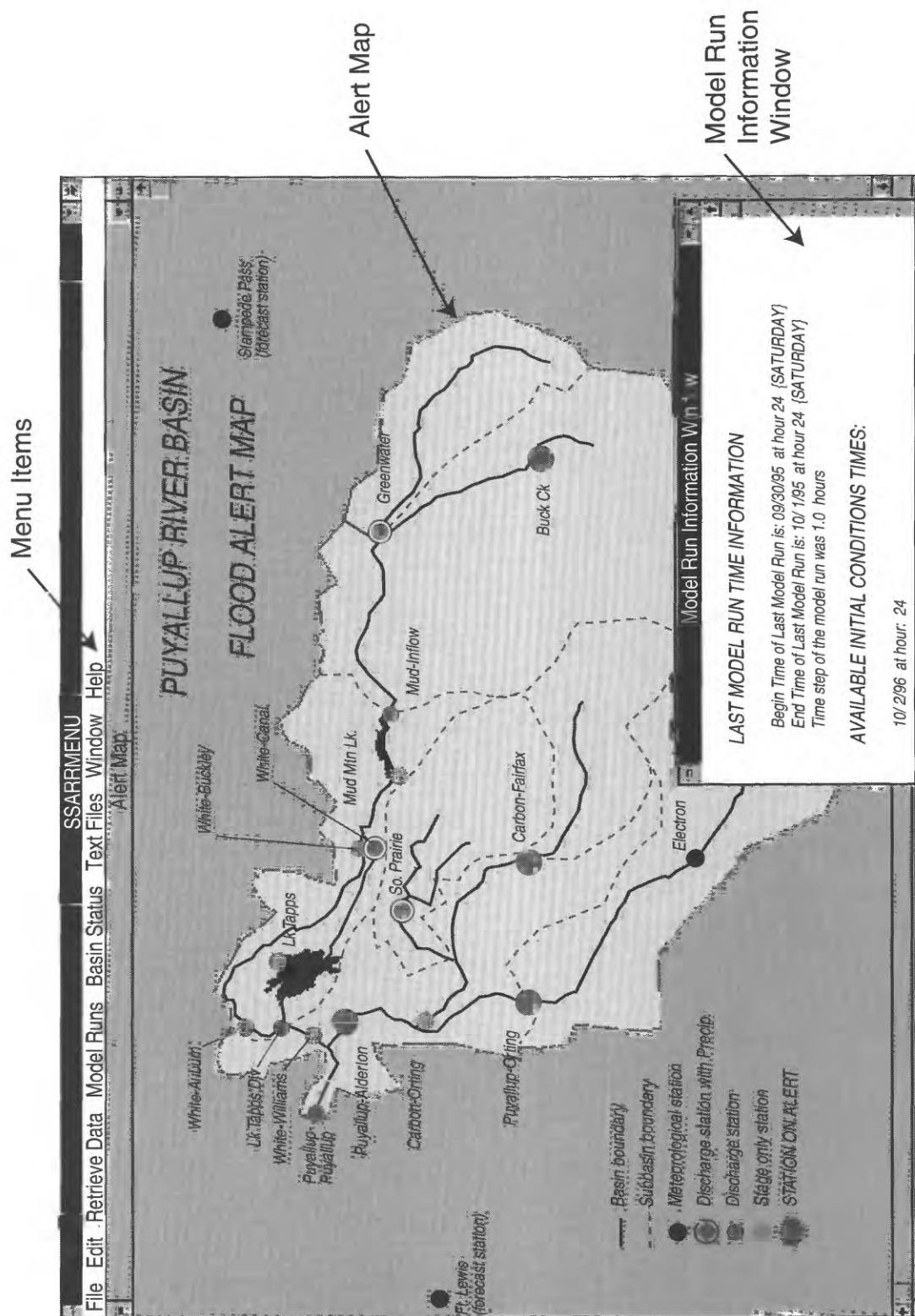
Figure 15. Computer screen display of the Puyallup River Basin, Washington, flood-alert map from the SSARRMENU program showing menu items, alert map, and model run information window.

User Interface for Real-time Simulation—SSARRMENU

SSARRMENU is a FORTRAN90 computer program that provides a graphical interface for the Puyallup Flood-Alert System. It was written for a Microsoft Windows NT system and contains windows applications that include drop-down menus accessed with a mouse click, dialog boxes to solicit user input, graphical displays, and plotting routines for making time-series plots of observed and simulated data. A Microsoft MS-DOS and Windows 3.1 version of the program is also available. It operates in a similar manner, but uses a simple user interface composed of batch files and FORTRAN77 programs and the PLOTIODC program that is distributed with the PC version of SSARR for making time-series plots.

The Windows NT version of SSARRMENU contains several of the default Microsoft menus— file, edit, window, and help—that are common to many window-application programs and that allow users to exit the program, organize the windows, display information about the Microsoft menus, select text, select graphics, make prints of graphics and text, and so on. The remaining menus are related to running the Puyallup Flood-Alert System. Figure 16 is a schematic of these menus in the order they appear on the computer screen and a short description of their functions.

General Procedure for using SSARRMENU

To make model runs with SSARRMENU, users should follow the general order and procedures outlined below.

1. Initialize the model with the model characteristics and initial discharges in the simulated river reaches beginning on October 1 of the water year being modeled.

2. Retrieve data by telnet from the USGS computer. A Perl script is used to retrieve all the stage, discharge, temperature, and precipitation data from the ADAPS program as WATSTORE-formatted files. Users are prompted for the dates of the data retrieval and whether to use a 1-hour time step (storm mode) or a 6-hour time step (backup mode) between data values.

3. Convert the stage, temperature, and discharge data to SSARR-formatted files and load into the BULK file. Users are prompted by SSARRMENU to select the Mud Mountain Lake stage or the combined discharge of White River at Buckley and White River Canal at Buckley to simulate regulated outflow at Mud Mountain Lake. The program provides the option to produce time-series graphs of both sets of data before users need to make a choice.

4. Select precipitation stations that are deemed unusable and eliminate them from the data input. Station records of precipitation are converted into SSARR-formatted subbasin records of precipitation and loaded into the BULK file. A program menu item is available for plotting the precipitation data in order to assess their quality.

5. Make a SSARR model run. The SSARRMENU program uses dialog boxes to prompt users for the begin time, the end time, the time-step, and the temperature records. The program makes a plot of the temperature time-series data so that users can assess the quality of the data before deciding to eliminate a temperature record. All model runs made after the first model run of the water year should begin exactly at the end time of a previous model run; the hydrologic state of the simulated watershed values and river-reach discharges are saved by the SSARR model for use as the initial conditions for the next model run. SSARRMENU provides a "Model Run Information Window" that gives the dates and times of the stored conditions at the ends of prior model runs.

6. Review the results of the simulation by making selected plots of the simulated data against available observed data or as text files of stage and discharge.

7. Run backup model runs (6-hour time step) periodically to keep the model current and determine if the simulations are significantly deviating from observed discharges. If a significant deviation is found, use an "adjust" model run with the 6-hour time step option to adjust user-selected subbasins. The adjust model run is made with the same start and end times as the last model run.

8. Adjust the simulated discharge values, if needed, to more closely agree with observed discharge values prior to making a forecast model run. If the simulated data do not produce a good match with the observed discharge, the initial conditions for the forecast model run may be in error. Typically, an "adjust" model run begins a day or two before the anticipated start time of the forecast model run and ends exactly on the start time of the forecast model run. Users are prompted for each of the five gaged subbasins that need adjustment, and then the

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                    ┌─────────────────┐
                    │   SSARRMENU     │
                    └─────────────────┘
                             │
     ┌────────────────┬──────────────┬──────────────────┐
┌──────────────┐ ┌──────────────┐ ┌──────────────┐ ┌──────────────┐
│ Retrieve Data│ │  Model Runs  │ │ Basin Status │ │  Text Files  │
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       │                │                │                │
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│  Pick Plot   │ │  Initialize  │ │  SMI plots   │ │ Select Data Files│
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│Load (Telenet)│ │    Adjust    │ │  Prec. Plots │ │   Log File   │
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│Data Conversion│ │ Forecast Run │ │  Water Bal.  │
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│ Plot Precip. │
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│Prec. Sta. Select│
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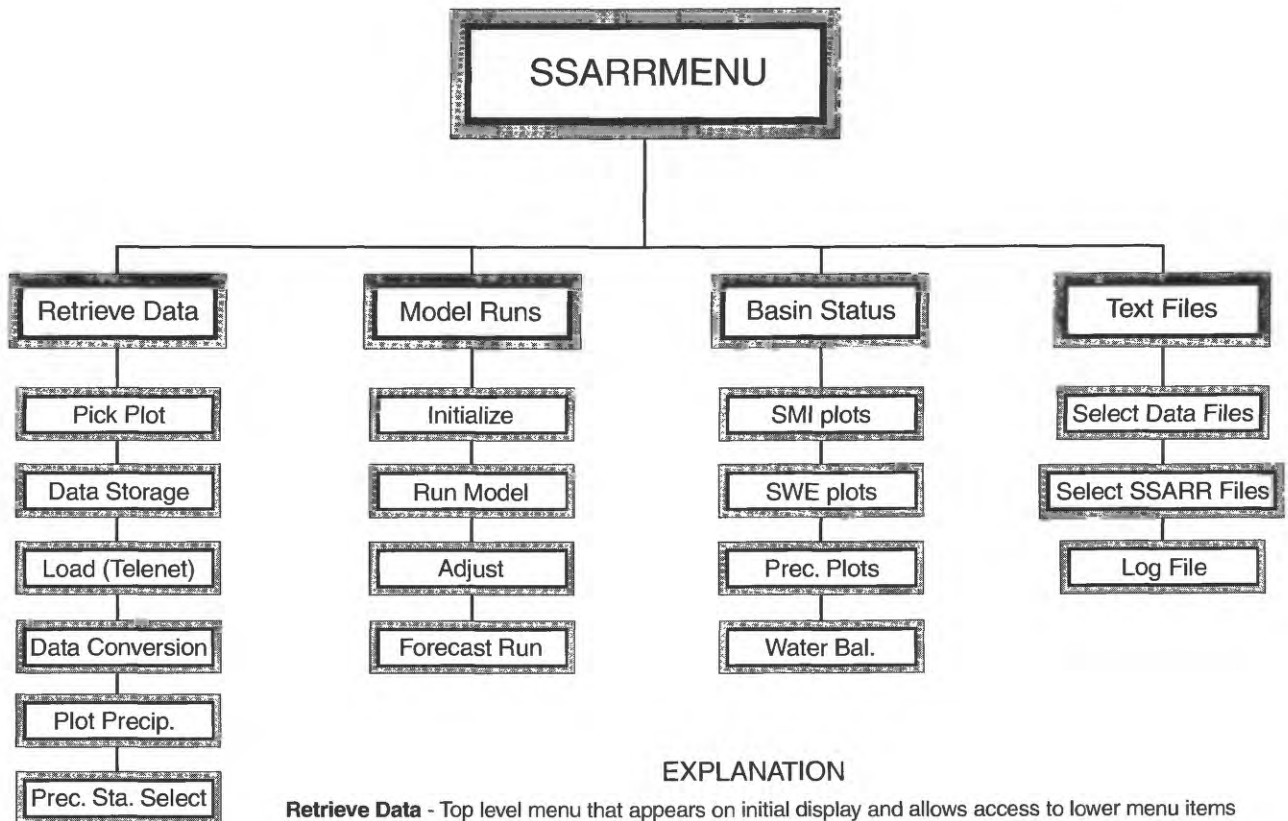
EXPLANATION

Retrieve Data - Top level menu that appears on initial display and allows access to lower menu items
  Pick-Plot - allows the user to select a station by mouse input on the flood-alert map for making time-series plots of simulated and observed data
  Data Storage - initiates the Bulkmain.exe program to view the contents of the BULK file
  Load (Telenet) - initiates the Telnet program to retrieve data from ADAPS
  Data Conversion - converts WATSTORE-formatted data to SSARR-formatted data and loads them into the BULK file
  Plot Precip. - plots precipitation data
  Prec. Sta. Select - brings up a dialog box for user to select the precipitation stations to use in the current model run
Model Runs - Top level menu that appears on initial display and allows access to lower menu items
  Initialize - initializes the SSARR model at the beginning of the water year
  Run Model - makes·SSARR model run
  Adjust - makes automated adjustments of simulated discharge to observed discharge for the most recent model run
  Forecast Run - make a forecast model run
Basin Status - Top level menu that appears on initial display and allows access to lower menu items
  SMI Plots - plots soil moisture index for selected subbasins
  SWE Plots - plots simulated snow-water equivalence for selected subbasins
  Prec. Plots - plots mean annual precipitation or the 10-year, 24-hour precipitation frequency maps for the basin
  Water Bal. - plots selected simulated subbasin water-balance components of runoff for the last model run
Text Files - Top level menu that appears on initial display and allows access to lower menu items
  Select Data Files - view hydrologic and meteorologic data files
  Select SSARR Files - view SSARR-related files
  Log File - view log file of model runs

Figure 16. Schematic and description of menu items for SSARRMENU.

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automated adjustment procedures corrects the simulated hydrograph to agree with the observed hydrograph. At the end of the model run the hydrologic conditions of the basin are saved for use as the initial conditions of the forecast model run.

9. Download the quantitative temperature forecasts for Stampede Pass and Fort Lewis, the two nearest forecast points for the NWS meteorological forecast models, and the quantitative precipitation for Enumclaw, Ohanapecosh, and Stampede Pass from the NWS into the PC as three files into the data directory, SMP.WMO for the Stampede Pass temperature data, GRF.WMO for the Fort Lewis temperature data, and SEA.QPF for the precipitation data (table 17). These data are available at a 6-hour time step for 54 hours. SSARRMENU reformats the data, adjusts the characteristic file for the Puyallup River Basin model for the forecast data, and makes the forecast run with 6-hour time steps. Results are presented as time-series graphs of simulated hydrographs and as text files of discharge and stage.

Example of a Real-Time Simulation

Figure 17 provides results from a typical sequence of model runs in storm mode that demonstrate the automated adjust capability and the type of results that can be obtained for a forecast model run. Late in the day on December 31, 1996, the Puyallup River still had high flows from a recent peak flow on December 29, and the forecast for the next day was for more rain. There was serious concern that flooding would occur the next day, on January 1. Early on the New Year's Day, a model run was made, and the hydrograph for the upper Puyallup subbasin showed significant differences between the observed and simulated discharges (fig. 17, top hydrograph). Because it was known in advance that a forecast model run would be needed, the necessary precipitation and temperature data files were retrieved from the Seattle NWS office, and the start time for the forecast was noted. (In this example, forecasted precipitation for NWS station SeaTac was substituted for Fort Lewis, which was not available.) A model run begun at midnight on December 28 was ended on December 31 at 10:00 p.m., the time when the forecast data began, so that the model would store the initial conditions for the start of the forecast run. At this point the large discrepancy between the observed and simulated discharge at the end time signaled a need to make an adjustment for this particular subbasin. The model was rerun with the same start and end times, and the simulation was adjusted for the upper Puyallup River Basin (fig. 17, middle hydrograph). Since the simulation was underestimating discharge, the model automatically increased the amount of subbasin precipitation from 6.61 inches computed for the original model run to 8.48 inches for the adjust model run. The adjust run increased the simulated peak on December 29, which was already overestimating the observed peak; but the initial conditions for the forecast run were corrected to agree closely with the observed record late on December 31, and the forecast model run was given a much better starting point to more accurately forecast the peak flow on January 1. In this case the forecast model run made a more accurate prediction of the peak discharge than a model run made after the flood, when actual precipitation recorded in the basin was used as model input (fig. 17, bottom hydrograph). The forecasted precipitation total at SeaTac Airport was 1.87 inches, and the observed rainfall for the same period was 2.33 inches (U.S. Department of Commerce, 1977). The forecasted precipitation total at Stampede Pass was 2.52 inches, but no observed precipitation data for Stampede Pass were available for this period for comparison.

Table 17. Example of the quantitative precipitation file, SEA.QPF, and temperature forecast file, GRF.WMO, from the National Weather Service for use in the Puyallup River Basin model, Washington

SEA.QPF

```
ZCZC SEAQPSSEA
ÅTTAA00 KSEA 071249
:FN 10:
:.....INTERNAL NWS PRODUCT FOR GUIDANCE PURPOSES ONLY.............
:
.B SEA 0208¹ DC110712
.B1          /DH18/PPQFZ /DRH+06/PPQFZ/DRH+12/PPQFZ/DRH+18/PPQFZ
.B2          /DRH+24/PPQFZ/DRH+30/PPQFZ/DRH+36/PPQFZ/DRH+42/PPQFZ
.B3          /DRH+48/PPQFZ/DRH+54/PPQFZ/DRH+60/PPQFZ/DRH+66/PPQFZ   :
:.....FORECAST PRECIPITATION (INCHES)...........................:
:
     **UPDATES- LEAVE PAST DATA AS ORIGINALLY FORECAST.          :
:
     DAY1-------------> DAY2--------------> DAY3------------->:
      ²06Z 12Z 18Z 00Z  06Z 12Z 18Z 00Z  06Z 12Z 18Z 00Z
UIL    .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
ABEW1  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
FRAW1  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
GLAW1  .05/ .05/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
MARW1  .10/ .10/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
VERW1  .05/ .05/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
SKYW1  .05/ .05/ .00/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
SEA    .05/ .00/ .00/ .00/  .00/ .00/ .00/ .00/ '.00/ .00/ .00/ .00
ENUW1³ .05/ .75/ .75/ .60/  .20/ .00/ .00/ .00/  .00/ .00/ .00/ .00
SMP⁴   .10/ .75/ .75/ .75/  .18/ .00/ .00/ .00/  .00/ .00/ .00/ .00
OHAW1⁵ .10/ .80/ .70/ .80/  .30/ .00/ .00/ .00/  .00/ .00/ .00/ .00
CINW1  .10/ .05/ .05/ .00/  .00/ .00/ .00/ .00/  .00/ .00/ .00/ .00
```

GRF.WMO

```
FOUS14 KWBC 071200
GRF⁶  W    NGM MOS  GUIDANCE   02/08/96   0600 UTCDAY
 /NOV   7                /NOV   8                    /NOV   9            /
HOUR  ²06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 18 21
MN/MX                    41                53                34                 58
TEMP⁷ 50 51 51 49 47 48 49 47 45 43 42 39 43 47 48 39 34 32 31
DEWPT 46 45 46 46 44 43 42 41 44 44 42 40 37 36 34 34 40 39 37
CLDS  OV OV OV BK OV OV OV OV BK SC SC CL CL CL CL CL CL CL CL
WDIR  18 23 32 00 14 00 00 00 00 02 00 00 00 00 00 00 00 00 00
WSPD  03 05 04 00 01 00 00 00 00 01 00 00 00 00 00 00 00 00 00
POP06       40    37    23    13    0    0    0    0    0
POP12             42          10          0          0
QPF        0/    0/    0/0    0/    0/0    0/    0/0    0/    0/0
TSV06      5/ 0  1/ 0  0/ 1  0/ 0  0/ 2  0/ 0  0/ 0  0/ 0  0/ 0
TSV12            5/ 0         0/ 0         0/ 2         1/ 0
PTYPE  R  R  R  R  R  R  R  R  R  R  R     R     R     R     R
POSN   0  0  0  0  0  1  1  0  0  0  0     0     0     0     0
SNOW       0/    0/    0/0    0/    0/0    0/    0/0    0/    0/0
CIG    4  4  5  5  5  5  4  3  7  7  7     7     7
VIS    4  5  5  5  4  4  4  3  5  5  5     5     5
OBVIS  F  N  N  N  F  F  F  F  N  N  N     N
```

¹Start date.

²06Z or 06 = 6:00 a.m. (Greenwich Mean Time.)

³ENUW1 = quantitative precipitation forecast for Enumclaw.

⁴SMP = quantitative precipitation forecast for Stampede Pass.

⁵OHAW1 = quantitative precipitation forecast for Ohanapecosh.

⁶GRF = station code for Fort Lewis.

⁷TEMP = forecasted air temperatures.
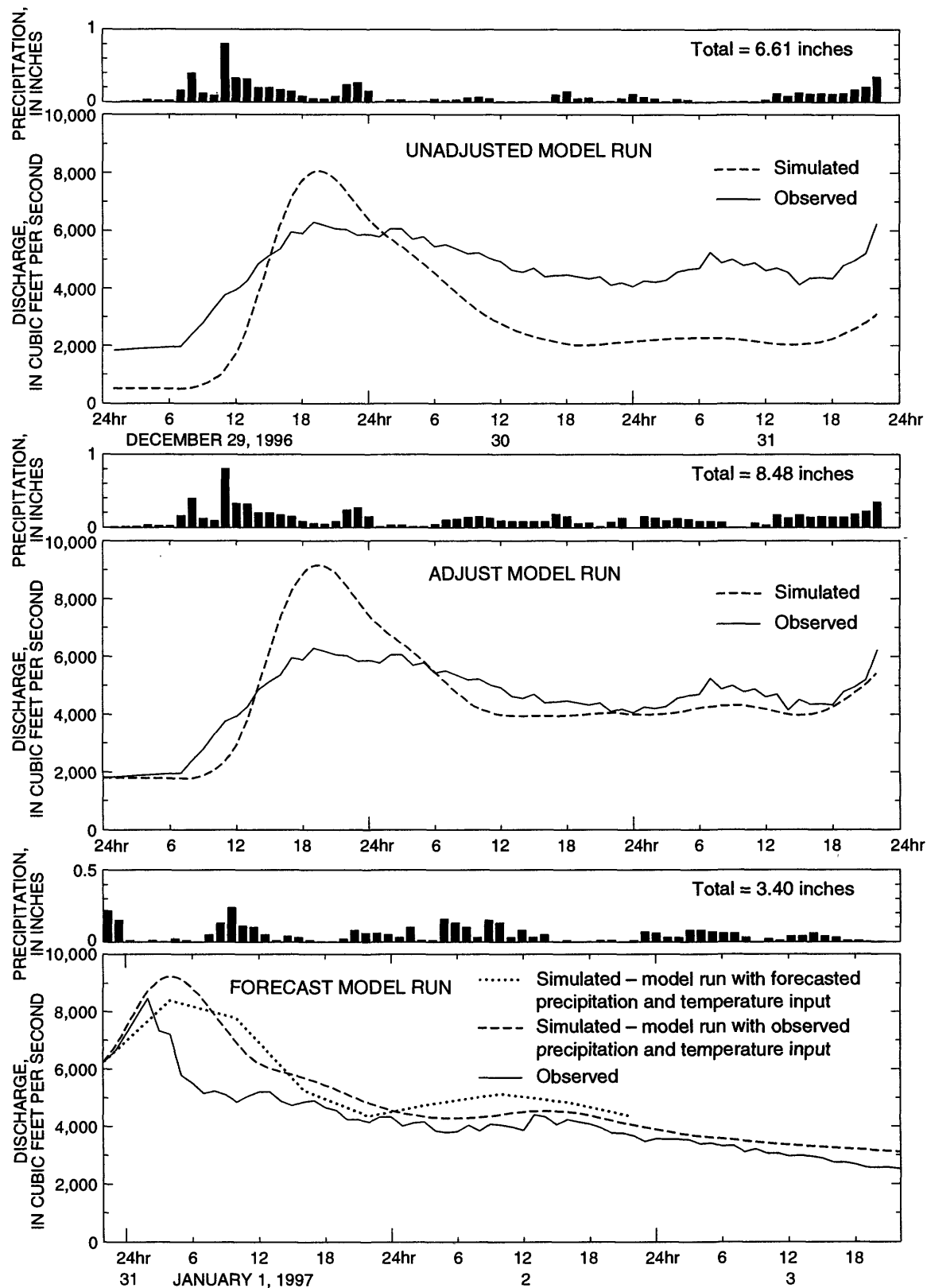
Figure 17. Simulated discharge and subbasin precipitation results from three model runs for the upper Puyallup subbasin in the Puyallup River Basin Model and observed discharge at Puyallup River near Orting, station number 12093500, Pierce County, Washington.

SUMMARY

The U.S. Geological Survey (USGS), in cooperation with Pierce County River Improvement (PCRI) of the Pierce County Public Works and Utilities, has developed an operational system for determining flood-alert and flood-forecasting information for the Puyallup River Basin. The system consists of a network of USGS-operated river discharge and stage, precipitation, and temperature gages equipped with real-time telemetry; a numerical watershed and streamflow-routing model; and a computer interface that runs the model and displays the results and the flood-alert status. The system described in this report provides PCRI with options to obtain both current and 54-hour forecasts of river discharges and stages so that the agency can monitor impending flooding and deploy its resources to the highest priority potential problem areas at flood-control levees and other facilities that it is responsible for maintaining.

A conceptual model of flooding in the Puyallup River Basin, developed from observed meteorological conditions during the largest recorded peak flows, relies on five factors identified as important to the magnitude and timing of floods. (1) Topography strongly influences the precipitation totals, with precipitation generally increasing with increasing elevation. (2) Spatial patterns of precipitation totals for individual storms may vary from the pattern defined by annual totals. (3) Flooding is primarily associated with storms bringing heavy rain to the basin, but snowmelt also contributes to flooding. (4) The extent of snow cover and the freezing level during a storm are important factors in controlling snowmelt contributions to runoff. (5) Most soil moisture storage capacity must be filled before major flooding can occur.

The Streamflow Synthesis and Reservoir Regulation (SSARR) numerical watershed runoff and streamflow-routing model was chosen for this study because of its capability to make flood forecasts, its proven ability to simulate river flows in the Puyallup River Basin and other similar basins in the Pacific Northwest, its compatibility with personal computers, its ability to simulate streamflow regulation and diversions, and its ability to simulate floods according to the conceptual model of the Puyallup River Basin. The Puyallup River Basin was divided into seven subbasins or watersheds, each containing its own set of runoff parameters. Thirteen elevation bands further divided the Puyallup River Basin into snowbands, in which precipitation inputs are distributed according to user-defined relations between precipitation and elevation and temperature inputs are altered according to temperature lapse rates. An isohyet map of annual precipitation and a digital-elevation model were used to define average-annual subbasin precipitation and the relationships between precipitation and elevation for each subbasin.

The SSARR model application was created from an existing National Weather Service (NWS) SSARR model application for the Puyallup River Basin by making alterations to accommodate a different version of the model that simulates snow accumulation and melt and a finer network of subbasins. Data from the current network of stream gages during eight storms in the 1995, 1996 and 1997 water years were used to calibrate (four storms) and validate (four storms) the numerical model. During one of the calibration storms (February 1996), peak discharges at many gaging sites were the highest ever recorded at the gages. Geographic Information System coverages of snow-water equivalent (SWE) of the basin's snowpack were available before, during, and after the February 1996 storm from the National Operational Hydrologic Remote Sensing Center (NOHRSC). These coverages were found generally to underestimate SWE when compared to measurements at a few sites with snow pillows, especially at the high elevation sites, but they provided the only basin-wide estimates available for comparison to simulated SWE from the Puyallup River Basin model.

Storm-volume-runoff and peak-discharge statistics were calculated for the five gaged subbasins in the upper portions of the basin for eight storms. Two-thirds of the simulated peak discharges for the calibration storms were within 36 percent of the observed peak discharge, and two-thirds of the 5-day storm runoff volumes were within 17 percent of observed storm runoff volumes. For the validation storms, the corresponding values were 24 percent and 30 percent, respectively. There was a bias to under-simulate peak discharges despite calibration efforts to overcome this deficiency. A strong seasonal bias was detected, resulting in a -21.9 percent bias for all the peaks that occurred before January 1 of the water year and a +23.4 percent bias for all peaks after January 1. Simulated SWE also showed a bias for the February 1996 storm. The SWE in the high-elevation zones was generally oversimulated, and in the lower-elevation zones, it was undersimulated. The midelevation zones were in general agreement with the NOHRSC estimates of SWE.

Tests using data from variously spaced precipitation stations to estimate precipitation at a particular location demonstrated the value of a relatively dense network of reliable precipitation stations. Gages that are heated so that they function during snowstorms are preferred. Tests of the model's sensitivity to number and location of precipitation stations used in the model produced ranges in

simulated peak discharges and runoff volume equal in magnitude to the error in the calibrated model. Other sensitivity tests showed that the accuracy of the model increases when the number of temperature stations used in the model is increased from two to four. Simulations of one storm during which snowmelt contributed to runoff showed that peak discharge and runoff volume were more sensitive to underestimates than overestimates of prestorm SWE.

The computer program SSARRMENU is a user interface between the SSARR model and the real-time data inputs to and outputs from the model. The interface is used to access and obtain input data from ADAPS (a USGS data-base program), make the model runs customized for the Puyallup River Basin, display the results with time-series plots, and display the flood-alert status of selected stations where discharges have exceeded threshold values. Trials demonstrated the capabilities of the model to make 54-hour forecasts of discharge based on quantitative precipitation and temperature forecasts acquired from the NWS. The model's ability to simulate a wide range of flood peaks seen during the calibration and validation period and the Puyallup Flood-Alert System's customized interface for easy operation should greatly enhance PCRI's ability to quickly assess flooding potentials. However, the accuracy of the discharges that it simulates can be no better than the accuracy of both observed and forecasted precipitation inputs to the model.

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APPENDIX A. SSARR-CODE NAMES, CHARACTERISTICS FILE, AND TABLED CHARACTERISTICS

The following includes a listing of the SSARR-code names for all the time series used in the model, a listing of the characteristic file for the final Puyallup River Basin model including the adjust REACH5 model (ADJRCH5) and the river stage ratings, and a listing of the tabled characteristics. The characteristic file, adjust REACH5 model, river stage ratings, and the tabled characteristics are used in conjunction with a job card and time-series data to make model runs with the SSARR model.

SSARR-code names for time series used in the Puyallup River Basin model

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Subbasins

			Subbasin precipitation
UPPUY	-	Upper Puyallup River Subbasin	UPPP
LWPUY	-	Lower Puyallup River Subbasin	LPUP
UPWHT	-	Upper White River Subbasin	UPWP
LWWHT	-	Lower White River Subbasin	LWHP
SOPRE	-	South Prairie Creek Subbasin	SOPP
CARBON	-	Carbon River Subbasin	CARP
GRNWTR	-	Greenwater River Subbasin	GRNP

Observed precipitation

BUCP	-	Buck Creek. Camp Meteorological Site Station Number 470118121330800
ELEP	-	Puyallup River at Electron, Station Number 1209200
SOPR	-	South Prairie Creek, Station Number 12095000
CARB	-	Carbon River. near Fairfax, Station Number 12094000
WHTP	-	White River Canal, Station Number 12099000
GNWP	-	Greenwater River at Greenwater, Station Number 12097500

Observed temperature

BUCT	-	Buck Creek Camp Meteorological Site
ELET	-	Puyallup River at Electron
SPRT	-	South Prairie Creek at South Prairie
CAYU	-	Cayuse Pass Snow Pillows
GNWT	-	Greenwater River at Greenwater
CART	-	Carbon River near Fairfax

Forecasted temperature

STMP	-	Stampede Pass
FTLT	-	Fort Lewis

Simulated discharge

Observed discharge

Simulated discharge	Observed discharge		
UPPUY (basin outflow)	ORTOBS	-	Puyallup River near Orting, Station Number 12093500
CARBON (basin outflow)	CRFOBS	-	Carbon River near Fairfax, Station Number 12094000
SOPRE (basin outflow)	SOPOBS	-	South Prairie at South Prairie, Station Number 12095000
GRNWTR (basin outflow)	GRNOBS	-	Greenwater River at Greenwater, Station Number 12097500
SUM1Q (summation point)	WBCOBS	-	White River below Clearwater, Station Number 12097850
MMDQ (reservoir outflow)	WNBOBS	-	White River near Buckley, Station Number 12098500 (not available for real-time)
CANAL (CANALB outflow)	WCBOBS	-	White River Canal at Buckley, Station Number 12099000
SUM2Q (summation point	WBQOBS	-	White River at Buckley, Station Number 12100000
TAPPSQ (reservoir outflow)	LTDOBS	-	Lake Tapps Diversion, Station Number 12101100
PUYSIM (REACH5 outflow)	PUYOBS	-	Puyallup River at Puyallup, Station Number 12101500
PUYDIF (difference between	MCQOBS	-	addition of flows (WCBOBS + WBQOBS)
PUYOBS and PUYSIM)	WCQOBS	-	subtraction of flows (WBCOBS - GRNOBS)

Simulated stage	Observed stage	
ORSSIM (ORSSTG rating)	ORSOBS	- Puyallup River near Orting, Station Number 12093500
CRSSIM (CRSSTG rating)	CRSOBS	- Carbon River at Orting, Station Number 12095690
PASSIM (PASSTG rating)	PASOBS	- Puyallup at Alderton, Station Number 12096500
MMDE	MMDOBS	- Forebay elevation, Mud Mountain Lake, Station Number 120980()
WASSIM (WASSTG rating)	WASOBS	- White River near Auburn, Station Number 12100496
TAPPSE	TAPOBS	- Lake Tapps near Sumner, Station Number 12101000
PUSSIM (PUSSTG rating)	PUSOBS	- Puyallup River at Puyallup, Station Number 12101500

```
ZC1 UPPUY UPPER_PUYALLUP_RIVER  169 SQ. MI.

 NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIM
ZC2 UPPUY,169,13,4,2.5,2,30.,3,60.,2,1000.,36.,2.0,.05,0,0,

    NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT, LAPSE
ZC3 UPPUY,ELPUPU,MRCR,.98,.84,.100,.03,.9,6000,3.3

    NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
ZC4 UPPUY,SM21,BI79,SS07,KE04,ETPPUY,DKE,ETM

  NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
ZC5 UPPUY,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4

    NAME, MRPCT,OBS-STA
ZC6 UPPUY,MRPCT,ORTOBS

    NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
ZCP UPPUY,0,0.0,500,0.9,1000,11.9,1500,18.6,2000,35.6,2500,47.1,3000,54.9,3500,
ZCP UPPUY,61.6,4000,69.6,4500,78.2,5000,84.5,6000,90.8,8000,96.5,15000,100.0

    NAME,PERCENT-AREA1,PERCENT-AREA2,PERCENT-AREA3,ETC FOR EACH BAND
ZCA UPPUY,0.9,11.0,6.7,17.0,11.5,7.8,6.7,8.0,8.6,6.3,6.3,5.7,3.5

    INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
    SURFACE

    NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
Z2S UPPUY,,1,5,10,20

    SUBSURFACE
    NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
Z2SS UPPUY,,20,20

    BASEFLOW
    NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
Z2B UPPUY,,100,100,100

    LOWERZONE
    NAME,TIME-DATE,FLOW
Z2LZ UPPUY,,200,200

    SNOWBANDS
    NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
Z201 UPPUY,,,,0,0,60,0,0.0,2.0,0,.1
Z202 UPPUY,,,,0,0,60,0,0.0,2.0,0,.1
Z203 UPPUY,,,,0,0,55,0,0.0,2.0,0,.1
Z204 UPPUY,,,,0,0,50,0,0.0,2.0,0,.1
Z205 UPPUY,,,,0,0,45,0,0.0,2.0,0,.1
```

```
Z206 UPPUY,,,,0,0,40,0,0.0,2.0,0,.1
Z207 UPPUY,,,,0,0,35,0,0.0,2.0,0,.1
Z208 UPPUY,,,,0,0,30,0,0.0,2.0,0,.1
Z209 UPPUY,,,,0,0,25,0,0.0,2.0,0,.1
Z210 UPPUY,,,,0,0,20,0,0.0,2.0,0,.1
Z211 UPPUY,,,,0,0,15,0,2.0,2.0,0,.1
Z212 UPPUY,,,,0,0,10,0,5.0,2.0,0,.1
Z213 UPPUY,,,,0,0,5,0,20.0,2.0,0,.1

     HYDROMET STATIONS
     BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
ZCH UPPUY,4,ELET,100,4,CAYU,100,3,UPPP,100


ZC1 SOPRE SOUTH_PRAIRIE_CREEK_BASIN

 NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIⁿ
ZC2 SOPRE,90.2,11,3,3.0,3,6.,2,40.,2,1000.,36.,2.0,.05,0,0,


     NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT, LAPSE
ZC3 SOPRE,ELPSOP,MRCR,.98,.84,.100,.03,.9,6000,3.3


     NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
ZC4 SOPRE,SM17,BI79,SS81,KE04,ETPMMD,DKE,ETM


   NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
ZC5 SOPRE,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4


     NAME, MRPCT,OBS-STA
ZC6 SOPRE,MRPCT,SOPOBS


     NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
ZCP SOPRE,0,0.0,500,.7,1000,17.4,1500,31.7,2000,51.1,2500,64.1,3000,74.0
ZCP SOPRE,3500,82.2,4000,89.6,4500,95.3,5000,98.8,6000,100.0
     NAME,PERCENT-AREA1,PERCENT-AREA2,PERCENT-AREA3,ETC FOR EACH BAND
ZCA SOPRE,.7,16.7,14.3,19.4,13.0,9.9,8.2,7.4,5.7,3.5,1.2


     INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
     SURFACE

     NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
Z2S SOPRE,,1,5,10


     SUBSURFACE
     NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
Z2SS SOPRE,,10,10,10


     BASEFLOW
     NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
Z2B SOPRE,,50,50


     LOWERZONE
     NAME,TIME-DATE,FLOW
Z2LZ SOPRE,,0,0
```

```
SNOWBANDS
      NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
Z201 SOPRE,,,,0,0,60,0,0.0,2.0,0,.1
Z202 SOPRE,,,,0,0,60,0,0.0,2.0,0,.1
Z203 SOPRE,,,,0,0,55,0,0.0,2.0,0,.1
Z204 SOPRE,,,,0,0,50,0,0.0,2.0,0,.1
Z205 SOPRE,,,,0,0,45,0,0.0,2.0,0,.1
Z206 SOPRE,,,,0,0,40,0,0.0,2.0,0,.1
Z207 SOPRE,,,,0,0,35,0,0.0,2.0,0,.1
Z208 SOPRE,,,,0,0,30,0,0.0,2.0,0,.1
Z209 SOPRE,,,,0,0,25,0,0.0,2.0,0,.1
Z210 SOPRE,,,,0,0,20,0,0.0,2.0,0,.1
Z211 SOPRE,,,,0,0,15,0,2.0,2.0,0,.1


   HYDROMET STATIONS
   BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
ZCH SOPRE,4,SPRT,100,4,ELET,100,3,SOPP,85


ZC1 CARBON CARBON_RIVER_BASIN


 NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIM
ZC2 CARBON,80.0,11,3,3.0,3,6.,2,40.,2,1000.,36.,2.0,.05,0,0,


      NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT,  LAPSE
ZC3 CARBON,ELPCRB,MRCR3,.98,.84,.200,.03,.9,6000,3.3


      NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
ZC4 CARBON,SM21,BI79,SS81,KE04,ETPMMD,DKE,ETM


0  NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
ZC5 CARBON,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4


      NAME, MRPCT,OBS-STA
ZC6 CARBON,MRPCT,CRFOBS


      NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
ZCP CARBON,1000,0.0,1500,2.2,2000,10.7,2500,18.8,3000,28.1,3500,38.7,4000,50.5
ZCP CARBON,4500,63.2,5000,75.0,6000,89.2,8000,96.3,16000,100.0
ZCA CARBON,2.2,8.5,8.1,9.3,10.6,11.8,12.7,11.8,14.2,7.1,3.7


      INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
      SURFACE

      NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
Z2S CARBON,,1,5,10


      SUBSURFACE
      NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
Z2SS CARBON,,10,10,10


      BASEFLOW
      NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
Z2B CARBON,,50,50
```

```
LOWERZONE
     NAME,TIME-DATE,FLOW
Z2LZ CARBON,,100,100


     SNOWBANDS
     NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
Z201 CARBON,,,,0,0,55,0,0.0,2.0,0,.1
Z202 CARBON,,,,0,0,50,0,0.0,2.0,0,.1
Z203 CARBON,,,,0,0,45,0,0.0,2.0,0,.1
Z204 CARBON,,,,0,0,40,0,0.0,2.0,0,.1
Z205 CARBON,,,,0,0,35,0,0.0,2.0,0,.1
Z206 CARBON,,,,0,0,30,0,0.0,2.0,0,.1
Z207 CARBON,,,,0,0,25,0,0.0,2.0,0,.1
Z208 CARBON,,,,0,0,20,0,0.0,2.0,0,.1
Z209 CARBON,,,,0,0,15,0,2.0,2.0,0,.1
Z210 CARBON,,,,0,0,10,0,5.0,2.0,0,.1
Z211 CARBON,,,,0,0,5,0,20.0,2.0,0,.1


   HYDROMET STATIONS
   BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
ZCH CARBON,4,ELET,100,3,CARP,120


ZC1 LWPUY LOWER_PUYALLUP_RIVER_BASIN


 NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIM
ZC2 LWPUY,129,8,4,10.,3,10.,3,60.,2,1000.,36.,2.0,.05,0,0,


     NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT, LAPSE
ZC3 LWPUY,ELPLPU,MRCR3,.98,.84,.200,.03,.9,6000,3.3


     NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
ZC4 LWPUY,SM17,BI31,SS80,KE03,ETPPUY,DKE,ETM


   NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
ZC5 LWPUY,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4


     NAME, MRPCT,OBS-STA
ZC6 LWPUY,MRPCT


     NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
ZCP LWPUY,0,0.0,500,41.0,1000,72.1,1500,79.5,2000,88.0,2500,95.1,3000,98.9,
ZCP LWPUY,3500,99.9,4000,100.0
ZCA LWPUY,41.0,31.1,7.4,8.5,7.1,3.8,1.0,0.1


     INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
     SURFACE
     NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
Z2S LWPUY,,1,2,5,10


     SUBSURFACE
     NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
Z2SS LWPUY,,5,5,10
```

```
BASEFLOW
      NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
Z2B LWPUY,,10,10,10


      LOWERZONE
      NAME,TIME-DATE,FLOW
Z2LZ LWPUY,,0,0


      SNOWBANDS
      NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
Z201 LWPUY,,,,0,0,60,0,0.0,2.0,0,.1
Z202 LWPUY,,,,0,0,60,0,0.0,2.0,0,.1
Z203 LWPUY,,,,0,0,55,0,0.0,2.0,0,.1
Z204 LWPUY,,,,0,0,50,0,0.0,2.0,0,.1
Z205 LWPUY,,,,0,0,45,0,0.0,2.0,0,.1
Z206 LWPUY,,,,0,0,40,0,0.0,2.0,0,.1
Z207 LWPUY,,,,0,0,35,0,0.0,2.0,0,.1
Z208 LWPUY,,,,0,0,30,0,0.0,2.0,0,.1
   HYDROMET STATIONS
   BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
ZCH LWPUY,4,SPRT,100,3,LPUP,100


ZC1 GRNWTR GREENWATER_RIVER_BASIN

 NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIM
ZC2 GRNWTR,75.8,9,4,2.5,2,30.,3,60.,2,1000.,36.,2.0,.05,0,0,


      NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT, LAPSE
ZC3 GRNWTR,ELPGWT,MRCR3,.98,.84,.100,.03,.9,6000,3.3


      NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
ZC4 GRNWTR,SM17,BI37,SS80,KE03,ETPMMD,DKE,ETM


   NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
ZC5 GRNWTR,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4


      NAME, MRPCT,OBS-STA
ZC6 GRNWTR,MRPCT,GRNOBS


      NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
ZCP GRNWTR,1000,0.0,1500,3.2,2000,10.0,2500,20.7,3000,34.1,3500,50.6,4000,69.1,
ZCP GRNWTR,4500,84.1,5000,99.0,6000,100.0,8000,100.0
ZCA GRNWTR,3.2,6.8,10.7,13.4,16.5,18.5,15.0,14.9,1.0


      INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
      SURFACE
      NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
Z2S GRNWTR,,1,5,10,10


      SUBSURFACE
      NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
Z2SS GRNWTR,,10,10
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      BASEFLOW
            NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
      Z2B GRNWTR,,50,50,50


            LOWERZONE
            NAME,TIME-DATE,FLOW
      Z2LZ GRNWTR,,0,0


            SNOWBANDS
            NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
      Z201 GRNWTR,,,,0,0,50,0,0.0,2.0,0,.1
      Z202 GRNWTR,,,,0,0,45,0,0.0,2.0,0,.1
      Z203 GRNWTR,,,,0,0,40,0,0.0,2.0,0,.1
      Z204 GRNWTR,,,,0,0,35,0,0.0,2.0,0,.1
      Z205 GRNWTR,,,,0,0,30,0,0.0,2.0,0,.1
      Z206 GRNWTR,,,,0,0,25,0,0.0,2.0,0,.1
      Z207 GRNWTR,,,,0,0,20,0,0.0,2.0,0,.1
      Z208 GRNWTR,,,,0,0,15,0,2.0,2.0,0,.1
      Z209 GRNWTR,,,,0,0,10,0,5.0,2.0,0,.1
         HYDROMET STATIONS
         BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
      ZCH GRNWTR,4,BUCT,100,3,GRNP,75


      ZC1 UPWHT UPPER_WHITE_RIVER_BASIN


       NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIM
      ZC2 UPWHT,299,11,4,2.5,2,30.,3,60.,2,1000.,36.,2.0,.05,0,0,


            NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT, LAPSE
      ZC3 UPWHT,ELPUWT,MRCR,.98,.84,.100,.03,.9,6000,3.3


            NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
      ZC4 UPWHT,SM21,BI37,SS80,KE03,ETPMMD,DKE,ETM


         NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
      ZC5 UPWHT,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4


            NAME, MRPCT,OBS-STA
      ZC6 UPWHT,MRPCT,WCQOBS


            NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
      ZCP UPWHT,1000,0,1500,1.6,2000,6.8,2500,14.8,3000,25.2,3500,36.7
      ZCP UPWHT,4000,48.5,4500,60.7,5000,70.8,6000,88.1,8000,97.80,15000,100.0
      ZCA UPWHT,1.6,5.2,8.0,10.4,11.5,11.8,12.2,10.1,17.3,9.7,2.2


            INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
            SURFACE
            NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
      Z2S UPWHT,,1,5,20,50


            SUBSURFACE
            NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
      Z2SS UPWHT,,20,20
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BASEFLOW
        NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
Z2B UPWHT,,100,100,100


        LOWERZONE
        NAME,TIME-DATE,FLOW
Z2LZ UPWHT,,200,200


        SNOWBANDS
        NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
Z201 UPWHT,,,,0,0,55,0,0.0,2.0,0,.1
Z202 UPWHT,,,,0,0,50,0,0.0,2.0,0,.1
Z203 UPWHT,,,,0,0,45,0,0.0,2.0,0,.1
Z204 UPWHT,,,,0,0,40,0,0.0,2.0,0,.1
Z205 UPWHT,,,,0,0,35,0,0.0,2.0,0,.1
Z206 UPWHT,,,,0,0,30,0,0.0,2.0,0,.1
Z207 UPWHT,,,,0,0,25,0,0.0,2.0,0,.1
Z208 UPWHT,,,,0,0,20,0,0.0,2.0,0,.1
Z209 UPWHT,,,,0,0,15,0,2.0,2.0,0,.1
Z210 UPWHT,,,,0,0,10,0,5.0,2.0,0,.1
Z211 UPWHT,,,,0,0,5,0,20.0,2.0,0,.1


     HYDROMET STATIONS
     BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
ZCH UPWHT,4,BUCT,100,4,CAYU,100,3,UPWP,100


ZC1 LWWHT LOWER_WHITE_RIVER_BASIN


 NM,DA,SBND,NPS,TSS,NPSS,TSSS,NPBF,TSBF,NPLZ,TSLZ,BIITS,BIIMX,BFLIM,PBLZ,DGLIM
ZC2 LWWHT,106,10,4,10.,3,10.,3,60.,2,1000.,36.,2.0,.05,0,0,


        NAME,EL-PT,SMR-CR,TIPMR,TIPM,RMR,PLWHC,SNETF,ELINT,  LAPSE
ZC3 LWWHT,ELPLWT,MRCR3,.98,.84,.200,.03,.9,6000,3.3


        NAME,SMI,BFP,S/SS,EKE,ETP,DKE,ETMO
ZC4 LWWHT,SM17,BI31,SS80,KE03,ETPPUY,DKE,ETM


   NAME,TINTMX,BASE,PXTEMP,PMIN,PMAX,GMLT,ETIPCT,WEMIN,WEPCT,WEMAX
ZC5 LWWHT,.2,32,34,.017,.033,GMLT,ETIPCT,2,60,.4


        NAME, MRPCT,OBS-STA
ZC6 LWWHT,MRPCT


        NAME,ELEV1,AREA1,ELEV2,AREA2,ELEV3,AREA3,ETC.
ZCP LWWHT,0,0,500,15.0,1000,59.1,1500,73.8,2000,81.7,2500,87.0,3000,92.0
ZCP LWWHT,3500,96.0,4000,98.2,4500,99.6,5000,100.0
ZCA LWWHT,15.0,44.1,14.7,7.9,5.3,5.0,4.0,2.2,1.4,0.4


        INITIAL CONDITIONS: (IF DATE MISSING,START TIME FROM T CARD USED)
        SURFACE
        NAME,TIME-DATE,FLOW-PHS1,FLOW-PHS2,FLOW-PHS3,ETC.
Z2S LWWHT,,1,2,5,10
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```
SUBSURFACE
      NAME,TIME-DATE,FLOW-PHSS1,FLOW-PHSS2,FLOW-PHSS3,ETC.
Z2SS LWWHT,,5,5,10


      BASEFLOW
      NAME,TIME-DATE,FLOW-PHBF1,FLOW-PHBF2,FLOW-PHBF3,ETC.
Z2B LWWHT,,10,10,10


      LOWERZONE
      NAME,TIME-DATE,FLOW
Z2LZ LWWHT,,0,0


      SNOWBANDS
      NAME,TIME,ROP,BFP,CC,SLIQW,ATIMR,ATICC,WE,SMI,BII,TINT
Z201 LWWHT,,,,0,0,60,0,0.0,2.0,0,.1
Z202 LWWHT,,,,0,0,60,0,0.0,2.0,0,.1
Z203 LWWHT,,,,0,0,55,0,0.0,2.0,0,.1
Z204 LWWHT,,,,0,0,50,0,0.0,2.0,0,.1
Z205 LWWHT,,,,0,0,45,0,0.0,2.0,0,.1
Z206 LWWHT,,,,0,0,40,0,0.0,2.0,0,.1
Z207 LWWHT,,,,0,0,35,0,0.0,2.0,0,.1
Z208 LWWHT,,,,0,0,30,0,0.0,2.0,0,.1
Z209 LWWHT,,,,0,0,25,0,0.0,2.0,0,.1
Z210 LWWHT,,,,0,0,20,0,0.0,2.0,0,.1
   HYDROMET STATIONS
   BASIN NAME,DATA CODE,STA.NAME,WEIGHT,DATA CODE,STA.NAME,WEIGHT,ETC.
ZCH LWWHT,4,SPRT,100,3,LWHP,100


      NAME,ELEV,SNW-WT,PX-TEMP
ZH   SPRT, 400,100,35
ZH   ELET,1633,100,35
ZH   BUCT,2638,100,35
ZH   CAYU,5300,100,35
ZH   STMP,3958,100,35
ZH   FTLT,280,100,35


      RUN CONTROL (L=PRINT INDIVIDUAL SNOWBAND RESULTS, S=SUPPRESS BASIN PRINTOUTS,
                  BUPD=OPEN BULK FILE-ZBSTORE COMMANDS)
ZR L 7



      REACH CHARACTERISTICS
CC01 WBQOBS         1        OBSERVED DISCHARGE-WHITE R. AT BUCKLEY
CC01 GRNOBS         1        OBSERVED DISCHARGE-GREENWATER R.
CC01 WBCOBS         1        OBSERVED DISCHARGE-WHITE R. BLW CLEARWATER
CC01 WCBOBS         1        OBSERVED DISCHARGE-WHITE R. CANAL
CC01 WCQOBS         1        OBS. CALCULATED DISCHARGE: WBCOBS - GRNOBS
CC01 MCQOBS         1        OBS. CALCULATED DISCHARGE: WBQOBS + WCBOBS
CC01 LTDOBS         1        OBSERVED DISCHARGE-LAKE TAPPS DIVERSION
CC01 ORTOBS         1        OBSERVED DISCHARGE-PUYALLUP R. NR. ORTING
CC01 CRFOBS         1        OBSERVED DISCHARGE-CARBON R. NR. FAIRFAX
CC01 SOPOBS         1        OBSERVED DISCHARGE-SOUTH PRAIRIE CREEK
CC01 PUYOBS         1        OBSERVED DISCHARGE-PUYALLUP R. AT PUYALLUP
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CC01 MMDOBS          1           OBSERVED FOREBAY ELEV.-MUD MTN.LAKE
CC01 WASOBS          1           OBSERVED STAGE-WHITE R. NEAR AUBURN
CC01 WWBOBS          1           OBSERVED STAGE-WHITE R. WILLIAMS BRIDGE
CC01 WBSOBS          1           OBSERVED STAGE-WHITE R. AT BUCKLEY
CC01 CRSOBS          1           OBSERVED STAGE-CARBON RIVER AT ORTING
CC01 PASOBS          1           OBSERVED STAGE-PUYALLUP R. AT ALDERTON
CC01 TAPOBS          1           OBSERVED STAGE-LAKE TAPPS NR SUMNER
     Sum Point above Mud Mountain Dam at Station No. 12097850
CC01 SUM1
     Sum Point at White River Canal Diversion
CC01 SUM2
     Sum Point at Mouth of White River
CC01 SUM3
     White River Canal as an adjacen station to REACH1
CC01 CANALA
CC01 CANALB
      The "1" in column 15 specifies the outflow is multiplied
      by -1, and therefore, water is subtracted from SUM2
CC02 CANALB   1
     Sum Point at confluence of South Prairie and Carbon River
CC01 SUM4
     Sum Point at confluence of Carbon River and Puyallup River
CC01 SUM5
     Sum Point of White River and Puyallup Headwaters
CC01 SUM6
     Sum Point PUYBAL and PUYSIM
CC01 SUM7
     Puyallup Balance station with PUYOBS as the local station
CC01 PUYBAL
CC02 PUYBAL       PUYOBS
CR01 REACH1                     WHITE RIVER FROM MUD MTN TO DIVERSION
     ADAPTED FROM NWS--MMD2--780 FEET DROP IN 34 MILES - SLOPE 23 FT PER MILE
CR02 REACH1              5
C110 REACH1                  0    24              1000    12
C111 REACH1             20000     8              30000     6
C112 REACH1         999999999     6

CR01 REACH2                     WHITE RIVER FROM DIVERSION TO MOUTH
   Changed from stg/discharge relation to equation
   Use equation for REACH2 (16/.8/35) (PHASES/n/KST)
            |          |    PHS-N--KTS.XX  |           |
CR02 REACH2              160800  3500

CL01 TAPPS                    LAKE TAPPS RESERVOIR
CL02 TAPPS                          543     516
     TAPPS    Elev-Storage table from Puget Power (1959).
               ELEV       Q        STORAGE ELEV       Q        STORAGE
C101 TAPPS      515       0              0  517      100          1902
C102 TAPPS      519      250          3901  521      450          6023
C103 TAPPS      523      700          8251  525      950         10929
C104 TAPPS      527     1200         13812  529     1500         16923
C105 TAPPS      531     1800         20303  533     2200         24025
C106 TAPPS      535     2700         28081  537     3300         32413
C107 TAPPS      539     4000         36967  541     4800         41694
C108 TAPPS      543     5700         46655  99999999999999999999999999
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CL01 MMD                          MUD MOUNTAIN RESERVOIR
CL02 MMD                               1241    870
     MMD    Discharge table updated 10/2786. The data is from the NWS and includes
     MMD    the combined capacity of both tunnels. The inver of the 23ft. tunnel is
     MMD    is 970 ft. The invert of the spillway is 1215 ft.
     MMD    Lowered minimum elevation from 896 TO 870, MCM 10/31/95
     MMD    Raised the discharge to reflect rating curve dated 9/95--combined for
the
     MMD    23 ft. tunnel and the 9 ft. tunnel at 90%(change from 910-1200ft)
     MMD    Changed discharge and storage at 870ft. from 0.0 to 10.10 because it
was
     MMD    unstable at 0.0.
                    ELEV        Q       STORAGE ELEV       Q          STORAGE
C101 MMD            870        10           10   900      500             14
C102 MMD            910      1200           52   920     1900            107
C103 MMD            930      3600          191   940     5700            366
C104 MMD            950      7100          641   970     9200           1522
C105 MMD            980     10000         2145   990    10800           2913
C106 MMD           1002     11600         4030  1030    13400           7870
C107 MMD           1050     14400        11850  1100    16900          29050
C108 MMD           1150     20000        55860  1200    20900          92560
C109 MMD           1218     22000       109210  1222    26700         111200
C110 MMD           1225     47800       116290  1230    74900         121580
C111 MMD           1235     90000       127100  1240   130000         132830
C112 MMD           1241    137000       134010999999999999999999999999999999

CR01 REACH3                   Puyallup at Orting to confluence with Carbon River
   Adapted from NWS(ORTW2)...340 ft. drop in 20 miles - slope 17 ft. per mile
CR02 REACH3              4
C101 REACH3                   0      40                   1000      15
C102 REACH3             10000       15                  12000      45
C102 REACH3            9999999      45

CR01 REACH4                   Carbon R. to confluence with Puyallup River
   Adapted from NWS(FFXW2)...450 ft. drop in 27 miles - slope 17 ft. per mile
CR02 REACH4              1
C101 REACH4                   0      60                   1000      15
C102 REACH4             10000       15                  12000      45
C102 REACH4            9999999      45

CR01 REACH5                      MAINSTEM PUYALLUP RIVER
   changed from cal3--from stg/discharge relation to equation
   Use equation for REACH5 (2/.4/15) (PHASES/n/KST)
        |              |     PHS-N--KTS.XX  |            |
CR02 REACH5                 20400  1500  .
```

                                    65

9 - SYSTEM CONFIGURATION CONTROL

U STA.N.	P D STA	D STA.	D STA.	D STA.	D STA.	D STA
N MAINSTEM						
P GRNWTR	SUM1					
P GRNOBS						
P UPWHT	SUM1					
P WBCOBS						
P WCQOBS						
P SUM1	MMD					
P MCQOBS						
P MMD	REACH1					
P REACH1	SUM2					
P WCBOBS						
P CANALA	CANALB	TAPPS				
P CANALB	SUM2					
P SUM2	REACH2					
P WBQOBS						
P LWWHT	REACH2					
P REACH2	SUM3	WASSTG				
P LTDOBS						
P TAPPS	SUM3					
P UPPUY	REACH3	ORSSTG				
P ORTOBS						
P REACH3	SUM5					
P CARBON	SUM4					
P CRFOBS						
P SOPRE	SUM4					
P SOPOBS						
P SUM4	REACH4					
P REACH4	SUM5	CRSSTG				
P LWPUY	SUM5					
P SUM5	SUM6	PASSTG				
P SUM3	SUM6					
P SUM6	REACH5					
P REACH5	PUYOBS	PUSSTG				
P PUYOBS						
P PUYBAL						

After a "MAINSTEM" model run, the following run
can be made to adjust REACH5 to the observed discharge
values at Puyallup at Puyallup, Station No. 12101500.
(PUYBAL values saved as PUYDIF and REACH5 values
saved as PUYSIM after MAINSTEM model run)

N ADJRCH5		
P PUYSIM	SUM7	
P PUYDIF	SUM7	
P SUM7	REACH5	
P REACH5	PUSSTG	
P REACH5		

Ratings for river-stage sites

    NOTE: The time series are saved as reservoir regulation time series
           (record type 100) with the ZSE <source> <target> command. The
           SSARR codes for the source and target are as follows:

           Source Time Series   Target Time Series
           ORSSTG   ORSSIM
           CRSSTG   CRSSIM
           PASSTG   PASSIM
           PUSSTG   PUSSIM
           WASSTG   WASSIM

    Puyallup River near Orting, Station No. 12093500
    Adapted from rating No. 28 and current stage shift: .51SH @ 4.OO, .51FT
    @ 5.15 AND 0.00SH @ 10.02FT.   8/18/97
CR01 ORSSTG   PUYALLUP RIVER NEAR ORTING
                  #PHASES   n
CR02 ORSSTG   1
                  STAGE   Q   TS   STAGE   Q   TS
                  |-----||-----||----| |-----||-----||----|
C101 ORSSTG   300   0   10   399   108   10
C101 ORSSTG   400   110   10   500   483   10
C102 ORSSTG   600   1211   10   700   2469   10
C103 ORSSTG   800   4236   10   900   6575   10
C104 ORSSTG   1000   9517   10   1100   13470   10
C105 ORSSTG   1200   18140   10   1300   23840   10
C106 ORSSTG   99999999999999   10

    Puyallup River at Puyallup, Station No. 12101500
    Adapted from rating No. 11 and current stage shift: -.78 shift below
    19.00 ft. prorated to -1.20 shift at 24.50 ft.   8/18/97
CR01 PUSSTG   PUYALLUP RIVER AT PUYALLUP
                  #PHASES   n
CR02 PUSSTG   1   0
                  STAGE   Q   TS   STAGE   Q   TS
                  |-----||-----||----| |-----||-----||----|
C101 PUSSTG   854   348   10   1000   1163   10
C102 PUSSTG   1200   3225   10   1400   6045   10
C103 PUSSTG   1600   9530   10   1800   13620   10
C104 PUSSTG   2000   18060   10   2200   22820   10
C105 PUSSTG   2400   28040   10   2600   34000   10
C106 PUSSTG   2800   40550   10   3000   47560   10
C107 PUSSTG   3170   53850   10   999999999999999999999

    Puyallup River at Alderton, Station No. 12096500
    ADAPTED FROM RATING #6   1/22/97
CR01 PASSTG   PUYALLUP RIVER AT ALDERTON
                  #PHASES   n
CR02 PASSTG   1   0
                  STAGE   Q   TS   STAGE   Q   TS
                  |-----||-----||----| |-----||-----||----|
C101 PASSTG   4500   241   10   4700   1704   10
C102 PASSTG   4900   4547   10   5100   8805   10

```
C103  PASSTG              5300  14500     10           5500  21640      10
C104  PASSTG              5700  30250     10           5900  40340      10
C105  PASSTG              6100  51920     10           6300  64990      10
C106  PASSTG              6500  79560     10      99999999999999        10
```

Carbon River at Orting, Station No. 12095690
Adapted from rating 3 and current shifts: 0.48sh below 24.20 ft.
and zero shift at 26.80 ft. and abv. 1/22/97

```
CR01  CRSSTG                        CARBON RIVER AT ORTING
                    #PHASES    n
CR02  CRSSTG                1    0
                    STAGE     Q                   STAGE      Q
                    |-----||-----||----|          |-----||-----||----|
C101  CRSSTG              2250    213     10           2400   1193      10
C102  CRSSTG              2600   3450     10           2700   5046      10
C103  CRSSTG              2800   7311     10           2900   9994      10
C104  CRSSTG              3000  13100     10           3100  16610      10
C105  CRSSTG              3200  20550     10      99999999999999        10
```

White River nr. Auburn, Station No. 12100496
Adapted from rating 3 and current shifts: -2.32sh throughout the
entire range of the rating 1/22/97

```
CR01  WASSTG                        WHITE RIVER AT AUBURN
                    #PHASES    n
CR02  WASSTG                1    0
                    STAGE     Q                   STAGE      Q
                    |-----||-----||----|          |-----||-----||----|
C101  WASSTG              7702      0     10           7800    264      10
C102  WASSTG              7900   1033     10           8000   2283      10
C103  WASSTG              8100   4002     10           8200   6181      10
C104  WASSTG              8300   8815     10           8400  11900      10
C105  WASSTG              8500  15420     10           8600  19390      10
C106  WASSTG              8732  25300     10      99999999999999        10
```

Puyallup River Model Tabled Characteristics

```
                    ZCT THREE DIMENSION TABLE OR FUNCTION
     NAME,WORD2,WORD3,WORD4,WORD5,ETC
ZCT,MRCR,3,0,0.02,0.025,100,0.03,0.025,300,0.06,0.025,999,0.06,0.025
ZCT,MRCR2,3,0,0.04,0.025,100,0.06,0.025,300,0.06,0.025,999,0.06,0.025
ZCT,MRCR3,3,0,0.08,0.025,100,0.10,0.025,300,0.10,0.025,999,0.10,0.025


                     ZCT TWO DIMENSION TABLE OR FUNCTION
     NAME,WORD2,WORD3,WORD4,WORD5,ETC
ZCT,ELPGWT,2,1750,72.0,2250,83.6,2750,94.1,3250,100.3,3750,103.0,4250,104.2,
ZCT,ELPGWT,4750,105.1,5500,103.8,7000,99.6,8000,99.6
ZCT,ELPUWT,2,1250,76.6,1750,79.2,2250,83.4,2750,87.6,3250,91.1,3750,94.9,
ZCT,ELPUWT,4250,98.3,4750,102.5,5500,108.9,7000,127.7,11000,166.4,16000,166.4
ZCT,ELPLWT,2,250,83.6,750,86.4,1250,102.0,1750,112.9,2250,130.2,2750,141.7,
ZCT,ELPLWT,3250,143.3,3750,142.9,4250,139.1,4750,143.1,5000,143.1
ZCT,ELPSOP,2,250,75.5,750,77.8,1250,86.1,1750,96.7,2250,108.2,2750,118.3,3250,
ZCT,ELPSOP,122.7,3750,126.0,4250,128.1,4750,132.2,5500,135.4,7000,135.4
ZCT,ELPCRB,2,1250,66.3,1750,71.5,2250,83.0,2750,86.6,3250,93.8,3750,100.1,
ZCT,ELPCRB,4250,102.6,4750,105.2,5500,112.9,7000,127.5,11000,148.5,16000,148.5
ZCT,ELPUPU,2,250,53.2,750,54.7,1250,63.4,1750,74.6,2250,89.5,2750,103.1,3250,
ZCT,ELPUPU,114.9,3750,118.8,4250,122.0,4750,127.1,5500,134.9,7000,146.3,11000,
ZCT,ELPUPU,163.7,16000,163.7
ZCT,ELPLPU,2,250,87.5,750,92.4,1250,106.6,1750,118.5,2250,133.9,2750,154.1,
ZCT,ELPLPU,3250,177.7,3750,192.0


     NAME,WORD2,WORD3,WORD4,WORD5,ETC
ZCT,ELPUW,2,1250,76.6,1750,79.2,2250,83.4,2750,87.6,3250,91.1,3750,94.9,
ZCT,ELPUW,4250,95.7,4750,88.1,5500,81.8,7000,88.1,11000,88.1,16000,88.1
ZCT,ELPCR,2,1250,66.3,1750,71.5,2250,83.0,2750,86.6,3250,93.8,3750,100.1,
ZCT,ELPCR,4250,97.3,4750,92.8,5500,84.0,7000,77.4,11000,77.4,16000,77.4
ZCT,ELPUP,2,250,53.2,750,54.7,1250,63.4,1750,74.6,2250,89.5,2750,103.1,3250,
ZCT,ELPUP,114.9,3750,118.8,4250,114.2,4750,108.2,5500,102.2,7000,96.2,11000,
ZCT,ELPUP,96.2,16000,96.2


ZCT,SM07,2,0,10,2.5,20,5,36,12,100,15,100,999,100
ZCT,SM08,2,0,10,2.5,20,5,36,8,60,10,74,12,86,14,100,999,100
ZCT,SM10,2,0,15,2.5,23,5,36,12,100,15,100,999,100
ZCT,SM12,2,0,15,2,20,4,30,6,45,8,70,9,88,10,95,11,100,999,100
ZCT,SM14,2,0,20,2,30,4,40,6,60,7,80,8,100,999,100
ZCT,SM15,2,0,20,2,30,4,40,6,54,7,61,8,68,10,80,12,90,14,100,999,100
ZCT,SM16,2,0,15,2,20,4,30,6,52,8,76,9,88,10,95,11,100,999,100
ZCT,SM17,2,0,10,2.5,20,5,36,6,50,7,65,8,76,9,82,10,88,12,96,14,100,999,100
ZCT,SM20,2,0,20,2,30,4,40,6,60,7,70,8,75,10,80,12,85,14,90,16,95,18,100,99,100
ZCT,SM21,2,0,10,2,15,4,30,6,60,7,70,8,75,10,79,12,83,14,87,16,90,20,100,99,100


ZCT,BI37,2,0,80,.1,57,.2,45,.3,37,.4,32,.5,29,.6,27,1.0,20,2.0,10,9999,10
ZCT,BI31,2,0,75,.2,60,.4,48,.6,37,.8,31,1.0,27,1.2,25,9999,25
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ZCT,BI79,2,0,90,.2,75,.4,63,.6,52,.8,46,1.0,45,1.2,45,9999,45
ZCT,SS80,2,0,0,.02,.006,.04,.014,.06,.024,.08,.036,.1,.05,.5,.37,1.0,.77,100,
ZCT,SS80,99.77
ZCT,SS07,2,0,0,.02,.004,.04,.010,.06,.018,.08,.028,.1,.04,.12,.054,.14,
ZCT,SS07,.07,100,99.93

ZCT,KE03,2,0,100,.1,.70,.4,30,.6,20,1.0,10,2.0,0.0,999,0.0
ZCT,KE04,2,0,100,.5,30,2.0,0.0,999,0.0

ZCT,ETPPUY,2,-100,0,32,0,40,.023,50,.058,60,.097,70,.137,80,.179,90,.222,100,
ZCT,ETPPUY,.266
ZCT,ETPMMD,2,-100,0,32,0,40,.028,50,.065,60,.103,70,.140,80,.179,90,.216,100,
ZCT,ETPMMD,.255

ZCT,DKE,2,0,0,3,50,6,90,10,100,9999,100

ZCT,ETM,2,1,77,2,80,3,102,4,114,5,130,6,132,7,133,8,122,9,104,
ZCT,ETM,10,93,11,78,12,73,13,77

ZCT,GMLT,2,1,.004,2,.01,3,.02,4,.025,5,.03,10,.01,11,.005,13,.004

ZCT,MRPCT,2,1,31,2,37,3,53,4,70,5,87,6,100,7,100,8,91,9,76,10,58,11,41,12,32,13,
ZCT,MRPCT,31,9999,31

ZCT,ATTR1,2,1,2,2,5,3,11,4,18,5,26,6,34,7,41,8,49,9,56,10,63,11,68,12,74,13,78
ZCT,ATTR1,14,82,15,86,16,89,17,92,18,4,19,95,20,97,21,98,22,99,23,99,24,100
```

        RELATION FOR ADJACENT STATION CANALA--WHITE R. CANAL DIVERSION AS A
        FUNCTION OF FLOW IN REACH1 (WHITE R. NR. BUCKLEY)
```
ZCT,CDIV,2,150,0,400,265,2000,1500,8000,1500,12000,0,60000,0
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