APPENDIX C

APRIL 1, 2005 PI ENGINEERING DRAFT TECHNICAL MEMORANDUM - SKAGIT RIVER BASIN HISTORICAL FLOOD MODELING - HYDROLOGY

Draft Technical Memorandum

Skagit River Basin Historical Flood Modeling - Hydrology

Introduction

This technical memorandum presents details and an analysis of the Skagit River watershed rainfall-runoff modeling for the two 1990, the 1995, and the 2003 flood events using HEC-HMS software Version 2.2.2 (U.S. Army Corps of Engineers, 2003a), HEC-RAS software Version 3.1 (U.S. Army Corps of Engineers 2004), and HEC-5 software Version 8.0 (U.S. Army Corps of Engineers 1998). Output from the HEC-HMS watershed model was used as input to the Skagit River HEC-RAS and HEC-5 flood routing models, which route and combine flood hydrographs representing flow contribution from sequential subbasins along the Skagit River from Ross Dam to Skagit Bay. The HEC-RAS and HEC-5 model development and analysis is described in a separate technical memorandum, *Skagit River Basin Historical Flood Modeling – Hydraulics* (Pacific International Engineering, 2004).

Purpose

The purpose of using the HMS model was to develop flood hydrographs that reasonably represent flow contribution from ungaged subbasins in the Skagit River Basin during the recent four historical events occurring in 1990 (two events), 1995 and 2003. These HMS-generated flood hydrographs were then used to improve calibration and verification of the HEC-RAS and HEC-5 flood routing models. Both HEC-RAS and HEC-5 models used the same four recent floods occurring in 1990, 1995, and 2003 for model calibration and verification. The HEC-RAS and HEC-5 routing models required input of hydrographs along the routing reaches that represent appropriate flow contribution from the subbasins during these events. For gaged subbasins, including those above Ross Dam, above Thunder Creek gage, above Newhalem gage, above Newhalem Creek gage, above Sauk River gage, and above Baker River gage, observed hydrographs were available and were used directly in the HEC-RAS and HEC-5 routing models. For the ungaged subbasins (with a total drainage area approximately 30 percent of the entire Skagit River Basin of 3,115 square miles), flow hydrographs were not available and needed to be generated by the HMS models.

Use of the HMS-generated hydrographs for the ungaged subbasins have improved the calibration and verification of the HEC-RAS and HEC-5 flood routing models. The HMS model sufficiently takes into consideration the actually observed storm patterns and the watershed geometric and hydrologic characteristics. With better representation of subbasin flow contribution, the HEC-RAS and HEC-5 routing models could then be more accurately developed. The HMS modeling approach to improve the accuracy of the HEC-RAS and HEC-5 routing models was not used before, and its use is an improvement to the hydrology and hydraulics of the Skagit River Flood Damage Reduction Study.

Approach

The HEC-HMS model is a single-event flood rainfall-runoff model that simulates flood runoff hydrographs from storm precipitation, taking into account antecedent ground conditions, loss rates, and base flow. The runoff hydrograph from each Skagit River subbasin's response to a storm was derived by application of the Clark's unit hydrograph methodology to rainfall excesses.

There are a total of 44 subbasins within the entire 3,115-square-mile Skagit River Basin (see Figures 1 and 2). Modeling of the Skagit River Basin included all subbasins below Ross Dam to the confluence of the North and South Forks of the Skagit River, except the 714-square-mile Sauk River subbasin above the streamgage at river mile (RM) 5.4 [U.S. Geological Service (USGS) Gage No. 12189500]. The modeled area, which totaled 1,380 square miles, was subdivided into 41 subbasins. Among the modeled subbasins, three subbasins (Baker River, Newhalem Creek, and Thunder Creek) are gaged and the remaining are ungaged.

The subbasin above Ross Dam and the 714-square-mile Sauk River subbasin above the streamgage at RM 5.4, as well as the subbasin below the confluence of the North and South Forks of the Skagit River were not included in the model. Since observed hydrographs are available for the Sauk River subbasin and the subbasin above Ross Dam, and also due to lack of sufficient hydrometeorological data and different orographic effects on the certainties of the model results, very minimal benefits could be gained from modeling these two areas. The drainage area below the confluence of the North and South Forks does not contribute significant inflow to the Skagit River because, in this area, the Skagit River channels are all confined by levees on both banks.

A two-step approach was used in the HEC-HMS modeling of the runoff from the Skagit River subbasins. First, unit hydrograph, base flow, and loss rate parameters were optimized to achieve a best-fit with respect to observed hydrographs for the gaged subbasins. Second, these optimized parameters were used with appropriate adjustments for drainage area and hydrologic characteristics (such as the time of concentration and the storage parameter) for rainfall-runoff modeling of the ungaged subbasins. The HEC-HMS modeling requires input of subbasin drainage geometric data, recorded rainfall data, streamgage hydrographs, and other hydrologic data including Clark's unit hydrograph parameters, precipitation losses, and base flow estimates.

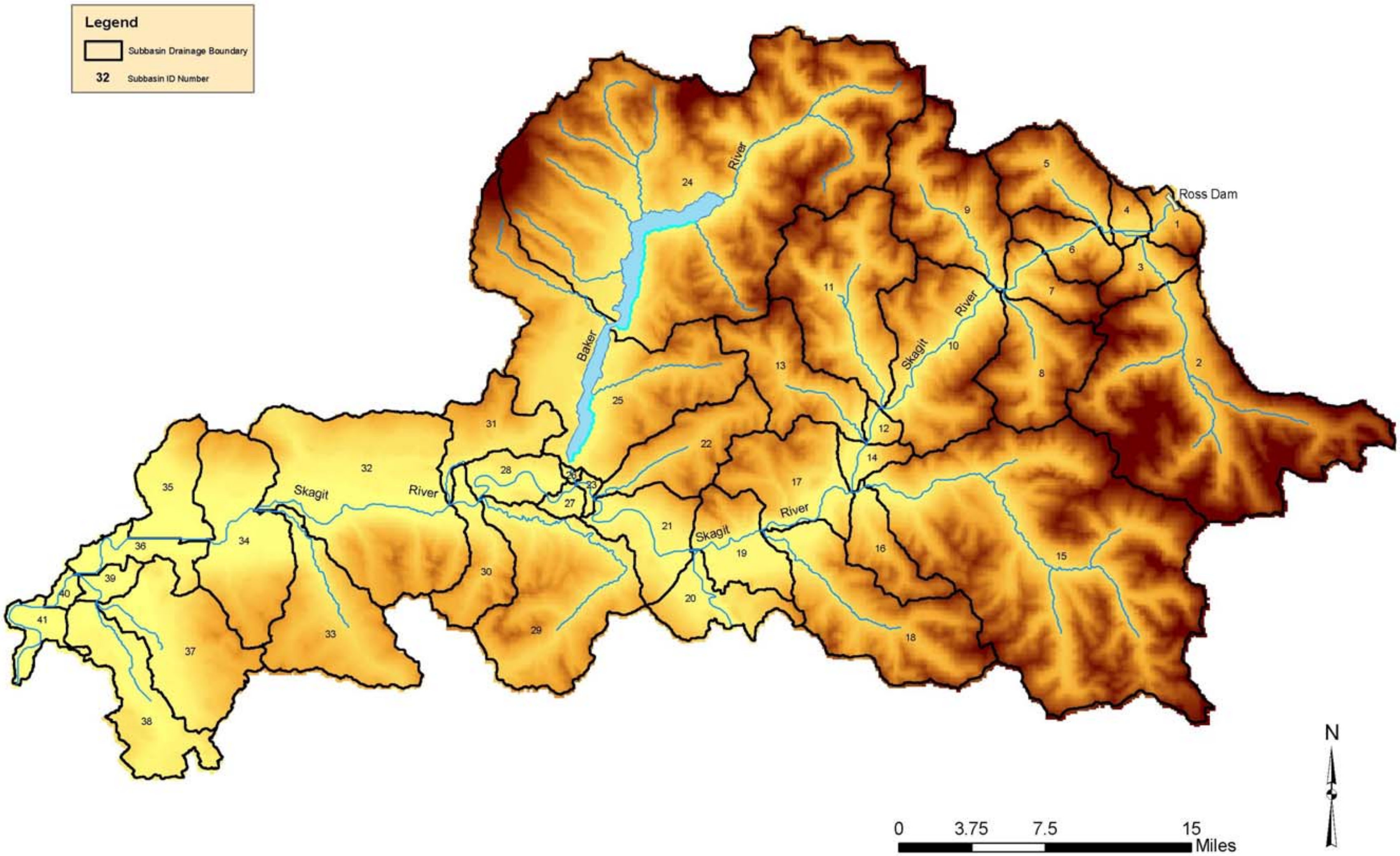

Figure 1 Skagit River subbasin division map

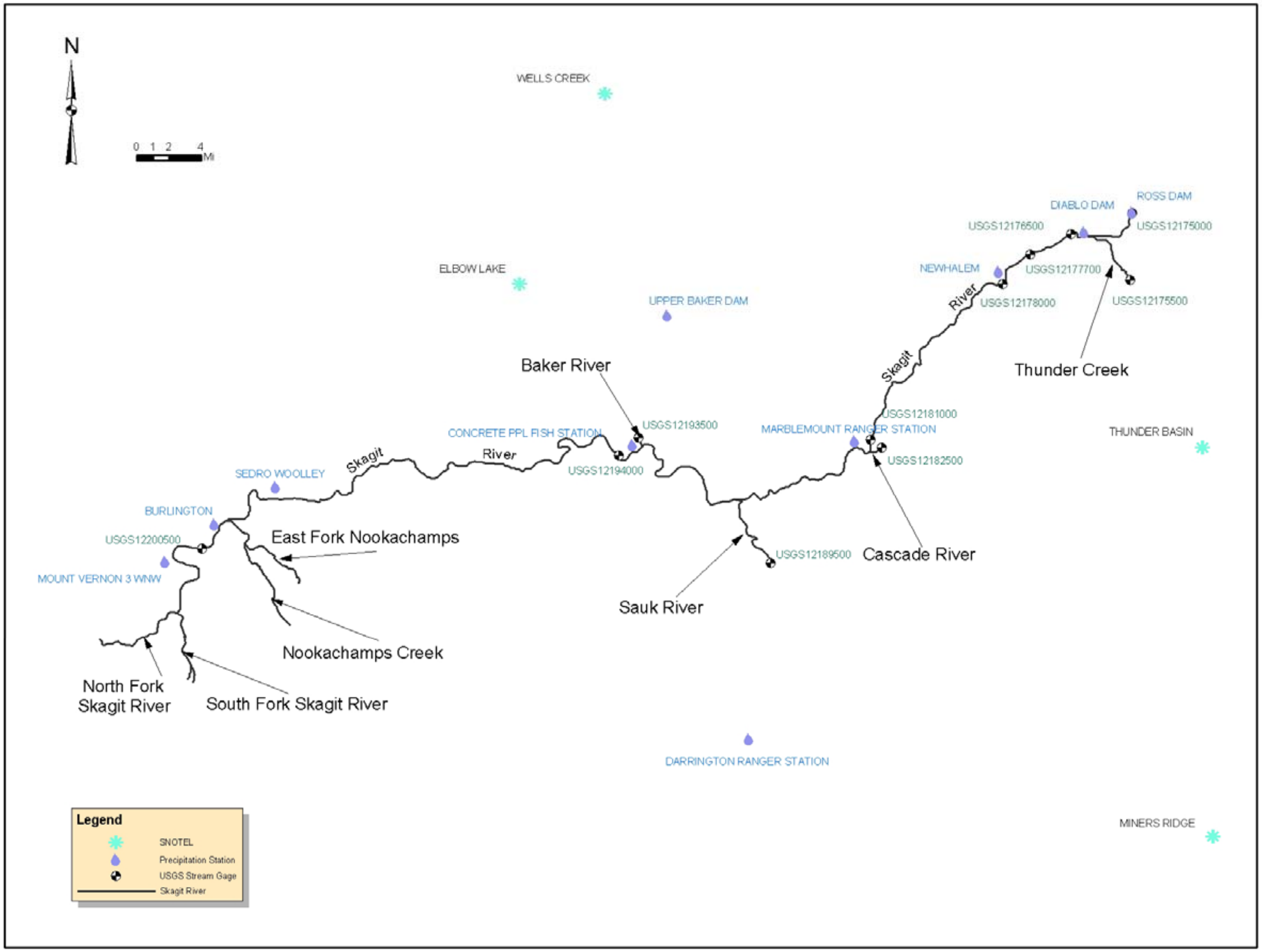

Figure 2 Skagit River streamgage and meteorological station location map

Due to generally recognized orographic effects on the rain pattern and lack of sufficient hourly rainfall, snowpack, temperature and other meteorological data during the historical events, the approach was simplified by performing only minimal optimization of unit hydrograph parameters and loss rates, neglecting snowfall/snowmelt computations, and weighting and shifting rainfall data as needed to match as closely as possible the HMS modeled hydrographs to the observed streamflow hydrographs. Realizing uncertainties of the rainfall-runoff and ground loss process associated with the HMS model, the approach elected was to refine the subbasin areas as much as practical, expecting that a refined watershed geometrical setup would offset such uncertainties, and would improve overall accuracy of the HEC-RAS and HEC-5 routing models.

The use of the HMS model was to reasonably distribute, in conjunction with river routing, the differential hydrographs between observed upstream inflow and downstream outflow hydrographs of a routing reach (for example from Marblemount to Concrete), with consideration that such distribution should be sufficiently accurate as not to compromise accuracy of the HEC-RAS and HEC-5 routing models.

HEC-HMS, HEC-RAS, and HEC-5 models use a large quantity of hydrologic data, including input and output. The HEC-DSS database with HEC-DSSVue Version 1.0.08 (U.S. Army Corps of Engineers, 2003b) was used to provide a database system that enabled HEC-HMS, HEC-RAS and HEC-5 models to conveniently store and retrieve data from a central storage in a common format. The HEC-DSS database system used in this Skagit River Basin historical flood modeling includes observed and computed hourly flow and stage hydrographs, hourly and 15-minute rainfall data, and other hydrologic and hydraulic data.

Four recent major floods were selected for the Skagit River Basin historical flood modeling: two in November 1990, one in November 1995, and the other in October 2003. Selection of these floods for modeling was based on criteria including availability and reliability of adequate observed meteorological and hydrological data, and significant flooding in the downstream Sedro Woolley – Burlington – Mount Vernon floodplain. The computation steps for the HEC-HMS modeling were chosen to be on a 10-minute basis considering the subbasin drainage size and the modeling accuracy.

The 1995 event was used for calibration of the HMS model, and for the HEC-RAS and HEC-5 river routing models. The 2003 event was used as the primary event for verification of these models involving additional back and forth adjustments of the models between calibration and verification. The two 1990 events were strictly used only for verification runs, and involved no additional model adjustment (except that observed debris plugging during a specific event was included in the HEC-RAS model at some bridges).

Subbasin Definition

Figure 1 is a map of the Skagit River Basin that shows the boundaries of the modeled 41 subbasin drainage areas. Each subbasin is listed in Table 1 along with the drainage area, river mile location of the subbasin outlet along the Skagit River, and inflow type (either uniform or local inflow) used in the HEC-RAS model.

Figure 2 is a map of the Skagit River streamgage network. Each gage is listed in Table 2 along with the gage station identification number, gage elevation, drainage area, location of river mile, and period of record. Also shown in Figure 2 are the locations of meteorological stations that record precipitation and other climatological data.

All subbasin geometric data, including the drainage boundary delineation, drainage area, and stream length and slope, were determined by analyzing a Digital Elevation Model (DEM) with HEC-GeoHMS software Version 1.1 (U.S. Army Corps of Engineers, 2003c). The DEM, based on a 10-meter by 10-meter grid, was obtained from the Regional Ecosystem Office (U.S. Bureau of Land Management, 2004).

Meteorological Data

Precipitation data were used as input to the HEC-HMS model. Precipitation and snowpack (SNOTEL) data were obtained from a network of 16 meteorological stations in the region operated by the National Weather Service. Table 3 lists each station along with the station elevation, data type (hourly or daily), annual average precipitation, and period of record. Station locations are shown in Figure 2. In addition, Seattle City Light provided observed hourly precipitation data from Gorge Dam and Thunder Basin during the October 2003 flood.

Hourly precipitation records at nearby stations were assigned to subbasins and used as precipitation temporal distribution for daily record stations. Daily records were converted to hourly records by using the selected precipitation temporal distribution from hourly stations. Daily records were converted to hourly records using the ratio of the total daily precipitation volume between the hourly record station and the daily record station. The accumulated precipitation data recorded at several hourly and daily record stations for the four selected flood events are shown in Figures 3a, 3b, and 3c.

Recorded snowpack levels at SNOTEL stations in the study area vicinity show that there was no snowpack on the ground below elevation 5,000 ft during the 2003 flood. Recorded data show that snow water equivalent was reduced by 0.2 inch at elevation 4,200 ft, and 0.4 inch at elevation 6,200 ft during the 1995 flood. During the first 1990 flood, the snow water equivalent was reduced by 1.0 inch at 4,200 ft, and accumulated by 1.6 inches at 6,200 ft.

Table 1 Subbasin Watershed Data

	Subbasin Watershed	Outlet At Skagit River Mile	Drainage Area (mi^2)	Inflow Type in HEC-RAS
1	Skagit R above Thunder Cr	105.50-103.10	7.12	Uniform Inflow
2	Thunder Cr above gage	NA*	105.81	Local Inflow
3	Thunder Cr below gage	102.00	9.54	Uniform Inflow
4	Skagit R above Stetattle Cr	103.10-101.00	5.22	Uniform Inflow
5	Stetattle Cr	100.00	23.48	Local Inflow
6	Skagit R above Gorge Dam	100.00-96.60	13.74	Uniform Inflow
7	Skagit R above Newhalem Cr	96.60-93.50	12.33	Uniform Inflow
8	Newhalem Cr	93.50	28.01	Local Inflow
9	Goodell Cr	93.10	39.19	Local Inflow
10	Skagit R above Bacon Cr	93.00-82.90	47.26	Uniform Inflow
11	Bacon Cr	82.90	51.14	Local Inflow
12	Skagit R above Diobsud Cr	82.90-80.50	3.17	Uniform Inflow
13	Diobsud Cr	80.50	26.75	Local Inflow
14	Skagit R above Cascade R	80.50-78.00	6.01	Uniform Inflow
15	Cascade R above gage	NA	170.45	Local Inflow
16	Cascade R below gage	78.00	14.46	Local Inflow
17	Skagit R above Illabot Cr	78.00-71.10	28.23	Uniform Inflow
18	Illabot Cr	71.10	48.40	Local Inflow
19	Skagit R above Sauk R	71.10-67.00	19.30	Uniform Inflow
20	Sauk R below Sauk Gage	67.10	16.21	Local Inflow
21	Skagit R above Jackman Cr	67.00-58.00	20.17	Uniform Inflow
22	Jackman Cr	58.00	24.18	Local Inflow
23	Skagit R above Baker R	58.00-56.10	1.53	Uniform Inflow
24	Baker R above Upper Baker Dam	NA	214.19	Local Inflow
25	Baker R between Upper and Lower Baker Dam	NA	83.20	Local Inflow
26	Baker R below Lower Baker Dam	56.10	0.70	Local Inflow
27	Skagit R above Concrete Gage	56.10-54.10	2.97	Uniform Inflow
28	Skagit R above Finney Cr	54.10-47.20	11.01	Uniform Inflow
29	Finney Cr	47.20	53.87	Local Inflow
30	Pressentin Cr	47.00	16.52	Local Inflow
31	Grandy Cr	45.50	18.05	Local Inflow
32	Skagit R above Day Cr	45.50-32.10	77.01	Uniform Inflow
33	Day Cr	32.10	36.00	Local Inflow
34	Skagit R above Hansen Cr	32.10-27.50	40.15	Uniform Inflow
35	Hansen Cr	24.90	17.37	Local Inflow
36	Skagit R above Nookachamps Cr	23.00-18.66	11.04	Uniform Inflow
37	East Fork Nookachamps Cr	NA	36.77	Local Inflow
38	Nookachamps Cr	NA	27.52	Local Inflow
39	Lower Nookachamps Cr	18.66	4.70	Uniform Inflow
40	Skagit R above Mount Vernon Gage	18.66-17.10	2.46	Uniform Inflow
41	Skagit R below Mount Vernon Gage	17.10-8.24	7.80	Uniform Inflow

*NA indicates outlet is not at Skagit River

Table 2 Streamgage Data

Station Name	Type	USGS Station ID	Gage Datum feet above NGVD29	Drainage Area (sq. mi)	RM above confluence	Record Period Water Year
Thunder Creek near Newhalem	Stage/Flow	12175500	1220.00	105.0	3.4	1931 to Present
Skagit River above Ladder Creek near Newhalem	Stage/Flow	12177800	580.00	1160.0	95.4	2004 to Present
Skagit River at Newhalem	Stage/Flow	12178000	401.50	1175.0	93.7	1909 to Present
Newhalem Creek near Newhalem	Stage/Flow	12178100	1080.00	27.9	1.5	1961 to Present
Bacon Creek below Oakes Creek near Marblemount	Stage/Flow	12179900	410.00	48.0	1.5	1999 to Present
Skagit River at Marblemount	Stage/Flow	12181000	305.10	1381.0	78.7	1944 to Present
Skagit River near Rockport	Stage/Flow	12184700	0.00	1655.0	70.8	1985 to Present
Sauk River above Whitechuck River near Darrington	Stage/Flow	12186000	930.00	152.0	32.5	1918 to Present
Baker Lake at Upper Baker Dam near Concrete	Stage/Flow	12191600	0.00	215.0	9.3	1959 to Present
Lake Shannon at Concrete	Stage/Flow	12193000	0.00	197.0	1.2	1926 to Present
Baker River at Concrete	Stage/Flow	12193500	0.00	297.0	0.7	1911 to Present
Skagit River near Concrete	Stage/Flow	12194000	130.00	2737.0	54.1	1925 to Present
Skagit River near Sedro Woolley	Stage/Flow	12199000	0.00	3015.0	22.3	1908 to Present
Skagit River near Mount Vernon	Stage/Flow	12200500	0.00	3093.0	15.7	1941 to Present
Stetattle Creek near Newhalem	Stage/Flow	12177500	906.53	22.0	0.4	1914 to 1984
Skagit River above Alma Creek near Marblemount	Stage/Flow	12179000	358.80	1274.0	85.5	1951 to 1995
SF Cascade River at S Cascade Gl near Marblemount	Stage/Flow	12181100	5290.61	2.4	N/A	1957 to 1993
Salix Creek at S Cascade Gl near Marblemount	Stage/Flow	12181200	5200.00	0.1	N/A	1961 to 1993
Ross Reservoir near Newhalem	Stage	12175000	1.79	999.0	105.2	1940 to Present
Diablo Reservoir near Newhalem	Stage	12176500	0.00	1125.0	101.0	1930 to Present
Gorge Reservoir near Newhalem	Stage	12177700	0.00	1159.0	96.6	1960 to Present
Sauk River near Sauk	Stage	12189500	266.00	714.0	5.4	1911 to Present
Cascade River at Marblemount	Stage	12182500	330.00	172.0	0.9	1929 to 1980

Table 3 Precipitation and SNOTEL Station Data

Station Name	COOP[1]	Elevation (ft)	Data Type	Avg. Annual Precip. (in)	Period of Record
Upper Baker dam	458715	690	Hourly	100.59	10/1965 to Present
Darrington Ranger Station	451992	550	Hourly	80.98	12/1911 to Present
Newhalem	455840	525	Daily	79.50	1/1959 to Present
Diablo Dam	452157	891	Daily	78.87	12/1912 to Present
Sauk River	457353	266	Daily	75.00	8/1966 to Present
Concrete PPL Fish Station	451679	195	Daily	71.39	12/1905 to Present
Marblemount Ranger Station	454999	348	Hourly	70.00	4/1950 to Present
Ross Dam	457185	1,236	Daily	57.44	9/1960 to Present
Sedro Woolley	457507	60	Daily	46.56	8/1896 to Present
Burlington	450986	30	Hourly	37.50	4/1950 to Present
Mount Vernon 3 WNW	455678	14	Daily	32.70	1/1956 to Present
Anacortes	450176	20	Daily	27.05	9/1892 to Present
Thunder Basin (SNOTEL)	20a07s	4,200	Daily	--[2]	10/1988 to Present
Miners Ridge (SNOTEL)	20a40s	6,200	Daily	--[2]	10/1989 to Present
Wells Creek (SNOTEL)	21a31s	4,200	Daily	--[2]	10/1996 to Present
Elbow Lake (SNOTEL)	21a32s	3,200	Daily	--[2]	10/1996 to Present

1. Cooperative Observer Program
2. No Data

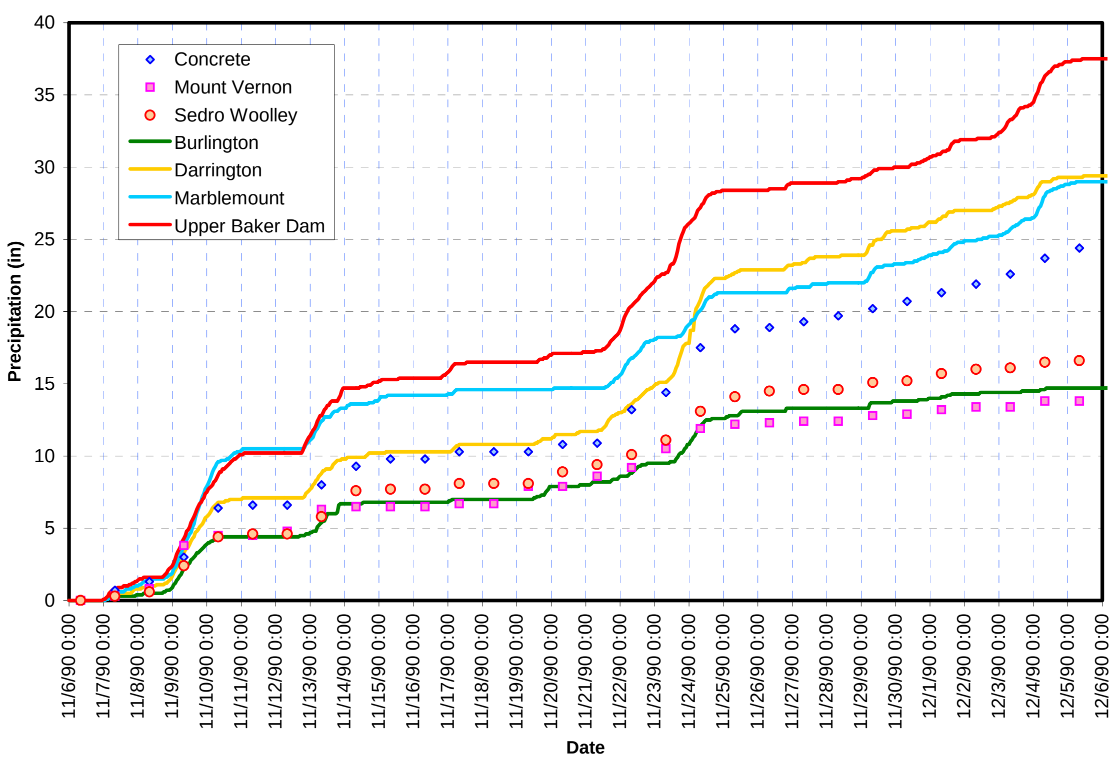

Figure 3a Accumulated precipitation curves (November 1990)

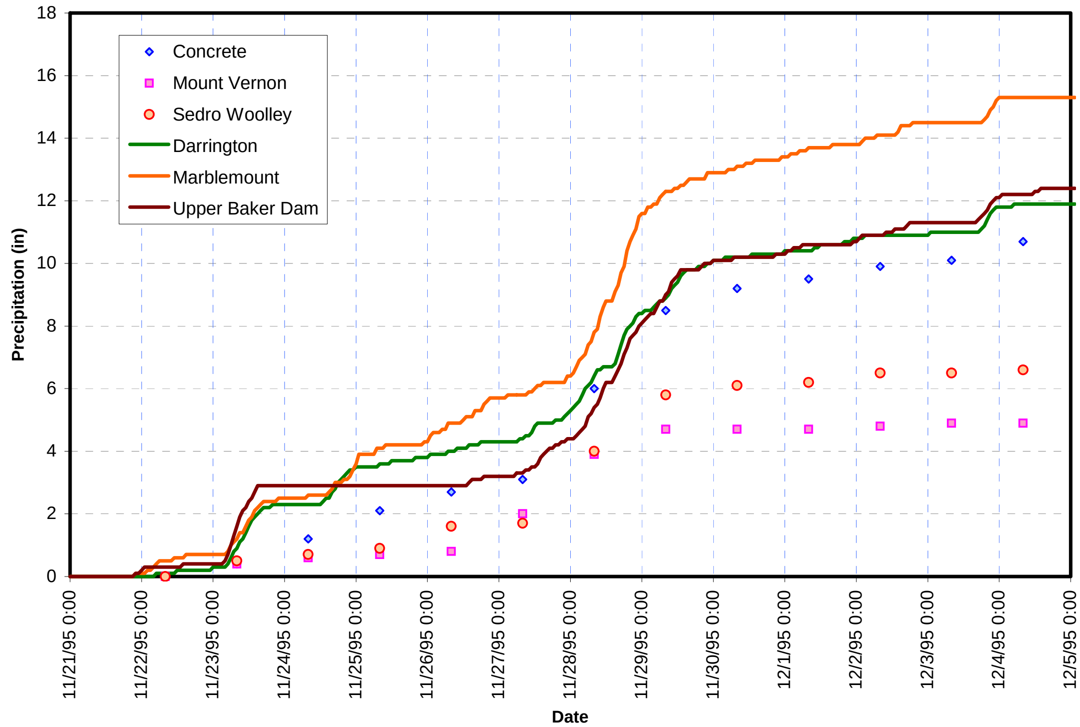

Figure 3b Accumulated precipitation curves (November 1995)

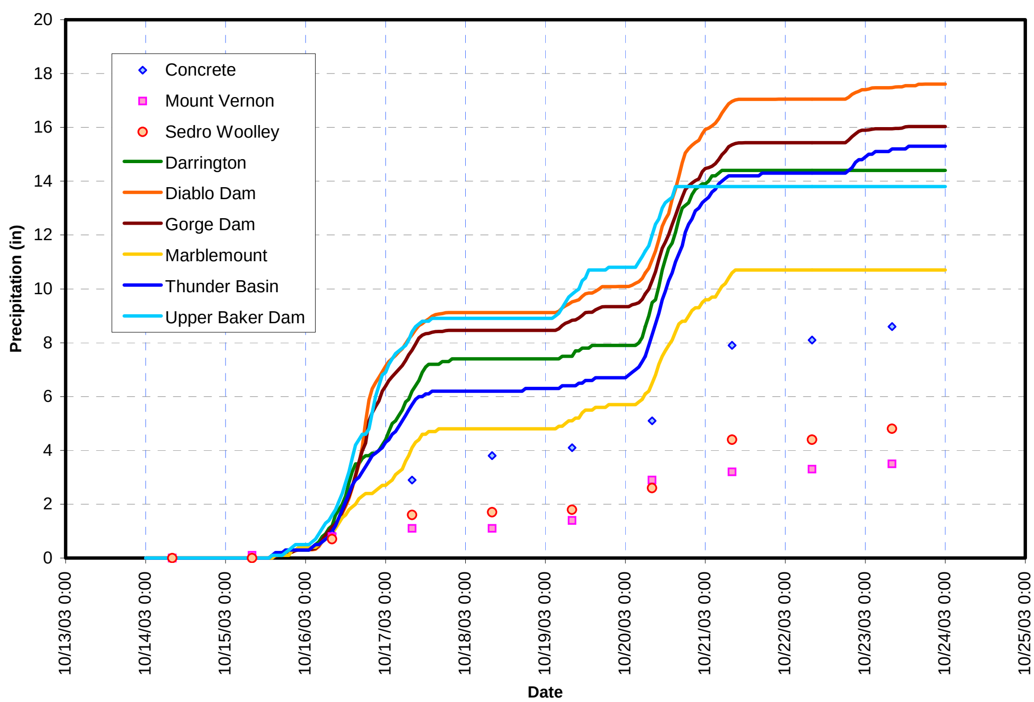

Figure 3c Accumulated precipitation curves (October 2003)

During the second 1990 flood, the snow water equivalent was reduced by 3.2 inches at 4,200 ft and accumulated by 8.8 inches at 6,200 ft. Net snowmelt contribution to the four recent floods selected for the modeling was not considered to be significant enough to warrant separate calculations of snowmelt- and rain-induced runoff. Runoff hydrographs for all subbasins modeled were developed based on calculations of subbasin drainage average rainfalls, ground losses, and base flows.

For the 1995 flood, a separate HEC-1 model was used (as the HMS model does not have the snowfall/snowmelt computational algorithm) to analyze the snowfall/snowmelt effects on the HMS model results for the subbasin above Thunder Creek gage. The HEC-1 analysis indicated that the snowfall /snowmelt effects would add approximately 5 percent of runoff to the HMS modeled peak at this gage during the 1995 flood. The average elevation of the Thunder Creek subbasin above the gage is approximately 5000 feet. The average elevation of the total ungaged drainage area (347 square miles, including Cascade River) between Marbelmount and Concrete, where use of the HMS model to determine the local inflow contribution was most important, is below 3000 feet, much lower than the Thunder Creek subbasin. The snowfall/snowmelt effects on the HMS model results for this area would be less than 5 percent of the HMS modeled peak during the 1995 flood. These effects are insignificant to the HEC-RAS and HEC-5 routing models (as discussed later in the section titled HMS/HEC-RAS/HEC-5 Sensitivity Analyses).

For the 1995 event, only daily rainfall data were available at ThunderBasin. The nearest hourly rainfall data were observed at Marblemount. These hourly data were shifted for 13 hours (with daily totals consistent with observed data) in order to match with the flood hydrograph observed at Thunder Creek gage. A review of snowpack and temperature data, and simulated snowfall /snowmelt using the HEC-1 model was performed to see whether this 13-hour time shift was unreasonable. It was concluded from this review and simulation that the 13-hour shift was reasonable.

Different storms moved differently as observed. Different gage weights were used between different storms as a simplified HMS modeling approach to suit the current study needs. This simplified approach ignores some consistency of rain gage weights between events, sacrifices some accuracy of storm pattern and intensity in consideration of each specific subbasin, and instead emphasizes the importance of the overall storm movement timing.

The effects of orographics on storms are significant temporally and spatially. These effects are generally known but could not be accurately quantified due to lack of storm-specific data. To account for the orographic effects and observed storm movements, time shifting, factoring and weighting of the observed rainfall data was used, as judged to be appropriate, for subbasin rainfall/runoff modeling.

Stream Gage Data

Figure 2 shows locations of the USGS streamgage stations currently in operation in the Skagit River Basin. Table 2 summarizes pertinent data for the current and historical stations. Among these stations, Skagit River near Mount Vernon has 63 years of records, Skagit River near Concrete has 84 years of records, Skagit River at Newhalem has 92 years of records, Skagit River at Marblemount has 39 years of records, Sauk River near Sauk has 75 years of records, Baker River at Concrete has 63 years of records, Thunder Creek near Newhalem has 83 years of records, and Newhalem Creek near Newhalem has 42 years of records.

Data for the largest floods published by USGS for the Skagit River Basin are summarized in Table 4. Recorded flood peaks have been affected by regulation of specific flood control storage provided at Ross Dam since 1954, and at Upper Baker Dam since 1956. Incidental flood storage has likely been provided at Gorge Dam since 1924, at Lower Baker Dam since 1925, and at Diablo Dam since 1931. However, total storage available at these three dams is relatively small.

Optimization of Hydrological Parameters for Gaged Subbasins

Modeling flood runoff with the HEC-HMS program requires complete definition of unit hydrograph and precipitation loss rate criteria for each subbasin. The controlling parameters can be estimated by correlating flood runoffs with storm precipitation, using a suitable number of gaged subbasins. HEC-HMS provides an optimization subroutine in which these variables are optimized by comparing the simulated flood (derived from rainfall volume) and its time distribution and drainage area, with the observed flood hydrograph. The "best" reconstitution is considered to be that which minimizes the weighted squared deviations between the observed hydrograph and a reconstituted hydrograph.

This optimization process for unit hydrograph parameters and ground loss rates was carried out for three gaged subbasins in the vicinity having historical records of flood hydrographs and storm precipitation. These subbasins are the Baker River, Thunder Creek, and Newhalem Creek.

The HEC-HMS computer program derives unit hydrographs by the Clark's Method. The Clark's Method requires two parameters: time of concentration (Tc) and basin storage coefficient (R), both in hours. Loss rates were typically computed by using an initial and uniform loss rate. With this method, all rainfall is lost until the volume of initial loss is satisfied. After the initial loss is satisfied, rainfall is lost at a constant rate. Both loss rate parameters and unit hydrograph parameters were determined through the process of optimization. The optimized loss rates were examined and further adjusted as necessary to be consistent with soil information and antecedent ground conditions. The optimization results of the unit hydrograph parameters for the three gaged subbasins are presented in Table 5, together with estimated Tc and R values for the 38 ungaged subbasins.

Table 4 Historical Floods

Skagit River near Concrete 12194000				Sauk River near Sauk 12189500				Baker River at Concrete 12193500				Thunder Creek near Newhalem 12175500			
Year	Disch. (cfs)	Stage (ft)	Rank	Year	Disch. (cfs)	Stage (ft)	Rank	Year	Disch. (cfs)	Stage (ft)	Rank	Year	Disch. (cfs)	Stage (ft)	Rank
1815	500000	69.30	1	Dec. 1980	98600	18.24	1	Nov. 1962	36600	186.60	1	Apr. 1905	15400		1
1856	350000	57.30	2	Nov. 1990	83400	16.99	2	Nov. 1949	35200		2	Dec. 1980	14500	14.50	2
Nov. 1897	275000	51.10	3	Nov. 1949	82400	16.93	3	Dec. 1979	31200	185.08	3	Nov. 1995	10900	12.76	3
Nov. 1909	260000	49.10	4	Nov. 1995	79000	16.57	4	Jan. 1914	31000		4	Oct. 1955	10800	12.68	4
Dec. 1921	240000	47.60	5	Feb. 1932	68500	15.83	5	Feb. 1951	29700		5	Apr. 1905	10400		5
Dec. 1917	220000	45.70	6	Dec. 1975	65300	15.03	6	Jul. 1972	29400	184.58	6	Nov. 1999	10100	12.34	6
Nov. 1995	160000	41.57	7	Feb. 1951	62700	14.97	7	Jul. 1983	29400	184.57	7	Nov. 1949	9630	12.14	7
Nov. 1949	154000	40.80	8	Dec. 1989	59600	14.55	8	Nov. 1995	29400	184.58	8	Nov. 1962	9610	12.09	8
Nov. 1990	149000	40.20	9	Dec. 1933	56600	14.40	9	Nov. 1983	27500	184.01	9	Jan. 1984	9400	11.98	9
Dec. 1980	148700	40.19	10	Dec. 1979	56200	14.27	10	Nov. 1999	27100	183.90	10	Oct. 1988	9030	11.78	10
Feb. 1932	147000	39.99	11	Dec. 1982	52500	13.84	11	Oct. 1945	27000		11	Apr. 1905	8800		11
Feb. 1951	139000	38.99	12	Nov. 1934	49400	13.54	12	Oct. 1963	27000	183.85	12	Feb. 1932	8780	11.30	12
Dec. 1979	135800	38.57	13	Jan. 2002	48400	13.32	13	Nov. 1955	26900		13	Nov. 1990	8570	11.53	13
Jan. 1935	131000	37.90	14	Jan. 1986	47600	13.22	14	Dec. 1975	26900	183.80	14	Oct. 1963	8490	11.49	14
Dec. 1975	122000	36.88	15	Oct. 1967	47400	13.20	15	Apr. 1992	26300	183.61	15	Dec. 1989	7650	11.01	15
Dec. 1989	119000	36.39	16	Jan. 1974	46700	13.10	16	Sep. 1968	24700	183.06	16	Oct. 1937	7630	11.00	16
Nov. 1932	116000	35.60	17	Nov. 1999	46700	13.03	17	Nov. 1910	24600		17	Dec. 1979	7610	10.99	17
Nov. 1962	114000	35.73	18	Nov. 1962	44800	12.83	18	Nov. 1998	24000	182.96	18	Jul. 1983	6420	10.26	18
Jan. 1984	109000	34.94	19	Nov. 1959	44600	12.80	19	Oct. 1985	23600	182.71	19	Apr. 1905	6360		19
Nov. 1955	106000	34.48	20	Nov. 1932	42500	12.62	20	Apr. 1959	23500		20	Jul. 1997	6130	10.07	20
Nov. 1999	103000	34.15	21	Nov. 1986	42100	12.44	21	Oct. 1947	23000		21	Nov. 1934	6120	10.00	21
Oct. 1945	102000	34.00	22	Oct. 1955	40600	12.23	22	Nov 1990	22500	184.01	22	Jun. 1968	6020	10.00	22

Base flow quantities were also estimated through the optimization process. Base flows were determined from the exponential recession limb preceding the storm runoff hydrograph. This base flow was added to the computed runoff hydrograph ordinates to obtain the subbasin hydrograph. When the flow is below a recession threshold flow, the program prevents it from receding faster by using the pre-flood base flow recession rate.

The current study needs did not warrant extensive calibration of the HMS model. Only limited calibration of the HMS model was performed by optimization of the unit hydrograph parameters, loss rates, etc. for the 1995 event. This optimization result was then applied to the other three events. The main goal of the HMS modeling was to calibrate and verify the HEC-RAS and HEC-5 river routing models, using results of the HMS model to help achieve this goal.

The reproduced and observed flow hydrographs for the selected four flood events at Thunder Creek, Newhalem Creek, and Baker River subbasins are shown in Figures 4 through 7, and indicate reasonable results of optimization. The observed flow hydrographs for the Baker River subbasin were the unregulated flood hydrographs estimated from data provided by Puget Sound Energy.

Table 5 Clark Unit Hydrograph Parameters for Subbasins

	Subbasin Watershed	Tc Optimized (hour)	R Optimized (hour)
1	Skagit R above Thunder Cr	2.90	5.30
2	Thunder Cr above gage	6.50	12.00
3	Thunder Cr below gage	2.60	4.80
4	Skagit R above Stetattle Cr	2.10	3.90
5	Stetattle Cr	3.90	7.11
6	Skagit R above Gorge Dam	1.70	3.20
7	Skagit R above Newhalem Cr	2.10	3.70
8	Newhalem Cr	3.90	6.90
9	Goodell Cr	5.50	9.60
10	Skagit R above Bacon Cr	2.80	5.00
11	Bacon Cr	5.70	10.00
12	Skagit R above Diobsud Cr	0.80	1.40
13	Diobsud Cr	4.90	8.70
14	Skagit R above Cascade R	1.10	1.80
15	Cascade R above gage	10.20	18.00
16	Cascade R below gage	4.20	7.40
17	Skagit R above Illabot Cr	3.20	5.60
18	Illabot Cr	6.60	11.70
19	Skagit R above Sauk R	2.50	4.10
20	Sauk R below Sauk Gage	2.70	4.80
21	Skagit R above Jackman Cr	3.00	5.30
22	Jackman Cr	5.30	9.40
23	Skagit R above Baker R	1.10	1.90
24	Baker R above Upper Baker Dam	8.00	13.50
25	Baker R between Upper and Lower Baker Dam	8.00	13.50
26	Baker R below Lower Baker Dam	0.80	1.40
27	Skagit R above Concrete Gage	1.20	2.10
28	Skagit R above Finney Cr	2.20	3.75
29	Finney Cr	9.23	15.72
30	Pressentin Cr	5.21	8.88
31	Grandy Ck	4.89	8.32
32	Skagit R above Day Cr	4.95	8.34
33	Day Cr	6.76	11.51
34	Skagit R above Hansen Cr	4.70	8.00
35	Hansen Cr	5.11	8.70
36	Skagit R above Nookachamps Cr	2.40	4.09
37	East Fork Nookachamps Cr	6.24	10.62
38	Nookachamps Cr	7.37	12.55
39	Lower Nookachamps Cr	2.08	3.53
40	Skagit R above Mount Vernon Gage	1.89	3.22
41	Skagit R below Mount Vernon Gage	1.70	2.89

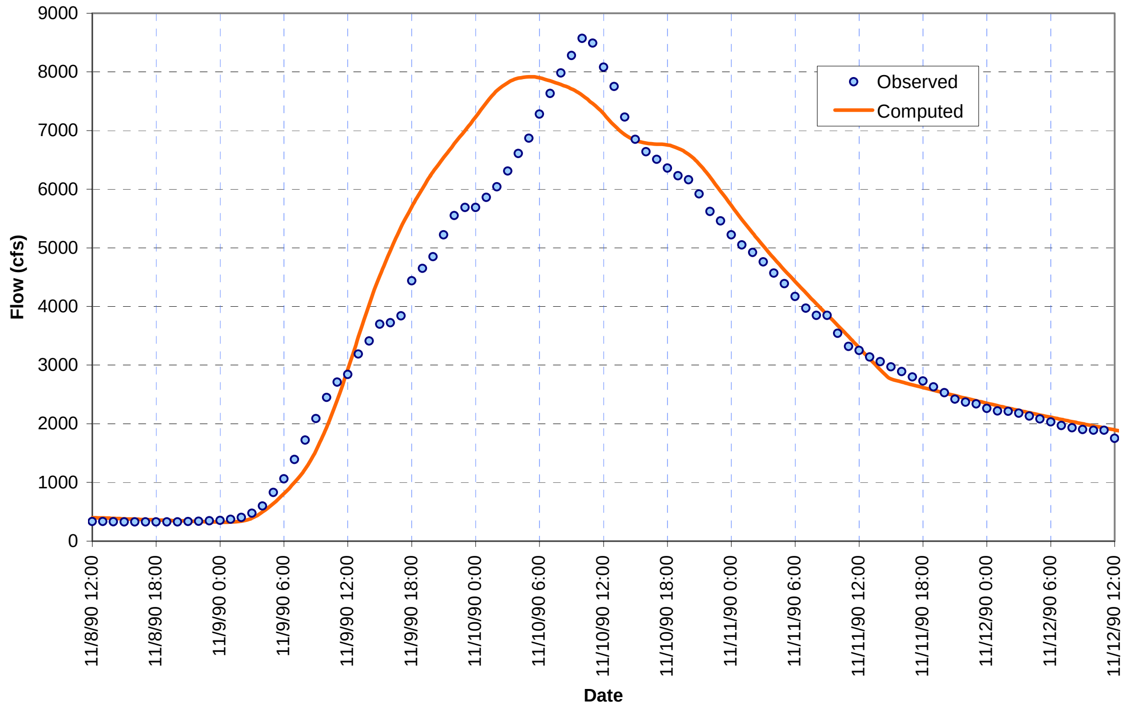

Figure 4a Comparison of computed and observed hydrographs for Thunder Creek, November 1990 flood

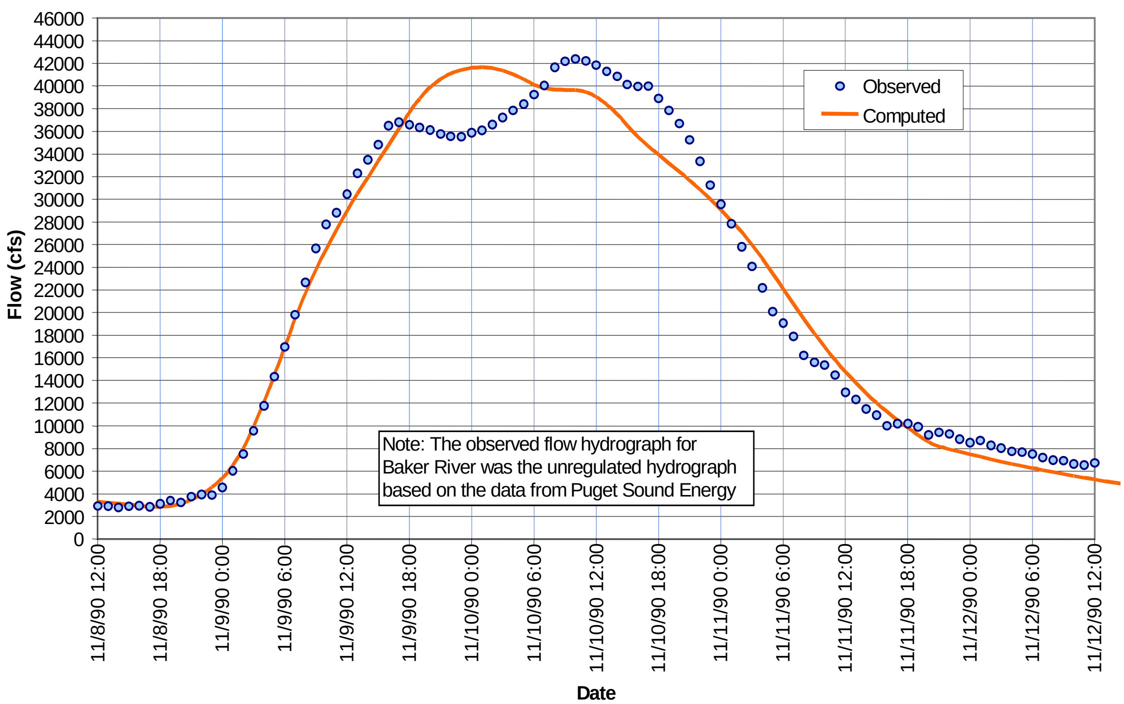

Figure 4b Comparison of computed and observed hydrographs for Baker River, November 1990 flood

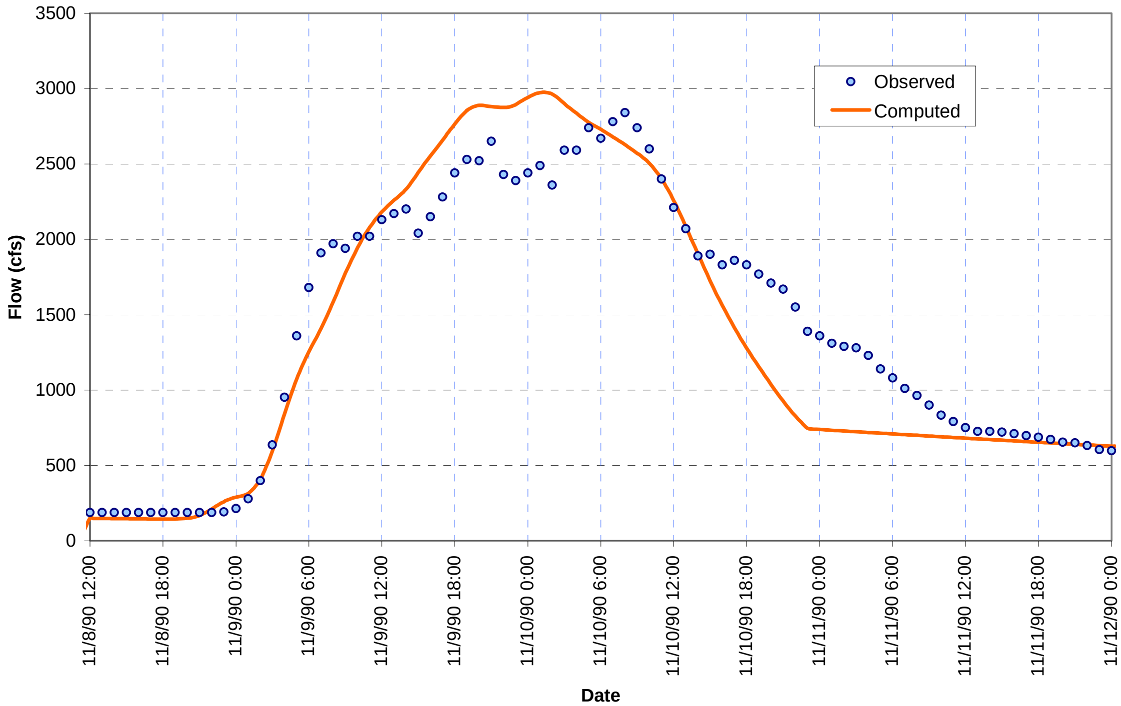

Figure 4c Comparison of computed and observed hydrographs for Newhalem Creek, November 1990 flood

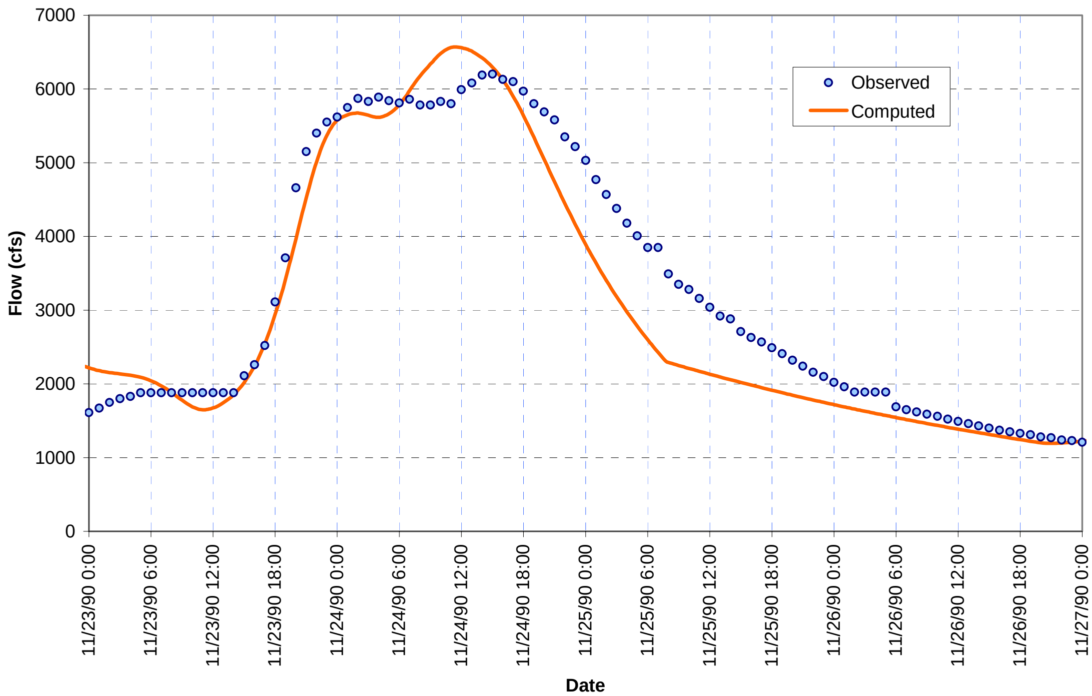

Figure 5a Comparison of computed and observed hydrographs for Thunder Creek, November 1990 flood

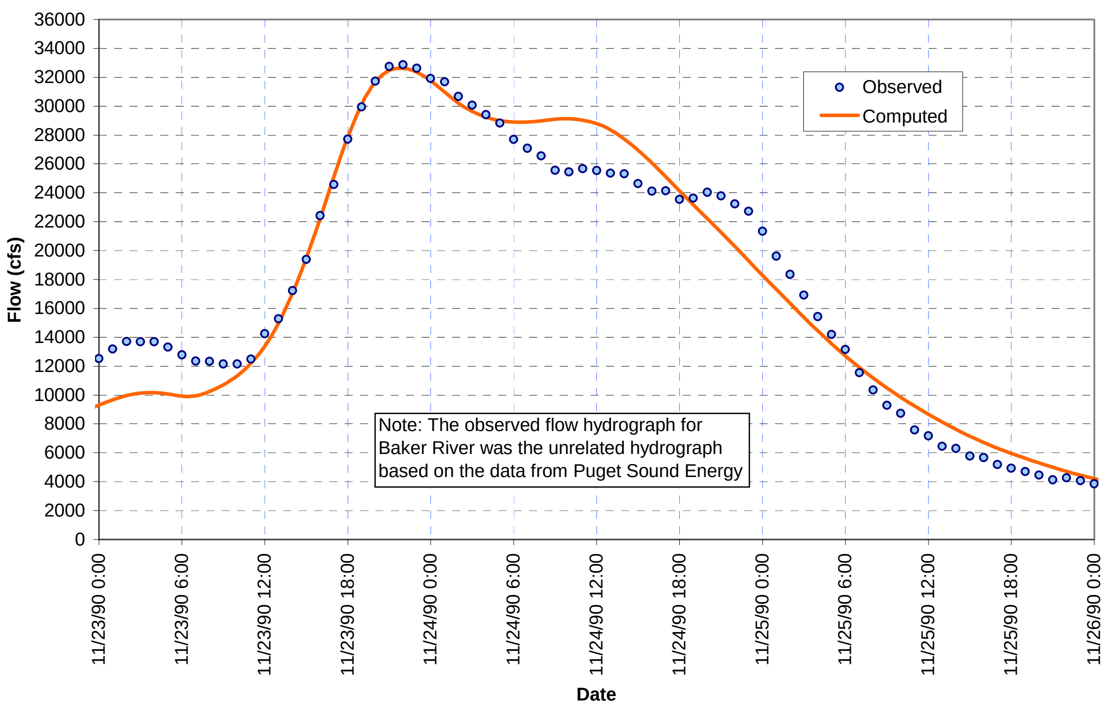

Figure 5b Comparison of computed and observed hydrographs for Baker River, November 1990 flood

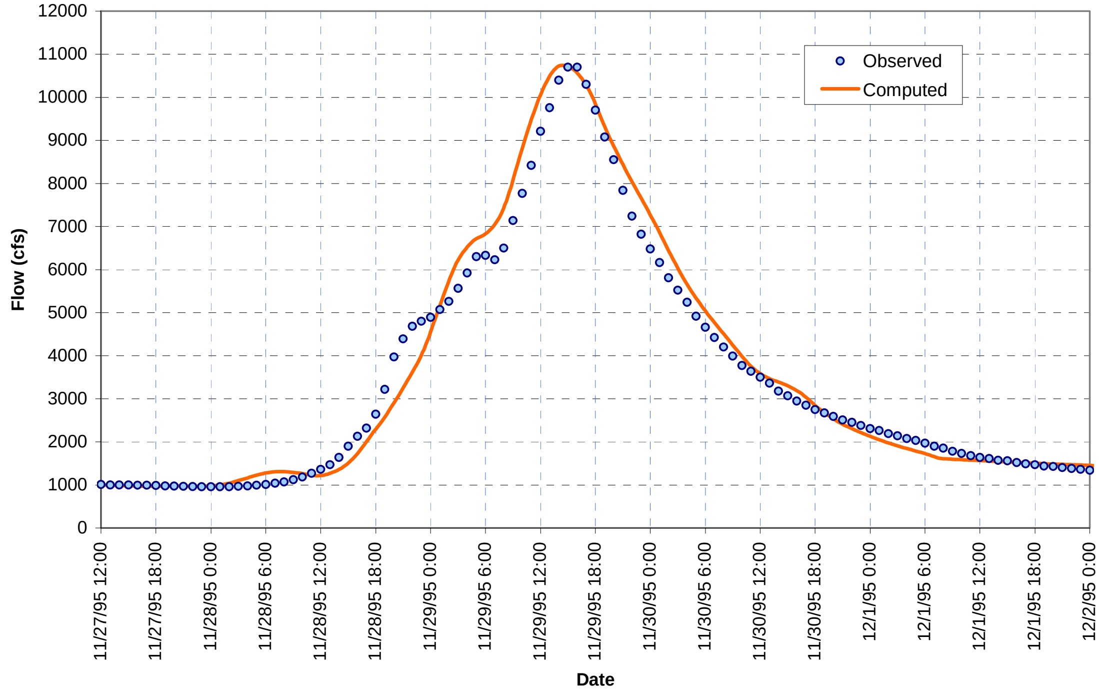

Figure 6a **Comparison of computed and observed hydrographs for Thunder Creek, November 1995 flood**

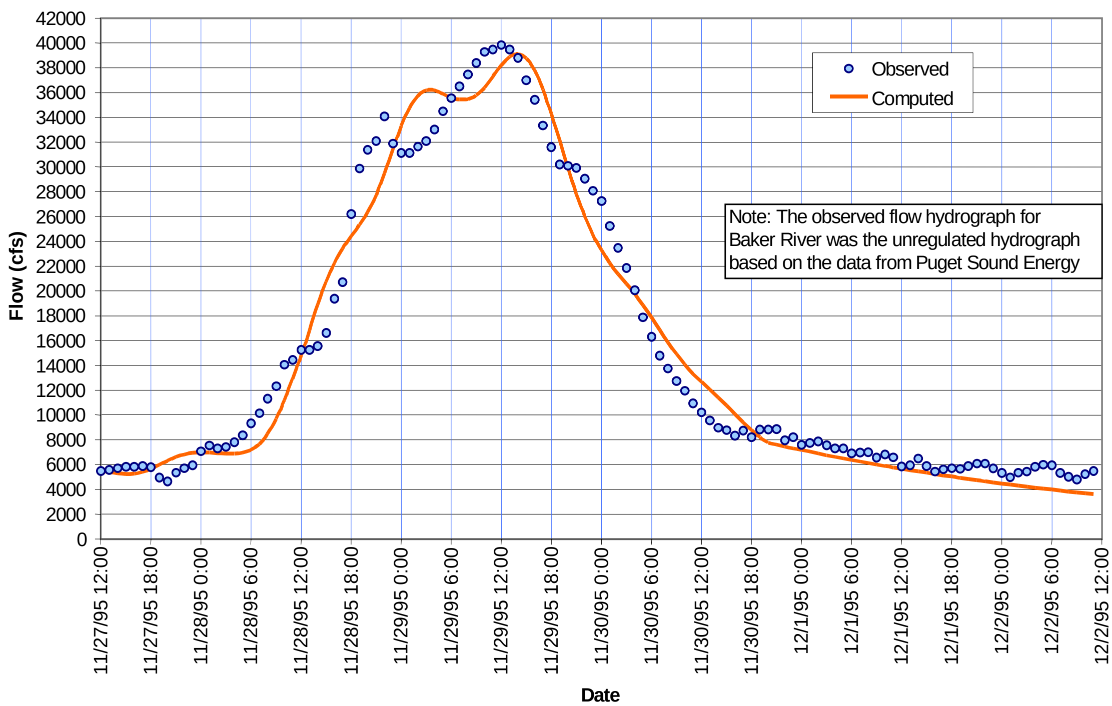

Figure 6b **Comparison of computed and observed hydrographs for Baker River, November 1995 flood**

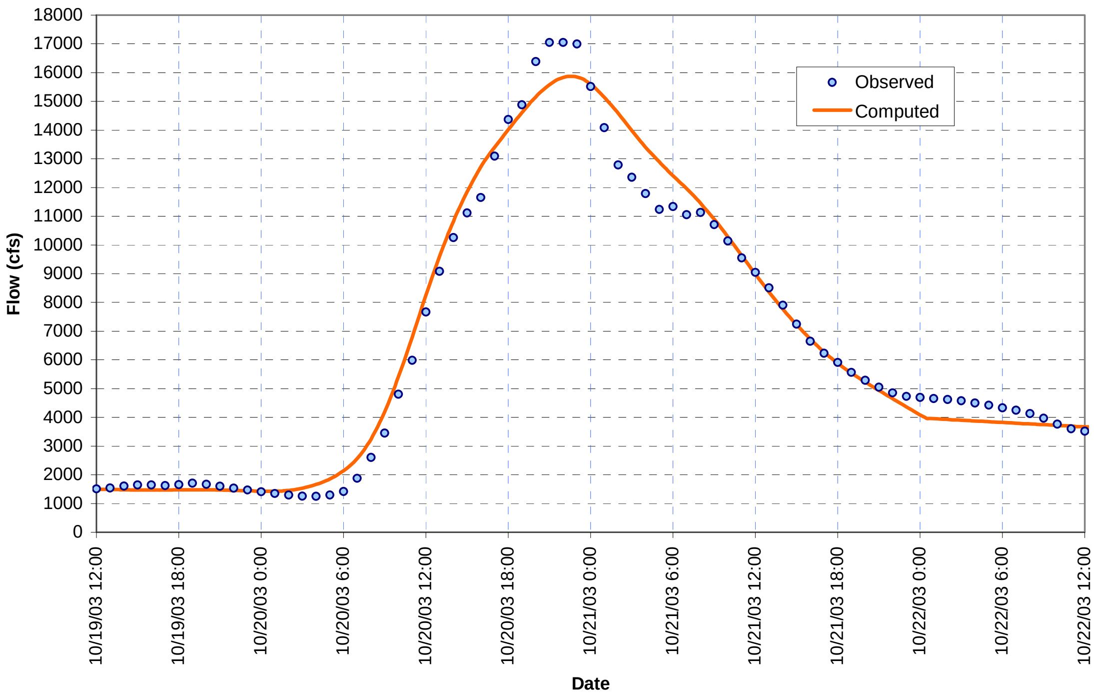

Figure 7a Comparison of computed and observed hydrographs for Thunder Creek, October 2003 flood

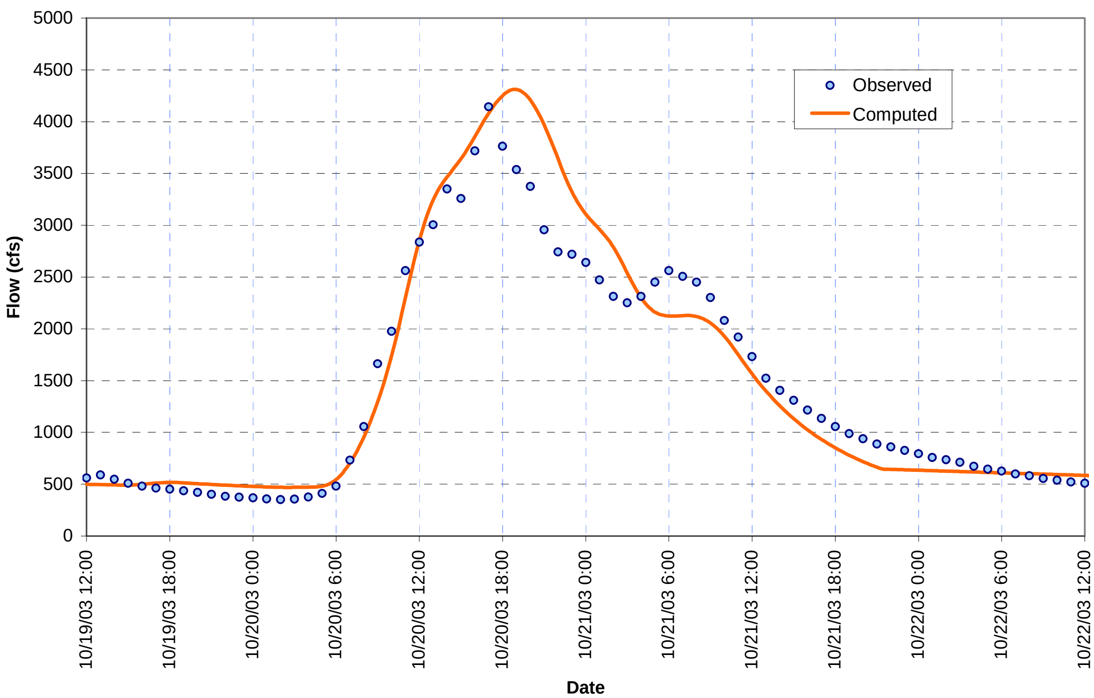

Figure 7b Comparison of computed and observed hydrographs for Newhalem Creek, October 2003 flood

Derivation of Hydrological Parameters for Ungaged Subbasins

Upon optimization of hydrological parameters for gaged subbasins, a consistent relationship between the two Clark's unit hydrograph parameters (Tc and R) was established. The R/(Tc+R) ratios for the 1995 and 2003 events with and without snowfall and snowmelt calculations vary between 0.60 and 0.67. A constant ratio of R/(Tc+R)=0.63 was selected for use for all subbasins and flood events.

The Tc parameters as optimized by HEC-HMS were then compared with a computed Tc using the equation provided in the Design of Small Dams, p. 41, Figure 3-7 Unit Hydrograph Lag Relationships - Coastal and Cascade Ranges of California, Oregon, and Washington (U.S. Bureau of Reclamation, 1987): $L_g = 26K_n(\frac{LL_{ca}}{S^{0.5}})^{0.33}; K_n = 0.150$, resulting in an adjustment factor being applied to the computed Tc value for each gaged subbasin and flood event. Applying a similar Tc adjustment factor and the constant R/(Tc+R) ratio to a Tc value computed by the above equation, final values for both Tc and R were derived and used as input to the HEC-HMS rainfall runoff model for each of the 38 ungaged subbasins for each of the four selected flood events.

Available regional R/Tc+R) values are very limited. In order to quantify the sensitivity, further modeling was conducted. For the subbasins between Marblemount and Concrete, use of the R/(Tc+R) values between 0.54 and 0.72 were examined in conjunction with a plus/minus 20 percent variation of the Tc values used in the HMS model. It was found that these R/(Tc+R) values would impact the HEC-RAS model flood peak results by less than plus/minus 2 percent changes measured at Concrete gage for the 1995 and 2003 floods. The corresponding maximum changes in the flood stage profile based on the HEC-RAS modeling between Marblemount and Concrete would be up to plus/minus 0.3 feet. These changes are insignificant, well within accuracy of the HEC-RAS model calibration and verification. The HEC-1 model optimization including snowmelt calculations for the Thunder Creek subbasin (only for the 1995 event; no snowmelt for 2003 event) show that the R/(Tc+R) values are 0.60 and 0.62 for the 1995 and 2003 floods, respectively. The corresponding values are 0.47 and 0.67 for the first and the second 1990 floods.

Other hydrograph parameters, including precipitation losses and base flows for the ungaged subbasins, were estimated and were part of the HEC-HMS input for flow hydrograph computation. Loss rates were based on optimized results from the gaged subbasins and soil data, adjusted to account for the ground condition between events. Base flow was based on optimized results from the gage subbasins adjusted proportionally to the basin area. The final Clark's unit hydrograph parameters (Tc and R) after optimization are summarized in Table 5 for each Skagit River subbasin.

HMS / HEC-RAS / HEC-5 Sensitivity Analyses

The HMS modeling approach is better than any other approach for the purpose of generating hydrographs that most closely represent actual flow contribution from the ungaged subbasins during the observed events. In order to answer the question of how extensive the HMS modeling needs to be in order to trust in the accuracy of the HEC-RAS and HEC-5 results, additional sensitivity analyses were performed to quantify the extent to which the HMS model could affect the HEC-5 and HEC-RAS results. The results of these sensitivity analyses (presented below) demonstrate that even an assumed significant lack of accuracy of the HMS model would have insignificant effects on the results of the HEC-RAS or the HEC-5 routing models.

Initially, in developing the HMS model in conjunction with improving the HEC-RAS and HEC-5 routing models, the distinct characteristics of the Skagit River routing reaches were recognized, and the level of modeling details and accuracy for each routing reach were selected accordingly and in consistency with the quality of available hydrometeorological data. For a general characterization, the Skagit River is divided into three routing reaches. The first (or upper) reach is above the Marblemount gage, the second (or middle) reach is between the Marblemount gage and the Concrete gage, and the third (or lower) reach is below the Concrete gage. Their characteristics are separately discussed below.

A. Upper Routing Reach - Above Marblemount Gage

The first reach does not have much floodplain storage to attenuate flood peaks, and observed flood hydrographs are readily available at Ross Dam, Newhalem gage, and Marblemount gage. For this reach, flood routing does not have significant effects on re-shaping the hydrographs, other than lagging the time. The reach lengths between two adjacent gages are short, and the flow travel times are only 1 hour (from Ross Dam to Newhalem gage) or 2 hours (from Newhalem gage to Marblemount gage). The total local flow contribution could be adequately determined either by a direct subtraction of the observed hydrographs between two adjacent gages (for example, Newhalem gage and Marblemount gage), or from the HMS model. Whether we input the total local inflow hydrographs as one tributary inflow for combination at the downstream gage site (Marblemount gage), or as several tributary inflows for combination and routing, or as a uniform inflow for river routing (between Newhalem gage and Marblemount gage), the difference between any of these combined/routed total hydrographs and the observed hydrographs is insignificant.

This indicates that the local inflow hydrographs generated either by direct subtraction of observed hydrographs or from the HMS model would have very insignificant, or no, effects on the calibration and verification of the HEC-RAS and HEC-5 routing models in this reach.

B. Middle Routing Reach - Between Marblemount Gage and Concrete Gage

The second reach has significant floodplain storage to attenuate flood peaks, and has three major tributaries (Cascade, Sauk, and Baker Rivers). Along this reach, the total ungaged drainage area (347 square miles, including Cascade River) is 12.7 percent of the total drainage area at Concrete gage (2,737 square miles). The total local inflow contribution to the Concrete gage peak during the most recent two floods, the 1995 and the 2003 events, from this area was estimated to be 12.4 and 5.7, respectively. The HMS model results for this reach are relatively more significant than those for the other two reaches for calibration and verification of the HEC-RAS and HEC-5 routing models.

The order of the sensitivity magnitude of the HMS model results to the HEC-RAS model results was examined. A deviation of 20 percent was assumed by adding to or subtracting from all of the flood hydrographs generated from the HMS model for the ungaged subbasins along this reach. These plus and minus 20 percent deviations from the HMS model results would impact the HEC-RAS model flood peak results by +2.5 and -2.3 percent, respectively, for the 1995 flood, and by +1.5 and -1.3 percent, respectively, for the 2003 flood, as measured at the Concrete gage. The corresponding maximum changes in the flood stage profile based on the HEC-RAS modeling in this reach would be +0.63 and -0.62 feet for the 1995 flood, and +0.33 and -0.32 feet for the 2003 flood, respectively. These numbers are well within the accuracy of some observed highwater mark surveys, and within the accuracy of the HEC-RAS model calibration and verification.

Based on the above-discussed sensitivity analysis, it was concluded that even an assumed significant lack of accuracy of the HMS model would have insignificant effects on the accuracy of the HEC-RAS routing model for this reach. This conclusion is also true for the HEC-5 routing model.

C. Lower Routing Reach - Below Concrete Gage

The third reach has a major floodplain storage area along the lower Nookachamps Creek, and has a relatively small amount of total local flow contribution to the flood peak at Mt. Vernon gage. The primary efforts to improve the HEC-RAS routing model involved adding the Nookachamps Creek sub-reaches and storage areas for more accurately representing the flow channel and floodplain storage geometry and for more accurately reproducing the physical process during floods. A lower level of the HMS model accuracy was assumed for this reach as compared with the model accuracy for the second reach.

The order of the sensitivity magnitude of the HMS model results to the HEC-RAS model results was examined. A deviation of 40 percent was assumed by adding to or subtracting from all of the flood hydrographs generated from the HMS models for the ungaged subbasins along this reach. The plus and minus 40 percent deviations from the HMS model results would impact the HEC-RAS model flood peak results by +1.1 and -1.1 percent, respectively, for the 1995 flood, and by +1.0 and -1.0 percent, respectively, for the 2003 flood, as measured at the Mt. Vernon gage. The corresponding maximum changes in the flood stage profile based on the HEC-RAS modeling in this reach would be +0.18 and -0.18 feet for the 1995 flood, and +0.17 and -0.16 feet for the 2003 flood, respectively. These numbers are well within the accuracy of the observed highwater mark surveys and within the accuracy of the HEC-RAS model calibration and verification.

Based on the above-discussed sensitivity analysis, it was concluded that even an assumed very significant lack of accuracy of the HMS models would have insignificant effects on the accuracy of the HEC-RAS routing model for this reach. The HEC-5 routing model ends at Concrete gage and does not include this reach.

In summary, the results of the sensitivity analyses demonstrate that even an assumed significant lack of accuracy of the HMS model would have insignificant effects on the accuracy of the HEC-5 or the HEC-RAS routing models. The HMS modeling, as performed and discussed above, is the best approach and is adequate for generating required historical flood hydrographs for the purpose of the calibration and verification of the HEC-RAS and HEC-5 flood routing models.

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