BEFORE THE WASHINGTON UTILITIES AND TRANSPORTATION COMMISSION
Docket No. UE-070074
Puget Sound Energy, Inc.'s
Motion to Extend Deferred Accounting

EXHIBIT A

TECHNICAL MEMORANDUMS

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 1

DATA ACQUISITION

December 3, 2004
Revised December 22, 2004
Revised February 4, 2005
Revised July 15, 2005

(Revision 3 - FINAL)

Although a revision date of July 15, 2005 is indicated in the header, this memo actually reflects the project conditions and what was known of the project as of the end of February 2005. Since February, work has continued on the project, more data has been acquired, and there have been modifications to the work plan. However, this memo is intended to represent a "snapshot" in the project chronology, subsequent to the Board of Consultant (BOC) February review of the Phase I technical memorandums, of which this is one. The main report will be the ultimate product and final source of information for this project.

INTRODUCTION

This memorandum summarizes the data acquired thus far in support of the Part 12 Probable Maximum Precipitation (PMP) and the Probable Maximum Flood (PMF) analysis for the Baker River Project. The PMP portion of the study is being conducted using procedures from Hydrometeorological Report No. 57 (NWS 1994). The memo also itemizes additional data that will potentially be acquired subsequent to the issuance of this memo and prior to initiation of the PMP/PMF analysis.

The Baker River Project is comprised of the Upper Baker Dam and Lower Baker Dam. The reservoir impounded behind Upper Baker Dam is known as Baker Lake. The reservoir impounded behind Lower Baker Dam is known as Lake Shannon. The size of the tributary basin to Baker Lake is 215 square miles and the size of the local tributary basin to Lake Shannon is 82 square miles. The total tributary area upstream of Lower Baker Dam is therefore 297 square miles (see Figure 1). A brief comparison of the range of climatological conditions at two stations in the Baker River basin is summarized in Table 1. This table is reprinted from USACE (2004), which included data only through 1997. Both of these stations are still in operation.

Table 1. Summary of Climatologic Data

Station	Elev. (feet)	Period of Record	Mean Annual Precip. (inches)	Max. Annual Precip. (inches)	Min Annual Precip. (inches	Mean Annual Snowfall (inches)	Mean Annual Temp. (^{O}F)	Max Daily Temp. (^{O}F)	Min Daily Temp. (^{O}F)
Lower Baker Fish Trap	195	1920 – 1997	69.43	82.94	39.18	33.0	50.7	106	-1
Upper Baker Dam	690	1961 - 1997	101.83	132.61	72.76	not available	46.8	102	5

The data that were acquired or that will be acquired during Phase I of the PMF study is presented in this memorandum. The data are categorized into the following groups

- Physical Data
- Hydrologic Data
- Precipitation Data
- Snow Data
- Other Meteorologic and Climatologic Data

Once the data has been acquired, a subsequent task in the PMP/PMF analysis will be to identify candidate events that will be used for calibration and verification of the runoff model. The FERC Engineering Guidelines (FERC 2001) provide a list of desirable characteristics for the events that are to be used to calibrate and verify the runoff model. These characteristics include: largest floods that have occurred; similar type and season as the likely PMF; uniform spatial and temporal precipitation over entire basin; generation of at least one inch of runoff; and significant overbank flow.

An initial list of events that may meet these criteria was developed from the largest flood events on the main stem of the Skagit River and the largest runoff events from the Upper Baker tributary subbasin. A more detailed analysis of the events will be provided in the “Historical Data Analysis” technical memo to be produced later. Candidate events were identified by ranking the top 15 annual peaks on the main stem Skagit River in addition to the top 15 reconstructed average daily inflows to Upper Baker (Table 2). Reconstructed mean daily inflow values for Lake Shannon are not immediately available.

The period of record for Skagit River near Concrete (USGS gage 12194000) is 1924 to the present. However, the main stem peak flows itemized in Table 2 were drawn from a subset of this data, so as to include only the regulated conditions on the main stem. Existing flood control operation upstream of Concrete is that 74,000 acre-feet at Upper Baker Dam and 120,000 acre-feet at Ross Dam (City of Seattle) are available for flood control storage. This storage at Ross Dam has been available since 1954, and for Upper Baker Dam, flood control storage has been available since 1956. Therefore, although the period of record for Skagit River near Concrete (USGS gage 12194000) extends back to 1924, the peak flows in Table 2 were drawn from the subset of the record between water years 1956 and 2003, inclusive. As a point of comparison between events in Table 2, a 148,000 cfs event has a 20-year return period on the regulated flood frequency curve for USGS gage 12194000 (USACE 2004), and a 176,000 cfs event has a 50-year return period on the regulated flood frequency curve for USGS gage 12194000 (USACE 2004).

With three exceptions, the peak values for the listed events were obtained from the annual peak series for the Skagit River near Concrete (USGS gage 12194000). The published annual series does not yet include the October 2003 event, which produced the annual peak for water year 2004, and coincidentally the highest recorded peak flow at the station. Likewise, the published annual series does not yet include the December 2004 event, which produced the highest peak to date for the current Water Year 2005. Finally, the near record rainfall of November 1990 resulted in two distinct peaks on the main stem that were nearly identical in magnitude. The highest peak was included in the annual series. Since the two 1990 peaks were so close in magnitude, the second peak was also included in Table 2.

The reconstructed mean daily inflow values from the tributary area to Baker Lake were provided by PSE for the period of record of 1926 through 2004. However, the mean daily inflows included in Table 2 were drawn from a subset of this data so as to only include those years for which there is hourly precipitation data available within the watershed (1949 to present). Presumably, the pool of candidate calibration events will only include those years for which hourly precipitation is available within the watershed. Hydrologic model calibration will be complicated by the mountainous terrain, which effects the spatial and temporal distribution of precipitation. Therefore, a complete lack of precipitation data within the watershed makes consideration of events prior to 1949 unlikely for calibration. The maximum one-day flow for Water Year 2004 was obtained from USACE (2004) and added to the table so as to include the October 2003 event in the ranking.

Table 2. Ranking of Historical Flood Events

Ranking of Annual Peak Series for Skagit River Near Concrete, WA (USGS Gage 12194000)			**Ranking of Reconstructed Mean Daily Inflows to Baker Lake**		
Period of Record (Water Year 1955 to current)			**Period of Record (Calendar Year 1949 through 2003)**		
Ranking	**Date**	**Instantaneous Peak Flow (cfs)**	**Ranking**	**Date**	**Maximum One-Day Flow (cfs)**
1	10/21/03[a]	166,000	1	10/17/03	28,124
2	11/29/95	160,000	2	11/10/90	27,185
3	11/10/90	149,000	3	1/4/84	23,961
4	12/26/80	148,700	4	12/26/80	23,236
5	11/24/90[a]	146,000	5	10/20/03	23,026
6	12/18/79	135,800	6	11/29/95	23,022
7	12/4/75	122,000	7	11/8/95	22,385
8	12/4/89	119,000	8	1/7/02	22,073
9	11/20/62	114,000	9	2/10/51	19,912
10	1/5/84	109,000	10	10/17/75	19,858
11	11/3/55	106,000	11	11/9/90	19,699
12	11/12/99	103,000	12	11/24/90	19,581
13	12/4/82	101,000	13	12/13/98	19,037
14	12/11/04[a]	99,400	14	11/10/89	18,972
15	1/8/02	94,300	15	12/4/89	18,419

a. These values are not from the currently published annual series for Skagit River Near Concrete, WA (USGS Gage 12194000)

PHYSICAL DATA

This section provides a review of the available data and information that describe the physical attributes of the Baker Project, comprised of Upper Baker Dam, Lower Baker Dam, Baker Lake, and Lake Shannon. This section describes the data that is available, the data that Tetra Tech has obtained, and the data that will still need to be obtained prior to Phase II.

All of the data that describe the physical attributes of the Baker Project are available from the following resources:

- *Periodic Safety Inspection Report No. 7 for Upper Baker River Development and Lower Baker River Development*. Three Volumes. (Stone and Webster 1999)
- *Baker River Water Control Manual* (USACE 2004)
- *Baker River Hydroelectric Project Upper Baker Development FERC Part 12 Safety Inspection Report - FERC Project 2150.* Prepared for Puget Sound Energy. (MWH 2004).
- *Baker River Hydroelectric Project Lower Baker Development FERC Part 12 Safety Inspection Report - FERC Project 2150.* Prepared for Puget Sound Energy. (MWH 2004).
- *Hydrologic Information Relevant to the Relicensing of the Baker River Project*. Two CDs. Prepared for PSE by R2.

Tetra Tech has possession of each of the resources listed above, and therefore has the readily available, previously published information for the key physical characteristics of the project. Specific elevations of key components and operating elevations at each of the facilities can be found in the resources mentioned above or in the site visit technical memorandum (Tetra Tech 2004). The data and information contained in these resources that will be of primary use for the PMF analysis includes the following:

- Elevations of key features of each dam, including the top of the dam, the spillway crest, and the top of the spillway gates.
- Key operating pool elevations, including minimum operating pool, minimum flood control pool, top of flood control pool, maximum surcharge pool
- Spillway rating curves
- Spillway gate regulation schedule for Upper Baker Dam
- Flood control rule curve for Upper Baker Dam
- Reservoir rating tables, expressing the relationship between elevation and storage volume, are available for the two reservoirs. Current data is available at Upper Baker Dam up to the surcharge pool elevation (730.77 feet NAVD88), and is available at Lower Baker Dam up to the normal full pool elevation (442.35 feet NAVD88). The data is based on a survey that was completed in March 6, 2001.
- Extension of the elevation-storage curves to elevation 733.70 feet (NAVD88) at Upper Baker Dam and to elevation 448.70 feet (NAVD88) at Lower Baker Dam. The vertical extrapolation of these curves was conducted by staff at PSE.

Additional physical data and information that will be acquired for the PMF analysis includes:

- Routing of the PMF hydrograph through the reservoirs will result in pool elevations higher than the normal full pool elevation. Therefore the depth versus storage volume rating tables will have to be extended above what is currently available. An extended table of Upper Baker Dam reservoir storage is provided in USACE (2000), up to elevation 733.86 feet (NAVD88), along with an equation that computes storage volume from a known pool elevation. Similarly, an extended table of Lower Baker Dam reservoir storage is provided in USACE (2000), up to elevation 443.84 feet (NAVD88), along with an equation that computes storage volume from a known pool elevation. The top of Upper Baker Dam is at elevation 735.77 feet (NAVD88) and the top of Lower Baker Dam is elevation 450.62 feet (NAVD88).

- Spillway rating curves are available for Lower Baker and Upper Baker spillway (USACE 2004). The curves extend only up to elevation 442.35 NAVD88 (normal full pool) at Lower Baker and up to elevation 732.77 NAVD88 (five feet above normal full pool) for Upper Baker. Routing of the PMF hydrograph through the reservoirs will result in higher pool elevations, and therefore the rating curves will have to be extended up to at least the top of each dam.

HYDROLOGIC DATA

This section presents a review of hydrologic data that has been collected by various agencies and other entities. The first portion describes the data available. The second section indicates data that Tetra Tech has obtained and data that will still need to be obtained prior to Phase II.

Hydrologic Data Available

The two resources used for obtaining hydrologic data were Puget Sound Energy (PSE) and United States Geologic Survey (USGS). PSE maintains hourly operation data for each dam, including forebay elevation, turbine discharge, and total spillway discharge. USGS currently maintains and has historically maintained gaging stations throughout the greater Skagit River watershed.

Within the Baker River basin, there are seven abandoned USGS gaging stations and one currently operating USGS gaging station (see Figure 1). The sole gaging station that is currently in operation is Baker River at Concrete, WA (12193500) and is located just downstream of Lower Baker Dam. It is occasionally affected by backwater when stage in the Skagit River is high, and therefore, data from this station will likely not be used in the analysis. Available spill and penstock flow data from Lower Baker Dam can be used to supplement the data collected at this gaging station. In addition to peak and daily flow records, the abandoned USGS gaging stations likely have hourly records of gage height that can be converted to flow rate.

Outside of the Baker River basin, the USGS currently maintains and has historically maintained streamflow stations on the main stem Skagit River and numerous tributaries to the main stem Skagit River (see Figure 2). The main stem flow data will likely not be of use in the PMP/PMF analysis. However, hourly data from the local tributaries outside of the Baker River basin may be of use and will be obtained. This information, combined with snowpack and precipitation, may provide additional data to compare runoff and peak discharges produced from these tributaries with similar tributary areas within the Baker River basin.

The available hydrologic data and the respective periods of record are summarized in Table 3 and the locations of the gaging stations are shown in Figures 1 and 2.

Table 3. Hydrologic Data Stations

Station Number	Station	Elevation (Feet - NVGD29)	Drainage Area (mi^2)	Period of Record	Time Step
	BAKER RIVER BASIN				
12190700	MOROVITZ CREEK NEAR CONCRETE, WA	?	2.6	11/01/1965-12/19/1972	Peak
12190710	SWIFT CREEK NEAR CONCRETE, WA	?	36.4	8/1/1982-9/30/1990	Peak, Daily
12190718	PARK CREEK AT UPPER BRIDGE NEAR CONCRETE, WA	?	10.5	6/01/1982-10/29/1990	Peak, Daily
12191500	BAKER RIVER BELOW ANDERSON CR NEAR CONCRETE, WA	521	211.0	1815, 1897, 1910-1924, 1929-1931, 1956-1959	Peak, Daily
12191800	SULPHUR CREEK NEAR CONCRETE, WA	1750	8.4	3/01/1963-9/30/1982	Peak, Daily
12192600	BEAR CREEK BELOW TRIBUTARIES NEAR CONCRETE, WA	?	14.4	4/01/1982-9/30/1986	Peak, Daily
12192700	THUNDER CREEK NEAR CONCRETE, WA	?	22.4	8/01/1982-9/30/1994	Peak, Daily
12193500	BAKER RIVER AT CONCRETE, WA	?	297.0	10/01/1910-2/28/1915, 9/01/1943-Current	Realtime, Peak, Daily
PSE	PSE UPPER BAKER OPERATION DATA (pool elev., turbine release, spillway release)	694	--	1956 - Present	Hourly
PSE	PSE LOWER BAKER OPERATION DATA (pool elev., turbine release, spillway release)	424.8	--	1927 - Present	Hourly
	GREATER SKAGIT RIVER WATERSHED - Local Tributaries				
12172000	BIG BEAVER CREEK NEAR NEWHALEM, WA	1600	63.2	3/01/1940-9/30/1969	Peak, Daily
12173500	RUBY CR BELOW PANTHER CR, NR NEWHALEM, WA	1640	206.0	10/01/1948-9/30/1969	Peak, Daily
12174000	RUBY CREEK NEAR NEWHALEM, WA	1554	210.0	6/01/1919-5/31/1949	Peak, Daily
12175400	THUNDER CR BLW MCALLISTER CR NR NEWHALEM, WA	1700	91.7	10/01/1957-9/30/1962	Peak, Daily
12175500	THUNDER CREEK NEAR NEWHALEM, WA	1220	105.0	10/01/1930-Current	Realtime, Peak, Daily
12176000	THUNDER CREEK NEAR MARBLEMOUNT,WA	1085	114.0	3/01/1919-9/30/1930	Peak, Daily
12177500	STETATTLE CREEK NEAR NEWHALEM, WA	906	22.0	1/01/1914-11/23/1983	Peak, Daily
12177520	PYRAMID CR NEAR NEWHALEM, WA	1100	2.8	1/19/1971-2/21/1975	Peak
12177620	SKAGIT RIVER TRIB NR NEWHALEM, WA	?	0.4	3/13/1972-6/01/1975	Peak
12178100	NEWHALEM CREEK NEAR NEWHALEM, WA	1080	27.9	2/01/1961-Current	Realtime, Peak, Daily
12179900	BACON CREEK BELOW OAKES CREEK NEAR MARBLEMOUNT, WA	410	48.0	10/01/1998-Current	Realtime Only
12180000	BACON CREEK NEAR MARBLEMOUNT, WA	350	50.9	8/1/1943-9/30/1950	Peak, Daily
12181100	S.F. CASCADE R AT SO CASCADE GL NR MBLMNT, WA	5291	2.4	7/01/1957-9/30/1993	Peak, Daily
12181200	SALIX CR AT SO CASCADE GL NR MARBLEMOUNT, WA	5200	0.1	7/01/1961-9/30/1993	Peak, Daily
12182200	CASCADE R TR NEAR MARBLEMOUNT, WA	?	0.7	1/30/1971-1/16/1974	Peak
12182500	CASCADE RIVER AT MARBLEMOUNT, WA	330	172.0	1815,1898,1910-1912,1918,10/01/1928-10/10/1979	Peak, Daily
12184300	IRON CREEK NEAR ROCKPORT, WA	2300	1.7	11/30/1964-6/01/1975	Peak
12186000	SAUK RIVER AB WHITECHUCK RIVER NEAR DARRINGTON, WA	930	?	10/01/1917-3/31/1921, 6/01/1921-9/30/1922, 10/01/1928-Current	Realtime, Peak, Daily
12189500	SAUK RIVER NEAR SAUK, WA	216	714.0	4/01/1911-7/31/1912, 8/01/1928-Current	Realtime, Peak, Daily
12196000	ALDER CREEK NEAR HAMILTON, WA	125	10.7	9/01/1943-11/03/1978	Peak, Daily
12201500	SAMISH RIVER NEAR BURLINGTON, WA	45	87.8	7/01/1943-9/30/1971, 10/01/1996-Current	Realtime, Peak, Daily
	NOOKSACK RIVER WATERSHED - Local Tributaries				
12205000	NF NOOKSACK RIVER BL CASCADE CREEK NR GLACIER, WA	1245	105.0	10/01/1937-Current	Realtime, Peak, Daily
12205500	NF NOOKSACK RIVER NEAR GLACIER, WA	?	195.0	5/18/1911-9/30/38	Daily
12207200	NF NOOKSACK RIVER NEAR DEMING, WA	345	282.0	9/1/1964-12/17/75	Peak, Daily
12208000	MF NOOKSACK RIVER NEAR DEMING, WA	580	73.3	8/28/20-Current	Realtime, Peak, Daily
12209000	SF NOOKSACK RIVER NEAR WICKERSHAM, WA	385	103.0	5/01/1934-Current	Realtime, Peak, Daily
12209500	SKOOKUM CREEK NEAR WICKERSHAM, WA	400	23.1	7/1/1948-9/30/1969	Peak, Daily
	GREATER SKAGIT RIVER WATERSHED - Main Stem Skagit River				
12171500	SKAGIT RIVER AB DEVILS CR NR NEWHALEM, WA	1410	655.0	4/01/1940-9/30/1945	Peak, Daily
12172500	SKAGIT RIVER NR NEWHALEM, WA	1250	765.0	12/00/1921-3/31/1940	Peak, Daily
12174500	SKAGIT RIVER BELOW RUBY CR, NEAR NEWHALEM, WA	1190	999.0	6/01/1919-9/30/1930	Peak, Daily
12177000	SKAGIT RIVER AT REFLECTOR BAR, NR NEWHALEM, WA	880	1125.0	1815,1856,1898,1910,12/01/1913-9/30/1922	Peak, Daily
12177800	SKAGIT RIVER ABOVE LADDER CREEK NEAR NEWHALEM, WA	580	1160.0	11/25/2003-Current	Realtime Only
12178000	SKAGIT RIVER AT NEWHALEM, WA	401.5	1175.0	12/21/1908-5/31/1914, 10/01/1920-9/30/1991, 10/01/1992-Current	Realtime, Peak, Daily
12179000	SKAGIT RIVER ABV ALMA CR, NR MARBLEMOUNT, WA	359	1274.0	10/1/1950-9/30/1995	Peak, Daily
12179800	SKAGIT RIVER ABV BACON CR NR MARBLEMOUNT, WA	?	1289.0	4/27/1977-10/25/1983	Peak, Daily
12181000	SKAGIT RIVER AT MARBLEMOUNT, WA	305.1	1381.0	9/01/1943-7/07/1944, 10/01/1946-9/30/1951, 5/20/1976-Current	Realtime, Peak, Daily
12184700	SKAGIT RIVER NEAR ROCKPORT, WA	226.83	1655.0	8/01/1985-Current	Realtime Only
12194000	SKAGIT RIVER NEAR CONCRETE, WA	130	2737.0	10/01/1924-Current	Realtime, Peak, Daily
12196150	SKAGIT RIVER NEAR HAMILTON, WA	?	2870.0	10/01/1975-9/30/1977	Peak, Daily
12199000	SKAGIT RIVER NEAR SEDRO WOOLLEY, WA	?	3015.0	5/01/1908-12/31/1919, 2/01/1921-12/31/1923, 2/01/1975-6/30/1980, 1/01/1999-Current	Realtime, Peak, Daily
12200500	SKAGIT RIVER NEAR MOUNT VERNON, WA	?	3093.0	10/01/1940-Current	Realtime, Peak, Daily

Hydrologic Data Gaps

The data that will likely be most useful will be the PSE hourly operational data and any available historical hourly streamflow data for local tributaries within the Baker River basin. Data from local tributary stations outside of the Baker River basin may be used to correlate to data within the basin, and may also be used to analyze the timing, runoff per square mile, and runoff patterns to help in validating model calibration.

Hourly operational data are available for all major flood events and will be an important data set for calibration. Hourly inflow rates into each of the reservoirs will be determined by reverse routing. Computed hourly inflow rates will provide calibration data for modeled, lumped (total) inflow into each reservoir. However, these data will not allow for calibration to modeled outflow from subwatersheds if the basin is subdivided for the modeling effort.

Gage data for the local tributaries within the Baker watershed is readily available as mean daily data sets. Hourly data (if available) can be obtained from the USGS Federal Records Center in Seattle, likely within 7 to 10 days of ordering. A request for this data will be made prior to initiation of Phase II of this project.

Tetra Tech has obtained the following hydrologic data:

- Historical record of mean daily flows for all active USGS gages and most of the inactive gages included in Table 3
- Peak annual series for all USGS gages in Table 3
- Hourly operation data from PSE (forebay elevation, turbine discharge, and total spillway discharge) for November 1990, April 1992, November 1995, and October 2003

Additional hydrologic data that will be acquired for the PMF analysis includes:

- Historical data records (hourly time step when available) for the seven discontinued USGS gages in the Baker River basin. Only those stations that were in operation during moderate to severe flood events will be requested from USGS.
- Historical data records (hourly time step when available) for select USGS gages within local tributaries in the Upper Skagit watershed.
- Historical data records (hourly time step when available) for select USGS gages within local tributaries in the Nooksack River watershed.
- Hourly operation data for Upper Baker and Lower Baker Dams for any additional events in Table 2 that may be considered as calibration events.

PRECIPITATION DATA

The following two sections discuss the available precipitation data and precipitation information, and that data and information that has thus far been obtained for this study.

Precipitation Data Available

The three resources used for obtaining precipitation data were as follows:

- Puget Sound Energy (PSE)
- National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS)
- Natural Resources and Conservation Service (NRCS)

The only active, long-term hourly precipitation recording station within the Baker River basin is the NOAA station at Upper Baker Dam (Station 458715). The location of this station is shown in Figure 1. The station is equipped with a Fischer and Porter mechanical rain gage that provides rainfall totals at fifteen-minute increments on a punch tape. The data is reduced to a record of hourly precipitation depths to the nearest 0.1 inches by the National Climatic Data Center (NCDC). The station is also equipped with a standard non-mechanical rain gage. Daily readings are taken from the standard gage at the observation time of 7 AM local time.

There are two additional NOAA/NWS stations that are no longer active within the Baker River basin - The Mount Baker Lodge station (455663) and the Upper Baker River station (458718). Hourly precipitation data is available at both of these stations for the period of time that they were in operation.

The three nearest long-term hourly precipitation stations outside of the Baker River basin include the NOAA/NWS stations at Nooksack Salmon Hatchery, Glacier Ranger Station, and Marblemount Ranger Station (Figure 2).

Hourly and accumulated daily precipitation records (total precipitation including snowfall) are available from NRCS SNOTEL stations. As seen in Figure 1 there are no SNOTEL stations located within the Baker River basin. The Elbow Lake, Harts Pass, MF Nooksack, Rainy Pass, Thunder Basin, and Wells Creek SNOTEL stations record total accumulated precipitation at hourly intervals, dating back only as far as 1993 (note: hourly data is available at the MF Nooksack starting in 2002 and at Wells Creek and Elbow Lake starting in 1995). Daily accumulated precipitation records are available at the aforementioned sites plus the Swamp Creek, Beaver Pass, and Hozomeen Camp sites. These records extend back as far as 1981.

PSE currently maintains and utilizes the Hydrocomp Forecast and Analysis Model (HFAM) as a hydrologic analysis and forecasting tool for the Baker River basin. The model includes a database of continuous historical hourly precipitation for water years 1932 through 2004. Given the lack of long-term hourly precipitation in the basin, the database was compiled from available daily and hourly precipitation records at stations located both within and near the vicinity of the basin (Hydrocomp 2000). PSE staff hydrologists have continually updated the database. The time series database includes a continuous hourly dataset for Upper Baker Dam (Station 200), which was constructed by consolidating data from several stations, including Darrington Ranger Station, Diablo Dam, Upper Baker River, and Upper Baker Dam (Hydrocomp 1999).

The available precipitation data and the respective periods of record are summarized in Table 4 and the locations of the gaging stations are shown on Figures 1 and 2.

Table 4. Precipitation Data Stations

Station	Elevation (Feet - NVGD29)	Period of Record	Time Step	Source
BAKER RIVER BASIN				
Mt. Baker Lodge (455663)	4150	1948-1982	Hourly	NOAA
Upper Baker River (458718)	850	1960 - 1965	Hourly	NOAA
Upper Baker Dam (458715)	690	1964 - Present	Hourly	NOAA
Upper Baker Dam HFAM Database (Station 200)	690	1931- Present	Hourly	PSE
Concrete Pipeline Fish Station	195	1931-Present	Daily (Accum)	NOAA
GREATER SKAGIT RIVER WATERSHED				
Marblemount Ranger Station (4999)	348	6/1/48 - Present	Hourly	NOAA
Glacier Ranger Station (3160)	935	1942 - Present	Hourly	NOAA
Nooksack Salmon Hatchery (5876)	410	1/1/64 - Present	Hourly	NOAA
Diablo Dam (2157)	891	1932 - Present	Hourly	NOAA
Burlington (986)	30	1942 - Present	Hourly	NOAA
Marblemount Ranger Station (4999)	348	1941 - Present	Hourly	NOAA
Nooksack Salmon Hatchery (5876)	410	1965 - Present	Hourly	NOAA
Darrington Ranger Station (1992)	550	1924 - Present	Hourly	NOAA
Harts Pass (515)	6500	1/01/93-Present	Hourly	NRCS
MF Nooksack (1011)	4890	10/10/02 - Present	Hourly	NRCS
Rainy Pass (711)	4780	1/1/93 - Present	Hourly	NRCS
Wells Creek (909)	4200	08/24/95 - Present	Hourly	NRCS
Thunder Pass (817)	4200	1/1/93 - Present	Hourly	NRCS
Elbow Lake (910)	3200	8/24/95 - Present	Hourly	NRCS
Harts Pass (515)	6500	10/01/81 - Present	Daily	NRCS
MF Nooksack (1011)	4890	10/1/02 - Present	Daily	NRCS
Rainy Pass (711)	4780	10/01/81 - Present	Daily	NRCS
Wells Creek (909)	4200	10/1/95 - Present	Daily	NRCS
Thunder Basin (817)	4200	10/01/87 - Present	Daily	NRCS
Swamp Creek (975)	4000	10/1/99 - Present	Daily	NRCS
Beaver Pass (990)	3620	10/03/01 - Present	Daily	NRCS
Elbow Lake (910)	3200	10/1/95 - Present	Daily	NRCS
Hozomeen Camp (991)	1650	11/08/00 - Present	Daily	NRCS
Ross Dam	1240	9/01/60 - Present	Daily (Accum)	NOAA
Diablo Dam	890	12/24/14 - Present	Daily (Accum)	NOAA
Darrington Ranger Station	550	12/01/11 - Present	Daily (Accum)	NOAA
Skagit Power Plant	530	1/1/31-12/31/58	Daily (Accum)	NOAA
Newhalem	520	1/01/59 - Present	Daily (Accum)	NOAA
Sedro Woolley	60	1896 Present	Daily (Accum)	NOAA
Mount Vernon	10	01/01/56 - Present	Daily (Accum)	NOAA

Precipitation Data Gaps

Tetra Tech has acquired the following precipitation data:

- The HFAM precipitation database for the Upper Baker Dam station (Station 200).
- Hourly precipitation data for the three NOAA/NWS stations located within the Baker River basin
- Hourly precipitation data from all other NOAA stations listed in Table 4 for all events listed in Table 2
- The historical record of hourly recorded precipitation for all NRCS SNOTEL stations listed in Table 4.
- The historical record of daily recorded precipitation for all NRCS SNOTEL stations listed in Table 4

All available precipitation data, as listed in Table 4 has been acquired. As such, there will likely be no more data collection efforts for precipitation data.

SNOWPACK DATA

The following two sections discuss the available snowpack data and information, and that data and information that has thus far been obtained for this study.

Available Snowpack Data

Snowpack data is available primarily from snow course sites and NRCS SNOTEL sites. Within the Baker River watershed, there are nine snow course sites owned by various state and federal agencies. At these sites, monthly readings of snowpack depth are taken at the first of each month, typically for the months of January through June, although December readings have been included more recently. Snow water equivalent is currently estimated based on an assessment of current precipitation patterns and temperature conditions in the basin between survey dates.

NRCS SNOTEL sites are equipped with sensors that record data at regular, frequent time intervals (six-hour or one-hour). Hourly records are available as far back as 1993, while daily records are available as far back as 1982. Standard data sets include total precipitation, snow depth, snow water equivalent, and air temperature. At the enhanced SNOTEL sites, solar radiation and wind speed are also recorded. There are no NRCS SNOTEL sites located within the Baker River basin, however, as seen in Figure 1, there are four SNOTEL sites located in close proximity to the basin boundary and a total of nine located in the greater Skagit River watershed. Of those nearest the Baker River basin, the longest term SNOTEL sites are Elbow Lake and Wells Creek, both of which were on-line in August 1995. The other two nearby SNOTEL sites have only been on-line since 2001.

The available snowpack data and the respective periods of record are summarized in Table 5 and the locations of the stations are shown on Figures 1 and 2.

Table 5. Snow Course and SNOTEL Stations

Station	Elevation	Period of Record (Year)						Depth	SWE	Time Step	Type
	(feet)	January	Febuary	March	April	May	June				
BAKER RIVER BASIN											
Rocky Creek	2,100	1970-2004	1959-2004	1959-2004	1959-2004	1959-2004	1964-2004	x	x	Monthly	Snow Course
South Fork Thunder Creek	2,200	1970-2003	1959-2004	1959-2004	1959-2004	1959-2004	1964-2004	x	x	Monthly	Snow Course
Schreibers Meadow	3,400	1963-2004	1959-2004	1959-2004	1959-2004	1959-2004	1961-2004	x	x	Monthly	Snow Course
Marten Lake	3,600	1970-2004	1959-2004	1959-2004	1959-2004	1959-2004	2002-2004	x	x	Monthly	Snow Course
Dock Butte	3,800	1970-2004	1959-2004	1959-2004	1959-2004	1959-2004	1961-2004	x	x	Monthly	Snow Course
Watson Lake	4,500	1970-2004	1959-2004	1959-2004	1959-2004	1959-2004	1961-2004	x	x	Monthly	Snow Course
Easy Pass	5,200	1970-2004	1959-2004	1959-2004	1959-2004	1960-2004	1961-2004	x	x	Monthly	Snow Course
Jasper Pass	5,400	1969-2004	1959-2004	1959-2004	1959-2004	1959-2004	1961-2004	x	x	Monthly	Snow Course
Mt Blum	5,800	1970-2001	1965-2000	1965-2000	1970-2001	1970-2001	1968-2001	x	x	Monthly	Snow Course
GREATER SKAGIT RIVER WATERSHED											
Harts Pass (515)	6500	1/20/93 - Present							x	Hourly	SNOTEL - Enhanced
Harts Pass (515)	6500	8/25/00 - Present						x	x	Hourly	SNOTEL - Enhanced
MF Nooksack (1011)	4890	10/10/2002 - Present							x	Hourly	SNOTEL
Rainy Pass (711)	4780	1/20/93 - Present							x	Hourly	SNOTEL
Rainy Pass (711)	4780	8/29/02 - Present						x	x	Hourly	SNOTEL
Thunder Basin (817)	4200	2/05/93 - Present							x	Hourly	SNOTEL
Wells Creek (909)	4200	08/24/95 - Present							x	Hourly	SNOTEL - Enhanced
Wells Creek (909)	4200	10/01/96 - Present						x	x	Hourly	SNOTEL - Enhanced
Elbow Lake (910)	3200	8/24/95 - 9/30/01							x	Hourly	SNOTEL - Enhanced
Elbow Lake (910)	3200	10/01/96 - 9/30/01						x	x	Hourly	SNOTEL - Enhanced
Harts Pass (515)	6500	10/01/82 - Present							x	Daily	SNOTEL - Enhanced
Rainy Pass (711)	4780	10/01/82 - Present							x	Daily	SNOTEL
Thunder Basin (817)	4200	10/01/88 - Present							x	Daily	SNOTEL
Swamp Creek (975)	4000	10/13/99 - Present							x	Daily	SNOTEL
Beaver Pass (990)	3620	10/03/01 - Present							x	Daily	SNOTEL
Elbow Lake (910)	3200	10/01/95 - Present							x	Daily	SNOTEL - Enhanced
Hozomeen Camp (991)	1650	10/30/00 - Present							x	Daily	SNOTEL - Enhanced
Beaver Pass (990)	3,620	1944 - 2003 (intermittent)							x	Monthly	Snow Course
Elbow Lake (910)	3,200	1996 - 2003 (intermittent)							x	Monthly	Snow Course
Harts Pass (515)	6,500	1941 - 2003 (intermittent)						x	x	Monthly	Snow Course
Rainy Pass (711)	4,780	1930 - 2003 (intermittent)						x	x	Monthly	Snow Course
Schreibers Meadow	3400	1959 - 2003 (intermittent)						x	x	Monthly	Snow Course
Mount Blum	5800	1965 - 2003 (intermittent)						x	x	Monthly	Snow Course

Snowpack Data Gaps

Tetra Tech has acquired the following snowpack data:

- Snow course data for the nine stations located within the Baker River basin. This data was provide by PSE and includes monthly recorded snow depth and corresponding estimated snow water equivalent, typically at the beginning of each month.
- Hourly snow water equivalent and snow depth data at the NRCS SNOTEL stations located within close proximity to the Baker River basin. This data dates back to 1993 at select stations.
- Historical record of daily recorded snow water equivalent and snow depth at all NRCS stations within close proximity to the Baker River basin. This data dates back to 1982 at select stations.
- Historical record of monthly snow course readings at the NRCS sites, prior their conversion to an automated SNOTEL site.

All available snowpack data, as listed in Table 5 has been acquired. As such, there will likely be no more data collection efforts for snow related data.

OTHER METEOROLOGICAL AND CLIMATOLOGIC DATA

The following two sections discuss other available meteorological and climatological data along with information in this category that must still be obtained. Data included in this category include air temperature, wind speed, solar radiation, cloud cover, evaporation, dew point, and upper air (radiosonde) data.

Available Data

A majority of the recording stations for these types of data are located outside of the Baker River basin. Long term daily observed and maximum/minimum daily air temperature data is however available at the NOAA Upper Baker Dam station, and there may also be short term air temperature, wind speed, and solar radiation data at several of the snow course sites within the basin that was collected since the late 1980's. Hydrocomp (1999) states that the US Geological Survey operates stations in Baker River and that the USGS provided data series at Schriebers Meadow, Martin Lake, Jasper Pass, and Easy Pass. The records are from 1988 to 1999 for most data series, although there are some missing periods in the early years.

Table 6 summarizes the stations that record air temperature, and Table 7 summarizes the stations that provide wind speed, solar radiation, cloud cover and upper air (radiosonde) data.

Table 6. Air Temperature Data

Station	Elevation	Period of Record	Time Step	Source
	(Feet - NVGD29)			
BAKER RIVER BASIN				
Upper Baker River	850	1960 - 1965	Daily (MAX/MIN)	NOAA
Upper Baker Dam HFAM Database (Station 510)	690	1931 - Present	Daily (MAX/MIN)	PSE
Upper Baker Dam	690	10/1/65-Present	Daily (MAX/MIN)	NOAA
Concrete Pipeline Fish Station	195	1925 - Present	Daily (MAX/MIN)	NOAA
Jasper Pass	5400	1988 - 1999 (intermittent)	unknown	Snow Course
Easy Pass	5200	1988 - 1999 (intermittent)	unknown	Snow Course
Marten Lake	3600	1988 - 1999 (intermittent)	unknown	Snow Course
Schriebers Meadow	3400	1988 - 1999 (intermittent)	unknown	Snow Course
GREATER SKAGIT RIVER WATERSHED				
Harts Pass (515)	6500	1/20/93 - Present	Hourly	NRCS
MF Nooksack (1011)	4980	10/10/02 - Present	Hourly	NRCS
Rainy Pass (711)	4780	1/20/93 - Present	Hourly	NRCS
Wells Creek (909)	4200	08/24/95 - Present	Hourly	NRCS
Thunder Basin (817)	4200	2/05/93 - Present	Hourly	NRCS
Elbow Lake (910)	3200	8/24/95 - 9/30/01	Hourly	NRCS
Hozomeen Camp (991)	1650	10/30/00 - Present	Hourly	NRCS
Harts Pass (515)	6500	10/01/89 - Present	Daily (MAX/MIN)	NRCS
Rainy Pass (711)	4780	5/22/88 - Present	Daily (MAX/MIN)	NRCS
Thunder Basin (817)	4200	5/20/88 - Present	Daily (MAX/MIN)	NRCS
Swamp Creek (975)	4000	10/22/99-Present	Daily (MAX/MIN)	NRCS
Beaver Pass (990)	3620	10/03/01 - Present	Daily (MAX/MIN)	NRCS
Elbow Lake (910)	3200	10/01/95 - Present	Daily (MAX/MIN)	NRCS
Hozomeen Camp (991)	1650	11/15/00 - Present	Daily (MAX/MIN)	NRCS
Ross Dam	1240	9/01/60 - Present	Daily (MAX/MIN)	NOAA
Glacier Ranger Station	935	1949 - 1983	Daily (MAX/MIN)	NOAA
Diablo Dam	890	12/24/14 - Present	Daily (MAX/MIN)	NOAA
Darrington Ranger Station	550	12/01/11 - Present	Daily (MAX/MIN)	NOAA
Skagit Power Plant	530	1/1/31 - 12/31/58	Daily (MAX/MIN)	NOAA
Newhalem	520	1/01/59 - Present	Daily (MAX/MIN)	NOAA
Bellingham	161	01/01/31 - 12/31/41	Daily (MAX/MIN)	NOAA
Sedro Woolley	60	1896 - Present	Daily (MAX/MIN)	NOAA
Burlington	30	1972 - Present	Daily (MAX/MIN)	NOAA
Mount Vernon	10	01/01/56 - Present	Daily (MAX/MIN)	NOAA

Table 7. Other Meteorological and Climatologic Data

WIND SPEED/DIRECTION				
Station	**Elevation (feet NGVD29)**	**Period of Record**	**Time Step**	**Source**
BAKER RIVER BASIN				
Marten Lake	3600	1988 - 1999 (sporadic)	unknown	Snow Course
Schriebers Meadow	3400	1988 - 1999 (sporadic)	unknown	Snow Course
HFAM Database	--	1928 - 2004	Miles per day	PSE
Upper Baker Dam	690	???? - Present	hourly	PSE
GREATER SKAGIT RIVER WATERSHED				
Harts Pass (515)	6500	8/20/01 - Present	Hourly	NRCS
Wells Creek (909)	4200	10/01/96 - Present	Hourly	NRCS
Elbow Lake (910)	3200	10/01/96 - Present	Hourly	NRCS
Bellingham International Airport	157	1948 - 2000	Unknown	NOAA
Burlington Skagit Regional	140	3/01/81 - Present	Unknown	NOAA

SOLAR RADIATION				
Station	**Elevation (feet)**	**Period of Record**	**Time Step**	**Source**
BAKER RIVER BASIN				
Jasper Pass	5400	1988 - 1999 (sporadic)	unknown	Snow Course
HFAM Database	---	1928-2004	Daily	PSE
Upper Baker Dam	690	???? - Present	hourly	PSE
GREATER SKAGIT RIVER WATERSHED				
Harts Pass (515)	6500	8/02/01 - Present	Hourly	NRCS
Harts Pass (515)	6500	5/7/00 - Present	Daily	NRCS
Seattle (24233)	400	1961-1990	Average Monthly	NREL
Olympia (24227)	200	1961-1990	Average Montly	NREL
Seattle SRML Station	65	1995-Present	15 Minute	SRML

CLOUD COVER				
Station	**Elevation (feet)**	**Period of Record**	**Time Step**	**Source**
Bellingham International Airport	157	1948 - 2000	Unknown	NRCS
Burlington Skagit Regional	140	3/01/1981-Present	Unknown	NOAA

UPPER AIR (RADIOSONDE DATA)				
Station	**Elevation (feet)**	**Period of Record**	**Call #**	**Source**
FT LEWIS/GRAY AFB	87	1970-1996	742070	NCDC
OLYMPIA	58	1962-1966	727920	NCDC
QUILLAYUTE	56	1966-2000	727970	NCDC
SEATTLE (EMSU)	8	1946-1992	727930	NCDC
SEATTLE/NAS	10	1946-1956	727936	NCDC
SPOKANE	728	1997-2000	727860	NCDC
SPOKANE	720	1948-1995	727850	NCDC
TATOOSH ISLAND TO 727970	31	1946-1972	727980	NCDC

A continuous maximum/minimum daily ***air temperature*** data set is included in the HFAM database, and was developed at the Upper Baker Dam station (Station 510) using long term records from Concrete, Diablo Dam, Darrington, and Upper Baker Dam (Hydrocomp 1999). For the Part 12 PMF runoff model, temperature variation in the basin will be accounted for by applying a lapse rate to known temperatures at a base elevation, which will likely be the Upper Baker Dam station. However, the availability of hourly temperature data from nearby SNOTEL sites, and possibly from the snow course sites within the basin, could prove useful in determining or validating assumed lapse rates. If historical temperature data is available from the Jasper Pass, Easy Pass, Marten Lake and/or the Schriebers Meadow snow course sites, this data could be used during model calibration.

A continuous ***wind movement*** data set (miles per day) is included in the HFAM database, and was developed primarily using data from Stampede Pass, 100 miles southeast of the basin, and from the USGS station at the Tolt Reservoir. As seen in Table 7, there are two snow course sites within the Baker River basin that may have wind speed data. However, the period of record for the data is limited and the data is sporadic. PSE currently monitors and collects wind speed data at Upper Baker Dam. Although the data is current, the period of record and continuity of the data set is unknown at this time. At a minimum, however, this data will be useful for establishing a correlation to the more comprehensive data sets available at stations located outside of the Baker River basin. There are also three NRCS SNOTEL stations and two NOAA stations outside of the Baker River basin that include wind speed measurements. The NRCS stations record wind speed at hourly intervals, however, the period of record is relatively short. If historical wind speed data is available from the Marten Lake and/or the Schriebers Meadow snow course sites, this data could be used during model calibration.

A limited set of historic s***olar radiation*** data is available in the Baker River Basin. Hydrocomp (1999) indicates that solar radiation data was sporadically collected at the Jasper Pass snow course site (1988 – 1999). Additionally, PSE currently monitors and collects solar radiation data at Upper Baker Dam. Although the data is current, the period of record and continuity of the data set is unknown at this time. At a minimum, however, the data will be useful for establishing a correlation to the more comprehensive data sets available at stations located outside of the Baker River basin. The HFAM database of daily solar radiation data was developed using long term solar radiation data available at the Stampede Pass station, southeast of Seattle, from the Seattle Forecast System Meteorological Database (Hydrocomp 1999). The monthly data was disaggregated to daily values by using an average daily value. Other sources of solar radiation data that may be used to augment the HFAM dataset include data measured by the National Renewable Energy Laboratory (NREL) at Seattle and Olympia, by the University of Oregon Solar Radiation Monitoring Laboratory (SRML) at a Seattle station, and by the NRCS at Harts Pass (2000 – Present).

Historical daily ***evaporation*** data is not available in the Baker River basin. The HFAM database includes daily evaporation data estimated from records in Bellingham and Puyallup.

Upper air (radiosonde and rawinsonde) observation data is typically available twice a day at several stations in Washington State. Upper air data is taken from balloons which measure upper air conditions over a particular location at specified pressure and height levels. At each level the types of data that are typically taken include temperature, dewpoint, wind speed and wind direction.

Meteorologic and Climatologic Data Gaps

Tetra Tech has acquired the following air temperature, wind speed, and solar radiation data:

- The HFAM maximum and minimum daily ***air temperature*** database for the Upper Baker Dam station. This data was provided by PSE.
- The HFAM average daily ***wind movement*** database for the Upper Baker Dam station. This data was provided by PSE and the units are miles per day.

- The HFAM average daily ***solar radiation*** database for the Upper Baker Dam station. This data was provided by PSE.
- The hourly record of ***air temperature*** at the seven NRCS SNOTEL stations adjacent to the Baker River basin. Hourly data is available only as far back as 1993.
- The historical record of daily maximum and minimum ***air temperatures*** at the seven aforementioned NRCS SNOTEL stations plus the Swamp Creek, Beaver Pass, and Hozomeen Camp stations. Daily air temperature data is available as far back as 1988 at select stations.
- Hourly ***wind speed*** data at Harts Pass, Wells Creek, and Elbow Lake NRCS SNOTEL stations.
- ***Solar radiation*** data at the Harts Pass NRCS SNOTEL station. This period of record for this data is very limited, only going back as far as May 2000.

Additional potential meteorologic and climatologic data that will be acquired for the PMF analysis includes:

- ***Air temperature*** data at the snow course sites (Jasper Pass, Easy Pass, Marten Lake, and Schriebers Meadow) within the Baker River basin. This data is referenced in Hydrocomp (1999). PSE will be contacted for this data.
- ***Wind speed*** data at the snow course sites (Marten Lake and Schriebers Meadow) within the Baker River basin. This data is referenced in Hydrocomp (1999). PSE will be contacted for this data.
- ***Wind speed*** data collected by PSE at the Upper Baker Dam station.
- ***Wind speed*** data from the NOAA stations (Bellingham and Burlington) will be obtained from NOAA/NWS.
- ***Solar radiation*** data at the Jasper Pass snow course site within the Baker River basin. This data is referenced in Hydrocomp (1999). PSE will be contacted for this data.
- ***Solar radiation*** data collected by PSE at the Upper Baker Dam station.
- Average monthly ***solar radiation*** data from the National Renewable Energy Laboratory (NREL) at the Seattle and Olympia monitoring stations.
- Average daily ***solar radiation*** data from the University of Oregon's Solar Radiation Monitoring Laboratory (http://solardat.uoregon.edu/SolarData.html). This data is collected in Seattle at the NOAA station.
- ***Upper air sounding data*** for each of the storm events that will be considered for calibration of the hydrologic model. Data will likely be obtained from the Quillayute station.

REFERENCES

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects. Chapter VIII – Determination of the Probable Maximum Flood.*

Hydrocomp, Inc. 1999. *Baker River Model Data Base*. Prepared for Puget Sound Energy by Hydrocomp Inc., Menlo Park, CA.

Hydrocomp, Inc. 2000. *Baker River Watershed Model – Final Project Report*. Prepared for Puget Sound Energy by Hydrocomp Inc., Menlo Park, CA.

MWH. 2004. *Baker River Hydroelectric Project Upper Baker Development FERC Part 12 Safety Inspection Report - FERC Project 2150.* Prepared for Puget Sound Energy.

MWH. 2004. *Baker River Hydroelectric Project Lower Baker Development FERC Part 12 Safety Inspection Report - FERC Project 2150.* Prepared for Puget Sound Energy.

National Weather Service (NWS). 1994. *Probable Maximum Precipitation – Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages. Hydrometeorological Report No. 57.* October 1994

Tetra Tech. 2004. *Summary of Site Visit Conducted November 23, 2004*. Draft Technical Memorandum prepared for PSE as part of the Part 12 PMP/PMF analysis.

United States Army Corps of Engineers (USACE). 2004. *Hydrologic Technical Documentation (Draft Report)*. Prepared by the Seattle District for the Skagit River Flood Damage Reduction Feasibility Study.

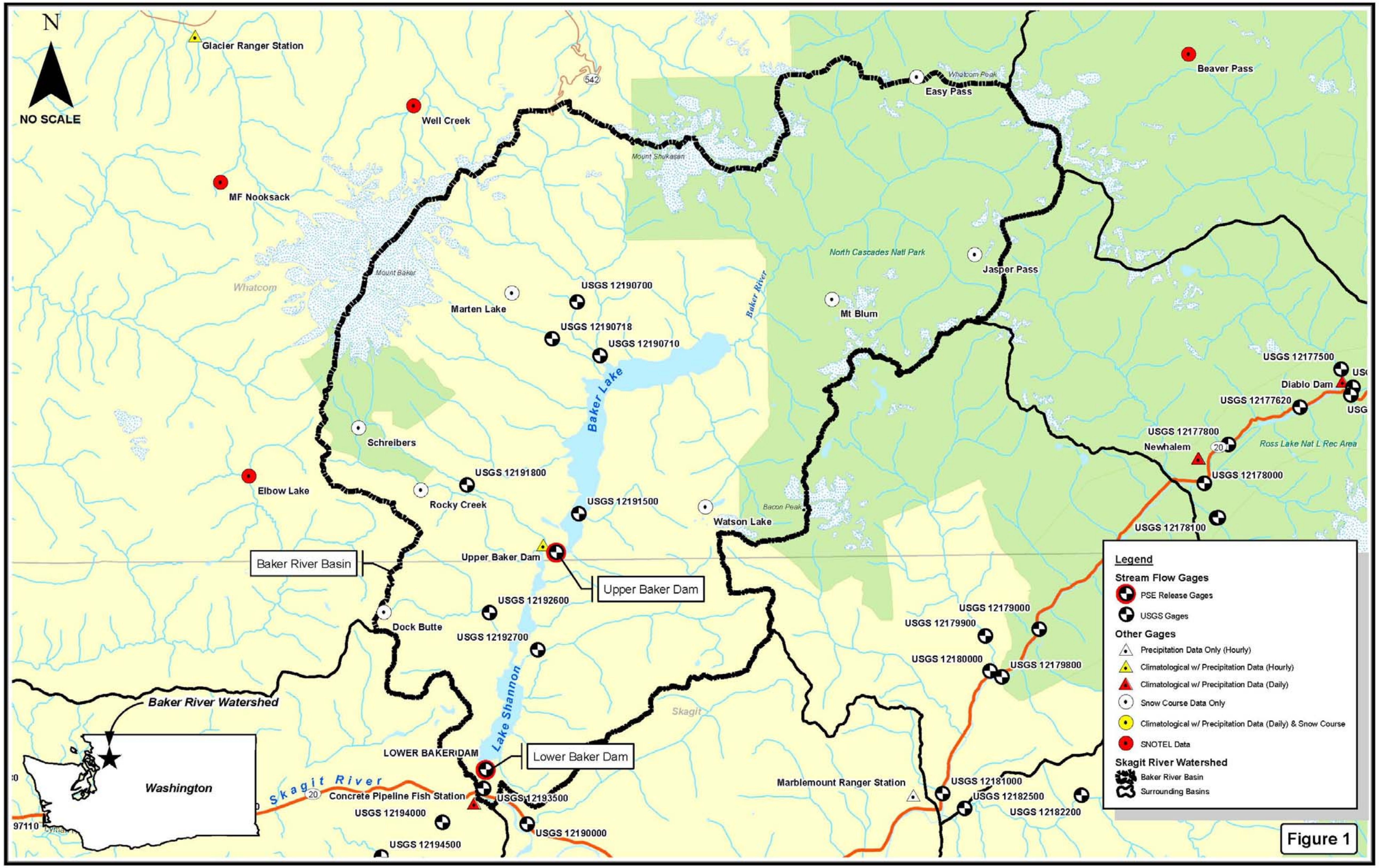

N
NO SCALE
Glacier Ranger Station
Well Creek
MF Nooksack
542
Whatcom
Mount Baker
Mount Shuksan
Whatcom Peak
Easy Pass
Beaver Pass
North Cascades Natl Park
Jasper Pass
Mt Blum
Baker River
Marten Lake
USGS 12190700
USGS 12190718
USGS 12190710
Baker Lake
Schreibers
Elbow Lake
USGS 12191800
Rocky Creek
USGS 12191500
Watson Lake
Bacon Peak
Upper Baker Dam
Baker River Basin
Upper Baker Dam
USGS 12192600
Dock Butte
USGS 12192700
Lake Shannon
Skagit
Baker River Watershed
Washington
Skagit River
20
LOWER BAKER DAM
Lower Baker Dam
Concrete Pipeline Fish Station
USGS 12193500
USGS 12194000
USGS 12190000
USGS 12194500
97110
Marblemount Ranger Station
USGS 12181000
USGS 12182500
USGS 12182200
USGS 12179000
USGS 12179900
USGS 12180000
USGS 12179800
USGS 12177500
Diablo Dam
USGS 12177620
USGS 12177800
Newhalem
Ross Lake Nat L Rec Area
USGS 12178000
USGS 12178100
Legend
Stream Flow Gages
PSE Release Gages
USGS Gages
Other Gages
Precipitation Data Only (Hourly)
Climatological w/ Precipitation Data (Hourly)
Climatological w/ Precipitation Data (Daily)
Snow Course Data Only
Climatological w/ Precipitation Data (Daily) & Snow Course
SNOTEL Data
Skagit River Watershed
Baker River Basin
Surrounding Basins

Figure 1


N
NO SCALE
Hozomeen Camp (991)
Nooksack Salmon Hatchery
USGS 12205000
USGS 12205500
Glacier Ranger Station
USGS 12207200
Beaver Pass (990)
Easy Pass
Whatcom Peak
USGS 12171000
USGS 12171500
Well Creek (909)
MF Nooksack (1011)
Whatcom
Mount Shuksan
Mount Baker
North Cascades Nat'l Park
Ross Lake Nat'l Rec Area
USGS 12172000
USGS 12208000
Marten Lake
Baker River
Mt Blum
Jasper Pass
USGS 12174500
USGS 12172500
Harts Pass (515)
USGS 12190718
USGS 12190710
Mount Baker Nat'l Rec Area
Schreibers
Baker Lake
USGS 12177500
Diablo Dam
USGS 12177000
USGS 12174000
USGS 12173500
Okanogan
Elbow Lake (910)
Rocky Creek
Newhalem
Watson Lake
Bacon Peak
Skagit Power Plant
USGS 12178000
USGS 12175500
USGS 12209500
USGS 12209000
USGS 12191800
Upper Baker Dam
USGS 12191500
USGS 12178100
Upper Baker Dam
Swamp Creek (975)
Dock Butte
USGS 12192600
Lake Shannon
USGS 12179000
USGS 12179800
USGS 12180000
Rainy Pass (711)
Lower Baker Dam
Concrete Pipeline Fish Station
Marblemount Ranger Station
USGS 12197680
USGS 12193500
Thunder Pass (817)
USGS 12197700
USGS 12196000
USGS 12194000
USGS 12181000
USGS 12182500
USGS 12197110
USGS 12190000
Skagit River
USGS 12194500
USGS 12196500
20
USGS 12196400
Skagit
547
USGS 12189500
530
USGS 12199800
USGS 12196200
USGS 12181200
USGS 12181100
USGS 12189000
USGS 12188400
Snohomish
Legend
Stream Flow Gages
PSE Release Gages
USGS Gages
Other Gages
Precipitation Data Only (Hourly)
Climatological w/ Precipitation Data (Daily)
Climatological w/ Precipitation Data (Hourly)
Snow Course Data Only
Climatological w/ Precipitation Data (Daily) & Snow Course
SNOTEL Data
Skagit River Watershed
Baker River Basin
Surrounding Basins

Figure 2

BAKER RIVER PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 2

SUMMARY OF SITE VISIT CONDUCTED NOVEMBER 23, 2004

November 30, 2004
Revised December 21, 2004
Revised February 4, 2005
Revised July 15, 2005

(Revision 3 - FINAL)

This document provides a summary of the site visit to the Lower Baker (Photo 1) and Upper Baker Projects (Photo 2) conducted on November 23, 2004. The purpose was to collect information to support the Part 12 Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) analysis for the Baker Projects. Chapter 8, Section 2.3 of the Engineering Guidelines (FERC 2001) outlines the types of information that should be collected, observed or discussed with the dam operators as part of the site visit. The suggestions in these guidelines were used to assist in conducting the site visit.

The attendees on the site visit were:

Puget Sound Energy (PSE) Bellevue:	Gene Galloway, Irena Netik and Cara Gudger
Puget Sound Energy (PSE) Lower Baker:	Byron Kurtz
Puget Sound Energy (PSE) Upper Baker:	Mike Kempkes
Tetra Tech, Inc.:	Jay Smith and Bill Fullerton

The site visit was initiated at 9:00 AM at the Lower Baker Visitors Center. The PSE Bellevue staff and the Tetra Tech staff meet briefly to discuss logistics then proceeded to the Lower Baker Powerhouse and met with Byron Kurtz for a tour of the powerhouse and discussion of operations. This group then proceeded to the top of Lower Baker Dam to observe the spillway gates and discuss their operation with Mr. Kurtz. Lunch was taken from 11:30 to 12:30 after which, the PSE and Tetra Tech staff proceeded to the Upper Baker powerhouse to meet Mike Kempkes. Mr. Kempkes provided a tour of the powerhouse and discussed the operations of the project. The group then proceeded to the top of the dam to observe the power inlet structure and spillway gates. At approximately 2:30 PM the tour of the facility was over. At this point, Tetra Tech staff drove up Baker Lake Road to observe conditions in the upper watershed and in the tributary stream systems. This reconnaissance was completed at 4:00 PM.

The Tetra Tech staff were already familiar with the facilities, having been previously contracted by PSE to perform flood operation simulations and assessments of downstream damages as part of the Corps' Skagit River Flood Damage Reduction Feasibility Study. The flood operation simulations considered alternative flood control operations associated with various flood storage allocations at Upper and Lower Baker. Both Mr. Smith and Mr. Fullerton had previously toured both the Upper and Lower Baker Projects on July 29, 2003. As part of the earlier effort, Tetra

Tech had reviewed and utilized the Project information for simulating reservoir operations during the flood season. This effort had been conducted for design floods ranging from the 10-year to the 500-year.

Information from the site visit is summarized below in three sections: Lower Baker, Upper Baker and the watershed.

Lower Baker

PSE and the US Army Corps of Engineers, Seattle District had previously provided to Tetra Tech, the physical data that describe and govern the operation of the Lower Baker Project during flood control operations. This data included current storage/elevation curves, spillway rating curves, pertinent elevations for the spillways and outlets, and operation rule curves. A copy of the Baker River Project Water Control Manual (USACE 2000) had also been previously provided to Tetra Tech by the US Army Corps of Engineers, Seattle District.

At the time of this writing, the Lower Baker Reservoir (Lake Shannon) does not include an allocated flood control volume. During flood control operations, Lower Baker operation is coordinated with that of Upper Baker, which does provide seasonal flood control storage.

As part of the current Baker Relicensing process, all pertinent elevations have been converted from the National Geodetic Vertical Datum of 1929 (NGVD29) to the North American Vertical Datum of 1988 (NAVD88). Tetra Tech has been provided a conversion table for pertinent features of the dam, which indicates a 3.75-foot adjustment that should be added to NGVD29 elevations to obtain NAVD88 elevations (refer to Exhibit 1).

The focus of the site visit to Lower Baker was to discuss the operation of the 23 spillway gates during flood control operations. The structure is relatively old, completed in 1925 and consequently, operation of the gates is more labor intensive and less automated than other facilities. The 23 gates are all vertical slide gates that must be lifted from above (Photo 3). Ten of the gates are operated from a traveling-type hoist cart (Photo 4) that must be moved across the top of the dam, positioned, and secured above the gate to be lifted. The other 13 gates have electrically powered drives attached to the gate (Photo 5). Five of these 13 gates can be operated remotely, whereas the other eight gates must be operated from controls immediately above each gate.

The following summarizes the main points concerning the operation of the spillway gates at Lower Baker:

- The main power supply for operating the 13 electric drives and the AC cart is provided from the powerhouse or local distribution system.
- The primary back-up power supply is a 100kW, AC, diesel generator set.
- The secondary back-up is DC power. There is a DC hoist cart on the dam that can be utilized if the AC cart does not have power or is inoperable for other reasons.
- Some debris catches on the gates, though the operator felt this has little effect on the spillway capacity during flood events. The operator indicated most of the debris entering

Lake Shannon had been broken into smaller pieces after having passed through the spillway of Upper Baker Dam. The 23 gates are each 9.5 feet wide by 14 feet high.

- To open the 10 gates operated by the hoist cart, requires at least two persons, preferably three.
- The 10 cart-operated gates require about 15 minutes each to operate, thereby requiring a minimum of 2 to 2.5 hours to fully open all 10 gates. The majority of the time is spent moving the cart, securing the cart and attaching the lifting devise to the gate.
- All gates are operated at least once per year per FERC requirements. The last such operation was in August 2004.
- During flood operations, instructions for operating the reservoir are given by the Corps of Engineers, Seattle District. The PSE staff perform the actual physical operation.
- The spillway operations are conducted by local operators which must be within 15 minutes of the facilities during their shifts.
- The 5 gates with remote operation capabilities can be operated from a control center in Redmond, Washington. However, for safety reasons, operation from Redmond is rarely conducted.
- The 13 fixed hoist gates can be raised 16 feet. The 10 hoist cart operated gates can be normally lifted 14 feet, though they can be completely removed to provide 21 feet of vertical opening.
- The 13 fixed electrical hoist gates are typically operated prior to operating the 10 hoist cart gates.
- Debris is removed daily from the structure if possible. A barge is utilized for debris removal. Debris that is removed is placed on the shoreline and burned.

In addition to the spillway, powerhouse discharge is typically maintained during flood events. The maximum discharge through the turbines is approximately 4,000 cfs. During portions of the October 2003 flood, the Seattle District USACE requested PSE to shutdown powerhouse operations while storage from Seattle City Light reservoirs was passed down the main stem of the Skagit. At other times, capacity has been reduced because of work on the generating facilities.

Under a separate task (Task 1) of the current scope of work, Tetra Tech is obtaining flow, precipitation and other hydrometeorological data to conduct the PMP and PMF analyses. The operator indicated there are two precipitation gages in the vicinity of the Lower Baker Dam. They are at the substation and the fish trap. The former gage is equipped with telemetry capabilities. Flow into the Lower Baker Reservoir (Lake Shannon) is not gaged directly, but instead can be back-calculated from measured changes in storage, outflow from Lower Baker, and inflow contributed from Upper Baker releases.

Upper Baker

PSE and the US Army Corps of Engineers, Seattle District had previously provided to Tetra Tech, the physical data that describe and govern the operation of the Upper Baker Project during flood control operations. This data included current storage/elevation curves, spillway rating curves, pertinent elevations for the spillways and outlets, operation rule curves, and the spillway gate regulation schedule. A copy of the Baker River Project Water Control Manual (USACE

2000) had also been previously provided to Tetra Tech by the US Army Corps of Engineers, Seattle District.

The Upper Baker Reservoir (Baker Lake) provides seasonal flood control storage between November 15th and March 1st. In coordination with the U.S. Army Corps of Engineers, 74,000 acre-feet of flood control storage is provided during this time.

As part of the current Baker Relicensing process, all pertinent elevations have been converted from the NGVD29 datum to NAVD88 datum. Tetra Tech has been provided a conversion table for pertinent features of the dam, which indicates a 3.77-foot adjustment that should be added to NGVD29 elevations to obtain NAVD88 elevations (refer to Exhibit 1).

The focus of the site visit to Upper Baker was to discuss the operation of the spillway gates during flood situations. Having been constructed in 1959, the Upper Baker facility generally has more modern features than Lower Baker. The spillway consists of three 25 foot wide by 30 foot high openings controlled by radial gates. The three gates are individually operated by a bridge-mounted, electrical drum hoist of 30 ton capacity (Photo 6). The gates can be operated both from the top of the dam and remotely from the powerhouse.

The following summarizes the main points concerning the operation of the spillway gates at Upper Baker:

- The gates can be operated remotely from the powerhouse at the base of the dam. To facilitate operation of the gates, there are video cameras that document the condition of the gates and show the reservoir above the gates (Photo7). The gates can also be operated locally from the top of the dam (12 foot access road).
- The gates are normally operated from AC power on the distribution system. In emergencies, the back-up power is a 100kW AC, diesel generator located at the powerhouse.
- Recently, a second back-up system was installed which provides the ability to operate the gates from a portable drive unit.
- The operator indicated that debris does not catch in the gate openings. The flow patterns upstream of the gates tend to align debris so that it passes through the spillway openings. The operator also indicated that the debris is typically broken into smaller pieces as it falls over the dam and down the spillway.
- As is the case with Lower Baker, during flood operations, the Corps of Engineers Seattle District takes over operation of the structure, providing verbal instructions to the PSE operators who continue to physically operate the dam.
- The operators must remain within 15 minutes of the dam. The operators are housed within 2 miles of the dam.
- Per FERC requirements, all three radial gates are operated annually. The last such operation was October 2004, when the gates were operated
- A public road passes across the crest of the dam (Photo 8).
- The power intake structure on the face of the dam has a fish baffle that is suspended from a floating structure. The baffle extends approximately 100 feet below the surface. The

floating structure does not adjust smoothly to changes in lake level and the operators must at times manually manipulate the baffle.

In addition to the spillway flow, powerhouse discharge is typically maintained during flood events as per the Water Control Manual (USACE 2000). The maximum discharge through the turbines is approximately 5,500 cfs. At other times, capacity has been reduced because of work on the generating facilities.

Under a separate task, Task 1, Tetra Tech is obtaining flow, precipitation and other hydrometeorological data to conduct the PMP and PMF analyses. There is an hourly precipitation gage at Upper Baker Dam. Flow into Upper Baker reservoir (Baker Lake) is not gaged directly, but instead can be back-calculated from changes in storage and outflow.

Watershed

Vehicular access to the watershed is limited, particularly the upper portions. Above Lake Shannon, most of the land is federal and includes Mount Baker Snoqualmie National Forest, Mount Baker National Recreational Area, Mount Baker Wilderness Area and the North Cascades National Park. The upper watershed includes the summits of Mount Baker and Mount Shuksan, both of which have significant glaciers on their slopes.

In the time available for the site visit, the Tetra Tech staff left the Upper Baker Dam site and drove up the Baker Lake Road. The primarily purpose was to observe the characteristics of the streams entering Baker Lake. The two largest streams observed were Boulder Creek and the Baker River.

Boulder Creek was observed near the head of Baker Lake at the end of the paved road. Boulder Creek was extremely steep with the slope estimated at approximately five percent. The stream carries a large bed load of gravel cobble and boulders. The braided channel was estimated to be approximately 200 feet wide and had a depth of 4 to 6 feet. The channel occupied the entire valley floor and the hill side slope rose steeply from the edge of the channel. The n-value was estimated at approximately 0.045 (Photo 9).

The Baker River at the head of Baker Lake is a braided channel with a width of 400 to 600 feet, with multiple shallow channels in the area observed (Photo 10). The bed is primarily gravel and cobble with some boulders. Significant large woody debris is also present. The n-value was estimated at 0.040. The valley floor is over a thousand feet wide at this location.

The portions of the watershed observed are steep and heavily forested (Photo 11) with only a few small meadow areas in the valley floor of several of the tributaries. Most of the timber observed was second growth. Review of aerial photographs and contacts with the Forest Service should be conducted to determine the land use practices within the watershed.

Photo 1 – Looking upstream towards the downstream face of Lower Baker Dam (photo taken from vicinity of the powerhouse)

Photo 2 – View of downstream face of Upper Baker Dam (powerhouse in foreground)

Photo 3 – View looking at upstream face of Lower Baker Dam, showing spillway gates in closed position. Water level is about 3 feet below crest. Reservoir elevation recorder in lower left corner adjacent to penstock intake structure.

Photo 4 – AC hoist cart near center of photo, DC hoist cart at right edge of photo. Steel chute directs debris away from face of dam. Lower Baker Dam

Photo 5 – Fixed electrical driven hoist equipment used to lift 13 of the 23 Lower Baker spillway gates. Manual switchbox appears at right edge of photo.

Photo 6 – Thirty ton capacity, bridge-mounted, electrical drum hoists are used to lift the three radial gates at Upper Baker Dam

Photo 7 – Video monitoring of spillway gates from Upper Baker Powerhouse to assist in remote gate operations.

Photo 8 – View to the north along access road across top of Upper Baker Dam

Photo 9 – View looking downstream on Boulder Creek from Baker Lake Road

Photo 10 – View looking downstream on the Baker River just above Baker Lake

Photo 11 – Looking to the northeast at steep watershed surrounding the Baker River above Baker Lake

References

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

Stone and Webster. 1999. Periodic Safety Inspection Report No. 7. Upper Baker River Development. FERC Project No. 2150. Volume 1.

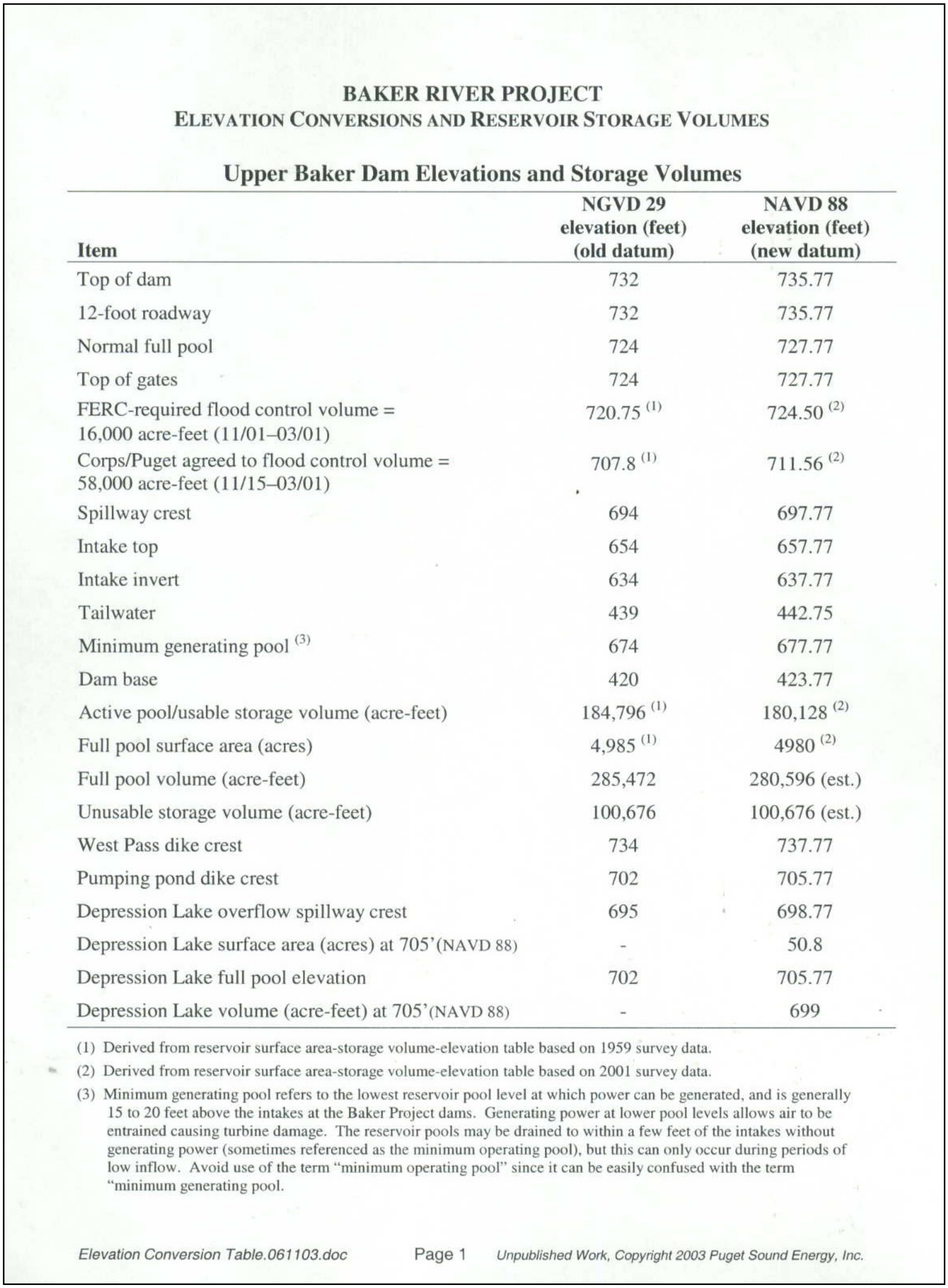
Stone and Webster. 1999. Periodic Safety Inspection Report No. 7. Lower Baker River Development. FERC Project No. 2150.

United States Army Corps of Engineers, Seattle District (USACE). 2000. Baker River Project Water Control Manual.

EXHIBIT 1

BAKER RIVER PROJECT
Elevation Conversions and Reservoir Storage Volumes

(Data provided by Puget Sound Energy)



BAKER RIVER PROJECT
ELEVATION CONVERSIONS AND RESERVOIR STORAGE VOLUMES

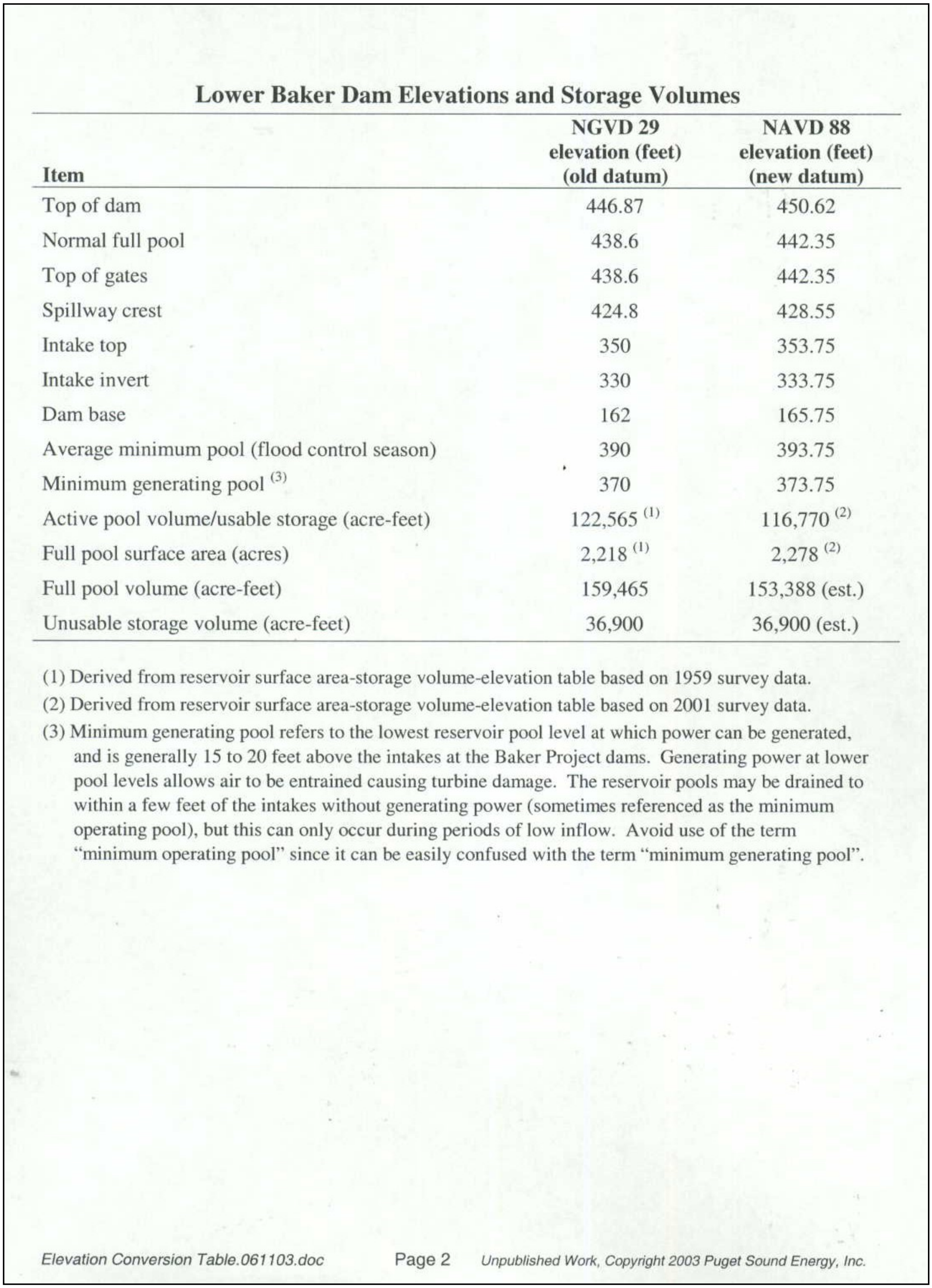
Upper Baker Dam Elevations and Storage Volumes

Item	NGVD 29 elevation (feet) (old datum)	NAVD 88 elevation (feet) (new datum)
Top of dam	732	735.77
12-foot roadway	732	735.77
Normal full pool	724	727.77
Top of gates	724	727.77
FERC-required flood control volume = 16,000 acre-feet (11/01–03/01)	720.75 (1)	724.50 (2)
Corps/Puget agreed to flood control volume = 58,000 acre-feet (11/15–03/01)	707.8 (1)	711.56 (2)
Spillway crest	694	697.77
Intake top	654	657.77
Intake invert	634	637.77
Tailwater	439	442.75
Minimum generating pool (3)	674	677.77
Dam base	420	423.77
Active pool/usable storage volume (acre-feet)	184,796 (1)	180,128 (2)
Full pool surface area (acres)	4,985 (1)	4980 (2)
Full pool volume (acre-feet)	285,472	280,596 (est.)
Unusable storage volume (acre-feet)	100,676	100,676 (est.)
West Pass dike crest	734	737.77
Pumping pond dike crest	702	705.77
Depression Lake overflow spillway crest	695	698.77
Depression Lake surface area (acres) at 705'(NAVD 88)	-	50.8
Depression Lake full pool elevation	702	705.77
Depression Lake volume (acre-feet) at 705'(NAVD 88)	-	699

(1) Derived from reservoir surface area-storage volume-elevation table based on 1959 survey data.

(2) Derived from reservoir surface area-storage volume-elevation table based on 2001 survey data.

(3) Minimum generating pool refers to the lowest reservoir pool level at which power can be generated, and is generally 15 to 20 feet above the intakes at the Baker Project dams. Generating power at lower pool levels allows air to be entrained causing turbine damage. The reservoir pools may be drained to within a few feet of the intakes without generating power (sometimes referenced as the minimum operating pool), but this can only occur during periods of low inflow. Avoid use of the term "minimum operating pool" since it can be easily confused with the term "minimum generating pool.



Lower Baker Dam Elevations and Storage Volumes

Item	NGVD 29 elevation (feet) (old datum)	NAVD 88 elevation (feet) (new datum)
Top of dam	446.87	450.62
Normal full pool	438.6	442.35
Top of gates	438.6	442.35
Spillway crest	424.8	428.55
Intake top	350	353.75
Intake invert	330	333.75
Dam base	162	165.75
Average minimum pool (flood control season)	390	393.75
Minimum generating pool (3)	370	373.75
Active pool volume/usable storage (acre-feet)	122,565 (1)	116,770 (2)
Full pool surface area (acres)	2,218 (1)	2,278 (2)
Full pool volume (acre-feet)	159,465	153,388 (est.)
Unusable storage volume (acre-feet)	36,900	36,900 (est.)

(1) Derived from reservoir surface area-storage volume-elevation table based on 1959 survey data.

(2) Derived from reservoir surface area-storage volume-elevation table based on 2001 survey data.

(3) Minimum generating pool refers to the lowest reservoir pool level at which power can be generated, and is generally 15 to 20 feet above the intakes at the Baker Project dams. Generating power at lower pool levels allows air to be entrained causing turbine damage. The reservoir pools may be drained to within a few feet of the intakes without generating power (sometimes referenced as the minimum operating pool), but this can only occur during periods of low inflow. Avoid use of the term "minimum operating pool" since it can be easily confused with the term "minimum generating pool".

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 3

REVIEW OF FERC GUIDELINES AND SUMMARY OF PMF ANALYSIS PROCEDURE FOR BAKER RIVER HYDROELECTRIC PROJECT

December 3, 2004
Revised December 22, 2004
Revised February 11, 2005
Revised July 15, 2005

(Revision 3 - FINAL)

Although a revision date of July 15, 2005 is indicated in the header, this memo actually reflects the project conditions and what was known of the project as of the end of February 2005. Since February, work has continued on the project, more data has been acquired, and there have been modifications to the work plan. However, this memo is intended to represent a "snapshot" in the project chronology, subsequent to the Board of Consultant (BOC) February review of the Phase I technical memorandums, of which this is one. The main report will be the ultimate product and final source of information for this project.

This memorandum serves two primary functions. The first is to present a review of the information and criteria presented in the *Engineering Guidelines for the Evaluation of Hydropower Projects* (Guidelines) pertaining to conducting Probable Maximum Flood (PMF) evaluations for hydropower facilities. The second is to utilize the Guidelines to identify and present the steps necessary to conduct the Baker Project PMF analysis. This information, along with the results of the data acquisition and analysis (Tasks 1 and 4 of Phase I) will be used in Task 5 of Phase I to recommend the most appropriate model(s) for conducting the PMF evaluation of the Baker Project.

At the completion of Phase I, the steps identified in this memorandum will be expanded and finalized then developed into the work plan for Phase II, the actual PMF evaluation. Details can be added to the steps presented in this memorandum once the actual model(s) is selected and the evaluation of the data requirements and availability is completed. Additionally, feedback from PSE and FERC staff on the analysis steps presented in this memorandum will be incorporated into the Phase II work plan.

Review of Guidelines

The review of the Guidelines was performed to identify FERC input on five main areas critical to the PMF evaluation:

1) Modeling approach
2) Storm development and selection
3) Assumptions for antecedent conditions

4) Operational considerations
5) Model sensitivity analysis

The majority of the input on these topics was obtained from Chapter 8, “Determination of the Probable Maximum Flood” with additional information from Chapter 2, “Selecting and Accommodating Inflow Design Floods for Dams.”

It should be noted that the Guidelines do not provide rigid criteria or detailed step by step procedures for conducting PMF determinations. Rather, they provide guidance on important aspects of conducting the PMF including recommendations on procedures to follow and important factors and physical processes to consider. In the introduction to Chapter 8, the Guidelines states:

> *The purpose of these guidelines is to provide consistency in PMF determinations. The guidelines are not a substitute for good engineering judgment when available data clearly call for a departure from recommended procedures. Therefore the recommended procedures should not be applied rigidly in place of other justifiable solutions.*

The following sections provide documentation of the relevant FERC guidance and performance criteria from Chapters 2 and 8.

Hydrograph Modeling Approach

This section identifies the guidance and recommendation provided on the modeling approach for development of the hydrograph. Topics covered include: general approach, model recommendations, watershed subdivision, and model parameter development (calibration and verification).

General Approach

Guidelines - The Guidelines indicate that the procedures presented are generally applicable for drainage basins up to 10,000 square miles (p 4). Additionally, the guidance proposes the use of the unit hydrograph theory as the “preferred” general hydrologic analysis procedure for development of the runoff hydrograph (pp 3 and 27). Furthmore, the Clark, Snyder, and SCS unit hydrographs are the synthetic unit hydrograph methods that are recommended for use by the Guidelines (pg 51).

Conclusions - Since the total tributary area to the Baker Project is approximately 300 square miles, it is well under the upper limit for application of the FERC guidance for PMF analysis and simulation. Therefore the Guidance will be used for the PMF analysis. To be consistent with the preference of the Guidance, the PMF modeling approach will utilize unit hydrographs. Prior PMF studies conducted for the Baker River Basin did not use unit hydrographs, and therefore, there are no previously developed unit hydrographs specific to the Baker River Basin. Some form of a synthetic unit hydrograph will be used in this study.

Model Recommendations

Guidelines – The guidelines indicate use of the US Army Corps of Engineers (USACE) HEC-1 model is recommended because of its widespread use and experience in application of the model (p 31). In addition, the model includes many features that provided capabilities for conducting the analysis consistent with the FERC recommended procedures. The use of the USACE HEC-HMS model, which has many of the capabilities of HEC-1 and runs under Windows, is also indicated. The Guidelines also indicate the potential for use of other models developed for specific modeling situations or regions, but that other programs "must be fully documented and verified" (p 32).

Use of runoff models such as HSPF (Hydrologic Simulation Program-FORTRAN) is also indicated, but it is mentioned in the context of utilizing it to develop estimates for historical snowpack conditions when snowcourse data are not available (p 24). This is due to the continuous simulation capabilities of the HSPF model, which include snowfall and snowpack development.

Conclusions – Further evaluation of the appropriate modeling tool is being performed as part of Task 5 of the Phase I effort; however, initial indications are that HEC-1 is likely to be the model that is recommended. Use of HEC-1 is consistent with the Guidelines. In the event that it is necessary to reconstitute snowpack data for historical floods, it may be done so using output from PSE's continuous simulation Hydrocomp Forecast and Analysis Modeling (HFAM). An HFAM model was developed and calibrated for the Baker River basin by Hydrocomp (Hydrocomp 1999).

Gaged or Ungaged Unit Hydrograph Development

Guidelines – The Guidelines provide criteria for whether to consider the basin as "gaged" or "ungaged"(p 29). Within the context of the Guidelines, a basin is considered "gaged" if it meets the following criteria:

1) At least one stream gage, preferably at the inlet to the reservoir be available or sufficient operational data at the reservoir available to reconstruct the inflow hydrograph.
2) At least one precipitation gage, preferably a recording gage, should be available within the watershed.
3) Concurrent rainfall and runoff records available for at least three severe historical storm that have the following characteristics
    - Contributions from all runoff producing portions of the watershed
    - Event should not be snowmelt dominated unless it is apparent that the PMF will be snowmelt dominated
    - Events should produce substantial runoff (considered to be more than 1 inch and produce overbank flow)

If the basin is considered "gaged", then the procedures in Section 8-6 of the Guidelines are to be utilized and if the basin is considered "ungaged", procedures in Section 8-7 are to be utilized.

Conclusions – Sufficient data exist at both Upper and Lower Baker dams to develop inflow hydrographs. Precipitation and snowpack information are also available. The development of the runoff model for the Baker projects will proceed as specified for a "gaged" basin.

Single Basin or Divide into Subbasins

Guidelines – The Guidelines recommend that watersheds be subdivided if they are large and not hydrologically homogeneous or are drained by more than one major tributary (p 28). Additionally, if the reservoir area is "relatively large", it should be considered as a separate subbasin. The Guidance does not specifically define the term "relatively large". Subdivisions may also be required to simulate the effects of spatial distribution of precipitation. The guidelines list other criteria for dividing into subbasins, of which, the following may be relevant to the Baker Project:

- Experience significantly different rainfall due to orographic effects
- Are upstream of dams with sufficient storage to affect the hydrograph
- Have additional functional stream records with good historical data

Conclusions – The data inventory indicate that the basins with the most extensive record of runoff (through reconstruction of inflow hydrographs from reservoir information) are the Upper Baker and Lower Baker drainage basins. Hourly records are available for the largest, most recent floods. Other flow data exists for smaller tributary subbasins such as Swift Creek (36 mi^2), Park Creek (11 mi^2), Sulphur Creek (8 mi^2), Bear Creek (14 mi^2) and Thunder Creek (22 mi^2). But the gaging stations for these tributaries were discontinued in the early 80's and the early 90's, respectively, and the tributary areas to these local drainages are relatively small compared to the total basin. Currently, it is proposed that the total watershed be divided into two main basins, that tributary to Upper Baker Dam and that tributary to Lower Baker. It is proposed that calibration proceed as per gaged basins. The data from the smaller tributary basins will be used to check to see if there is a large difference in runoff per square mile, runoff volume per square mile or hydrograph timing. This information will provide checks on overall reasonableness of the larger basin simulations and determine of there might be merit for subdividing to smaller basins. If calibrations cannot be satisfactorily produced assuming subdivision into just two basins, the effort will proceed to using more refined subbasin delineations, perhaps considering as many as seven subbasins tributary to Lower Baker Dam and as many as nine subbasins tributary to Upper Baker Dam (each reservoir surface area would be considered separate subbasins with direct rainfall).

Model Calibration and Verification

Guidelines - For gaged watersheds, the Guidelines indicate that at least three significant historic storms be used. Two of the storms should be utilized for calibration and the third for verification. The largest storms should be used for calibration. In addition to having the required hydrometeorological and runoff data, the storms should be less complex (single peak), occur in the same period as the critical PMP, and have the same rain or rain-on-snow characteristics as the critical PMP. The hydrographs should be calibrated to produce similar volume of runoff and peak discharge.

If HEC-1 is used, then program routines can be used to optimize the empirical coefficients for the unit hydrographs. The calibration process will be iterative, in that the values of the parameters will be modified until the model produces unit hydrographs that match the historical events. Since it is to be expected that there will not be perfect correlation for each of the historical events, judgment will be used to ensure that the final unit hydrographs generally reflect the largest historical event from the critical period for the PMF. The final adjustments should be based on adopted values of the empirical coefficients rather than adjusting ordinates.

The Guidelines allow for adjustments to the historically derived unit hydrographs, to account for the changed hydrologic response of the watershed under the extreme PMP conditions. Lag times should be adjusted to account for the fact that a PMP event will produce rainfall intensities much greater than any historical intensities measured within the watershed. These extreme conditions will shorten lag times, therefore requiring appropriate adjustments to the unit hydrographs (pg 70).

Calibration of each of the subbasins with sufficient historical data should be performed. In the case where subbasins are less than 20 square miles and data are not available, the SCS synthetic unit hydrograph may be applied.

Conclusions – As previously stated, data sets exist to calibrate the Upper and Lower Baker Basins as gaged watersheds. Potential storms for calibration are anticipated to be two November 1990 and November 1995 events. Additionally, the October 2003 storm will be included as a verification/calibration event. This later storm is somewhat different from the other three events in that there was not rain on snow and the watershed had received very little rainfall prior to this storm. Therefore, it is expected that the parameters will be somewhat different than those calibrated for the November events, though it will still provide a check of the reasonableness of the modeling, particularly the rainfall components.

Snowmelt

Guidelines - Snowmelt needs to be taken into consideration during the calibration storms that occurred while a snowpack was present. This requires historic data with snowpack water equivalent. The model requires the use of temperature at the base elevation and the temperature lapse rate. The energy budget method is recommended for calculation of snowmelt.

Conclusions – The majority of the largest runoff events were rain-on-snow events. Snowmelt will be included in the calibration process and the actual PMF event. Data exist to support calibration and application of the snowmelt component.

Channel and Reservoir Routing

Guidelines - If subbasins are linked together by channels, then the Muskingum-Cunge method should be used for channel routing. Reservoir routing can typically be performed by the level pool procedure. Dynamic routing may be appropriate for large or long riverine type reservoirs. When reservoir inflow hydrographs are reconstructed from reservoir outflow and storage information, the dynamic effects of the reservoir are incorporated into the calibrated unit hydrograph.

Conclusions – Outflows from Upper Baker Dam are conveyed directly into the Lower Baker reservoir, and a channel routing component is not considered necessary if a two basin model is developed. Reservoir routing is anticipated to utilize HEC-5, which has been developed for the Upper and Lower Baker and can account for operational rules. HEC-5 utilizes level pool routing algorithms.

Loss Rates

Guidelines – According to the Guidelines, the traditional loss rate method for PMF computations is a basin averaging method using initial and uniform losses (pg 53). However, the Guidelines appear to endorse other methodologies as well (SCS Runoff Curve Number, the Green-Ampt Equation, the Holtan Equation, and the exponential loss function). Regardless of the method that is selected, a basin averaged or distributed estimate of the infiltration rate under saturated conditions is required. Any of the listed methodologies can be applied in a based averaged or distributed mode. Regardless of the method used to compute losses, the hydrologic model must be verified with available historical storm data (pg 54). Resulting parameters should be checked against the expected basin values based on soil types for appropriateness.

Conclusions – Several loss rate methodologies will be considered, with the leading candidates including the initial abstraction and uniform loss procedure and the Holtan Equation. The Holtan equation offers many advantages over the uniform loss rate procedure in that it accounts for soil moisture storage capacity, the initial soil moisture content, as well as the minimum surface infiltration rate.

PMP Storm Development

The primary considerations for the storm are the rainfall amount, the spatial distribution, the storm duration, and the temporal distribution.

Storm Volume

Guidelines – The controlling PMF will be produced by the critical PMP that produces the largest routed peak flow from the reservoir. To determine the critical PMP, both the general storm (all-season and seasonal) PMP and the local storm PMP should be computed. For the Baker Projects, HMR-57 provides the appropriate information and procedures for computing the various PMP storm volumes.

Conclusions – Since the area of the basin is less than 500 square miles, HMR-57 will be utilized to develop both the general storm (all-season and seasonal) PMP and the local storm PMP. After reviewing the seasonal PMP maps in HMR-57, it appears likely that the all season PMP value will govern much of the winter flood season.

Spatial Distribution

Guidelines – The PMP typically needs to be distributed over the basin and then an average developed for the basin (or subbasins). Distribution of the PMP based on historic storms is not advised, since the information may be biased. In the west, for the general storm, the Guidelines indicate that distributing the storm per average annual or 50-year or greater storm volumes (NOAA Atlas 2) can more appropriately account for orographic and other local influences. If insufficient data exist to provide guidance for spatial distribution, the Guidance allows for a uniform distribution over the basin.

Conclusions – Distribution of the basin-averaged PMP volume will be based on frequency based mapping and not on historical storm distributions. Schaefer et al (2002) developed frequency based climatological mapping using the findings of regional precipitation-frequency analyses of 24-hour and 2-hour precipitation annual maxima. The 100 year, 24-hour mapping will be used for the PMP distribution.

Storm Duration

Guidelines – Local storms of short duration and high intensity can produce a critical PMF for dams that are located within relatively small drainages, which the Guidelines define as drainages less than about 1,000 square miles. Local short duration storms may also produce a critical PMF where the antecedent operating level of the reservoir can be higher during the late spring and summer months.

Conclusions – As per HMR57 guidelines, the local storm PMP will be determined along with the general storm PMP. The duration of the local storm is typically less than 6 hours, as compared to the general storm, which can have durations up to 72 hours. A determination will be made as to whether the local storm PMP is capable of producing the critical PMF.

Temporal Distribution

Guidelines – Guidelines recommend placing the highest 6-hour period between the half and 2/3 point of the storm and that the remaining 6-hour periods be alternated in descending order on each side of the peak. Hourly increments should be taken from the PMP envelope and distributed so as to provide a smooth temporal curve. The appropriate HMR should be checked for further instructions.

Conclusions – Temporal distribution of the PMP using guidance in HMR-57 will be given consideration. However more detailed regional studies such as Schaefer (1989) and Schaefer (1990) will also be considered. These additional studies may be more pertinent to the Baker River basin due to their specificity to extreme storms in Washington State.

Antecedent Conditions

The primary antecedent condition variables are initial loss rates, snowpack, and reservoir levels. FERC Guidelines on these parameters are discussed below.

Loss Rates

Guidelines - The recommended procedure for losses is initial abstraction with uniform loss. Loss rates should be assumed representative of saturated soils. Initial abstraction may be set to zero unless some condition justifies initial loss such as large depression storage. It is preferred to perform distributed loss rate determination as opposed to area averaged loss rate (p 55). The guidelines also provide a table of minimum loss rates based on SCS soils types. The Guideline point out, while the snowpack remains intact, the snowmelt loss rate (LM) overrides the uniform loss rate (LU). For frozen soils, wetland, soils with high silt or high groundwater, clays should be modeled as impervious. Forested soils or soils with minimum 4-inch humus depth should have loss rates for unfrozen soils (p 61).

Conclusions – If the initial abstraction with uniform loss rate method is used to model losses, it is anticipated that initial abstraction will be set at zero. The values selected for the uniform loss rate will be reflective of those determined during model calibration and will represent saturated soil conditions. If a more comprehensive loss rate model is used, such as the Holtan method, then the initial abstraction will likely be determined using a soil moisture budget accounting procedure for each season.

Snowpack and Snowmelt

Guidelines – Snowpack conditions during the PMF should be determined from historical data records. If total snowpack depth is available, the 100-year snowpack should be assumed over appropriate portions of the basin with a starting water equivalence of 30 percent. For basins west of the Continental Divide, the Guidelines require the evaluation of two PMF scenarios relative to snowmelt. The first scenario assumes a PMP occurring on a 100-year snowpack and the second scenario assumes a 100-year precipitation event on a Probable Maximum Snowpack (pg 68).

Snowmelt during the PMF should be computed with the energy budget method. After simplifying assumptions, the driving variables become temperature sequence, wind speed and snowpack water equivalent. The temperature sequence is provided in HMR 57. The wind speed and 100-year snowpack should be developed from local data (pp 67-68).

Conclusions – Previous PMF studies all utilized rain-on-snow conditions. In addition, the majority of the largest historical runoff events are rain-on-snow. Therefore, it is anticipated that rain-on-snow will be the critical condition for the current PMF study. Sufficient historical data exist to estimate the appropriate snowpack conditions. A 100-year snowpack will be developed for each seasonal PMP (October, November-February, March, April-May, and June). Using output from PSE's HFAM model, the 100-year snowpack will be distributed per elevation and possibly other factors if the data indicate. Initially, the two snowpack PMF scenarios described in the Guidelines will be evaluated separately to determine which is the controlling scenario. The watershed runoff model will likely not be used to simulate the two scenarios, but instead volumetric calculations, with conservative assumptions for snowmelt and rainfall transformation, will be used to determine which of the scenarios would produce the highest volume of inflow to the reservoirs. Given that the 24-hour duration all season PMP depth is nearly three times the 100-year, 24-hour duration precipitation depth of 5.5 inches (NOAA 1973 and NWS 1994), it seems likely that the controlling scenario will be a PMP on a 100-year snowpack.

A third snowpack PMF scenario will be developed in detail. The basis for this third scenario will be to set the snowpack near magnitudes that can be expected to completely melt out during the PMP event, while still be consistent with snowpack relationships historically exhibited. The snowpack conditions set under this scenario may be more representative of typical conditions rather than 100-year snowpack conditions, and may actually be the controlling scenario if the pack densities associated with the 100-year snowpack are substantially lower than yield densities, thereby resulting in a portion of the precipitation from the PMP event to be retained in the snowpack.

The temperature sequence during the PMP will be based on guidance in HMR-57. Other parameters will be based on typical conditions during historical rain on snow events.

Reservoir Levels

Guidelines – In the absence of a specific regional study conducted by a water resource agency regarding antecedent storms, the Guidelines indicate the following four procedures to determine a reasonable starting reservoir elevation when routing the inflow PMF event (pg 64):

- Consider the reservoir at a predetermined annual maximum at the start of the PMF
- Assume a 100-year, 24-hour storm occurs 3 days prior to the start of the PMP. The result need not be greater than the annual maximum reservoir level.
- Use or develop a wet year rule curve. Assume that the reservoir level is at the average of the five consecutive, highest wet-year reservoir levels during the season of the PMP (Need not be higher than annual maximum level)
- Analyze historic extreme floods and antecedent storms for the region.

Conclusions – Reservoir levels will be analyzed to determine for historical conditions. Antecedent reservoir elevations will be determined using each of the four procedures. It is likely that the sensitivity of the routed PMF hydrograph to antecedent reservoir conditions will be tested in the sensitivity analysis.

Operations Considerations and Criteria

The two operational considerations that should be addressed are the powerhouse discharges and debris conditions at the spillway gates. The operational criterion for passage of the PMF is the freeboard at the dam.

Powerhouse Discharge

Guidelines - Guidance on what outlets to be available during for the PMF are provided:

- Only release facilities that can be expected to operate under flood conditions. Need to justify generating unit availability, effects of debris, availability of emergency power for operating, design limits on operating head, accessibility of controls, reliability of access roads, availability of personnel, and other factors.
- Bypass outlets to turbines only if they can be isolated from turbines by gates or valves.
- Assume up to normal release values until the allocated storage elevations of the reservoirs are exceeded.
- Don’t allow total project outflow or rate of increase of total project outflow to exceed total project inflow or rate of increase of total project inflow, unless forecast information is available.

Conclusions – The conservative assumption would be that there is no discharge through either powerhouse (Upper Baker and Lower Baker) as the PMF hydrograph is routed through the reservoirs. A simulation of PMF performed by PSE (PSE 1981) assumed the Upper Baker powerhouse to be discharging and the Lower Baker to not be operating. This assumption was based on the conclusion that the Lower Baker powerhouse might experience moderate inundation during the PMF, thereby precluding turbine operation. The Upper Baker powerhouse was assumed operable, due to the conclusion that the water surface elevation in the Lower Baker reservoir was not high enough to cause inundation of the Upper Baker powerhouse. Based on initial review of the operation tables in the Hydrocomp PMF simulation (Hydrocomp 1969), it appears that powerhouse discharges were incorporated into the discharge rating curves.

It should be noted that neither the Upper Baker project nor the Lower Baker project can pass water through the penstocks under “no-load” conditions. Therefore, given the potential for inundation of the operating units during extreme events, the potential for regional power outages during the PMP, and the fact that water cannot be passed through the penstocks under “no-load” conditions, the initial assumption will likely be that there is zero discharge through the powerhouse during the PMP event.

Further discussion on powerhouse discharges will be held with PSE and the FERC to resolve this issue. The sensitivity analysis should include an evaluation of the assumptions applied influence on the routed PMF.

Spillway Gates

Guidance – The Guidance states that it is important to consider the possibility that a spillway or outlet works may be at least partially blocked by debris during a PMF. The Guidance further states that is acceptable to assume that blockage will be insignificant during passage of the PMF if a successful debris-handling plan has been utilized during prior flood events. If no plan exists, the loss of spillway capacity due to debris blockage must be considered.

Conclusions – None of the prior studies included a reduction in discharge capacity for debris build up upstream of the spillways. It is not anticipated that a reduction will be included in the analysis conducted under this study, though the assumptions regarding debris blockage will be discussed with FERC and PSE at the time that powerhouse discharge assumptions are addressed. Reduction in spillway capacity due to debris influence could be incorporated into the sensitivity analysis.

Additionally, the spillway rating curves will be verified prior to use, to ensure that they extend up to the maximum anticipated pool elevations and that the effect of spillway gate submergence is incorporated if necessary.

Freeboard Allowances

Guidelines – The Guidelines indicate embankment dams need to have more freeboard than concrete dams because of their susceptibility to wave damage or erosion when overtopped. The Guidelines specify, that if studies show the concrete dam can withstand the PMF while overtopping without significant erosion of the foundation or abutment material, then no freeboard is required. Special consideration may be required when a powerplant is located near the base of the dam. Page 20 of FERC (1993) refers to USBR developed guidelines (USBR 1981) for further freeboard considerations.

Conclusions – All prior PMF studies (Hydrocomp 1969 and PSE 1981) showed overtopping of Lower Baker Dam. It is anticipated that some level of overtopping of Lower Baker is likely under the current study. A structural analysis of the influences on the stability of Lower Baker of various surcharges or assessment of the stability of the foundation to overtopping flows is not part of the current scope. USBR (1981) will be obtained and reviewed to determine if there is further guidance for the overtopping of Lower Baker Dam.

The two prior PMF studies (Hydrocomp 1969 and PSE 1981) indicated that neither the Upper Baker Dam nor the West Pass Dike would overtop during the critical PMF. Both studies concluded that there would be at least two feet of freeboard at maximum pool elevation. The West Pass Dike is a rock filled dike with a crest elevation two feet higher than that of Upper Baker Dam. Since the West Pass Dike is an embankment dam, freeboard considerations will differ from those at Upper Baker Dam, and calculations of freeboard components from wave set-up and runup will be developed.

Probable Maximum Flood Study Steps

Based on the review of FERC guidelines and the general requirements for performing similar hydrologic simulations, the following steps have been identified for the Baker Project PMF evaluation. The following steps are based on completion of the PHASE I Tasks which included: data acquisition, site visit, regulatory review, historical data analysis, recommendation for a model(s) to conduct the study and initial coordination meeting with PSE and FERC.

Step 1 – Coordination: Tetra Tech will coordinate with PSE and FERC on the final scope for Phase II.

Step 2 – Develop PMP

This step involves the development of the PMP and development of the climatic conditions during the PMP for snowmelt. The procedures contained in HMR-57 will be used. Both the general storm PMP (all season and seasonal) and the local storm PMP will be developed.

<u>2.1 – Develop the General Storm PMP:</u> This task involves application of HMR-57 to develop both the all season general storm PMP and the seasonal general storm PMP.

  2.1.1 – Develop all season PMP index value
  2.1.2 – Develop seasonal index PMP estimates (October, November-February, March, April-May, June, July-August, and September).
  2.1.3 – Apply depth duration reduction factors to the seasonal index PMP estimates
  2.1.4 – Apply depth area reduction factors to the values obtained in the previous step
  2.1.5 – Determine temporal distribution of seasonal PMP estimates. Compare the FERC guidance (FERC 2001), the methodology presented in HMR-57, and the findings of Schaefer (1989) to determine the appropriate temporal distribution. Sensitivity analysis may be necessary to determine critical distribution
  2.1.6 – Determine areal distribution for PMP and distribute the PMP over the basin(s).

<u>2.2 – Develop the Local Storm PMP:</u> This task involves application of HMR-57 to develop the local storm PMP and involves determining if the local storm PMP would produce the controlling runoff event.

  2.2.1 – Determine basin average local storm index PMP
  2.2.2 – Adjust index value to account for basin elevation

2.2.3 – Apply adjust factor for duration
2.2.4 – Apply areal adjustment factors
2.2.5 – Determine temporal distribution of local storm PMP
2.2.6 – Determine areal distribution for local storm PMP
2.2.7 – Make determination as to whether or not the local storm PMP would be capable of producing the controlling PMF event. This determination will not be made with the runoff model, but will instead be made on a volumetric basis. It is anticipated that the local storm PMP will not produce the controlling event.

<u>2.3 – Develop snowpack parameters:</u> This task involves identification of appropriate snowpack water equivalents for various months and parameters required for simulation of snowmelt utilizing the energy budget method.

2.3.1 – Perform statistical analysis on the snowcourse data for the months of November through June to develop “typical” snowpack conditions and 100-year snowpack conditions
2.3.2 – Utilize historic records to determine distribution of snowpack by elevation for the various months
2.3.3 – Perform an analysis to determine the controlling PMF scenario for snow conditions west of the Continental Divide. Determine whether the PMP on a 100-year snow pack or a 100-year precipitation on a Probable Maximum Snowpack is the controlling event. Similarly, determine if the PMP on a “typical” snowpack is capable of producing the controlling runoff event. It may not be necessary to use the watershed runoff model to make this determination, but instead, conservative hand calculations of runoff transformation and snowmelt may be sufficient to make this determination.
2.3.4 – Determine snowmelt parameters prior to and during the PMP for use in the energy budget snowmelt simulation (temperature lapse rate and sequences for temperature, dew point, wind speed and solar radiation). Guidance is presented in HMR-57 for determining temperature, wind and dew point values both prior to and during the PMP.

Step 3 – Develop Runoff Model: This task involves the development of the rainfall runoff simulation model for the basin. It includes the basic model parameter development, model calibration and model verification. The following subtasks will be conducted.

<u>3.1 – Initial subbasin parameter development</u>: For the two subbasins (Upper and Lower Baker drainage areas) the following will be performed.

3.1.1 – Delineate the basin and subbasin boundaries and compute areas. Each reservoir surface will be included as a separate subbasin with direct rainfall accumulation
3.1.2 – Perform final selection of historical events for calibration and verification. Up to three events will be selected for model calibration and one additional event will be selected for model verification. Candidate events will likely include November 1990 (two events), November 1995, and October 2003 although other events may also be considered as needed.
3.1.3 – Prepare a memorandum summarizing the events available and associated data for the selected storms for calibration and verification.

<u>3.2 – Prepare Model for Calibration and Verification</u>: This step involves setting up the selected model for running the calibration and verification efforts (Model will be for cold season).

- 3.2.1 – Prepare initial watershed parameters
    - a. initial estimates of parameters for the selected loss rate methodology
    - b. initial estimates of unit hydrograph parameters
- 3.2.2 – Prepare historic runoff and hydrometeorological data
    - a. rainfall sequence including temporal and spatial distribution and subsequent determination of basin average. Use a frequency based climatological base map, along with recorded precipitation volumes at weather service stations and SNOTEL stations, to determine spatial and temporal distribution of historical precipitation.
    - b. temperature sequence
    - c. wind speed sequence
    - d. snowpack (distribution and water equivalent)
    - e. reconstructed inflow hydrographs from Upper Baker and Lower Baker historic storms to determine runoff hydrographs from subbasins
    - f. separate baseflow from hydrographs

<u>3.3 – Perform Calibration</u>: This step involves performing the calibration for a minimum of two storms, although it is expected that at least three storms will actually be used. Assuming equal quality of data for all calibration storms, the storm producing the highest peak will be given the most consideration in determination of the final unit hydrograph for each basin or subbasin.

- 3.3.1 - Perform the simulations based on initial estimates of hydrograph parameters
- 3.3.2. - Review simulated versus recorded hydrographs
- 3.3.3. - Adjust parameters to provide better agreement between recorded and simulated results and repeat 2.3.1 and 2.3.2(Note: If HEC-1 is utilized, it has options for the model to perform optimization of unit hydrograph parameters, though the guidelines indicate several iterations of the optimization should be performed using results of the previous optimization until convergence is achieved.)
- 3.3.4. - Review the results of the calibration then justify and document the results of the final calibration

<u>3.4 – Model Verification</u>: This step involves executing the model for a significant historical storm that was not included in the calibration, utilizing the adopted unit hydrograph parameters. If the resulting simulation agrees adequately with the reconstructed runoff hydrographs, then the process can continue to step 3. If the agreement is unsatisfactory, then the process needs to return to the beginning of Step 2. If the latter occurs, then further subdivision of the basin into smaller units, possibly adopting different runoff simulation techniques and different events for calibration need to be considered. In addition to using the reconstructed inflow hydrographs, checks should be made against gaged tributaries within the basin for additional comparison of such items as flood peak timing, runoff per square mile and peak discharge per square mile.

Step 4 – Develop Antecedent Conditions for the PMP

This step consists of determining the antecedent conditions for the PMF simulation.

4.1 – Develop antecedent reservoir level: This task involves review of historic reservoir levels, operations conditions and simulation of a 100-year flood to determine the appropriate starting reservoir level based on FERC guidelines. The starting reservoir level will be dependent on time of year based on different operating procedures during the year. In all cases, it is justifiable to assume that flood storage is recovered as rapidly as possible as permitted by Corps operating procedures (USACE 2000) in the event that a second event is forecasted.

4.2 - Determine loss rates: Saturated soil condition loss rates will be determined for the soils within the basin based on the distributed method outlined in the Guidelines. These values will be compared with values calibrated for the historic events and appropriate rates selected and justified. Initial abstraction will be set to zero.

4.3 – Baseflow: Develop estimates of baseflow from the historic records for the seasonal periods to be simulated in the PMF development. The average monthly baseflow for seasonal periods will be added to the corresponding PMF inflow hydrographs before reservoir routing is performed.

Step 5 – Develop Reservoir Operations Model

This effort involves developing the reservoir operations model to rout the PMF through both the Upper and Lower Baker projects. It is currently assumed that the USACE HEC-5 model currently developed for the Baker Projects and applied for simulation of storms ranging from the 10-year to 500-year will be utilized

5.1 – Review model parameters: Review the discharge rating curves, rule curves and other model input for accuracy. Discharge rating curve values will be checked against published procedures and generally adopted parameters.

5.2 – Perform reservoir simulations on historic events: Operations model will be executed for each of the historic events using the reconstructed inflow hydrographs. The resulting outflow hydrographs from both projects will be compared to the recorded hydrographs. If agreement is not made, the operating policies will be reviewed further and a determination made as to whether changes in the rule curves will be required to better reflect actual real time operations. Any changes will be justified, documented and distributed to the PSE, FERC and the Seattle District for review and concurrence.

Step 6 – Develop Inflow PMF Hydrographs

This step involves executing the runoff model with the input parameters developed in the previous tasks. This step will include a sensitivity analysis. This section assumes that the general storm PMP controls over the local storm PMP.

6.1 - Model parameter input: Develop the actual model with separate runs for each of the seasonally adjusted PMPs. This will require separate model runs for each seasonal PMP.

6.2 – Model execution: The runoff model will be executed for each of the seasonal PMP events.

6.3 – Review and sensitivity analysis: An initial review of the results will be performed. The review will include a sensitivity analysis that incorporates important parameters such as loss rate, unit hydrograph parameters, and snowmelt parameters. The results of the inflow hydrograph development and sensitivity analysis will be documented. If warranted from the sensitivity analysis, model parameters may be adjusted and the inflow hydrographs redeveloped (this would include re-running historical events).

Step 7 – Develop Outflow Hydrographs and Determine Critical PMF

This step consists of applying the reservoir routing model to the adopted inflow hydrographs. A sensitivity analysis on reservoir routing parameters is included in this step.

7.1 – Account for baseflow: Previously determined baseflow rates will be added to the PMF hydrographs prior to routing through the reservoirs.

7.2 – Reservoir routing: Each of the PMF hydrographs will be routed through Upper and Lower Baker Projects.

7.3 – Review and sensitivity analysis: The results will be reviewed and a sensitivity analysis performed. Parameters considered in the sensitivity analysis may include initial reservoir level, assumptions for debris blockage, and assumptions for powerhouse operation. If warranted the model parameters will be adjusted and outflow hydrographs reproduced.

7.4 – Select critical period PMF: The critical period PMF will be selected as the outflow hydrograph that produces the highest reservoir stage at each reservoir. The critical PMF may be different for Upper and Lower Baker.

Step 8 – Documentation

The assumptions, input parameter development, and results of the PMF evaluation will be documented in a report. This will include documentation of each of the steps and associated justification for adopted parameters and results. Use of both tables and graphs will be made to better illustrate comparisons such as between recorded and measured runoff. Printouts of modeling results and associated electronic copies of input and output dat will be provided.

References

Federal Energy Regulatory Commission (FERC). 1993. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter II – Selecting and Accommodating Inflow Design Floods for Dams.

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

Hydrocomp, Inc. 1999. *Baker River Watershed Model Calibration*. Prepared for Puget Sound Energy.

National Weather Service (NWS). 1994. *Probable Maximum Precipitation – Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages. Hydrometeorological Report No. 57.* October 1994.

National Oceanic and Atmospheric Administration (NOAA). 1973. *Precipitation-Frequency Atlas of the Western United States (Volume IX – Washington).*

Schaefer MG. 1989. *Characteristics of Extreme Precipitation Events in Washington State*. Washington State Department of Ecology, Water Resources Program, 89-51.

Schaefer MG. 1990. *Regional Analyses of Precipitation Annual Maxima in Washington State*. Water Resources Research, Vol 26, No. 1, pp 119-132.

Schaefer MG, Barker BL, Taylor GH, Wallis JR. 2002. Regional Precipitation-Frequency Analysis and Spatial Mapping for 24-Hour and 2-Hour Durations in Western Washington. Prepared for Washington State Department of Transportation.

United States Army Corps of Engineers (USACE). 2000. *Baker River Project Water Control Manual.* Seattle District US Army Corps of Engineers.

United States Bureau of Reclamation (USBR). 1981. Freeboard Criteria and Guidelines for Computing Freeboard Allowances for Storage Dams – ACER Technical Memorandum No. 2.

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 4

HISTORICAL DATA ANALYSIS

January 3, 2005
Revised February 4, 2005
Revised July 15, 2005

(Revision 2 - FINAL)

Although a revision date of July 15, 2005 is indicated in the header, this memo actually reflects the project conditions and what was known of the project as of the end of February 2005. Since February, work has continued on the project, more data has been acquired, and there have been modifications to the work plan. However, this memo is intended to represent a "snapshot" in the project chronology, subsequent to the Board of Consultant (BOC) February review of the Phase I technical memorandums, of which this is one. The main report will be the ultimate product and final source of information for this project.

INTRODUCTION

This memorandum presents a discussion of the predominant physical characteristics and hydroclimatic conditions that control peak flow hydrology in the Baker River basin. Additionally, an analysis of specific historical rainfall/flood events in the Baker River basin and the Skagit River watershed are presented. Attachment 1 includes a graphic of the Baker River basin and Attachment 2 includes an expanded graphic of the Baker River basin and neighboring basins. On both graphics, all current and abandoned data collection stations are identified.

There have been two prior PMF studies conducted for the Baker River basin. The events that were used for the calibration and verification of the associated models are summarized below in Table 1.

Table 1.
Calibration Events for Previous PMF Studies

Study	Calibration Events	Verification Events
Hydrocomp (1969)	SWE & SD for WY 1960-1961 SWE & SD for WY 1966-1967 Baker Lake Inflow November 19th, 1968	n/a
Pacific International Engineering (2004)	Inflow Hydrograph to Baker Lake for: November 24th, 1990 November 29th, 1995	Baker Lake Inflow November 10th, 1990

SWE = Snow Water Equivalent
SD = Snow Density

The primary purpose of this memorandum is to identify the most suitable events for calibration and verification of the hydrologic model for evaluation of the Baker River PMF. To be suitable for use in the calibration/verification process, the events must be large, represent similar season and type of event, and have the necessary data available to perform the calibration/verification. This memorandum is also intended to aid in selecting the appropriate model(s) for evaluating the PMF by providing the understanding of the system and information available to support its modeling. From this understanding, a model that considers the appropriate physical processes and can be supported by the available data can be identified (Note: actual selection of the model(s) for evaluation the PMF is presented in a separate document.).

SUMMARY OF PHYSICAL CHARACTERISTICS

The Baker River basin is a tributary to the 3,140 square mile Skagit River basin. The overall drainage area above Lower Baker Dam is 297 square miles, with 215 square miles of the basin draining into Baker Lake and 82 square miles draining into Lake Shannon below Upper Baker Dam.

Topography in the Baker River Basin is mountainous with extreme gradients and an elevation difference of nearly 10,500 feet. The low point in the basin is approximately 170 feet. The most prominent topographical features in the basin are Mount Baker and Mount Shuksan, with peak elevations of 10,778 feet and 9,131 feet, respectively. Other significant peaks along the basin divide include Whatcom Peak (Elev. 7,574) and Bacon Peak (Elev. 7,066). Table 2 summarizes the percent of the Baker Lake tributary area and the percent of the Lake Shannon tributary area that is within each of ten 1,000-foot elevation zones. This information was provided by PSE.

Table 2.
Summary of Elevations

Elevation Band	Baker Lake Subbasin (215 sq mi)		Lake Shannon Subbasin (82 sq mi)	
	Percent of Subbasin Incremental	Percent of Subbasin Cumulative	Percent of Subbasin Incremental	Percent of Subbasin Cumulative
0 – 1,000	9.2	9.2	17.4	17.4
1,000 – 2,000	11.5	20.7	24.4	41.8
2,000 – 3,000	15.1	35.8	17.3	59.1
3,000 – 4,000	22.0	57.8	24.2	83.3
4,000 – 5,000	21.2	79.0	13.9	97.2
5,000 – 6,000	13.5	92.5	1.5	98.7
6,000 – 7,000	5.5	98.0	0.9	99.6
7,000 – 8,000	1.3	99.3	0.5	100.0
8,000 – 9,000	0.5	99.8		
9,000 – 10,000	0.2	100.0		

The overall basin is generally steep, with slopes of 20 to 40 percent over much of the basin. Steeper slopes (60 to 80 percent) are prevalent in the upper portion of the tributary area to Baker Lake (Attachment 3). Also seen in Attachment 3 are the broad alluvial valleys of the Baker River and other smaller tributaries.

Land ownership and management in the Baker River basin are dominated by federal government holdings in the Mt. Baker-Snoqualmie National Forest and in the North Cascades National Park. Approximately 85 percent of the basin is within these National Forest and National Park boundaries. Private and state holdings account for the remainder. Consistent with these holdings, land use and vegetative cover within the basin is predominantly forested. Over 70 percent of the basin is comprised of evergreen forest cover. The forest cover is predominantly below elevation 5,500 feet. Perennial snowfields and glaciers occupy nearly 10 percent of the basin, with a vast majority of the glacier fields located on Mount Baker. The combined surface area of Baker Lake and Lake Shannon is nearly 4 percent of the total basin area. These three land cover categories alone comprise 85 percent of the Baker River basin.

The geology and the soil conditions within the Baker River basin are quite variable and unique due to the influence of Mount Baker and the extinct volcanic mountains in the area. Granitic and basaltic rocks are prevalent. According to United States Forest Service (USFS) mapping, a majority of the basin is comprised of soil types that are classified by the Natural Resource Conservation Service (NRCS) as belonging to hydrologic soil group D. The rest of the basin is split between soil types classified by the NRCS as belonging to hydrologic soil groups B and C (Washington Group 2004). Soils belonging to hydrologic soil group D have a very slow infiltration rate when thoroughly wetted, as opposed to soils belonging to hydrologic soil groups B and C, which have moderate to slow infiltration rates, even when thoroughly wetted.

SUMMARY OF HYDROCLIMATIC CONDITIONS

The Baker River basin lies within a convergence zone between Pacific weather systems that originate from the west and colder Arctic weather systems that originate from the north. The major factors that influence the climate of the Skagit River basin as a whole are the terrain, the proximity to the Pacific Ocean, and the position and intensity of semi-permanent high and low pressure centers over the north Pacific (USACE 2004).

The Pacific storm season begins in October, where average monthly rainfall nearly doubles from that of September. Some of these early season storms can be very powerful if they can tap some tropical moisture or energy from low pressure centers located over tropical waters. November and December are the wettest months of the storm season, where the Pacific storms hit the northwest with high winds and heavy precipitation. It is during these months when the highest frequency of low pressures occur in the Pacific Northwest. Snow accumulations usually begin in November, which subsequently affect the hydrology of basins with high elevation zones. In November and December, Pacific storms usually bring rain to the lower elevations because of the modifying effect by the Pacific on the low-level air. In January and February, Pacific storms continue to hit the northwest, and occasionally, cold air masses descend on the region from the east and north, causing temperatures to drop significantly, sometimes resulting in below freezing temperatures, even on the coast. These conditions don’t usually last long, because as soon as the winds turn more westerly (the prevailing direction), milder Pacific air returns. March continues with high precipitation rates, but by April, the storm season is tailing off. Sunshine and increasingly dry weather is the trend in the Pacific Northwest for the months of May through July. The Pacific high pressure builds offshore and feeds dry and stable air into the region. Beginning in the month of September, the high pressure weakens and the polar front drops south. The region sees a doubling of the monthly precipitation in September, which will double again in October.

The physical attributes of the Baker River basin result in precipitation patterns in the watershed that are quite variable, caused by the orographic controls of extreme elevations and variable topography throughout the basin. Mean annual precipitation as measured at the Lower Baker fish trap (Elev. 195 feet) is 69.43 inches. Further up in the watershed, the mean annual precipitation at Upper Baker Dam (Elev. 690 feet) is 101.83 inches (USACE 2004). Table 3 summarizes the mean annual climatic data at four stations in the Baker River basin, two of which are discontinued stations. According to NOAA (1973), the 24-hour 100-year point rainfall totals within the Baker River basin range between 5.5 inches up to nearly 10 inches.

Table 3.
Summary of Mean Annual Climatological Data in Baker River Basin (USACE 2000)

Station	Station Elevation (NGVD29)	Period of Record	Mean Annual Precipitation (inches)	Greatest Annual Precipitation (inches)	Least Annual Precipitation (inches)	Mean Annual Snowfall (inches)
Mt Baker Lodge	4,150	’26-’42, ’46-‘60	109.85	142.33	74.13	525.3
Upper Baker Dam (NOAA 8715)	690	1961-1997	101.83	132.61	72.76	not available
Baker Lake	670	1926-1934	102.88	133.36	69.26	58.1
Concrete PPL FS (NOAA 1679)	195	1920-1997	69.43	82.94	39.18	33.0

Table 4 illustrates the seasonal fluctuation in monthly precipitation at the two NOAA/NWS stations in the Upper Baker River Basin. This table will be referenced in subsequent sections of this memorandum when historical events are discussed. The values in Table 4 are taken from the Western Regional Climate Center (WRCC) website:

http://www.wrcc.dri.edu/summary/climsmwa.html.

Table 4.
Precipitation Norms (inches) in Upper Baker River Basin

Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Upper Baker	14.73	10.38	9.78	6.33	4.73	3.55	2.40	2.13	4.47	9.94	15.82	15.55
Concrete PPL FS	9.46	7.01	6.85	4.53	3.28	2.75	1.51	1.72	3.47	6.81	10.17	10.66

Within the Baker River Basin, the nine snow course sites are monitored monthly, generally beginning the first of the year once a sufficient snowpack depth has developed. The at-a-station mean value of the first of the year snow water equivalent ranges between 5 inches (South Fork Thunder Creek – El 2200) and 40 inches (Jasper Pass – El 5400). The mean value of the snowpack density at this time of year ranges between 33 and 36 percent. Steady accumulation of the snowpack begins in late December/early January and continues through the spring. On average, the snow water equivalent of the snowpack peaks in March or April at the two lowest elevation stations and in May at the remaining seven stations. Snowfall can be extremely heavy in the higher elevations of the basin as evidenced by the world record for annual snowfall of 1,140 inches set on Mount Baker during the 1998-1999 season.

Historic floods in the Baker River basin typically occur during the early months of the Pacific Northwest storm season. Unfortunately, a historic record of instantaneous peak inflows or unregulated peak flows downstream of the Baker Project is not readily available. However, an annual series of mean daily inflows to Upper Baker has been developed by PSE. The period of record for this data series is 1927 to present. This data series was also referenced in USACE (2004) in regards the flow frequency curve for annual maximum one-day inflows. After analysis of this annual series of maximum one-day inflows, it is concluded that the peak annual inflows predominantly occur in the months of October through January, with October and November being the most likely months for annual maximum peaks, followed closely by January.

Table 5 illustrates the monthly trend in occurrence of maximum annual mean daily inflows to Baker Lake. The grouping of occurrences in October, and the decreasing number of occurrences in subsequent winter months likely reflects the temporal distribution of annual rainfall in the basin. It also may provide some evidence that the deeper snowpacks that exist in the basin subsequent to January act to reduce the snowmelt contribution to flood events later in the flood season.

Table 5.
Distribution of Maximum Annual One Day Flows into Upper Baker[a]

Month	Number of Occurrences	Percent of Record
September	2	2.6
October	16	20.5
November	15	19.2
December	10	12.8
January	14	17.9
February	6	7.7
March	3	3.8
April	2	2.6
May-August	10	12.8

a. Based on historical record for water years 1927 - 2004

SUMMARY OF HISTORICAL PEAK FLOW EVENTS

Table 6 summarizes the highest ranked 15 annual regulated peak flows on the main stem Skagit River, and the highest ranked 15 reconstructed mean daily inflows to Baker Lake. This list is a key resource for selecting candidate events for model calibration and verification.

The period of record for Skagit River near Concrete (USGS gage 12194000) is 1924 to the present. However, the main stem peak flows itemized in Table 6 were drawn from a subset of this data, so as to include only the regulated conditions on the main stem. Existing flood control operation upstream of Concrete is that 74,000 acre-feet at Upper Baker Dam and 120,000 acre-feet at Ross Dam (City of Seattle) are available for flood control storage. This storage at Ross Dam has been available since 1954, and for Upper Baker Dam, flood control storage has been available since 1956. Therefore, although the period of record for Skagit River near Concrete (USGS gage 12194000) extends back to 1924, the peak flows in Table 6 were drawn from the subset of the record between water years 1956 and 2003, inclusive. As a point of comparison between events in Table 6, a 148,000 cfs event has a 20-year return period on the regulated flood frequency curve for USGS gage 12194000 (USACE 2004) and a 176,000 cfs event has a 50-year return period on the regulated flood frequency curve for USGS gage 12194000 (USACE 2004).

With three exceptions, the peak values for the listed events were obtained from the annual peak series for the Skagit River near Concrete (USGS gage 12194000). The published annual series does not yet include the October 2003 event, which produced the annual peak for water year 2004, and coincidentally the highest recorded peak flow at the station. Likewise, the published annual series does not yet include the December 2004 event, which produced the highest peak to date for the current Water Year 2005. Finally, the near record rainfall of November 1990 resulted in two distinct peaks on the main stem that were nearly identical in magnitude. The highest peak was included in the annual series. Since the two 1990 peaks were so close in magnitude, the second peak was also included in Table 6.

The reconstructed mean daily inflow values from the tributary area to Baker Lake were provided by PSE for the period of record of 1926 through 2004. However, the mean daily inflows included in Table 6 were drawn from a subset of this data so as to only include those years for which there is hourly precipitation data available within the watershed (1949 to present). Presumably, the pool of candidate calibration events will only include those years for which hourly precipitation is available within the watershed. Hydrologic model calibration will be complicated by the mountainous terrain, which effects the spatial and temporal distribution of precipitation. Therefore, a complete lack of precipitation data within the watershed makes consideration of events prior to 1949 unlikely for calibration. The maximum one-day flow for Water Year 2004 was obtained from USACE (2004) and added to the table so as to include the October 2003 event in the ranking.

Table 6.
Ranking of Historical Flood Events

Ranking of Annual Peak Series for Skagit River Near Concrete, WA (USGS Gage 12194000)			Ranking of Reconstructed Mean Daily Inflows to Baker Lake		
Period of Record (Water Year 1955 to current)			Period of Record (Calendar Year 1949 through 2003)		
Ranking	Date	Instantaneous Peak Flow (cfs)	Ranking	Date	Maximum One-Day Flow (cfs)
1	10/21/03 [a]	166,000	1	10/17/03	28,124
2	11/29/95	160,000	2	11/10/90	27,185
3	11/10/90	149,000	3	1/4/84	23,961
4	12/26/80	148,700	4	12/26/80	23,236
5	11/24/90 [a]	146,000	5	10/20/03	23,026
6	12/18/79	135,800	6	11/29/95	23,022
7	12/4/75	122,000	7	11/8/95	22,385
8	12/4/89	119,000	8	1/7/02	22,073
9	11/20/62	114,000	9	2/10/51	19,912
10	1/5/84	109,000	10	10/17/75	19,858
11	11/3/55	106,000	11	11/9/90	19,699
12	11/12/99	103,000	12	11/24/90	19,581
13	12/4/82	101,000	13	12/13/98	19,037
14	12/11/04 [a]	99,400	14	11/10/89	18,972
15	1/8/02	94,300	15	12/4/89	18,419

a. These values are not from the currently published annual peak series for Skagit River near Concrete, WA (USGS Gage 12194000)

This memorandum includes a detailed description of a select number of historical storm events. The description includes a discussion of antecedent conditions, presentation of available climatological data during the event, and an analysis of the hydrologic response of the basin. The events of October 2003, November 1995, and November 1990 are discussed in the most detail. These are the events for which the most hydrologic and climatic data are available. Also, the November 1995 and November 1990 events are the events that have been used for model calibration/verification for previous Baker Project PMF studies. For each event, evaluation is made in regards to the validity of the event for model calibration/verification.

Additional events are briefly presented at the end of this memorandum. For these events, the discussion primarily focuses on a description of the type of data available for each event. Finally, a summary table of data availability for all of the candidate events is included at the end of the memorandum. All of the events mentioned in this memorandum were selected from those presented in Table 6.

OCTOBER 2003

The high runoff and flood conditions at the Baker River Project during October 2003 developed as a result of below normal monthly precipitation in the months leading up to October, followed by record rainfall totals during the month of October. There were two distinct rainfall events that occurred back-to-back in the month of October. The first rainfall event resulted in peak runoff from the Baker River basin on October 17th. The second rainfall event resulted in peak runoff from the Baker River basin four days later on October 21st. Due to the lack of a significant snowpack prior to these events, the runoff produced by both of these storm events is associated purely with rainfall runoff.

Antecedent Conditions

During the two days prior to the start of rainfall on October 16th, the water surface elevation in Baker Lake was lower than that required by the flood control rule curve (see Attachment 4), ranging between 714.70 feet (NAVD88) and 715.50 feet (NAVD88). The water surface elevation in Lake Shannon was well below the normal full pool elevation (442.35 feet NAVD88), and was slowly being drawn down by releases through the penstock. The unusually dry conditions of the 2003 summer months resulted in below normal pool elevations at Lake Shannon. By midnight on October 15th, Lake Shannon was at elevation 422.74 feet (NAVD88), nearly twenty feet below the normal full pool elevation, and six feet below the crest of the spillway. Figure 1 shows the reservoir elevations antecedent to and in response to the storm events.

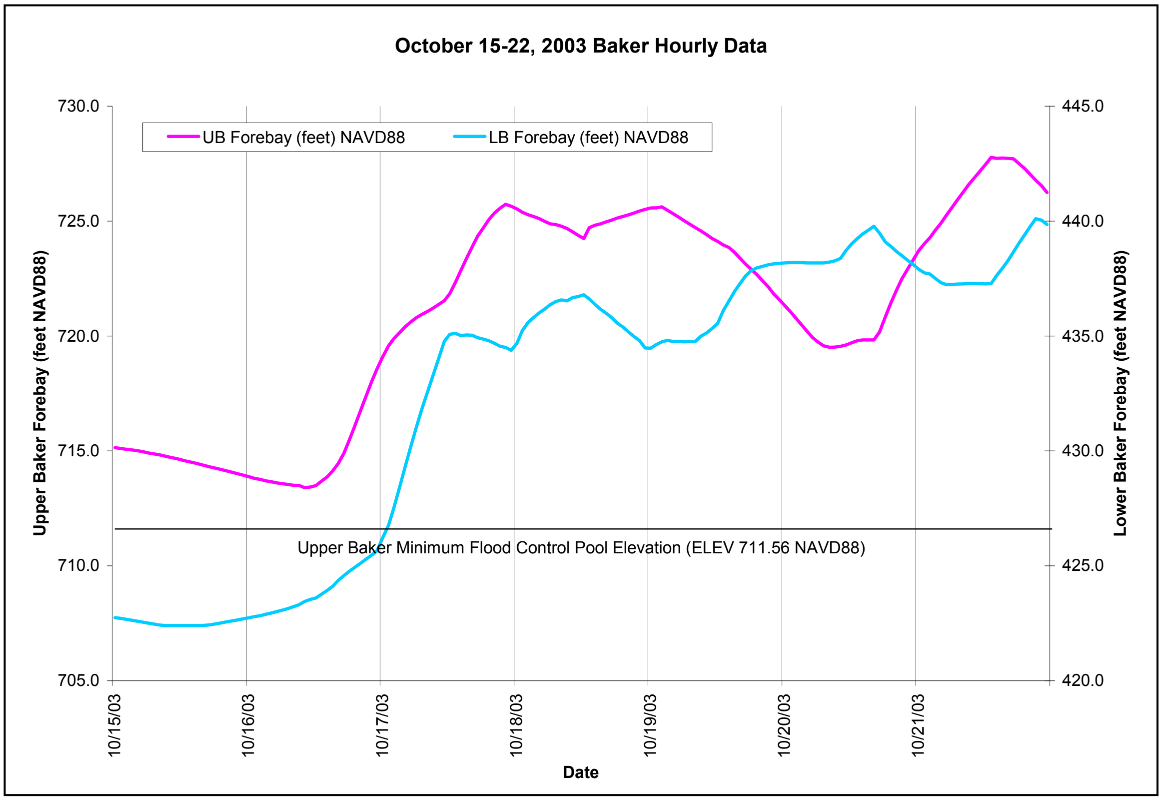


Figure 1. Upper and Lower Baker Pool Elevations – October 2003

The monthly rainfall total for the previous month (September), as measured at the Upper Baker gage, was 2.1 inches, approximately 57 percent of normal (NOAA 2004). The summer months of 2003 were recorded as the driest summer on record, and as a result, soil conditions were relatively dry when the first storm made landfall (USACE 2004).

Snow data from five nearby SNOTEL sites were analyzed for antecedent snowpack conditions. Manual measurement of snow depth and density does not start at the snow course sites until January. Since the only snow sites in the Baker River basin are snow course sites, there is no data for antecedent snow conditions within the basin. SNOTEL sites located in adjacent basins, which record year round data, were used to determine antecedent conditions. Based on this limited data, the depth of the snowpack was likely insignificant at elevations lower than 6500 feet. According to Table 2, this would translate to a conclusion that well over 90 percent of the Upper Baker subbasin had no significant snowpack and nearly the entire Lower Baker subbasin had no significant snowpack. Where there was snowpack, the snow water equivalent was likely very low, which is not unusual for this time of the year. Table 7 summarizes the average snow conditions on October 15th at various SNOTEL sites in the vicinity of Baker River basin.

Table 7.
Antecedent Snowpack Conditions – October 15th 2003

Site	Site Elevation (feet NGVD29)	Snow Depth (inches)	Snow Water Equivalent (inches)
Harts Pass	6500	4.4	1.1
MF Nooksack	4980	0.5	0.0
Rainy Pass	4780	2.6	0.2
Wells Creek	4200	0.2	0.1
Thunder Basin	4200	0.0	0.0
Elbow Lake	3200	0.0	0.0

Source of data: NRCS SNOTEL database

Description of Storm Event

The October 2003 storm event was actually comprised of back-to-back storm events, which produced two distinct peak runoff hydrographs. The first rainfall event occurred during the 72-hour period from October 15th through October 17th, and the second rainfall event occurred during the 72-hour period from October 19th through October 21st. Both storms were charged with a significant amount of tropical moisture that was transported into the area by the jet stream. These types of storms are sometimes referred to as “pineapple express” events, due to the long southwesterly moisture fetch. Being of tropical origin, the air contained very high concentrations of precipitable water, which combined with the high-speed jet stream, resulted in very heavy precipitation (USACE 2004). Early season storm events in the Pacific Northwest can be very powerful events if they tap into some tropical moisture or energy. This was exemplified by the events of October 2003. Figure 2 shows the rainfall hyetograph for the two October events as recorded at the Upper Baker station (NOAA 8715). At this particular precipitation station, hourly data is available throughout the first event; however, hourly data is available for only a portion of the second event. As a supplement, hourly data is available at one nearby NOAA station (Nooksack Salmon Hatchery), and at five nearby NRCS sites.

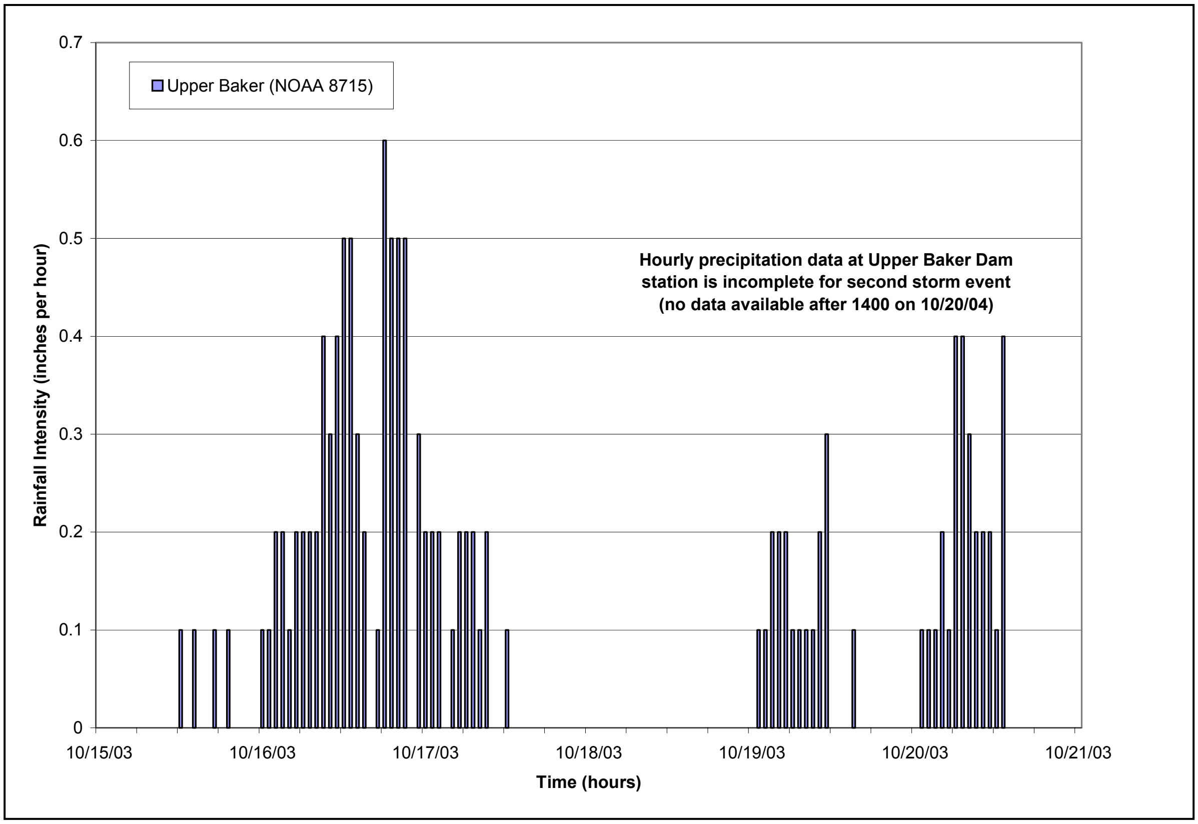


Figure 2. Rainfall Hyetograph at Upper Baker – October 2003
(Labels on the horizontal axis represent start of day)

Figures 3 and 4 show the cumulative precipitation totals for the duration of both of the storm events, as measured within the Baker River basin at the Upper Baker Dam gage, and as compared to several gages outside of the basin. As previously mentioned, hourly data is incomplete at the Upper Baker station for the second event, and hence the cumulative plot in Figure 4 for Upper Baker is incomplete. However, the daily totals are available at this station and were 0.87 inches, 1.7 inches, and 4.65 inches for the three consecutive days, for a three-day total of 7.22 inches.

During the first event, the Baker River basin received the greatest rainfall intensities and volumes relative to other neighboring stations. Peak intensities of 0.6 inches per hour occurred at 1900 on October 16th and nearly 9 inches fell during the three-day period. In comparing the cumulative plots of Figures 3 and 4, it can be seen that total rainfall depths and rainfall intensities during the first event were more spatially variable than those during the second event.

Record and near record 24-hour rainfall totals were recorded throughout the Skagit River watershed as a whole. Specifically within the Baker River basin, a record 24-hour total of 6.60 inches was recorded on October 16th at Upper Baker Dam, which has a period of record of more than 40 years.

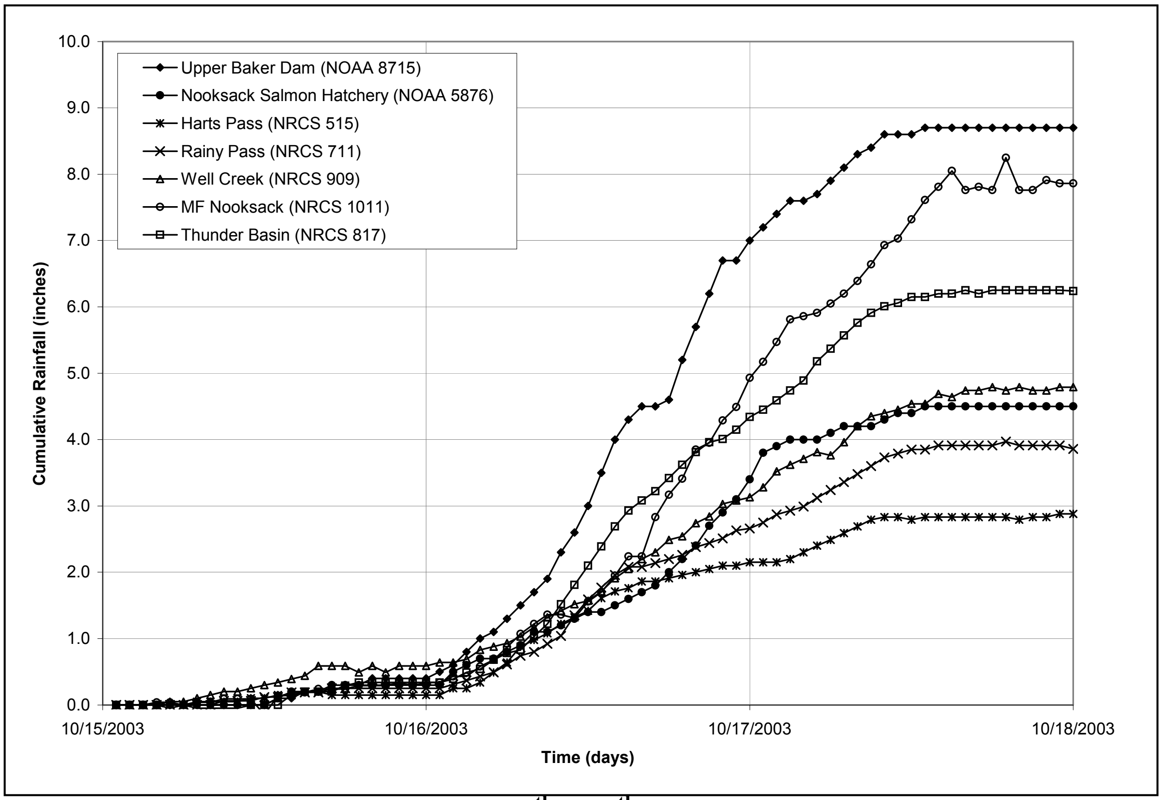
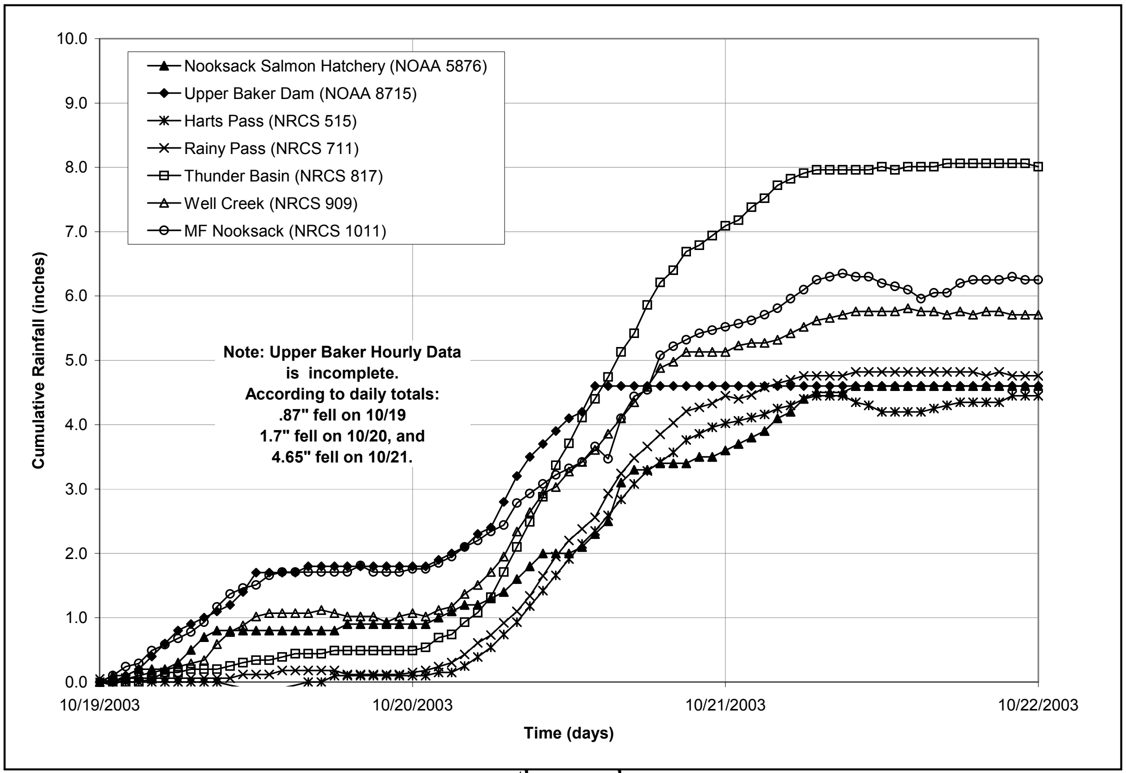


Figure 3. Cumulative Rainfall October 15th – 18th
(Labels on the horizontal axis represent start of day)



Note: Upper Baker Hourly Data is incomplete. According to daily totals: .87" fell on 10/19 1.7" fell on 10/20, and 4.65" fell on 10/21.

Figure 4. Cumulative Rainfall October 19th – 22nd
(Labels on the horizontal axis represent start of day)

In the days leading up to the first of the two rainfall events, minimum daily temperatures were below freezing at approximately at 6,500 feet (Table 8). Starting on October 17th average temperatures rose significantly (Table 9), with average daily temperatures sustained above 38 degrees F at elevations less than 5,000 feet. From October 17th through the 21st, minimum temperatures were well above freezing up to at least 6,500 feet. While none of the NRCS sites are located within the Baker River basin, the Wells Creek and MF Nooksack sites are in close proximity, directly to the northwest on the northwest slope of Mount Baker. The conclusion can be drawn that precipitation fell mostly as rainfall within the Baker River basin to at least elevation 6,500 feet, which accounts for nearly the entire Baker River tributary area (Table 2).

Table 10 shows snow accumulation at Harts Pass and Rainy Pass leading up to the peak of the first rainfall event on October 17th. However, the snow conditions were not such that snowmelt was a significant contributor to basin runoff (Table 10). As seen in Table 11, snow water equivalent as measured at Harts Pass was never more than 2.5 inches during the event, and by the end of the day on October 18th, the decrease in snow water equivalent was less than 0.5 inches.

Table 8.
Minimum Daily Temperatures (degrees F) - October 2003

Site	Basin	Site Elevation (NGVD29)	14th	15th	16th	17th	18th	19th	20th	21st
Harts Pass* (515)	Methow	6500	27	26	24	38	39	35	33	45
MF Nooksack* (1011)	Nooksack	4980	36	34	34	46	44	40	43	46
Rainy Pass* (711)	Lake Chelan	4780	29	29	30	38	37	36	37	47
Wells Creek* (909)	Nooksack	4200	36	35	36	47	47	42	43	49
Upper Baker Dam (8715)	Baker	690	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Concrete PPL FS (1679)	Baker	195	45	44	45	44	54	53	53	53

* NRCS sites measures in degrees C. Value converted to degrees F.

Table 9.
Average Daily Temperatures (degrees F) - October 2003

Site	Basin	Site Elevation (NGVD29)	14th	15th	16th	17th	18th	19th	20th	21st
Harts Pass* (515)	Methow	6500	30	27	32	42	44	38	39	48
MF Nooksack* (1011)	Nooksack	4980	40	37	43	47	49	43	50	53
Rainy Pass* (711)	Lake Chelan	4780	33	32	34	43	43	41	42	50
Wells Creek* (909)	Nooksack	4200	42	38	44	49	51	45	50	53
Upper Baker Dam (8715)	Baker	690	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Concrete PPL FS$^+$ (1679)	Baker	195	53	51	51	56	58	57	56	57

* NRCS sites measures in degrees C. Value converted to degrees F.

\+ Average temperature computed as an average of the maximum and minimum daily temperatures

Table 10.
Average Daily Snow Depth (inches) – October 2003

Site	Site Elevation (NGVD29)	14th	15th	16th	17th	18th	19th	20th	21st
Harts Pass* (515)	6500	3.7	4.4	12.0	6.7	4.4	3.2	2.1	0.4
MF Nooksack* (1011)	4980	0.4	0.5	0.6	0.4	0.2	0.5	0.4	0.2
Rainy Pass (711)	4780	2.3	2.7	10.3	3.8	2.7	1.4	0.7	0.6
Wells Creek* (909)	4200	0.0	0.2	0.1	0.2	0.0	0.3	0.2	0.1

Table 11.
Average Daily Snow Water Equivalent (inches) – October 2003

Site	Site Elevation (NGVD29)	14th	15th	16th	17th	18th	19th	20th	21st
Harts Pass (515)	6500	1.0	1.1	2.4	2.4	1.8	1.5	1.2	0.5
MF Nooksack (1011)	4980	0.0	0.0	0.2	0.1	0.1	0.1	0.1	0.1
Rainy Pass (711)	4780	0.2	0.2	1.0	0.9	0.4	0.0	0.0	0.0
Wells Creek (909)	4200	0.0	0.1	0.2	0.1	0.0	0.1	0.1	0.0

Hydrologic Response

Figure 5 shows the hydrologic responses of the Baker Lake and Lake Shannon tributary basins to the October 2003 storm events. These hydrographs were reconstructed using hourly reservoir elevation data and hourly outflow data provided by PSE, and therefore, there is some inherent uncertainty in the results.

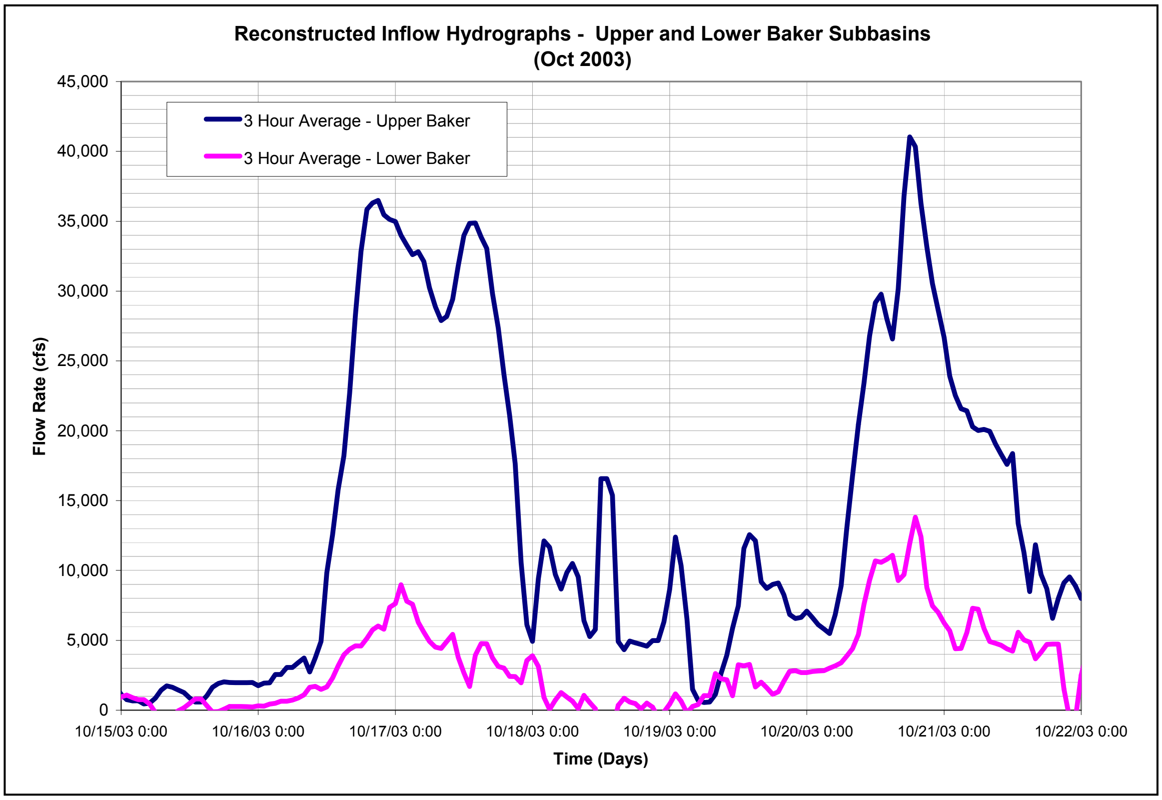


Figure 5. Reconstructed Inflow Hydrographs –October 2003 (Awaiting PSE operation data) ***(Labels on the horizontal axis represent start of day)***

The Baker project was operated for flood control during both of the October 2003 rainfall events. The Seattle District USACE directed flood control operation. The Upper Baker pool rose from 710.15 feet (NAVD88) to 722.04 feet (NAVD88) as a result of the first event. Lower Baker rose from 418.64 feet (NAVD88) to 433.05 feet (NAVD88) as a result of the first event. Subsequent to the first event, the reservoirs were drawn down to provide flood control storage in anticipation of the second rainfall event. Upper Baker was drawn down to 715.75 feet (NAVD88), approximately four feet above the minimum flood control pool elevation. Lower Baker was drawn down to 430.71 feet (NAVD88), which is approximately twelve feet below normal full pool.

NOVEMBER 1995

The November 1995 flood event was the product of the wettest November on record. Peak flows into Baker Lake and Lake Shannon occurred in the early afternoon of November 29th, 1995 after heavy rains fell in the basin for 48 hours, starting in the early morning hours of November 27th. Peak intensities were as high as 0.3 inches per hour at several points in the storm (Figure 6). Total rainfall for the 72-hour period was over 7 inches, as measured at the NOAA gage at Upper Baker Dam. The peak of the rainfall event occurred on November 28th at approximately 1800 hours.

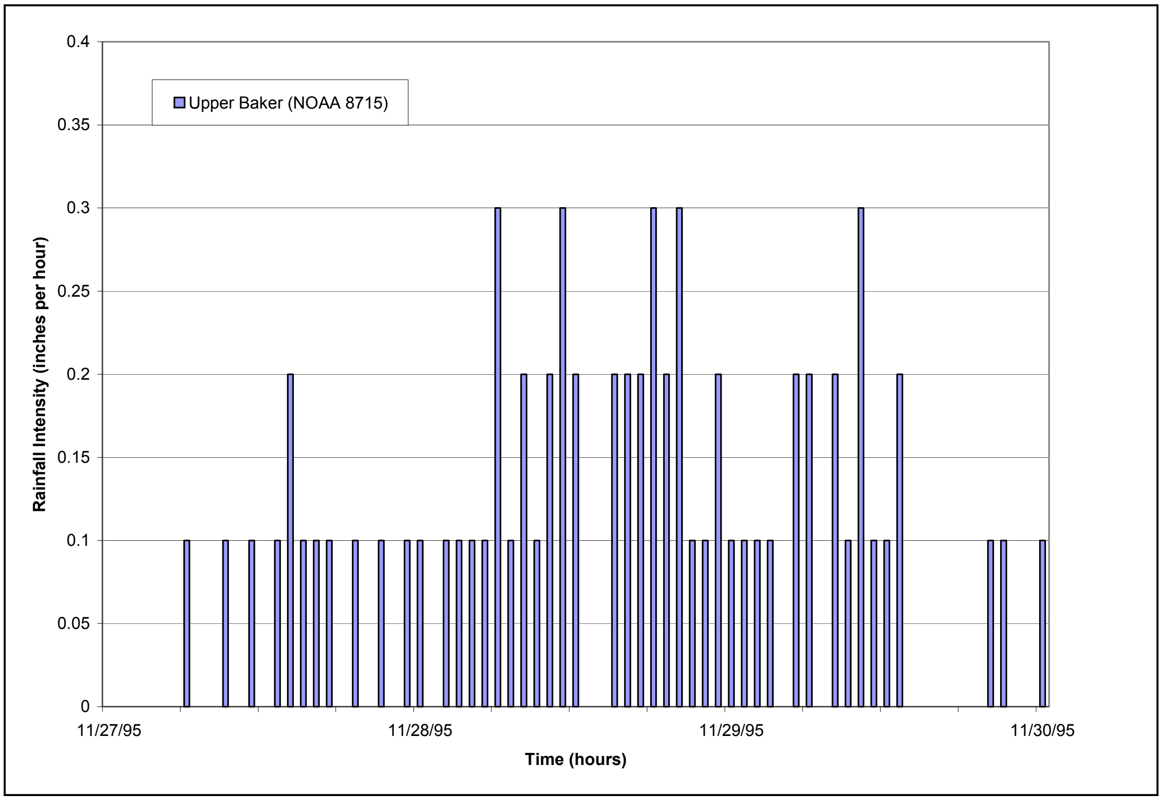


Figure 6. Rainfall Hyetograph at Upper Baker – November 1995
(Labels on the horizontal axis represent start of day)

Antecedent Conditions

As seen in Figure 7, on November 26th and November 27th, the pool elevation at Upper Baker was being drawn down to the minimum flood control elevation of 711.56 (NAVD88) in anticipation of the upcoming rainfall event. This was at the request of the Seattle District USAACE. During these two days, an average hourly flow of 4,500 cfs was being discharged over the spillway, in addition to the 4,800 cfs that was being discharged through the turbines. By the time the rainfall intensity began to increase on November 28th, Upper Baker was operating at the minimum flood control pool elevation of 711.56 (NAVD88).

At Lower Baker, the average pool elevation for the day of November 26th was 441.48 feet (NAVD88), which is nearly one foot below the normal full pool elevation (442.35 feet NAVD88). Lower Baker Dam was releasing an average hourly discharge of nearly 7,500 cfs throughout November 26th and 27th, in addition to the 3,800 cfs through the penstock, thereby maintaining the pool elevation just below the normal full pool elevation. Late at night on November 27th, PSE starting drafting at Lower Baker in anticipation of high inflows predicted the following day.

Rainfall totals for the month of November 1995 were well above normal, and soils were well saturated before the late November rainfall events passed through the basin. Average daily snow water equivalent at several sites outside of the Baker River basin is summarized in Table 12.

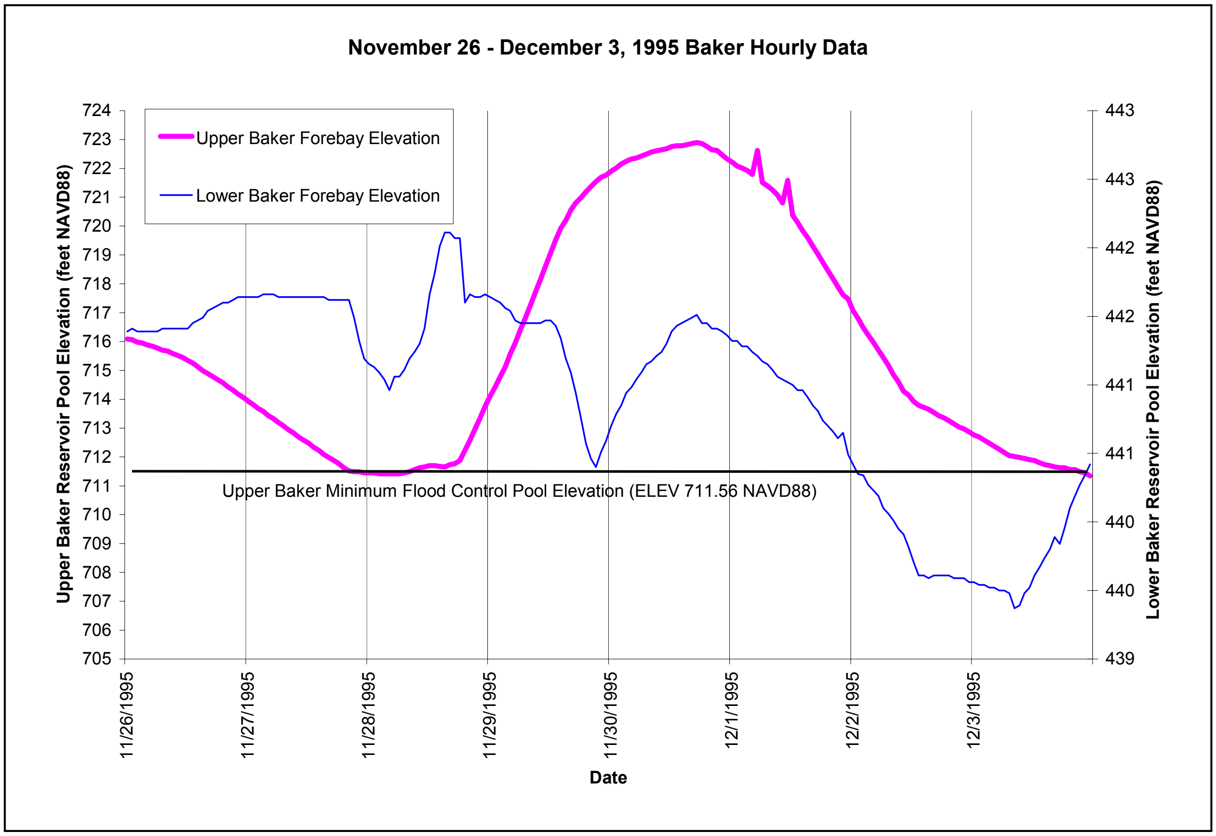


Figure 7. Upper Baker and Lower Baker Pool Elevations – November 1995
(Labels on the horizontal axis represent start of day)

Table 12.
Antecedent Snow-Water Conditions – November 26th, 1995

Site	Site Elevation (feet NGVD29)	Snow Depth (inches)	Snow Water Equivalent (inches)
Harts Pass	6500	n/a	12.6
Rainy Pass	4780	n/a	8.9
Wells Creek	4200	n/a	0.5
Thunder Basin	4200	n/a	5.4
Elbow Lake	3200	n/a	0.0

Description of Storm Event

The month of November began with an atmospheric low-pressure system fixed in the Gulf of Alaska that circulated Arctic air about its center. The resulting weather systems were propelled by a westerly jet stream into the northern part of the Columbia River Basin, producing normal amounts of rainfall and snow along the US-Canadian Border. Later in the month, the low pressure system moved to the southwest over more tropical waters. The air mass flowing through the low pressure system picked up additional heat and moisture before being propelled toward the Pacific Northwest by the jet stream. By the end of November, the jet stream was sending a steady stream of warm, moist air from near Hawaii, producing heavy precipitation throughout western Washington (USACE undated).

The event of November 27th through November 29th was actually the product of three separate storms that carried moisture laden, semi tropical air into the Pacific Northwest. The storms were fed by a very strong jet stream that helped produce strong orographic precipitation on south and west facing slopes of the Cascade Mountains. The heaviest rainfall from the first storm was in the central and northern Cascades, while the heaviest rainfall from the second two events was experienced in the Olympics and the southern Cascades (USACE 2004).

Figure 8 shows the cumulative precipitation for the three-day period from November 27th through November 29th. Similar to the October 2003 event, total precipitation at the Upper Baker gage was equal to or greater than the totals at neighboring stations. Three-day rainfall totals (November 27-29) were 7.0 inches at Upper Baker, and 5.9 inches at Darrington, the nearest hourly gage to Upper Baker. In the basin immediately north of the Baker River basin, the Wells Creek site recorded 6.8 inches in the three-day time period. The gage at Burlington was not in operation during this event.

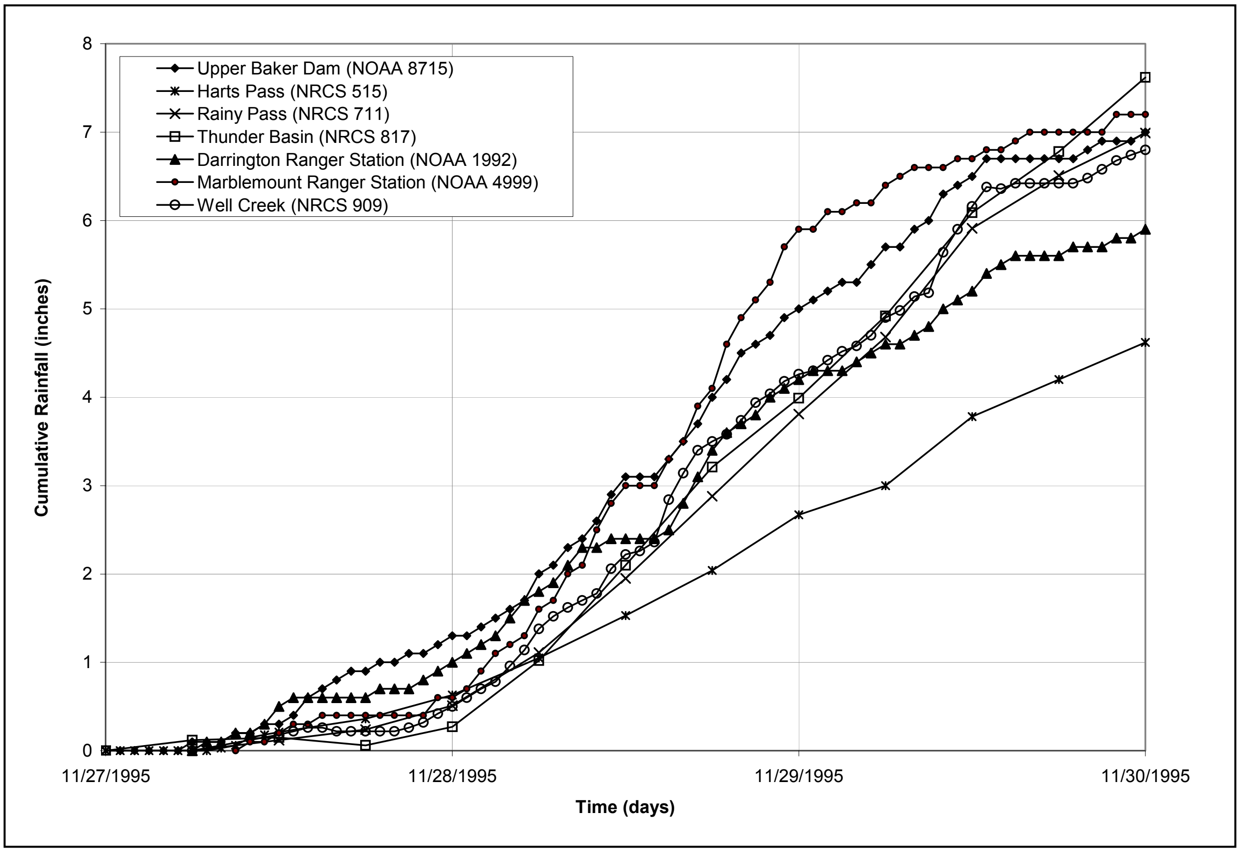


Figure 8. Cumulative Rainfall November 1995 Event
(Labels on the horizontal axis represent start of day)

There was an increasing trend in minimum daily temperatures leading up to the peak of the event (Table 13). Average daily temperatures (Table 14) were at or above freezing in the vicinity of the Baker River basin on the 28th and 29th, thus likely causing snowmelt as high as 6500 feet. According to USACE (undated), "during the storm, the freezing level…was high enough to cause snowmelt up to 10,000 feet. But since the snowpack did not cover a significant portion of the basins, it was only a minor contributing factor to (basin runoff)."

Table 13.
Minimum Daily Temperatures (degrees F) - November 1995

Site	Site Elevation (NGVD29)	26th	27th	28th	29th	30th
Harts Pass*	6500	21	19	28	26	23
Rainy Pass*	4780	27	25	28	32	29
Thunder Basin*	4200	27	26	32	32	31
Wells Creek*	4200	29	28	33	32	31
Elbow Lake*	3200	32	32	35	35	35
Upper Baker Dam	670	38	38	37	40	42
Concrete PPL FS	195	42	42	43	43	44

* NRCS sites measures in degrees C. Value converted to degrees F.

Table 14.
Average Daily Temperatures (degrees F) - November 1995

Site	Site Elevation (NGVD29)	26th	27th	28th	29th	30th
Harts Pass*	6500	23	22	32	32	25
Rainy Pass*	4780	29	27	31	34	31
Thunder Basin*	4200	30	29	34	36	32
Wells Creek*	4200	30	31	39	39	32
Elbow Lake*	3200	32	32	41	43	36
Upper Baker Dam+	670	43	40	39	46	48
Concrete PPL FS+	195	46	45	43	49	50

* NRCS sites measures in degrees C. Value converted to degrees F.

+ Average temperature computed as an average of the maximum and minimum daily temperatures

Hydrologic Response

Figure 9 shows the hydrologic responses of the Baker Lake and Lake Shannon tributary basins to the November 1995 storm event. These hydrographs were reconstructed using hourly reservoir elevation data and hourly outflow data provided by PSE, and therefore, there is some inherent uncertainty in the results. The time of the peak flow for the Upper Baker inflow hydrograph was at November 29th at 1300 hours.

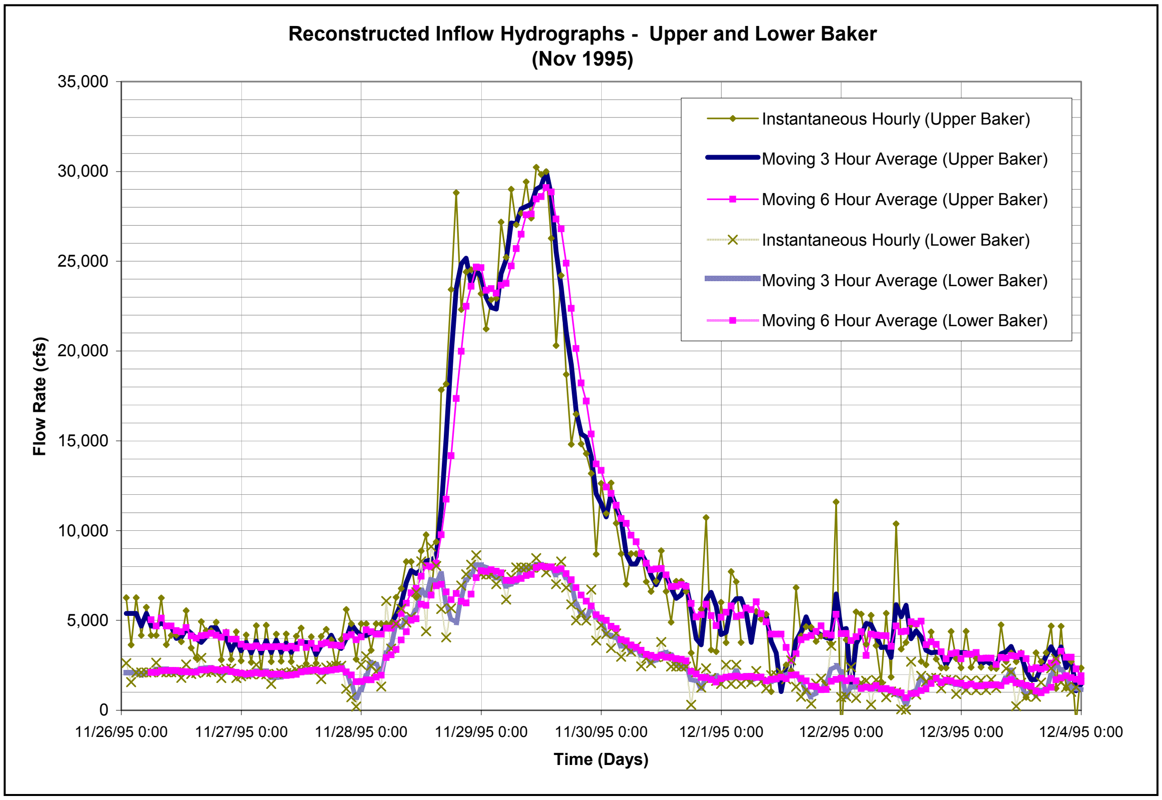


Figure 9. Reconstructed Inflow Hydrographs –November 1995
(Labels on the horizontal axis represent start of day)

NOVEMBER 1990

Similar to October 2003, the November 1990 event was also characterized by significant back-to-back storm events, this time three separate rainfall events within an eighteen-day time period. Peak flows into Baker Lake and Lake Shannon from each of these three events occurred on November 10th, November 13th, and November 23rd. There were seven days of relatively intermittent light rain between the second and third rainfall events, as seen in Figure 10.

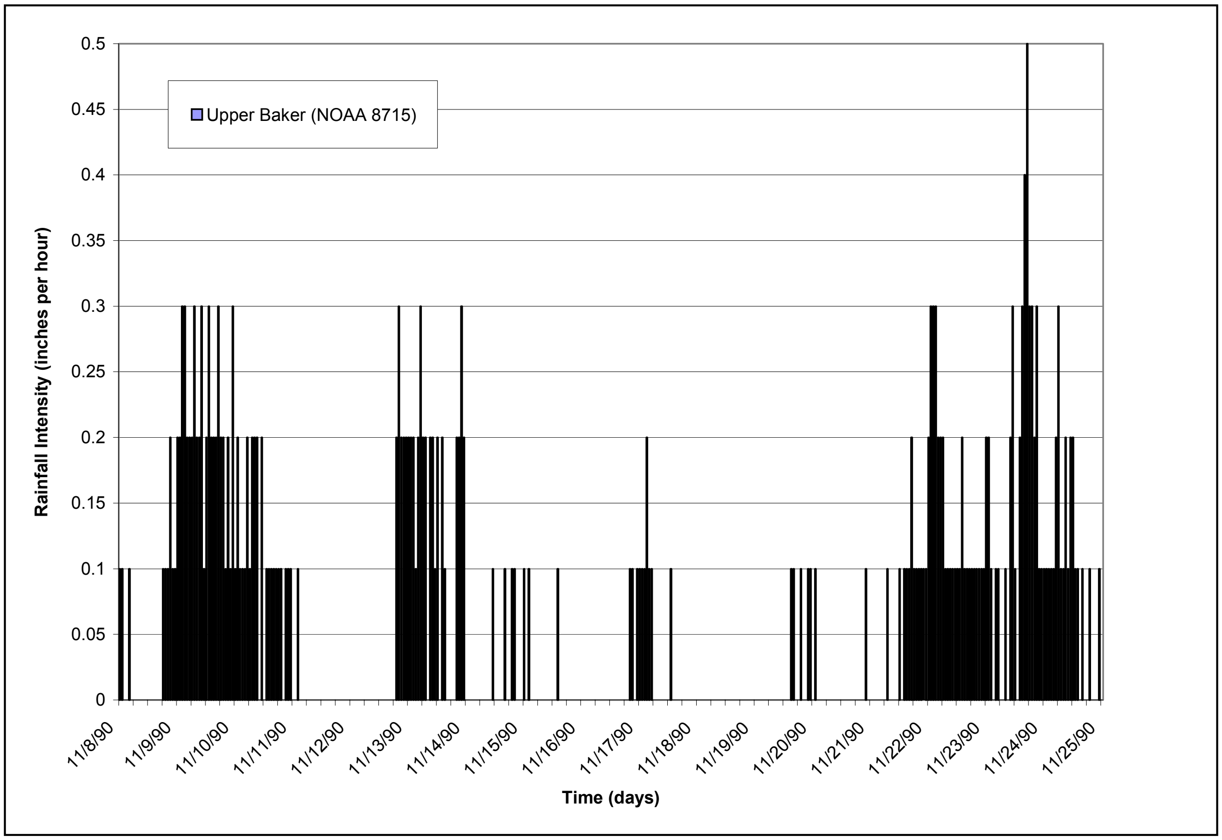


Figure 10. Rainfall Hyetograph at Upper Baker – November 1990
(Labels on the horizontal axis represent start of day)

Antecedent Conditions

As seen in Figure 11, prior to the first rainfall event, the pool elevation at Upper Baker was nearly three feet below the minimum flood control pool elevation (711.56 feet NAVD99) and Lower Baker was two feet below the normal operating pool elevation (442.35 feet NAVD88).

Above average precipitation in October 1990 and early November 1990 created saturated soil conditions throughout the basin before the first storm event moved through the basin. According to NOAA climatological data for 1990, rainfall totals in October were 13.10 inches at Darrington (184 percent of normal), 16.40 inches at Diablo Dam (220 percent of normal), and 16.99 inches at Upper Baker (186 percent of normal). Similarly, rainfall totals in November 1990 were 26.52 inches at Darrington (200 percent of normal), 38.46 inches at Diablo Dam (268 percent of normal), and 31.34 inches at Upper Baker (190 percent of normal).

According to USACE (2004), the snowpack [in western Washington] was also well above normal (nearly 200 percent), and the snowline was at about 2,000 feet. There was an excess of 2 inches of water in the pack above 2,500 feet (USACE 2004). The Cascade foothills averaged [snow depths of] 6-inches at elevations 1,000 to 2,000 feet; 12 inches at 2,000 to 3,000 feet; and 12-18 inches at 3,000 to 4,000 feet (PIE 2002).

The snowpack data that is available for gages in the vicinity of the Baker River basin is fairly consistent with these observations. Table 15 shows the recorded antecedent snow water equivalent at the four nearest SNOTEL sites to the Baker River basin. This small population of observations indicates an excess of at least 2 inches of water at elevations greater than 4200 feet, although the Thunder Basin site may be under representing the snowpack conditions given the readings at the other three sites. Also, assuming a 30% snow density, the snowpack could have been as deep as 20 to 30 inches in the elevation zone between 4,780 feet and 6,500 feet.

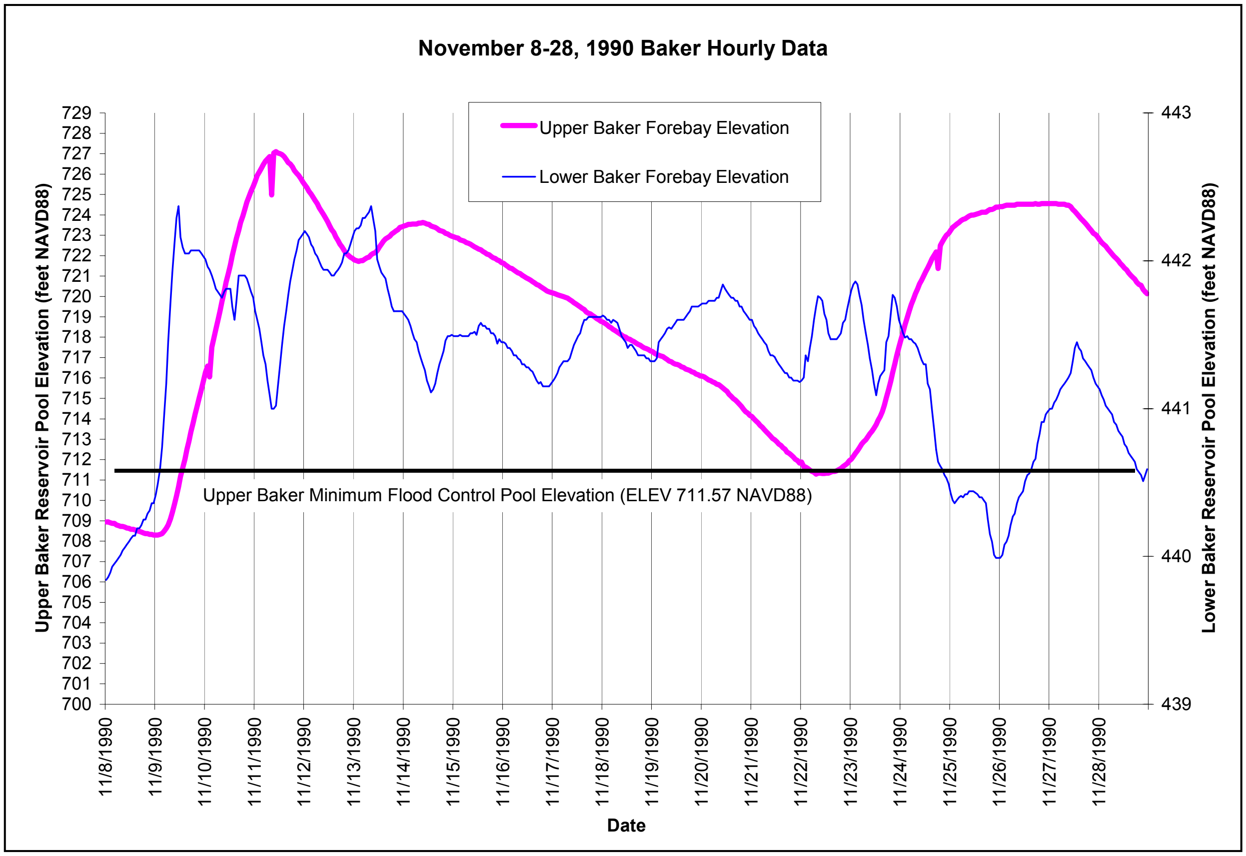


Figure 11. Upper Baker and Lower Baker Pool Elevations – November 1990
(Labels on the horizontal axis represent start of day)

Table 15.
Antecedent Snow-Water Conditions
November 8th, 1990

Site	Site Elevation (feet NGVD29)	Snow Water Equivalent (inches)
Harts Pass	6500	7.2
Miners Ridge	6200	9.4
Rainy Pass	4780	6.0
Thunder Basin	4200	1.6

Description of Storm Event

From November 9th through November 12th, western Washington was dominated by a warm, moist subtropical air mass whose source region was an area just north of the Hawaiian Islands. During this entire period, the polar jet was vigorous, strong and extraordinarily persistent. The core of the jet was generally oriented southwest to northeast and aimed at southern British

Columbia and northern Washington. Figure 12 shows the cumulative precipitation for the first two rainfall events, with the first rainfall event defined as occurring from November 8th to November 11th, and the second rainfall event defined as occurring from November 12th to November 14th. The Nooksack Salmon Hatchery gage was inoperable from November 12th through November 18th, and hence did not record rainfall during the second rainfall event.

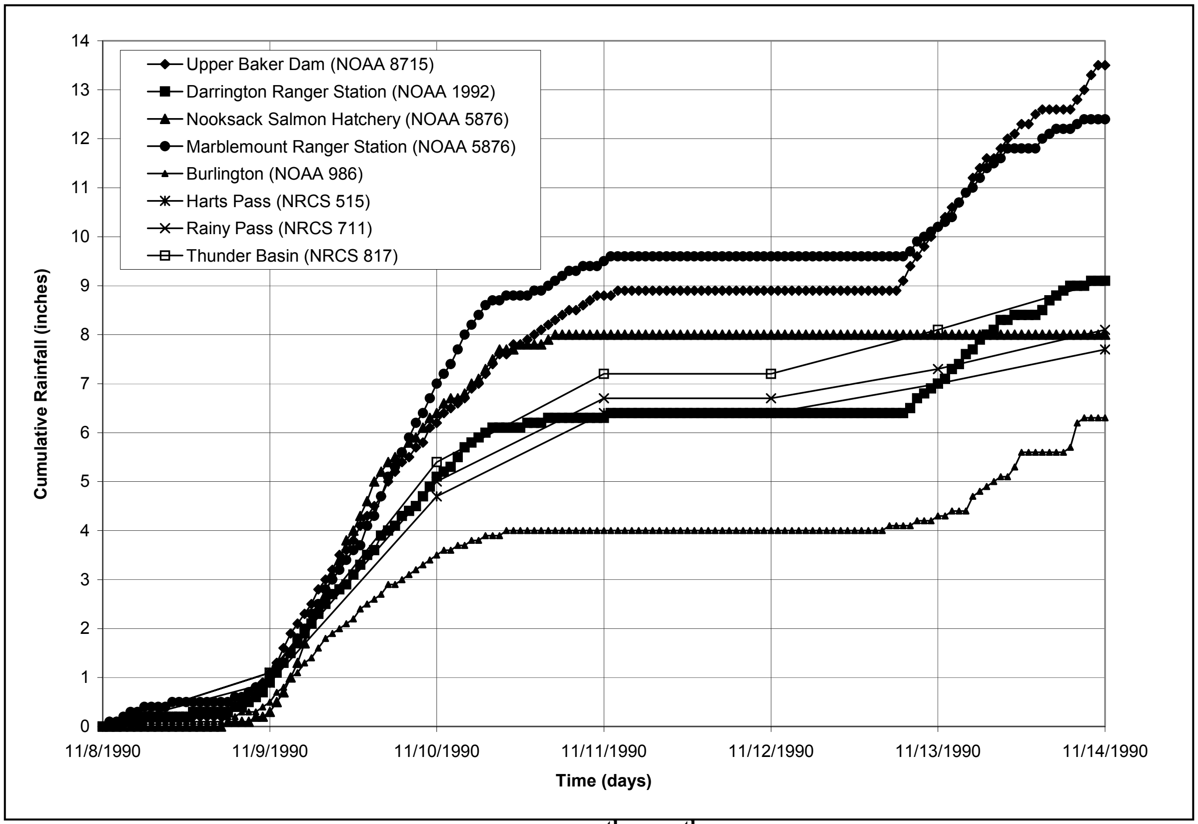


Figure 12. Cumulative Rainfall November 8th - 13th 1990
(Labels on the horizontal axis represent start of day)

Heavy rainfall occurred during the three days of the first event (8th, 9th, and 10th). Due to the strength and location of the core of the polar jet stream, the rains were highly orographic. Nearly 9 inches of rain fell at Upper Baker during this period, with 5.2 inches falling at Upper Baker in a single 24-hour time period. This is approximately equal to the 100-year 24-hour point rainfall at Upper Baker Dam (NOAA 1973).

Leading up to the first rainfall event, the minimum daily temperatures were below freezing at elevations greater than 4,000 feet, but temperatures rose as the tropical air mass moved through the basin (Tables 16 and 17). The freezing level stayed above 9,000 feet until November 13th, dropping down to about 3,000 feet late on November 14th. Warm air and rain falling on the snowpack melted an average of 2 inches of water from the snowpack between 2,500 feet and 5,500 feet, during this first rainfall event (USACE 2004), and therefore it can be concluded that snowmelt was a contributing factor to the runoff hydrograph. Table 18 summarizes the changing snowpack conditions during the event at the three nearest NRCS sites.

Table 16.
Minimum Daily Temperatures (degrees F) - November 1990

Site	Site Elevation (NGVD29)	8th	9th	10th	11th	12th	13th	14th	15th		20th	21st	22nd	23rd	24th	25th
Harts Pass	6500	16	21	30	32	33	33	20	15		13	11	14	27	29	26
Rainy Pass	4780	23	28	32	32	34	32	27	23		19	n/a	17	31	n/a	31
Thunder Basin	4200	29	30	33	35	33	33	29	25		22	21	22	32	34	32
Upper Baker Dam	690	36	37	44	50	43	43	32	34		31	32	32	38	42	38
Concrete PPL FS	195	39	41	46	52	46	47	37	38		33	34	36	42	46	42

Table 17.
Maximum Daily Temperatures (degrees F) - November 1990

Site	Site Elevation (NGVD29)	8th	9th	10th	11th	12th	13th	14th	15th		20th	21st	22nd	23rd	24th	25th
Harts Pass	6500	33	31	33	42	46	46	33	31		22	22	29	29	33	31
Rainy Pass	4780	32	32	33	40	47	49	37	28		25	n/a	32	33	n/a	32
Thunder Basin	4200	37	38	36	44	54	58	39	34		29	27	37	37	39	38
Upper Baker Dam	690	45	46	51	54	55	50	47	38		36	38	49	44	51	44
Concrete PPL FS	195	45	47	55	58	62	54	49	43		40	40	50	48	56	50

Table 18.
Snow Water Equivalent (inches) - November 1990

Site	Site Elevation (NGVD29)	8th	9th	10th	11th	12th	13th	14th	15th		20th	21st	22nd	23rd	24th	25th
Harts Pass	6500	7.2	8.6	11.3	12.2	12.2	12.1	12.2	12.7		13.9	13.9	15.3	18.0	20.8	21.3
Rainy Pass	4780	6.0	6.0	6.2	6.3	6.3	6.4	6.4	6.8		7.3	7.5	8.6	10.4	12.2	13.1
Thunder Basin	4200	1.6	1.2	0.6	0.0	0.0	0.0	1.1	1.6		1.3	1.5	3.2	3.2	0.0	0.0

The third rainfall event (November 21st through November 25th) in November 1990 was generated by a persistent low-pressure system in the Gulf of Alaska, which generated a series of frontal systems that tracked across the Pacific Northwest from November 21st through November 25th. Normally, there is sufficient cold air following these frontal systems that forces them over the Cascades. However during this event, the frontal systems lacked sufficient cold air to drive them swiftly through the region, and as such, they were slow moving and stalled in the Cascades. The cumulative rainfall for this third event was greater than the first, however, the first event had longer periods of high intensity rainfall. Figure 13 shows the cumulative rainfall for the third rainfall event, showing nearly 10 inches of rainfall at Upper Baker during a 72-hour period.

The snowpack in the western Cascades had built back up again following the melt from the first two rainfall events (USACE 2004). Not only was the snowpack restored, but also it continued to increase in depth as maximum daily temperatures remained below freezing for elevations above approximately 4500 feet. Table 18 shows the increasing snow water equivalent above elevation 4500 at two nearby NRCS sites. As seen in Table 17, maximum daily temperatures were at or below freezing throughout the course of this third event at Harts Pass and Rainy Pass.

There was a 12-inch snowpack on the ground at the Upper Baker Dam NOAA station (Elev. 690 feet) by the end of the day on November 20th, which was partially a product of a 6-inch snowfall on November 20th. However, as the rainfall intensity picked up for the third rainfall event, the 12 inches at Upper Baker Dam had melted entirely by the end of the day on November 22nd, nearly 24 hours before the peak of the event.

According to USACE (2004), an average of 2 to 3 inches of water melted from the snowpack at the lower elevations within the greater Skagit River watershed, while at elevations above 4,000 feet, the snowpack actually increased in depth. These observations are borne out in the temperature data in Tables 16 and 17 and by the daily snow water equivalent measurements (Table 18) at the three NRCS sites nearest to the Baker River basin. At Harts Pass (Elev. 6500), the snow water equivalent increased from 14 inches to 23 inches from November 20th to November 26th. At Rainy Pass (Elev. 4780), the snow water equivalent increased from 7 inches to 13 inches during the same time period. However, at Thunder Creek Basin (Elev. 4200), the snow water equivalent decreased from 2 inches to 0 inches. Since nearly 60 percent of the Baker Lake tributary area is equal to or below 4,000 feet, and more than 80 percent of the Lake Shannon tributary area is equal to or below 4,000 feet, snowmelt was likely a contributing factor to the Baker River basin runoff hydrograph associated with this third November 1990 rainfall event.

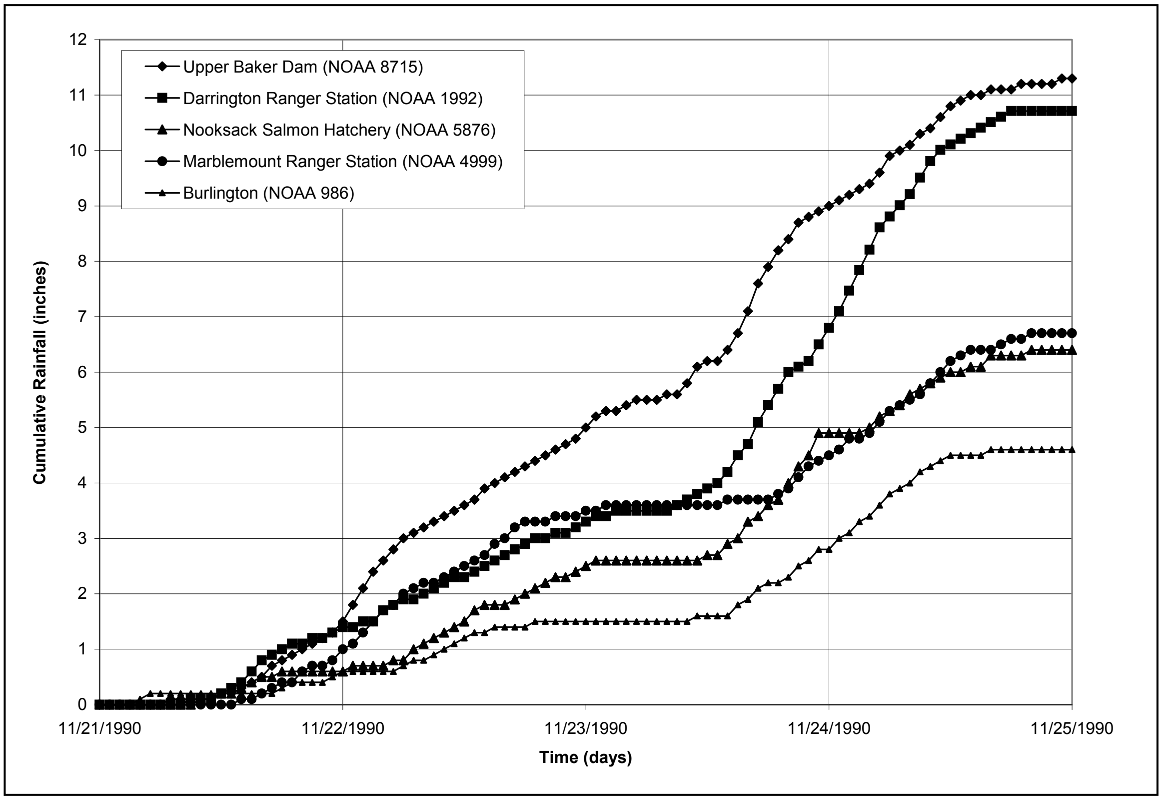


Figure 13. Cumulative Rainfall November 20th - 24th 1990
(Labels on the horizontal axis represent start of day)

Hydrologic Response

Figure 14 shows the hydrologic responses of the Baker Lake and Lake Shannon tributary basins to the November 1990 storm events, showing three significant runoff hydrographs during the month, with the first and third being the most significant. The hydrographs were reconstructed using hourly reservoir elevation data and hourly outflow data provided by PSE, and therefore, there is some inherent uncertainty in the results.

The Upper Baker inflow hydrograph for the first event is characterized by a much broader, higher peaked shape than that associated with the third event (the ratio of instantaneous peak flow to mean daily flow was 1.13 for the first event and 1.51 for the third event). This in spite of the fact that the first rainfall event produced less total precipitation in a 72-hour time period (8.8 inches vs. 9.9 inches) than did the third rainfall event. Also, the third rainfall event had the highest peak rainfall intensity (0.5 inches per hour). The significance of the runoff volume associated with the first rainfall event is illustrated by the fact that this event produced two days (November 9th and 10th) with mean daily inflows to Baker Lake that are within the top ten since 1975. As documented in Table 6, November 10th, 1990 was the second highest mean daily inflow into Baker Lake and November 9th, 1990 was the ninth highest mean daily inflow into Baker Lake.

There are several explanations for this apparent contradiction. First off, basin wide snowmelt might have been more of a contributing factor to the runoff hydrograph during the first event. Secondly, due to the relatively high temperatures up through November 13th, snowmelt likely occurred at higher elevations during the first event. Lastly, during the third rainfall event, portions of the Baker River basin may not have been contributing runoff due to precipitation falling as snow at higher elevations.

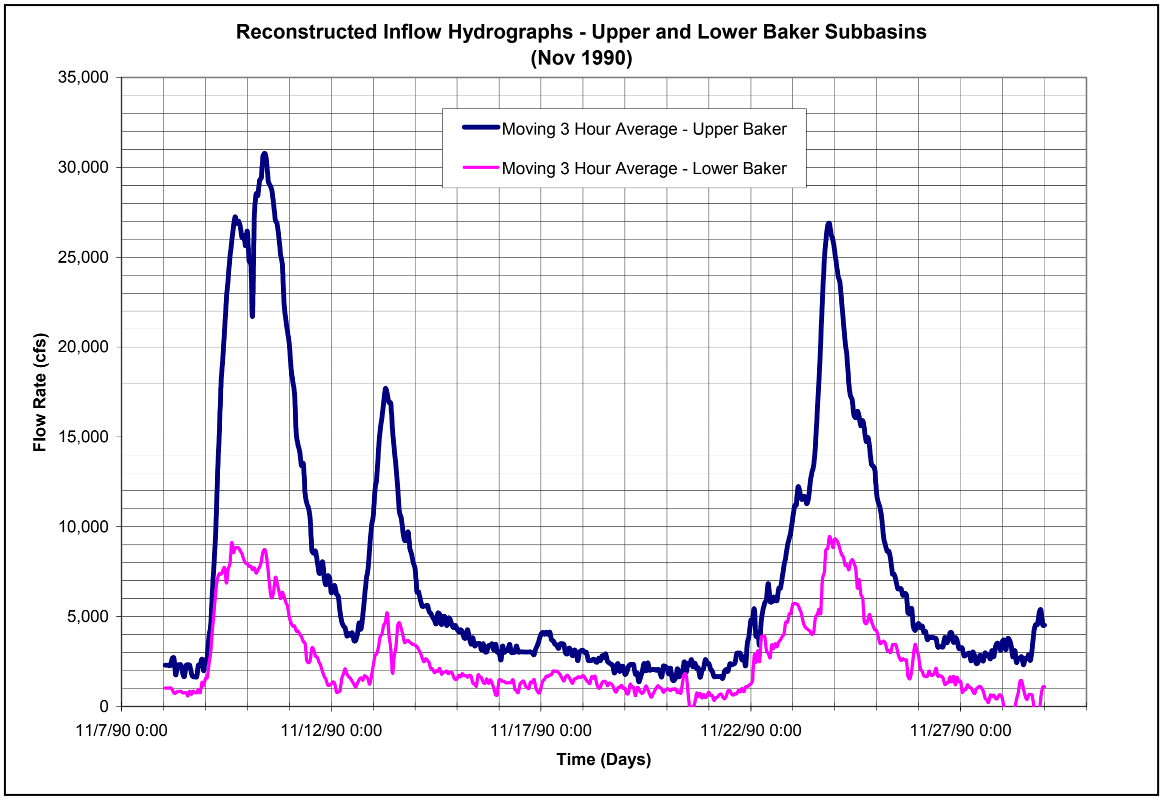


Figure 14. Reconstructed Inflow Hydrographs –November 1990
(Labels on the horizontal axis represent start of day)

OTHER EVENTS FOR CONSIDERATION

This section includes a brief discussion of the other candidate storm events. The events that are discussed in this section are drawn from the remaining top ten Upper Baker inflow events presented in Table 6. The discussion focuses primarily on the data that may be available for antecedent conditions and model calibration/verification.

January 6th-8th, 2002

- ***Antecedent snow depth and water content*** at snow courses within the Baker River basin are known for the month ending December 2001. Snow water equivalent at this time ranged between 6.8 inches (South Fork Thunder Creek – Elev. 2200) and 42 inches (Jasper Pass – Elev. 5400 site).
- ***Daily snow depth data*** is available within the Baker River basin at the NOAA Upper Baker station for the month of January. The measurements indicate a steadily decreasing depth from the 1st through the 6th. The depth of the snowpack at Upper Baker Dam was 5 inches on January 1st, 3 inches on January 5th, and was completely melted by January 7th.

- ***Hourly precipitation data*** are not available within the Baker River basin for the NOAA station at Upper Baker Dam; however, daily precipitation data are available at two NOAA stations within the basin - Upper Baker Dam and at Concrete PPL Fish Station. Total precipitation measured at these two stations was 5.1 inches and 2.6 inches, respectively. There is hourly precipitation data available for the NOAA stations and the NRCS sites that are located within adjacent basins.
- ***Maximum and minimum daily temperatures*** are available at Upper Baker Dam station. Maximum daily temperatures were 39° F, 51^0 F, and 49^0 F for the three consecutive days. Minimum daily temperatures were 34^0 F, 35^0 F, and 40^0 F for the three consecutive days.
- There is ***hourly temperature data*** available at four nearby NRCS sites in the adjacent basins. During the event, maximum daily temperatures were below freezing above elevation 4700, but ranged between 36^0 F to 44^0 F at the Wells Creek (Elev. 4200), which is located immediately north of Mt. Baker.
- The ***snow water equivalent*** as measured at Harts Pass (Elev. 6500) and Rainy Pass (Elev. 4780) steadily increased through the event. The snow water equivalent decreased by 0.5 inches on January 7th at both the Wells Creek site (Elev. 4200) and the Thunder Basin site (Elev. 4200).
- ***Hourly operation data*** are readily available for reconstructing the inflow hydrographs into both Lake Shannon and Baker Lake.

November 11th – 12th, 1999

- ***Antecedent snow depth and water content*** within the Baker River basin are not available for this storm event. There are however, hourly snow water equivalent and snow depth measurements at five NRCS sites in adjacent basins. Snow water equivalent ranged between 0 inches at 3200 feet to 5 inches at elevation 6500 feet.
- ***Hourly precipitation data*** are available for the NOAA station at Upper Baker Dam and also at several NOAA stations and five NRCS sites in adjacent basins. Total precipitation for the two days, as recorded at Upper Baker Dam, was 3.4 inches.
- ***Maximum and minimum daily temperatures*** are available at Upper Baker Dam station. Maximum daily temperatures were 52^0 F and 47^0 F for the two consecutive days. Minimum daily temperatures were 43^0 F and 44^0 F for the two consecutive days. Values were obtained from the PSE HFAM database.
- ***Hourly temperature data*** are available at the five nearby NRCS sites. During the event, there was a gradual increasing trend of the temperatures, with minimum daily temperatures at or slightly above freezing at the four NRCS sites above 4000 feet. At the Elbow Lake NRCS site (Elev. 3200), the minimum daily temperature reached 38^0 F by November 12th.
- ***Hourly snow water equivalent*** data are available at the five nearby NRCS sites. The snow water equivalent increased at the Harts Pass site (Elev. 6500) and decreased by less than 0.7 inches at both the Rainy Pass (Elev. 4780) and Thunder Basin (Elev. 4200) sites. At the two lowest elevation NRCS sites (Wells Creek – Elev. 4200 and Elbow Lake – Elev. 3200) there was no snowpack. Snowmelt was likely not a contributing factor to the runoff.

- ***Hourly operation data*** are readily available for reconstructing the inflow hydrographs into both Lake Shannon and Baker Lake.

March 17th – 19th, 1997

- ***Antecedent snow depth and water content*** at snow courses within the Baker River basin are known for this event. Snow water equivalent at the end of February and the beginning of March was well above average. In fact, at each of the nine snow course site within the basin, the snow water equivalent at this time was within the upper 36% for the period of record. For the nine snow courses within the Baker River basin that were read at the beginning of March, the snow water equivalent ranged between 14 inches (South Fork Thunder Creek – Elev. 2200) and 94 inches (Easy Pass – Elev. 5200 site).
- ***Hourly precipitation data*** are available for the NOAA station at Upper Baker Dam and also at several NOAA stations and five NRCS sites in adjacent basins. Total precipitation for the three day time period was 8.4 inches at the Upper Baker Dam station, with a maximum 24-hour rainfall of 3.8 inches.
- ***Maximum and minimum daily temperatures*** are available at the Upper Baker Dam station and several NOAA stations at NRCS sites in adjacent basins. Maximum daily temperatures were 48^0 F, 40^0 F, and 43^0 F for the three consecutive days. Minimum daily temperatures were 33^0 F, 37^0 F, and 39^0 F for the three consecutive days.
- There is ***hourly temperature data*** available at five nearby NRCS sites.
- Hourly ***snow water equivalent*** data is available at the five nearby NRCS sites and ***snow depth*** data at six-hour increments at the two lowest elevation NRCS sites (Wells Creek and Elbow Lake). At the Elbow Lake site (Elev. 3200), over 3.5 inches of snow water equivalent was lost from the snowpack on March 18th and 19th, and the depth of the snowpack decreased by 13 inches. At the Wells Creek site (Elev. 4200), the snow water equivalent decreased by nearly one inch on March 18th and 19th, and the depth of the snowpack decreased by 5 inches. At the three other nearby NRCS SNOTEL sites (Harts Pass, Rainy Pass, and Thunder Basin) there was a net increase in snow water equivalent (up to 4 inches). Therefore, lower elevation snowmelt on the 18th and 19th was likely a contributing factor to the runoff hydrograph.
- **Hourly operation data** are readily available for reconstructing the inflow hydrographs into both Lake Shannon and Baker Lake.

November 8th - 10th, 1989

- ***Antecedent snow depth and water content*** within the Baker River basin are not available for this storm event. There are however, daily snow water equivalent measurements at three NRCS sites in adjacent basins (Rainy Pass, Harts Pass, and Thunder Basin). On November 8th, snow water equivalent ranged between 1.9 inches at 4780 feet (Rainy Pass) to 4.2 inches at 6500 feet (Harts Pass).
- ***Daily snow depth data*** are available at the NOAA Upper Baker Dam station (Elev. 690). There was no snowpack at Upper Baker Dam prior to this event.
- ***Hourly precipitation data*** are available for the NOAA station at Upper Baker Dam and also for two NOAA stations in adjacent basins (Nooksack Salmon Hatchery and Glacier

Ranger Station). Total precipitation for the three day time period was 9.2 inches at the Upper Baker Dam station, with a maximum 24-hour rainfall of 3.6 inches. The one-day precipitation of 3.6 inches was recorded on November 8th and is nearly equal to the 10-year 24-hour point precipitation at Upper Baker Dam (NOAA 1973).

- ***Maximum and minimum daily temperatures*** are available at two NOAA stations within the Baker River basin (Upper Baker Dam and Concrete PPL Fish Station) in addition to three nearby NRCS sites (Harts Pass, Rainy Pass and Thunder Basin). During the event, minimum daily temperatures were well above freezing. At Upper Baker Dam, minimum daily temperatures were 40^0 F, 42^0 F, and 46^0 F for the three consecutive days. At the same station, the maximum daily temperatures were 44^0 F, 46^0 F, and 52^0 F for the three consecutive days. At Harts Pass (Elev. 6500), maximum daily temperatures were 25^0 F, 36^0 F, and 49^0 F for the three consecutive days, and minimum daily temperatures remained below freezing throughout.
- There is no ***hourly temperature data*** available within the basin. The nearby NRCS sites only began recording hourly temperatures in 1993.
- Daily ***snow water equivalent*** data is available at three of the nearby NRCS sites (Harts Pass, Rainy Pass and Thunder Basin). At Harts Pass (Elev. 6500) and Rainy Pass (Elev. 4780), the snow water equivalent of the snowpack increased as precipitation was likely falling as snow at these elevations throughout the event. At the Thunder Basin site (Elev. 4200), the snow water equivalent decreased by nearly 1 inch over the three-day period.
- ***Hourly operation data*** are available for reconstructing inflow hydrographs to Lake Shannon and Baker Lake, however, due to the fact that the data is not available digitally, it may be more difficult to obtain from the archives.
- ***Hourly streamflow data*** for two Upper Baker tributaries (Swift Creek and Park Creek) and a Lake Shannon tributary (Thunder Creek) may be available from the USGS records office. This will be acquired from the Federal Records Center and will be reviewed for completeness. At a minimum, instantaneous peak and mean daily streamflow data for these tributaries are available from the USGS.

January 2nd – 4th, 1984

- For the 1975 to 2004 period of record, this runoff event has the third highest mean daily inflow into Upper Baker, ranking lower than only the 10/17/03 and 11/10/90 mean daily flows.
- ***Antecedent snow depth and water content*** at snow courses within the Baker River basin are known for this event. Snow water equivalent at beginning of January ranged between 11 inches (Rocky Creek – Elev. 2100) and 42 inches (Jasper Pass – Elev. 5400 site).
- ***Hourly precipitation data*** are available at Upper Baker Dam for only the later half of the rainfall event. There are hourly data available at several nearby NOAA stations. Additionally, PSE has filled in the missing Upper Baker Dam hourly precipitation data for their HFAM model using temporal distributions and hourly records at nearby stations (Darrington and Diablo Dam). It is unknown how the database was constructed during this time period because the Diablo Dam and Darrington stations did not record hourly data for the first five days of January. Three-day precipitation of 7.6 inches is included in

the HFAM database for Upper Baker Dam. Nearby NOAA stations recorded three day total precipitation of 6.8 inches at the Nooksack Salmon Hatchery station, 4.6 inches at the Glacier Ranger Station, and 6.8 inches at the Marblemount Ranger Station.

- ***Maximum and minimum daily temperatures*** are available at the Upper Baker Dam station and at select stations in adjacent basins. No hourly temperature data is available. Maximum daily temperatures were 40^0 F, 41^0 F, and 46^0 F for the three consecutive days. Minimum daily temperatures were 31^0 F, 35^0 F, and 37^0 F for the three consecutive days. Values were obtained from the PSE HFAM database.
- Daily ***snow water equivalent*** data is available at only two of the nearby NRCS sites (Harts Pass and Rainy Pass). At the Harts Pass site (Elev. 6500), the snow water equivalent remained relatively constant (this may be suspect due to the fact that nearly 3.5 inches of total precipitation fell at Harts Pass). At the Rainy Pass site (Elev. 4780), the snow water equivalent increased by almost 6 inches during the event.
- ***Hourly operation data*** are available for reconstructing inflow hydrographs to Lake Shannon and Baker Lake, however, due to the fact that the data is not available digitally, it may be more difficult to obtain from the archives.
- ***Hourly streamflow data*** from Upper Baker tributaries (Swift Creek and Park Creek) and Lake Shannon tributaries (Bear Creek and Thunder Creek) may be available from the USGS records office. These data will be acquired from the Federal Records Center and will be reviewed for completeness. At a minimum, instantaneous peak and mean daily streamflow data for these tributaries are available from the USGS.

December 24th – 26th, 1980

- For the 1975 to 2004 period of record, this runoff event is the fourth highest mean daily inflow into Upper Baker, ranking lower than only the 10/17/03, 11/10/90, and 1/04/84 mean daily flows.
- ***Antecedent snow depth and water content*** within the Baker River basin are not available prior to start of this storm event. However, snow water equivalent at the end of December ranged between 11 inches (Schreibers Meadow – Elev. 3400) and 29 inches (Jasper Pass – Elev. 5400 site). Snow water equivalent at Rocky Creek (Elev. 2100) was virtually zero.
- ***Hourly precipitation data*** are not available at the NOAA Upper Baker Dam station. There is hourly data available at several nearby NOAA stations. Additionally, PSE has filled in the missing Upper Baker Dam hourly precipitation data for their HFAM model using temporal distributions and hourly records at nearby stations (Darrington and Diablo Dam). It is unknown how the database was constructed during this time period because only the Darrington station was recording hourly precipitation during the event. Three-day precipitation of 3.6 inches is included in the HFAM database for Upper Baker Dam. Nearby NOAA stations recorded three-day total precipitation of 7.1 inches at the Diablo Dam station, 4.6 inches at the Glacier Ranger Station, and 2.9 inches at the Nooksack Salmon Hatchery station.
- ***Maximum and minimum daily temperatures*** are available at Upper Baker Dam station and select stations in adjacent basins. No hourly temperature data is available. Maximum

daily temperatures were 44^0 F, 46^0 F, and 52^0 F for the three consecutive days. Minimum daily temperatures were 39^0 F, 41^0 F, and 45^0 F for the three consecutive days. Values were obtained from the PSE HFAM database.

- There are no hourly or daily ***snow water equivalent*** data available within the basins adjacent to the Baker River basin. The NRCS stations began collecting daily data in 1982.
- ***Hourly operation data*** are available for reconstructing inflow hydrographs to Lake Shannon and Baker Lake, however, due to the fact that the data is not available digitally, it may be more difficult to obtain from the archives.
- ***Hourly streamflow data*** from one Lake Shannon tributary (Sulphur Creek) may be available from the USGS records office. These data will be acquired from the Federal Records Center and will be reviewed for completeness. At a minimum, instantaneous peak and mean daily streamflow data for this tributary are available from the USGS.

December 1st – 3rd, 1975

- For the 1975 to 2004 period of record, this runoff event is the thirteenth highest mean daily inflow into Upper Baker and the seventh highest peak annual event on the main stem Skagit River at Concrete.
- ***Antecedent snow depth and water content*** data, within the Baker River basin, are not available prior to start of this storm event.
- ***Hourly precipitation data*** are not available at the NOAA Upper Baker Dam station. There are hourly data available at two nearby NOAA stations (Nooksack and Marblemount). Additionally, PSE has filled in the missing Upper Baker Dam hourly precipitation data for their HFAM model using temporal distributions and hourly records at nearby stations. Three-day precipitation of 8.6 inches is included in the HFAM database for Upper Baker Dam. Nearby NOAA stations recorded three-day total precipitation of 9.3 inches at the Marblemount Ranger Station and 4.7 inches at the Nooksack Salmon Hatchery station.
- ***Maximum and minimum daily temperatures*** are available at Upper Baker Dam station and select stations in adjacent basins. No hourly temperature data are available. Maximum daily temperatures were 45^0 F, 46^0 F, and 50^0 F for the three consecutive days. Minimum daily temperatures were 25^0 F, 36^0 F, and 37^0 F for the three consecutive days. Values were obtained from the PSE HFAM database.
- There are no hourly or daily ***snow water equivalent*** data available within the basins adjacent to the Baker River basin. The NRCS stations began collecting daily data in 1982.
- ***Hourly operation data*** are available for reconstructing inflow hydrographs to Lake Shannon and Baker Lake, however, due to the fact that the data is not available digitally, it may be more difficult to obtain from the archives.
- ***Hourly streamflow data*** from one Lake Shannon tributary (Sulphur Creek) may be available from the USGS records office. These data will be acquired from the Federal

Records Center and will be reviewed for completeness. At a minimum, instantaneous peak and mean daily streamflow data for this tributary are available from the USGS.

SUMMARY

Table 19 summarizes the data available for the events that are considered as candidates for the calibration and verification of the runoff model. These events are drawn from those in Table 6 and include the ten runoff events with the highest mean daily inflows to Baker Lake. The single rainfall event of November 8th through November 11th produced two of the top ten mean daily inflows to Baker Lake, however only November 10th is included in Table 19.

FERC guidelines indicate that at least three historical floods should be considered for the PMF model calibration and verification. Two of the floods should be used for calibration and one should be used for verification (FERC 2001). The following guidance is provided in FERC (2001) to guide the selection of these flood events:

- The selected events should have occurred during the season when the critical PMP is likely to occur.
- The selected events ideally should be single extreme rainfall events with uniform temporal and spatial distributions.
- If the critical PMP is anticipated to occur during a month when a significant part of the basin will be covered by snow, the calibration floods should include historical floods generated by rain on snow.
- The largest events on record should be considered first.
- All runoff producing portions of the watershed should have contributed runoff during the event.
- The flood hydrograph should have at least one inch of runoff from the contributing area and have generated significant overbank flow.
- Those events with the best and most reliable data should be considered first.

In considering the above guidance, the conclusion can be made that the candidate flood events that should be considered for the calibration and verification of the Baker River Project Part 12 PMP/PMF Study runoff model should have occurred during the same season and should be the same type of event that the PMF is expected to be. In general terms, this would mean a general storm event that occurred sometime between October and April. The runoff hydrograph should have a rain-on-snow component. The antecedent soil conditions should be nearly saturated as this is the typical condition during the winter flood months. The event should be one of the largest flood events on record, and should be fairly current so as to take advantage of the fact that more data and higher resolution data is available for the events that have occurred within the last fifteen to twenty years.

The November 12th, 1999 event was eliminated from further consideration due to the fact that snowmelt was not a contributing factor to the runoff and that the mean daily flow was not within the top ten. The November 10th, 1989 event was eliminated from further consideration for the same reasons. The December 4th, 1989 event was also eliminated for the same reasons plus for the fact that the hourly distribution of precipitation within the basin is unknown. Finally, the December 3rd, 1975 event was eliminated due to the fact the hourly distribution of precipitation within the basin is unknown plus the fact that there is a lack of information regarding antecedent snowpack conditions and snow accumulation during the event.

All other events presented in Table 19 are therefore recommended for further consideration as model calibration and verification events. It is anticipated that this list will be narrowed down during the duration of the first phase of the PMF study. The date corresponding to the peak of the runoff hydrograph is used to identify the event, and they are summarized as follows:

- ***October 17th, 2003*** – Although the runoff from this event did not have a snowmelt component, this is still considered a candidate event for model verification due to the fact that the rainfall from this event produced the highest one-day inflow into Baker Lake since 1975.
- ***January 7th, 2002*** – This event is included due to the low elevation antecedent snowpack conditions in the basin. The snowpack at Upper Baker Dam (Elev. 690) was two to three feet deep, and the entire snowpack melted during the event. This is a recent event and there is hourly precipitation and air temperature data from several nearby NRCS SNOTEL sites. The only drawback to this event is the fact that the hourly distribution of precipitation within the basin is unknown since the Upper Baker Dam station (NOAA 8715) was not recording hourly data during the event.
- ***March 19th, 1997*** – Antecedent snowpack conditions for this event included above average snow water equivalent throughout the Baker River basin. Snowmelt contribution to the basin runoff was a contributing factor.
- ***November 8th, 1995*** – This event produced the seventh highest one-day inflow to Baker Lake since 1975, had a possibly significant snowmelt contribution to the basin runoff, and has hourly temperature and precipitation data available in adjacent basins.
- ***November 29th, 1995*** **–** This event has been used as a calibration/verification flood event for previous Baker Project PMF studies.
- ***November 10th, 1990*** – This event has been used as a calibration/verification flood event for previous Baker Project PMF studies. One of the benefits of including this event is the potential availability of tributary streamflow data within the basin.
- ***November 24th, 1990*** – This event has been used as a calibration/verification flood event for previous Baker Project PMF studies. One of the benefits of including this event is the potential availability of tributary streamflow data within the basin.
- ***January 4th, 1984 or December 26th, 1980*** – These two events produced the third and fourth highest one-day inflow flow rate, respectively, into Baker Lake since 1975. Neither event includes a complete hourly data set of precipitation within the basin as the Upper Baker Dam station (NOAA 8715) was temporarily disrupted. One of the benefits of including these events is the potential availability of tributary streamflow data within the basin. Therefore it is recommended that one of these two events be included for further consideration.

Table 19.
Summary of Data Available for Model Calibration and Verification

DATA CATEGORY	OCT 17th 2003	JAN 7th 2002	NOV 12th 1999	MAR 19th 1997	NOV 8th 1995	NOV 29th 1995	NOV 10th 1990	NOV 24th 1990	NOV 10th 1989	DEC 4th 1989	JAN 4th 1984	DEC 26th 1980	DEC 3rd 1975
PHYSICAL DATA FOR EVENT													
Mean Daily Inflow to UB (cfs) and Rank[a]	28,124 (1)	21,582 (8)	17,872 (14)	17,056 (18)	22,169 (7)	22,579 (6)	27,106 (2)	23,012 (5)	18,918 (10)	18,258 (12)	23,775 (3)	23,140 (4)	18,152 (13)
Mean Daily Inflow Return Period (years)	42	13	6	8	14	16	37	16	9	7	19	17	6
Maximum Three Day Precipitation at Upper Baker Dam	8.7”	5.1”	4.3”	8.4”	6.6”	7.0”	8.8”	9.8”	9.2”	7.0”	n/a	n/a	n/a
Influence of Snowmelt on Runoff Hydrograph[b]	1	2	1	2/3	2	2	3	2	1	1	1	?	?
DATA AVAILABLE FOR EVENT													
Hourly Precipitation – In Basin	NOAA		NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA		NOAA		
Hourly Precipitation – Adjacent Basins[c]	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA
Air Temperature (Daily) – In-Basin[d]	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA
Air Temperature (Daily) – Adjacent Basins	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA NRCS	NOAA	NOAA	NOAA
Air Temperature (Hourly) – Adjacent Basins	NRCS	NRCS	NRCS	NRCS	NRCS	NRCS							
Lumped Reservoir Inflow Hydrograph (Hourly)	readily avail	readily avail	readily avail	readily avail	readily avail	readily avail	readily avail	readily avail	not as readily avail	not as readily avail	not as readily avail	not as readily avail	not as readily avail
Local Tributary Hydrograph (Hourly)							maybe	maybe	maybe	maybe	maybe	maybe	maybe
Antecedent Snow Data – In Basin		SWE/SD		SWE/SD							SWE/SD	SWE/SD	
Antecedent Snow Data – Adjacent Basin[e]	SWE/SD	SWE/SD	SWE/SD	SWE/SD	SWE/SD	SWE/SD	SWE	SWE	SWE	SWE	SWE		
Continuous Snow Data – In Basin													
Continuous Snow Data – Adjacent Basin[e]	SWE/SD	SWE/SD	SWE/SD	SWE/SD	SWE/SD	SWE/SD	SWE	SWE	SWE	SWE	SWE		
Wind Data – Adjacent Basin[f]	NRCS	NRCS	NRCS	NRCS									
Solar Radiation Data – Adjacent Basin[g]	NRCS	NRCS											

General Notes:

NOAA = National Oceanic and Atmospheric Administration
NRCS = Natural Resources Conservation Service
SWE = Snow Water Equivalent
SD = Snow Depth

Specific Notes:

a. Based on reconstructed mean daily inflows (1975-current)
b. Influence of snowmelt on runoff hydrograph was ranked as follows: (4=significant factor, 3 = possibly significant factor, 2=minor factor, 1 = not a factor)
c. Adjacent NOAA stations and NRCS sites
d. Daily max/min temperatures at Upper Baker Dam Station (NOAA 8715) and Concrete PPL Fish Station (NOAA 1679)
e. Hourly data generally available (WY93-03) and daily data generally available (WY82-WY93)
f. Hourly data at Wells Creek and Harts Pass NRCS stations
g. Hourly data at Harts Pass NRCS station

REFERENCES

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

National Oceanic and Atmospheric Administration (NOAA). 2003. *Climatological Data Washington 2003*.

National Oceanic and Atmospheric Administration (NOAA). Various Months and Years. *Hourly Precipitation Data – Washington.*

National Oceanic and Atmospheric Administration (NOAA). Various Months and Years. *Climatological Data – Washington.*

National Oceanic and Atmospheric Administration (NOAA). 1973. *Precipitation-Frequency Atlas of the Western United States (Volume IX-Washington).*

United States Army Corps of Engineers (USACE). undated. *The Northwest's Great Storms and Floods of November 1995 and February 1996.* US Army Corps of Engineers Northwestern Division, Pacific Region.

United States Army Corps of Engineers (USACE). 2000. *Baker River Project Water Control Manual.* Seattle District US Army Corps of Engineers.

United States Army Corps of Engineers (USACE). 2004. *Hydrology Technical Documentation – DRAFT Report*. Prepared as supporting documentation for the Skagit River Flood Damage Reduction Feasibility Study.

(http://www.intellicast.com/Almanac/Northwest/September/)

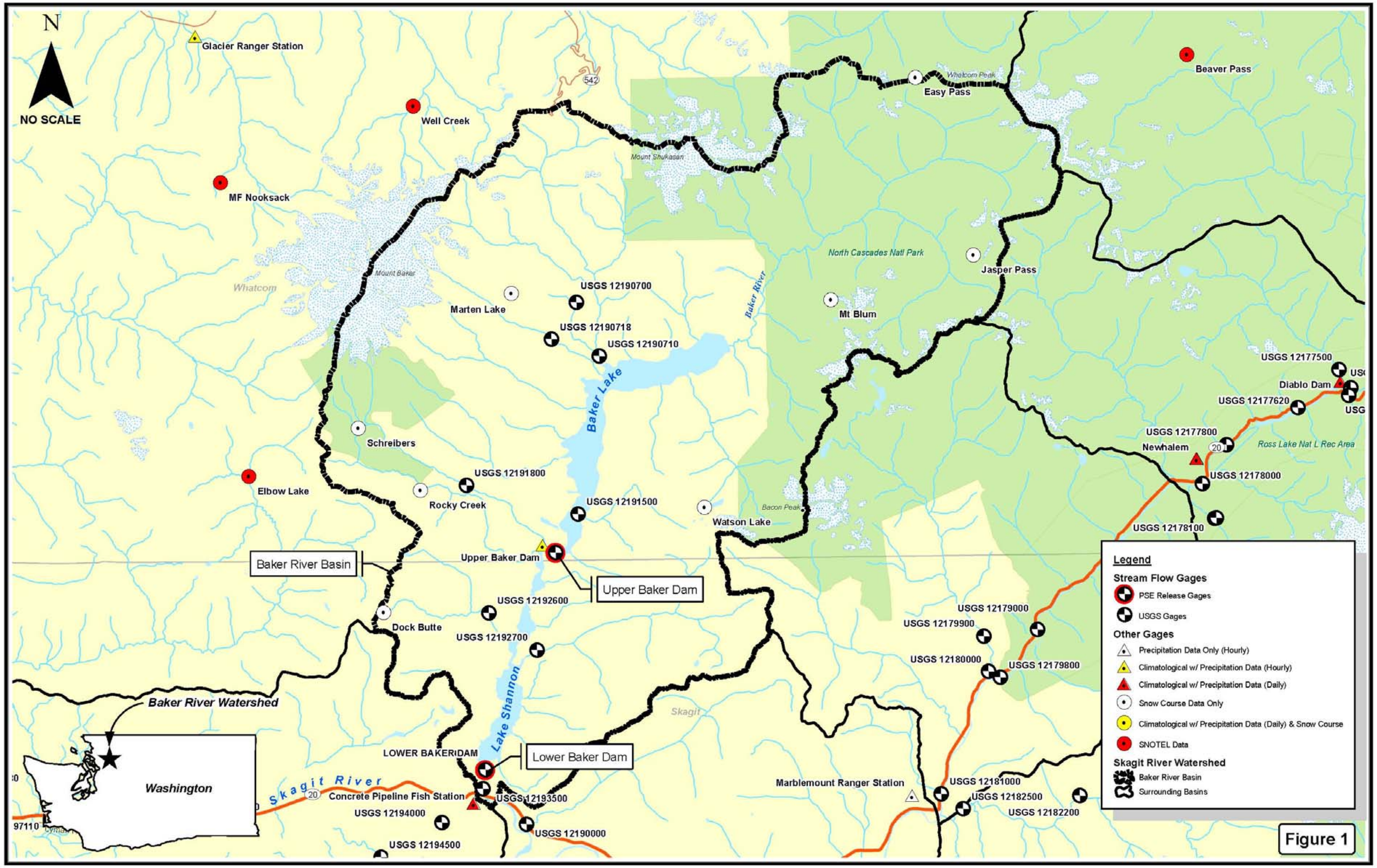
ATTACHMENTS

Attachment 1 - Baker River Basin

Attachment 2 - Baker River Basin and Vicinity

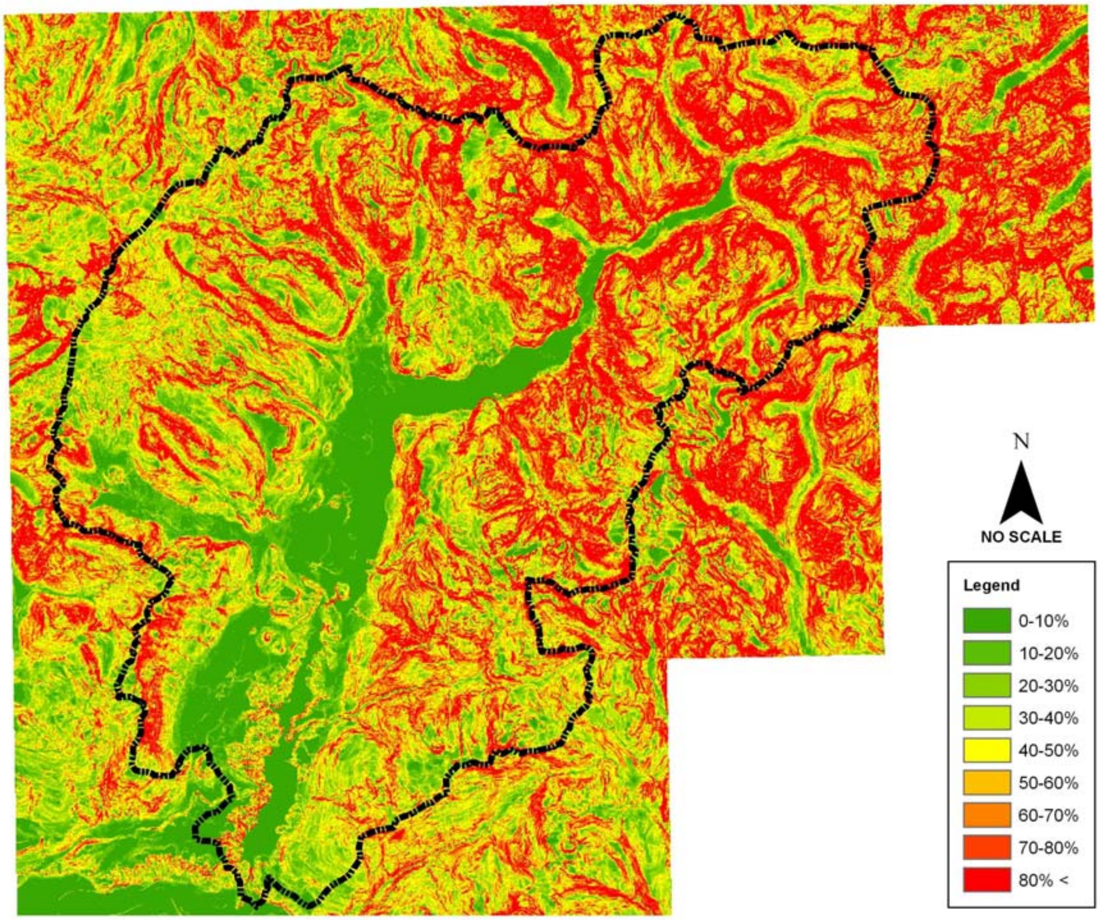
Attachment 3 - Baker River Basin Ground Slopes

Attachment 4. Upper Baker River Project Flood Control Rule Curve

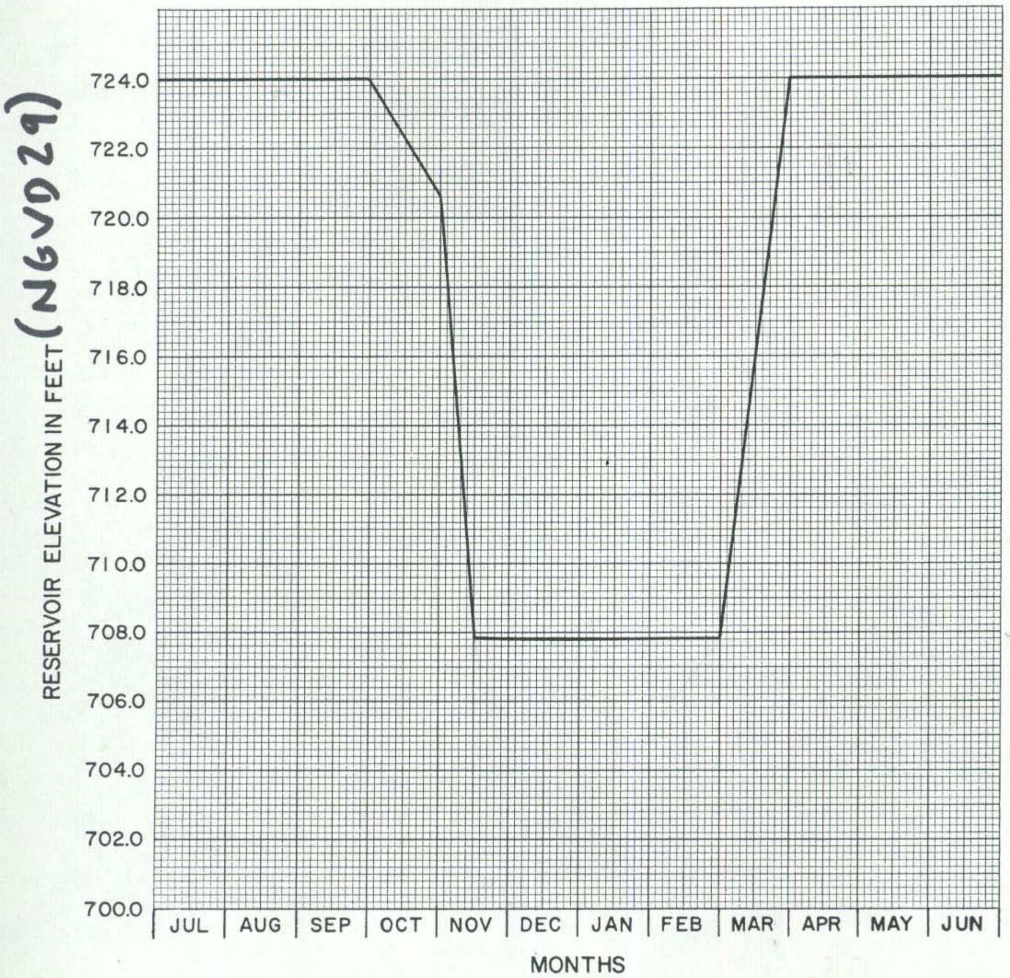


Attachment 1. Baker River Basin

Attachment 2. Baker River Basin and Vicinity



Attachment 3. Baker River Basin Ground Slopes (percent)
(Source: USGS 10 meter Digital Elevation Model)



BAKER RIVER PROJECT
UPPER BAKER DEVELOPMENT
FLOOD CONTROL
RULE CURVE

NJM JUNE 1985

PLATE 7-1

Attachment 4. Upper Baker River Project Flood Control Rule Curve
(Source: Baker River Project Water Control Manual. Seattle District US Army Corp of Engineers. June 2000)

BAKER RIVER PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 5

MODEL RECOMMENDATION

January 11, 2005
Revised February 4, 2005
Revised July 15, 2005

(Revision 2 - FINAL)

Although a revision date of July 15, 2005 is indicated in the header, this memo actually reflects the project conditions and what was known of the project as of the end of February 2005. Since February, work has continued on the project, more data has been acquired, and there have been modifications to the work plan. However, this memo is intended to represent a "snapshot" in the project chronology, subsequent to the Board of Consultant (BOC) February review of the Phase I technical memorandums, of which this is one. The main report will be the ultimate product and final source of information for this project.

INTRODUCTION

This memorandum presents a summary of the runoff models that were considered for the Baker River Project Part 12 PMP/PMF study, and ultimately includes a recommended model for the analysis. This memorandum also includes a recommended reservoir operations model that will be used to route the inflow PMF through the reservoirs and dam outlet works to obtain the outflow PMF and the maximum reservoir elevation at the each facility.

The FERC guidance (FERC 2001) recommends the use of the United States Army Corps of Engineers (USACE) HEC-1 Flood Hydrograph package, due primarily to its widespread use and the familiarity that it offers to review agencies. The guidance does not exclude consideration of other software packages or models. It is, however, recommended that any other software packages or models that are considered should be evaluated for their applicability to the site-specific needs before they are recommended for use. This is the intent of this memorandum.

MODEL SELECTION CRITERIA

Many models have been created throughout the world for modeling of watershed hydrology. The primary process modeled is rainfall runoff. A subset of these models includes the capability to simulate the portion of the hydrologic cycle associated with snowmelt and snow accumulation. USACE (1998a) lists more than thirty hydrologic models that include the capabilities of modeling snowmelt. The capability to model both rainfall and snowmelt runoff is essential for the determination of the PMF for the Baker Projects. Several other model capabilities were identified as essential for PMF determination.

As a first step in the review of available models, the essential capabilities were identified and an initial screening was used to narrow the list of models to be considered in this memorandum. The screening criteria that were used to initially narrow down the list of models to be considered are described below:

First Tier criteria:

- Capability of simulating ***snow accumulation.***
- Capability of ***simulating snowmelt*** using the energy budget equation.
- ***Unit hydrograph capability*** for transformation of direct runoff to a surface runoff hydrograph. FERC guidance (FERC 2001) proposes the use of unit hydrograph theory as the preferred runoff model for developing the inflow PMF hydrograph.
- ***Single event precipitation runoff transformation*** capability.
- Capability of using ***hourly time steps*** in the computations.
- Capability to simulate hydrologic response for ***large watersheds*** (at least 300 sq miles in size).

Second Tier Criteria:

- It is preferable that the software can be obtained from ***suppliers within the United States***.
- ***Review agency familiarity*** with the software.

Hydrologic models presented in USACE (1998a) and Cunderlik (2003) were considered using the criteria outlined above. Models that failed to meet any of the criteria were immediately eliminated. Models that met only one or two of the criteria were also eliminated. Models that met at least three of the first tier criteria were kept for further consideration.

Table 1 includes the list of models that remained after the initial screening was applied. The table further subdivides the models based on whether they are considered lumped parameter, semi-distributed, or distributed models. These three classifications are summarized as follows:

- ***Lumped Parameter Hydrologic Models*** – A single set of parameters define the basin, and thus parameters do not vary spatially. Parameters in lumped models often do not represent physical features of hydrologic processes and usually involve a certain degree of empiricism. Basin response is evaluated at the outlet of the basin (Cunderlik 2003).
- ***Semi-Distributed Parameter Hydrologic Models*** – Spatial variability of the hydrologic processes in the basin are accounted for by subdividing the basin into subbasins. This classification of models includes both single event and continuous streamflow models.
- ***Distributed Parameter Hydrologic Models*** – This grouping of models is considered physically based in that the physical characteristics of the basin are described by a finite grid system that accounts for the spatial variability of both the physical characteristics of the basin and the hydrologic processes. Additionally, runoff is usually modeled by equations representing the actual physical process as opposed to empirical relationships. Distributed parameter models generally require the most data for input.

Table 1. Hydrologic Runoff Models Considered in Detail	
MODEL	**SOURCE or AUTHOR**
Lumped Models	
n/a	
Semi-Distributed Models	
HEC-1	USACE-HEC (1998b)
HEC-HMS	USACE-HEC (2001&2003)
Hydrologic Simulation Program Fortran (HSPF)	Bicknell et al (1992)
Hydrocomp Forecasting and Analysis Model (HFAM)	Hydrocomp (2004)
Precipitation-Runoff Modeling System (PRMS)	Leavesley et al (1983)
Streamflow Synthesis and Reservoir Regulation (SSARR)	USACE (1991)
National Weather Service River Forecast System (NWSRFS)	Anderson (1973)
Distributed Models	
HYDROTEL	Fortin et al. (2001)
MIKE 11/SHE	DHI Software (2000a,b)
WATFLOOD	Kouwen (2001)

MODEL BACKGROUND

This section provides a brief discussion of the nine models that are included in Table 1.

HEC-1

HEC-1 is a computer model for rainfall-runoff analysis, originally developed in 1967 by the United States Army Corps of Engineers' (USACE) Hydrologic Engineering Center (HEC). The most current version of the HEC-1 software package that is publicly available from the USACE is version 4.1 (June 1998). HEC-1 is an event-type model, applicable for modeling flood runoff only. A runoff hydrograph is simulated by applying a unit hydrograph to rainfall excess and snowmelt, then computing the total hydrograph by adding base flow. Kinematic wave routing is also available for hydrograph determination and a variety of procedures are available for hydrologic routing of accumulated runoff in channel elements. Several loss rate functions are available, including initial loss and constant loss rate; a unique four parameter exponential loss function; the SCS curve number method; the Holtan formula; and the Green and Ampt method. There is no representation of the effects of frozen ground. There is no direct accounting for water properties that change with temperature. Parameter optimization capabilities are also included (USACE 1998a).

Where snowfall and snowmelt are to be considered, there is the provision for separate computations in up to ten elevation zones within each subbasin. The input temperature data are those corresponding to the lowest elevation zone. Temperatures are reduced by a user input lapse rate, in degrees per increment of elevation. Snowmelt may be computed by the degree-day or energy-budget methods and the algorithms are based on equations published in USACE (1998a).

There are separate energy budget equations used to determine snowmelt during rain and during rain free periods. Both equations are based on the generalized snowmelt equations presented in USACE (1998a).

The equation used to compute snowmelt for rain-on-snow conditions assumes that solar radiation is minimal and that the atmosphere is saturated. The rain-on-snow equation referenced in the HEC-1 User's Manual (USACE 1998b) is the equation developed for open or partly forested basin conditions (i.e. where mean canopy cover is 10% to 60% of the basin). The equation includes a dimensionless coefficient that the user can modify to account for variation from the generalized equation in the program.

The equation used in HEC-1 to compute snowmelt during rain free conditions includes the effect of solar radiation, and does not assume saturated atmospheric conditions. Four rain-free snowmelt equations are derived in USACE (1998a), each one for a different category of forest cover. The HEC-1 program includes only one of these equations, that being the one suitable for partly forested conditions. Again, the equation includes a dimensionless coefficient that the user can modify to account for variation from the generalized equation in the program.

HEC-HMS

HEC-HMS is considered the "next-generation" software package for precipitation-runoff simulation that will eventually supersede the HEC-1 software. HEC-HMS differs from HEC-1 in that it posseses a graphical user interface, integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities. HEC-HMS will eventually contain all of the watershed-runoff and routing capabilities of HEC-1 in addition to many improved algorithms.

The current version of HEC-HMS (Version 2.2.2) does not include the capability to simulate snowmelt or snow accumulation. Future versions of the model (Version 3.0) will incorporate the snowmelt algorithms originally developed by the US Army Engineer Research and Development Center (ERDC) for the Distributed Snow Process Model (DSPM). DSPM estimates snowpack conditions in a large number of distributed cells that describe a watershed or a watershed sub-basin. The resolution of the grid cell system typically ranges between 0.4 and 0.8 square miles.

DSPM uses the SSARR-grid snow process model, which was extracted from the "Snow-Band" snowmelt computations contained within the original SSARR model, to simulate the snow processes in each grid. The SSARR-grid snow process model is a temperature index model that accounts for cold content and liquid water content of the snow. The melt factor can be a constant, or a function of the antecedent temperature or time of year and can vary between grid cells. The melt factor can also be automatically increased during higher rainfall intensities. Additional information regarding DSPM can be found at the following website:

http://www.erdc.usace.army.mil/pls/erdcpub/www_welcome.NAVIGATION_PAGE?tmp_next_page=52719

Version 3.0 of HEC-RMS is currently being Beta tested by USACE staff and is not yet available to the public (Daly 2004, personal communication). Versions subsequent to Version 3.0 will include energy budget snowmelt simulation, amongst other capabilities.

Hydrologic Simulation Program – Fortran (HSPF)

The US Environmental Protection Agency (US-EPA) HSPF program has its origin in the Stanford Watershed Model originally developed by Crawford and Linsley (1966). In 1976, the EPA commissioned Hydrocomp Inc. to develop a system of simulation modules that would handle all of the functions currently being offered by modeling software separately developed by others (Crawford and Linsley; Hydrocomp Inc.). The product was HSPF, which is a comprehensive, conceptual, continuous watershed simulation model design to simulate all water quantity and quality processes that occur in a watershed.

Spatial variability is accounted for by dividing the basin into hydrologically homogenous land segments. Runoff for each land segment is then simulated independently. The model uses three main modules (PERLND, IMPLN, and RCHRES), which simulate the runoff from pervious land segments, impervious land segments, and free flowing reaches respectively. In pervious land segments, HSPF models the movement of water along three paths: overland or surface flow, interflow, and groundwater flow. Snow accumulation and melt, evaporation, precipitation and other hydrologic fluxes are also represented. Actual evapotranspiration is a function of the potential evapotranspiration demand and the amount of water available in the soil and on the land surface.

The subroutines used to account for snow accumulation and snowmelt are based on the work previously conducted by others (USACE 1956, Anderson and Crawford 1964, and Anderson 1968). The snow algorithms use meteorologic data to determine whether precipitation falls as rain or as snow, to simulate an energy balance for the snowpack, and to determine the effect of the heat fluxes on the snowpack. The five primary processes that cause snowmelt (solar radiation, convection, condensation, ground melt, rainfall) are simulated in HSPF. There are several user input parameters that can be modified to affect the rate and timing of snowmelt - SHADE (fraction of land segment shaded from solar radiation), CCFACT (factor to adjust rate of heat transfer from atmosphere to the snowpack, and MGMELT (maximum rate of snowmelt by ground heat) (Bicknell et al 1992).

There are limited means to alter snow accumulation in HSPF. There are three hydroclimatic related parameters that control snow accumulation: TSNOW (wet bulb air temperature), SNOWCF (factor to account for poor gage catch efficiency), and SNOWEVP (factor to adjust sublimation from snowpack).

Hydrocomp Forecast and Analysis Modeling System (HFAM)

HFAM is a semi-distributed model developed by Hydrocomp Inc. and is based on the widely used Stanford Watershed Model (SWM) and the HSPF model. The HFAM system consists of a set of physically based, continuous, deterministic models. The main components of the system are a hydrologic simulation model (which builds upon the HSPF model) and a river-reservoir model. For the hydrologic simulation model, the basin is divided into hydrologically homogenous land segments. Each segment is simulated independently using local precipitation, evapotranspiration, temperature, solar radiation and wind. Hydrologic processes that are simulated include snow accumulation and snowmelt, canopy interception, overland and interflow, and evapotranspiration.

HFAM offers three types of simulations: analysis, forecasting, and probabilistic. Of the three, the analysis simulation would be the only one used for the PMF analysis.

The hydrologic algorithms used to transform precipitation to surface runoff, to account for snow accumulation and aging, and to account for snowmelt are analogous to those used in HSPF.

Precipitation Runoff Modeling System (PRMS)

The US Geological Survey (USGS) PRMS model is a modular-design, determinininistic modeling system that evaluates the impacts of various combinations of precipitation, climate and land use on streamflow, sediment yields and general basin hydrology. It is a multipurpose model for stormflow hydrographs and long-term simulations of mean daily runoff from snowmelt.

The basin can be subdivided into subunits based on basin characteristics. Two levels of partitioning are available. The first divides the basin into homogenous units based on basin characteristics and is used to produce the daily system response and streamflow for a basin. Runoff is computed from each unit using a series of linear and non-linear reservoirs whose output sums to stream outflow. The reservoirs depict surface flow, subsurface flow, and base flow. Although typically only the characteristics of the surface flow reservoir varies between units.

The second level of partitioning conceptualizes the basin as a series of interconnected flow planes and channel segments. Surface runoff is routed over the flow planes and into the channel segments; channel flow is then routed through the watershed channel system. Parameter optimization and sensitivity analysis capabilities are included (Cunderlik 2003).

Snowmelt is modeled using an energy budget approach. The snowpack routines account for initiation, accumulation, and depletion of the snowpack for each Hydrologic Response Unit (HRU). The energy budget considers net shortwave and longwave radiation, as well as the heat content of precipitation. Other energy sources, including condensation, advection, and ground conduction are not accounted for in the energy budget terms. Frozen ground or the temperature dependence of important water properties is also not included (USACE 1998a).

Streamflow Synthesis and Reservoir Regulation Model (SSARR)

The Streamflow Synthesis and Reservoir Regulation (SSARR) Model was originally developed by the North Pacific Division of the U.S. Army Corps of Engineers in 1956.

The SSARR model can be visualized as comprising two modules, the snow computation module and the runoff analysis module. The Runoff Analysis Module uses a single soil-moisture reservoir whose level or state determines the percentage of available precipitation or snowmelt that eventually runs off via combined surface, subsurface, and base-flow components. Water that does not run off is apportioned between soil-moisture reservoir gains and evapotranspiration losses. Model routing in the watershed is accomplished by cascading linear reservoirs. The model does not presently deal directly with moisture of frozen ground or the temperature-dependence of important water properties that affect runoff (USACE 1998a).

The snow computation module computes snowmelt through either a temperature index approach with lapse rate correction or by a generalized energy snowmelt equation. The state of the basin snowpack can be defined by two different options: the snowcover depletion curve option or the integrated snowband option. The depletion curve model computes snowmelt with an algorithm that is based on the temperature index or energy budget and a snow cover depletion curve.

National Weather Service River Forecast System (NWSRFS)

The National Weather Service River Forecast System (NWSRFS) model is a further development of the Stanford Watershed Model developed by Crawford and Linsley in 1966. It was developed in 1972 by the Hydrologic Research Laboratory (HRL) of the NWS Office of Hydrology (USACE 1998a).

The NWSRFS model uses the Sacramento Soil-Moisture Accounting Model (SAC-SMA), which divides soil-moisture among five reservoirs, using both “free” water and “tension” soil moisture levels. Conceptually, once water has percolated through the topsoil, the model uses a series of five “storage buckets” to simulate the storage and movement of water in the subsurface zones. Available runoff is computed also using SAC-SMA and is translated to runoff using a unit hydrograph approach. An index approach for simulating the effect of frozen ground has been incorporated into the model (USACE 1998a).

In mountainous basins with significant snowfall, it is often useful to divide the basin into two or more elevation zones for modeling. This helps to capture variations in hydrometeorology and basin hydrology that are highly correlated with elevation. Where snowmelt is not a significant factor, the capability also exists for the basin to be subdivided into subbasins based on topographical divides.

The snow accumulation and snowmelt model contained in NWSRFS is documented in HYDRO-17, which is a snow model developed in the early 1970’s by the National Weather Service. Snowmelt is computed differently for rain and rain-free periods. Melt during rain-free periods is computed using a degree-day approach, which uses a seasonally varying melt-factor. Melt during rainy periods is determined from an energy balance equation that calculates the net radiative, latent, sensible, and rainwater heat transfer to calculate the amount of melt. Areal distribution of the snowpack is dealt with using an areal depletion curve that relates extent of the snow cover to the ratio of mean areal snow water equivalent. In either rain or nonrain cases, once the heat deficit of the snowpack has been satisfied, the available melt water is lagged and attenuated to simulate the transmission of water through snow. The final excess liquid water is then made available to the runoff portion of NWSRFS (USACE 1998a).

HYDROTEL

HYDROTEL was developed by the Institut National de la Recherche Scientifique, Eau, Terre, et Environnement (INRS-ETE) and is a spatially distributed hydrologic model with physical bases specifically developed to facilitate the use of remote sensing and geographical information system (GIS) data. The program is modular in nature, allowing for the addition or modification of algorithms.

The complete drainage structure of a basin is obtained with a software program designed specifically to prepare the watershed database. The basin is first discretized in square cells allowing the creation of a digital elevation model (DEM), with a pre-determined accuracy, from which the slope and aspect of each cell are obtained. The cell that is considered to be the outlet of the basin is determined, and all upstream cells are identified. Once all cells constituting a watershed are identified, together with the drainage structure, it is possible to trace the river network corresponding to cells draining a number of cells greater than a specified threshold. Finally, sub-watersheds are determined, with outlets at the river junctions. Those sub-watersheds can be further sub-divided or grouped to obtain relatively homogeneous hydrological units (RHHU).

Daily snowmelt and accumulation are estimated by a modified degree-day method in which the energy budget at the snow/air interface is estimated by the degree-day approach but that is estimated by a more physical approach within the snowpack (Cunderlik 2003). Four equations are available to estimate potential evapotranspiration. The vertical water budget is simulated using the algorithms from another INRS-ETE developed software package (CEQUEAU). The kinematic wave methodology is used to estimate down slope flow from cell to cell.

MIKE 11/SHE

MIKE 11 is a commercial engineering software package developed at the Danish Hydraulic Institute (DHI). The MIKE 11 software includes basic modules for rainfall runoff, hydrodynamics, advection-dispersion, water quality, and sediment transport. The rainfall runoff module contains three different models that can be used to estimate basin runoff: (1) a lumped, continuous simulation module that simulates the overland, interflow, and baseflow components as a function of the moisture contents in four storages, (2) the unit hydrograph method, and (3) a monthly soil moisture accounting model.

Snowmelt and snow accumulation can be simulated using one of two approaches; a simple lumped calculation or a more general approach that divides the catchment into a number of altitude zones, with separate snowmelt parameters, temperature, and precipitation input. Regardless of the approach, snowmelt is calculated using a degree-day approach with the primary inputs being base level temperature and the degree-day melt coefficient. Generated melt water is retained in the snow storage as liquid water until the total amount exceeds the water retention capacity of the snow storage.

Seasonal variation of the degree day coefficient can be accounted for, which will conceptually reflect the seasonal variation of the incoming short wave radiation and the variation in the albedo of the snow surface.

Additionally, the melting effects caused by absorbed short wave radiation can be modeled explicitly, where snowmelt is a function of a radiation coefficient and the incoming short wave radiation. The condensation of humid air on the snow surface and the advective heat transferred to the snowpack by precipitation can also be modeled explicitly. Snowmelt is computed as a function of a degree-day coefficient, precipitation, and the difference between the air temperature and the base level temperature.

MIKE 11 can be coupled with the MIKE SHE modeling system, which is an integrated, physically based, fully distributed, modular modeling system. MIKE SHE is the DHI version of the original SHE (Systeme Hydrologique European) program. MIKE SHE uses a square grid or cell network as the basic structure. MIKE SHE includes all of the processes in the land phase of the hydrologic cycle, including precipitation (rain or snow), evapotranspiration, interception, overland sheet flow, unsaturated sub-surface flow and saturated groundwater flow. Overland flow is computed using a 2D finite difference diffusive wave approach. Snowmelt is computed using either the degree-day method or the energy budget method.

WATFLOOD

WATFLOOD is a distributed hydrologic model for real time flood forecasting and continuous simulation that was developed by Dr. Nicholas Kouwen at the University of Waterloo. The emphasis of this modeling system is on making optimal use of remotely sensed data, as radar rainfall data and LANDSAT land use and land cover data can be directly incorporated into the model. WATFLOOD uses Grouped Response Units (GRU), in which process parameters are tied to land cover. This leads to a universal parameter set because parameters are associated with land cover and not watersheds (Cunderlik 2003).

The model is aimed at flood forecasting and long term hydrologic simulation using distributed precipitation data from radar or numerical weather models. The processes modeled include interception, infiltration, evaporation, snow accumulation and ablation, interflow, recharge, baseflow, and overland and channel routing (Kouwen 2001).

In WATFLOOD, snow-free and snow covered areas are modeled separately. Snow accumulation and melt is simulated using a temperature index method or a radiation-temperature index method. The temperature index method is based on the National Weather Service River Flow Forecast (NWSRFS) system. This well-known algorithm is used in many operational models and expresses snowmelt as a function of a melt factor, the air temperature, and the temperature at which the snow begins to melt (Kouwen 2001).

The radiation-temperature index method is a combination of the temperature index budget and the surface radiation budget. This method expresses snowmelt as a function of a melt factor, the average air temperature, the base temperature at which the snow will begin to melt, the conversion factor for energy flux density to snowmelt, and the net all-wave radiation acting on the snowpack. The equation represents the turbulent energy components of the energy budget, namely the sensible and latent heat exchanges, and the surface radiation budget in a manner similar to that used in energy balance models (Kouwen 2001).

MODEL RECOMMENDATION

The nine hydrologic model packages summarized in the preceding section are considered relative to one another in terms of the criteria outlined at the beginning of this memorandum.

The accuracy of the results from any numerical model is a function of the accuracy of the input data. The more complex the model, the more complex are the input data requirements. The model that is selected must fit with the types of data and resolution of the data that are available. A very rigorous and complex hydrologic model need not be selected if the input data is not available or is of too coarse of a resolution to meet model requirements.

The Baker basin has inflow hydrologic data available for calibration for each of the two reservoirs and potentially at two or three small tributaries (10 to 40 square mile tributary areas). There is a single recording gage for hourly precipitation and nine snow course sites in the basin that provide monthly snow depth and snow water equivalent data. Therefore, there appears little justification for using a high-resolution distributed model that requires the basin to be subdivided into subunits on the order of 0.5 to 1.0 square miles in size. It is for these reasons that the HYDROTEL, WATFLOOD, and MIKE SHE models are eliminated from further consideration. These models are proven tools in hydrologic modeling; however, the limited level of data that is available does not correspond with the rigorousness of the models and would dilute the effectiveness of the models.

FERC guidance (FERC 2001) and discussions with FERC staff indicated that snowmelt during the PMF be determined using an energy-budget approach. The energy-budget method is preferable to the degree-day (temperature index) method because the degree-day method was developed specifically for rain-free periods. All of the nine model packages described in this memorandum include some capability for simulating snowmelt with an energy budget method. However, the snowmelt algorithms included in HYDROTEL, and WATFLOOD are not true energy budget equations, but are instead modified degree-day equations that only account for select additional energy sources. Additionally HEC-HMS does not yet include snowmelt capabilities at all, although the current Beta test version includes a distributed degree-day method. It is for these reasons that the HYDROTEL, WATFLOOD, and HEC-HMS models are eliminated from further consideration.

Unit hydrograph theory is recommended for use in developing the PMF hydrograph (FERC 2001). Unit hydrograph theory is based on several assumptions one of which is that the basin (or subbasins) is represented by lumped parameters instead of distributed parameters. Consistent with the FERC guidelines, unit hydrograph theory will be used in developing the Baker River Project Part 12 PMP/PMF study. For this reason, HSPF, HFAM, PRMS, SSARR, HYDROTEL, and WATFLOOD are eliminated from further consideration, due to the absence of unit hydrograph simulation capabilities.

The models that remain for consideration therefore are HEC-1, NWSRFS, and MIKE 11. MIKE 11 snowmelt computations use a simple degree-day approach. The software does, however, include supplemental equations to account for other energy sources associated with snowmelt. MIKE 11 includes a supplemental equation that computes the snowmelt component attributed to short wave radiation and a separate supplemental equation that computes the snowmelt component attributed to the combined effects of condensation (latent heat) and the advective heat transferred to the snowpack from precipitation. These supplemental equations are simplified versions of the comparable equations presented in USACE (1998a) and do not account for all of the processes involved in the melting of a snowpack. For this reason, the MIKE 11 software is rated lower than either the NWSRFS or HEC-1 models in terms of snowmelt computation capabilities.

The NWSRFS model is the current hydrologic tool used by the National Weather Service to provide NWS Flood Warnings to the public. Specific to the Baker River basin, the NWS currently uses the NWSRFS model for inflow predictions for Baker Lake and Lake Shannon, using six-hour time steps. This model is a very good candidate for use in the Baker River Project Part 12 PMP/PMF Study, given its current use in the basin, its unit hydrograph capabilities for runoff modeling, and its energy budget based methodology for snowmelt.

The HEC-1 model is the model that FERC currently recommends for use in PMF studies (FERC 2001). The HEC-1 model is familiar to many federal agencies and has been applied to the Baker River basin for previous PMF studies. It incorporates the unit hydrograph technique for conversion of precipitation and snowmelt excess to a surface runoff hydrograph, and it includes the ability to simulate snowmelt using an energy budget methodology.

The NWSRFS and HEC-1 model both appear to be ranked equally for application to the Baker project. However, the HEC-1 model is recommended over the NWSRFS because of its familiarity to both FERC and the Corps in terms of PMF development.

ADDITIONAL PHASE II MODEL APPROACH RECOMMENDATION

It is recommended that three models be used for the Baker Project Part 12 PMF study.

1) The Corps of Engineers' HEC-1 model should be used for the event runoff modeling of the PMF. Consideration may be given to simulating snowmelt off-line from the HEC-1 model due to several built in limitations in the snowmelt algorithms in the model, one of which assumes that the snowpack is at yield density at the start of the simulation. This assumption may not represent the physical conditions in the Baker River watershed. Therefore consideration will be given to determining the snowmelt contribution using a spreadsheet based model or a separate program entirely. Output from the snowmelt model would be input into the HEC-1 model.
2) The calibrated HFAM model of the Baker River Basin (Hydrocomp 1999) should be used as a supplementary tool to assist in defining antecedent conditions (snowpack depth, snow water equivalent, soil moisture) in the basin for input into the event model during the calibration/verification process.
3) The Corps of Engineers' HEC-5 model (or equivalent) should be used for routing the PMF hydrograph through the two reservoirs and the controlled outlets.

The HFAM model currently used by PSE was calibrated for water years 1964 to 1994 based on annual streamflow volumes in the Baker River downstream of Lower Baker Dam, mean daily inflows to Baker Lake, and snow water equivalent at seven snow course sites in the basin (Hydrocomp 1999).

The HEC-1 model is recommended for the event modeling of the calibration storms and the PMP conditions. The HEC-1 model is an event based runoff model, and as such antecedent reservoir level, soil moisture and snowpack conditions must be determined using manual estimates or with a separate continuous simulation type model. For the calibration model runs, antecedent conditions must reflect the conditions in the basin that existed prior to the initiation of the specific event modeled. For events that occurred later in the flood season (January – April), available Baker basin snow course data can help to define these antecedent conditions. However, the availability of a calibrated continuous event model of the Baker River Basin (Hydrocomp 1999) will be a useful tool to help define the antecedent conditions. For the PMP model runs, antecedent conditions will be determined manually based on the calibration results and recommendations presented in HMR-57.

Since the HEC-1 model package does not include the capabilities to route hydrographs through a reservoir with a controlled outlet, a third model is necessary to develop the regulated outflow PMF hydrographs. The Corps of Engineers is currently using the HEC-5 (USACE 1998c) reservoir simulation software to route hydrographs through the spillway of the Upper Baker project for the ongoing Skagit River Flood Damage Reduction Feasibility Study, and it is for this reason that the HEC-5 program is recommended for use in the Baker Project Part 12 PMF study.

REFERENCES

Anderson, E.A. 1968. *Development and Testing of Snow Pack Energy Balance Equations.* Water Resour. Res. 4(1):19-37

Anderson, E.A. 1973. *National Weather Service River Forecast System – Snow Accumulation and Ablation Model.* NOAA Technical Memorandum NWS HYDRO-17. U.S. Department of Commerce.

Anderson, E.A, and Crawford, N.H. 1964. *The Synthesis of Continuous Snowmelt Runoff Hydrographs on a Digital Computer.* Department of Civil Engineering, Stanford University. Stanford, CA. Technical Report No. 36.

Crawford, N.H., Linsley, R.K. 1966. *Digital Simulation in Hydrology: Stanford Watershed Model IV.* Stanford University, Department of Civil Engineering. Technical Report 39.

Cunderlik, Juraj M. 2003. *Hydrologic Model Selection for the CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions.*

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S. Jr., and Johanson, R.C. 1992. *Hydrological Simulation Program--Fortran: User's Manual for Release 10*. U.S. Environmental Protection Agency, Environmental Research Laboratory; Office of Research and Development. Athens, Georgia.

Daly, Steven. December 10th, 2004. *Personal communication between Jay Smith (Tetra Tech, Inc) and Steven Daly (U.S. Army Engineer Research and Development Center).*

DHI Software. 2000a. *Mike 11: A Modelling System for Rivers and Channels. Reference Manual.*

DHI Software. 2000b. *Mike 11: A Modelling System for Rivers and Channels. Users Guide.*

Environmental Protection Agency, 1980. *Hydrologic Simulation Program Fortran HSPF User Manual*. Environmental Research Lab. Athens, GA.

Fortin J.P., Turcotte, R., Massicotte, S., Moussa R., Fitzback, J. Villeneuve, J.P. *Distributed Watershed Model Compatible with Remote Sensing and GIS Data: Description of Model.* Published in Journal of Hydrologic Engineering. Volume 6.

Hydrocomp, Inc. 1999. *Baker River Watershed – Model Calibration*. Prepared for Puget Sound Energy by Hydrocomp Inc., Menlo Park, CA.

Hydrocomp, Inc. 2004. *Hydrocomp Forecast and Analysis Modeling*. URL:http://www.hydrocomp.com/HFAMinfo.html

Kouwen, Nicholas. 2001. *WATFLOOD/SPL9 Hydrological Model & Flood Forecasting System*. Department of Civil Engineering, University of Waterloo. Waterloo, Ontario, Canada.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindou, L.G. 1983. *Precipitation-Runoff Modeling System – User's Manual.* United States Geological Survey Water Resources Investigators Report B3-4238.

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

United States Army Corps of Engineers (USACE). 1956. *Snow Hydrology, Summary Report of the Snow Investigations.* North Pacific Division. Portland Oregon.

United States Army Corps of Engineers (USACE). 1991. *User Manual, SSARR Model, Streamflow Synthesis and Reservoir Regulation.* North Pacific Division USACE.

United States Army Corps of Engineers (USACE). 1998a. *Runoff from Snowmelt*. Engineer Manual (EM) 1110-2-1406.

United States Army Corps of Engineers (USACE). 1998b. *HEC-1 Flood Hydrograph Package – User's Manual.*

United States Army Corps of Engineers (USACE). 1998c. *HEC-5 Simulation of Flood Control and Conservation Systems. User's Manual. Version 8.0.*

United States Army Corps of Engineers (USACE). 2001. *Hydrologic Modeling System (HEC-HMS). User's Manual. Version 2.1.*

United States Army Corps of Engineers (USACE). 2003. *Hydrologic Modeling System (HEC-HMS). Release Notes. Version 2.2.2.*

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 6

DETERMINATION OF PROBABLE MAXIMUM PRECIPITATION USING HMR 57

Tetra Tech, Inc.
August 15, 2005
Revised March 13, 2006

(FINAL)

INTRODUCTION

This memo summarizes the development of the probable maximum precipitation (PMP) estimate for use in the Baker River probable maximum flood (PMF) analysis. Also presented is the proposed methodology that will be used to determine spatial distribution of the general storm PMP for input into the calibrated watershed model. Finally, this memo presents several methodologies that can be used for determining the temporal distribution of the PMP, ultimately recommending a single methodology.

At this time, estimation of the PMP for the Baker River Project is being determined using the standardized methodology presented in Hydrometeorological Report No. 57, hereafter referred to as HMR 57 (NWS 1994). This technical memorandum summarizes the results of this determination. A parallel effort is being conducted that is investigating the potential effect that a site-specific PMP study would have in regards to possibly producing different PMP estimates than those obtained from the standard methodology presented in HMR 57. This parallel effort involves identification of extreme storms in HMR 57 and extreme storms that have occurred since publication of HMR 57, conducting in-place maximization of these storms, comparing the resulting in-place maximization values to the HMR 57 general storm PMP values for each storm location, and finally, transpositioning of storms to the Baker River basin that occurred over similar topography as the Baker River basin. The results of this parallel effort will be used to provide an estimate of the differences in PMP values that would potentially result if a future site specific study was conducted. The results of this parallel effort are documented in Technical Memorandums Nos. 8 & 9 (Applied Weather Associates 2006a and 2006b).

DETERMINATION OF PMP USING HMR 57

The probable maximum precipitation (PMP) estimate was determined for the Baker River Basin using HMR 57 (NWS 1994). HMR57 recommends that when making PMP estimates for drainages less than 500 square miles in size, that both general and local storm PMP values be calculated. The larger of the two estimates should be taken to represent the basin PMP. As per this guidance, both the general storm PMP estimate and the local storm PMP estimate were determined.

General Storm Procedure

This section briefly describes how the general storm PMP estimates were derived for the project area and presents the resulting calculations.

Given that the study area includes two dams within the tributary area, consideration of various storm centering scenarios was necessary. Therefore, general storm PMP estimates were developed while considering three different storm centering scenarios. Each dam will have a different controlling scenario, which will be determined as the worst case from the following three scenarios:

- General storm centered over entire basin – this may be the critical centering for Lower Baker Dam;
- General storm centered over the portion of the basin upstream of Upper Baker Dam – this is likely the critical centering for Upper Baker Dam;
- General storm centered over the portion of the basin between Upper Baker Dam and Lower Baker Dam – this may be the critical storm centering for Lower Baker Dam.

Figure 1 illustrates the delineation of the total tributary area, plus the delineation of the area solely tributary to Upper Baker Dam and the area between the two dams that is locally tributary to Lower Baker Dam.

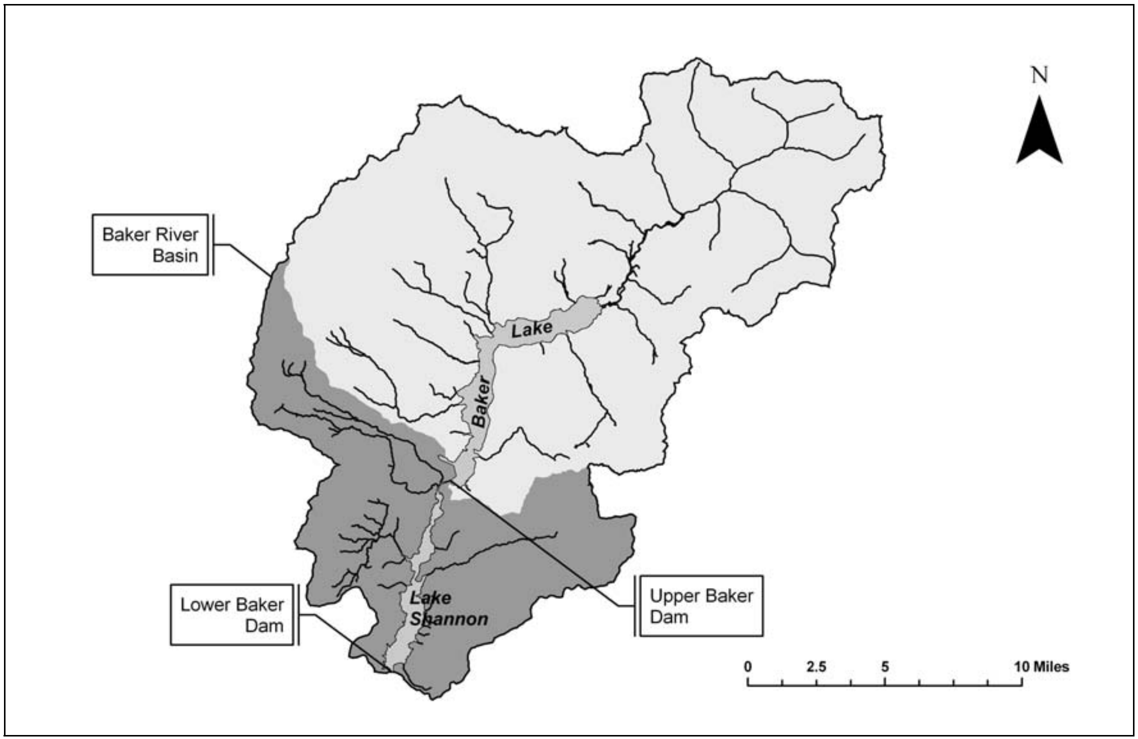


Figure 1. Baker River Basin Delineation

Basin Averaged All Season Index PMP Value

An overlay of the entire drainage basin was placed over the all season 10-mi^2, 24 hour PMP index map published in HMR 57. The scale of this map is 1:1,000,000. The PMP isohyets were traced on the overlay, and the areas between the isohyets were measured using a hand planimeter. Basin average index PMP values were then computed for the total basin (298.7 mi^2), the area upstream of Upper Baker Dam (214.9 mi^2), and the area between Upper Baker Dam and Lower Baker Dam (83.8 mi^2). These values were 20.3”, 20.7” and 19.4”, respectively.

Seasonal Adjustment Factors

Since seasonal variation of PMP is considered in this study, the seasonal index maps in HMR 57 were used to derive seasonal PMP estimates. Figures 15.2 through 15.8 in HMR 57 were used to estimate area weighted seasonal average reduction factors for each season for the total 299 square mile basin. The seasonal reduction factors were then applied to the index PMP estimate to obtain the seasonal index PMP estimate. The seasonal adjustment factors are used in conjunction with the all season index value to compute mid-month PMP estimates.

Depth-Duration Adjustment Factors

Evidence presented in HMR 57 led the authors of the document to conclude that depth-duration relations exhibit regional variation across the Pacific Northwest. Seven climatological subregions (three west of the Cascades and four east of the Cascades) were developed in HMR 57, and are based on the terrain classes for the State of Washington as published in NOAA Atlas 2. The climatological subregion that the Baker River basin is located within is Subregion 4 (West of Cascades – Orographic). Depth-duration ratios for this subregion were obtained from Table 15.1 of HMR 57 and were applied to the seasonally adjusted PMP values. The depth duration ratios presented in Table 15.1 of HMR 57 were adopted from work conducted by Schaefer (1989) and only included selected durations. Therefore, Schaefer (1989) was used to fill in additional depth duration values for the 2-, 3-, 9-, 12-, 36-, and 60-hour durations for the project area.

Areal Reduction Factors

Areal reduction factors are a function of both the size of the tributary drainage and the duration of the storm event, and vary depending upon whether the drainage is located in an orographic or least-orographic subregion. The Baker River basin is located within an orographic subregion west of the Cascade mountain range. Therefore, Figure 15.10 of HMR 57 was used to determine the magnitude of the areal reduction factors.

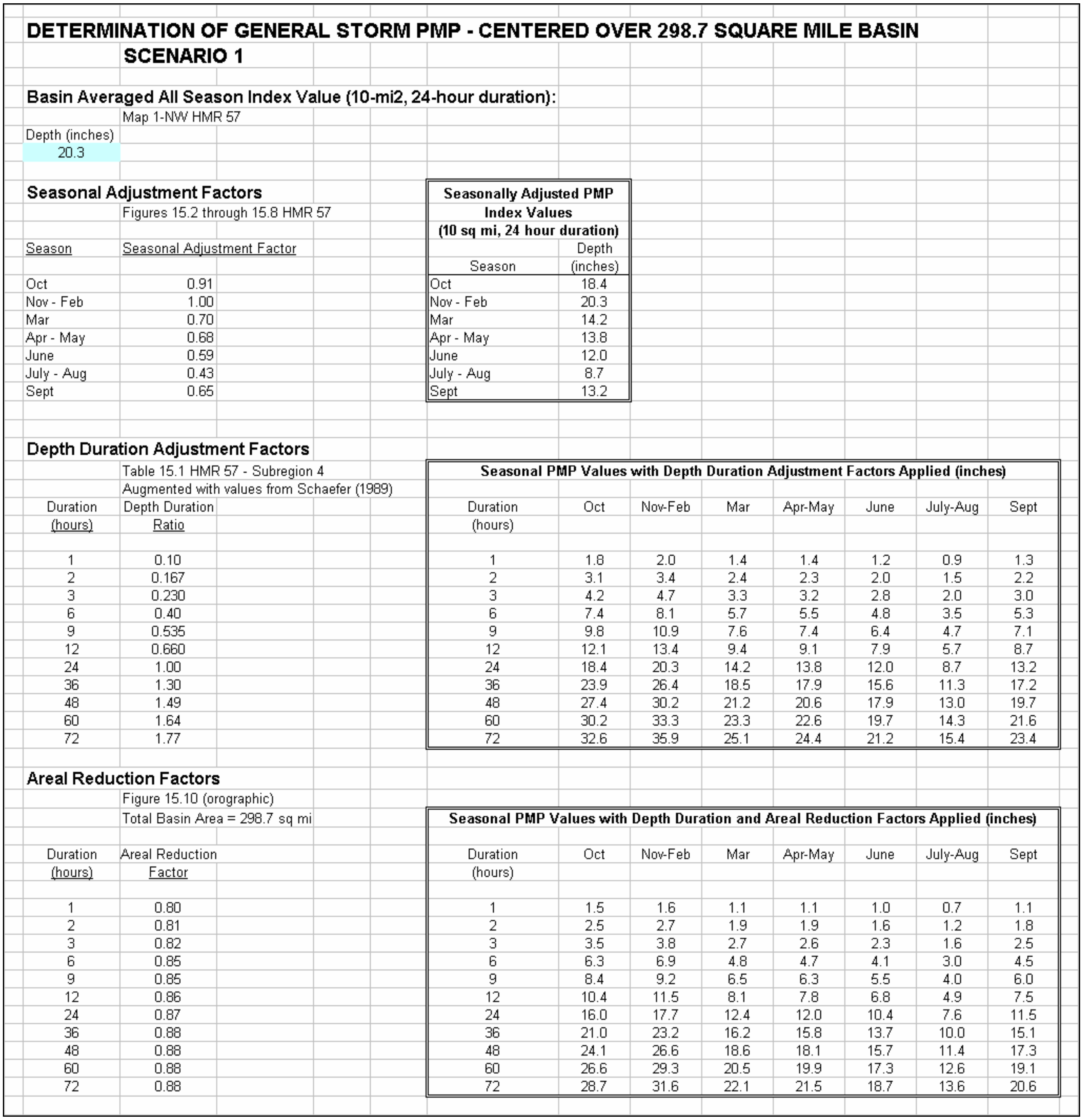
Areal reduction factors were determined for each of the three general storm centering scenarios. Each of the 1-, 2-, 3-, 6-, 9-, 12-, 24-, 36-, 48-, 60- and 72-hour 10-mi^2 basin average PMP estimates were then multiplied by the appropriate areal reduction factor.

Results

The results and intermediate calculations in support of the general storm PMP estimation are summarized in Tables 1 through 3. The PMP amounts and seasonality factors included in these tables represent mid-month values.

Figure 2 illustrates the PMP depth-duration curves for the general storm assumed centered over the total basin. Figure 3 illustrates the PMP depth-duration curves for the general storm assumed centered over the Upper Baker tributary area. Finally, Figure 4 illustrates the PMP depth-duration curves for the general storm centered over the portion of the basin between the two dams.

Table 1. – General Storm PMP Calculations – Storm Centered Over Total Basin



DETERMINATION OF GENERAL STORM PMP - CENTERED OVER 298.7 SQUARE MILE BASIN
SCENARIO 1

Basin Averaged All Season Index Value (10-mi2, 24-hour duration):

Map 1-NW HMR 57

Depth (inches)
20.3

Seasonal Adjustment Factors

Figures 15.2 through 15.8 HMR 57

Season	Seasonal Adjustment Factor
Oct	0.91
Nov - Feb	1.00
Mar	0.70
Apr - May	0.68
June	0.59
July - Aug	0.43
Sept	0.65

Seasonally Adjusted PMP Index Values (10 sq mi, 24 hour duration)

Season	Depth (inches)
Oct	18.4
Nov - Feb	20.3
Mar	14.2
Apr - May	13.8
June	12.0
July - Aug	8.7
Sept	13.2

Depth Duration Adjustment Factors

Table 15.1 HMR 57 - Subregion 4
Augmented with values from Schaefer (1989)

Duration (hours)	Depth Duration Ratio
1	0.10
2	0.167
3	0.230
6	0.40
9	0.535
12	0.660
24	1.00
36	1.30
48	1.49
60	1.64
72	1.77

Seasonal PMP Values with Depth Duration Adjustment Factors Applied (inches)

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.8	2.0	1.4	1.4	1.2	0.9	1.3
2	3.1	3.4	2.4	2.3	2.0	1.5	2.2
3	4.2	4.7	3.3	3.2	2.8	2.0	3.0
6	7.4	8.1	5.7	5.5	4.8	3.5	5.3
9	9.8	10.9	7.6	7.4	6.4	4.7	7.1
12	12.1	13.4	9.4	9.1	7.9	5.7	8.7
24	18.4	20.3	14.2	13.8	12.0	8.7	13.2
36	23.9	26.4	18.5	17.9	15.6	11.3	17.2
48	27.4	30.2	21.2	20.6	17.9	13.0	19.7
60	30.2	33.3	23.3	22.6	19.7	14.3	21.6
72	32.6	35.9	25.1	24.4	21.2	15.4	23.4

Areal Reduction Factors

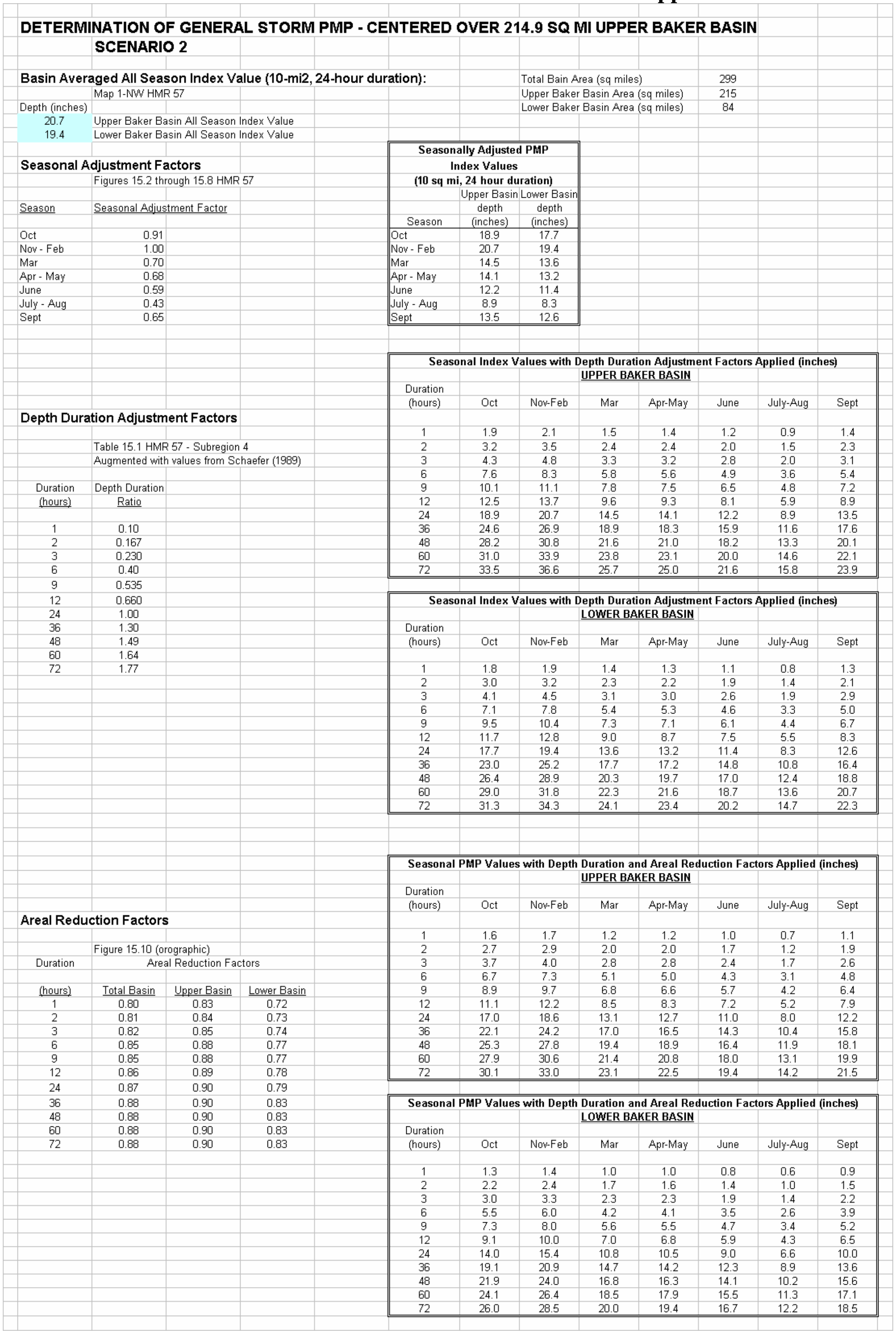
Figure 15.10 (orographic)
Total Basin Area = 298.7 sq mi

Duration (hours)	Areal Reduction Factor
1	0.80
2	0.81
3	0.82
6	0.85
9	0.85
12	0.86
24	0.87
36	0.88
48	0.88
60	0.88
72	0.88

Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.5	1.6	1.1	1.1	1.0	0.7	1.1
2	2.5	2.7	1.9	1.9	1.6	1.2	1.8
3	3.5	3.8	2.7	2.6	2.3	1.6	2.5
6	6.3	6.9	4.8	4.7	4.1	3.0	4.5
9	8.4	9.2	6.5	6.3	5.5	4.0	6.0
12	10.4	11.5	8.1	7.8	6.8	4.9	7.5
24	16.0	17.7	12.4	12.0	10.4	7.6	11.5
36	21.0	23.2	16.2	15.8	13.7	10.0	15.1
48	24.1	26.6	18.6	18.1	15.7	11.4	17.3
60	26.6	29.3	20.5	19.9	17.3	12.6	19.1
72	28.7	31.6	22.1	21.5	18.7	13.6	20.6

Table 2. – General Storm PMP Calculations – Storm Centered Over Upper Baker Portion of Basin



DETERMINATION OF GENERAL STORM PMP - CENTERED OVER 214.9 SQ MI UPPER BAKER BASIN
SCENARIO 2

Basin Averaged All Season Index Value (10-mi2, 24-hour duration):

Map 1-NW HMR 57

Depth (inches)	
20.7	Upper Baker Basin All Season Index Value
19.4	Lower Baker Basin All Season Index Value

Total Bain Area (sq miles)	299
Upper Baker Basin Area (sq miles)	215
Lower Baker Basin Area (sq miles)	84

Seasonal Adjustment Factors

Figures 15.2 through 15.8 HMR 57

Season	Seasonal Adjustment Factor
Oct	0.91
Nov - Feb	1.00
Mar	0.70
Apr - May	0.68
June	0.59
July - Aug	0.43
Sept	0.65

Seasonally Adjusted PMP Index Values (10 sq mi, 24 hour duration)

Season	Upper Basin depth (inches)	Lower Basin depth (inches)
Oct	18.9	17.7
Nov - Feb	20.7	19.4
Mar	14.5	13.6
Apr - May	14.1	13.2
June	12.2	11.4
July - Aug	8.9	8.3
Sept	13.5	12.6

Depth Duration Adjustment Factors

Table 15.1 HMR 57 - Subregion 4
Augmented with values from Schaefer (1989)

Duration (hours)	Depth Duration Ratio
1	0.10
2	0.167
3	0.230
6	0.40
9	0.535
12	0.660
24	1.00
36	1.30
48	1.49
60	1.64
72	1.77

Seasonal Index Values with Depth Duration Adjustment Factors Applied (inches)
UPPER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.9	2.1	1.5	1.4	1.2	0.9	1.4
2	3.2	3.5	2.4	2.4	2.0	1.5	2.3
3	4.3	4.8	3.3	3.2	2.8	2.0	3.1
6	7.6	8.3	5.8	5.6	4.9	3.6	5.4
9	10.1	11.1	7.8	7.5	6.5	4.8	7.2
12	12.5	13.7	9.6	9.3	8.1	5.9	8.9
24	18.9	20.7	14.5	14.1	12.2	8.9	13.5
36	24.6	26.9	18.9	18.3	15.9	11.6	17.6
48	28.2	30.8	21.6	21.0	18.2	13.3	20.1
60	31.0	33.9	23.8	23.1	20.0	14.6	22.1
72	33.5	36.6	25.7	25.0	21.6	15.8	23.9

Seasonal Index Values with Depth Duration Adjustment Factors Applied (inches)
LOWER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.8	1.9	1.4	1.3	1.1	0.8	1.3
2	3.0	3.2	2.3	2.2	1.9	1.4	2.1
3	4.1	4.5	3.1	3.0	2.6	1.9	2.9
6	7.1	7.8	5.4	5.3	4.6	3.3	5.0
9	9.5	10.4	7.3	7.1	6.1	4.4	6.7
12	11.7	12.8	9.0	8.7	7.5	5.5	8.3
24	17.7	19.4	13.6	13.2	11.4	8.3	12.6
36	23.0	25.2	17.7	17.2	14.8	10.8	16.4
48	26.4	28.9	20.3	19.7	17.0	12.4	18.8
60	29.0	31.8	22.3	21.6	18.7	13.6	20.7
72	31.3	34.3	24.1	23.4	20.2	14.7	22.3

Areal Reduction Factors

Figure 15.10 (orographic)

Duration	Areal Reduction Factors		
(hours)	Total Basin	Upper Basin	Lower Basin
1	0.80	0.83	0.72
2	0.81	0.84	0.73
3	0.82	0.85	0.74
6	0.85	0.88	0.77
9	0.85	0.88	0.77
12	0.86	0.89	0.78
24	0.87	0.90	0.79
36	0.88	0.90	0.83
48	0.88	0.90	0.83
60	0.88	0.90	0.83
72	0.88	0.90	0.83

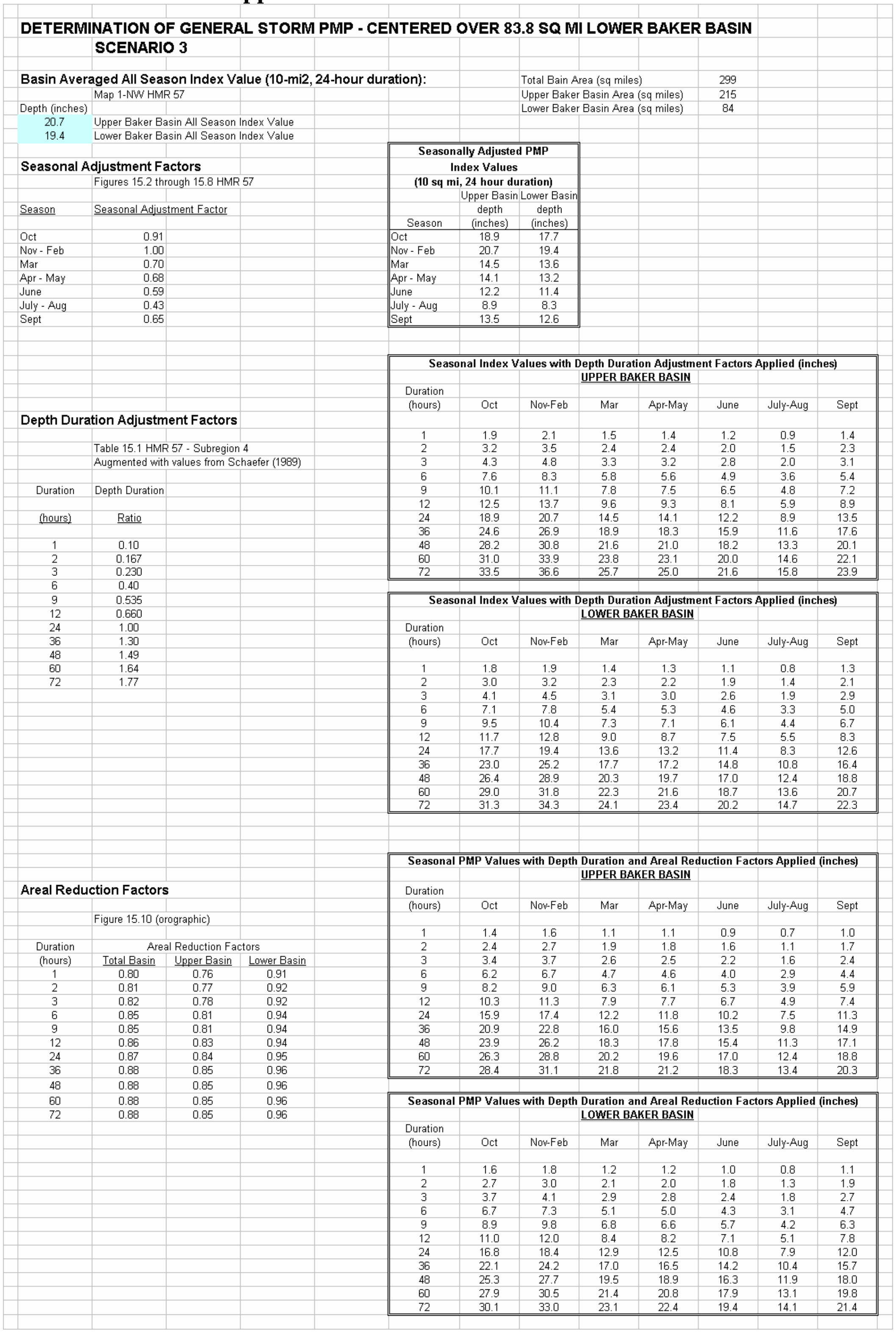
Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)
UPPER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.6	1.7	1.2	1.2	1.0	0.7	1.1
2	2.7	2.9	2.0	2.0	1.7	1.2	1.9
3	3.7	4.0	2.8	2.8	2.4	1.7	2.6
6	6.7	7.3	5.1	5.0	4.3	3.1	4.8
9	8.9	9.7	6.8	6.6	5.7	4.2	6.4
12	11.1	12.2	8.5	8.3	7.2	5.2	7.9
24	17.0	18.6	13.1	12.7	11.0	8.0	12.2
36	22.1	24.2	17.0	16.5	14.3	10.4	15.8
48	25.3	27.8	19.4	18.9	16.4	11.9	18.1
60	27.9	30.6	21.4	20.8	18.0	13.1	19.9
72	30.1	33.0	23.1	22.5	19.4	14.2	21.5

Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)
LOWER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.3	1.4	1.0	1.0	0.8	0.6	0.9
2	2.2	2.4	1.7	1.6	1.4	1.0	1.5
3	3.0	3.3	2.3	2.3	1.9	1.4	2.2
6	5.5	6.0	4.2	4.1	3.5	2.6	3.9
9	7.3	8.0	5.6	5.5	4.7	3.4	5.2
12	9.1	10.0	7.0	6.8	5.9	4.3	6.5
24	14.0	15.4	10.8	10.5	9.0	6.6	10.0
36	19.1	20.9	14.7	14.2	12.3	8.9	13.6
48	21.9	24.0	16.8	16.3	14.1	10.2	15.6
60	24.1	26.4	18.5	17.9	15.5	11.3	17.1
72	26.0	28.5	20.0	19.4	16.7	12.2	18.5

Table 3. – General Storm PMP Calculations – Storm Centered Over Portion of Basin between Upper Baker Dam and Lower Baker Dam



DETERMINATION OF GENERAL STORM PMP - CENTERED OVER 83.8 SQ MI LOWER BAKER BASIN

SCENARIO 3

Basin Averaged All Season Index Value (10-mi2, 24-hour duration):

Map 1-NW HMR 57

Depth (inches)	
20.7	Upper Baker Basin All Season Index Value
19.4	Lower Baker Basin All Season Index Value

Total Bain Area (sq miles)	299
Upper Baker Basin Area (sq miles)	215
Lower Baker Basin Area (sq miles)	84

Seasonal Adjustment Factors

Figures 15.2 through 15.8 HMR 57

Season	Seasonal Adjustment Factor
Oct	0.91
Nov - Feb	1.00
Mar	0.70
Apr - May	0.68
June	0.59
July - Aug	0.43
Sept	0.65

Seasonally Adjusted PMP Index Values (10 sq mi, 24 hour duration)

Season	Upper Basin depth (inches)	Lower Basin depth (inches)
Oct	18.9	17.7
Nov - Feb	20.7	19.4
Mar	14.5	13.6
Apr - May	14.1	13.2
June	12.2	11.4
July - Aug	8.9	8.3
Sept	13.5	12.6

Depth Duration Adjustment Factors

Table 15.1 HMR 57 - Subregion 4
Augmented with values from Schaefer (1989)

Duration (hours)	Depth Duration Ratio
1	0.10
2	0.167
3	0.230
6	0.40
9	0.535
12	0.660
24	1.00
36	1.30
48	1.49
60	1.64
72	1.77

Seasonal Index Values with Depth Duration Adjustment Factors Applied (inches)
UPPER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.9	2.1	1.5	1.4	1.2	0.9	1.4
2	3.2	3.5	2.4	2.4	2.0	1.5	2.3
3	4.3	4.8	3.3	3.2	2.8	2.0	3.1
6	7.6	8.3	5.8	5.6	4.9	3.6	5.4
9	10.1	11.1	7.8	7.5	6.5	4.8	7.2
12	12.5	13.7	9.6	9.3	8.1	5.9	8.9
24	18.9	20.7	14.5	14.1	12.2	8.9	13.5
36	24.6	26.9	18.9	18.3	15.9	11.6	17.6
48	28.2	30.8	21.6	21.0	18.2	13.3	20.1
60	31.0	33.9	23.8	23.1	20.0	14.6	22.1
72	33.5	36.6	25.7	25.0	21.6	15.8	23.9

Seasonal Index Values with Depth Duration Adjustment Factors Applied (inches)
LOWER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.8	1.9	1.4	1.3	1.1	0.8	1.3
2	3.0	3.2	2.3	2.2	1.9	1.4	2.1
3	4.1	4.5	3.1	3.0	2.6	1.9	2.9
6	7.1	7.8	5.4	5.3	4.6	3.3	5.0
9	9.5	10.4	7.3	7.1	6.1	4.4	6.7
12	11.7	12.8	9.0	8.7	7.5	5.5	8.3
24	17.7	19.4	13.6	13.2	11.4	8.3	12.6
36	23.0	25.2	17.7	17.2	14.8	10.8	16.4
48	26.4	28.9	20.3	19.7	17.0	12.4	18.8
60	29.0	31.8	22.3	21.6	18.7	13.6	20.7
72	31.3	34.3	24.1	23.4	20.2	14.7	22.3

Areal Reduction Factors

Figure 15.10 (orographic)

Duration	Areal Reduction Factors		
(hours)	Total Basin	Upper Basin	Lower Basin
1	0.80	0.76	0.91
2	0.81	0.77	0.92
3	0.82	0.78	0.92
6	0.85	0.81	0.94
9	0.85	0.81	0.94
12	0.86	0.83	0.94
24	0.87	0.84	0.95
36	0.88	0.85	0.96
48	0.88	0.85	0.96
60	0.88	0.85	0.96
72	0.88	0.85	0.96

Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)
UPPER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.4	1.6	1.1	1.1	0.9	0.7	1.0
2	2.4	2.7	1.9	1.8	1.6	1.1	1.7
3	3.4	3.7	2.6	2.5	2.2	1.6	2.4
6	6.2	6.7	4.7	4.6	4.0	2.9	4.4
9	8.2	9.0	6.3	6.1	5.3	3.9	5.9
12	10.3	11.3	7.9	7.7	6.7	4.9	7.4
24	15.9	17.4	12.2	11.8	10.2	7.5	11.3
36	20.9	22.8	16.0	15.6	13.5	9.8	14.9
48	23.9	26.2	18.3	17.8	15.4	11.3	17.1
60	26.3	28.8	20.2	19.6	17.0	12.4	18.8
72	28.4	31.1	21.8	21.2	18.3	13.4	20.3

Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)
LOWER BAKER BASIN

Duration (hours)	Oct	Nov-Feb	Mar	Apr-May	June	July-Aug	Sept
1	1.6	1.8	1.2	1.2	1.0	0.8	1.1
2	2.7	3.0	2.1	2.0	1.8	1.3	1.9
3	3.7	4.1	2.9	2.8	2.4	1.8	2.7
6	6.7	7.3	5.1	5.0	4.3	3.1	4.7
9	8.9	9.8	6.8	6.6	5.7	4.2	6.3
12	11.0	12.0	8.4	8.2	7.1	5.1	7.8
24	16.8	18.4	12.9	12.5	10.8	7.9	12.0
36	22.1	24.2	17.0	16.5	14.2	10.4	15.7
48	25.3	27.7	19.5	18.9	16.3	11.9	18.0
60	27.9	30.5	21.4	20.8	17.9	13.1	19.8
72	30.1	33.0	23.1	22.4	19.4	14.1	21.4

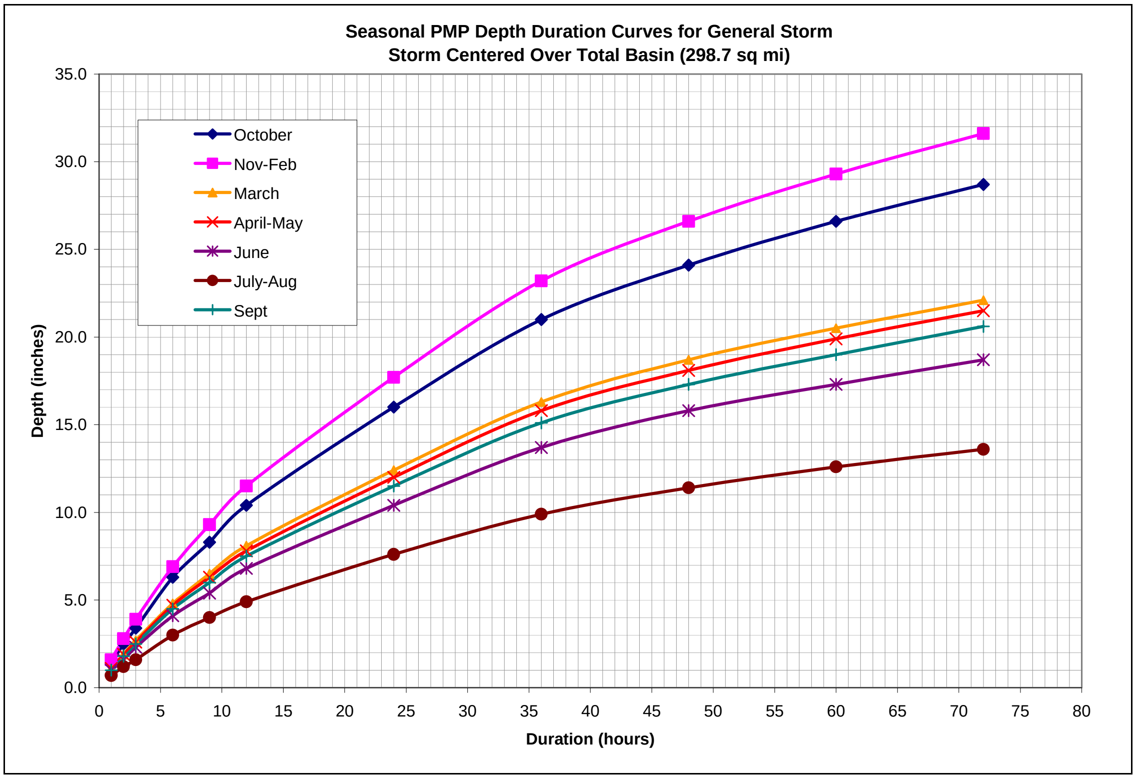


Figure 2. General Storm PMP Depth-Duration Curves for Total Basin (Scenario 1)

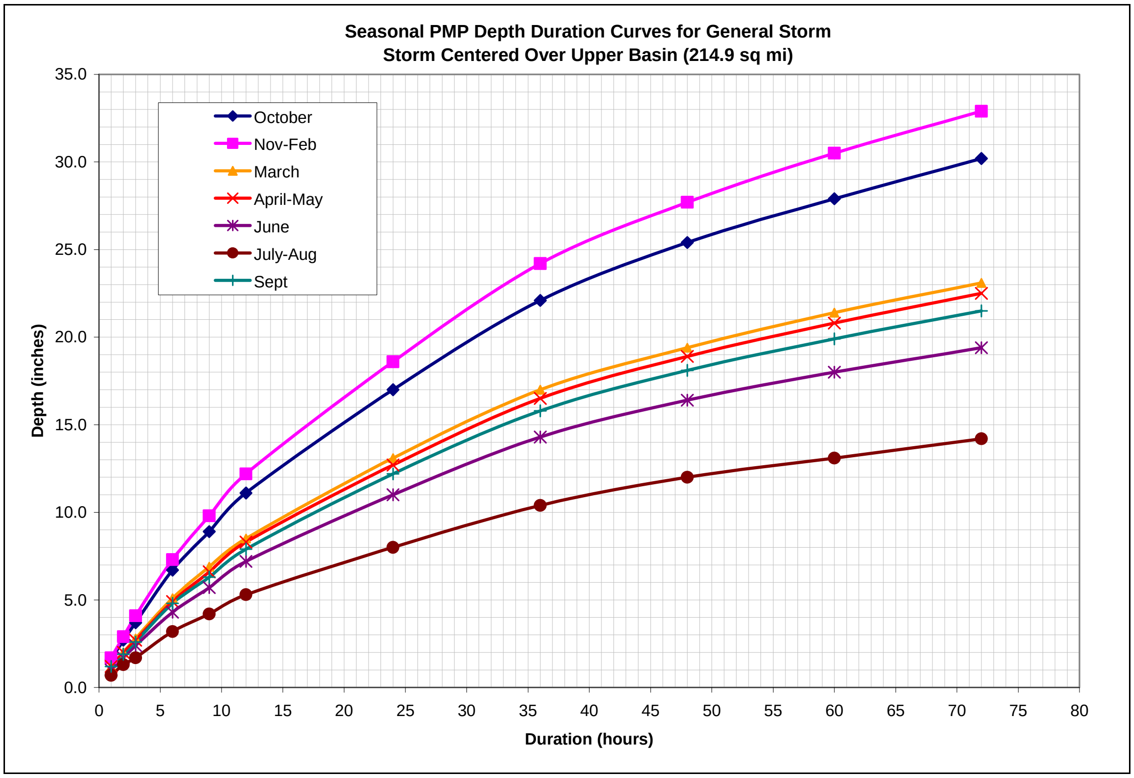


Figure 3. General Storm PMP Depth-Duration Curves for Tributary Area Upstream of Upper Baker Dam (Scenario 2)

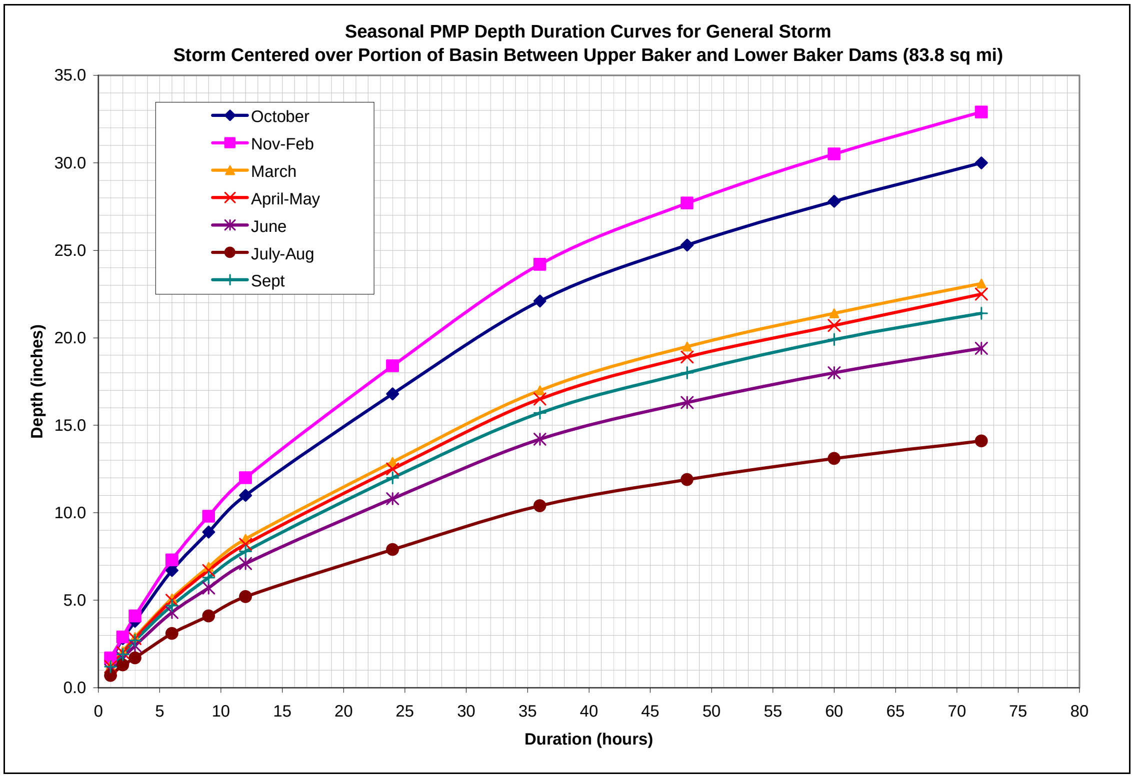


Figure 4. General Storm PMP Depth Duration Curves for Portion of Basin between Upper and Lower Baker Dam (Scenario 3)

Local Storm Procedure

Intense localized thunderstorms during the warm season (April through October) have been known to produce the greatest observed short duration rainfalls over small areas in the Pacific Northwest. These storms are not typically associated with the general storms that produce widespread heavy precipitation in the cold season, which usually extends from November through March (NWS 1994). In HMR 57 the term “localized thunderstorm” is synonymous with the term “local storm” and is used to describe an “extreme rainfall event, not associated with widespread heavy precipitation, that produces rain for durations of 6 hours or less, and is concentrated over an area of 500-mi^2 or less” (NWS 1994). This section of the memo describes how the local storm PMP estimates were derived for the project area, followed by a presentation of the resulting calculations.

Again, given that the study area includes two dams within the tributary area, local storm PMP values, and the associated areal reduction factors, were determined based on the assumption that the local thunderstorm could occur within any of one of the following three drainages:

- Local storm occurring somewhere within the total 299 mi^2 tributary area;
- Local storm occurring somewhere within the 215 mi^2 upper watershed, within the tributary area to Upper Baker Dam;
- Local storm occurring somewhere within the 84 mi^2 portion of the basin between Upper Baker Dam and Lower Baker Dam.

Since the Baker River Basin is fairly large, approximately 300 mi^2, it is unlikely that any local storm will be the controlling event for the Baker River PMF study. The local storm is not capable of producing the magnitude of runoff volume that even the 6-hour duration local storm is estimated to produce (Figures 2 through 4). It is more likely that one of the seasonal general storms will be the controlling event. However, to be complete, local storm PMP estimates were developed. In the final analysis, the local storm will be evaluated relative to the general storm estimates so as to thoroughly document which is the controlling event.

Local Storm Index PMP Value

Using Figure 15.36 in HMR 57, the basin average, 1-hour duration, 1-mi^2 local storm index PMP value was determined to be 5.0 inches.

Adjustment for Elevation

HMR 57 indicates that there is no evidence for variation in local storm precipitation potential for basins with mean elevations less than 6,000 feet in elevation. Above this elevation, a decrease consistent with the reduction in available moisture is expected. Therefore, adjustments to the basin average 1-mi^2 local storm PMP are made for basins that have a mean elevation greater than 6,000 feet. The reduction is equal to 9 percent of the local storm index PMP estimate for every 1,000 feet that the basin average elevation is greater than 6,000 feet.

The 299 mi^2 Baker River basin has a mean elevation of 3,300 feet. Therefore, elevation adjustments to the Baker River basin local storm index PMP value are not required. The mean elevation of the portion of the basin upstream of Upper Baker Dam is 3,650 feet, and therefore elevation adjustments for the local storm centered within the Upper Baker portion of the basin are also not required.

Adjustment for Duration

Adjustments to the local storm PMP index value, for durations less than 1-hour and up to 6 hours were obtained from Figure 15.38 in HMR 57. The adjustments are expressed as a percentage of the 1-hour local storm PMP index value.

Adjustment for Basin Area

Basin area reduction factors were determined for the total basin area (299 mi^2), the Upper Baker portion of the basin (215 mi^2), and the portion of the basin between Upper Baker and Lower Baker Dams. The reduction factors were obtained from depth-area relation shown in Figure 15.39 in HMR 57, and were applied to the duration adjusted index values obtained in the previous step.

Results

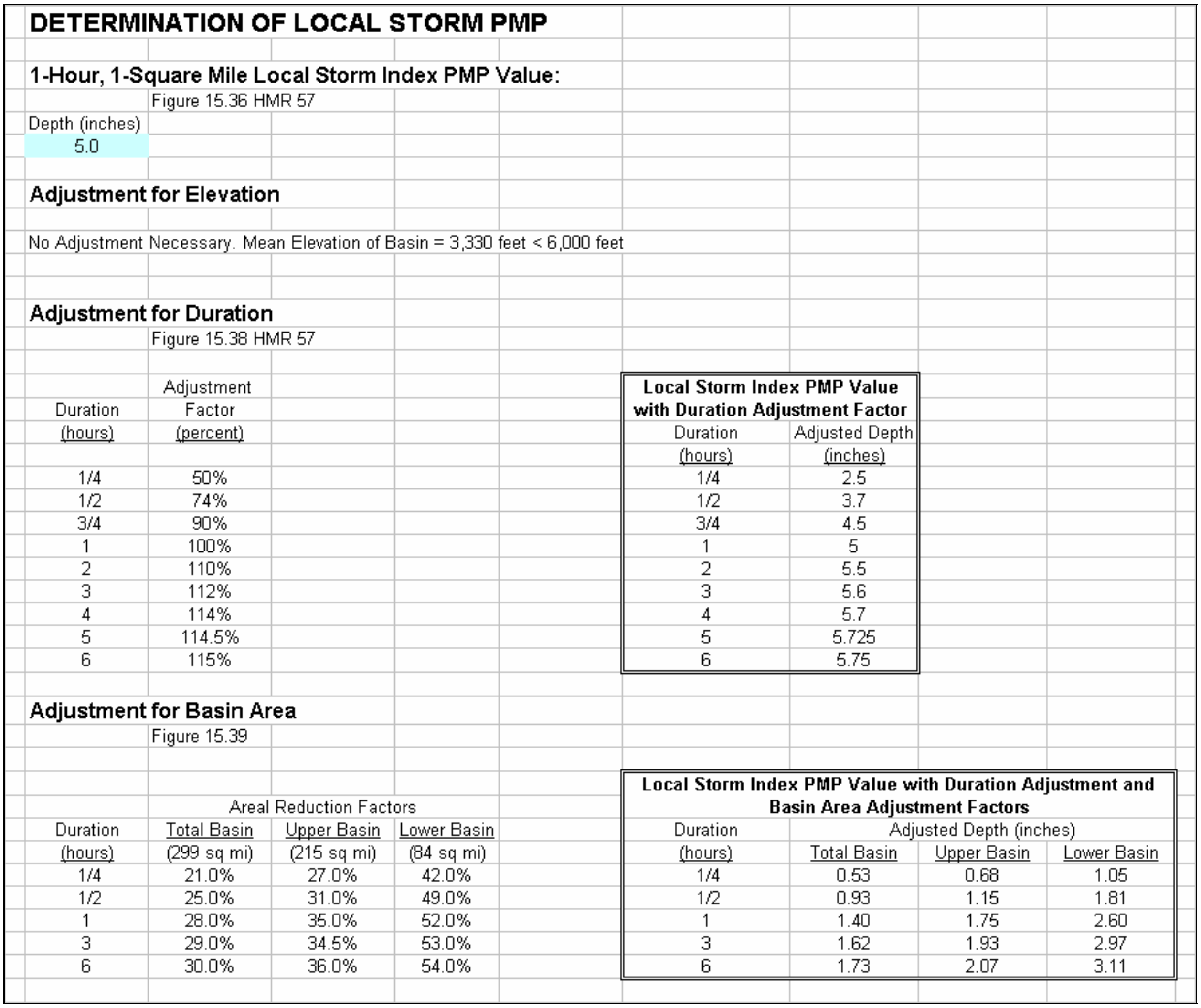
The results and intermediate calculations in support of the local storm PMP estimation, using the methodology outline in HMR 57, are summarized in Table 4 and Figure 5. Figure 5 represents depth duration curves for each of the three different scenarios where the local storm is centered over the total basin, over the tributary area upstream of the Upper Baker Dam, and over the tributary area between the two dams.

As seen in Table 4, the 6-hour duration local storm PMP estimate for the total basin scenario is 1.7”, which is only 25% of that for the 6-hour general storm PMP estimate (6.9” from Table 1). Interestingly, the 1-hour duration values are approximately equal for the local storm and general storm PMP estimates for the total basin scenario (1.6” for the general storm versus 1.4” for the local storm). Therefore, it seems highly unlikely that the local storm will be the controlling event for this analysis. Additionally, the response time for most of the subbasins in the watershed is greater than 1 hour so the entire basin would likely not be fully contributing during the 1-hour high intensity portion of the local storm.

A local storm PMP scenario that could be critical is for a local storm centered in the lower portion of the basin. In this scenario, the 1-hour duration value is 2.6” for the local storm (Table 4) versus 1.8” for the general storm (Table 3). However, the magnitude of runoff volume will be a significant factor in determining the controlling event. For the 6-hour duration local storm centered in the lower portion of the basin, the resulting 14,000 acre-feet of potential runoff volume (excluding any snowmelt) does not appear to be of sufficient magnitude to result in the critical water surface elevation, even if Lower Baker Dam was operating at normal full pool.

Although the above discussion would lead to the conclusion that the local storm is unlikely to be the controlling storm event for the Baker River Project PMP/PMF study, a thorough comparison will be made during the study to verify that this is indeed the case.

Table 4. Local Storm PMP Calculations



DETERMINATION OF LOCAL STORM PMP

1-Hour, 1-Square Mile Local Storm Index PMP Value:

Figure 15.36 HMR 57

Depth (inches)

5.0

Adjustment for Elevation

No Adjustment Necessary. Mean Elevation of Basin = 3,330 feet < 6,000 feet

Adjustment for Duration

Figure 15.38 HMR 57

Duration (hours)	Adjustment Factor (percent)
1/4	50%
1/2	74%
3/4	90%
1	100%
2	110%
3	112%
4	114%
5	114.5%
6	115%

Local Storm Index PMP Value with Duration Adjustment Factor

Duration (hours)	Adjusted Depth (inches)
1/4	2.5
1/2	3.7
3/4	4.5
1	5
2	5.5
3	5.6
4	5.7
5	5.725
6	5.75

Adjustment for Basin Area

Figure 15.39

	Areal Reduction Factors		
Duration (hours)	Total Basin (299 sq mi)	Upper Basin (215 sq mi)	Lower Basin (84 sq mi)
1/4	21.0%	27.0%	42.0%
1/2	25.0%	31.0%	49.0%
1	28.0%	35.0%	52.0%
3	29.0%	34.5%	53.0%
6	30.0%	36.0%	54.0%

Local Storm Index PMP Value with Duration Adjustment and Basin Area Adjustment Factors

	Adjusted Depth (inches)		
Duration (hours)	Total Basin	Upper Basin	Lower Basin
1/4	0.53	0.68	1.05
1/2	0.93	1.15	1.81
1	1.40	1.75	2.60
3	1.62	1.93	2.97
6	1.73	2.07	3.11

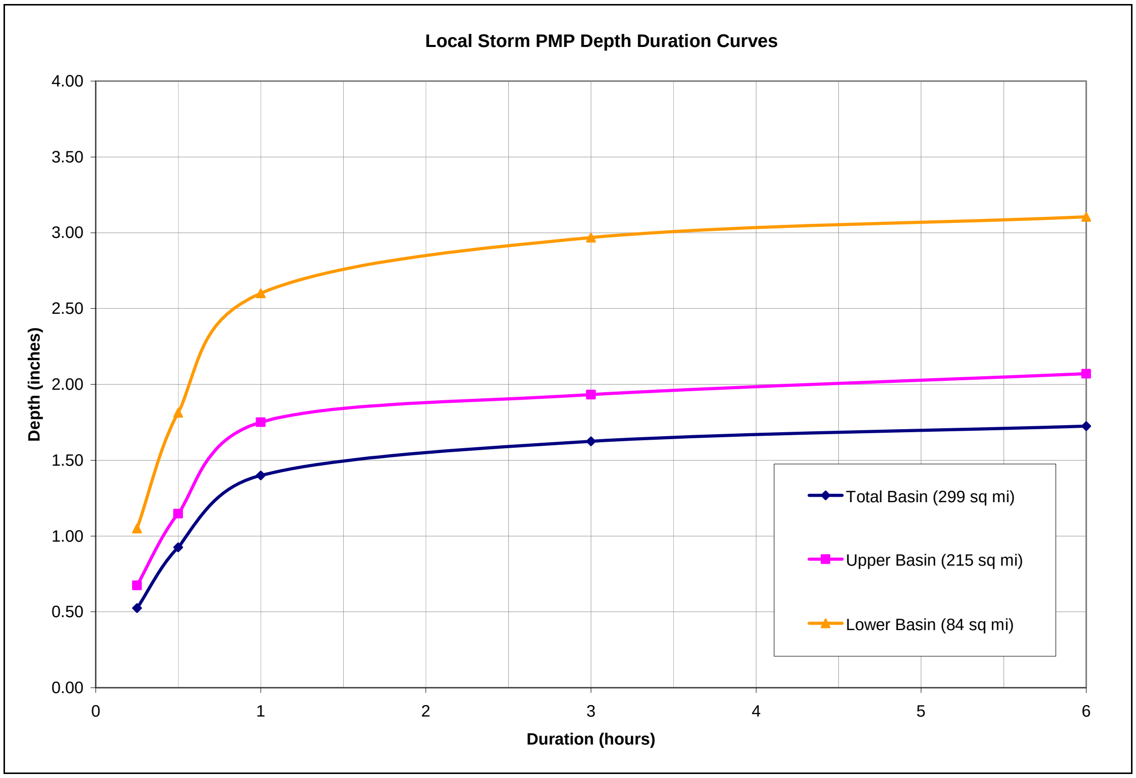


Figure 5. Local Storm PMP Depth Duration Curves

AREAL DISTRIBUTION OF PMP

The methodology for areal distribution of both the general storm PMP estimate and the local storm PMP estimate are discussed in the following sections.

General Storm

HMR 57 does not provide specific guidance for determining the spatial distribution of the general storm PMP, partly due to the complicating effect of orographic terrain on distribution. HMR 57 does however recommend that an approximate distribution may be derived by developing an isopercental analysis using 100-year precipitation frequency maps published in NOAA Atlas 2 (Miller et al 1973).

For the Baker River project, a modified version of this recommendation will be used to derive the precipitation distribution. Schaefer et al (2006) conducted a study for the Washington State Department of Transportation (WSDOT), which updated the information contained in NOAA Atlas 2. The study was entitled “*Regional Precipitation-Frequency Analysis and Spatial Mapping of Precipitation for 24-Hour and 2-Hour Durations in Eastern Washington*”. The mapping developed in this study will be used in lieu of the NOAA Atlas 2 mapping.

Spatial distribution of the general storm PMP values will be conducted within ArcGIS using the climatological mapping developed by Schaefer et al (2006). The procedure to be followed is summarized below:

1. Determine the basin averaged general storm PMP value for the given season, storm duration, and storm centering.
2. Using the gridded data sets for the 100-year, 24-hour precipitation (Schaefer et al 2006), determine the basin average 100-year, 24-hour precipitation depth.
3. Compute the ratio of the general storm PMP depth to the 100-year 24-hour precipitation depth.
4. Multiply the value of each of the 2-km^2 grids in the 100-year 24-hour data set by the computed ratio. Develop a gridded data set for the specific PMP event.
5. For each of the tributary subbasins that are represented in the watershed model, compute the subbasin average PMP using the PMP gridded data set.

Local Storm

HMR 57 presents a methodology which uses an idealized elliptical pattern to estimate the areal distribution of the local storm PMP. If this methodology is used, then the local storm index PMP value is multiplied by reduction factors that account for reductions due to area and duration. These reduction factors are presented as Table 15.2 in HMR 57. Using this methodology, the areal distribution for each local storm PMP duration is computed by multiplying the local storm index PMP value (5.0 inches) by each of the reduction factors in Table 15.2 of HMR 57. The results are summarized below in Table 5.

The isohyetal values in Table 5 are then applied to the idealized elliptical pattern in HMR 57 for each duration. The pattern is placed over the drainage basin so as to maximize precipitation volume into the basin.

Table 5. Ishohyet Label Values for Local Storm PMP (Baker River Basin 299 mi^2)

Isohyet (mi^2)	**Duration (hours)**								
	1/4	**1/2**	**3/4**	**1**	**2**	**3**	**4**	**5**	**6**
A (1)	2.5	3.7	4.5	5.0	5.5	5.6	5.7	5.7	5.8
B (5)	1.6	2.7	3.4	3.7	4.2	4.3	4.4	4.4	4.4
C (25)	1.1	1.9	2.4	2.8	3.2	3.3	3.3	3.3	3.4
D (55)	0.9	1.4	1.9	2.2	2.4	2.5	2.5	2.6	2.6
E (95)	0.6	1.1	1.4	1.6	1.9	1.9	1.9	2.0	2.0
F (150)	0.4	0.7	1.0	1.1	1.3	1.3	1.3	1.3	1.4
G (220)	0.3	0.4	0.6	0.7	0.8	0.8	0.9	0.9	0.9
H (300)	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5
I (385)	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2
J (500)	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2

TEMPORAL DISTRIBUTION OF PMP

A discussion of potential methodologies for deriving temporal distributions of both the general storm PMP estimate and the local storm PMP estimate are presented in the following sections.

General Storm Temporal Distribution

The temporal distribution of the general storm PMP estimate represents the sequential ordering of increments of PMP. The ordering of these increments will have a significant effect on the resulting probable maximum flood hydrographs, and it is a critical step in the PMP study. For example, storms with the high intensity segment near the end of the storm will generally produce larger flood peaks than similar storms with the high intensity segment near the beginning of the storm (Schaefer 1989).

Three different references were considered for determining a methodology for the temporal distribution of the general storm. The first is the HMR 57 manual itself (NWS 1994), the second is Chapter VIII of the Federal Energy Regulatory Commissions Engineering Guidelines (FERC 2001), and the last is a study conducted by Washington State Department of Ecology (Schaefer 1989) on characteristics of extreme storms in Washington State.

This memo presents three PMP time sequences that will initially be used for the PMF study. Of the three, the time sequence that maximizes runoff volume and peak runoff will be determined as the critical time sequence. During the sensitivity analysis, variations on these three time sequences will be considered to ensure that the most critical one has been included in the analysis.

HMR 57 Guidance

HMR 57 presents a method, which is taken directly from HMR 43 (NWS 1966), for developing the temporal distributions for general storms. The methodology is based on previous examinations of extreme storm sequences that were used to identify characteristic groupings of precipitation increments. The methodology as described in HMR 57 will result in numerous possible PMP time sequences for a given storm duration. The methodology is described as a "guideline that the user may follow in developing the most critical sequence for the specific application" (NWS 1994). Using a 72-hour duration general storm event as an example, the steps involved in deriving the temporal distribution are summarized as follows:

1. Using the depth-duration curve, read off the depth estimates at 6-hour intervals, and then compute incremental depths for each 6-hour increment (12 total increments).
2. Rank the 6-hour increments from highest to lowest.
3. Group the four largest 6-hour increments together, the middle four together, and the lowest four together. This will result in three 24-hour groupings.
4. Within each 24-hour group, arrange the four increments such that the second largest is next to the largest, the third largest is adjacent to the first two, and the fourth largest is located at either end.

5. Arrange the three 24-hour groups so that the second highest 24-hour group is adjacent to the first highest, and the third highest is at either end.

Numerous possible temporal distributions are possible using the methodology outlined in HMR 57, and according to the authors of HMR 57, “it is left to the user to identify which sequence will provide the temporal distribution most critical to the specific drainage” (NWS 1994). Figure 6 is reprinted from HMR 57, illustrating five of the possible combinations. It should be noted that HMR 57 states on page 200 that “(i)n most 72-hour storms, the evidence indicates that the highest 24-hour group does not occur in the first 24 hours of the sequence” (NWS 1994).

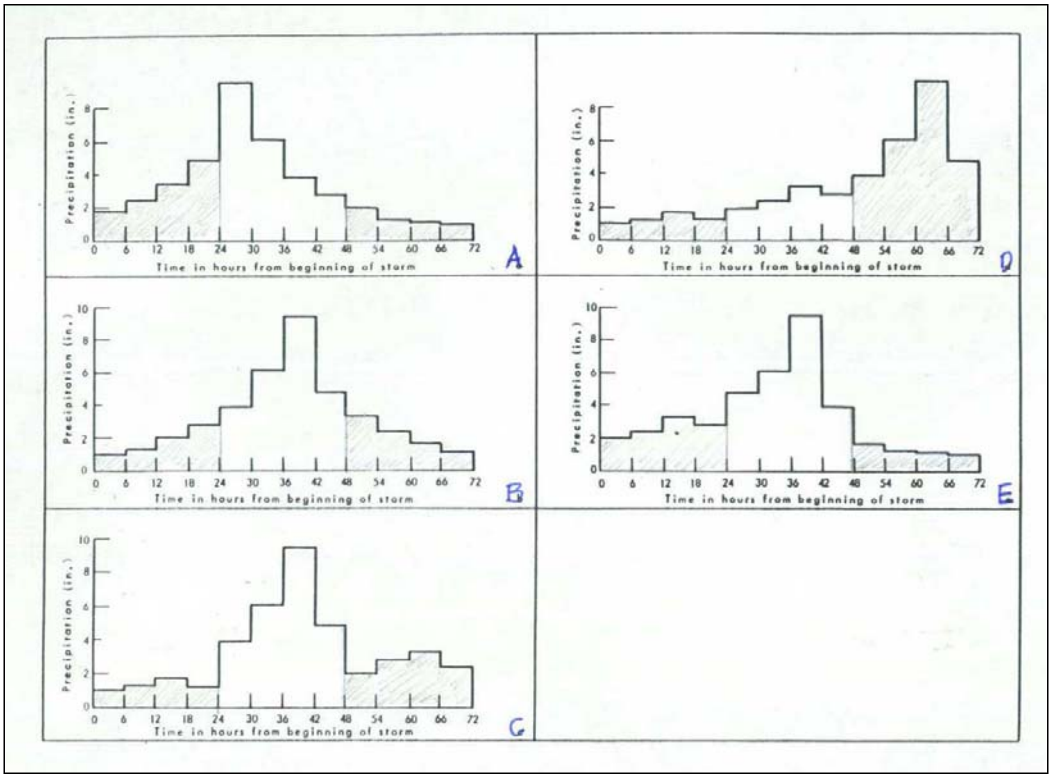


Figure 6. Sample PMP Time Sequences (reprinted from HMR 57)

FERC Guidance

Chapter VIII of the Engineering Guidelines for the Evaluation of Hydropower Projects (FERC 2001) also provides some guidance for developing temporal distribution of the PMP. While FERC (2001) states that reference should be made to the appropriate HMR study, the FERC guidelines provide the following recommendations for determining the temporal distribution of the general storm PMP:

1. Place the peak 6-hour period of rainfall between the half and two-thirds point of the general storm duration. For the 72-hour duration general storm, this would result in the peak of the storm occurring between 36 and 48 hours of elapsed time.
2. The remaining 6-hour increments should be arranged in alternating descending order on each side of the peak 6-hour increment, with the second highest 6-hour increment placed in the time period preceding the peak 6-hour increment.

3. Hourly increments within the 6-hour increments should be obtained from the depth-duration curve and distributed so as to provide a smooth temporal distribution.

Application of this methodology would result in a temporal distribution very similar to that which is shown in Cell B of Figure 6.

Schaefer (1989)

The third resource that was considered was a study conducted by the Washington State Department of Ecology (Schaefer 1989), which included a detailed examination of extreme precipitation events that occurred in the State of Washington. Portions of the findings from the study were included in HMR 57.

Among other things, Schaefer (1989) investigated the temporal distributions of extreme storms by examining the general arrangement of the incremental precipitation amounts that comprised the event. The study considered storms of three different independent durations (2-, 6-, and 24-hour) that occurred within five different climatic zones in the state. The products of the study included, but were not limited to, probabilistic information for specific temporal characteristics of extreme storms and a methodology that could be used to develop time sequences for synthetic storms for watershed modeling. A frequency based characterization was developed for the following attributes of extreme storms:

- Time of occurrence of the high intensity segment within the storm event;
- Ordering, or sequencing, of incremental precipitation amounts immediately surrounding the high intensity segment;
- Ordering, or sequencing, of the incremental precipitation amounts that comprise the independent duration of the storm event;
- For longer duration events, the ordering, or sequencing, of the trisector segments that together create the storm macro pattern.

The information and analysis presented in the study allows for a frequency based methodology that can be used to develop temporal distributions of synthetic storm events, such as the PMP, and is more detailed than that presented in either the HMR 57 or the FERC guidelines. The methodology essentially “builds” the sequence from the “inside out”, starting first with determining the time of occurrence of the high intensity segment. Once this timing is identified, then the second two highest increments are ordered around that high intensity segment. Then larger groupings of increments are ordered within the span of the independent duration, and finally, the increments are fit into the framework of the larger scale storm macro pattern. The methodology for sequencing incremental precipitation segments as per Schaefer (1989) is described below, using the 72-hour general storm as an example. As a side note, the Baker River basin is located within Climate Region 4.

1. ***Determine the incremental precipitation amounts*** – This is accomplished by reading off the ordinate values from the pertinent depth-duration curve. For this example the total basin 72-hour November-February general storm will be used (Figure 2), which has a 72-hour precipitation total of 31.6 inches.

2. ***Identify the time of occurrence of the high intensity segment*** **–** Schaefer (1989) related the time of occurrence of the high intensity segment to an exceedance probability (EP) based on a Beta distribution of data from a sample population of extreme storm events. For 24-hour independent storms in Climate Region 4, the study found that the time of occurrence for the high intensity segment associated with a 50 percent EP (or median value) was 33 hours of elapsed time. In order to identify the time of occurrence of the high intensity segment, the first step is to select the EP associated with this temporal characteristic. A selected EP less than 50% would place the high intensity segment beyond 33 hours of elapsed time, and a selected EP greater than 50% would place the high intensity segment somewhere before 33 hours of elapsed time. As previously mentioned, storms with the high intensity segment near the end of the storm generally produce larger flood peaks. Therefore, the choice of EP is used to create temporal distributions that are either conservative (exceedance probability less than 50%) or typical (exceedance probability equal to 50%). For the purposes of this example, it was assumed that the PMP event would have a high intensity time of occurrence typical of the storms that were analyzed in the study (50% exceedance probability), which is equal to 33.3 hours of elapsed time in the total storm duration.
3. ***Select a sequence for the three highest intensity segments*** **–** In this example for the 72 hour duration storm, the three highest intensity segments are 1-hour duration segments. In Climatic Region 4, a vast majority (65 percent) of the storms analyzed exhibited either a 2-1-3 or a 3-1-2 sequencing, and 22 percent of the storms had either a 2-3-1 or a 3-2-1 sequencing. As discussed previously, a more conservative sequence would place the highest intensity segment at the end of the sequence, and based on the findings of the study, a more typical sequence would include the high intensity segment in the middle. For the purposes of this example, assume the more conservative 3-2-1 sequence for ordering the three highest 1-hour precipitation intervals.
4. ***Select a sequence for the four 6-hour segments that comprise the 24-hour independent duration*** **–** The most commonly occurring sequences of the 6-hour precipitation intervals within storms occurring in Climatic Region 4 are 4-3-1-2, 4-2-1-3, and 4-1-2-3. For the purposes of this example, select the 4-2-1-3 sequence.
5. ***Select a macro storm pattern*** **–** The macro storm pattern represents the framework of the entire duration of the storm event, which for this example is 72 hours. Typically, macro patterns are subdivided into trisectors of three equal duration intervals. This is consistent with the methodology outlined in HMR 57, where the precipitation intervals are grouped and ordered into three 24-hour trisectors (see Figure 6). The selected macro pattern should be consistent with the timing and sequencing selections made in the previous steps. For this example the macro storm pattern 2-1-3 is chosen. This pattern is similar to those of Cell A or E in Figure 6, where the second highest 24-hour group is at the front of the storm, with the highest 24-hour group falling in the middle of the storm.

The results of applying the methodology outlined in Schaefer (1989) to the 72-hour duration November – February general storm PMP for the entire basin are summarized in Figures 7, 8, and 9. As seen in Figure 7, the steepest portion of the mass curve represents the occurrence of the high intensity segment, which for this example, occurred between hour 33 and hour 34. The time sequence shown in Figure 8 is based on the 6-hour intervals only, and does not show the more detailed distribution of the hourly segments. Figure 9 compares the sequencing of the 6-hour intervals using guidance provided by FERC (FERC 2001) against the sequencing of the 6-hour intervals using the methodology presented in Schaefer (1989).

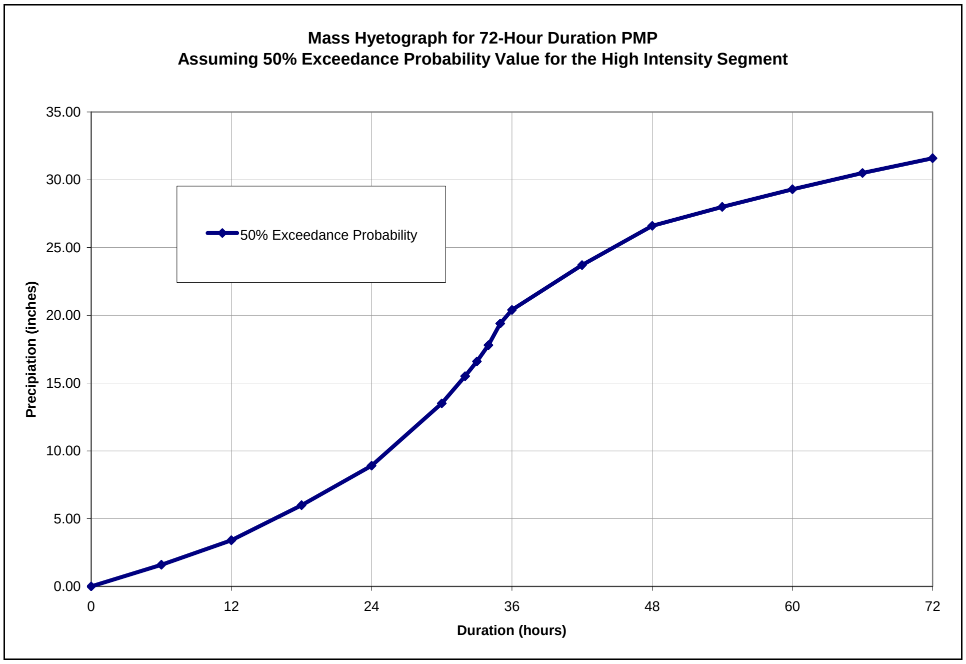


Figure 7. Mass Hyetograph for 72-Hour General Storm Example

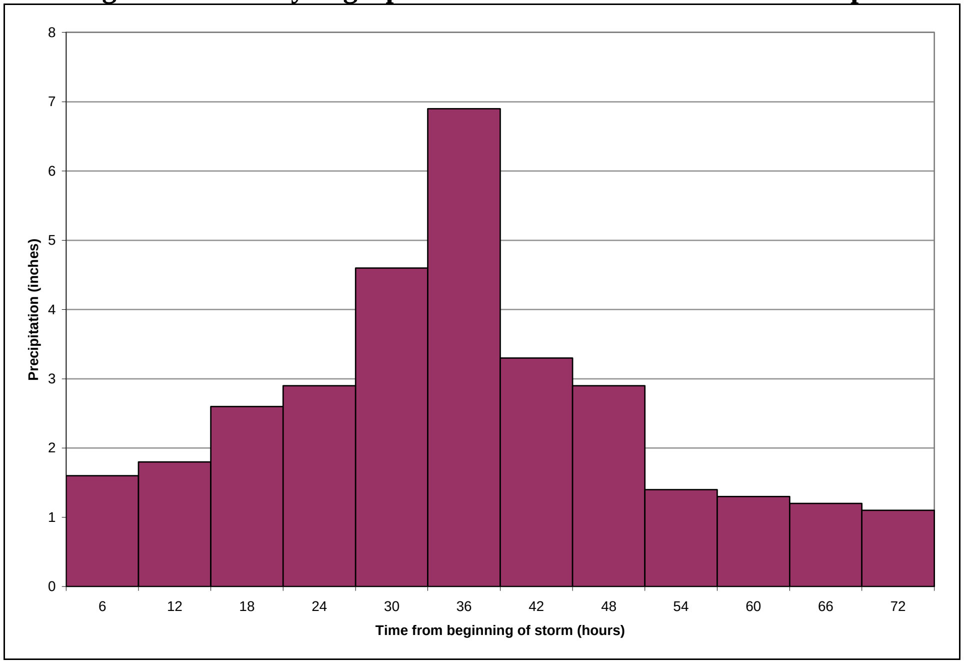


Figure 8. PMP Time Sequence for 72-Hour General Storm Example using Schaefer (1989)

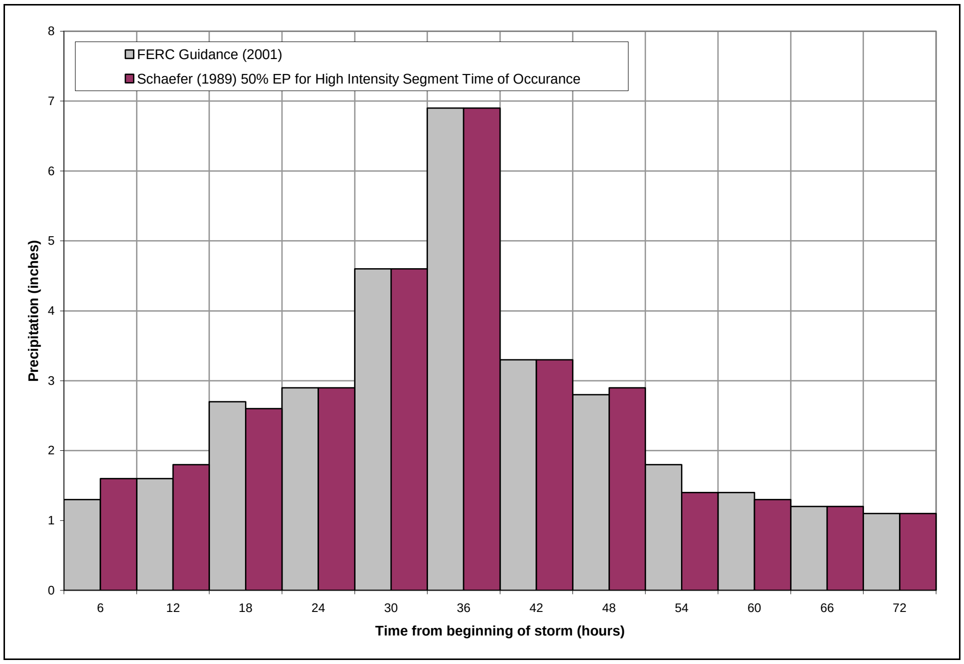


Figure 9. PMP Time Sequence for 72-Hr General Storm Example (FERC Guidance vs. Schaefer 1989)

Recommendations

It is recommended that the frequency based methodology presented in Schaefer (1989) be used to develop the candidate time sequences for the general storm PMP. As seen in Figure 9, if a 50% EP is assumed for the time of occurrence of the high intensity segment, the resulting time sequence is very similar to that which would be developed if the FERC guidance is used. The added benefit of using the methodology in Schafer (1989) is that other temporal distributions can be developed based on characteristics of observed storms in the region. This method will therefore result in consideration of several temporal distributions in the analysis, much as HMR 57 proposes, but the basis of their development will be from storm characteristics of observed storms in the region.

A total of three storm temporal distributions will be included in the analysis and each will be evaluated to determine which produces the critical PMF hydrograph for the project. Each is developed from the methodology in Schaefer (1989) with the primary difference being the time of occurrence of the high intensity segment. Time of occurrence associated with the 50% EP (33 hrs), the 20% EP (46 hrs) and the 5% EP (58 hrs) define the three distributions. As previously mentioned the storm distribution based on the 50% EP for the high intensity segment is similar to the FERC derived distribution, while the other two represent back-loaded storm distributions.

The only other temporal distribution that may need to be included in a sensitivity analysis is a front-loaded distribution where the peak rainfall occurs early in the storm. This distribution would have the potential to produce a runoff hydrograph where peak snowmelt coincides with the peak rainfall intensity. This front loaded distribution only has the potential to be a critical one if most of the snowmelt occurred prior to the peak intensities for the more back-loaded distributions.

The mass hyetographs of the three distributions that will initially be considered in the PMF analysis are shown in Figure 10 and the associated time sequences are shown in Figures 11 through 13. These specific distributions are based on the 72-hour duration general storm that is centered over the basin for the November – February seasonal condition. The development of the 72-hour general storm patterns for all other seasons and storm centerings will be based on these patterns.

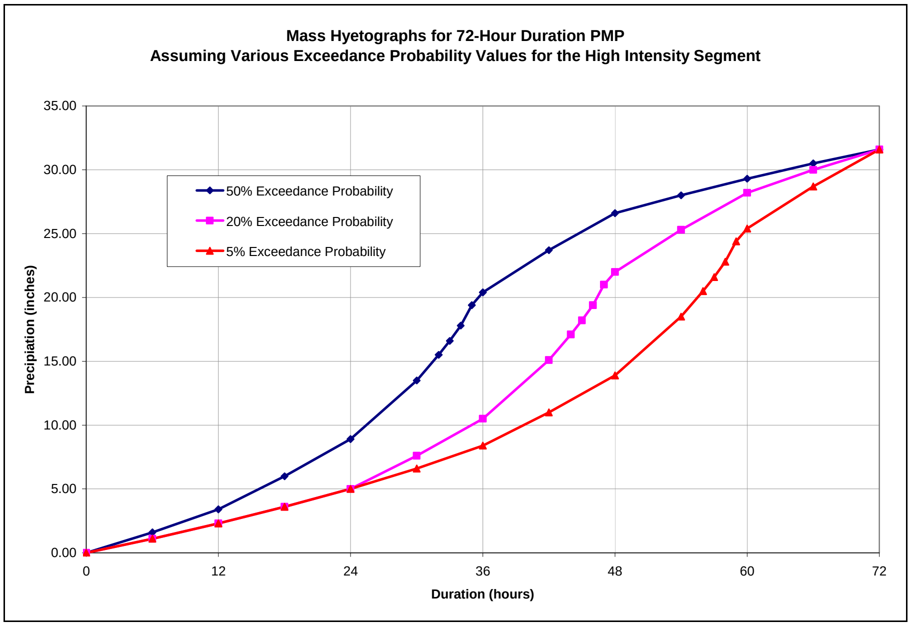


Figure 10. Mass Hyetographs for 72-Hour General Storm

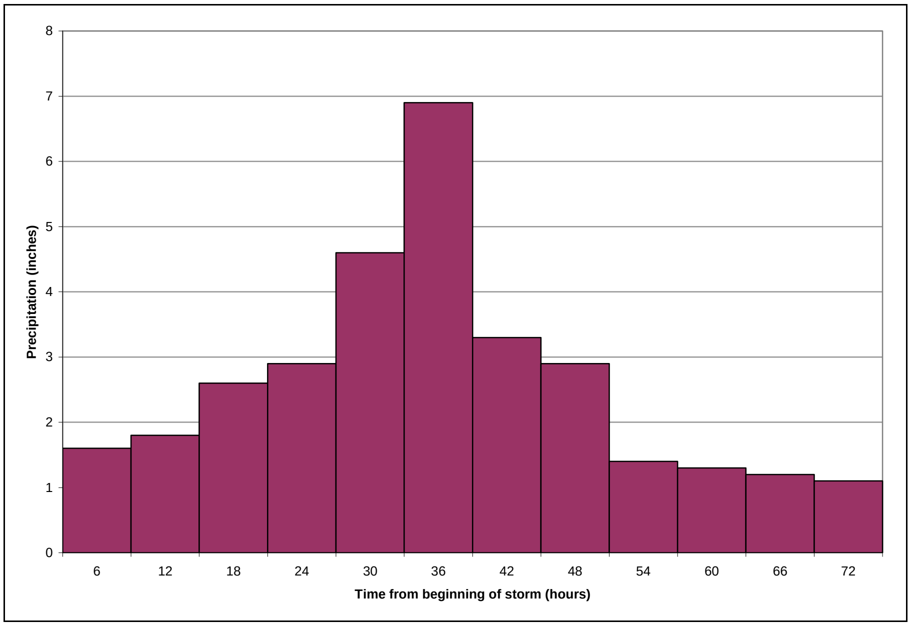


Figure 11. PMP Time Sequence – 50% EP for High Intensity Segment Time of Occurrence

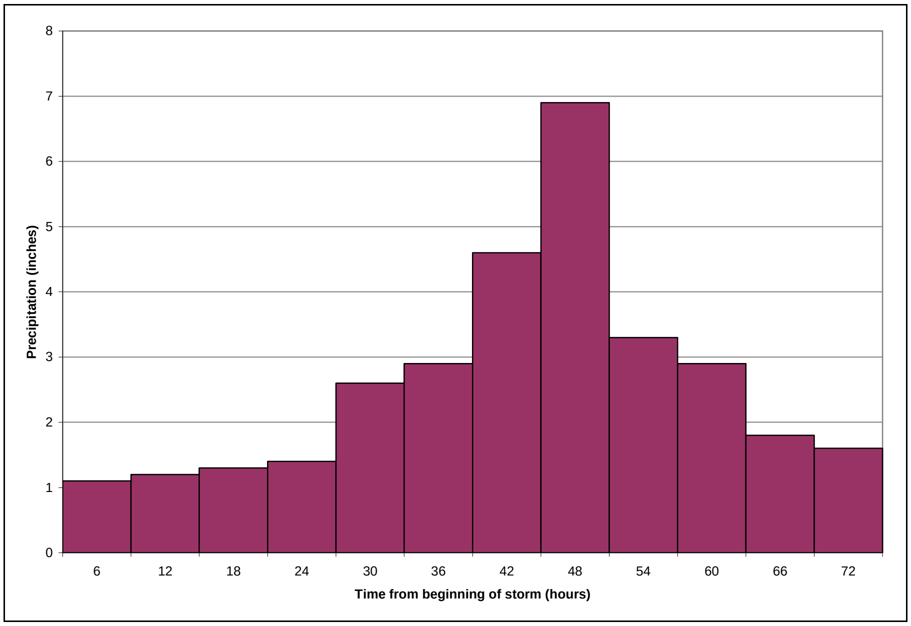


Figure 12. PMP Time Sequence – 20% EP for High Intensity Segment Time of Occurrence

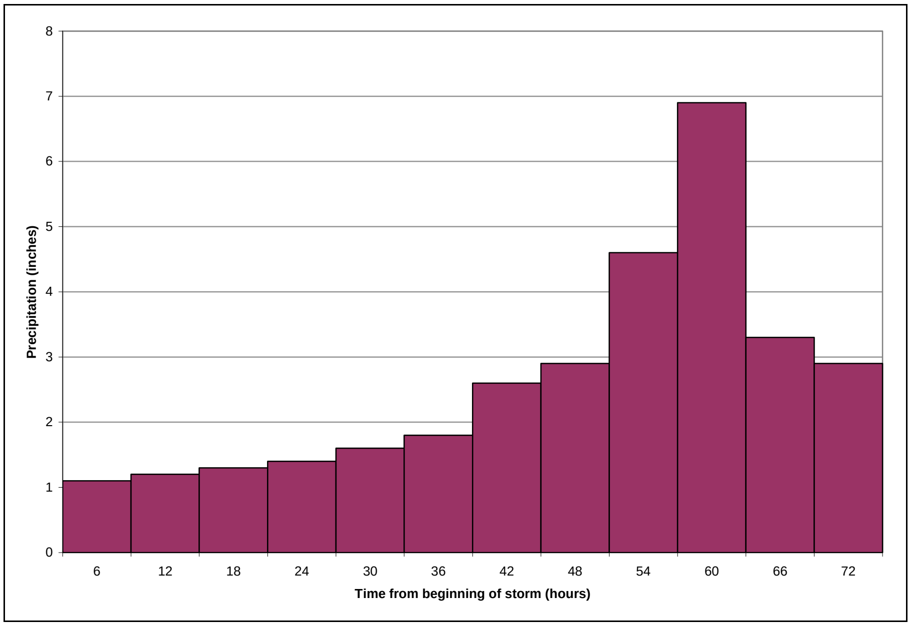


Figure 13. PMP Time Sequence – 5% EP for High Intensity Segment Time of Occurrence

Local Storm Temporal Distribution

Research conducted by Schaefer (1989) indicate that Pacific Northwest local storms primarily draw on a limited amount of moisture, which has difficulty penetrating much of the region due to terrain blockage. Lacking a constant source of moisture, these local storms produce their heaviest rainfall within the first hour.

Therefore, the temporal distribution of the local storm is determined by obtaining the ordinate values from the local storm depth-duration curve in Figure 5 and arranging the ordinates in a front loaded sequence, with the highest intensity 15-minute segment occurring within the first hour. The 1-hour segments are arranged in a descending order. For example, following this recommended methodology, the temporal distribution of the 6-hour local storm that is centered over the Lower Baker portion of the watershed is indicated in Table 6.

Table 6. Temporal Distribution of 6-Hour Local Storm PMP

Time (hours)	Incremental Precipitation Amount (inches)	Mass Ordinate Value (inches)
0.00	0.00	0.00
0.25	0.69	0.69
0.50	0.76	1.45
0.75	1.05	2.50
1.00	0.10	2.60
2.00	0.15	2.75
3.00	0.10	2.85
4.00	0.10	2.95
5.00	0.10	3.05
6.00	0.06	3.11

REFERENCES

Applied Weather Associates. 2006a. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 8 – Reconnaissance Level PMP Study and Storm Maximizations – Revision 1.* Technical Memorandum prepared for Puget Sound Energy.

Applied Weather Associates. 2006b. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 9 – October 2003 Storm Analysis and Supplementary Storm Analyses for Calibration Events – Revision 1.* Technical Memorandum prepared for Puget Sound Energy.

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

Miller JF, Frederick RH, Tracey RS. 1973. NOAA Atlas 2, Precipitation-Frequency Atlas of the Western United States, Volume IX – Washington. U.S. Department of Commerce, NOAA, National Weather Service, Washington DC.

National Weather Service (NWS). 1966. *Probable Maximum Precipitation for the Pacific Northwest. Hydrometeorological Report No. 43.* U.S. Department of Commerce - National Oceanic and Atmospheric Administration, U.S. Weather Bureau.

National Weather Service (NWS). 1994. *Probable Maximum Precipitation – Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages. Hydrometeorological Report No. 57.* U.S. Department of Commerce - National Oceanic and Atmospheric Administration, U.S Department of Interior – Bureau of Reclamation, U.S. Department of Army – Corps of Engineers.

Schaefer MG. 1989. *Characteristics of Extreme Precipitation Events in Washington State*. Washington State Department of Ecology, Water Resources Program, 89-51.

Schaefer MG, Barker BL, Taylor GH, Wallis JR. 2006. *Regional Precipitation-Frequency Analysis and Spatial Mapping for 24-Hour and 2-Hour Durations in Eastern Washington. Prepared for Washington State Department of Transportation (WSDOT).*

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 7

MODEL CALIBRATION AND VERIFICATION

Tetra Tech Inc.
August 25, 2005
Revised March 15, 2006
Revised June 20, 2006

(FINAL)

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1 INTRODUCTION

This memo summarizes the development, calibration and verification of the watershed model for the Baker River Project Part 12 Probable Maximum Precipitation/Probable Maximum Flood (PMP/PMF) Study. The purpose of the effort presented in this memo was to determine appropriate values for parameters describing the hydrologic response of the Baker Rive watershed. General categories of parameters included those describing soil infiltration and losses to groundwater, the timing and shape of the interflow hydrograph, the timing and shape of the surface runoff hydrograph, and snowmelt characteristics.

Five historical storm events were initially identified as potential calibration/verification events from a pool of extreme events that occurred since 1949. An evaluation and ranking methodology was used to rank the historical storms, which is documented in a separate memo (Tetra Tech 2005a). The top five events identified in Tetra Tech (2005a) were chosen for use in calibrating the Baker River watershed model. Table 1 lists these events in descending order of their ranking.

Table 1. Events Used for Model Calibration/Verification

Ranking	Event[a]	Start Date[b]	End Date[b]	Number of Hours of Precipitation Event
1	NOV 90(1)	11/8/90	11/14/90	144
2	NOV 90(2)	11/21/90	11/26/90	120
3	OCT 03	10/14/03	10/19/03	120
4	NOV 89	11/8/89	11/12/89	96
5	NOV 95(2)	11/26/95	12/1/95	120

Notes:

a. The value in parentheses is used to differentiate between two events that occurred in the same month.

b. Start and end time for all events was midnight of the indicated date

The calibration and verification effort are documented in three primary sections. Section 2 describes the modeling approach including the models applied, the overall watershed delineation, the use of a distributed characterization of watershed parameters, and key procedures used to represent the hydrologic processes. Section 3 provides the estimation of the watershed model input parameters. This includes basic data such as precipitation, air temperature and snowpack conditions, as well as initial estimations of the parameters to be calibrated. The actual calibration procedure and results are presented in Section 4.

2 MODELING APPROACH

This section provides background information regarding the hydrologic simulation models that were used for the study, and also provides the basis of the watershed subdivision that was necessary to support the distributed methodology used to model the rainfall-runoff process.

2.1 Model Background

The original project work plan identified the USACE HEC-1 model (USACE 1998) as the hydrologic model for the Baker River project (Tetra Tech 2005b). Several recommendations by the Board of Consultants (BOC) resulted in subsequent modifications to the original project work plan. The project work plan was modified so as to use the **S**tochastic **E**vent **F**lood **M**odel (SEFM) (MGS 2004) in conjunction with the HEC-1 model. The SEFM model was included primarily due to its capabilities for simulating snowmelt and snow accumulation using the United States Bureau of Reclamation Snow Compaction Procedure (USBR 1966) and for its interflow modeling capabilities. These are capabilities that are not included in the HEC-1 software.

SEFM was developed by MGS Engineering for the Bureau of Reclamation as a deterministic flood computation model that allows the input parameters to be treated as variables instead of fixed values. The model can be run in a purely stochastic mode, whereby all hydrometeorological parameters are allowed to vary based on probabilistic input, or in a completely deterministic mode with all parameters fixed (MGS 2004). For the Baker River project, the SEFM model was used in the deterministic flood mode.

The SEFM model simulates snow accumulation and snowmelt, and determines excess precipitation (including drainage from the snowpack) at each time ordinate after accounting for losses due to infiltration. Infiltrated water is modeled as interflow using a linear reservoir routing procedure. For each subbasin, SEFM output therefore includes the time series of precipitation excess, the unit hydrograph ordinates, and the interflow hydrograph. Output from SEFM is formatted as standard HEC-1 input, thereby allowing the use of the HEC-1 program to transform the precipitation excess to a surface runoff hydrograph using unit hydrograph techniques. Hydrologic routing is also performed within HEC-1. The interflow hydrograph is combined with the surface runoff hydrograph and the base flow within HEC-1, to produce the total runoff hydrograph.

In addition to the HEC-1 and SEFM hydrologic models, two other modeling software were used for the Baker River PMP/PMF study. The **S**torm **P**recipitation **A**nalysis **S**ystem (SPAS) (Tomlinson et al 2004) was used for distributing point rainfall measurements to a regularly spaced gridded field for each of the flood events considered for the hydrologic model calibration. This gridded precipitation field was used to develop precipitation time series for each of the model subbasins, which were subsequently input into the SEFM model. The **H**ydrocomp **F**orecast and **A**nalysis **M**odeling (HFAM) software was used to provide supplementary information regarding the snowpack conditions for the calibration flood events, which were all early season events. Figure 1 is a flow chart that illustrates the relationship of each of the models used in the process of developing runoff hydrographs for the Baker River watershed.

Figure 1 also shows the relationship of some of the hydrometeorological elements that supported the modeling effort. Each of these elements is discussed in more detail in later sections of this memo; however, some basic information is presented here. Gridded mean annual precipitation mapping published by the Oregon Climate Service (OCS 2005), using the **P**arameter-elevations **R**egressions on **I**ndependent **S**lopes **M**odel (PRISM) was used as a base map in the SPAS model for the distribution of point rainfall data. Hourly NexRad maps were used to provide additional timing information for regions in the watershed that lacked adequate hourly rainfall data. Data collected from the nine snow course stations within the watershed and from the several SNOTEL stations immediately adjacent to the watershed provided the necessary data to develop air temperature time series for each of the calibration storms and to determine antecedent snowpack conditions.

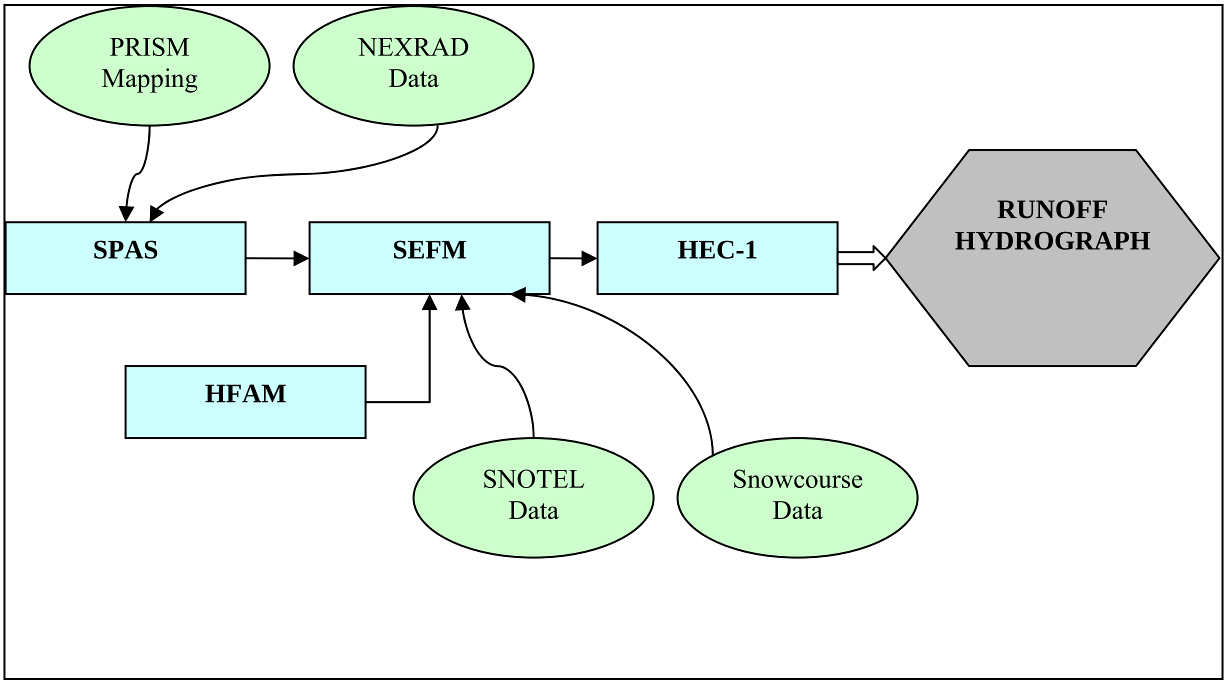


Figure 1. Flow Diagram of Models Used in Study

2.2 Model Calibration Method

Calibration of the watershed model was conducted using concepts from a procedure based on generalized likelihood measures (Beven et al 1992). The procedure is referred to as **G**eneralized **L**ikelihood **U**ncertainty **E**stimation (GLUE) and is based on the premise that "any model/parameter set combination that predicts the variable or variables of interest must be considered equally likely as a simulator of the system". The GLUE procedure differs from most calibration procedures used in hydrology, in which some global optimum parameter set is sought and any assessment of parameter uncertainty is made relative to that global optimum. In following such an approach, the analyst may exclude sets of parameters that give a qualitatively more correct simulation of the response mechanisms in the watershed but which has parameter values in a completely different part of the parameter space (Beven et al 1992).

The GLUE procedure seeks to find that combination of parameter values that can replicate the observed hydrographs and in the process considers the equivalence or near equivalence of different sets of parameters in reproducing the observed hydrographs. In application, the approach was to use the SEFM model to assemble multi-thousand parameter sets based on sampling of the individual parameters within a realistic, yet wide sampling range. The watershed model was then executed using each of the multi-thousand parameter sets. Objective functions were computed from the results and were used to incrementally narrow the sampling ranges of the individual parameters when appropriate, by identifying values of the parameters that resulted in poor fits to the observed hydrographs. Once the sampling ranges were sufficiently narrowed, multi-thousand runs were again executed and those parameter sets that produced good fits to the observed hydrographs were identified as "behavioral". The behavioral parameter sets then formed the basis for identifying the calibrated parameter set.

Because the calibration process was based on conducting a large number of model runs with different sets of parameter values, chosen randomly from specific distributions, the initial estimates of the calibration parameters are described in this memo as sampling ranges and not as distinct values.

2.3 Watershed and Subbasin Delineation

Delineation of the 299 square mile (mi^2) Baker River watershed upstream of Lower Baker Dam was performed to support the hydrologic modeling effort. The overall watershed and the individual subbasin delineations were based on topography derived from USGS 10-Meter Digital Elevation Models (DEMs) (USGS 2005). The DEMs have the following source data:

- Source: United States Geologic Survey (USGS)
- Level of accuracy:
  - Horizontal: 10-meter Grids
  - Vertical: 1-meter (NGVD 29 – Meters)
- Coordinate System: Global Coordinate System (NAD27)
- Projection: Universal Transverse Mercator, Zone 10 (NAD27)

The DEMs were combined to form a complete model for the Baker River watershed. Additionally the complete DEM model was translated into NGVD 29 (feet) using raster algebra. Contours were developed using ArcGIS 9.0 in combination with Spatial Analyst and 3d Analyst extensions. Contour intervals were defined at 10-foot increments. To aid in the delineation a hill shade model was developed to highlight ridgelines and valleys. It was decided not to use an automated delineation routine such as ArcHydro because of the irregular subbasin delineations, and instead subbasins were manually delineated using the digital elevation database. The subbasin delineations are shown in Figure 2. The subbasins for two of the tributaries (Sulphur Creek and Park Creek) were further subdivided to allow for the potential to model those portions of these tributaries that were gaged by the USGS in the 1980's and 1990's.

When back checking the gaged drainage areas published by the USGS versus the drainage areas delineated using the current DEM, there was a discrepancy found at the Sulphur Creek Gage (USGS No. 12191800). The USGS published drainage area was 8.4 mi^2, as compared to the 6.9 mi^2 that was determined through the delineation. The USGS delineation was likely developed in 1963 when the stream gage was installed. The stream network shapefile taken from the USGS was compared with the topography and the 1-meter digital ortho-rectified photographs. This comparison still supported the 6.9 mi^2 delineation. It was therefore hypothesized that either the original USGS delineation had included a portion of the Sulphur Creek drainage that is now tributary to the Rocky Creek drainage, or that the mapping which was the basis for the USGS delineation was not accurate. Very steep, unstable slopes on the flank of Mt Baker can contribute to debris slides and stream sedimentation, resulting in channel switching. For the purposes of this study, the gaged portion of the Sulphur Creek drainage was set to the 6.9 mi^2 delineation determined from the DEM.

The total Baker River watershed area was determined to be 298.7 mi^2. The watershed was then subdivided into two tributary areas designated as the Upper Baker tributary area and the Lower Baker tributary area. The Upper Baker designation represents the total area upstream of Upper Baker Dam and comprises 214.9 mi^2 of the total basin. The Lower Baker designation represents the area locally tributary to Lower Baker and comprises 83.8 mi^2 of the total basin. The areas of each of the subbasins comprising these two tributary areas are presented in Table 2.

Table 2. Baker River Subbasin Summary

Subbasin ID	Subbasin Name	Subbasin Area Centroid[a]		Area	
		Easting	Northing	Sq Miles	Acres
LB 1	Nearshore - Lake Shannon	1428069	580342	21.2	13,560
LB 2	Bear Creek	1412832	593341	13.3	8,525
LB 3	Rocky Creek	1408662	615345	13.0	8,335
LB 4	Sulphur Creek - Gaged	1406883	625477	6.9	4,410
LB 5	Sulphur Creek - Ungaged	1426622	608746	3.2	2,052
LB 6	Thunder Creek	1450519	588710	22.8	14,604
LB 7	Lake Shannon	1425093	580470	3.4	2,193
UB 1	Sandy Creek	1418374	624181	13.5	8,626
UB 2	Boulder Creek	1421915	633343	15.4	9,854
UB 3	Park Creek - Gaged	1420548	646297	9.6	6,146
UB 4	Park Creek - Ungaged	1435223	633676	2.5	1,592
UB 5	Swift Creek - Gaged	1435774	657405	36.5	23,377
UB 6	Nearshore - Baker Lake	1449561	622884	26.6	16,993
UB 7	Baker River	1484710	654236	89.0	56,964
UB 8	Noisy Creek	1463683	614942	14.1	9,005
UB 9	Baker Lake	1444787	623628	7.7	4,916

Note:
a. Centroid coordinates are in terms of Washington State Plane Coordinate System, North (NAD83)

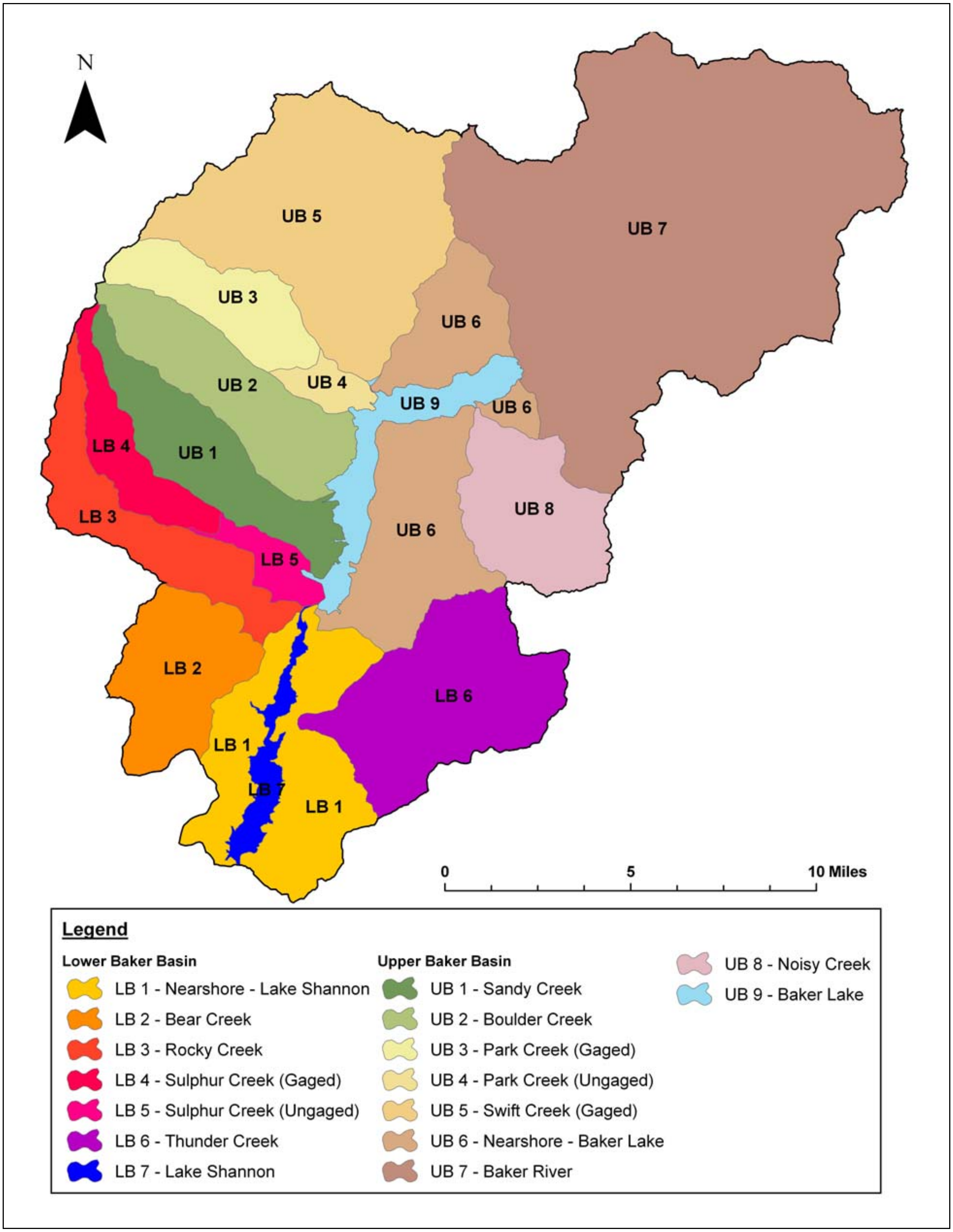


Figure 2. Subbasin Delineation

2.4 Distributed Methodology

To properly account for the spatial variability of soil characteristics, antecedent precipitation, storm event precipitation, and snowpack conditions, a distributed approach was used in the hydrologic model. Use of a distributed model required that in addition to subdividing the watershed into subbasins, that the watershed also be subdivided into distinct elevation zones, mean annual precipitation zones, and soil zones. Once the basin was subdivided into these zones, ArcGIS was then used to intersect the polygons of each subdivision so as to create a mosaic of hydrologic runoff units (HRUs). As a result of this process, the Baker River basin was subdivided into 253 HRUs out of a possible combination of 640 HRUs. Each HRU represents a unique combination of soil zone, elevation zone and mean annual precipitation zone.

2.4.1 Elevation Zones

The Baker River watershed was subdivided into eight distinct elevation zones to allow for spatial allocation of the snowpack and to allow for more accurate computation of snowmelt and snow accumulation. For the snowmelt and snow accumulation computations, ground temperatures are lapsed to the median elevation of each elevation zone. Selection of the elevation zone increments was based on a plot of elevation versus cumulative area for the entire watershed using the USGS 10-meter gridded data set. The upper and lower boundaries of the elevation zone increments were identified at breaks in the plot so that the computed average elevation within the zone was approximately equal to the computed median elevation within the zone. Figure 3 graphically shows the elevation zones, and Table 3 summarizes statistics of the resulting eight elevation zones.

Table 3. Elevation Zones

Elevation Zone	Lower Bound (feet)	Upper Bound (feet)	Average Elevation (feet)	Computed Median Elevation (feet)	Adopted Median (feet)	Allocation within Watershed (%)
1	420	1200	810	845	800	16.3
2	1200	2200	1700	1710	1700	13.4
3	2200	3200	2700	2751	2700	16.7
4	3200	4200	3700	3710	3700	21.8
5	4200	5000	4600	4560	4600	14.7
6	5000	5800	5400	5340	5400	9.3
7	5800	6600	6200	6118	6200	5.2
8	6600	10800	8700	7363	7400	2.6

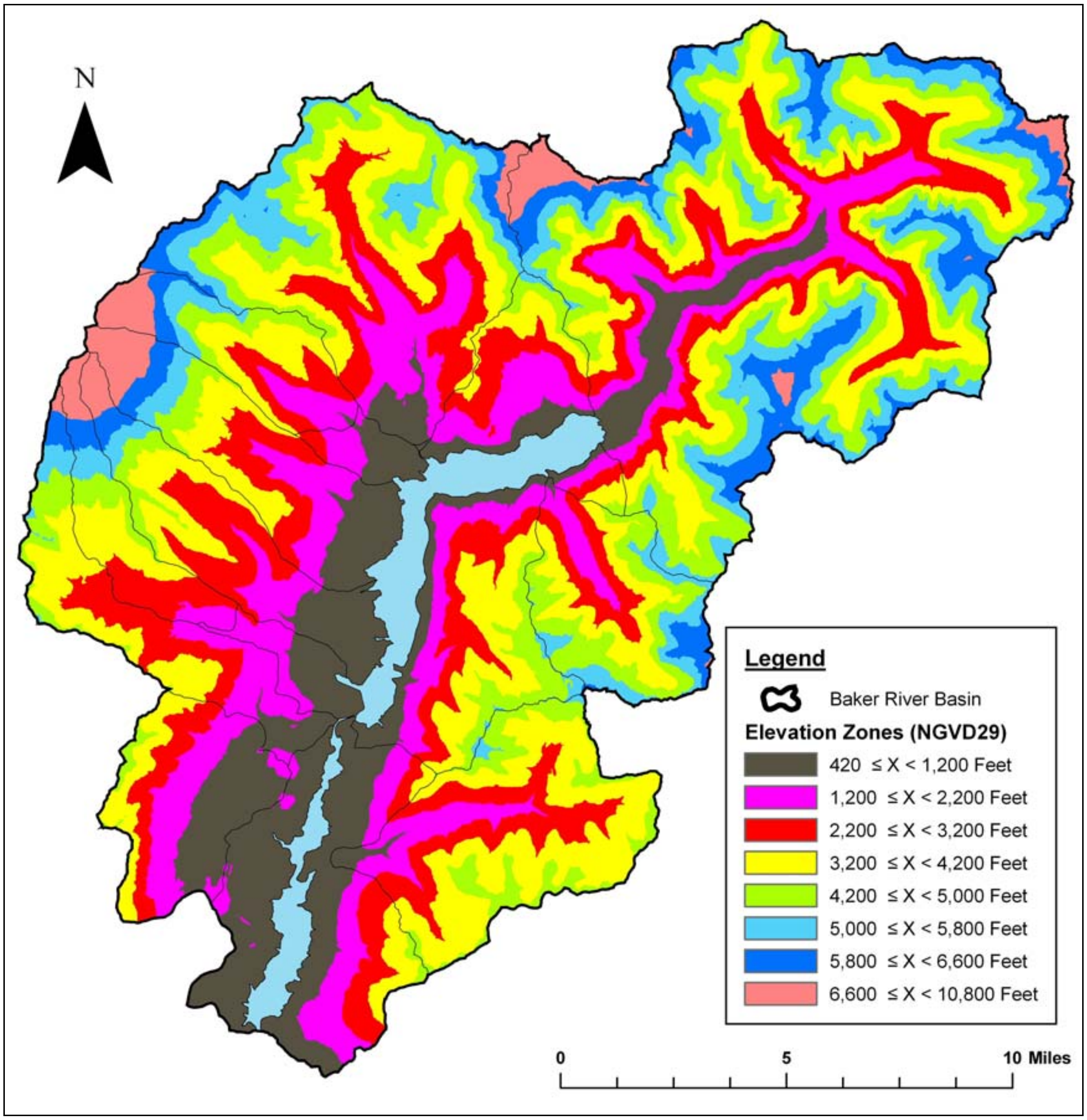


Figure 3. Elevation Zones

2.4.2 Mean Annual Precipitation Zones

The watershed was subdivided into eight zones of mean annual precipitation to allow for spatial allocation of the snowpack and to allow for more accurate computation of snowmelt and snow accumulation. For the determination of antecedent snowpack, it was assumed that antecedent snow water equivalent (SWE) varied linearly with mean annual precipitation. Therefore, watershed subdivision into zones of mean annual precipitation was essential in allowing for proper allocation of the antecedent snowpack.

The base map used for determination of the zones of mean annual precipitation was the 2005 version of the PRISM mapping of mean annual precipitation for the United States (OCS 2005). Documentation for the use of this base map in the watershed model is included in Tetra Tech (2005c). Several candidate mapping products were considered by comparing mean annual precipitation predicted by each mapping product against streamflow records in the watershed. The analysis verified that the OCS (2005) PRISM mapping product was the most consistent with the long term streamflow records in the watershed (Tetra Tech 2005c).

A slight adjustment was made to the mean annual precipitation base map before the mean annual precipitation zones were delineated. Comparison against streamflow records indicated that the 2005 PRISM mapping compared well with long term mean daily runoff records for the watershed as a whole, but slightly overpredicted precipitation in the southeast portion of the watershed (Thunder Creek and Anderson Creek subbasins) and slightly underpredicted precipitation in the northwest portion of the watershed (Swift Creek subbasin). Therefore, the gridded dataset was adjusted in these subbasins to match within 15% of the streamflow records (Tetra Tech 2005c). The adjustments were made while keeping intact the 129.65" mean annual precipitation for the watershed. A secondary benefit of making this adjustment was to allocate more precipitation to the Upper Baker tributary area and to reduce precipitation in the Lower Baker tributary area, so as to be more consistent with the long term runoff records, which indicated an Upper Baker to Lower Baker mean annual runoff ratio of 1.19 (Tetra Tech 2005c). By making the this adjustment, the Upper Baker to Lower Baker mean annual precipitation ratio was increased from 1.08 (unadjusted) to 1.12 (adjusted).

Delineation of the mean annual precipitation zones was based on a plot of mean annual precipitation versus cumulative surface area for the entire watershed, using a resampled version of the adjusted 2-km mean annual precipitation base mapping. The upper and lower boundaries of the mean annual precipitation zones were identified at breaks in the plot so that the computed average mean annual precipitation within the zone was approximately equal to the computed median mean annual precipitation within the zone. Figure 4 graphically shows the mean annual precipitation zones, and Table 4 presents a statistical summary of the eight zones of mean annual precipitation used in the distributed model.

Table 4. Mean Annual Precipitation Zones

Mean Annual Precipitation Zone	Lower Bound (inches)	Upper Bound (inches)	Average MAP (inches)	Computed Median MAP (inches)	Adopted Median (inches)	Allocation within Watershed (%)
1	55	75	66	67	67	1.5
2	75	95	86	86	86	3.7
3	95	105	101	102	102	5.6
4	105	116	111	112	112	16.0
5	116	128	123	122	122	28.3
6	128	151	140	140	140	28.3
7	151	164	158	156	156	10.5
8	164	238	202	188	188	6.2

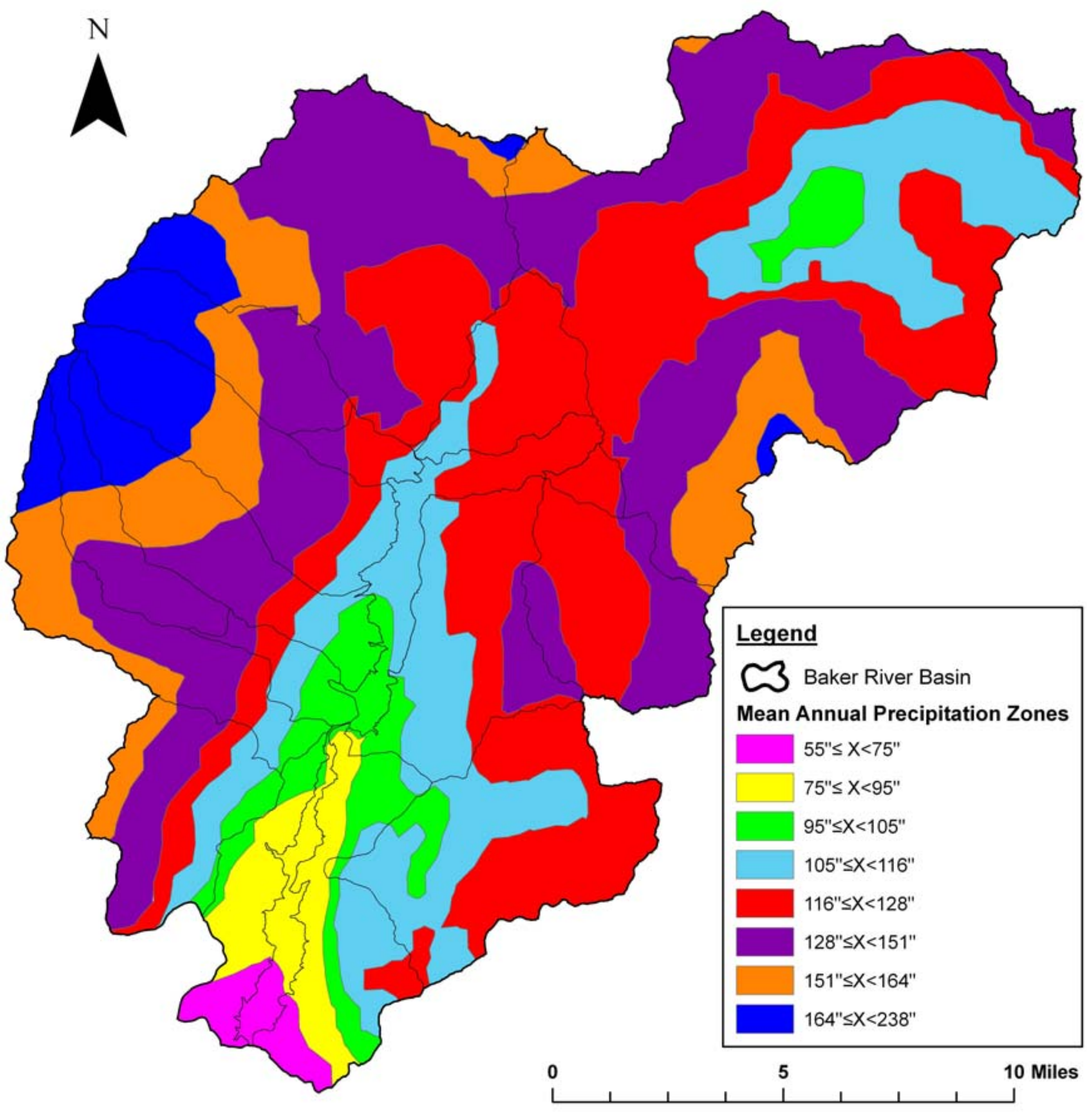


Figure 4. Mean Annual Precipitation Zones

2.4.3 Soil Zones

Delineation of the watershed into distinct soil zones was necessary to properly describe the spatial variability of the characteristics of the soil and the underlying bedrock parent material. Due to the wide variation of bedrock types, the history of glaciation, and the history of volcanic activity, soil distribution in the Baker River watershed is quite complex.

The Baker River watershed was originally delineated into ten soil zones as described in Tetra Tech (2005d). However, the original delineation was modified to address comments from the BOC (Mason et al 2005). The methodology that was used to address the BOC comments and to revise the original soil zone delineation included the following steps, presented in the order that each was implemented:

1. Define the coverage of glaciers. The primary resource used was spatial data provided by Frank Granshaw, a faculty member at Portland Community College. Frank Granshaw developed a spatial dataset of glacier coverage in the North Cascade National Park Complex as part of his doctoral thesis for Portland Statue University's Glacier Research Department (Granshaw 2001). Tetra Tech augmented this dataset with a one derived by the U.S. Geological Survey in cooperation with U.S. Environmental Protection Agency using the National Hydrography Dataset (**http://nhd.usgs.gov/**). The datasets were combined and then were verified against an aerial photo mosaic compiled from aerial photos taken between 1990 and 1998.
2. Define the coverage of rock outcrop and areas of very thin surface soils. The primary resource was the 1992 Nation Land Cover Dataset (NLCD), which was verified against an aerial photo mosaic compiled from aerial photos taken between 1990 and 1998.
3. Define the coverage of the reservoir areas.
4. Define the coverage of the geologically recent lava flow in Sulphur/Rocky Creek drainage. Geologically recent andesite-basalt volcanic deposits in the Sulphur/Rocky Creek drainage form a unique bedrock feature that has significant affect on the hydrologic response of these two drainages. The primary resource for the delineation of this feature was the USGS Geologic Map of the Mt Baker 30- by 60- minute quadrangle (Tabor et al 2003).
5. Subdivide the watershed based on bedrock characterization. Three classifications were used: low degree of fracturing, medium to high degree of fracturing, and geologically recent lava flows of andesite and basalt. The resources that were used included USFS (1970) and Tabor et al (2003).
6. Subdivide the watershed into soil categories based on the SCS hydrologic soil group classification system. The watershed was divided into four soil groups (A, B, C, and D). This soil group classification system subdivides soil mapping units into groups according to a soil's saturated infiltration capacity, which is a function of soil texture and soil depth. The resources that were used included the NRCS SSURGO database (NRCS 1994a) the NRCS STATSGO database (NRCS 1994b), and USFS (1970).
7. Further subdivide the soil categories to consider depth of the surface layer. The resources that were used included the NRCS SSURGO database (NRCS 1994a) the NRCS STATSGO database (NRCS 1994b), and USFS (1970).

The above steps were followed to create a variety of soil and geologic coverages that could then be used in an overlay analysis to define the soil zones. In total thirteen soil zones were identified within the boundaries of the Baker River watershed. These thirteen zones were subsequently simplified into ten zones, as summarized in Table 5 and graphically illustrated in Figure 5.

Soil Zone 1 represents the reservoir surfaces. Soil Zone 2 represents the glacial coverage, which was estimated to be approximately 15 square miles, roughly 5 percent of the watershed. Soil Zone 3 represents that portion of the watershed which is covered by rock outcrop with minimal soil coverage. Using the overlay analysis it was found that a large majority of rock outcrop was moderately to highly fractured igneous, sedimentary or metamorphic units. Soil Zones 4 through 9 represent soil coverages with a range of thicknesses, textures, and underlying bedrock parent material. The bedrock parent material was subcategorized as either minimally fractured or moderately to highly fractured igneous, sedimentary or metamorphic rock. Finally, Soil Zone 10 was reserved for the portion of the Sulphur/Rocky Creek drainages which are underlain by geologically recent andesite-basalt volcanic deposits. The rock comprising these deposits is fractured into blocky fracture systems and is quite porous (USFS 1970).

Table 5. Description of Soil Zones

Soil Zone ID	SCS Hydrologic Group Class	Soil Texture/Description	Median Depth of the Surface Layer (inches)	Bedrock Fracturing	Allocation within Watershed (%)
1	---	Open water	---	----	3.7 %
2	---	Glaciers	---	----	5.0 %
3	---	Bedrock outcropping with very shallow soil layer	6”	Moderately to highly fractured	14.5 %
4	A	Deep well drained soils. Very gravelly loams, loamy sands, and glacially deposited sands and gravels.	48”	Minimally fractured	4.1 %
5	B	Some gravelly silt loams in addition to finer textured sandy loams, silty loams, loamy sands and loams	18”	Moderate to highly fractured	21.1 %
6	B	Same as above	28”	Minimally fractured	11.2 %
7	B	Same as above	28”	Moderate to highly fractured	11.9 %
8	C	Predominantly silty loams	23”	Moderate to highly fractured	4.2 %
9	C/D	Poorly drained sandy clay loams, silty clays derived from glaciolacustrine deposits, and organic material	38”	Minimally fractured	21.4 %
10	-----	Soils overlying the Sulphur Creek basalt/andesite lava flow are primarily deep sandy loams	28”	Geologically recent basalt/andesite lava flows	2.8 %

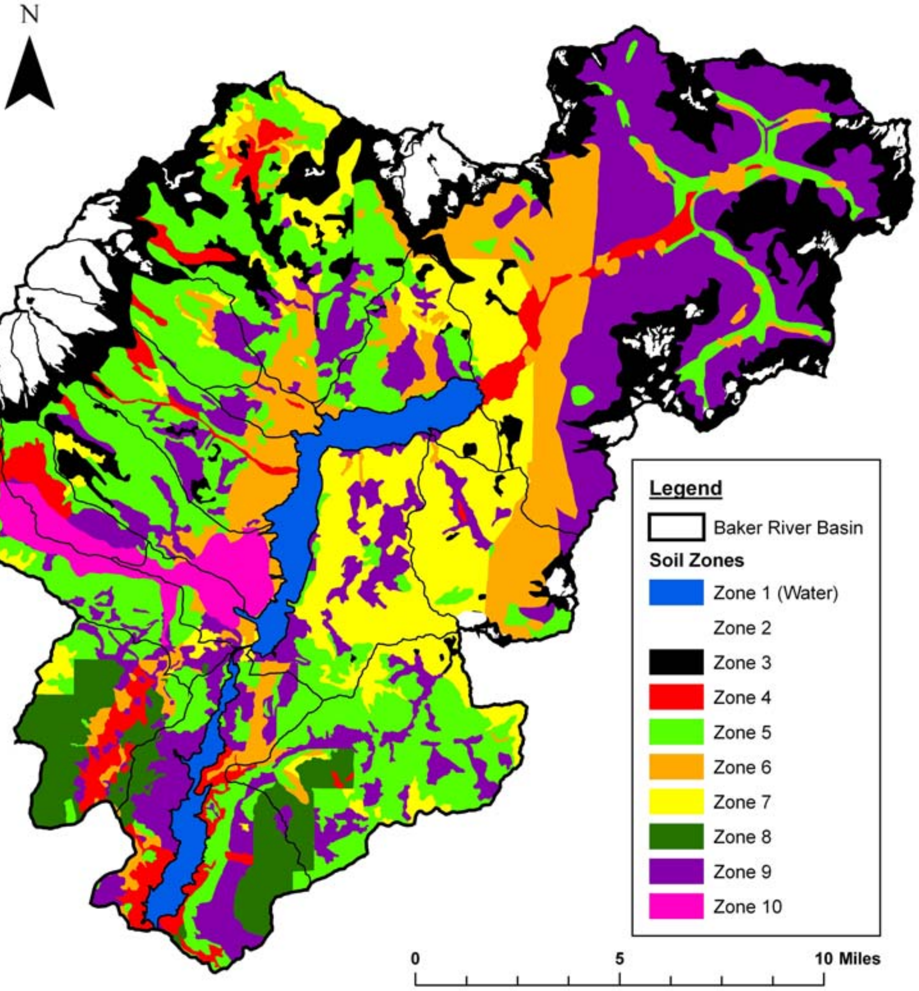


Figure 5. Soil Zones

2.4.4 Hydrologic Runoff Units

Using ArcGIS, the individual elevation zone, mean annual precipitation zone, and soil zone polygons were intersected to create a mosaic of irregular polygons known as Hydrologic Runoff Units (HRUs). Out of a possible combination of 640 HRUs, 253 HRUs were delineated within the Baker River watershed. The subbasin delineations were then intersected with the HRU delineations, and subbasin specific HRU area components were tabulated. Table 6 summarizes the percentage of each soil zone, elevation zone, and mean annual precipitation zone within the Upper Baker tributary area (214.8 sq mi), the Lower Baker tributary area (83.9 sq mi) and within the entire watershed (298.7 sq mi).

Table 6. Distribution of Elevation, Mean Annual Precipitation, and Soil Types

	Zone ID	Distribution within Upper Baker Tributary Area (%)	Distribution within Lower Baker Tributary Area (%)	Distribution within Total Watershed (%)
Elevation Zone	1	11.5	28.7	16.3
	2	12.0	17.0	13.4
	3	16.3	17.6	16.7
	4	20.9	24.0	21.8
	5	16.8	9.1	14.7
	6	12.3	1.6	9.3
	7	6.9	1.0	5.2
	8	3.3	1.0	2.6
Mean Annual Precipitation Zone	1	0.0	5.3	1.5
	2	0.1	12.9	3.7
	3	3.3	11.6	5.6
	4	14.6	19.7	16.0
	5	31.1	20.9	28.3
	6	33.2	15.8	28.3
	7	10.8	9.7	10.5
	8	7.0	4.1	6.2
Soil Type Zone	1	3.6	4.1	3.7
	2	6.2	1.8	5.0
	3	19.4	2.1	14.5
	4	2.7	7.9	4.1
	5	17.5	30.6	21.1
	6	13.8	4.8	11.2
	7	13.6	7.5	11.9
	8	0.0	15.0	4.2
	9	22.2	19.2	21.4
	10	1.1	7.1	2.8

2.5 Rainfall Runoff

As per guidelines presented in FERC (2001), the unit hydrograph method was used to transform precipitation excess to a surface runoff hydrograph. A synthetic unit hydrograph technique was used with parameters analogous to the Snyder unit hydrograph to describe the shape and timing of the synthetic unit hydrograph. Separate unit hydrographs were used for each of the delineated subbasins, including the subbasins that represented the reservoir surfaces. The unit duration of the unit hydrograph was 30-minutes. The effective rainfall for each unit duration was determined within the SEFM, after accounting for drainage from the snowpack, infiltration, and loss to groundwater. Output from the SEFM therefore included the effective rainfall time series and the unit hydrograph for each subbasin. The output was in HEC-1 format, thereby enabling the use of the HEC-1 model to transform the effective rainfall time series to surface runoff hydrographs.

2.6 Snowmelt and Snow Accumulation

Snowmelt was computed within the SEFM using a form of the Bureau of Reclamation's Snow Compaction methodology (USBR 1966). This methodology utilizes empirical energy budget snowmelt equations similar to those in HEC-1 (USACE 1998). However, the improvement over the methodology included in HEC-1 is the added ability to account for the effect of rainfall on the depth and water content of the snowpack and the ability to begin a model simulation (either design storm or historical storm) using a snowpack density below the yield density. A water budget is used to track the changing conditions in snow water equivalent and snowpack density throughout the duration of the storm event. For densities less than the yield density, free water is retained in the snowpack. Once sufficient compaction of the pack has resulted in the snowpack density equaling the threshold density, the pack is allowed to melt, thereby releasing free water. The magnitude of released water is computed using empirical energy budget snowmelt equations. This methodology is most important when meteorological conditions support fresh snowfall resulting in a low density pillow followed by warm rains.

Tests conducted by the USBR found that significant drainage from the snowpack was found to take place when the snowpack reached a threshold density between 40 and 45 percent (USBR 1966). Based on these findings, the threshold density used in the hydrologic analysis was set at 40 percent.

2.7 Interflow

Interflow represents a portion of the event runoff hydrograph. Precipitation which infiltrates into the soil column can flow through the subsurface layer and reemerge downslope in a stream channel. This subsurface flow is referred to as interflow. The response time of the interflow component is typically between that of the surface response and the groundwater response.

The interflow component of the runoff hydrograph is determined internally within SEFM based on a two-stage linear reservoir routing procedure. The two stages conceptually represent an upper and lower storage zone in the soil column. The two zones are included in the model in series, and each zone uses a different storage constant which is used to define the lag time for hydrologic routing procedure. The storage constant for the upper interflow zone is hereafter referred to as UZ and the storage constant for the lower interflow zone is hereafter referred to as LZ. A proportioning factor allows a percentage of the upper zone to directly discharge to the stream instead of being routed first through the lower zone. The two stage reservoir routing procedure therefore allows for significant flexibility in the modeling of the recession limb of the runoff hydrograph.

3 INPUT DEVELOPMENT AND PARAMETER ESTIMATION

Input data (precipitation time series, air temperature time series, antecedent snowpack conditions, and atmospheric lapse rate) was required for the model to describe the meteorology of the five historical storm events used in the model calibration. Additionally, initial estimates of the model calibration parameters (soil characteristics, unit hydrograph parameters, and interflow parameters) were required to describe the hydrologic response of the watershed to each of these events. This section documents the development of the meteorological input data and the initial estimation of the hydrologic model calibration parameters.

3.1 Precipitation

For the events that were considered for model calibration and verification, recorded hourly precipitation was only available at a single recording station within the watershed (Upper Baker Dam Station No. 458715), and daily recorded precipitation was available at an additional station in the watershed (Concrete PPL Fish Station No. 451679). Due to the terrain influenced variability in spatial and temporal precipitation distribution, a method for distributing point rainfall measurements to a regularly spaced gridded field was necessary. A rainfall analysis software package known as the Storm Precipitation Analysis System (SPAS) was used for this task (Tomlinson et al 2004). SPAS has the capability to analyze rainfall associated with extreme storms over complex terrain. Using digital precipitation data with Geographical Information Systems (GIS), detailed rainfall analyses were conducted that resulted in high spatial resolution hourly rainfall fields that quantified the spatial and temporal distribution of storm rainfall over the watershed. The results were used to compute subbasin average rainfall totals and temporal distributions. The details of the methodology relative to the application to the Baker River watershed model are described in Technical Memorandum No. 9 (Applied Weather Associates 2006).

Additionally, for the 1995 and 2003 storms, pseudo precipitation stations were created within the watershed and hourly rainfall values at these pseudo stations were computed using NEXRAD data at the 1.32 and 1.36 elevation scan angles. Applied Weather Associates (2006) discusses the details of how the NEXRAD data were used to compute the pseudo station rainfall values.

Attachment A includes an example ArcGIS figure that illustrates the spatial distribution of precipitation for the NOV 89 storm event using the SPAS software.

3.2 Air Temperatures

Modeling of snowmelt and snow accumulation required an hourly air temperature time series to represent atmospheric conditions in the Baker River watershed. Available temperature data within the watershed is limited to daily reports of maximum and minimum temperatures at the Upper Baker Dam precipitation station. Therefore, an algorithm was developed to estimate a serially complete hourly temperature profile representative of the conditions at the Upper Baker Dam station. The algorithm used a known hourly temperature profile at a nearby reference station. Each hourly temperature recorded at the reference station was converted into a value that equaled the percent of the total daily temperature range (maximum minus minimum). Starting at the hour when the temperature was lowest for the day at the reference station, the Upper Baker temperature was assumed to have also been at its minimum for the day. For subsequent hours, the percentage change computed at the reference station was applied to each hour of the Upper Baker temperature series. This was done until the maximum temperature was reached at the reference station and the Upper Baker station. Then a new temperature range was computed and the process repeated. Daily observation forms from Upper Baker Dam also reported the temperature at the 7 AM observation time, thereby providing a single known hourly temperature at Upper Baker Dam. If the algorithm did not correctly estimate the observation temperature, then manual modifications were made to the temperature profile to ensure continuity

Table 7 summarizes the reference stations that were used for each storm. For the NOV 95(2) and the OCT 03 events, SNOTEL stations which are in close proximity to the watershed were used. For the NOV 89, NOV 90(1), and NOV 90(2) events, hourly data from SNOTEL stations were not available, and the Stampede Pass station was used as the reference station. The air temperature time series that were developed to represent the conditions at Upper Baker Dam for each storm event are shown in Figures 6 through 10.

The final step in developing the air temperature time series for each storm event was to adjust the serially complete hourly temperature profile to each of the eight elevation zones of the watershed model. Information relative to the atmospheric lapse rates was therefore necessary. Computed lapse rates from upper air radiosonde data were used. Radiosondes are typically released twice daily, and in Washington State, they are released from several sites on the west coast and interior of the state. The radiosondes are typically released at times corresponding with midnight and noon Greenwich Mean Time (GMT). Measurements of upper air temperature and pressure, relative humidity, and wind direction and speed are taken at standard pressure levels as the balloon ascends into the upper atmosphere. Data from the Quilleyute station were assumed to represent atmospheric conditions at the project site.

Attachment B includes summary spreadsheets of the twice-daily radiosonde data from the Quillayute station for each of the five storm events. The sole exception is the NOV 90(2) event, for which a complete set of radiosonde data was not available for the entire event. As seen in Attachment B, the vertical temperature gradient cannot be described by a single lapse rate at a given time, and the vertical temperature gradient can also be seen to vary from day to day throughout the course of the storm event. Therefore, a consistent methodology was needed to determine air temperature time series at each elevation zone. The lapse rates shown in Attachment B were used to adjust the temperature time series developed for Upper Baker Dam to each of the elevation zones, accounting for the vertical change in temperature gradient as well as temporal change. Figures 6 through 10 show the derived air temperature time series for each event at the elevation associated with the Upper Baker Dam precipitation station (elevation 690 feet) as well as the adjusted series for Elevation Zone 8 (median elevation of 7,400 feet).

The set of derived air temperature time series for the range of elevation zones were then used to develop time histories of the freezing level throughout each of the storm events. This information was generated for informative purposes only, to graphically illustrate how much of the watershed was contributing snowmelt to the runoff hydrograph throughout the duration of each of the storm events. Another way to interpret these graphics is that the freezing level time histories also illustrate how much of the watershed is receiving liquid precipitation versus how much is receiving snow throughout the duration of each of the storm events.

The snowmelt algorithms in the SEFM model compute snowmelt for a given HRU when the air temperature is equal to or greater than 34 degrees F. Therefore, for the graphical depiction of the freezing level time histories in Figures 11 through 15, the freezing level is defined as that elevation at which the air temperature equals 34 degrees F. Each of the five figures includes a table which summarizes the cumulative elevation distribution in the Baker River watershed. Therefore, knowing the freezing level at a given time for a given storm event, a quick estimation of the percentage of the watershed that is contributing snowmelt to the runoff hydrograph can be made.

Table 7. Reference Stations used for Deriving Hourly Temperature Time Series

Storm Event	Station	Elevation	Latitude	Longitude
NOV 89	Stampede Pass	3,958	N 47° 17’ 00”	121° 20’ 00” W
NOV 90(1)	Stampede Pass	3,958	N 47° 17’ 00”	121° 20’ 00” W
NOV 90(2)	Stampede Pass	3,958	N 47° 17’ 00” N 48° 45’ 00”	121° 20’ 00” W 122° 29’ 00” W
NOV 95(2)	Elbow Lake	3,200	N 48° 41’ 00”	121° 54’ 00” W
OCT 03	Middle Fork Nooksack Wells Creek	4,980 4,200	N 48° 49’ 00” N 48° 51’ 00”	121° 55’ 00” W 121° 47’ 00” W

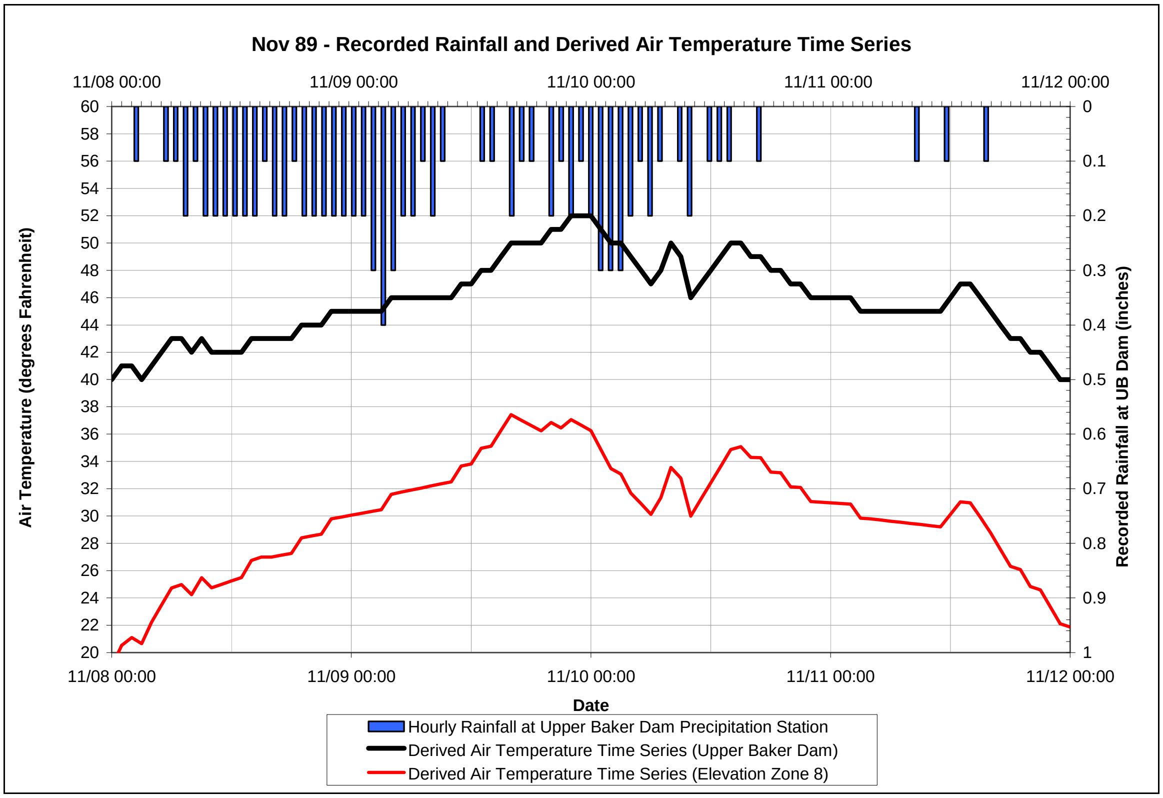


Figure 6. Air Temperature and Recorded Rainfall at Upper Baker Dam – NOV 89

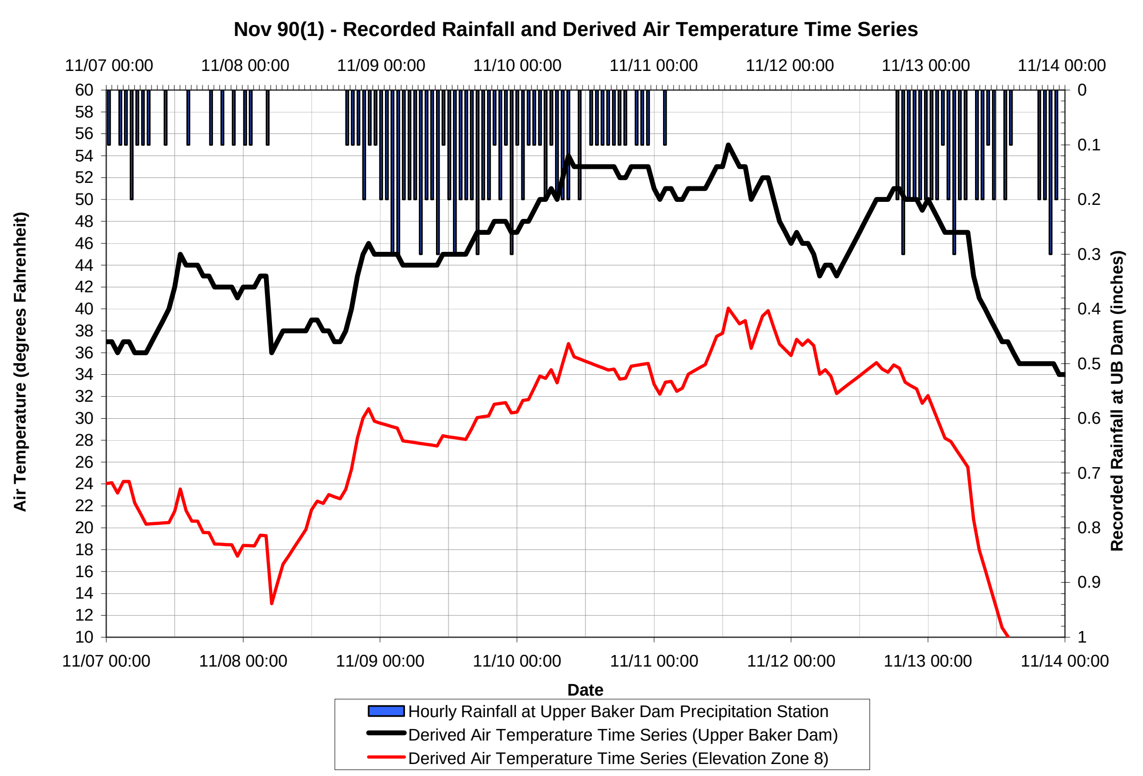


Figure 7. Air Temperature and Recorded Rainfall at Upper Baker Dam – NOV 90(1)

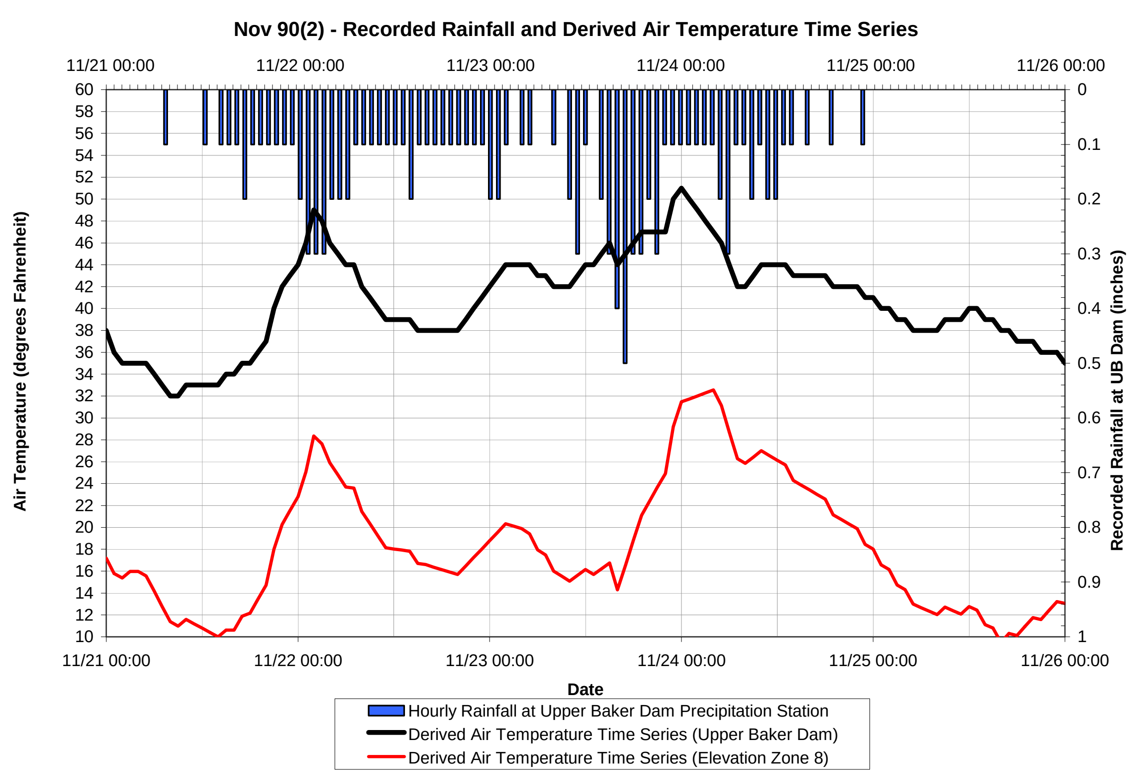


Figure 8. Air Temperature and Recorded Rainfall at Upper Baker Dam – NOV 90(2)

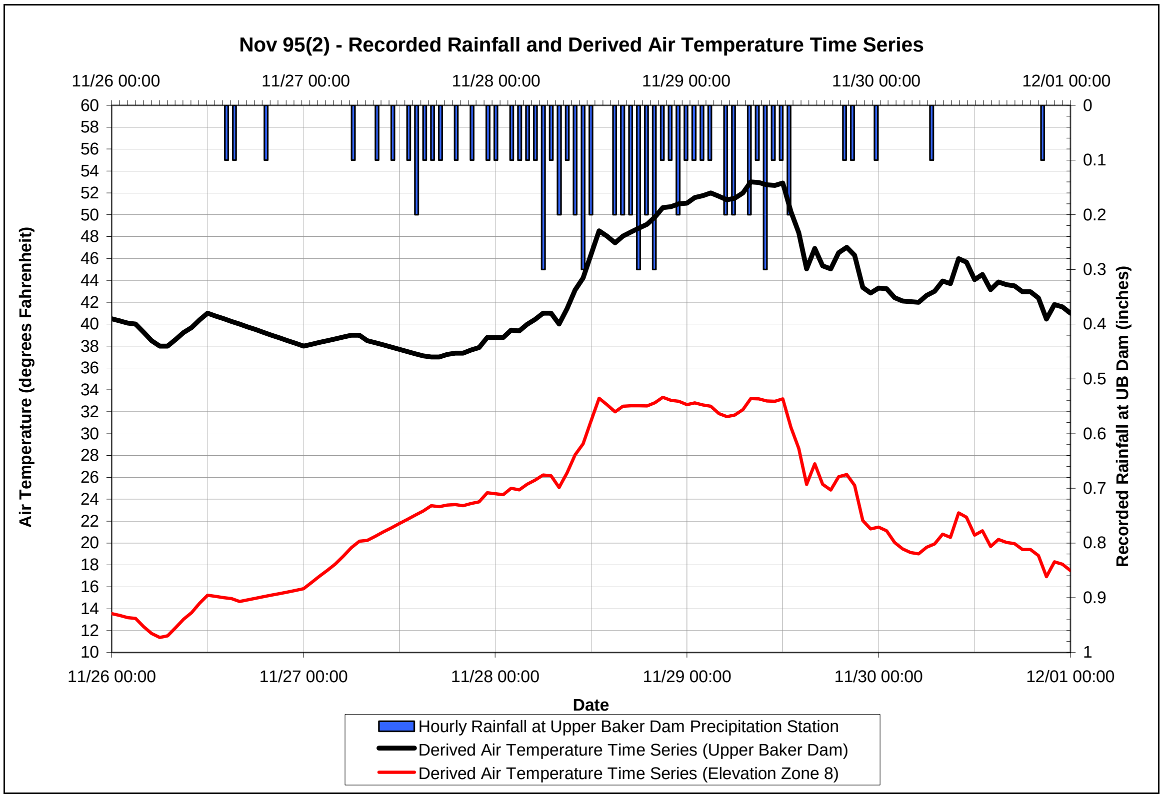


Figure 9. Air Temperature and Recorded Rainfall at Upper Baker Dam – NOV 95(2)

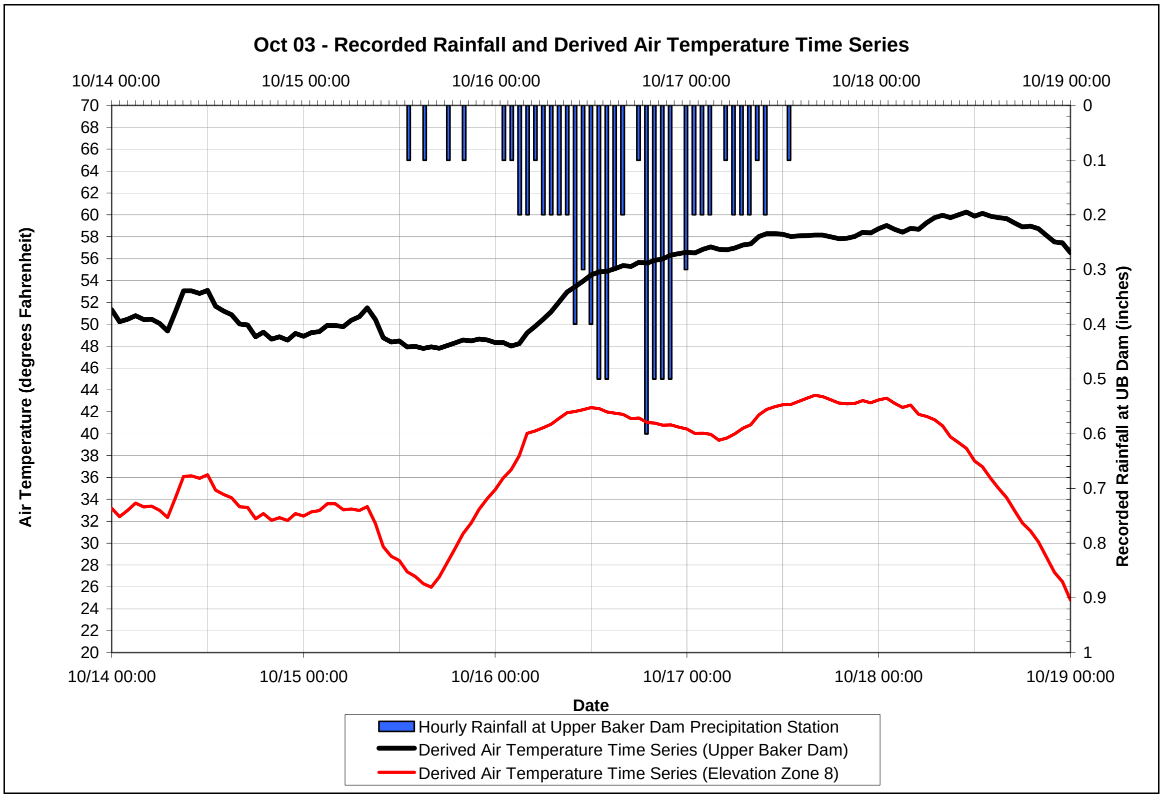


Figure 10. Air Temperature and Recorded Rainfall at Upper Baker Dam – OCT 03

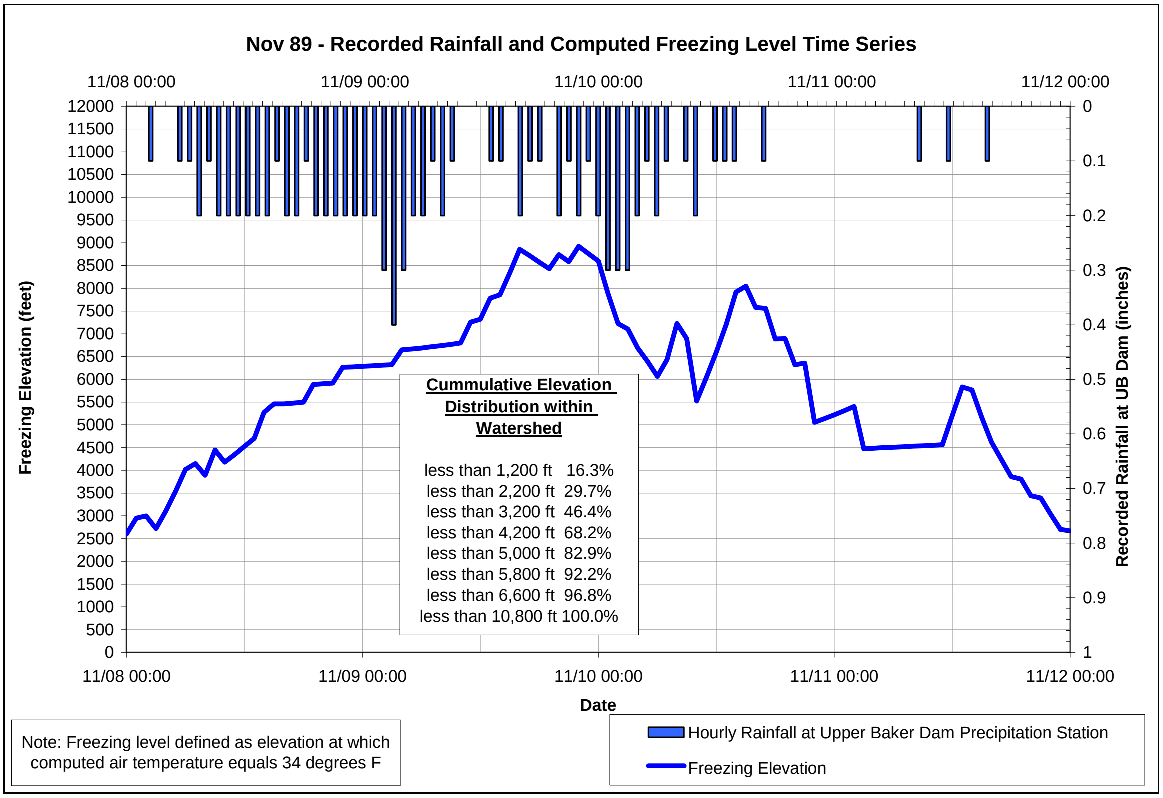


Figure 11. Freezing Level and Recorded Rainfall at Upper Baker Dam – NOV 89

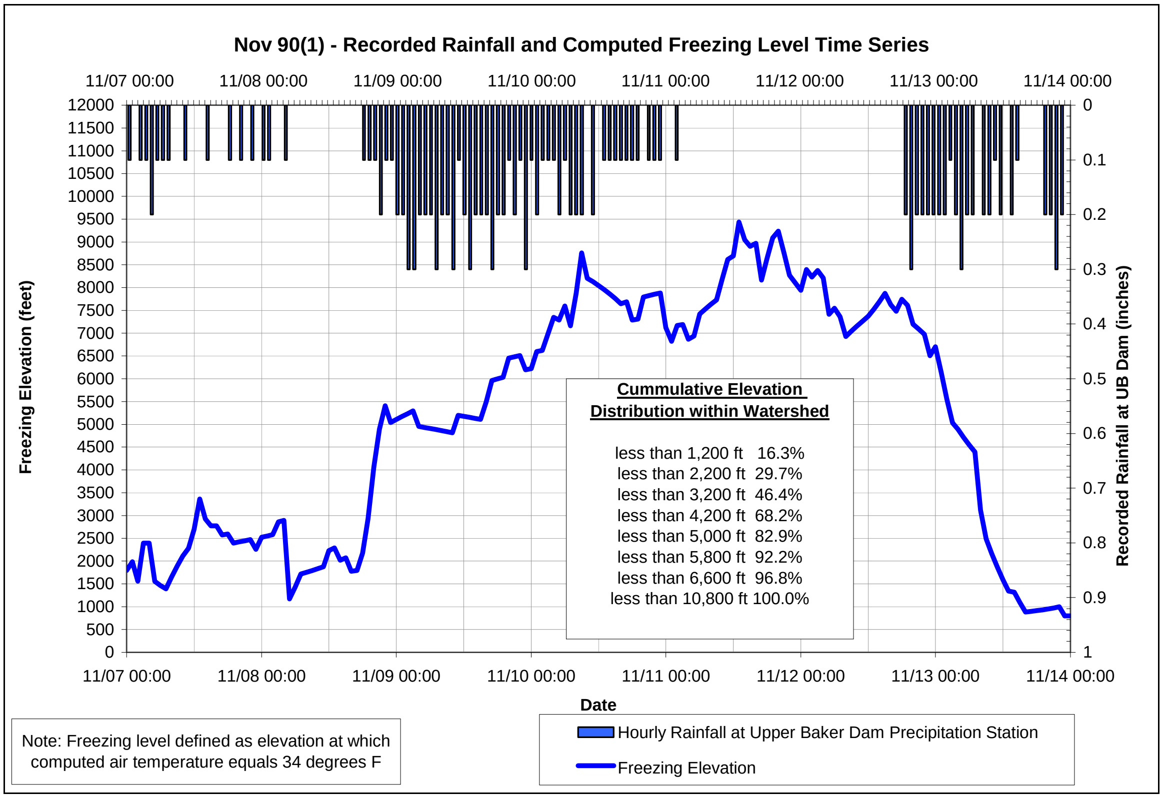


Figure 12. Freezing Level and Recorded Rainfall at Upper Baker Dam – NOV 90(1)

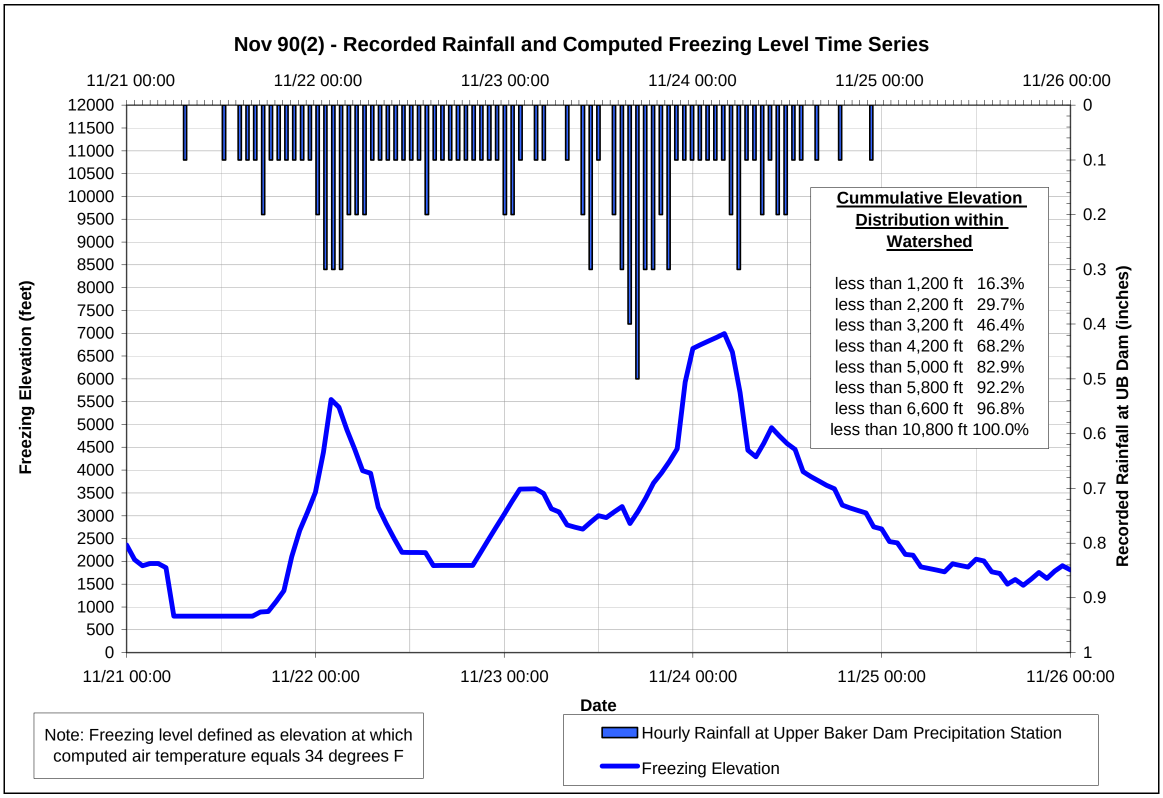


Figure 13. Freezing Level and Recorded Rainfall at Upper Baker Dam – NOV 90(2)

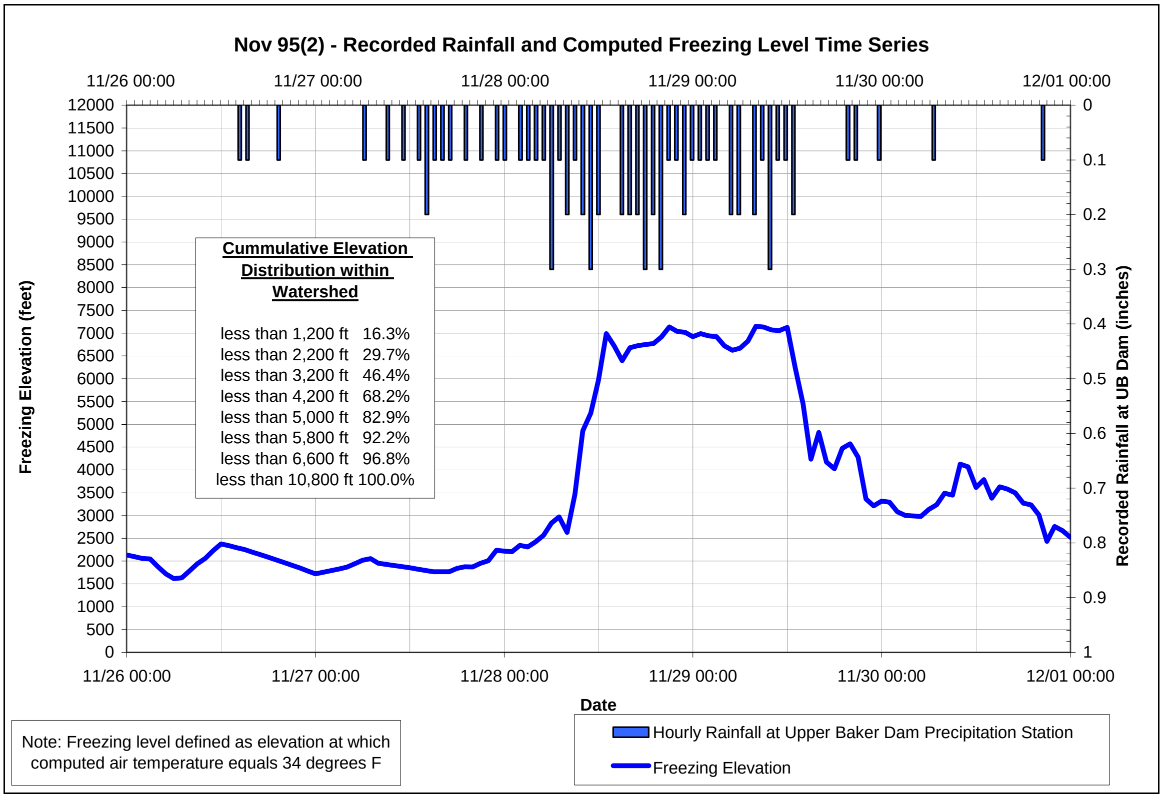


Figure 14. Freezing Level and Recorded Rainfall at Upper Baker Dam – NOV 95(2)

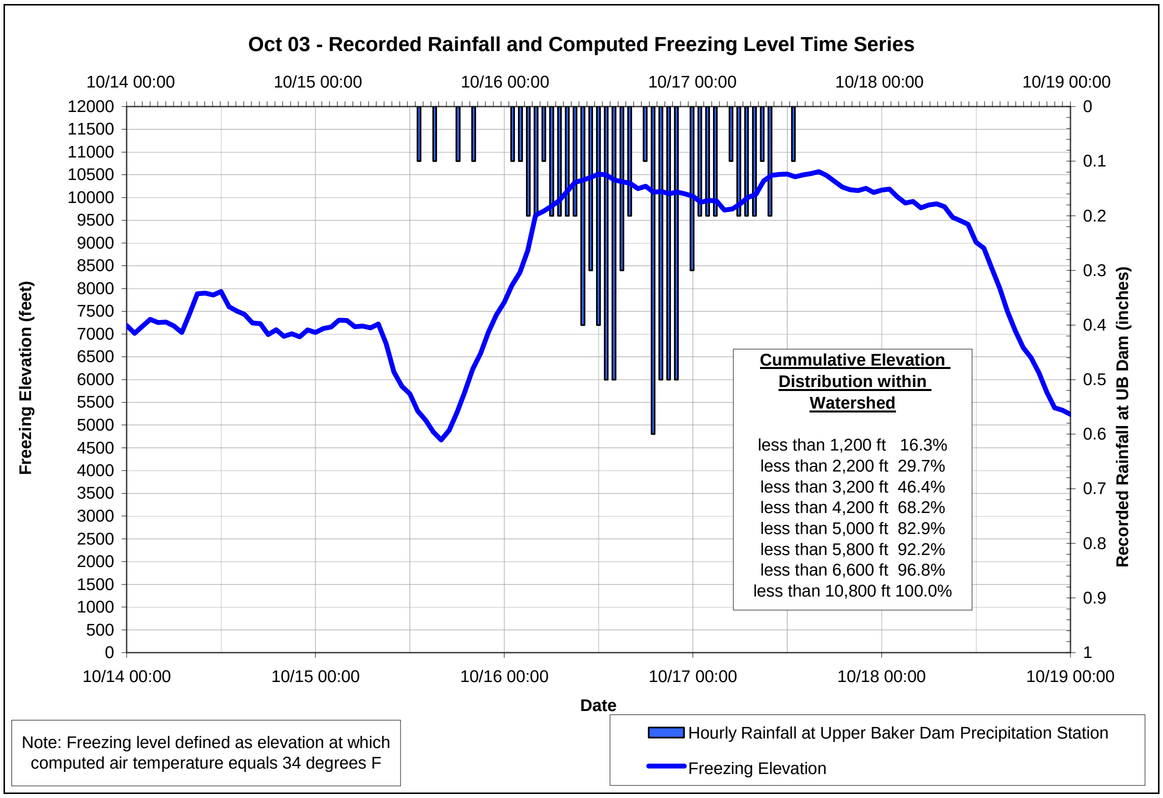


Figure 15. Freezing Level and Recorded Rainfall at Upper Baker Dam – OCT03

3.3 Antecedent Snowpack Conditions

A first attempt to determine antecedent snowpack conditions for each storm event used correlations between coincidently measured snow water equivalent data from SNOTEL stations immediately adjacent to the watershed and the snow course stations within the watershed. Coincident measurements occurred during the months of January through June, and regression analyses were used to establish relationships between SNOTEL stations and snow course stations. Attempts were then made to use these relationships to determine snow water equivalent at sites within the watershed for the calibration storm events, all of which occurred in October and November. This method ultimately proved unsuccessful and a second approach was used.

The second approach used output from the calibrated HFAM model for the Baker River watershed (Hydrocomp 1999). Model output included daily values of snowpack density and snow water equivalent at seven of the nine snow course site located within the watershed. The model output from the seven stations were used to estimate the antecedent snowpack density and snow water equivalent at the onset of each of the calibration events.

Average daily snow water equivalent and snowpack density were exported from HFAM for the first day of each storm event. The exported values for each of the seven snow course sites were normalized to the median value of the lowest mean annual precipitation zone (67 inches), thereby making elevation the explanatory variable for determining the distribution of snow water equivalent in the watershed. For each storm event, the normalized snow water equivalent values were then plotted against elevation and a best fit function was fit to the points. In all cases this was a linear function. Figure 16 shows the variation in snow water equivalent associated with elevation for each of the five events. Assuming a linear relationship between mean annual precipitation and snow water equivalent, the normalized values of snow water equivalent were then linearly increased so as to provide estimated values at higher zones of mean annual precipitation. Table 8 summarizes the resulting estimates of snow water equivalent for the matrix of elevation and mean annual precipitation zones for each of the calibration events. Table 8 also includes the estimated elevation of the snowline for each event. This elevation was determined by reviewing the historical snowpack data from all nearby SNOTEL stations and comparing against the HFAM model output.

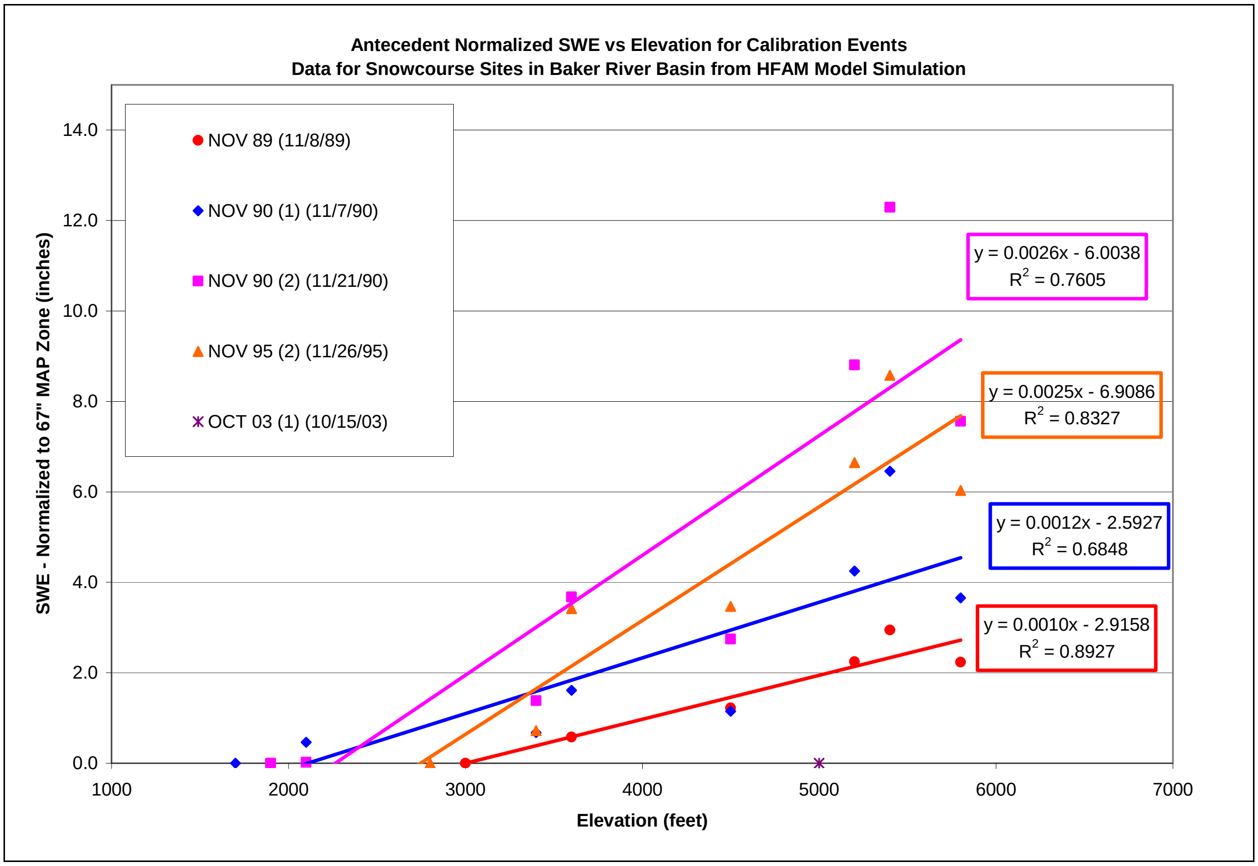


Figure 16. Antecedent Normalized Snow Water Equivalent

Table 8. Antecedent Snow Water Equivalent for Calibration Storm Events

		Antecedent Snow Water Equivalent by Elevation Zone (inches)							
NOV 89 Snowline = 3,000 feet									
		1	2	3	4	5	6	7	8
Mean Annual Precipitation Zone	1	0.0	0.0	0.4	0.8	1.7	2.5	3.3	4.5
	2	0.0	0.0	0.5	1.0	2.2	3.2	4.2	5.8
	3	0.0	0.0	0.6	1.2	2.6	3.8	5.0	6.8
	4	0.0	0.0	0.7	1.3	2.8	4.2	5.5	7.5
	5	0.0	0.0	0.7	1.4	3.1	4.5	6.0	8.2
	6	0.0	0.0	0.8	1.6	3.5	5.2	6.9	9.4
	7	0.0	0.0	0.9	1.8	3.9	5.8	7.6	10.4
	8	0.0	0.0	1.1	2.2	4.7	7.0	9.2	12.6
NOV 90(1) Snowline = 1,700 feet									
Mean Annual Precipitation Zone	1	0.0	0.0	0.6	1.8	2.9	3.9	4.8	6.3
	2	0.0	0.0	0.8	2.4	3.8	5.0	6.2	8.1
	3	0.0	0.0	1.0	2.8	4.5	5.9	7.4	9.6
	4	0.0	0.0	1.1	3.1	4.9	6.5	8.1	10.5
	5	0.0	0.0	1.2	3.4	5.3	7.1	8.8	11.4
	6	0.0	0.0	1.4	3.9	6.1	8.1	10.1	13.1
	7	0.0	0.0	1.5	4.3	6.8	9.1	11.3	14.6
	8	0.0	0.0	1.8	5.2	8.2	10.9	13.6	17.6
NOV 90(2) Snowline = 1,900 feet									
Mean Annual Precipitation Zone	1	0.0	0.0	1.0	3.6	6.0	8.0	10.1	13.2
	2	0.0	0.0	1.3	4.6	7.6	10.3	13.0	17.0
	3	0.0	0.0	1.5	5.5	9.1	12.2	15.4	20.2
	4	0.0	0.0	1.7	6.0	10.0	13.4	16.9	22.1
	5	0.0	0.0	1.9	6.6	10.8	14.6	18.4	24.1
	6	0.0	0.0	2.1	7.6	12.4	16.8	21.1	27.7
	7	0.0	0.0	2.4	8.4	13.9	18.7	23.6	30.8
	8	0.0	0.0	2.9	10.1	16.7	22.5	28.4	37.1
NOV 95(2) Snowline = 2,800 feet									
Mean Annual Precipitation Zone	1	0.0	0.0	0.0	2.3	4.6	6.6	8.6	11.6
	2	0.0	0.0	0.0	3.0	5.9	8.5	11.0	14.9
	3	0.0	0.0	0.0	3.6	7.0	10.0	13.1	17.6
	4	0.0	0.0	0.0	3.9	7.7	11.0	14.4	19.4
	5	0.0	0.0	0.0	4.3	8.4	12.0	15.6	21.1
	6	0.0	0.0	0.0	4.9	9.6	13.8	18.0	24.2
	7	0.0	0.0	0.0	5.5	10.7	15.3	20.0	27.0
	8	0.0	0.0	0.0	6.6	12.9	18.5	24.1	32.5
OCT 03 Snowline = 5,000 feet									
Mean Annual Precipitation Zone	1	0.0	0.0	0.0	0.0	0.1	0.6	1.1	1.8
	2	0.0	0.0	0.0	0.0	0.1	0.7	1.4	2.3
	3	0.0	0.0	0.0	0.0	0.1	0.9	1.6	2.7
	4	0.0	0.0	0.0	0.0	0.2	1.0	1.8	3.0
	5	0.0	0.0	0.0	0.0	0.2	1.0	1.9	3.2
	6	0.0	0.0	0.0	0.0	0.2	1.2	2.2	3.7
	7	0.0	0.0	0.0	0.0	0.2	1.3	2.5	4.1
	8	0.0	0.0	0.0	0.0	0.3	1.6	3.0	5.0

3.4 Soil Moisture

A soil moisture budgeting algorithm within SEFM, using a monthly water budget, was used to determine the water storage deficit of each soil zone at the onset of each calibration event. The initial soil moisture deficient was in turn was used to determine the initial infiltration rate at the onset of the each event. Specific input parameters used in defining the soil moisture budgeting algorithm include the antecedent precipitation that occurred in the months prior to the event, the monthly potential evapotranspiration, and change in monthly snow water equivalent.

Monthly incremental antecedent precipitation was determined for each storm event in the months leading up to the start of the storm. Table 9 presents this data. Each increment reflects the end of the month total. The value for the month in which the storm occurred reflects the cumulative precipitation for the days of the month prior to the start of the event.

Table 9. Incremental Antecedent Precipitation at Upper Baker Dam

Storm Event	End-of-Month Incremental Precipitation (inches) Recorded at Upper Baker Dam		
	SEPT	**OCT**	**NOV**
NOV 89	0.30	9.35	3.62
NOV 90(1)	0.61	16.99	1.65
NOV 90(2)	0.61	16.99	18.55
NOV 95 (2)	3.06	15.82	21.07
OCT 03	2.44	4.40	-

The SEFM model requires monthly estimates of potential evapotranspiration (PET) for use in the soil moisture budgeting algorithm. Determination of PET was conducted offline from the model. PET was determined on an individual water year basis, using a grass-related, temperature-based method as shown in Equation (1). This equation (Hargreaves et al 1982, 1985) was chosen because it incorporates a solar radiation component while only requiring direct input of monthly minimum, monthly maximum and monthly average temperatures. Equation (1) was used to compute monthly evapotranspiration using recorded temperatures at Upper Baker Dam for each water year associated with the historical calibration events.

$$E_{to} = 0.0023 * R_a * TD^{1/2} * (T + 17.8) \tag{1}$$

where,

E_{to} = Monthly reference crop evapotranspiration rate (mm per month)
R_a = extraterrestrial radiation (megajoules per square meter per day)
TD = Temperature difference between mean month maximum and mean monthly Minimum (degrees C)
T = Average monthly temperature (degrees C)

Monthly E_{to} values were assumed to represent the monthly PET experienced at the elevation of Upper Baker Dam. Monthly values were summed to determine annual evapotranspiration, and then the annual values were adjusted to each elevation zone based on an assumed lapse rate of 4 degrees F per 1000-feet. Values used in the SEFM model are shown in Table 10. Figure 17 shows the monthly distribution of annual evapotranspiration that was determined for the water years associated with each event.

Table 10. Annual Potential Evapotranspiration

	Annual Potential Evapotranspiration (inches) per Elevation Zone							
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Storm	800	1,700	2,700	3,700	4,600	5,400	6,200	7,400
NOV 89	22.3	20.7	18.8	17.0	15.3	13.9	12.4	10.2
NOV 90(1) & NOV 90(2)	26.2	24.0	21.5	19.1	16.9	14.9	12.9	10.0
NOV 95(2)	31.4	29.4	26.7	24.3	22.1	20.1	18.2	15.2
OCT 03	30.9	28.8	26.4	24.1	22.0	20.1	18.2	15.4

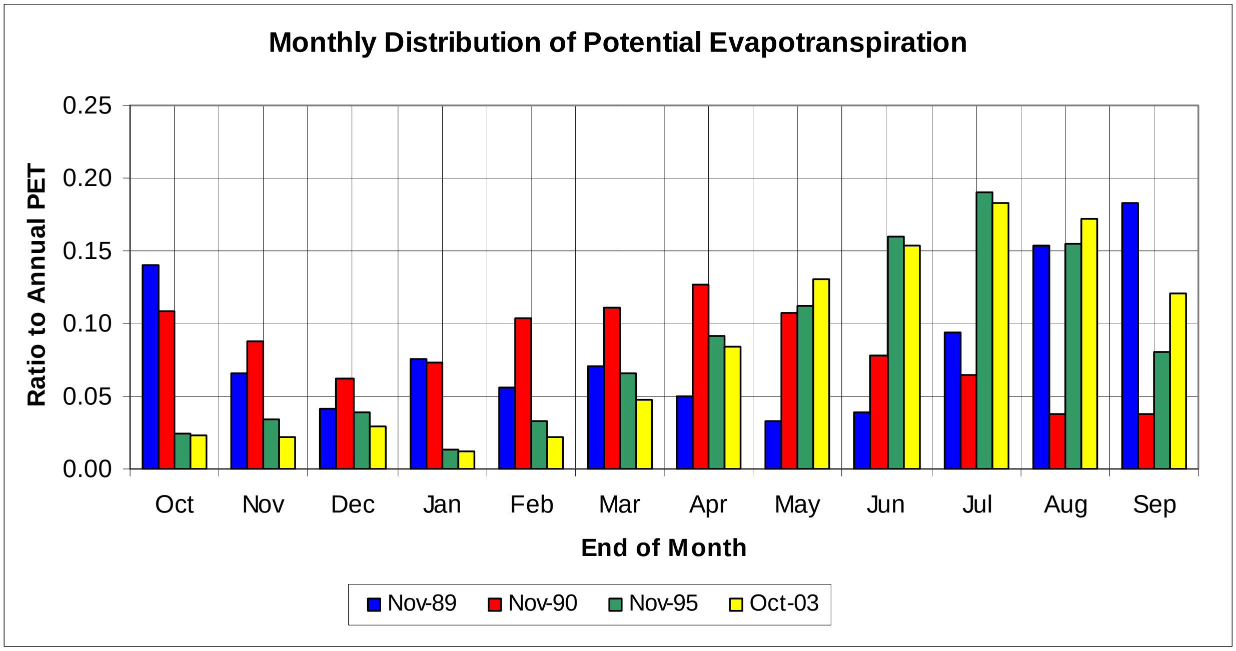


Figure 17. Monthly Distribution of Potential Evapotranspiration

Change in snow water equivalent was based on end of month snow water equivalent estimates using the procedure described in the previous section to determine snow water equivalent at the onset of the each storm. End of month snow water equivalent values for the month in which the storm occurred reflect the net change from the beginning of the month to the start of the event.

The SEFM soil moisture budgeting algorithm is based on Equation (2) and reflects the initial storage moisture deficit at the time of the storm event. This value is used in determining the infiltration rate at the onset of the storm based on the Holtan loss rate methodology.

$$\begin{aligned} SMD &= SMD_{MAX} - SMC \\ SMC_{Monthly} &= P_{Monthly} - PET_{Monthly} - \Delta SWE \end{aligned} \qquad (2)$$

where,

SMD = Storage moisture deficit (in)
SMD_{MAX} = Maximum storage moisture deficit (in)
$SMC_{Monthly}$ = Monthly Storage Moisture Capacity (in)
$P_{Monthly}$ = End of the month cumulative precipitation (in)
$PET_{Monthly}$ = Monthly PET (in)

ΔSWE = Monthly change in snow water equivalent (in)

3.5 Soil and Forest Cover Parameters

Surface infiltration is computed within SEFM using a modified form of the Holtan loss rate methodology (Holtan 1961, Holtan et al 1975) which is described as Equations (3) and (4).

$$f = KS_d^{1.4} + f_c \tag{3}$$

$$K = \left(f_{\max} - f_c\right) / S_{\max}^{1.4} \tag{4}$$

where,

f = surface infiltration rate (in/hr)
S_d = available moisture storage in the surface layer (in)
f_c = minimum, or constant, surface infiltration rate (in/hr)
$f_{\max}$ = maximum surface infiltration rate (in/hr)
$S_{\max}$ = maximum soil moisture storage capacity (in)

The three parameters in the Holtan infiltration methodology that were included as calibration parameters were the minimum infiltration rate (f_c), the maximum infiltration rate (f_{max}), and the maximum soil moisture storage capacity (S_{max}).

A fourth soil parameter, not included in the Holtan infiltration model, was included as a calibration parameter. The rate of deep percolation (f_d) represents the losses to groundwater. In the SEFM model, the rate of interflow is computed as the difference between the rate of surface infiltration (f) and the rate of deep percolation (f_d). Groundwater is not modeled within SEFM, so the f_d parameter is a constant loss rate from the model domain.

Table 11 summarizes the initially estimated range that each of these soil calibration parameters were allowed to vary during model calibration.

Table 11. Initial Sampling Range for Soil Calibration Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (in)	Minimum Surface Infiltration Rate, f_c (in/hr)	Deep Percolation Rate, f_d (in/hr)	Maximum Surface Infiltration Rate, f_{max} (in/hr)	Notes
1	---	---	---	---	Open Water
2	0	f_d + 10	0.10 – 0.50	10	Glaciers
3	0.4 – 11.1	f_d + (0.00 to 0.30)	0.00 – 0.30	4	Rock Outcrop
4	0.2 – 12.0	f_d + (0.00 to 0.40)	0.00 – 0.10	6	A Soils
5	0.4 – 11.1	f_d + (0.00 to 0.30)	0.00 – 0.30	4	B Soils Shallow
6	0.6 – 16.5	f_d + (0.00 to 0.30)	0.00 – 0.10	4	B Soils Deep
7	0.6 – 24.8	f_d + (0.00 to 0.30)	0.00 – 0.30	4	B Soils Deep
8	0.4 – 12.6	f_d + (0.00 to 0.15)	0.00 – 0.30	4	C Soils Shallow
9	0.2 – 18.0	f_d + (0.00 to 0.15)	0.00 – 0.10	2	C/D Soils Deep
10	0.6 – 24.8	f_d + (0.00 to 0.30)	0.10 – 0.50	4	Sulphur/Rocky

The S_{max} parameter is equal to the maximum soil moisture deficit for a given soil. The value of S_{max} can be computed using Equation (5). In this equation, the available water capacity (AWC) is the capacity of the soil to hold water and is commonly defined as the difference between the amount of soil water at field moisture capacity and the amount at wilting point. The depth of the soil profile (D) is assumed to be the median soil depth as previously summarized in Table 5. By inputting a range of values for AWC into Equation (5), a range of values for S_{max} can be computed. This range is summarized in Table 11. AWC is a function of soil texture and ranged between 0.03 inches per inch and 0.40 inches per inch.

$$S_{\max} = AWC \times D \tag{5}$$

where,

$S\max =$ maximum soil moisture storage (in)
$AWC =$ available water capacity (inches per inch of soil);
$D =$ depth of the soil profile (in)

The minimum infiltration rate parameter (f_c) was assumed as a function of the SCS hydrologic soil class and the sampling range for this calibration parameter was taken from Maidment (1993). The sole exception was for the soil zone representing the glacial coverage (Soil Zone 2) where the fc parameter was fixed at an artificially high value so as to force precipitation excess into either the interflow or groundwater regimes. Precipitation excess and snowmelt is likely conveyed predominantly through the crevasses and fractures of the glacier, thereby contributing to a more delayed response in the subbasin hydrograph. The transmission of excess precipitation and snowmelt through the crevasses and fractures of the glacier is sufficiently long whereby the glaciers create more of an interflow response and less of a surface response.

The deep percolation parameter is used to allocate runoff between groundwater and interflow. It therefore is a function of the surficial conditions, namely the bedrock material and texture. Bedrock which is more porous or which is highly fractured is expected to have higher rates of deep percolation. This is a difficult parameter to estimate, however it plays an important role in determining the runoff volume. Therefore a wide range was initially assumed. For those soil zones with minimally fractured bedrock (Soil Zones 4, 6, and 9), the upper bound of the fd sampling range was set lower. For those soil zones with moderate to high degrees of fracturing (Soil Zones 3, 5, 7, 8), the upper bound was set higher. The f_d parameter sampling range was set even higher for Soil Zone 2 (Glaciers) and Soil Zone 10 (Sulphur/Rocky Creek) so as to result in a delayed groundwater response.

The fourth parameter in Table 11 is the maximum surface infiltration rate, which was assumed to be approximated by a representative permeability rate within the soil column of each soil zone. The permeability rate was obtained from USFS (1970), the NRCS SSURGO database (NRCS 1994a), and the NRCS STATSGO database (NRCS 1994b) for each of the soil mapping units. A representative value of the permeability was then chosen for each soil zone based on the predominant soil texture.

Forest cover was determined for the use in the SEFM snowmelt algorithm based on the 1992 National Land Cover Dataset (NLCD). The percent of forest cover per elevation zone was determined using GIS. The NLCD was overlaid with the subbasin delineations and the elevation zone delineations to calculate the surface area within each elevation-subbasin zone. Only the land use classification for deciduous, evergreen, and mixed forest were used in percentage calculations. These percentages are used in the SEFM model to determine convection melt coefficient and was assumed fixed for all events. Figure 18 shows NLCD dataset overlaid with the elevation zones.

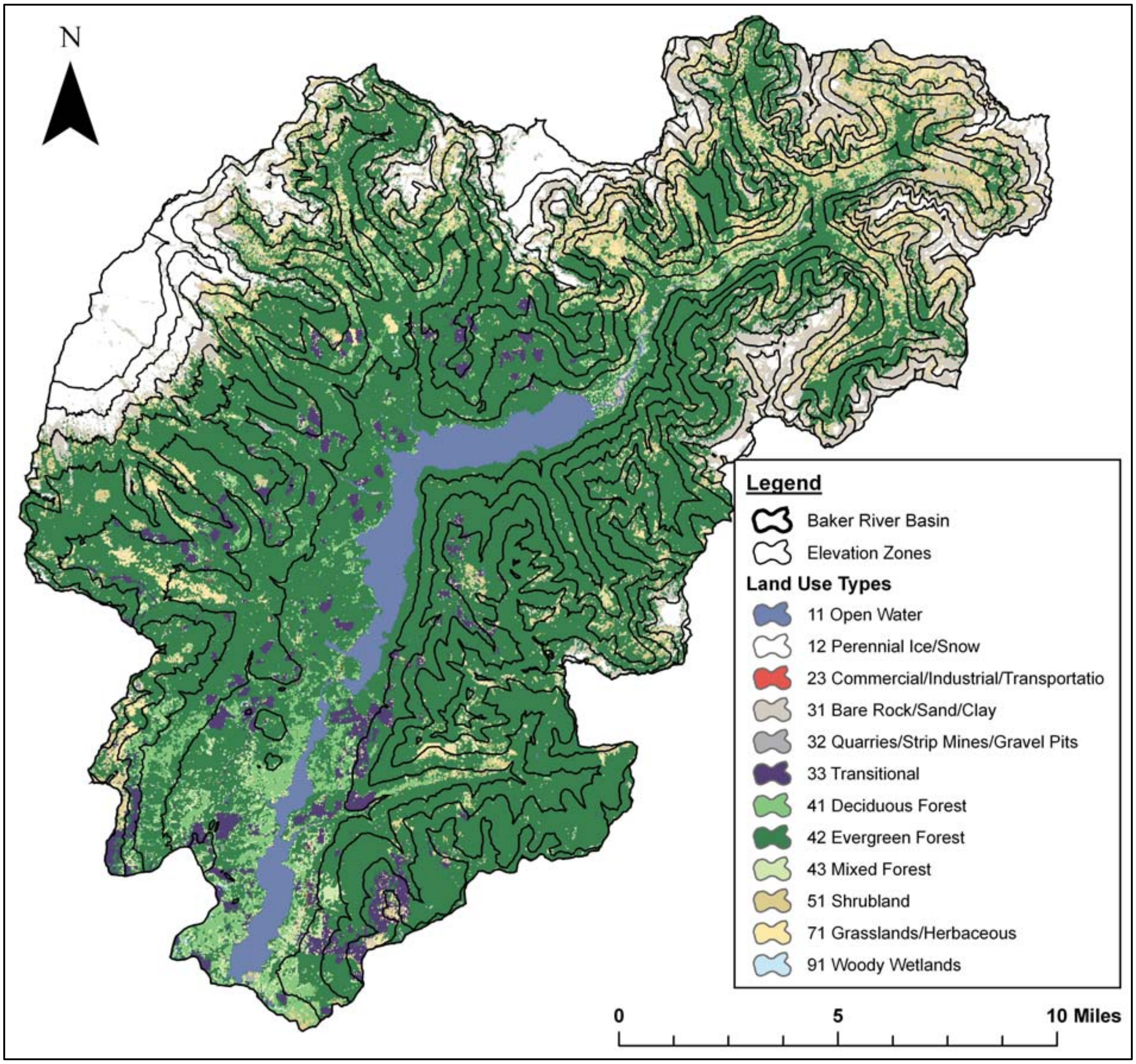


Figure 18. Forest Cover per Elevation Zone

3.6 Unit Hydrograph and Interflow Parameters

The SEFM includes options to use either a synthetic unit hydrograph technique that is analogous to the Snyder unit hydrograph method or to use a user input unit hydrograph. This is consistent with some of the options that are available in the HEC-1 software. There are no previously developed unit hydrographs for the Baker River watershed nor for any of the local tributaries within the watershed. Therefore, the synthetic unit hydrograph technique was the chosen method for developing surface runoff hydrographs.

The parameters that are used to describe the unit hydrograph are defined as follows:

- $LagTime_{peak}$ = the unit hydrograph lag time. This parameter is defined as the elapsed time from the centroid of precipitation that produces runoff to the occurrence of the flood peak discharge at the subbasin outlet
- D = the unit duration of runoff, taken to be 30 minutes for this analysis.
- Q_p = peak discharge of the unit hydrograph

Equations (6) and (7) define specific attributes of the unit hydrograph, namely the lag time and the magnitude of the peak. The shape of the unit hydrograph is determined internally in the SEFM model using a gamma distribution along with the values of the period of rise, P_r, and the peak flow rate, Q_p.

$$\mathrm{Pr} = D/2 + LagTime_{peak} \tag{6}$$

where,

Pr = the period of rise, (hours)
D = unit duration, (hours)
$LagTime_{peak}$ = the lag time, (hours)

$$Q_p = \frac{C_p A}{P_r} \tag{7}$$

where,

Q_p = peak discharge of the unit hydrograph, (cfs)
C_p = peaking factor of the unit hydrograph
A = watershed area, (square miles)
Pr = period of rise, (hours)

The variable $LagTime_{peak}$ describes the elapsed time between the centroid of the precipitation that produces runoff and the occurrence of the flood peak discharge. Alternative definitions of the lag time have been used which define the lag time as the time from the center of unit rainfall excess to the time that 50 percent of the volume of unit runoff from the drainage basin has passed the concentration point (USBR 1989).

It has been documented that "reconstitution of numerous observed flood events using the unit hydrograph approach has led to the conclusion that the lag time of the unit hydrograph is a function of certain measurable basin parameters" (USBR 1989). Therefore, as a starting point in estimating the $\text{LagTime}_{\text{peak}}$ variable, the lag time equation presented in USBR (1989) was used. Equation (8) relates the lag time to measurable physical basin parameters.

$$L_g = 26K_n\left(\frac{LL_{ca}}{S^{0.5}}\right)^N \tag{8}$$

where,

L_g = lag time (hours)
K_n = a constant based on an estimate of the weighted average Manning's n value of the principal watercourses in the basin;
L = distance of longest watercourse (miles)
L_{ca} = distance from basin outlet to a point opposite the centroid of the basin (miles)
S = overall slope of the longest watercourse (feet per mile)
N = an exponent, which was assumed to equal 0.33

Table 12 summarizes the initially estimated sampling range that the unit hydrograph and interflow lag time parameters were allowed to vary during model calibration. The range for the Pr parameter was determined by varying the K_n value in Equation (8) within a range of 0.08 to 0.15, which are typical of conditions in the Coast and Cascade Ranges of California, Oregon, and Washington (USBR 1989). The range for the peaking factor was based on information presented in MGS (2004). An initially very wide range was assumed for both the UZ and LZ constants to account for the potential for long time delays in the interflow hydrograph attributed to the presence of glaciers, fractured bedrock, or deep volcanic geologic material.

Throughout the model calibration, the UZ storage constant was computed as a function of Pr and likewise, the LZ storage constant was computed as a function of the UZ storage constant. This ensured that the lag times for the interflow component were longer than that for the surface runoff component. As seen in the table, for each model run, the UZ storage constant will initially be computed as Pr/60 plus a constant ranging from 1 to 50. The LZ storage constant will initially be computed as the UZ value plus a constant ranging from 1 to 200.

Table 12. Initial Sampling Range for Subbasin Calibration Parameters

Subbasin	Period of Rise, Pr (minutes)	Peaking Factor	UZ Storage Constant (hours)	LZ Storage Constant (hours)
UB1	140 – 300	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB2	120 – 260	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB3	110 – 240	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB4	100 – 210	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB5	160 – 350	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB6	110 – 230	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB7	180 – 410	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB8	120 – 250	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB9	---	---	---	---
LB1	100 - 200	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB2	100 – 210	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB3	180 – 400	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB4	130 – 280	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB5	90 – 190	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB6	150 – 320	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB7	---	---	---	---

3.7 Channel Routing Parameters

All subbasins were delineated such that the outlet was located at the reservoir interface. However, both the Park Creek and Sulphur Creek subbasins were further delineated at the USGS gaging station location. Therefore, channel routing was only necessary for the channels downstream of the two gaging stations. The respective lengths of the streams that included channel routing were 9,900 feet and 18,450 feet. These channel lengths are relatively short and therefore channel routing was not critical, but still was included in the model. The kinematic wave channel routing model was chosen. The channel section geometry was defined using an eight point cross section. All parameters that were required for the routing model were obtained from USGS field notes for the two gaging stations and are summarized in Table 13

Table 13. Hydrologic Channel Routing Parameters

Channel Location	Channel Length (ft)	Channel Slope (ft/ft)	Channel Roughness
Park Creek Downstream of USGS Gage	9,920	0.020	0.050
Sulphur Creek Downstream of USGS Gage	18,450	0.052	0.046

4 MODEL CALIBRATION AND VERIFICATION

The hydrologic model was calibrated and verified using reconstructed inflow hydrographs for Baker Lake and Lake Shannon. Hourly reservoir elevation and project discharge data were used to construct the reservoir inflow hydrographs for each of the calibration events. Separate inflow hydrographs were developed for the 214.9 mi^2 Upper Baker tributary area and the 83.8 mi^2 Lower Baker tributary area.

Two tributary subbasins in the Upper Baker watershed were equipped with USGS gaging stations which were only operative during the NOV 89 storm event and these provided additional hydrographs for calibration of the NOV 89 event.

As previously mentioned, calibration of the watershed model was accomplished using concepts from the Generalized Likelihood Uncertainty Estimation (GLUE) procedures developed by Beven et al (1992). The specific approach that was used was to identify initial ranges of each of the calibration parameters and to assemble multi-thousand trial parameter sets based on sampling over a wide, yet plausible range of values for each parameter. The watershed model was then executed and a measure was made of the goodness-of-fit between the observed and the simulated hydrographs for each of the parameter sets for each of the calibration storm events. A numerical threshold was set for the goodness-of-fit measure, to eliminate parameter values that do not produce good fits and to allow the sampling range of the parameters to be narrowed. This process was repeated, incrementally narrowing the bounds of the sampling range based on review of the goodness-of-fit measures. Once the sampling range of the calibration parameters values was narrowed as much as possible, parameter sets were then identified as "behavioral" based on goodness-of-fit measures for all storms in the calibration process. The behavioral parameter sets then formed the basis for identifying the calibrated parameter set that yielded the "best-fit" for the historical flood events.

Model calibration and verification proceeded in five phases as summarized below:

- PHASE I – Narrowing of Hydrograph Volume Parameters
- PHASE II – Narrowing of Hydrograph Shape Parameters
- PHASE III – Identification of Preliminary Calibration Parameter Set
- PHASE IV – Verification of the Preliminary Calibration Parameter Set
- PHASE V – Determination of the Final Calibration Parameter Set

4.1 Inflow Hydrographs

For each storm event, inflow hydrographs were reconstructed from recorded data for the tributary area to Upper Baker Dam (Baker Lake) and for local area tributary to Lower Baker Dam (Lake Shannon). These hydrographs were developed using hourly operations data provided by Puget Sound Energy (PSE) and the Seattle District USACE. The operation data included hourly values of reservoir elevation, outflow through the penstock, and total outflow over the spillways. Ordinate values for each inflow hydrograph were computed using a simple mass balance equation as shown below:

$$I - O = \Delta S \tag{9}$$

where,

$I =$ total inflow to the reservoir in a 1-hour time period (ac-ft)
$O =$ total outflow from the reservoir (penstock + spillway) in a 1-hour time period (ac-ft)
$\Delta S =$ change in reservoir volume over the one hour time period (ac-ft)

The inflow hydrographs were reconstructed using a 1-hour time interval. The resulting hydrographs naturally had a significant amount of "noise" that could be attributed to sudden changes in reservoir release, the large volume of reservoir storage associated with the 0.01 foot reporting accuracy of the reservoir stage, and possibly erroneous data. The hydrographs were "smoothed" by first using a 5-hour simple moving average technique. This was followed by a manual process of visually smoothing the hydrographs, which was primarily necessary for the Lower Baker inflow hydrographs. Visual smoothing of each of the inflow hydrographs was done is such a way as to ensure that the change in volume attributed to the smoothing was less than 5% of the initially computed inflow volume using the 5-hour average.

4.2 Events Used for Model Calibration

Five storm events were initially identified for potential use in calibrating the watershed model, with the intention that the reconstructed inflow hydrographs for both Upper and Lower Baker tributary areas would be used for each of the events.

Of the five events, the NOV 90(2) event was eliminated from further consideration due primarily to the lack of sufficient upper air data to help in defining the atmospheric lapse rate. This was important information for this particular storm due to the fact that this event had the largest antecedent snowpack of the five storms and that snow accumulation was significant during the storm, as indicated by the low air temperatures. Unlike the other four storm events, a large portion of the watershed was likely experiencing sub-freezing temperatures throughout the event. To properly model the response of the watershed for this event, it was especially critical to know the temporal and vertical changes in air temperature. Initial model runs for this storm failed to produce a hydrograph that properly matched the timing of the runoff hydrograph leading up to the peak, especially so for the Upper Baker portion of the watershed.

Of the remaining four events, the Upper Baker inflow hydrograph was eliminated from further consideration in the calibration process for the NOV 95(2) and the OCT 03 events, due to difficulties in producing proper temporal and general spatial characteristics for the precipitation in the upper watershed. Preliminary runs of the hydrologic model indicated that even assuming minimal soil losses, volumetric error for the Upper Baker inflow hydrograph was no better than a negative 20%. Given the fact that a single low-elevation gage is the only source of precipitation data within the watershed, precipitation mapping for the higher elevations is very difficult, but was found to be especially problematic for the NOV 95(2) and OCT 03 events. It is difficult to know how the terrain is affecting the storm pattern and distribution in the high elevation, as exemplified by the runoff volumes for the OCT 03 event. Precipitation distribution in the watershed was unique for this storm event, given the high ratio of Upper Baker runoff relative to Lower Baker runoff as summarized in Table 14.

Table 14. Inflow Hydrograph Volumes for the Initially Identified Calibration Events

Event	Hydrograph Start Time	Hydrograph End Time	Upper Baker (ac-ft)	Lower Baker (ac-ft)	TOTAL (ac-ft)	Ratio of UB/LB
NOV 89	11/08/89 00 hrs	11/12/89 00 hrs	102,676	34,300	136,976	3.0
NOV 90(1)	11/08/90 00 hrs	11/14/90 00 hrs	152,567	46,167	198,734	3.3
NOV 90(2)	11/21/90 00 hrs	11/26/90 00 hrs	98,399	39,918	138,317	2.5
NOV 95(2)	11/26/95 00 hrs	12/01/95 00 hrs	100,954	38,140	139,094	2.6
OCT 03	10/14/03 00 hrs	10/19/03 00 hrs	103,501	17,480	120,981	5.9

The hydrographs used to calibrate the watershed model are summarized in Table 15. The events used for actual model calibration were the NOV 89, the NOV 95(2), and the OCT 03 events and the event used for model verification was the NOV 90(1) event. The two tributary hydrographs that were available for the NOV 89 event were used in a supplementary fashion. They were both used during the hydrograph volume calibration step (Section 4.5) to provide additional insight while calibrating the interflow parameters and during the hydrograph shape calibration step (Section 4.6) to provide validation for decisions made regarding the unit hydrograph period of rise parameter.

Table 15. Hydrographs Used for Model Calibration/Verification

Event	Swift Creek Tributary	Park Creek Tributary	Baker Lake Inflow	Lake Shannon Inflow
NOV 89	**X**	**X**	**X**	**X**
NOV 90(1)			**X**	**X**
NOV 90(2)				
NOV 95(2)				**X**
OCT 03				**X**

4.3 Objective Functions and Likelihood Measures

Objective functions were used to quantify how well a given parameter produced a simulated runoff hydrograph that matched the observed hydrograph. There are many objective functions available; however, two were selected for use in the model calibration. The first is a modified form of the objective function that is included in the USACE HEC-1 package (USACE 1998), and the second is the Nash-Sutcliffe Efficiency (NSE) objective function.

The modified form of the USACE HEC-1 objective function (HEC) is shown as equation (10). This objective function includes a weighting function, WT_i that results in placing a heavier emphasis on matching peak flows and lesser emphases on lower flows. The value of the HEC objective function decreases as the similarity between observed and simulated flows increases and equals to 0.0 for a perfect fit.

$$HEC = \sum_{i=1}^{n} \left(\frac{Qobs_i - Qsim_i}{\overline{Qobs}} \right)^2 x \frac{WT_i}{n} \qquad (10)$$

where,

$HEC =$ value of the objective function for a single flood hydrograph

$Qobs_i =$ the value of the observed hydrograph at time step i (cfs)

$Qsim_i =$ the value of the model predicted hydrograph at time step i (cfs)

$\overline{Qobs} =$ the mean flow rate of the observed hydrograph (cfs)

$n =$ the total number of hydrograph ordinates

$WT_i = \frac{\left(Qobs_i + \overline{Qobs}\right)}{2\overline{Qobs}}$ = weighting factor for hydrograph ordinate i

The NSE objective function is shown as Equation (11). Unlike the HEC objective function, the NSE objective function places equal weight on each ordinate of the hydrograph, regardless of the magnitude. The value of the NSE objective function increases as the agreement between observed and simulated flows increases and equals 1.0 for a perfect fit.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Qobs_i - Qsim_i\right)^2}{\sum_{i=1}^{n} \left(Qobs_i - \overline{Qobs}\right)^2} \right] \tag{11}$$

where,

$NSE =$ value of the objective function for a single flood hydrograph

$Qobs_i =$ the value of the observed hydrograph at time step i (cfs)

$Qsim_i =$ the value of the simulated hydrograph at time step i (cfs)

$\overline{Qobs} =$ the mean flow rate of the observed hydrograph (cfs)

Both of the objective functions were used during the model calibration to evaluate goodness-of-fit of the simulated hydrograph. The form of equations (10) and (11) are for use for computing the value of the objective function for a single hydrograph at a single location in the watershed. For the NOV 89 and NOV 90(1) events, both the Upper and Lower Baker inflow hydrographs were used in the calibration process, so an equation was required to compute the objective function for the storm event comprised of multiple hydrographs at multiple locations in the watershed. Equation (12) was used for this purpose. The W_j parameter is a weighting function applied to each hydrograph and is equal to the ratio of the drainage to the total drainage. For the remaining events which incorporated only the Lower Baker inflow hydrograph, the objective function for the storm event was equal to the computed value of the objective function for the Lower Baker inflow hydrograph.

$$HEC_{group} = \sum_{j=1}^{n} HEC_j x W_j \tag{12}$$

where,

$HEC_{group} =$ the value of the modified form of the HEC objective function for the flood event with observed hydrographs at multiple sites

$HEC_j =$ the value of the objective function for the single flood hydrograph at site j

$W_j =$ weighting factor for the hydrograph at site j, which was computed as 0.70 for the Upper Baker inflow hydrograph and 0.30 for the Lower Baker inflow hydrograph.

A likelihood measure was used to assist in identifying and ranking "behavioral" parameter sets from a group of simulations. Behavioral sets are defined as those parameter sets that best reproduced the observed flood hydrographs for the set of calibration storm events. A threshold value of the objective function is used to separate "behavioral" parameter sets from "non-behavioral" parameter sets.

Likelihood measures were primarily used during the last stages of calibration (Phases III through V) to rank the "behavioral" parameter sets. The value of the likelihood measure for a given parameter set for a single flood event is computed as shown in Equation (13).

$$L_k = \left(\frac{1}{HEC_{group}} \right)^M \tag{13}$$

where,

$L_k =$ the value of the likelihood measure for flood event k with observed hydrographs at multiple sites

$HEC_{group} =$ the value of the modified form of the HEC objective function for the flood event with observed hydrographs at multiple sites

$M =$ a user specified parameter, which for this study was assumed to be 1.0

The value of the likelihood function for a given parameter set for the group of flood events is computed as Equation (14).

$$Lps = \sum_{k=1}^{n} L_k W_k \tag{14}$$

where,

$Lps =$ the value of the likelihood measure for a given parameters set for the group of flood events

$L_k =$ the value of the likelihood measure for flood event k

$W_k =$ weighting factor for flood event k

4.4 Initial Model Runs

The first stage of the model calibration was to conduct an initial run of the SEFM model, using the wide parameter sampling ranges that were identified previously in Section 3.5 and Section 3.6. The tables are copied below from these sections and are relabeled as Tables 16 and 17.

Table 16. Initial Sampling Range of Subbasin Calibration Parameters

Subbasin	Period of Rise, Pr (minutes)	Peaking Factor	UZ Storage Constant (hours)	LZ Storage Constant (hours)
UB1	140 – 300	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB2	120 – 260	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB3	110 – 240	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB4	100 – 210	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB5	160 – 350	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB6	110 – 230	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB7	180 – 410	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB8	120 – 250	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
UB9	---	---	---	---
LB1	100 – 200	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB2	100 – 210	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB3	180 – 400	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB4	130 – 280	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB5	90 – 190	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB6	150 – 320	450 – 550	Pr/60 + 1 to 50	UZ + 1 to 200
LB7	---	---	---	---

Table 17. Initial Sampling Range of Soil Calibration Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (in)	Minimum Surface Infiltration Rate, f_c (in/hr)	Deep Percolation Rate, f_d (in/hr)	Maximum Surface Infiltration Rate, f_{max} (in/hr)	Notes
1	---	---	---	---	Open Water
2	0	f_d + 10	0.10 – 0.50	10	Glaciers
3	0.4 – 11.1	f_d + (0.00 – 0.30)	0.00 – 0.30	4	Rock Outcrop
4	0.2 – 12.0	f_d + (0.00 – 0.40)	0.00 – 0.10	6	A Soils
5	0.4 – 11.1	f_d + (0.00 – 0.30)	0.00 – 0.30	4	B Soils Shallow
6	0.6 – 16.5	f_d + (0.00 – 0.30)	0.00 – 0.10	4	B Soils Deep
7	0.6 – 24.8	f_d + (0.00 – 0.30)	0.00 – 0.30	4	B Soils Deep
8	0.4 – 12.6	f_d + (0.00 – 0.15)	0.00 – 0.30	4	C Soils Shallow
9	0.2 – 18.0	f_d + (0.00 – 0.15)	0.00 – 0.10	2	C/D Soils Deep
10	0.6 – 24.8	f_d + (0.00 – 0.30)	0.10 – 0.50	4	Sulphur/Rocky

The SEFM model was run to produce 3,000 simulations and 3,000 corresponding HEC-1 input files. The HEC-1 program was then run in batch mode to produce 3,000 HEC-1 output files. Scatter plots were developed for each of the calibration parameters, plotting the parameter value versus the value of the goodness-of-fit objective function. Scatter plots are used in the GLUE methodology to evaluate sensitivity of the objective function to the value of specific model parameters. An example of a scatter plot that illustrates sensitivity of the objective function to the value of the minimum infiltration rate for Soil Zone 5 is shown in Figure 19.

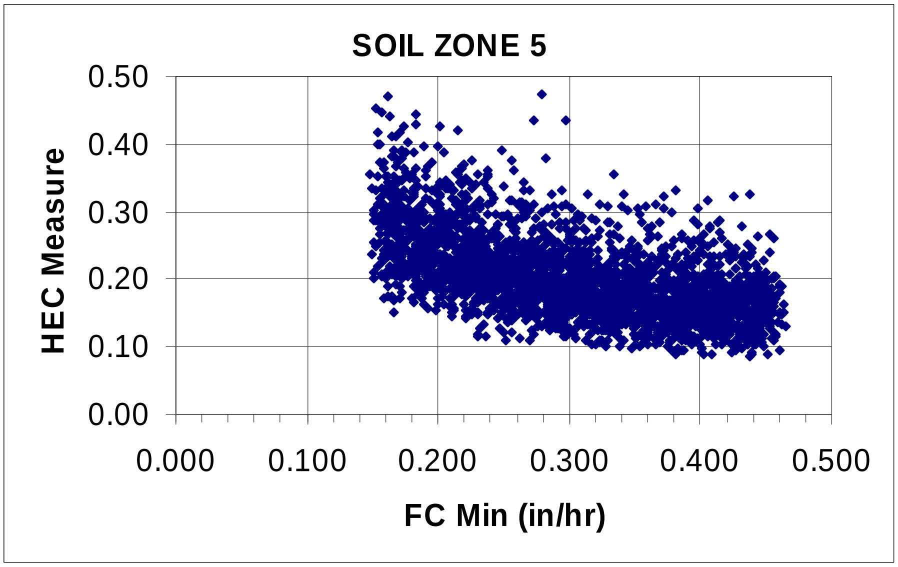


Figure 19. Example Scatter Plot for Soil Zone 5

The scatter plots for the initial model runs were reviewed to determine if there was any indication of specific parameters that are dominant factors in the runoff hydrograph or if the objective function is particularly sensitive particular parameters. The scatter plots were also reviewed to determine if the any of the parameter sampling ranges could be narrowed. The review did not strongly indicate any parameters to be dominant factors nor was it evident that there was any ability to narrow the sampling range of any of the parameters. This was due likely to the large number of parameters that were being sampled.

It was therefore difficult to develop any definitive conclusions regarding narrowing of any of the parameters at this time and it was decided to proceed with model calibration by first focusing on those parameters most a factor in determining total runoff volume.

4.5 Phase I – Hydrograph Volume Parameters

In order to reduce the number of calibration parameters in the hydrologic model, those parameters that directly affect runoff volume, namely the rate of deep percolation (f_d) and the maximum soil moisture storage capacity (S_{max}) were focused on first. The upper and lower interflow zone storage constants (UZ and LZ) have an indirect affect on runoff volume and were also focused on in this phase. Their effect on runoff volume however is solely due to the wide sampling range used for each of these two parameters which in the case of high values can cause a sufficiently long delay in the interflow that extends beyond the observation time of a particular storm event's hydrograph.

Therefore the goal of this first phase was twofold. The first was to determine fixed values for the f_d and S_{max} parameters for each soil zone. The second was to sufficiently narrow the sampling ranges for the UZ and LZ storage constants for each subbasin.

To better understand the magnitude of the lag times associated with the upper and lower interflow zones, the scatter plots for the two gaged tributaries, Swift Creek and Park Creek, were reviewed for the NOV 89 storm event. The scatter plots were developed from the results of the initial 3,000 simulations. Figures 20 through 23 show the scatter plots for the UZ and LZ storage constants for each of these two tributaries and both indicate the ability to narrow the sampling range based on goodness-of-fit to the tributary runoff hydrographs. The trend for lower values for these two parameters was strongly indicated using these two hydrographs, and therefore the conclusion was that the sampling range could realistically be narrowed.

The plots indicated that the Park Creek subbasin has slightly shorter lag times for the interflow component relative to the interflow lag times for the Swift Creek subbasin. This seems reasonable based on the specific conditions of the Park Creek subbasin, which is characterized by shallower soils, lesser coverage of fractured bedrock, and a shorter time of concentration than is the case for the Swift Creek subbasin.

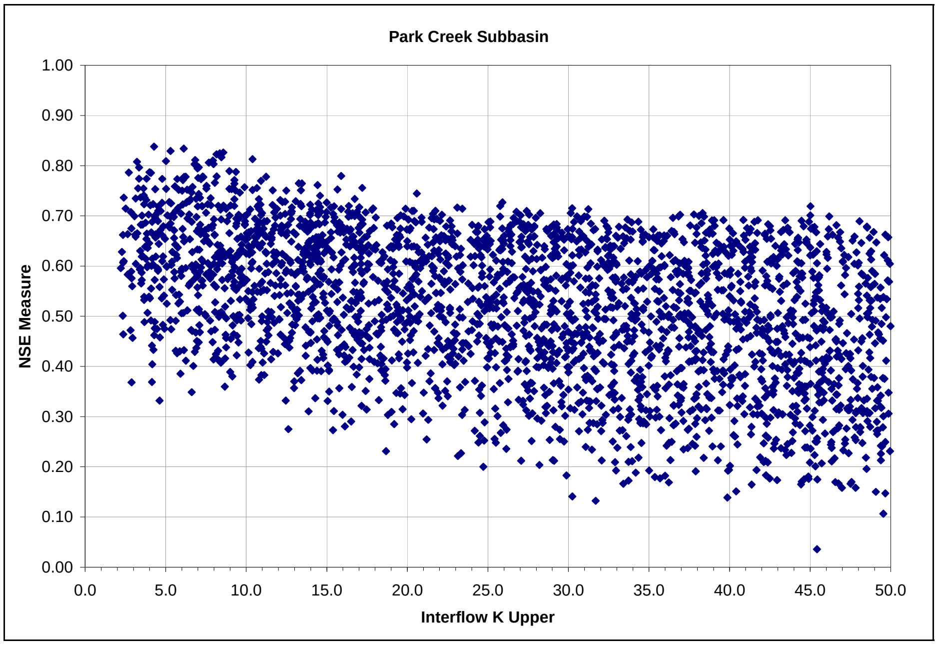


Figure 20. Scatter Plot of Upper Zone Interflow Constant for Park Creek Subbasin

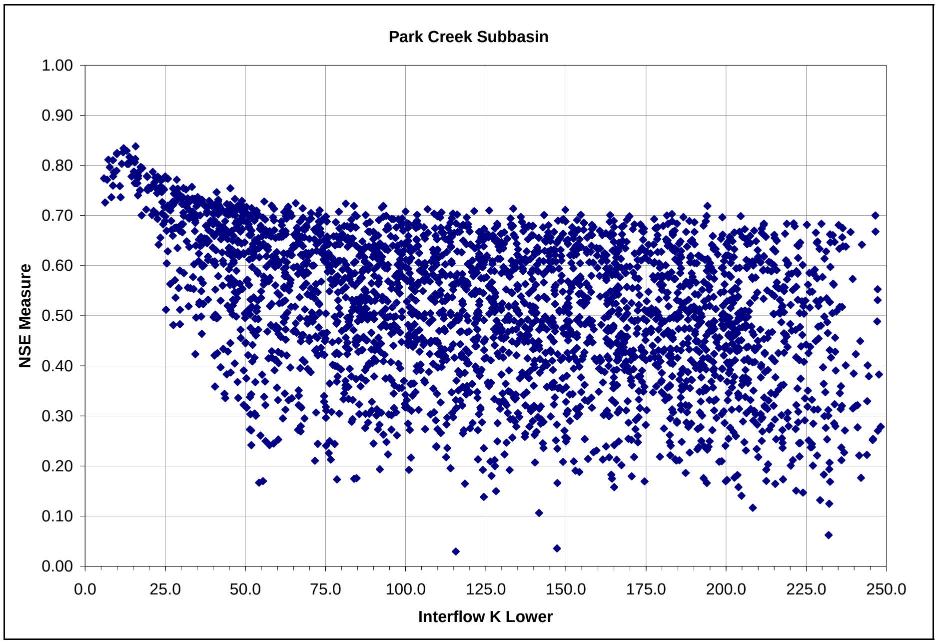


Figure 21. Scatter Plot of Lower Zone Interflow Constant for Park Creek Subbasin

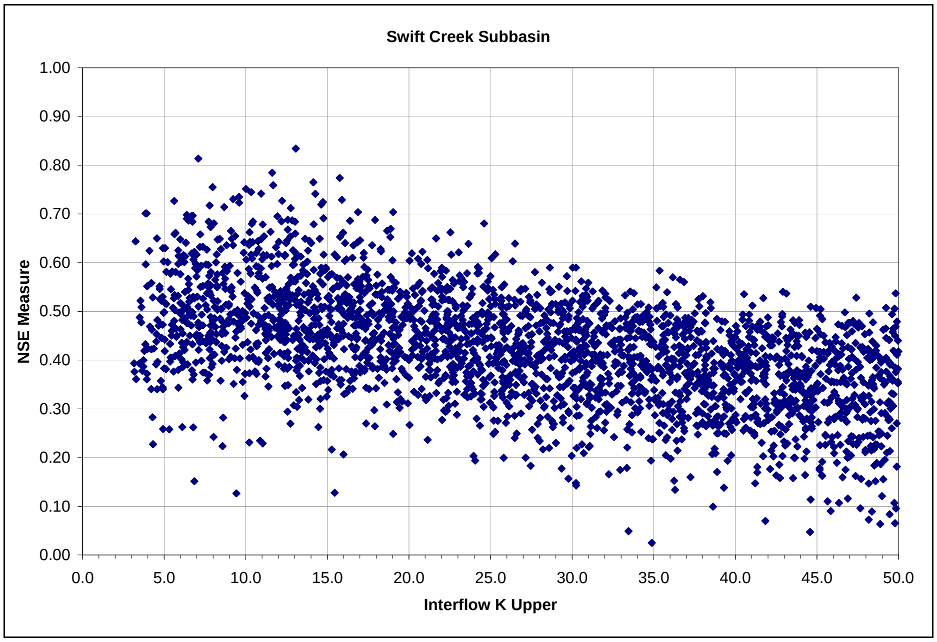


Figure 22. Scatter Plot of Upper Zone Interflow Constant for Swift Creek Subbasin

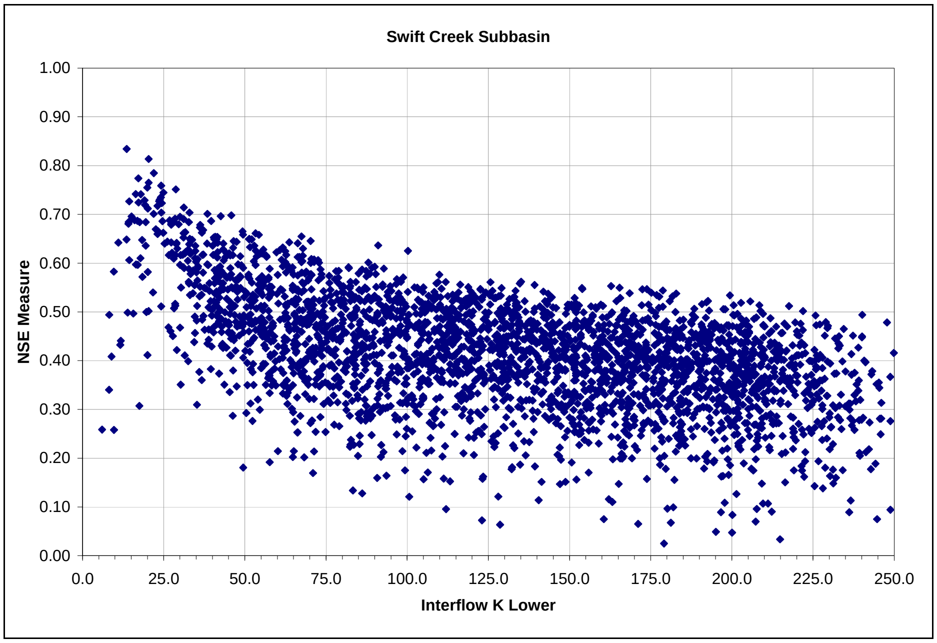


Figure 23. Scatter Plot of Lower Zone Interflow Constant for Swift Creek Subbasin

Taking advantage of this information, the fourteen non-reservoir subbasins were separated into two groups based on their geologic and hydrologic similarity to either the Swift Creek or Park Creek subbasins. Group I included those subbasins which are characterized by linear stream networks, shallow soils and/or a smaller coverage of highly fractured bedrock. This group was deemed similar to the Park Creek subbasin. Group II included those subbasins which are characterized by more dendritic stream networks, deeper soils and/or a larger coverage of highly fractured bedrock. This group was deemed similar to the Swift Creek subbasin.

The subbasins were grouped as follows and the sampling range of the interflow lag times for each of the two groups was narrowed using a threshold NSE value of 0.75 for Park Creek and 0.70 for Swift Creek:

- Group I (UZ = Pr + 0 to 20hrs and LZ = UZ + 0 to 10hrs)
  - UB 1,2,3,4
  - LB 1,2,3,4,5
- Group II (UZ = Pr + 0 to 25hrs and LZ = UZ + 0 to 20hrs)
  - UB 5,6,7,8
  - LB 6

With the interflow lag times sufficiently narrowed, the SEFM model was then run to produce 3,000 simulations and 3,000 HEC-1 input files for each of the three calibration storms. The HEC-1 program was then run in batch mode to produce 3,000 HEC-1 output files so as to allow investigation for the narrowing of the f_d and S_{max} parameters. Using a volumetric threshold of 10%, 1478, 288, and 157 simulations were identified that fell within this threshold for the NOV 89, NOV 95(2), and OCT 03 storm events, respectively. Of these simulations, 18 were identified as common amongst all three storms. The mean value of these behavioral parameters was the basis of fixing S_{max}. No narrowing of the f_d parameter occurred at this time.

With the fixed values of S_{max} and the narrowed ranges for the UZ and LZ storage constants, the SEFM model was run to produce 3,000 simulations and 3,000 HEC-1 input files. The HEC-1 program was then run in batch mode to produce 3,000 HEC-1 output files so as to allow for narrowing of the f_d parameter. Review of the scatter plots for this run lead to the conclusion that fd for Soil Zones 4 and 8 could be narrowed slightly and that a third subbasin grouping for the interflow parameter was necessary. Scatter plots for Subbasins LB1 and LB2 indicated better goodness-of-fit values for lower interflow lag times. Therefore a third group of subbasins was added to the interflow grouping and the values for all three groups were narrowed slightly. The final subbasin grouping for the interflow parameters was as follows:

- Group I (UZ = Pr + 0 to 18hrs and LZ = UZ + 0 to 15hrs)
  - UB 1,2,3,4
  - LB 3,4,5
- Group II (UZ = Pr + 0 to 15hrs and LZ = UZ + 0 to 15hrs)
  - UB 5,6,7,8
  - LB 6
- Group III (UZ = Pr + 0 to 7hrs and LZ = UZ + 0 to 5hrs)
  - LB 1,2

The final step in the volume calibration phase included a final run of the SEFM model with the objective to fix the magnitude of the fd parameter for each soil zone. The SEFM model was run to produce 3,000 simulations and 3,000 HEC-1 input files. The HEC-1 program was then run in batch mode to produce 3,000 HEC-1 output files so as to allow for final fixing of the fd parameters. For each of the three storms, the model output was reviewed and parameter sets that satisfied a threshold of less than 10% error for a given runoff hydrograph (Upper or Lower Baker inflow) while at the same time not exceeding a 10% total volume error for the storm were identified. Of the 3,000 simulations, 396, 1408, and 717 sets from the NOV 89, NOV 95(2), and OCT 03 events, respectively met this threshold. Of these, two of the parameter sets were identified as common amongst all three storms. The deep percolation rates for each of the ten soil zones were then computed as the average value from these two common sets.

During this process the objective function was found to be insensitive to the magnitude of the unit hydrograph peaking factor, which was therefore fixed at the average value of the sampling range.

The Phase I calibration effort resulted in narrowing the sampling range for several parameters and fixing the values of the parameters most influential in determining hydrograph volume. The results are summarized in Tables 18 and 19.

Table 18. Sampling Range of Subbasin Calibration Parameters – Results of Phase I

Subbasin	Period of Rise, Pr (minutes)	Peaking Factor	UZ Storage Constant (hours)	LZ Storage Constant (hours)
UB1	140 – 300	500	Pr/60 + 1 to 18	UZ + 1 to 15
UB2	120 – 260	500	Pr/60 + 1 to 18	UZ + 1 to 15
UB3	110 – 240	500	Pr/60 + 1 to 18	UZ + 1 to 15
UB4	100 – 210	500	Pr/60 + 1 to 18	UZ + 1 to 15
UB5	160 – 350	500	Pr/60 + 1 to 15	UZ + 1 to 15
UB6	110 – 230	500	Pr/60 + 1 to 15	UZ + 1 to 15
UB7	180 – 410	500	Pr/60 + 1 to 15	UZ + 1 to 15
UB8	120 – 250	500	Pr/60 + 1 to 15	UZ + 1 to 15
UB9	---	---	---	---
LB1	100 - 200	500	Pr/60 + 1 to 7	UZ + 1 to 5
LB2	100 – 210	500	Pr/60 + 1 to 7	UZ + 1 to 5
LB3	180 – 400	500	Pr/60 + 1 to 18	UZ + 1 to 15
LB4	130 – 280	500	Pr/60 + 1 to 18	UZ + 1 to 15
LB5	90 – 190	500	Pr/60 + 1 to 18	UZ + 1 to 15
LB6	150 – 320	500	Pr/60 + 1 to 15	UZ + 1 to 15
LB7	---	---	---	---

Table 19. Sampling Range of Soil Zone Calibration Parameters – Results of Phase I

Soil Zone	Maximum Soil Moisture Storage, S_{max} (in)	Minimum Surface Infiltration Rate, f_c (in/hr)	Deep Percolation Rate, f_d (in/hr)	Maximum Surface Infiltration Rate, f_{max} (in/hr)	Notes
1	---	---	---	---	Open Water
2	0	f_d + 10	0.209	10	Glaciers
3	5.58	f_d + (0.00 – 0.30)	0.044	4	Rock Outcrop
4	5.02	f_d + (0.00 – 0.40)	0.058	6	A Soils
5	3.80	f_d + (0.00 – 0.30)	0.115	4	B Soils Shallow
6	7.84	f_d + (0.00 – 0.30)	0.071	4	B Soils Deep
7	10.10	f_d + (0.00 – 0.30)	0.197	4	B Soils Deep
8	5.89	f_d + (0.00 – 0.15)	0.115	4	C Soils Shallow
9	6.49	f_d + (0.00 – 0.15)	0.067	2	C/D Soils Deep
10	10.59	f_d + (0.00 – 0.30)	0.374	4	Sulphur/Rocky

4.6 Phase II – Hydrograph Shape Parameters

With the deep percolation rate and maximum soil moisture storage capacity fixed for each of the soil zones, and with the sampling range sufficiently narrowed for the time delay associated with the interflow component, the calibration process proceeded to consider those parameters which directly affect the shape of the hydrograph. The sampling ranges for each of the parameters as outline above in Tables 18 and 19 were used as the starting point for this phase. The SEFM model was run to produce 3,000 simulations and 3,000 HEC-1 input files. The HEC-1 program was then run in batch mode to produce 3,000 HEC-1 output files so as to allow for the investigation of narrowing the remaining parameters.

Scatter plots of the model runs for all three storms were used to conservatively narrow the sampling range of each of the calibration parameters. The following threshold values for the HEC objective function were used in the evaluation of the scatter plots to narrow the remaining parameters:

- NOV 89 Storm Event – 0.10 HEC
- NOV 95(2) Storm Event – 0.02 HEC
- OCT 03 Storm Event – 0.05 HEC

Review of the interflow time delay scatter plots resulted in a decision to further narrow the sampling range for the Group II upper and lower zone interflow constants. Scatter plots for this group illustrated a strong indication that the upper bound of both the upper and lower zone constants should be decreased. Figure 24 illustrates an example scatter plot for the lower zone interflow constant for the NOV 89 event. In this plot, the lower zone interflow constant for Subbasin UB6 is plotted against the HEC objective function. It should be noted that the x-axis of for this plot is the computed value of the lower zone interflow constant.

The sampling range for the minimum infiltration rate was narrowed for a few of the soil zones where appropriate. For the most part, the scatter plots did not illustrate any strong indication for narrowing the ranges, especially for those soils that occupy only a small percentage of the overall watershed (i.e. Soil Zones 2, 4, 8, and 10).

The sampling range for each of the subbasin unit hydrograph period of rise values, Pr, was also narrowed during this phase. Primarily the upper bound of the Pr sampling range was reduced for each subbasin. Scatter plots of sampled Pr values for specific subbasins versus the value of the objective function for the total basin hydrograph were used to evaluate the sensitivity of Pr to the objective function. The objective function values were computed using the simulated and observed hydrographs for the Upper and Lower Baker tributary areas.

The availability of observed tributary subbasin hydrographs (Swift Creek and Park Creek) for the NOV 89 event allowed a more detailed consideration of Pr values for these two subbasins for this particular storm event. Separate scatter plots were developed that considered the sensitivity of the basin specific Pr value to the objective function specifically for the Swift Creek and Park Creek hydrographs. These plots are shown as Figures 25 and 26. Since sampling of the Pr parameter was conducted at discreet 30-minute increments as opposed to being sampled as a continuous variable like all of the other calibration parameters, the resulting data points in the Pr scatter plots are grouped in 30-minutes segments. As seen in Figures 25, the goodness of fit to the observed Park Creek hydrograph was best for lower values of Pr as indicated by smaller values of the HEC objective function. These basin specific scatter plots validated the decision to narrow the upper bound of the Pr sampling range for the other subbasins, which was based on the broader review of the scatter plots for the Upper and Lower Baker tributary areas hydrographs.

Tables 20 and 21 illustrate the results of this phase. At the end of this phase, it was concluded that the parameter sampling ranges had been narrowed as much as possible, and that the sampling ranges were within physically reasonable bounds. The next phase used the sampling ranges in Tables 20 and 21 to determine an initial set of calibration parameters.

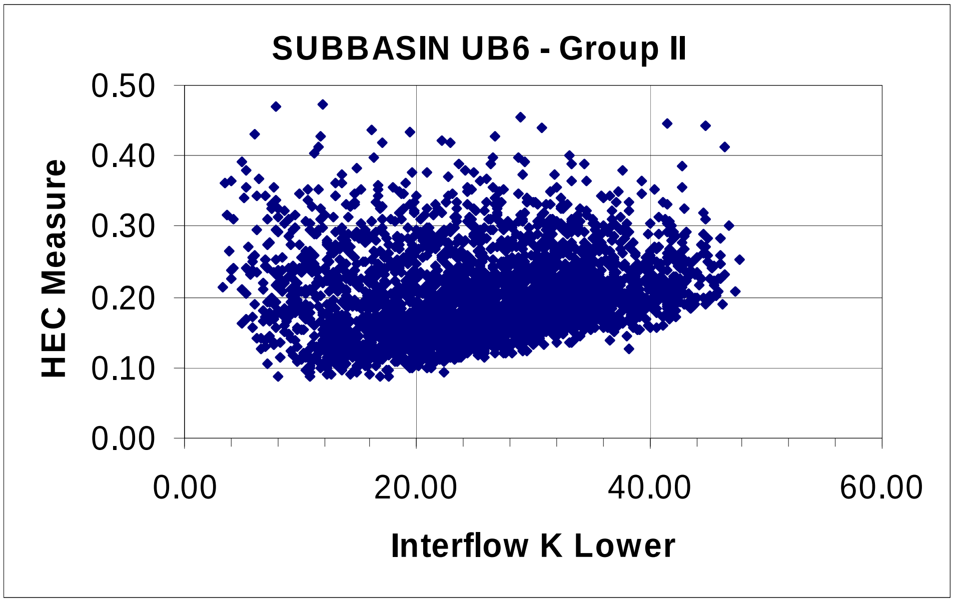


Figure 24. Scatter Plot of Group II Lower Zone Interflow Constant for NOV 89

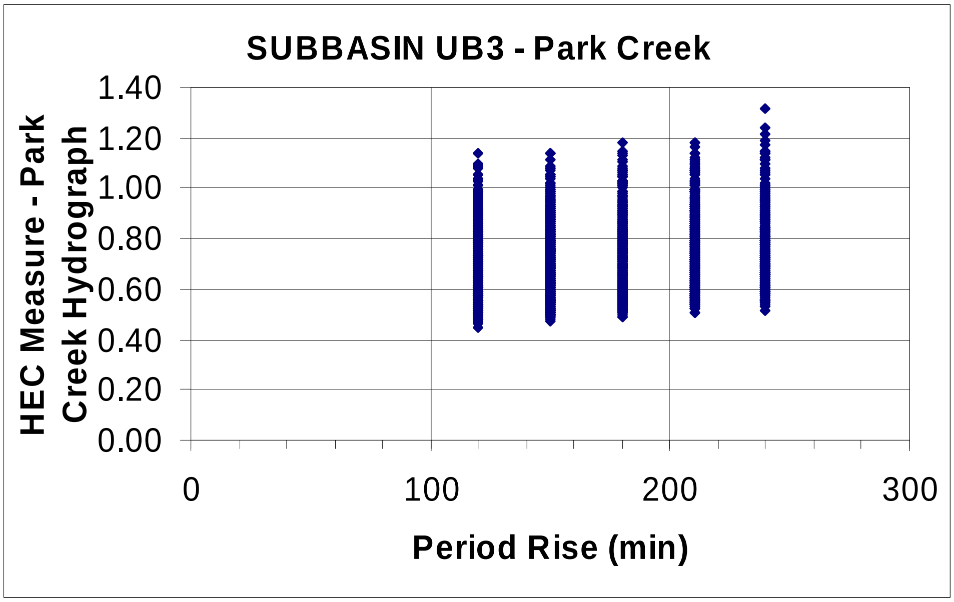


Figure 25. Scatter Plot of Park Creek Period of Rise for NOV 89 Park Creek Hydrograph

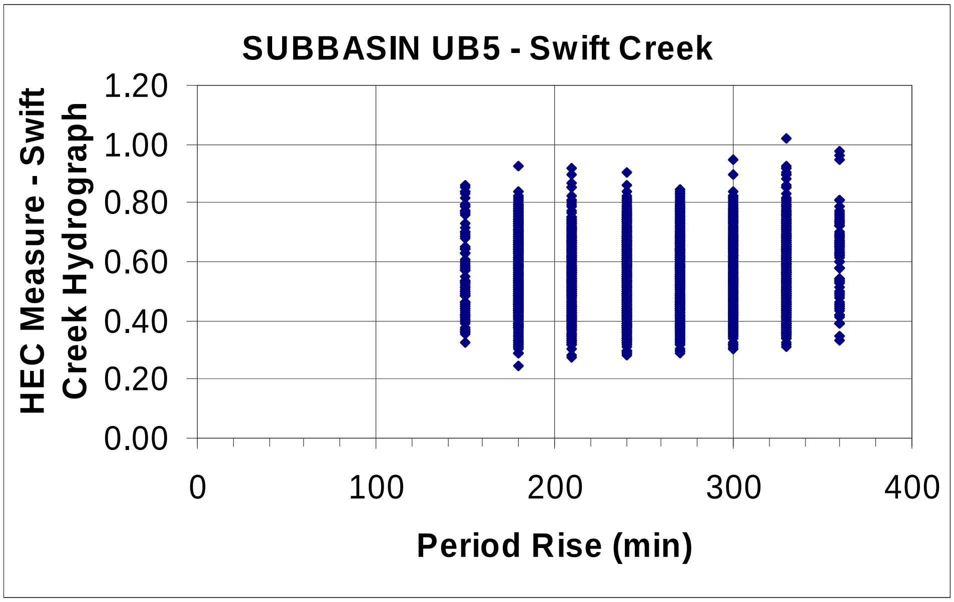


Figure 26. Scatter Plot of Swift Creek Period of Rise for NOV 89 Swift Creek Hydrograph

Table 20. Sampling Range of Subbasin Calibration Parameters – Results of Phase II

Subbasin	Period of Rise, Pr (minutes)	Peaking Factor	UZ Storage Constant (hours)	LZ Storage Constant (hours)	Grouping
UB1	150 – 300	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
UB2	120 – 240	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
UB3	120 – 210	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
UB4	120 – 210	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
UB5	180 – 330	508	Pr/60 + 1 to 10	UZ + 1 to 10	II
UB6	120 – 210	508	Pr/60 + 1 to 10	UZ + 1 to 10	II
UB7	210 – 390	508	Pr/60 + 1 to 10	UZ + 1 to 10	II
UB8	120 – 210	508	Pr/60 + 1 to 10	UZ + 1 to 10	II
UB9	---	---	---	---	
LB1	120 – 210	508	Pr/60 + 1 to 7	UZ + 1 to 5	III
LB2	120 – 210	508	Pr/60 + 1 to 7	UZ + 1 to 5	III
LB3	210 – 390	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
LB4	150 – 270	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
LB5	90 – 180	508	Pr/60 + 1 to 18	UZ + 1 to 15	I
LB6	180 – 300	508	Pr/60 + 1 to 10	UZ + 1 to 10	II
LB7	---	---	---	---	

Table 21. Sampling Range of Soil Zone Calibration Parameters – Results of Phase II

Soil Zone	Maximum Soil Moisture Storage, S_{max} (in)	Minimum Surface Infiltration Rate, f_c (in/hr)	Deep Percolation Rate, f_d (in/hr)	Maximum Surface Infiltration Rate, f_{max} (in/hr)	Notes
1	---	---	---	---	Open Water
2	0	f_d + 10	0.209	10	Glaciers
3	5.58	f_d + (0.000 – 0.300)	0.044	4	Rock Outcrop
4	5.02	f_d + (0.000 – 0.400)	0.058	6	A Soils
5	3.80	f_d + (0.075 – 0.300)	0.115	4	B Soils Shallow
6	7.84	f_d + (0.050 – 0.290)	0.071	4	B Soils Deep
7	10.10	f_d + (0.050 – 0.250)	0.197	4	B Soils Deep
8	5.89	f_d + (0.010 – 0.150)	0.115	4	C Soils Shallow
9	6.49	f_d + (0.000 – 0.130)	0.067	2	C/D Soils Deep
10	10.59	f_d + (0.000 – 0.300)	0.374	4	Sulphur/Rocky

4.7 Phase III – Identification of Preliminary Calibrated Parameter Set

Using the parameters listed above in Tables 20 and 21, the SEFM model was run for each of the three calibration storm events to produce 8,000 simulations and 8,000 HEC-1 input files. The HEC-1 program was run in batch mode to produce 8,000 HEC-1 output files which allowed for the determination of the initial calibration parameter set. Since sufficient narrowing of the parameter sampling ranges had been conducted during the previous phases of the calibration, it was expected that the 8,000 runs would include a large number of parameter sets that were capable of reproducing the observed hydrographs.

Behavioral parameter sets were identified for each of the three storm events, using the NSE objective function. A threshold value of 0.850 was used to differentiate behavioral parameter sets from non-behavioral parameter sets, meaning that any parameter set that produced a hydrograph with an NSE value greater than 0.850 was identified as behavioral for the given storm event. Any parameter set that resulted in an NSE value less than or equal to 0.850 was identified as non-behavioral. Of the 8,000 simulations 4631, 6494, and 3236 parameter sets met this condition for the NOV 89, NOV 95(2), and OCT 03 storm events, respectively. Table 22 summarizes the objective function values for the Phase III simulations.

Table 22. Summary of Objective Functions for Individual Calibration Storm Events – PHASE III

Objective Function	NOV 89 Event	NOV 95(2) Event	OCT 03 Event
NSE Objective Function - All 8,000 Parameter Sets			
Best Simulation	0.913	0.927	0.941
Median Value	0.852	0.873	0.833
Worst Simulation	0.610	0.712	0.584
Evaluation Threshold	0.850	0.850	0.850
Number of Behavioral Parameter Sets	4,631	6,494	3,236
HEC Objective Function – Behavioral Parameter Sets Only			
Best Simulation	0.092	0.030	0.078
Median Value	0.141	0.050	0.180
Worst Simulation	0.170	0.067	0.224

Parameter sets identified as behavioral for a single storm event will not necessarily be so for another storm event. Of the behavioral parameter sets identified in Table 22 for the individual storm events, 1113 of them were identified as behavioral for all three storm events. This pool of parameter sets was then used to identify the preliminary calibrated parameter set. Likelihood measures were computed for each of storm events for each of the 1113 parameter sets using Equation (13). Using Equation (14) the likelihood value for each parameter set for the group of flood events was calculated. All storms were equally weighted in computing the likelihood value for the group of flood events. The parameter sets were ranked in descending order using the value of the likelihood measure for the group of flood events.

The top ten parameter sets, based on the highest combined likelihood values, were extracted. Table 23 summarizes key information about each of these parameter sets, including the runoff volume and goodness-of-fit measures. Due to the large number of parameters included in a given parameter set, parameter values are not included in this table.

The mean value for each parameter from this list of top ten behavioral parameter sets was computed. This collection of mean values was identified as the preliminary calibrated parameter set. Tables 24 and 25 present the values for each of the parameters in this preliminary calibrated parameter set.

Table 23. Model Results for Top Ten Behavioral Parameter Sets from Phase III Calibration

Sim No.	Average Likelihood	NOV 89 Event							NOV 95(2) Event					OCT 03 Event				
		Runoff Volume UB (ac-ft)	% Error	Runoff Volume LB (ac-ft)	% Error	HEC	NSE	Likelihood	Runoff Volume LB (ac-ft)	% Error	HEC	NSE	Likelihood	Runoff Volume LB (ac-ft)	% Error	HEC	NSE	Likelihood
5032	15.73	113,982	-1%	40,246	7%	0.15	0.86	6.76	33,714	-10%	0.03	0.92	30.80	15,450	-8%	0.10	0.92	9.62
6575	14.92	113,790	-1%	40,229	7%	0.15	0.86	6.51	33,616	-10%	0.03	0.92	29.77	15,326	-8%	0.12	0.91	8.48
1442	14.90	113,948	-1%	40,245	7%	0.16	0.85	6.07	33,727	-10%	0.03	0.92	28.90	15,443	-8%	0.10	0.93	9.72
7729	14.81	113,954	-1%	40,231	7%	0.14	0.87	7.35	33,595	-11%	0.04	0.92	28.45	15,306	-9%	0.12	0.92	8.62
4582	14.73	113,963	-1%	40,246	7%	0.16	0.85	6.14	33,777	-10%	0.04	0.92	28.40	15,430	-8%	0.10	0.93	9.66
6116	14.70	113,957	-1%	40,237	7%	0.16	0.85	6.25	33,695	-10%	0.03	0.92	28.76	15,367	-8%	0.11	0.92	9.09
3377	14.65	113,602	-2%	40,235	7%	0.13	0.88	7.77	33,645	-10%	0.04	0.92	28.39	15,295	-9%	0.13	0.91	7.81
3975	14.47	113,904	-1%	40,231	7%	0.16	0.85	6.25	33,605	-10%	0.03	0.92	28.90	15,285	-9%	0.12	0.91	8.25
6521	14.41	113,567	-2%	40,226	7%	0.16	0.85	6.27	33,524	-11%	0.04	0.92	28.29	15,318	-9%	0.12	0.92	8.69
1286	14.34	113,691	-1%	40,223	7%	0.16	0.85	6.22	33,541	-11%	0.04	0.92	28.40	15,279	-9%	0.12	0.92	8.40

Notes:

1. The value of the HEC and NSE objective function for the NOV 89 storm is a weighted computation to include both the Upper Baker and Lower Baker inflow hydrographs. The value of the HEC and NSE objective function for the NOV 95(2) and OCT 03 storm is based only on the Lower Baker inflow hydrograph

Table 24. Preliminary Calibrated Subbasin Parameters

Subbasin	Period of Rise, Pr (minutes)	Peaking Factor	UZ Storage Constant (hours)	LZ Storage Constant (hours)
UB1	240	500	6.4	11.1
UB2	180	500	5.6	10.3
UB3	150	500	5.2	9.9
UB4	180	500	5.6	10.3
UB5	240	500	8.8	12.6
UB6	180	500	7.7	11.5
UB7	330	500	10.1	13.9
UB8	180	500	7.7	11.5
UB9	---	---		
LB1	180	500	5.1	7.4
LB2	150	500	4.6	7.0
LB3	300	500	7.4	12.1
LB4	210	500	6.0	10.7
LB5	120	500	4.6	9.3
LB6	210	500	8.5	12.3
LB7	---	---	---	---

Table 25. Preliminary Calibrated Soil Zone Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (in)	Minimum Surface Infiltration Rate, f_c (in/hr)	Deep Percolation Rate, f_d (in/hr)	Maximum Surface Infiltration Rate, f_{max} (in/hr)	Notes
1	---	---	---	---	Open Water
2	0	10.209	0.209	10	Glaciers
3	5.58	0.247	0.044	4	Rock Outcrop
4	5.02	0.312	0.058	6	A Soils
5	3.80	0.352	0.115	4	B Soils Shallow
6	7.84	0.299	0.071	4	B Soils Deep
7	10.10	0.373	0.197	4	B Soils Deep
8	5.89	0.212	0.115	4	C Soils Shallow
9	6.49	0.110	0.067	2	C/D Soils Deep
10	10.59	0.484	0.374	4	Sulphur/Rocky

4.8 Phase IV – Verification of Preliminary Calibrated Parameter Set

The preliminary calibrated parameter set was verified using the NOV 90(1) storm event. Both the Upper Baker and Lower Baker inflow hydrographs were used to verify the validity of the preliminary calibrated parameter set. Figures 27 and 28 show a comparison between the simulated and observed hydrographs for this verification event using the preliminary calibrated parameter set.

The Lower Baker inflow hydrograph for the NOV 90(1) storm event (Figure 27) was reproduced well using the preliminary calibrated parameter set. As reported in Table 26, the predicted volume for this hydrograph was within 5% of the observed volume. The rising limb of the hydrograph was also well replicated indicating the response of the watershed to precipitation was accurately modeled and that the antecedent soil conditions were well estimated. The primary peak of the observed hydrograph was predicted to within 12% of the observed, indicating that the unit hydrographs used in the model accurately predicted the surface runoff response. The reproduction of the observed Lower Baker inflow hydrograph for this storm event was also aided by the likelihood that the temporal distribution of the precipitation input matched that which actually occurred. The single precipitation gage in the watershed provided the only known point for temporal distribution and it likely better represented the lower portion of the watershed more so than the upper portion of the watershed. In reviewing Figure 28, it does appear that perhaps the portion of the storm event that produced the secondary peak at approximately 1200 hours on 11/10/89 was not picked up in the spatial analysis of the historical precipitation. This is not an indication of shortcomings of the precipitation analysis but more indicative of the lack of hourly precipitation data in the higher elevations of the watershed. This is also not a problem unique to this particular storm event.

The Upper Baker inflow hydrograph for the NOV 90(1) storm event (Figure 28) is fairly well replicated using the preliminary calibrated parameter set. The predicted volume was short by 18%, but it is felt that a portion of this volumetric shortcoming is attributed to the challenge of accurately mapping the precipitation input in the upper high elevation portion of the watershed, as discussed in Section 4.2. Although the first peak of the hydrograph matched very well with the observed, the precipitation that produced the largest peak at approximately 1100 hours on 11/10/89 was not picked up in the spatial precipitation analysis. This is evident in the decreasing rainfall intensities in the model input throughout the day on 11/10/89. Therefore, since this volumetric input was missing, the hydrologic model was not able to reproduce this higher peak. The first peak of the simulated hydrograph is within 10% of observed, and like the Lower Baker inflow hydrograph, the rising limb was well replicated indicating the response of the watershed to precipitation is being accurately modeled and that the antecedent soil conditions were well estimated.

The preliminary calibrated parameter set was also used to produce runoff hydrographs for the three calibration storm events. This was done for informative purposes since this was not the final calibration phase. Figures 29 through 32 show the simulated hydrographs for the calibration storm events using this preliminary calibration parameter set

Table 26. Summary of Model Results for Preliminary Calibrated Parameter Set

Objective Measure	NOV 90(1) (Verification)	NOV 89	NOV 95(2)	OCT 03
% Volume Error UB	- 18%	- 1%	---	---
% Volume Error LB	- 5%	+ 7%	- 10%	- 8%
HEC Objective Function	0.111	0.143	0.036	0.121
NSE Objective Function	0.764	0.868	0.916	0.915

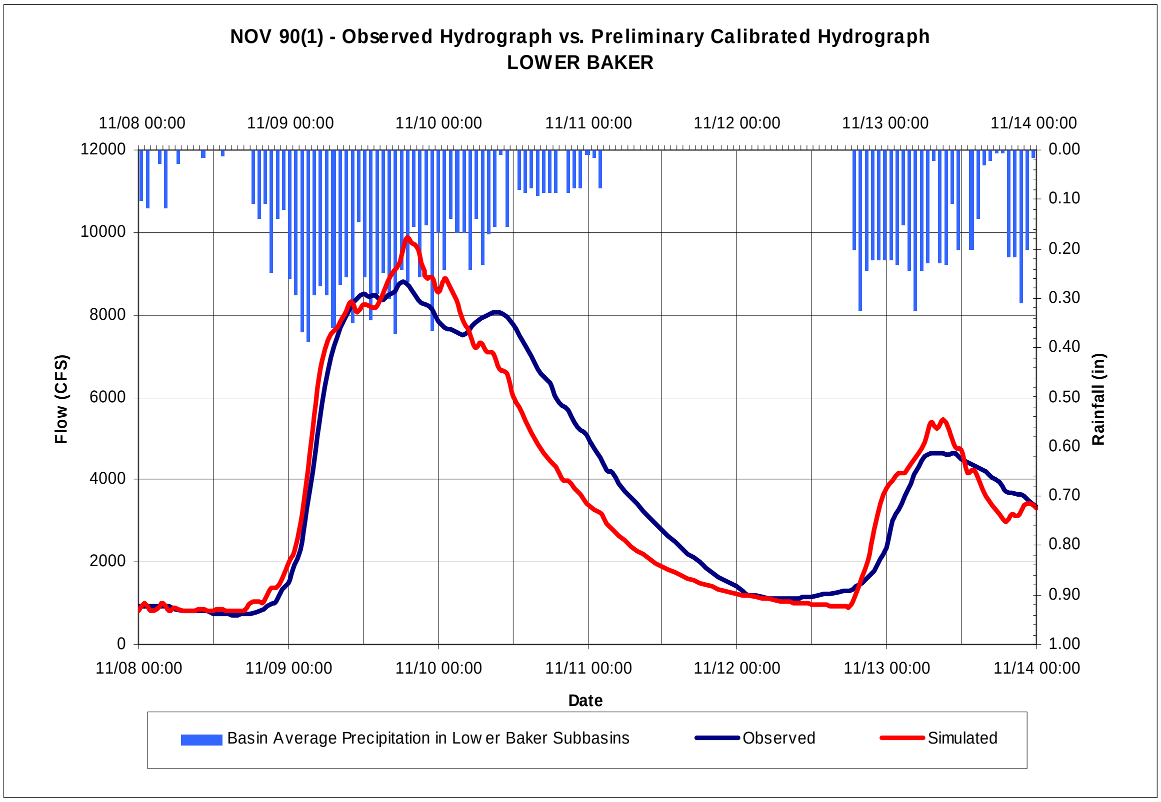


Figure 27. Verification of Preliminary Calibrated Parameter Set – Lower Baker Inflow NOV 90(1)

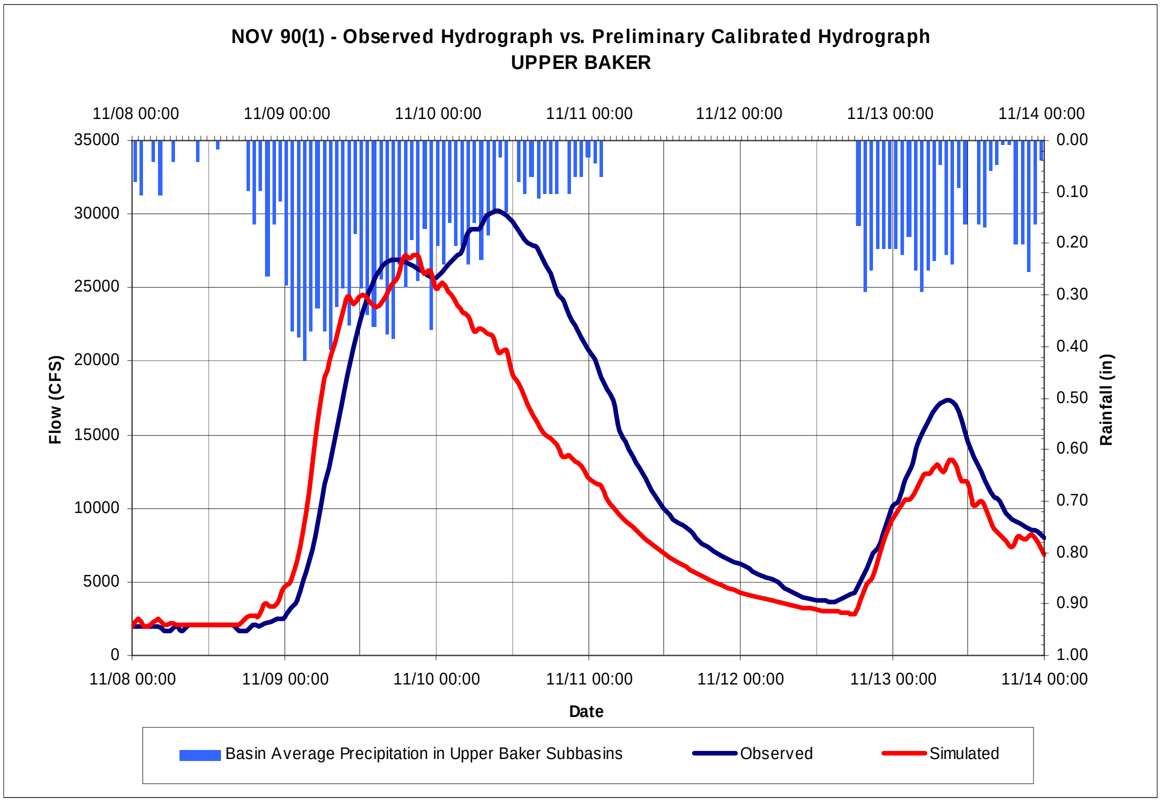


Figure 28. Verification of Preliminary Calibrated Parameter Set – Upper Baker Inflow NOV 90(1)

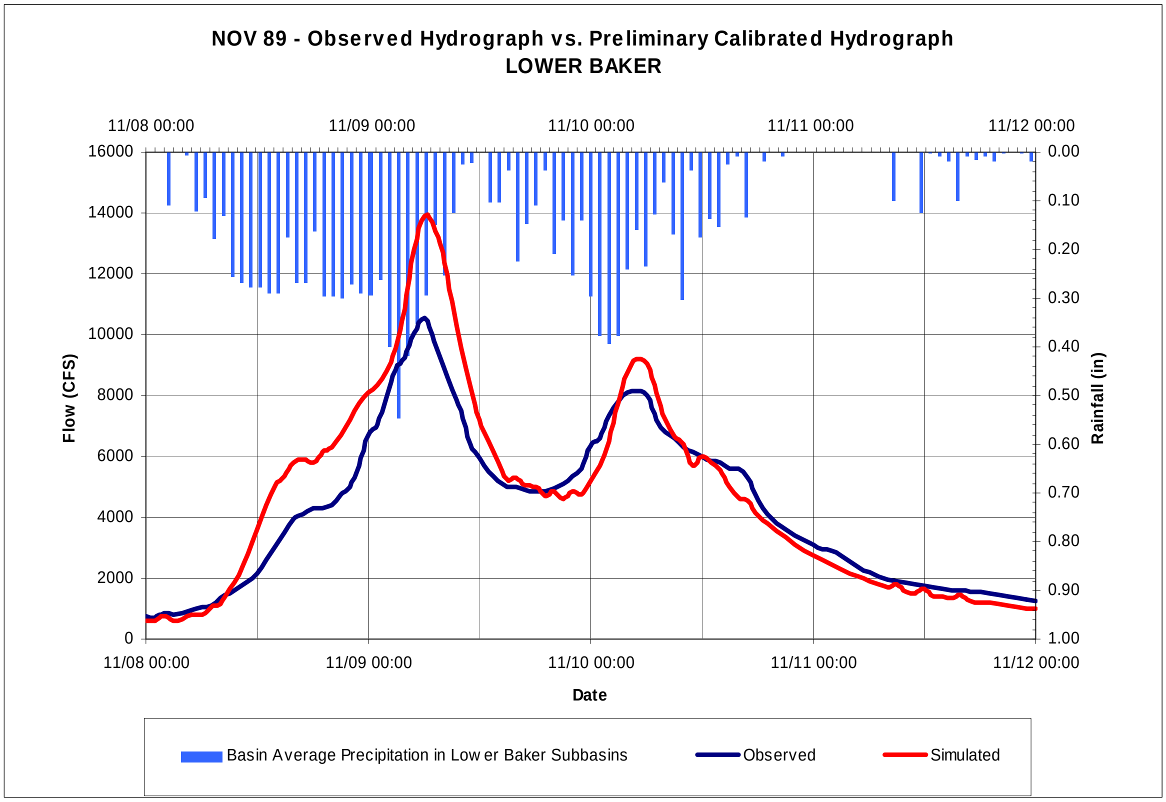


Figure 29. NOV 89 Lower Baker Inflow Hydrograph – Preliminary Calibrated Parameter Set

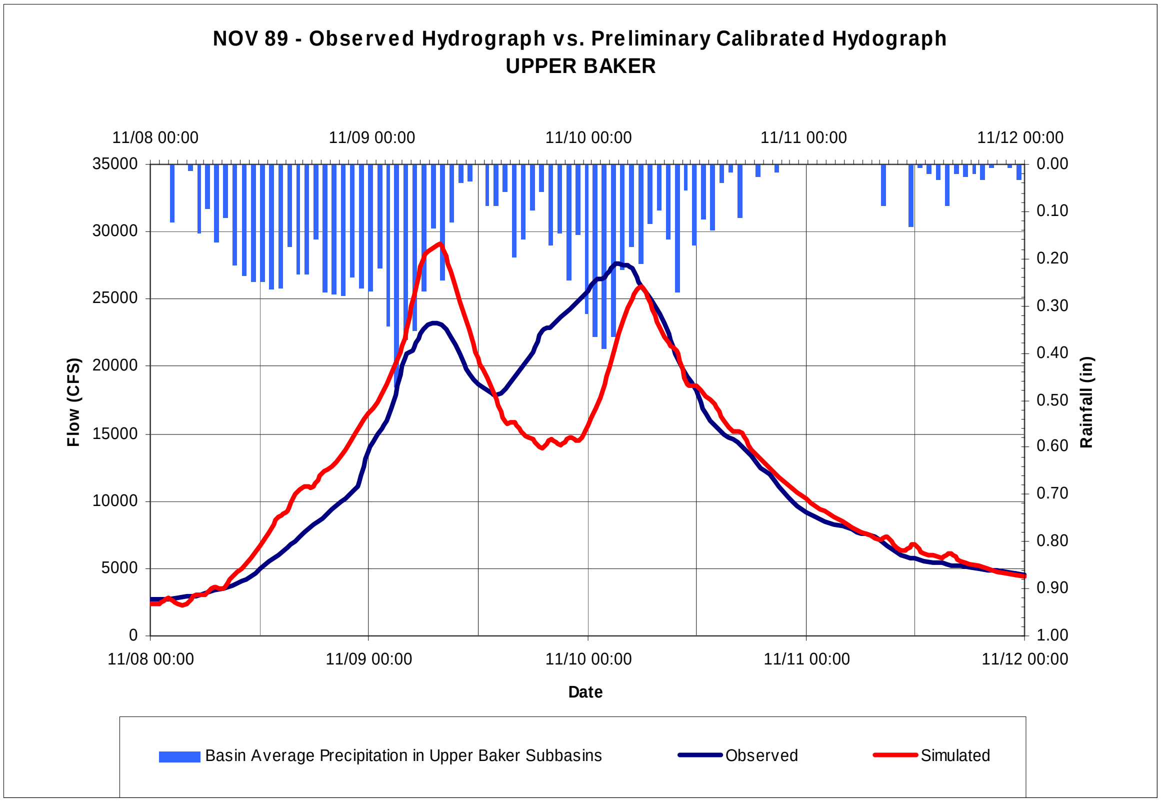


Figure 30. NOV 89 Upper Baker Inflow Hydrograph – Preliminary Calibrated Parameter Set

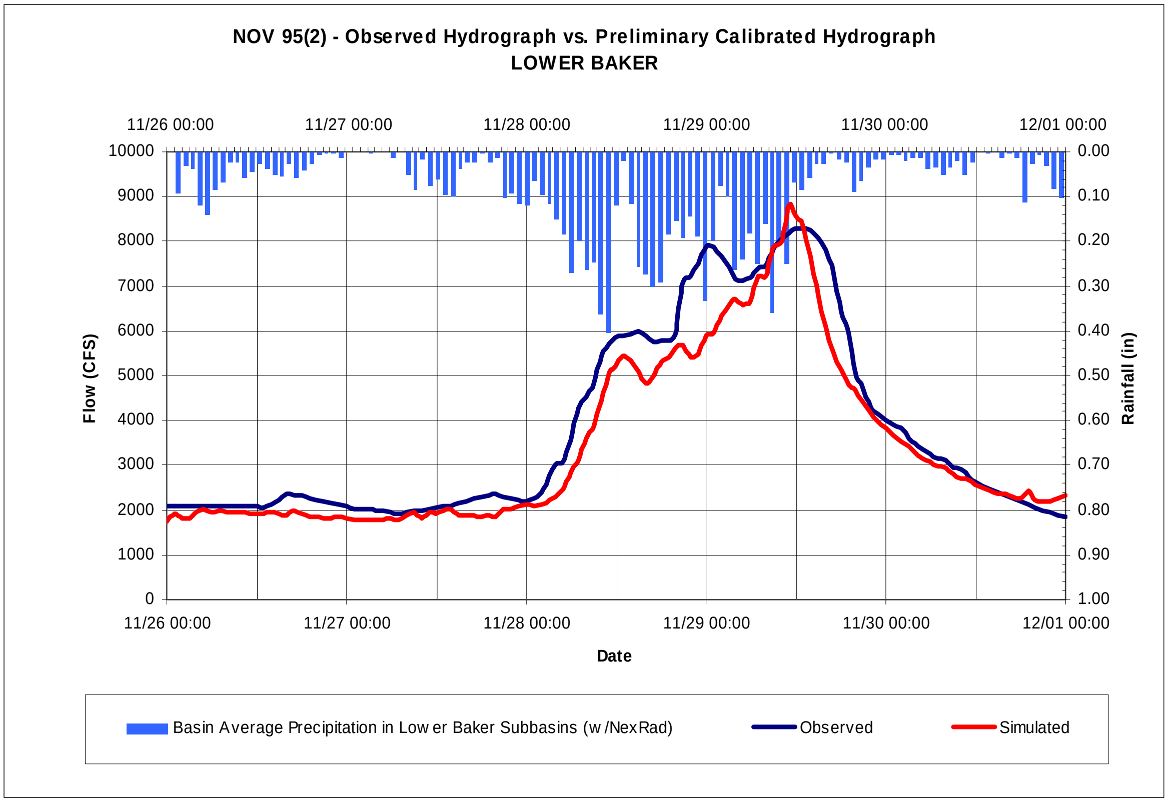


Figure 31. NOV 95(2) Lower Baker Inflow Hydrograph – Preliminary Calibrated Parameter Set

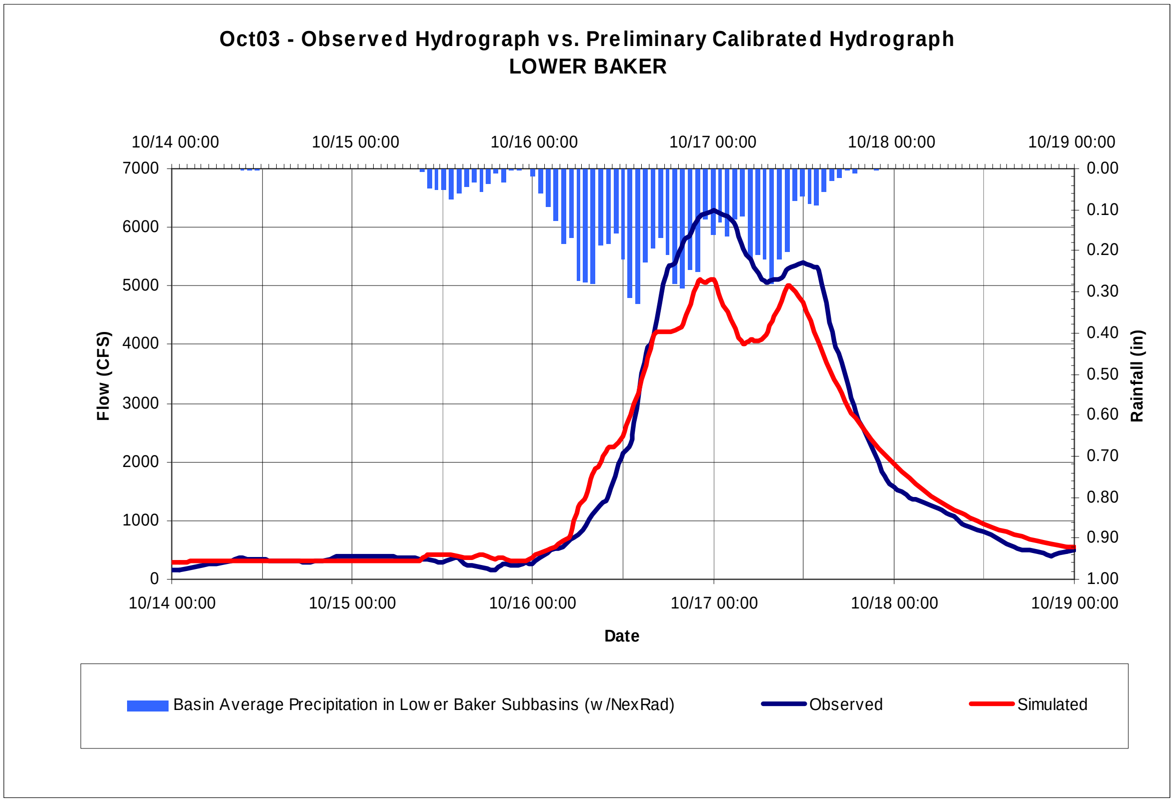


Figure 32. OCT 03 Lower Baker Inflow Hydrograph – Preliminary Calibrated Parameter Set

4.9 Phase V – Determination of Final Calibrated Parameter Set

In determining the final calibrated parameter set, it was decided to incorporate the NOV 90(1) event into the calibration process. This was an important step especially given the fact that although three inflow hydrographs were used for calibrating the Lower Baker portion of the watershed model, the preliminary calibrated parameter set was based on using a single inflow hydrograph for the Upper Baker portion of the watershed. Incorporating the event originally used for verification provided additional refinement to the calibration.

The 8,000 parameter sets that were used in identifying the preliminary calibrated parameter set in Phase III were then input into the NOV 90(1) verification event model. As such the same parameter sampling ranges summarized in Tables 20 and 21 were used. The process that was used to define the preliminary calibrated parameter set in Phase III was repeated.

Behavioral parameter sets were identified for each of the four storm events, using the NSE objective function. A threshold value of 0.850 was used to differentiate behavioral parameter sets from non-behavioral parameter sets, consistent with the approach used in Phase III. However, since no parameter sets satisfied this threshold for the NOV 90(1) event, a 0.750 threshold value for the NSE objective function was used for the NOV 90(1) event.

The same parameter sets were identified as behavioral for the original three calibration storms, and 676 sets were identified as behavioral for the NOV 90(1) storm event. Table 27 summarizes the objective function values for the Phase V simulations.

Table 27. Summary of Objective Functions for Individual Calibration Storm Events – PHASE IV

Objective Function	NOV 90(1) Event	NOV 89 Event	NOV 95(2) Event	OCT 03 Event
NSE Objective Function - All 8,000 Parameter Sets				
Best Simulation	0.815	0.913	0.927	0.941
Median Value	0.757	0.852	0.873	0.833
Worst Simulation	0.745	0.610	0.712	0.584
Evaluation Threshold	0.750	0.850	0.850	0.850
Number of Behavioral Parameter Sets	674	4,631	6,494	3,236
HEC Objective Function – Behavioral Parameter Sets Only				
Best Simulation	0.091	0.092	0.030	0.078
Median Value	0.118	0.141	0.050	0.180
Worst Simulation	0.128	0.170	0.067	0.224

Of the behavioral parameter sets identified in Table 27 for each of the individual storms, 233 of them were identified as behavioral for all four storm events. This pool of parameter sets was then used in the identification of the final calibrated parameter set. Likelihood measures were computed for each of storm events for each of the 233 parameter sets using Equation (13). Then, using Equation (14) the likelihood value for each parameter set for the group of flood events was calculated. All storms were equally weighted in computing the likelihood value for the group of flood events. The parameter sets were then ranked in descending order using the value of the likelihood measure for the group of flood events.

The top ten parameter sets based on the highest combined likelihood values were then identified. Table C-1 in Appendix C summarizes key information about each of these parameter sets, including the runoff volume and the goodness-of-fit measures. Due to the large number of parameters included in a given parameter set, parameter values are not included in this table.

The mean value for each parameter from this list of top ten behavioral parameter sets was then computed. This collection of mean values was identified as the final calibrated parameter set.

A sensitivity analysis was then conducted on this final calibrated parameter set, utilizing a series of manual adjustments to determine if there was the ability to improve upon the goodness-of-fit to the observed hydrographs for the four storm events as a group. Adjustments were made to the parameter set equally across all soil zones or subbasins. In other words, for example, all minimum infiltration rates were incrementally increased and decreased by an equivalent percentage to test the sensitivity of the goodness-of-fit measures to the minimum infiltration parameter. For each sensitivity model run, the group likelihood measure, expressed as Equation (14), was used to compare results of each parameter sets to determine if an improvement was made over the final calibrated parameter set. The following parameters were included in the sensitivity analysis:

- Rate of deep percolation, f_d
- Rate of minimum infiltration, f_c
- Upper and lower interflow zone storage constants, UZ and LZ
- Unit hydrograph peaking factor, C_p
- Unit hydrograph period of rise, Pr

Through the sensitivity analysis, it was found that reducing the deep percolation rate improved the volumetric percent error and the likelihood measure. However, a reduction of more than 10% caused the volume for the NOV 89 Upper Baker inflow hydrograph to become excessively high. Reduction in the minimum infiltration rate parameter was beneficial for small reductions, but negatively affected the likelihood measure for anything more than a 5% reduction. Changing the interflow lag constants did not result in improvements to the goodness-of-fit measures, and likewise the unit hydrograph period of rise. Finally, it was found that reducing the unit hydrograph peaking factor resulted in slight improvements. In total, the sensitivity analysis found that the following global adjustments resulted in slightly better fits to the observed hydrographs and an improved value for the group likelihood measure.

- Rate of deep percolation, f_d, was decreased by 10% for all soil zones
- Rate of minimum infiltration, f_c, was decreased by 5% for all soil zones
- Unit hydrograph peaking factor, C_p, was reduced from 500 to 474

The final calibrated parameter set is summarized in Tables 28 and 29. Figures 33 and 34 graphically illustrate the calibrated surface runoff unit hydrographs for each of the subbasins, for the Upper Baker tributary area and the Lower Baker tributary area, respectively.

The calibrated parameter set was then used to predict the runoff hydrographs for all of the storm events considered in the analysis. Figures 35 through 40 compare the simulated versus the observed hydrographs for each of the storm events. These figures show the total runoff hydrographs, each of which includes a base flow component, an interflow component and a surface runoff component. To illustrate the relative magnitude of the interflow component to the total hydrograph, Figures 41 through 46 show the simulated interflow hydrograph and the simulated total hydrograph for each of the storm events. The temporal pattern of the model input basin average precipitation is included at the top of all of these figures so as to illustrate the response of the watershed to the precipitation input.

Table 30 presents a comparison of the simulated and observed runoff hydrographs using the calibrated parameter set. A comparison is made between the runoff volumes, the flow rate of the primary peaks, and the flow rate of the secondary peaks. This table also includes a summary of the HEC and NSE objective functions. Finally, Tables 31 and 32 summarize some of the key hydrologic model inputs and outputs using the results from the final calibrated model runs. Table 31 expresses the values in units of acre-feet and Table 32 expresses the values in units of inches.

Table 28. Final Calibrated Subbasin Parameters

Subbasin	Period of Rise, Pr (minutes)	Peaking Factor	UZ Storage Constant (hours)	LZ Storage Constant (hours)
UB1	240	474	7.1	12.0
UB2	180	474	6.1	10.9
UB3	180	474	5.9	10.8
UB4	180	474	6.0	10.9
UB5	270	474	8.5	13.5
UB6	180	474	6.6	11.6
UB7	360	474	9.6	14.6
UB8	180	474	6.6	11.6
UB9	---	---	---	---
LB1	180	474	5.0	7.8
LB2	180	474	5.1	7.9
LB3	300	474	7.8	12.6
LB4	210	474	6.6	11.4
LB5	150	474	5.5	10.3
LB6	240	474	7.9	12.9
LB7	---	---		

Table 29. Final Calibrated Soil Zone Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (in)	Minimum Surface Infiltration Rate, f_c (in/hr)	Deep Percolation Rate, f_d (in/hr)	Maximum Surface Infiltration Rate, f_{max} (in/hr)	Notes
1	0.00	0.000	0.00	0.0	Open Water
2	0.00	10.000	0.188	10.0	Glaciers
3	5.58	0.255	0.039	4.0	Rock Outcrop
4	5.02	0.284	0.052	6.0	A Soils
5	3.80	0.353	0.103	4.0	B Soils Shallow
6	7.84	0.282	0.064	4.0	B Soils Deep
7	10.10	0.354	0.177	4.0	B Soils Deep
8	5.89	0.170	0.104	4.0	C Soils Shallow
9	6.49	0.138	0.061	2.0	C/D Soils Deep
10	10.59	0.458	0.336	4.0	Sulphur/Rocky

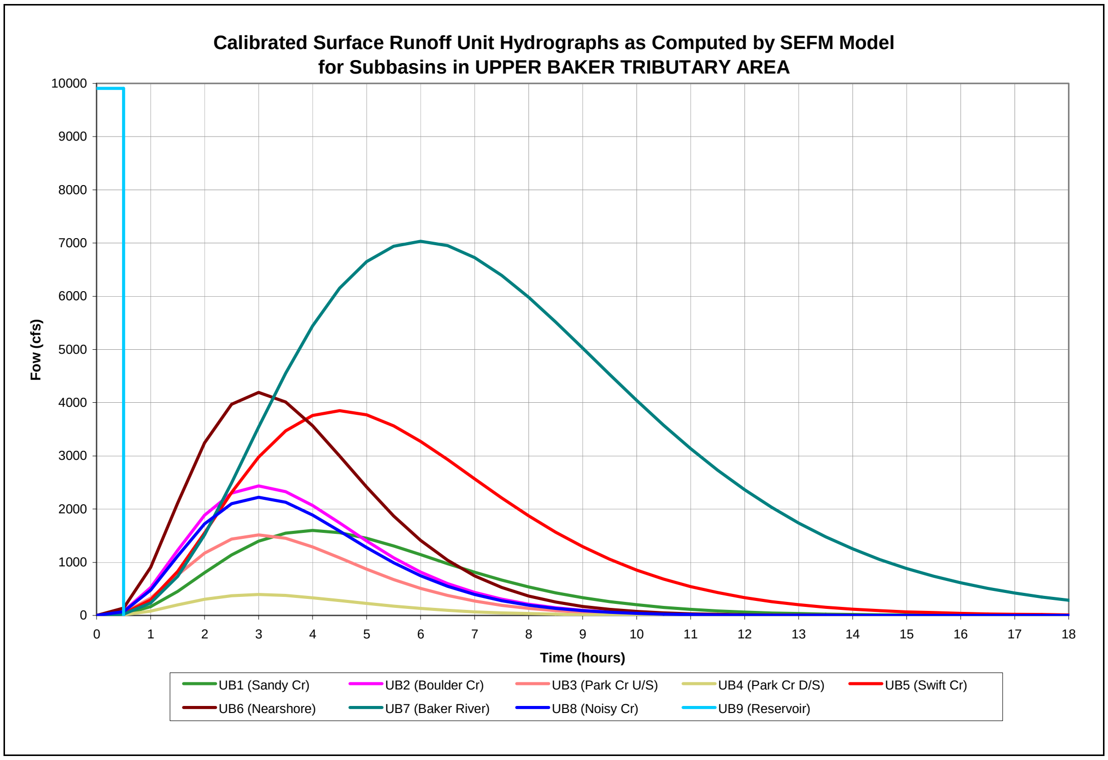


Figure 33. Calibrated Surface Runoff Unit Hydrographs – Upper Baker Subbasins

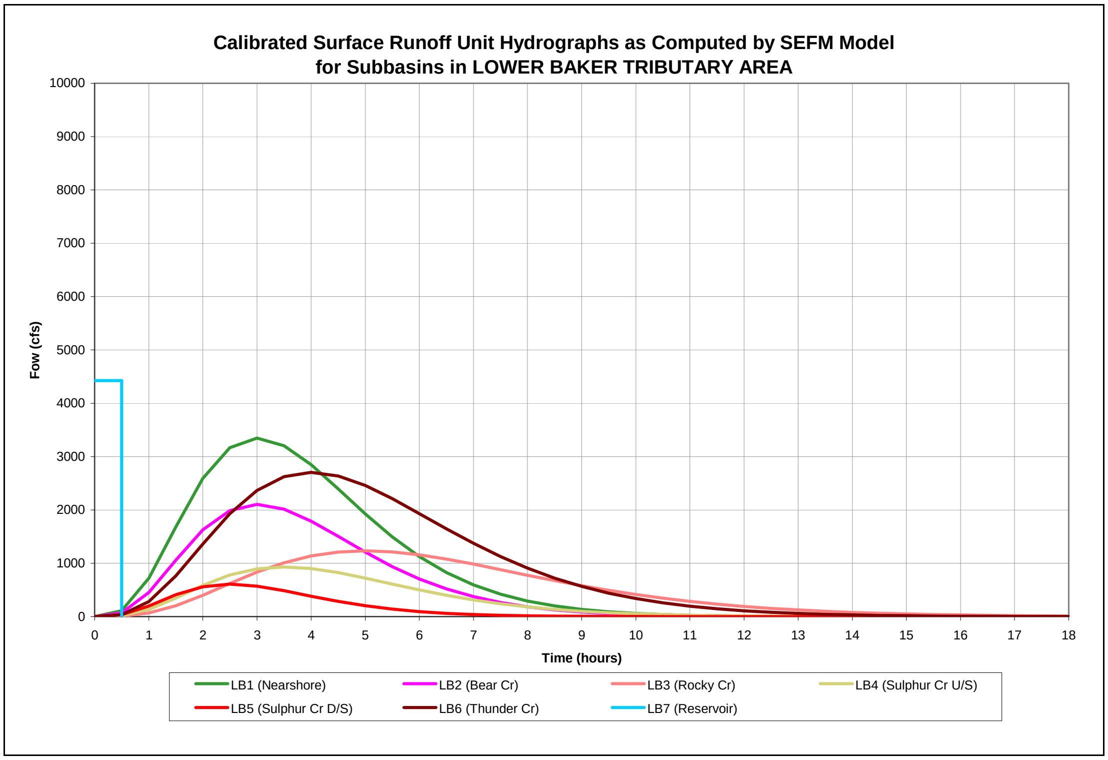


Figure 34. Calibrated Surface Runoff Unit Hydrographs – Lower Baker Subbasins

Table 30. Summary of Model Results for Final Calibrated Parameter Set

Objective Measure	NOV 90(1)		NOV 89		NOV 95(2)	OCT 03
	Lower Baker	Upper Baker	Lower Baker	Upper Baker	Lower Baker	Lower Baker
RUNOFF VOLUME (AC-FT)						
Observed	46,167	152,567	34,300	102,676	38,009	17,480
Simulated	46,050	130,935	39,604	106,727	35,330	17,265
% Error	0%	-14%	+15%	+4%	-7%	-1%
FLOW RATE OF PRIMARY PEAK (CFS)						
Observed	8,754	26,950	10,541	27,546	8,301	6,300
Simulated	10,061	27,611	13,844	25,797	8,954	5,262
% Error	+15%	+2%	+31%	-6%	+8%	-16%
FLOW RATE OF SECONDARY PEAK (CFS)						
Observed	4,650	17,377	8,129	23,168	n/a	n/a
Simulated	5,685	13,156	9,479	28,969	n/a	n/a
% Error	+22%	-24%	+17%	+25%	n/a	n/a
OBJECTIVE FUNCTIONS						
HEC Objective Function	0.038	0.109	0.183	0.129	0.026	0.090
NSE Objective Function	0.918	0.773	0.839	0.876	0.937	0.931

Table 31. Key Hydrologic Inputs and Outputs for Calibrated Model Expressed in Acre-Feet

	NOV 90(1)		NOV 89		NOV 95(2)	OCT 03
	Lower Baker	Upper Baker	Lower Baker	Upper Baker	Lower Baker	Lower Baker
INPUTS						
Total Precipitation (ac-ft)	72,570	197,440	58,890	143,170	47,200	35,430
Rain	65,090	163,810	57,840	134,550	41,200	35,380
Snow	7,470	33,600	1,050	8,610	5,990	50
Snowpack Yield (ac-ft)	-410	-11,900	2,350	3,360	-7,570	480
Initial Snow Water Equivalent	9,380	49,220	5,060	29,500	12,460	530
Final Snow Water Equivalent	9,790	61,120	2,710	26,140	20,030	50
Total Moisture Input (ac-ft)	72,160	185,540	61,240	146,530	39,630	35,910
OUTPUTS						
Total Runoff (ac-ft)	46,050	130,935	39,604	106,727	35,330	17,265
Base Flow	9,521	23,802	4,760	18,565	17,355	2,975
Precipitation Excess	12,382	37,331	12,305	26,254	6,254	3,666
Interflow Volume	24,211	69,685	22,475	61,662	11,560	10,595

Notes:

1. Negative snowpack yield indicates snow accumulation for the storm event

Table 32. Key Hydrologic Inputs and Outputs for Calibrated Model Expressed in Inches

	NOV 90(1)		NOV 89		NOV 95(2)	OCT 03
	Lower Baker	Upper Baker	Lower Baker	Upper Baker	Lower Baker	Lower Baker
INPUTS						
Total Precipitation (inches)	16.22	17.23	13.16	12.50	10.55	7.92
Rain	14.55	14.30	12.93	11.74	9.21	7.91
Snow	1.67	2.93	0.23	0.75	1.34	0.01
Snowpack Yield (inches)	-0.09	-1.04	0.52	0.30	-1.69	0.11
Initial Snow Water Equivalent	2.10	4.30	1.13	2.58	2.79	0.12
Final Snow Water Equivalent	2.19	5.34	0.61	2.28	4.48	0.01
Total Moisture Input (inches)	16.13	16.19	13.68	12.80	8.86	8.03
OUTPUTS						
Total Runoff (inches)	10.29	11.43	8.85	9.32	7.90	3.86
Base Flow	2.13	2.08	1.06	1.62	3.88	0.67
Precipitation Excess	2.77	3.26	2.75	2.29	1.40	0.82
Interflow Volume	5.41	6.08	5.02	5.38	2.58	2.37

Notes:

1. Negative snowpack yield indicates snow accumulation for the storm event

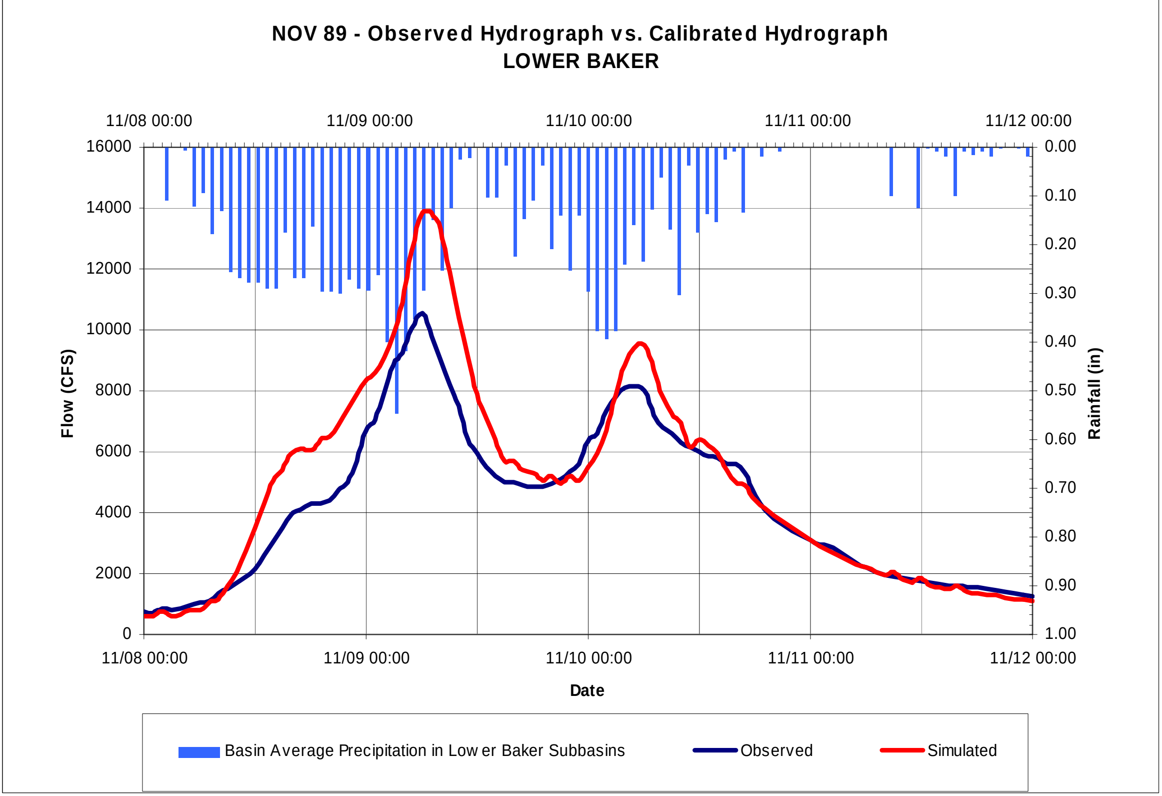


Figure 35. Final Calibrated Lower Baker Inflow Hydrograph for NOV 89 Event

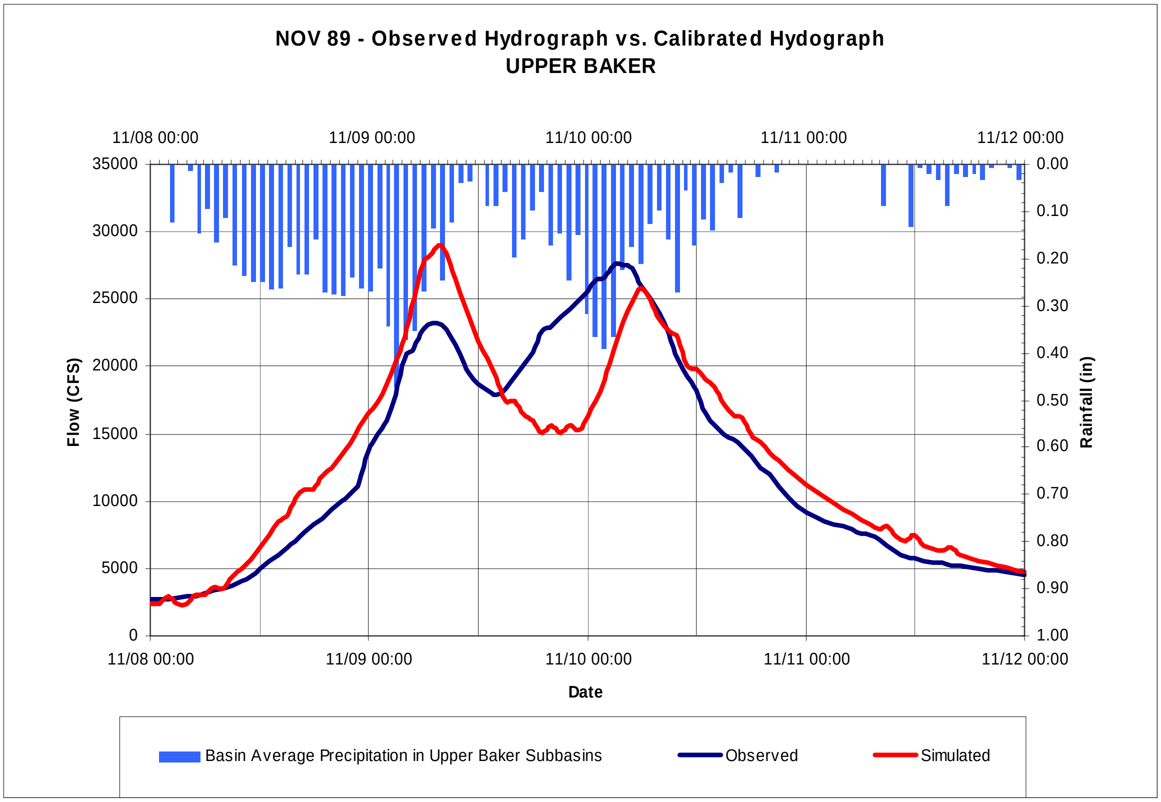


Figure 36. Final Calibrated Upper Baker Inflow Hydrograph for NOV 89 Event

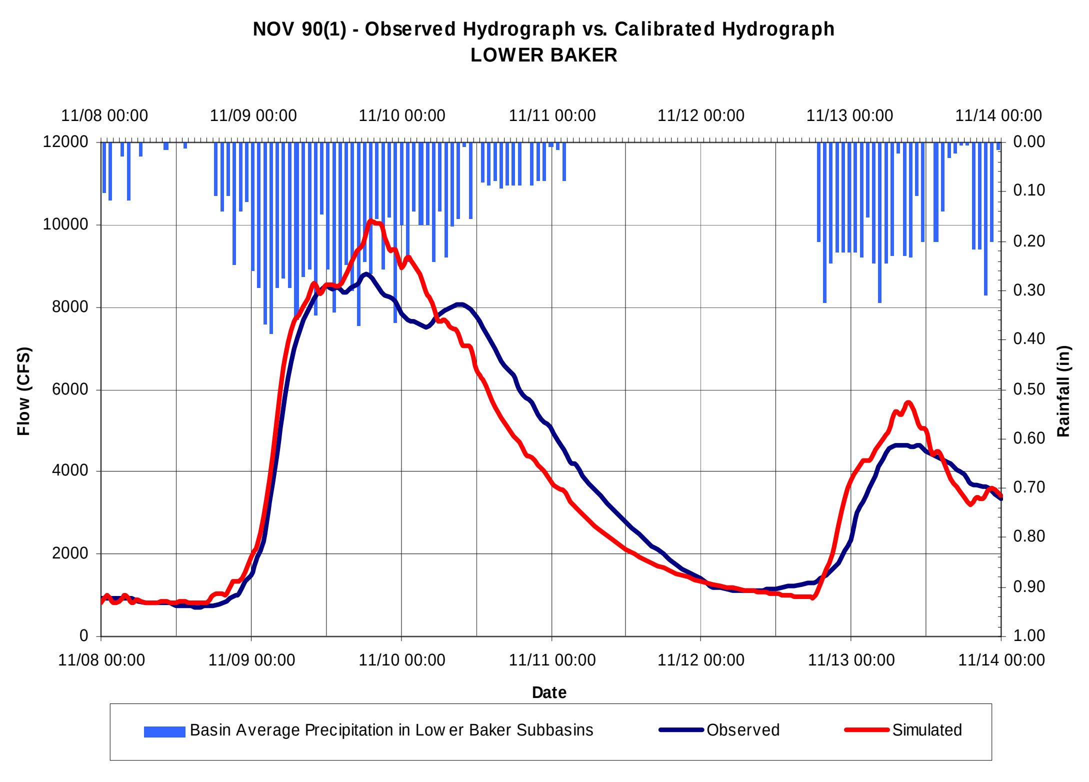


Figure 37. Final Calibrated Lower Baker Inflow Hydrograph for NOV 90(1) Event

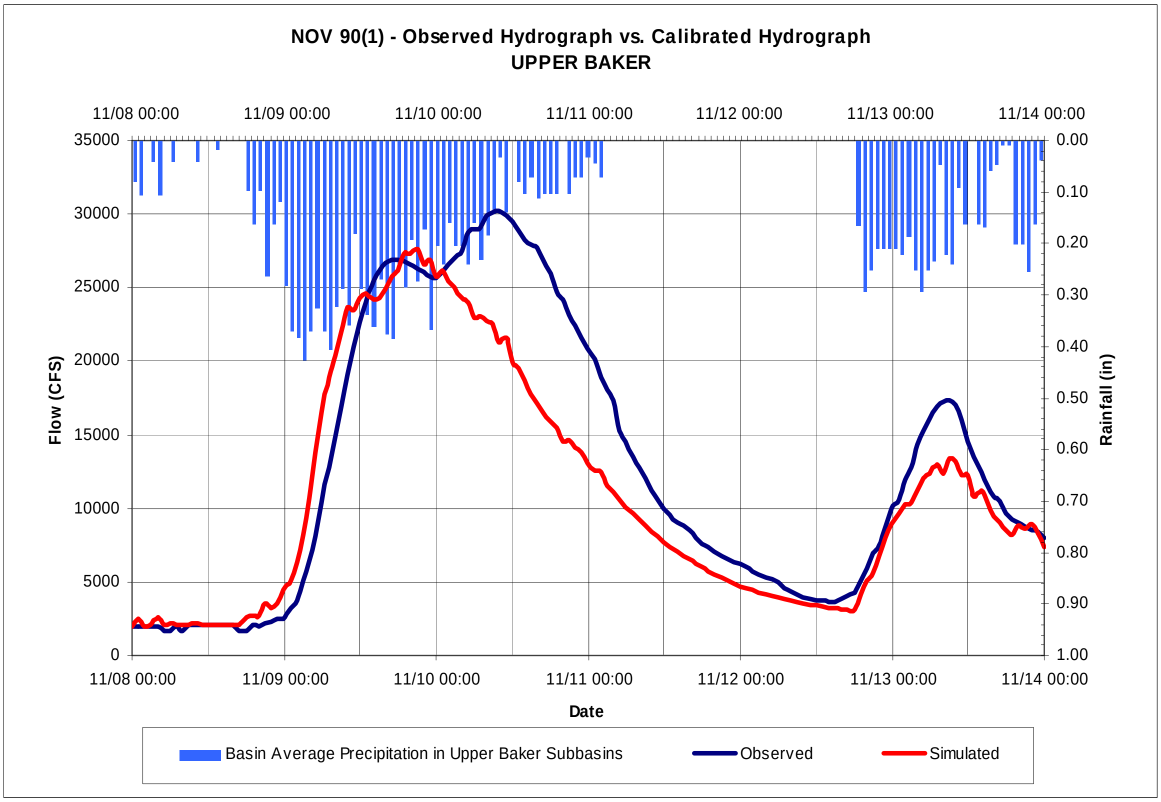


Figure 38. Final Calibrated Upper Baker Inflow Hydrograph for NOV 90(1) Event

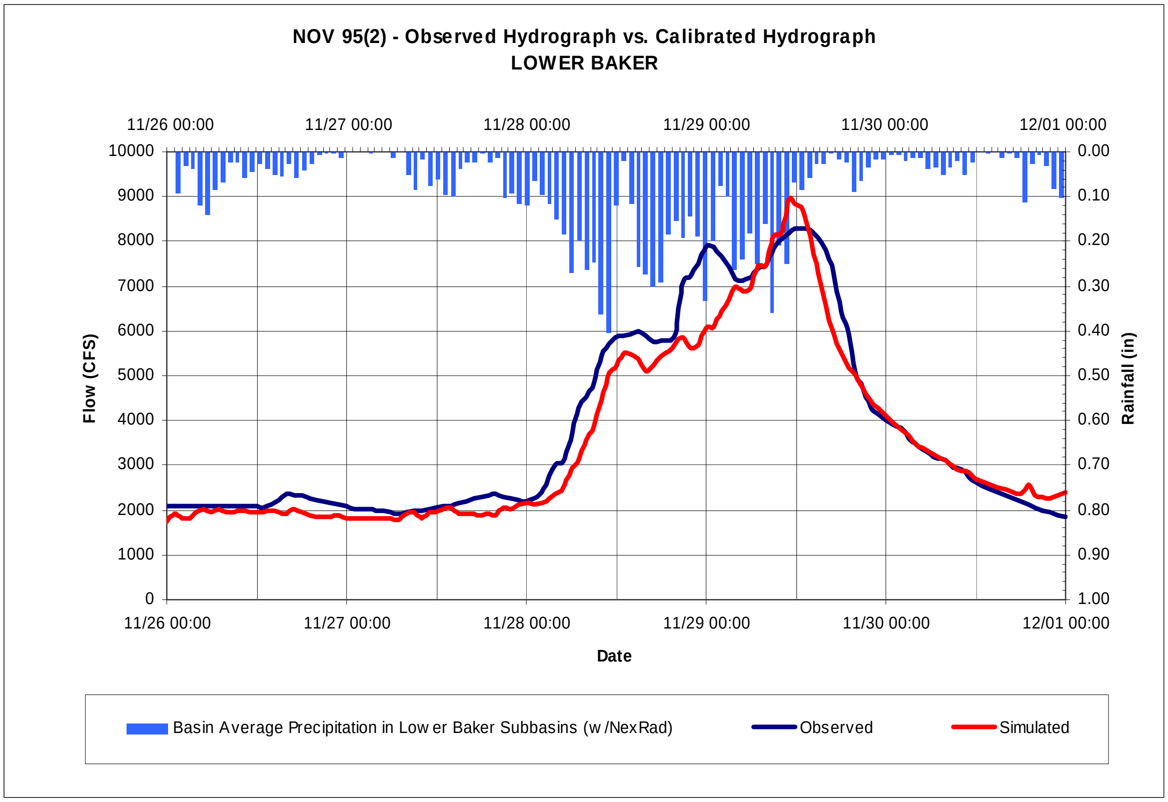


Figure 39. Final Calibrated Lower Baker Inflow Hydrograph for NOV 95(2) Event

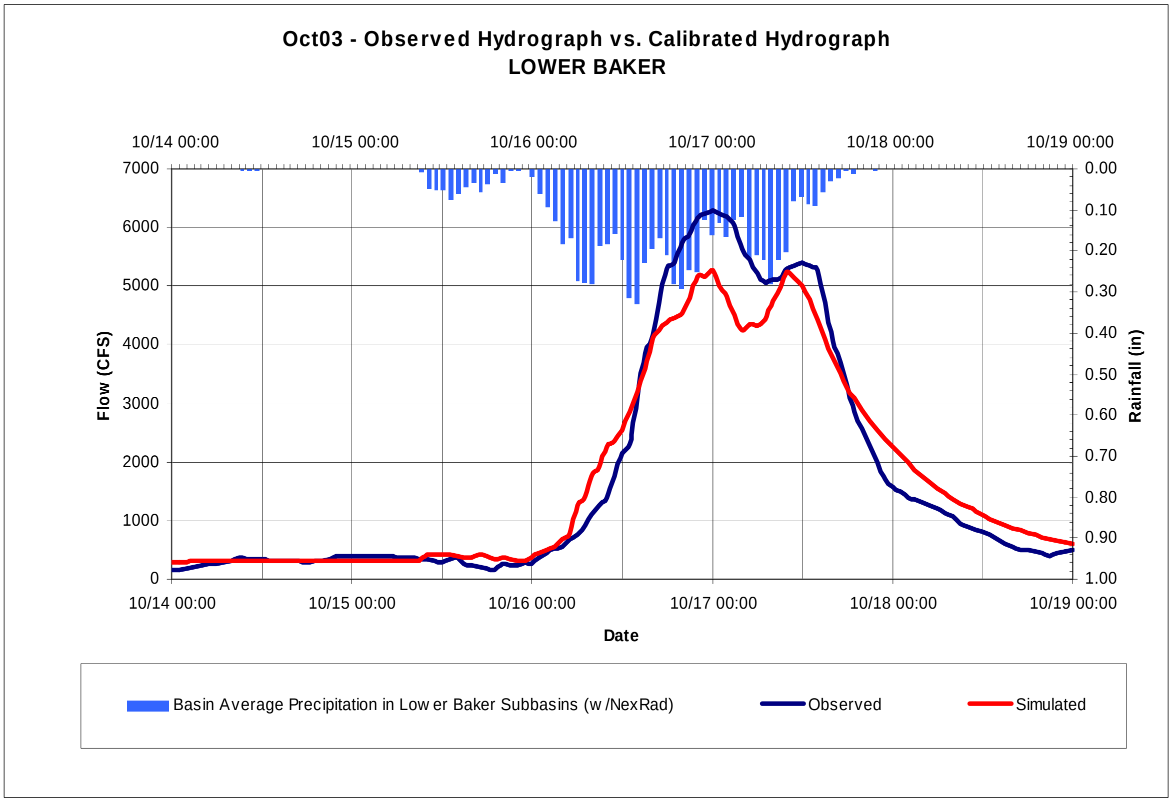


Figure 40. Final Calibrated Lower Baker Inflow Hydrograph for OCT 03 Event

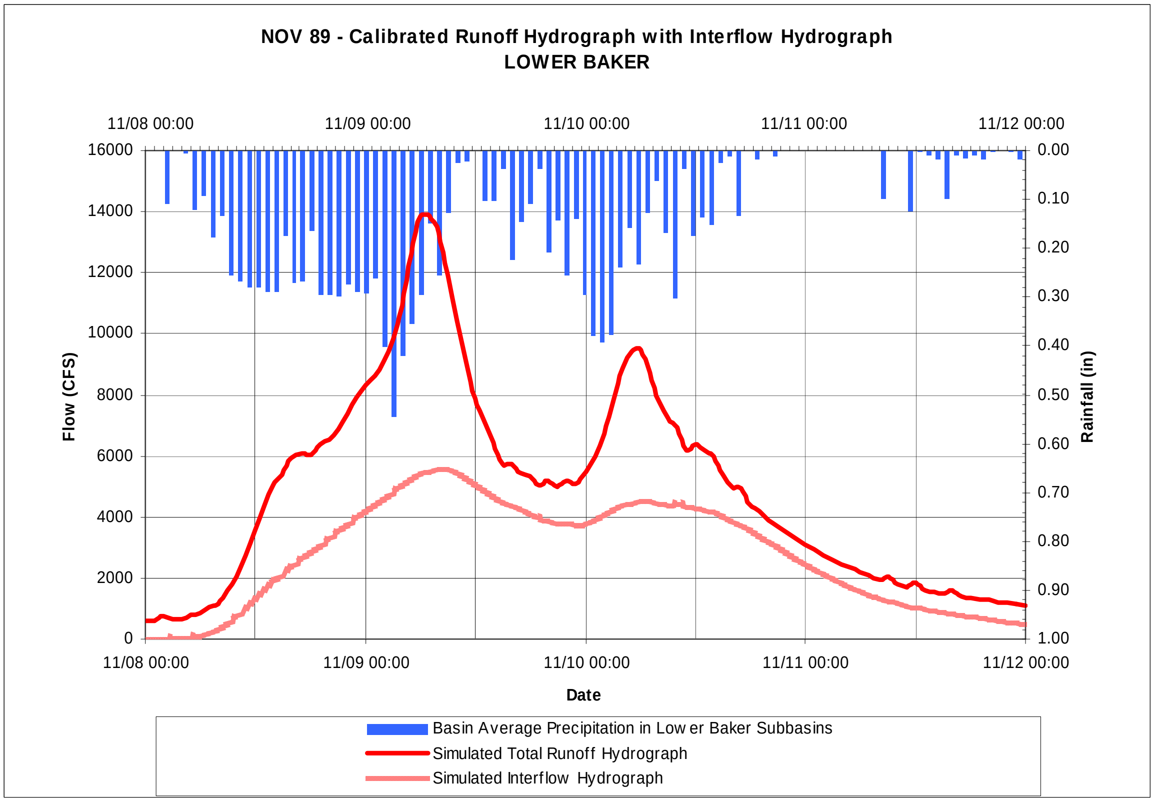


Figure 41. Interflow Hydrograph for Lower Baker Inflow Hydrograph – NOV 89 Event

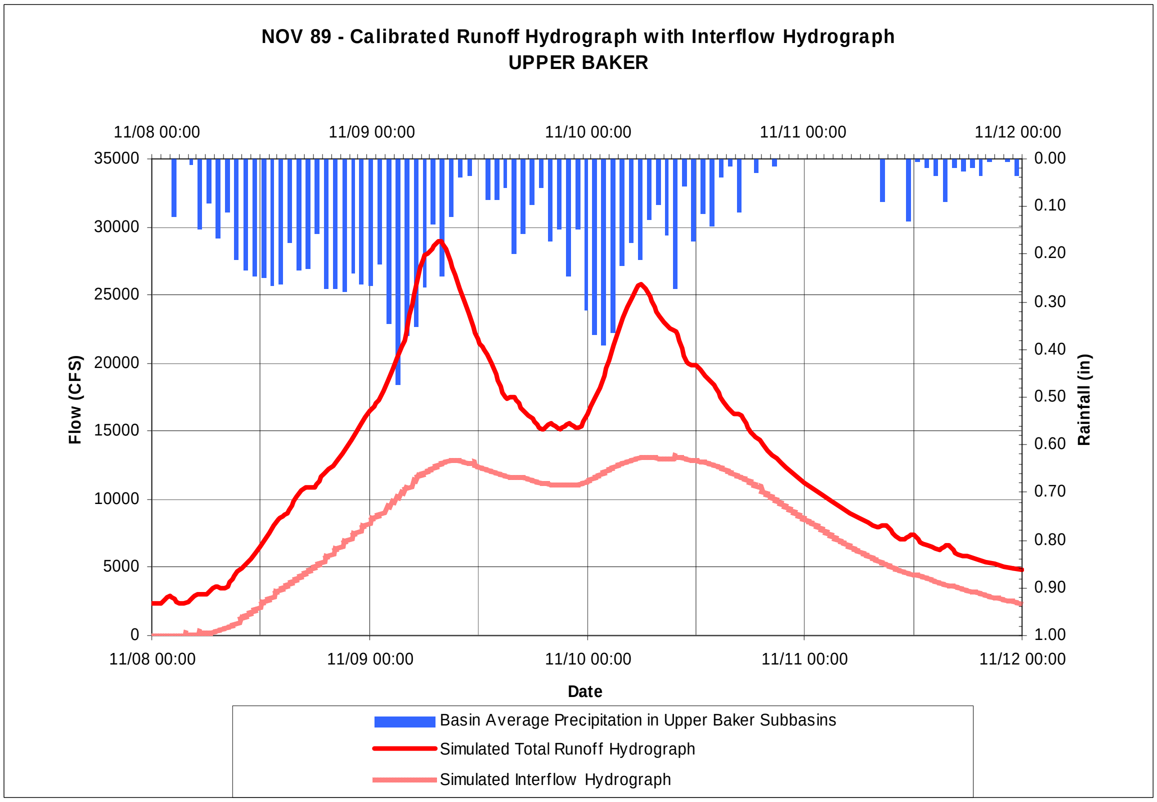


Figure 42. Interflow Hydrograph for Upper Baker Inflow Hydrograph – NOV 89 Event

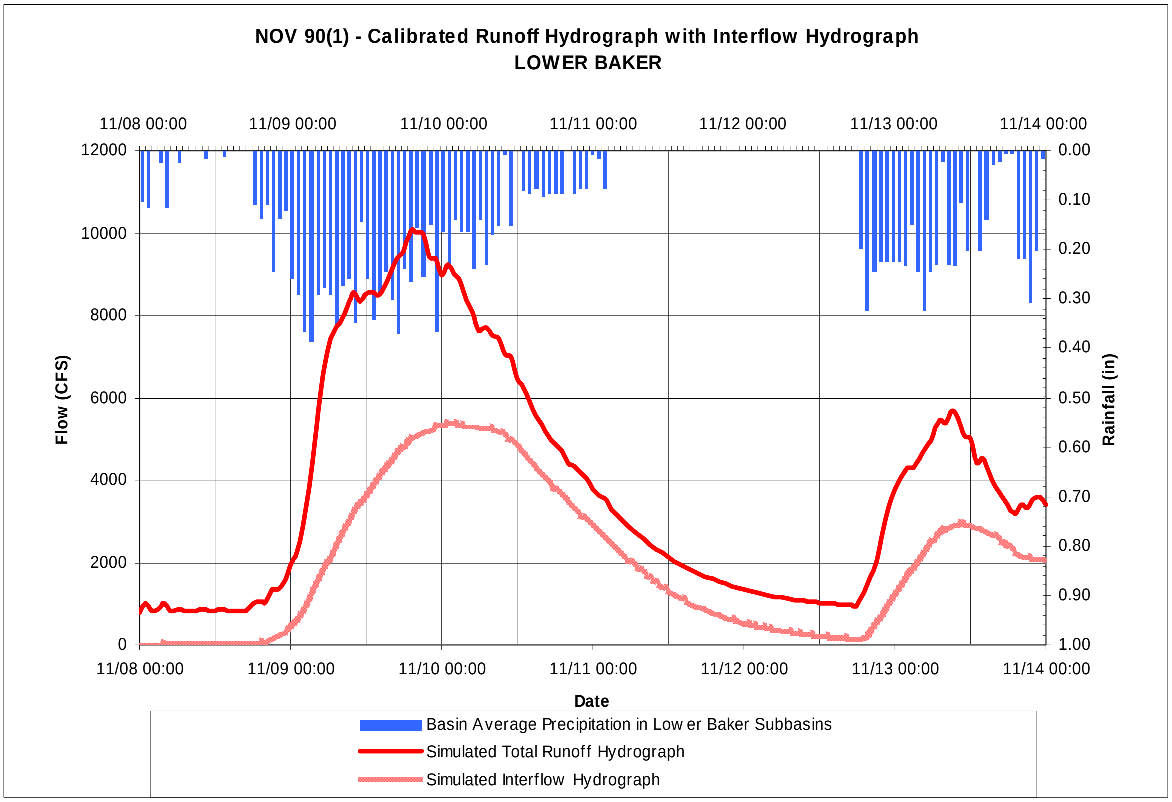


Figure 43. Interflow Hydrograph for Lower Baker Inflow Hydrograph – NOV 90(1) Event

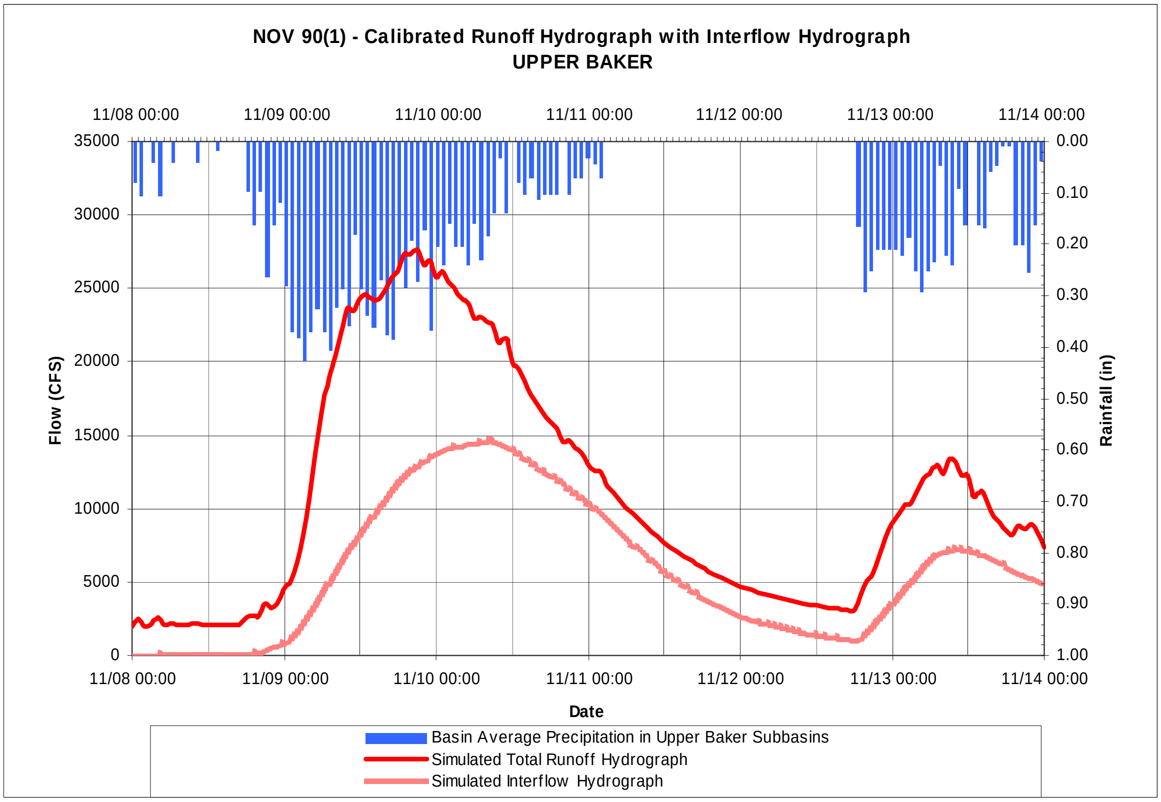


Figure 44. Interflow Hydrograph for Upper Baker Inflow Hydrograph – NOV 90(1) Event

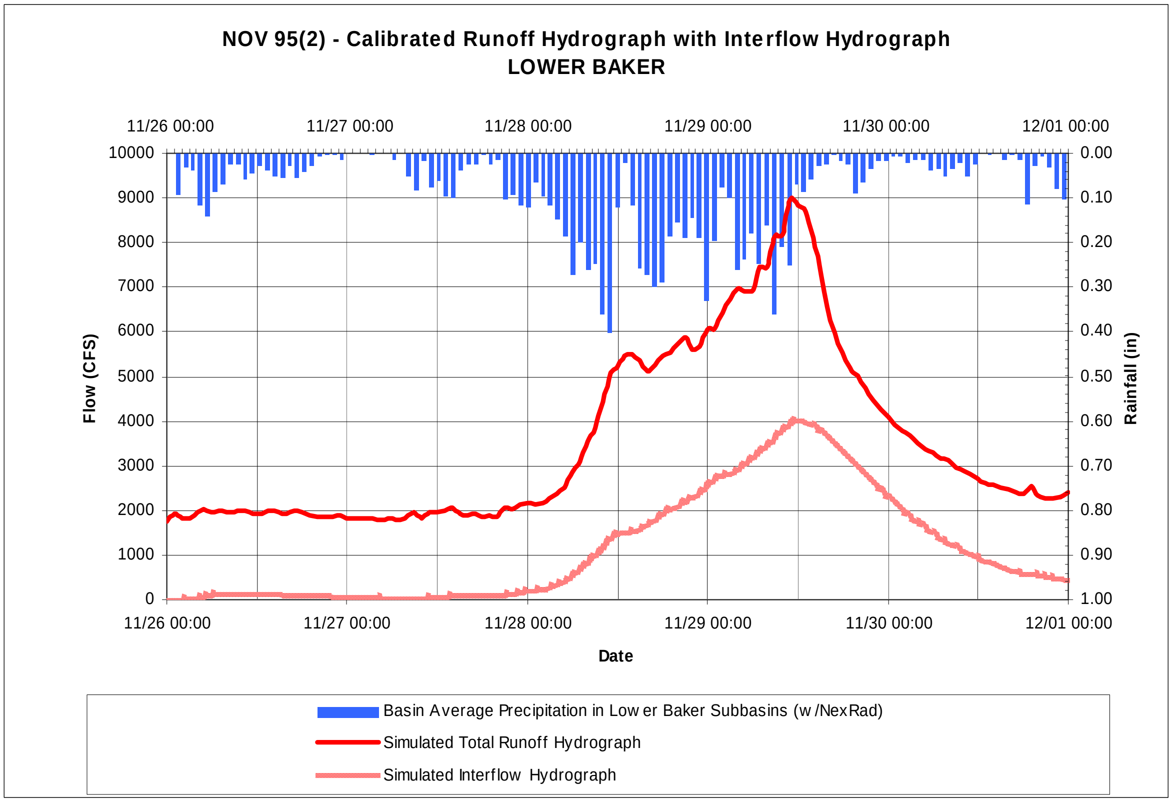


Figure 45. Interflow Hydrograph for Lower Baker Inflow Hydrograph – NOV 95(2) Event

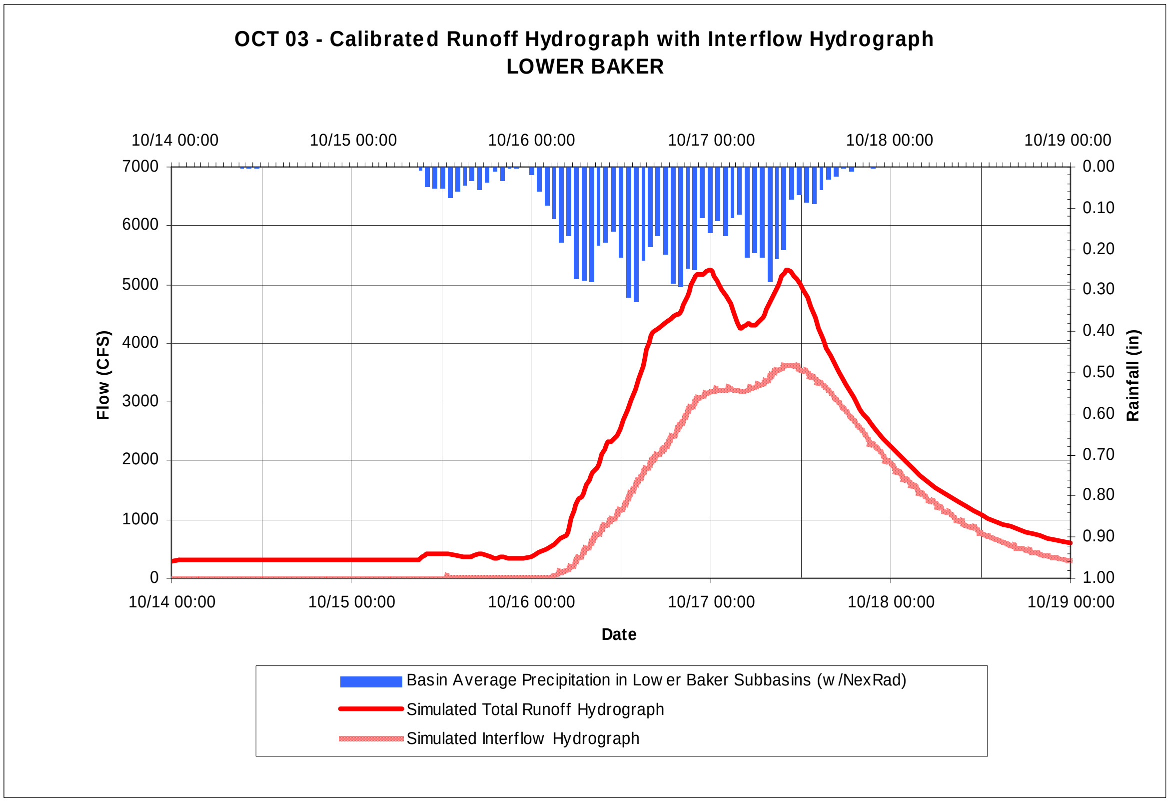


Figure 46. Interflow Hydrograph for Upper Baker Inflow Hydrograph – OCT 03 Event

5 DISCUSSION OF RESULTS

The success of a calibrated hydrologic model is measured by how well the model is able to reproduce the shape, timing, and volume of observed hydrographs. When considering the success of hydrologic model calibration, it must be remembered that inaccuracies in the recorded data that are used to calibrate the model are also present. Inaccuracies are associated with precipitation gage data and streamflow measurements, and in the case of the Baker River watershed, inaccuracies are also associated with the reconstruction of the primary inflow hydrographs and with the estimation of air temperature time series input data.

As has been discussed in this memorandum, objective measures can provide a quantifiable measure of the success of a calibrated model. In particular the NSE is a measure of model performance that is similar to the R-squared value. The value of the NSE roughly corresponds to the percentage of variation that is explained by the model. Although there is no threshold minimum value of NSE that indicates satisfactory model calibration, some publications have indicated that threshold values of .800 to 0.850 have been used for this purpose during the calibration of continuous simulation HSPF models (Chew et al. 1991; Price 1994; and Duncker et al 1995). Referring specifically to the Baker River watershed model calibration, it is seen in Table 30 that calibration to the Lower Baker tributary area hydrograph resulted in NSE values that ranged between 0.839 and 0.937, all of which are roughly equal to or in exceedance of the aforementioned threshold values. Calibration to the Upper Baker tributary hydrograph resulted in NSE values of 0.773 and 0.876.

Graphical and tabular comparisons of the simulated and observed hydrographs are also used to evaluate how well a model has been calibrated to observed data. Figures 35 through 40 compare the simulated and observed hydrographs and Table 30 summarizes the percent error for the peak flows and runoff volumes. In reviewing the graphs, it is possible to quickly identify the most successful aspects of the model calibration and those aspects where model calibration was perhaps less not as successful.

Successful aspects of the Baker River watershed model calibration included matching the timing of the hydrograph peaks, reproduction of the recession limbs, and reasonable reproduction of the runoff volume. The use of the GLUE calibration methodology was a significant contributor to these successes, in that it allowed for a thorough investigation of the parameter space for each of the calibration parameters.

A visual inspection of Figures 35 through 40 indicates that the time of occurrence of the observed hydrograph peaks were reproduced by the calibrated hydrologic model. In fact, for the NOV 89 hydrographs, the simulated hydrographs peaked within 1 hour of the observed hydrographs, with the exception of the second peak for the Upper Baker inflow hydrograph which was within 2 hours. For the NOV 90(1) hydrographs, the simulated hydrographs peaked within 1 hour of the observed hydrographs, with the exception of the first peak for the Upper Baker inflow hydrograph which was within 3 hours. The time of occurrence of the peaks for the NOV 95(2) and OCT 03 hydrographs were within 2 hours of the time of occurrence of the peaks of the observed hydrographs.

Modeling of the interflow portion of the runoff hydrograph allowed for successful reproduction of the recession limb of the runoff hydrographs. As seen in Figures 35, 36, and 39, the NOV 89 and NOV 95(2) recession limbs were especially well reproduced.

Volumetrically, the simulated hydrographs resulted in runoff volumes that were within 15% of the observed runoff hydrographs, which was felt to be within the tolerance of the error associated with the observed data. The deep percolation rate, which simulated the loss of infiltrated water to deep groundwater zones, was the primary parameter which controlled runoff volume in the model. For the ten soil zones, the calibrated value of the deep percolation rate ranged between 0.039 in/hr and 0.336 in/hr. The highest rate of deep percolation was for the soil zone located within the Sulphur/Rocky Creek drainage which has been characterized as a drainage area with substantial deep groundwater losses. If the deep percolation rates are area weighted, then the basin average value is 0.094 in/hr which is a very reasonable loss rate for a mountainous watershed with volcanic and highly fractured bedrock characteristics.

Less-successful aspects of the model calibration were directly related to the difficulties that were encountered in developing spatial and temporal precipitation input for the model. The complicating influence of terrain on precipitation patterns in the watershed, combined with the fact that only a single hourly precipitation gage was available within the watershed, presented difficulties in accurately developing spatial and temporal precipitation input for the hydrologic model. The recorded hourly precipitation data at the only gage in the watershed, which is located at Upper Baker Dam (Elevation 690 feet), is likely more representative of the precipitation patterns in the lower watershed than in the upper watershed. This is seen by reviewing Figures 35 and 36. It is seen in Figure 36 that the spatial and temporal precipitation pattern that was developed for input into the NOV 89 hydrologic model were insufficient to produce the volume associated with the second peak for the Upper Baker portion of the model. However, for the Lower Baker portion of the model, the precipitation input was sufficient and actually allowed for very good calibration to the second peak (Figure 35). Likewise, in Figure 38, the observed inflow hydrograph for Upper Baker for the NOV 90(1) event was characterized by two successive peaks on November 9th and 10th. However, as seen at the top of the graph, the precipitation intensities following the first peak were insufficient to produce the volume and peak associated with this second hydrograph peak. However, as seen in Figure 37, the precipitation input into the model allowed for fairly good reproduction of the inflow hydrograph for the Lower Baker portion of the model.

Several different techniques were utilized in conjunction with the SPAS software to attempt to resolve the difficulties in developing accurate precipitation mapping for the historical storm events. This included using a different climatological base mapping, incorporating NEXRAD data, and using pseudo-stations to resolve the temporal characteristics of the storm events. As described in Section 4.2, the Upper Baker inflow hydrographs for the NOV 95(2) and OCT 03 events were eliminated from consideration for model calibration due specifically to the difficulties in mapping the precipitation for these events. Without an hourly precipitation gage located in the upper watershed, development of the precipitation input relied on hourly data observed outside, but adjacent, to the watershed boundaries.

6 SUMMARY

The SEFM model and the HEC-1 model were together used to successfully develop a calibrated watershed model for the Baker River watershed. The model was calibrated using four historical storm events. For two of the storm events, inflow hydrographs for the Upper Baker and Lower Baker tributary areas were used and for the other two storm events, only the inflow hydrograph for the Lower Baker tributary area was used. Additionally, two smaller tributary area hydrographs (Swift Creek and Park Creek Subbasins) were used as part of the calibration process for unit hydrograph and interflow timing.

Calibration of the watershed model was conducted using concepts from a procedure based on generalized likelihood measures (Beven et al 1992). The procedure is referred to as the Generalized Likelihood Uncertainty Estimation (GLUE) and is based on the premise that “any model/parameter set combination that predicts the variable or variables of interest must be considered equally likely as a simulator of the system”. The procedure seeks to find that combination of parameter values that can replicate the observed hydrographs and in the process considers the possibility that more than one parameter set may be capable. A series of multi-thousand model runs were used to evaluate the sensitivity of objective measures to specific calibration parameter values, using an initially wide yet plausible range for calibration parameter. Scatter plots were used to narrow the sampling range of the parameters. Once the sampling range was sufficiently narrowed, multi-thousand runs were again executed and those parameter sets that produced good fits to the observed were identified as “behavioral”. Behavioral parameters then formed the basis for identifying the calibrated parameter set. This procedure is an improvement over traditional trial-and-error procedures in that it allows for a more thorough exploration of the parameter space.

Success of the model calibration was based on the ability of the models to reproduce the observed hydrographs based goodness-of-fit measures and volumetric considerations. Based on the procedures and results summarized in this technical memorandum, it is concluded that the calibrated watershed model developed for the Baker River watershed reasonably replicates the observed runoff hydrographs produced by a set of extreme precipitation events. This model therefore reasonably simulates the complex hydrologic processes acting within this mountainous terrain, and will provide a sound basis for analysis the PMP/PMF for the Baker River watershed.

7 REFERENCES

Applied Weather Associates. 2006. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 9 – October 2003 Storm Analysis and Supplementary Storm Analyses for Calibration Events – Revision 1.* Technical Memorandum prepared for Puget Sound Energy.

Beven, Keith and Andrew Binley. 1992. The Future of Distributed Models: Model Calibration and Uncertainty Prediction. Hydrologic Processes, Volume 6. Pages 272 – 298.

Chew, C. Y., Moore, L. W., and R. H. Smith. 1991. *Hydrologic Simulation of Tennessee's North Reelfoot Creek Watershed*. Research J. Water Pollution Control Federation, v.63: 10-16.

Duncker, J.J., Vail, T.J., and C.S. Melching. 1995. *Regional Rainfall-Runoff Relations for Simulation of Streamflow for Watersheds in Lake County, Illinois*. USGS WRIR 95-4023.

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

Granshaw, Frank D. 2001. *Glacier Change in the North Cascades National Park Complex, Washington State USA, 1958 to 1998*. A thesis prepared in partial fulfillment of Master of Science in Geology at Portland State University.

Hargreaves, G.H., and Samani, Z.A. (1982), "*Estimating Potential Evapotranspiration.*" Tech. Note. J. Irrigation and Drainage Engineering, ASCE, 108(3):225-230.

Hargreaves, G.H., and Samani, Z.A. (1985), "*Reference Crop Evapotranspiration from Temperature.*" Applied Engrg. in Agric., 1(2):96-99).

Holtan HN. 1961. *A Concept for Infiltration Estimates in Watershed Engineering*. US Department of Agriculture, ARS 41-51.

Holtan HN, Stitner GJ, Hensen WH, and Lopez NC. 1975. *USDAHL-74 Revised Model of Watershed Hydrology*. Technical Bulletin No 1518. Agricultural Research Service. US Department of Agriculture.

Hydrocomp, Inc. 1999. *Baker River Watershed – Model Calibration*. Prepared for Puget Sound Energy, Inc.

Maidment, DR. 1993. Handbook of Hydrology. McGraw-Hill. New York.

Mason, Ron, Schaefer MG, Taylor GH. 2005. *Baker River Project Probable Maximum Flood Study. Board of Consultants Report Second BOC Meeting – September 7, 2005.* Consensus Report of Recommended Actions Following Review of Technical Memoranda Produced by Tetra Tech for Puget Sound Energy for Probable Maximum Flood Study for Baker River Project. Dated March 9, 2005.

MGS Engineering Consultants, Inc. 2004. *General Storm Stochastic Event Flood Model (SEFM) Technical Support Manual.* Prepared for the United States Department of Interior Bureau of Reclamation Flood Hydrology Group. Original Publication Date October 1998. Revision Date June 2004.

Natural Resources Conservation Service (NRCS). 1994a. “*Soil Survey Geographic (SSURGO) Database for Skagit County*, Washington”. United States Department of Agriculture (USDA). Accessed 3/1/05 <http://soildatamart.nrcs.usda.gov>

Natural Resources Conservation Service (NRCS). 1994b. “*State Soil Geographic (STATSGO) Database for Washington*”. United States Department of Agriculture (USDA). Accessed 3/1/05 <http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/>

Oregon Climate Service (OCS). 2005. Mean Annual Precipitation for the United States. Provided to Tetra Tech via email from George Taylor from the Oregon Climate Service.

Price, T.H., 1994. *Hydrologic Calibration of HSPF Model for Du Page County – West Branch Du Page River at West Chicago, West Branch Du Page River at Warrenville, East Branch Du Page River at Maple Avenue, Salt Creek at Western Springs; including hydraulic evaluation – Salt Creet at Western Springs, Salt Creek at Rolling Meadows*. Northeastern Illinois Planning Commission, IL.

Tabor RW, Haugerud RA, Hildreth W, and Brown EH. 2003. *Geologic Map of the Mount Baker 30- by 60-Minute Quadrangle, Washington.* Prepared in Cooperation with the Washington State Department of Natural Resources, Division of Geology and Earth Resources.

Tetra Tech, Inc. 2005a. *Baker River Project Part 12 PMP/PMF Study - Calibration/Verification Events.* Technical Memorandum prepared for Puget Sound Energy. April 2005.

Tetra Tech, Inc. 2005b. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 5 – Model Recommendation.* Technical Memorandum prepared for Puget Sound Energy. Revision 2. July 2005.

Tetra Tech, Inc. 2005c. *Baker River Project Part 12 PMP/PMF Study – Mean Annual Precipitation Map Analysis and Comparison.* Technical Memorandum prepared for Puget Sound Energy. Revision Date November 4, 2005.

Tetra Tech, Inc. 2005d. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 7 – Model Calibration and Verification.* Technical Memorandum prepared for Puget Sound Energy. August 25, 2005.

Tomlinson EM, Parzybok TW. 2004. *Storm Precipitation Analysis System (SPAS)*. Association of State Dam Safety Officials Annual Conference, Phoenix, Arizona, September 26-30, 2004

United States Army Corps of Engineers Hydrologic Engineering Center (USACE). 1998. *HEC-1 Flood Hydrograph Package – User’s Manual*. Version 4.1.

United States Department of Agriculture (USDA). 1989. *Soil Survey of Skagit County Area, Washington*.

United States Bureau of Reclamation (USBR). 1966. *Effect of Snow Compaction on Runoff from Rain and Snow – A Water Resources Technical Publication. Engineering Monograph No. 35.* United States Department of the Interior.

United States Bureau of Reclamation (USBR). 1989. *Flood Hydrology Manual – A Water Resources Technical Publication*. United States Department of the Interior.

United States Forest Service (USFS) Pacific Northwest Region. 1970. *Mount Baker National Forest Soil Resource Inventory – Pacific Northwest Region.* Prepared by Robert V. Snyder and John M. Wade.

United States Geologic Service (USGS). 2005. *Ten-Meter Digital Elevation Model*. (Accessed 4/15/05) <http://duff.geology.washington.edu/data/raster/tenmeter/>

ATTACHMENTS

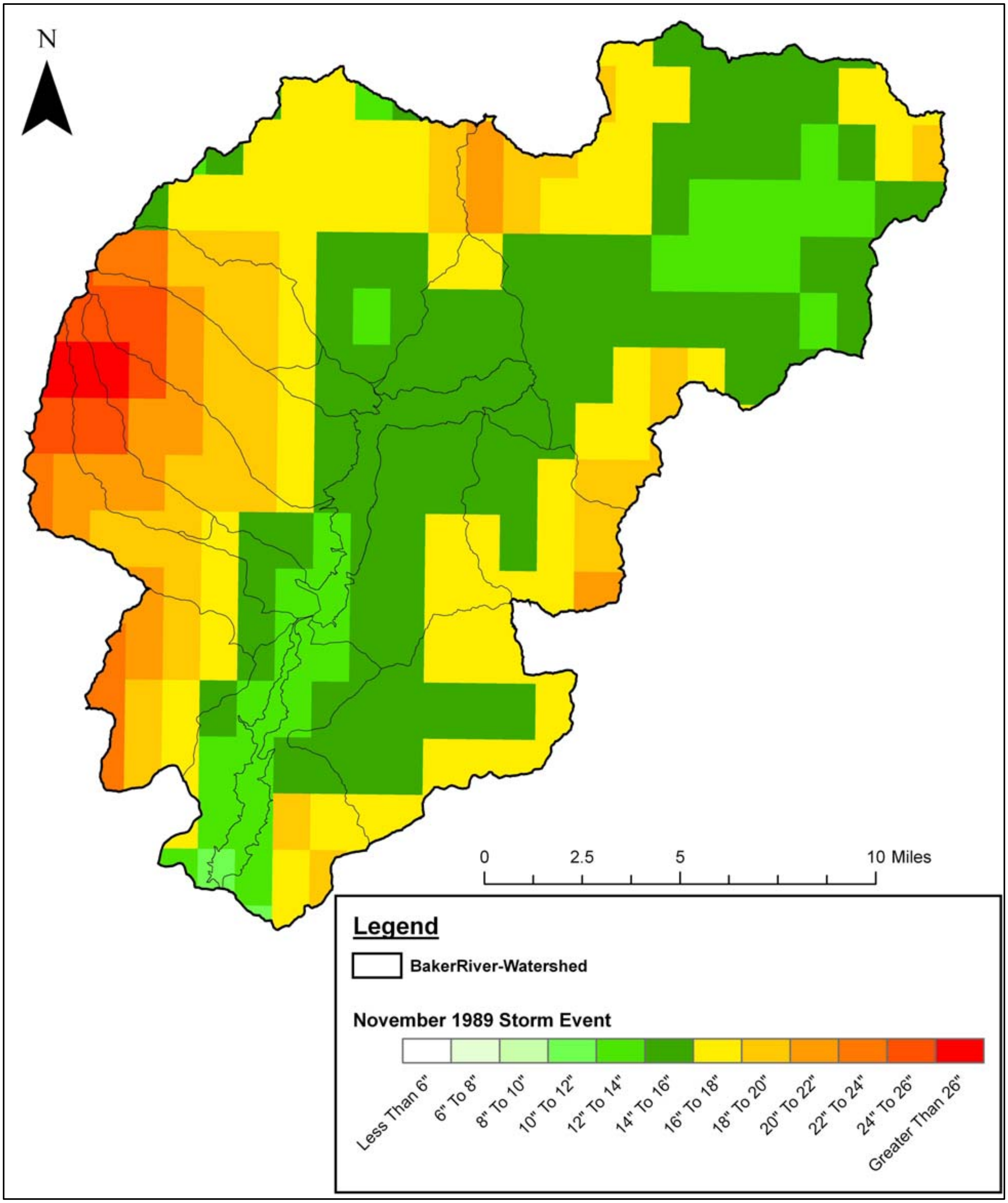
ATTACHMENT A
SPATIAL DISTRIBUTION OF HISTORICAL STORM EVENTS

ATTACHMENT B
LAPSE RATE COMPUTATION BACKUP

ATTACHMENT C
RESULTS OF THE TOP 25 BEHAVIORAL PARAMETER SETS AS COMPARED TO THE FINAL CALIBRATED PARAMETER SET

ATTACHMENT A - SPATIAL DISTRIBUTION OF HISTORICAL STORM EVENTS

(Note: Only the NOV89 event is included in this memo. If requested the distributions of the other events will be provided)



ATTACHMENT B - LAPSE RATE COMPUTATION BACKUP

NOV 89

NOTES:

Exclude Radiosonde observation data from 11/8/89 12Z from "Freezing Level" lapse rate calculations

Average Lapse Rate to "Freezing Level"	**2.3**
Maximum Lapse Rate to "Freezing Level"	**2.5**
Minimum Lapse Rate to "Freezing Level"	**2.1**

	GMT Time	Local PST			
	11/8/89 12Z	11/8/89 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	457	51.3	174	19.6	
950	1857	47.3	199	42.6	2.9
900	3320	43.0	214	44.9	2.9
850	4852	38.5	223	46.0	2.9
800	**6461**	**33.3**	**232**	**42.6**	**3.0**
750	**8158**	**30.7**	**254**	**42.6**	**2.7**
700	9966	28.9	274	52.9	2.4
650	11894	23.9	281	62.1	2.4
600	13953	18.5	281	64.5	2.4
Freezing Level	**7310**	**32.0**			**2.8**

	GMT Time	Local PST			
	11/9/89 00Z	11/8/89 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	349	55.4	249	13.8	
950	1763	52.9	270	26.5	1.8
900	3246	50.2	275	35.7	1.8
850	4808	47.5	277	46.0	1.8
800	6450	43.2	281	46.0	2.0
750	**8177**	**35.2**	**287**	**50.6**	**2.6**
700	**9996**	**31.8**	**288**	**59.8**	**2.4**
650	11934	25.7	286	62.1	2.6
600	13998	19.0	286	59.8	2.7
Freezing Level	**9889**	**32.0**			**2.5**

	GMT Time	Local PST			
	11/9/89 12Z	11/9/89 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	404	54.7	214	19.6	
950	1817	52.7	248	42.6	1.4
900	3300	50.4	250	46.0	1.5
850	4860	47.8	250	50.6	1.5
800	6502	42.8	255	55.2	2.0
750	8230	37.2	255	59.8	2.2
700	**10056**	**32.0**	**262**	**57.5**	**2.4**
650	11998	26.0	265	64.5	2.5
600	14064	20.1	265	62.1	2.5
Freezing Level	**10056**	**32.0**			**2.4**

	GMT Time	Local PST			
	11/10/89 00Z	11/9/89 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	247	54.1	189	21.9	
950	1657	51.4	210	44.9	1.9
900	3135	48.6	220	42.6	1.9
850	4688	45.3	223	42.6	2.0
800	6325	42.6	238	46.0	1.9
750	8057	39.6	254	44.9	1.9
700	9897	36.1	269	55.2	1.9
673	**10938**	**32.2**	**272**	**59.8**	**2.1**
650	**11850**	**28.2**	**275**	**64.4**	**2.2**
600	13929	23.0	274	71.3	2.3
Freezing Level	**10979**	**32.0**			**2.1**

	GMT Time	Local PST			
	11/10/89 12Z	11/10/89 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	275	54.9	245	11.5	
950	1687	52.0	270	17.3	2.0
900	3166	48.7	248	17.3	2.1
850	4719	45.3	245	33.4	2.1
800	6352	40.1	249	35.7	2.4
750	8070	34.5	251	42.6	2.6
700	9890	32.2	249	55.2	2.4
685	**10460**	**32.0**	**251**	**57.5**	**2.2**
650	11835	28.2	254	64.4	2.3
600	13912	22.1	259	73.7	2.4
Freezing Level	**10460**	**32.0**			**2.2**

	GMT Time	Local PST			
	11/11/89 00Z	11/10/89 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	326	48.7	13	4.6	
950	1715	44.1	318	11.5	3.4
900	3169	40.5	303	17.3	2.9
850	4691	35.2	285	17.3	3.1
800	6295	34.3	268	31.1	2.4
750	**7998**	**32.0**	**269**	**44.9**	**2.2**
700	9809	29.5	268	55.2	2.0
650	11740	24.8	266	57.5	2.1
600	13803	19.0	267	62.1	2.2
Freezing Level	**7998**	**32.0**			**2.2**

NOV 90(1)

NOTES

Exclude Radiosonde observation data from 11/11/90 12Z and 11/12/90 00Z from "Freezing Level" lapse rate calculations

Average Lapse Rate to "Freezing Level"	**2.5**
Maximum Lapse Rate to "Freezing Level"	**2.7**
Minimum Lapse Rate to "Freezing Level"	**2.2**

	GMT Time	Local PST			
	11/9/90 00Z	11/8/90 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	561	45.9	168	13.8	
950	1945	42.1	172	24.2	2.7
900	3392	37.9	187	28.8	2.8
850	**4908**	**33.4**	**203**	**38.0**	**2.9**
800	**6504**	**31.1**	**226**	**46.0**	**2.5**
750	8201	31.6	256	59.8	1.9
700	10005	27.7	270	66.7	1.9
650	11929	21.7	276	72.0	2.1
600	13976	16.3	280	71.3	2.2
Freezing Level	**5879**	**32.0**			**2.6**

	GMT Time	Local PST			
	11/9/90 12Z	11/9/90 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	376	53.6	224	24.2	
950	1784	50.5	236	59.8	2.2
900	3258	47.1	252	71.3	2.3
850	4805	43.3	263	64.4	2.3
800	6418	39.2	258	62.1	2.4
750	8134	35.1	251	66.7	2.4
700	**9955**	**32.4**	**258**	**73.7**	**2.2**
650	**11896**	**26.2**	**261**	**77.1**	**2.4**
600	13964	20.3	264	81.7	2.5
Freezing Level	**10080**	**32.0**			**2.2**

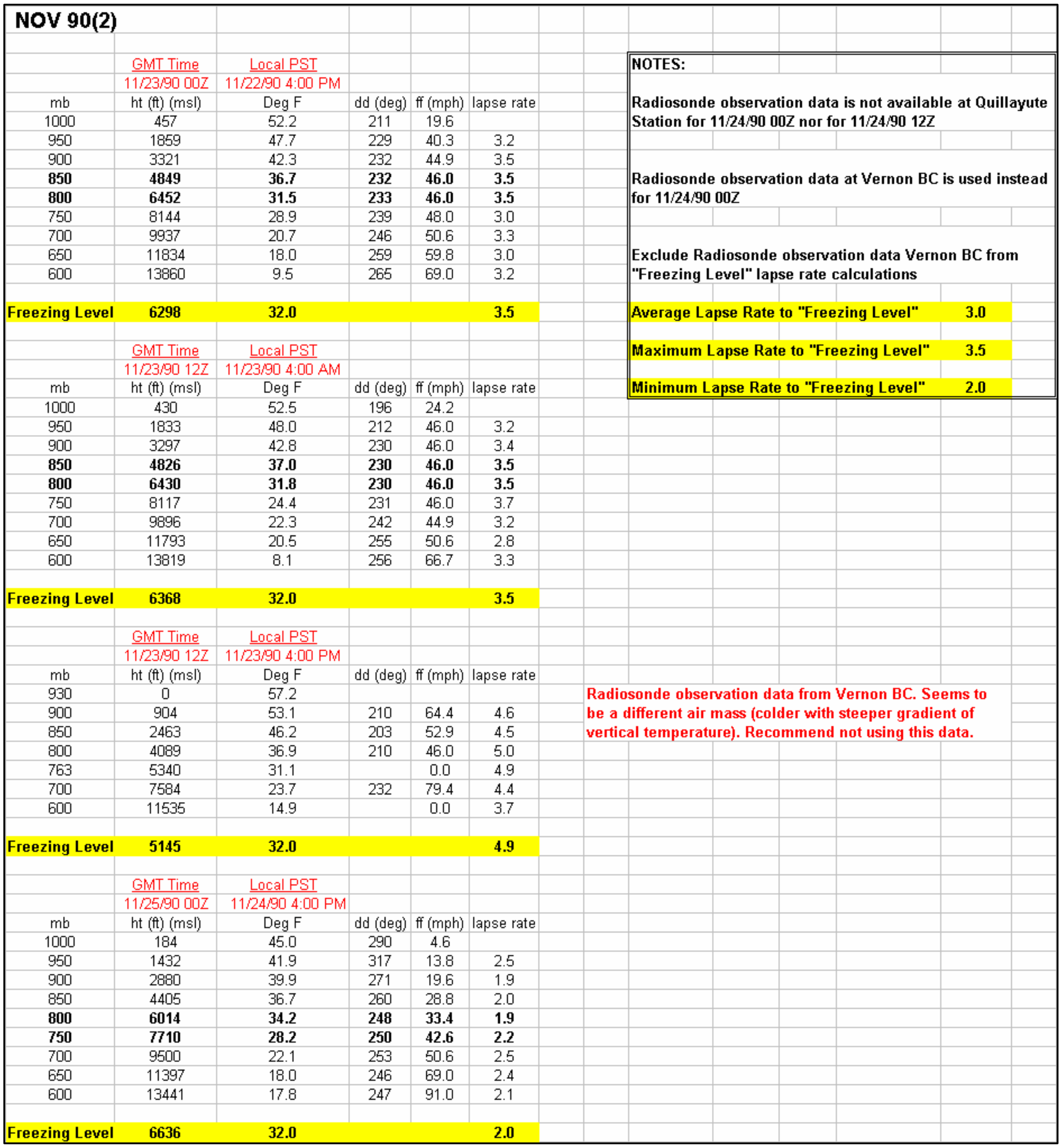
	GMT Time	Local PST			
	11/10/90 00Z	11/9/90 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	349	54.9	240	21.9	
950	1761	52.2	252	42.6	1.9
900	3240	48.2	257	40.3	2.3
850	4790	43.9	255	46.0	2.5
800	6420	40.1	254	53.0	2.4
750	**8139**	**35.1**	**255**	**60.0**	**2.5**
700	**9958**	**30.6**	**257**	**64.0**	**2.5**
650	11898	25.9	259	71.0	2.5
600	13966	20.3	262	84.0	2.5
Freezing Level	**9392**	**32.0**			**2.5**

	GMT Time	Local PST					
	11/10/90 12Z	11/10/90 4:00 AM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
1000	165	55.6	221	21.9		13.1	19
950	1579	52.9	231	48.3	1.9	11.6	42
900	3064	50.9	238	48.3	1.6	10.5	42
850	4618	45.0	227	50.6	2.4	7.2	44
800	6253	41.9	235	52.9	2.2	5.5	46
750	7978	36.7	241	55.2	2.4	2.6	48
700	9802	32.4	247	57.5	2.4	0.2	50
686	**10334**	**32.2**	**246**	**59.8**	**2.3**	0.1	52
650	**11743**	**26.4**	**245**	**62.1**	**2.5**	-3.1	54
550	16023	12.4	265	73.7	2.7	-10.9	64
Freezing Level	**10378**	**32.0**			**2.3**		

	GMT Time	Local PST					
	11/11/90 00Z	11/10/90 4:00 PM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
1000	247	54.7	187	15.0		12.6	13
950	1659	51.8	214	55.2	2.0	11	48
900	3140	48.7	229	52.9	2.1	9.3	46
850	4690	43.7	231	44.9	2.5	6.5	39
800	6319	39.4	223	46.0	2.5	4.1	40
750	8033	32.7	227	55.2	2.8	0.4	48
735	**8565**	**32.0**	**226**	**46.0**	**2.7**	0	40
700	9847	30.6	229	73.7	2.5	-0.8	64
650	11788	28.6	230	84.0	2.3	-1.9	73
600	13875	26.2		0.0	2.1	-3.2	
Freezing Level	**8565**	**32.0**			**2.7**		

	GMT Time	Local PST					
	11/11/90 12Z	11/11/90 4:00 AM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
1000	302	54.9	192	17.3		12.7	15
950	1711	51.3	211	42.6	2.6	10.7	37
900	3187	47.5	208	44.9	2.6	8.6	39
850	4735	43.3	206	40.3	2.6	6.3	35
800	6363	39.4	219	42.6	2.6	4.1	37
750	8081	34.3	231	46.0	2.6	1.3	40
736	**8578**	**32.2**	**233**	**48.3**	**2.7**	0.1	42
700	**9893**	**29.1**	**237**	**55.2**	**2.7**	-1.6	48
650	11814	26.4	241	59.8	2.5	-3.1	52
600	13886	18.7	243	59.8	2.7	-7.4	52
Freezing Level	**8655**	**32.0**			**2.7**		

	GMT Time	Local PST					
	11/12/90 00Z	11/11/90 4:00 PM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
1000	275	54.0	157	19.6		12.2	17
950	1685	52.0	189	40.3	1.4	11.1	35
900	3165	48.6	194	38.0	1.9	9.2	33
850	4716	44.2	209	33.4	2.2	6.8	29
800	6346	39.7	226	38.0	2.3	4.3	33
749	8101	39.0	242	38.0	1.9	3.9	33
708	**9595**	**32.4**	**242**	**38.0**	**2.3**	0.2	33
700	**9894**	**30.9**	**242**	**40.3**	**2.4**	-0.6	35
648	11907	25.9	244	48.3	2.4	-3.4	42
600	13891	20.7	244	57.5	2.4	-6.3	50
Freezing Level	**9670**	**32.0**			**2.3**		



NOV 90(2)

	GMT Time	Local PST			
	11/23/90 00Z	11/22/90 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	457	52.2	211	19.6	
950	1859	47.7	229	40.3	3.2
900	3321	42.3	232	44.9	3.5
850	**4849**	**36.7**	**232**	**46.0**	**3.5**
800	**6452**	**31.5**	**233**	**46.0**	**3.5**
750	8144	28.9	239	48.0	3.0
700	9937	20.7	246	50.6	3.3
650	11834	18.0	259	59.8	3.0
600	13860	9.5	265	69.0	3.2
Freezing Level	**6298**	**32.0**			**3.5**

NOTES:

Radiosonde observation data is not available at Quillayute Station for 11/24/90 00Z nor for 11/24/90 12Z

Radiosonde observation data at Vernon BC is used instead for 11/24/90 00Z

Exclude Radiosonde observation data Vernon BC from "Freezing Level" lapse rate calculations

Average Lapse Rate to "Freezing Level"	**3.0**
Maximum Lapse Rate to "Freezing Level"	**3.5**
Minimum Lapse Rate to "Freezing Level"	**2.0**

	GMT Time	Local PST			
	11/23/90 12Z	11/23/90 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	430	52.5	196	24.2	
950	1833	48.0	212	46.0	3.2
900	3297	42.8	230	46.0	3.4
850	**4826**	**37.0**	**230**	**46.0**	**3.5**
800	**6430**	**31.8**	**230**	**46.0**	**3.5**
750	8117	24.4	231	46.0	3.7
700	9896	22.3	242	44.9	3.2
650	11793	20.5	255	50.6	2.8
600	13819	8.1	256	66.7	3.3
Freezing Level	**6368**	**32.0**			**3.5**

	GMT Time	Local PST			
	11/23/90 12Z	11/23/90 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
930	0	57.2			
900	904	53.1	210	64.4	4.6
850	2463	46.2	203	52.9	4.5
800	4089	36.9	210	46.0	5.0
763	5340	31.1		0.0	4.9
700	7584	23.7	232	79.4	4.4
600	11535	14.9		0.0	3.7
Freezing Level	**5145**	**32.0**			**4.9**

Radiosonde observation data from Vernon BC. Seems to be a different air mass (colder with steeper gradient of vertical temperature). Recommend not using this data.

	GMT Time	Local PST			
	11/25/90 00Z	11/24/90 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	184	45.0	290	4.6	
950	1432	41.9	317	13.8	2.5
900	2880	39.9	271	19.6	1.9
850	4405	36.7	260	28.8	2.0
800	**6014**	**34.2**	**248**	**33.4**	**1.9**
750	**7710**	**28.2**	**250**	**42.6**	**2.2**
700	9500	22.1	253	50.6	2.5
650	11397	18.0	246	69.0	2.4
600	13441	17.8	247	91.0	2.1
Freezing Level	**6636**	**32.0**			**2.0**

NOV 95(2)

NOTES

Exclude Radiosonde observation data from 11/30/95 12Z from "Freezing Level" lapse rate calculations

Average Lapse Rate to "Freezing Level"	**2.6**
Maximum Lapse Rate to "Freezing Level"	**2.9**
Minimum Lapse Rate to "Freezing Level"	**2.2**

	GMT Time	Local PST			
	11/28/95 12Z	11/28/95 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	266	52.9	240	10.4	
950	1756	49.0	265	27.6	2.6
900	3104	42.6	265	26.5	3.6
850	4682	43.2	270	44.9	2.2
800	6284	38.6	285	61.0	2.4
750	7999	36.4	285	58.7	2.1
700	**9885**	**32.0**	**275**	**58.7**	**2.2**
650	11850	27.8	285	66.7	2.2
600	13765	16.3	285	77.0	2.7
Freezing Level	**9885**	**32.0**			**2.2**

	GMT Time	Local PST			
	11/29/95 00Z	11/28/95 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	231	54.3	230	13.8	
950	1785	51.0	245	49.5	2.1
900	3020	48.4	255	62.1	2.1
850	4667	45.0	270	59.8	2.1
800	6040	40.6	265	63.3	2.4
750	8028	36.5	255	72.5	2.3
700	**9848**	**32.0**	**260**	**70.2**	**2.3**
650	11897	26.4	265	69.0	2.4
600	14243	17.3	260	72.5	2.6
Freezing Level	**9848**	**32.0**			**2.3**

	GMT Time	Local PST			
	11/29/95 12Z	11/29/95 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	184	55.0	180	15.0	
950	1599	53.8	217	38.0	0.8
900	3085	51.1	225	40.3	1.3
850	4640	45.0	230	46.0	2.2
800	6267	38.3	228	57.5	2.7
750	**7978**	**32.9**	**236**	**64.4**	**2.8**
700	**9790**	**28.0**	**242**	**81.7**	**2.8**
650	11713	22.1	247	88.6	2.9
600	13764	17.4	258	102.4	2.8
Freezing Level	**8311**	**32.0**			**2.8**

	GMT Time	Local PST					
	11/30/95 00Z	11/29/95 4:00 PM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
996	0	50.2	190	9.2		10.1	8
950	1286	46.6	214	35.7	2.8	8.1	31
900	2747	40.8	223	38.0	3.4	4.9	33
850	4273	36.9	222	40.3	3.1	2.7	35
800	5876	32.4	227	42.6	3.0	0.2	37
787	**6307**	**32.0**	**229**	**44.9**	**2.9**	0	39
750	7569	28.0	230	52.9	2.9	-2.2	46
700	9354	20.3	233	59.8	3.2	-6.5	52
650	11243	13.8	235	66.7	3.2	-10.1	58
600	13250	4.8	240	81.7	3.4	-15.1	71
Freezing Level	**6307**	**32.0**			**2.9**		

	GMT Time	Local PST					
	11/30/95 12Z	11/30/95 4:00 AM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
999	0	48.0	230	6.9		8.9	6
950	1366	45.0	230	26.5	2.2	7.2	23
900	2819	39.2	241	31.1	3.1	4	27
850	**4335**	**32.5**	**241**	**38.0**	**3.6**	0.3	33
800	**5923**	**27.7**	**237**	**35.7**	**3.4**	-2.4	31
750	7598	23.0	226	33.4	3.3	-5	29
700	9361	13.8	237	33.4	3.7	-10.1	29
650	11224	8.4	235	40.3	3.5	-13.1	35
600	13212	3.6	246	50.6	3.4	-15.8	44
Freezing Level	**4511**	**32.0**			**3.6**		

OCT 03

NOTES:	
Average Lapse Rate to "Freezing Level"	**2.4**
Maximum Lapse Rate to "Freezing Level"	**2.8**
Minimum Lapse Rate to "Freezing Level"	**1.9**

	GMT Time	Local PST			
	10/16/03 12Z	10/16/03 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	150	51.1	160	16.1	
950	1492	47.6	160	63.3	2.6
900	2957	44.6	179	69.0	2.3
850	4501	44.6	205	77.1	1.5
800	6138	43.2	226	76.0	1.3
750	**7872**	**39.5**	**238**	**67.9**	**1.5**
700	**9705**	**33.1**	**235**	**65.6**	**1.9**
650	11653	29.8	235	72.5	1.9
600	13741	24.8	239	79.4	1.9
Freezing Level	**10354**	**32.0**			**1.9**

	GMT Time	Local PST			
	10/17/03 00Z	10/16/03 4:00 PM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	143	57.9	165	38.0	
950	1539	54.5	194	69.0	2.4
900	3027	51.6	210	82.9	2.2
850	4591	49.6	215	93.2	1.9
800	6234	46.2	215	104.7	1.9
750	7970	41.4	215	117.4	2.1
700	**9826**	**36.3**	**215**	**130.0**	**2.2**
650	**11783**	**31.5**	**215**	**145.0**	**2.3**
600	13866	26.6	215	158.8	2.3
Freezing Level	**11579**	**32.0**			**2.3**

	GMT Time	Local PST			
	10/17/03 12Z	10/17/03 4:00 AM			
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate
1000	258	56.8	165	13.8	
950	1675	53.1	198	26.5	2.6
900	3156	48.5	216	26.5	2.9
850	4705	43.2	220	23.0	3.1
800	6330	39.4	235	34.5	2.9
750	**8055**	**37.5**	**240**	**50.6**	**2.5**
700	**9881**	**31.5**	**225**	**50.6**	**2.6**
650	11825	29.0	215	64.4	2.4
600	13911	24.4	229	81.7	2.4
Freezing Level	**9729**	**32.0**			**2.6**

	GMT Time	Local PST					
	10/18/03 00Z	10/17/03 4:00 PM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
1000	83	56.5	190	28.8		13.6	25
925	2235	52.9	190	62.1	1.7	11.6	54
850	4549	48.2	205	52.9	1.9	9	46
789	6567	43.2			2.1	6.2	
700	**9762**	**34.2**	**210**	**67.9**	**2.3**	1.2	59
632	**12438**	**25.0**			**2.5**	-3.9	
598	13871	24.3			2.3	-4.3	
Freezing Level	**10392**	**32.0**			**2.4**		

	GMT Time	Local PST					
	10/18/03 12Z	10/18/03 4:00 AM					
mb	ht (ft) (msl)	Deg F	dd (deg)	ff (mph)	lapse rate		
1000	55	57.2	175	19.6		14	17
925	2204	50.7	180	52.9	3.0	10.4	46
900	2953	48.9			2.9	9.4	
850	4515	48.2	195	50.6	2.0	9	44
783	6737	41.0			2.4	5	
757	7639	38.5			2.5	3.6	
720	**8969**	**33.1**			**2.7**	0.6	
700	**9708**	**28.6**	**210**	**61.0**	**3.0**	-1.9	53
662	11159	27.1			2.7	-2.7	
617	12985	23.2			2.6	-4.9	
Freezing Level	**9146**	**32.0**			**2.8**		

ATTACHMENT C - RESULTS OF TOP 25 BEHAVIORAL PARAMETER SETS AS COMPARED TO THE FINAL CALIBRATED PARAMETER SET

Table C-1. Model Results for Top 25 Behavioral Parameter Sets and Final Calibrated Parameter Set

Sim No.	Average Likelihood	NOV 89 Event							NOV 90(1) Event							NOV 95(2) Event					OCT 03 Event				
		RO VOL – UB (ac-ft)	% Error	RO VOL – LB (ac-ft)	% Error	HEC	NSE	Likelihood	RO VOL – UB (ac-ft)	% Error	RO VOL – LB (ac-ft)	% Error	HEC	NSE	Likelihood	RO VOL – LB (ac-ft)	% Error	HEC	NSE	Likelihood	RO VOL – LB (ac-ft)	% Error	HEC	NSE	Likelihood
FINAL CALIBRATED	**16.92**	**118,592**	**-3%**	**42,420**	**13%**	**0.15**	**0.87**	**6.87**	**127,108**	**-15%**	**44,964**	**-1%**	**0.09**	**0.82**	**11.37**	**34,791**	**-7%**	**0.03**	**0.94**	**38.29**	**16,333**	**-2%**	**0.09**	**0.93**	**11.15**
5032	**14.18**	**113,982**	**-1%**	**40,246**	**7%**	**0.15**	**0.86**	**6.76**	**124,267**	**-17%**	**42,969**	**-5%**	**0.11**	**0.77**	**9.52**	**33,714**	**-10%**	**0.03**	**0.92**	**30.80**	**15,450**	**-8%**	**0.10**	**0.92**	**9.62**
3377	**13.39**	**113,602**	**-2%**	**40,235**	**7%**	**0.13**	**0.88**	**7.77**	**120,359**	**-19%**	**42,789**	**-5%**	**0.10**	**0.79**	**9.59**	**33,645**	**-10%**	**0.04**	**0.92**	**28.39**	**15,295**	**-9%**	**0.13**	**0.91**	**7.81**
7762	**12.95**	**113,917**	**-1%**	**40,241**	**7%**	**0.14**	**0.88**	**7.39**	**122,464**	**-18%**	**42,820**	**-5%**	**0.11**	**0.78**	**9.42**	**33,683**	**-10%**	**0.04**	**0.91**	**27.03**	**15,336**	**-8%**	**0.13**	**0.91**	**7.96**
3675	**12.86**	**113,688**	**-1%**	**40,224**	**7%**	**0.13**	**0.88**	**7.51**	**122,154**	**-18%**	**42,811**	**-5%**	**0.10**	**0.79**	**9.69**	**33,485**	**-11%**	**0.04**	**0.91**	**26.62**	**15,297**	**-9%**	**0.13**	**0.91**	**7.63**
7784	**12.81**	**113,894**	**-1%**	**40,239**	**7%**	**0.15**	**0.86**	**6.68**	**123,464**	**-17%**	**42,842**	**-5%**	**0.11**	**0.76**	**9.08**	**33,673**	**-10%**	**0.04**	**0.91**	**27.49**	**15,342**	**-8%**	**0.13**	**0.91**	**7.98**
231	**12.66**	**113,858**	**-1%**	**40,236**	**7%**	**0.12**	**0.89**	**8.08**	**122,195**	**-18%**	**42,620**	**-6%**	**0.11**	**0.78**	**9.40**	**33,590**	**-11%**	**0.04**	**0.91**	**26.13**	**15,268**	**-9%**	**0.14**	**0.90**	**7.02**
5969	**12.58**	**113,842**	**-1%**	**40,202**	**7%**	**0.13**	**0.88**	**7.83**	**122,470**	**-18%**	**42,686**	**-6%**	**0.11**	**0.77**	**9.18**	**33,444**	**-11%**	**0.04**	**0.91**	**26.45**	**15,119**	**-10%**	**0.15**	**0.90**	**6.87**
4479	**12.44**	**113,701**	**-1%**	**40,231**	**7%**	**0.14**	**0.87**	**7.04**	**121,292**	**-19%**	**42,581**	**-6%**	**0.12**	**0.76**	**8.48**	**33,562**	**-11%**	**0.04**	**0.91**	**26.94**	**15,244**	**-9%**	**0.14**	**0.90**	**7.30**
7098	**12.30**	**113,916**	**-1%**	**40,220**	**7%**	**0.14**	**0.87**	**7.08**	**122,531**	**-18%**	**42,593**	**-6%**	**0.11**	**0.77**	**9.04**	**33,553**	**-11%**	**0.04**	**0.91**	**26.22**	**15,139**	**-10%**	**0.15**	**0.90**	**6.86**
6177	**12.26**	**113,890**	**-1%**	**40,235**	**7%**	**0.13**	**0.88**	**7.74**	**122,120**	**-18%**	**42,672**	**-6%**	**0.11**	**0.77**	**9.04**	**33,587**	**-11%**	**0.04**	**0.91**	**25.66**	**15,214**	**-9%**	**0.15**	**0.89**	**6.59**
4800	**12.21**	**113,897**	**-1%**	**40,225**	**7%**	**0.11**	**0.90**	**8.77**	**122,112**	**-18%**	**42,466**	**-6%**	**0.10**	**0.80**	**10.39**	**33,546**	**-11%**	**0.04**	**0.90**	**23.88**	**15,176**	**-9%**	**0.17**	**0.88**	**5.80**
5569	**12.19**	**113,901**	**-1%**	**40,242**	**7%**	**0.15**	**0.86**	**6.81**	**122,788**	**-18%**	**42,569**	**-6%**	**0.12**	**0.75**	**8.29**	**33,666**	**-10%**	**0.04**	**0.91**	**26.10**	**15,331**	**-8%**	**0.13**	**0.91**	**7.57**
1020	**12.15**	**113,881**	**-1%**	**40,205**	**7%**	**0.16**	**0.85**	**6.43**	**123,526**	**-17%**	**42,843**	**-5%**	**0.12**	**0.75**	**8.44**	**33,537**	**-11%**	**0.04**	**0.91**	**26.45**	**15,160**	**-9%**	**0.14**	**0.90**	**7.27**
4278	**12.14**	**113,838**	**-1%**	**40,216**	**7%**	**0.13**	**0.88**	**7.50**	**122,620**	**-18%**	**42,677**	**-6%**	**0.11**	**0.76**	**8.79**	**33,450**	**-11%**	**0.04**	**0.91**	**25.63**	**15,155**	**-9%**	**0.15**	**0.89**	**6.63**
4285	**12.09**	**113,939**	**-1%**	**40,242**	**7%**	**0.14**	**0.87**	**7.29**	**123,783**	**-17%**	**42,566**	**-6%**	**0.11**	**0.77**	**9.32**	**33,675**	**-10%**	**0.04**	**0.90**	**24.31**	**15,332**	**-8%**	**0.13**	**0.91**	**7.44**
5257	**12.03**	**113,856**	**-1%**	**40,234**	**7%**	**0.14**	**0.87**	**7.35**	**122,454**	**-18%**	**42,748**	**-5%**	**0.12**	**0.75**	**8.56**	**33,656**	**-10%**	**0.04**	**0.91**	**24.85**	**15,324**	**-8%**	**0.14**	**0.90**	**7.35**
5454	**11.99**	**113,752**	**-1%**	**40,205**	**7%**	**0.14**	**0.87**	**7.29**	**122,489**	**-18%**	**42,760**	**-5%**	**0.11**	**0.77**	**9.05**	**33,453**	**-11%**	**0.04**	**0.91**	**25.00**	**15,080**	**-10%**	**0.15**	**0.89**	**6.64**
5394	**11.98**	**113,931**	**-1%**	**40,231**	**7%**	**0.13**	**0.88**	**7.94**	**123,152**	**-17%**	**42,483**	**-6%**	**0.12**	**0.75**	**8.62**	**33,539**	**-11%**	**0.04**	**0.90**	**24.55**	**15,263**	**-9%**	**0.15**	**0.90**	**6.81**
5619	**11.94**	**113,956**	**-1%**	**40,191**	**7%**	**0.14**	**0.87**	**7.30**	**124,175**	**-17%**	**42,663**	**-6%**	**0.11**	**0.75**	**8.77**	**33,417**	**-11%**	**0.04**	**0.91**	**24.97**	**15,093**	**-10%**	**0.15**	**0.90**	**6.72**
5685	**11.92**	**113,943**	**-1%**	**40,224**	**7%**	**0.14**	**0.87**	**7.09**	**123,233**	**-17%**	**42,503**	**-6%**	**0.11**	**0.75**	**8.70**	**33,458**	**-11%**	**0.04**	**0.90**	**24.93**	**15,196**	**-9%**	**0.14**	**0.90**	**6.97**
4196	**11.89**	**113,812**	**-1%**	**40,222**	**7%**	**0.15**	**0.86**	**6.50**	**121,820**	**-18%**	**42,770**	**-5%**	**0.12**	**0.75**	**8.46**	**33,571**	**-11%**	**0.04**	**0.91**	**26.05**	**15,208**	**-9%**	**0.15**	**0.89**	**6.56**
6891	**11.89**	**113,650**	**-2%**	**40,220**	**7%**	**0.12**	**0.89**	**8.50**	**120,793**	**-19%**	**42,594**	**-6%**	**0.10**	**0.80**	**10.06**	**33,456**	**-11%**	**0.04**	**0.90**	**23.16**	**15,188**	**-9%**	**0.17**	**0.88**	**5.83**
4571	**11.86**	**113,940**	**-1%**	**40,236**	**7%**	**0.12**	**0.89**	**8.63**	**122,282**	**-18%**	**42,562**	**-6%**	**0.10**	**0.79**	**9.87**	**33,593**	**-11%**	**0.04**	**0.90**	**23.03**	**15,238**	**-9%**	**0.17**	**0.88**	**5.90**
7542	**11.85**	**113,938**	**-1%**	**40,197**	**7%**	**0.14**	**0.87**	**7.20**	**123,086**	**-17%**	**42,553**	**-6%**	**0.11**	**0.76**	**8.85**	**33,500**	**-11%**	**0.04**	**0.91**	**25.43**	**15,066**	**-10%**	**0.17**	**0.88**	**5.93**
7311	**11.81**	**113,883**	**-1%**	**40,203**	**7%**	**0.14**	**0.88**	**7.34**	**122,445**	**-18%**	**42,403**	**-6%**	**0.11**	**0.77**	**9.12**	**33,468**	**-11%**	**0.04**	**0.90**	**24.60**	**15,056**	**-10%**	**0.16**	**0.89**	**6.19**

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 8

RECONNAISSANCE LEVEL PMP STUDY AND STORM MAXIMIZATION

Applied Weather Associates, Inc.
August 17, 2005
Revised March 14, 2006

(FINAL)

INTRODUCTION

This memo summarizes the reconnaissance level PMP study intended to evaluate the potential effects of a full site-specific PMP study for the Baker River Project. This effort involves identification of extreme storms in HMR 57 and extreme storms that have occurred since publication of HMR 57, conducting in-place maximization of these storms, comparison of the resulting in-place maximization values to the HMR 57 general storm PMP values for each storm location, and finally, transpositioning of storms to the Baker River basin that occur over similar topography as the Baker River basin. The results of this analysis will be used to provide an estimate of the differences in PMP values that would potentially result if a future site specific study was conducted.

Additionally, comparison of storm maximization factors derived using dewpoint observations and/or sea surface temperatures vs using atmospheric sounding data is provided. This effort is evaluating the use of measured atmospheric precipitable water to the estimation of atmospheric precipitable water using observed dewpoint data and/or sea surface temperature observations.

RECONNAISSANCE LEVEL PMP STUDY

The potential effect of a site-specific probable maximum precipitation (PMP) study for the Upper and Lower Baker Dams drainage basin is being investigated in this reconnaissance level PMP study. A preliminary estimate of PMP values based on analyses of the most significant rainfall storm events that have occurred over regions that are meteorologically and geographically similar to the drainage basin is being determined. Rainfall amounts associated with these events are adjusted using standard procedures for PMP development. These include in-place maximization and for one storm that occurred over similar topography, transposition to the Baker River drainage basin.

This reconnaissance level study has identified significant meteorological and climatological factors that influence extreme rainfall over northwestern Washington. A detailed summary of these factors is provided. Significant extreme rainfall storm events listed in HMR 57 that are appropriate for western Washington have been identified. A storm search using rainfall data from the National Climatic Data Center has been completed that identifies extreme rainfall events that have occurred since the publication of HMR 57.

The rainfall amounts associated with the extreme storm events identified have been maximized in-place using maximization factors provided in HMR 57. When adequate data were available, maximization factors have been independently computed.

Comparisons have been made between the in-place maximized rainfall values, the most significant rainfall storm events at their historic storm locations and the HMR 57 general storm PMP values at the same locations. The HMR 57 procedure is based on analyzed storm rainfall data and uses various procedures to first adjust the observed rainfall amounts to maximum rainfall amounts at the historic storm locations, and then to adjust the rainfall values for other locations. Inherent in the procedures that follow in-place maximization are enveloping and smoothing of the rainfall values, both spatially and temporally. Comparison of the in-place maximized storm rainfall amounts with the HMR 57 PMP values at the historic storm locations provides an estimate of the effect of the HMR procedures beyond the initial storm maximization adjustment at the locations where the historic storms occurred. Adjustments associated with transposition factors, "K-factors" and "M-factors" are not used in determining in-place maximized storm rainfall values, i.e. no smoothing or enveloping is introduced with transpositioning and orographic adjustments. Orographic effects on each storm's rainfall are inherent in the storm's in-place rainfall analysis for the location where the storm occurred, i.e. the K and M factors are inherently included in the in-place rainfall amounts. The in-place maximization adjustment increases the in-place rainfall amounts to maximum amounts assuming additional atmospheric moisture were available for rainfall production at the location where the storm occurred. Hence, the comparison of in-place maximized extreme rainfall values at historic storm locations to the HMR 57 PMP values at the historic storm locations provides an estimate of the effect of the additional adjustments made by applying the additional HMR procedures.

The topography associated with each of the extreme rainfall storms has been compared with the topography of the Baker River drainage basin. Only one storm occurred over terrain with very similar features and that storm has been transpositioned to the Baker River drainage basin location with no modifications of the storm rainfall amounts based on topographic differences. This evaluation compared terrain elevations, slopes and orientation at the two locations. The maximized and transpositioned rainfall values for this storm are compared to the HMR 57 values for the Baker River watershed location.

TOPOGRAPHIC AND CLIMATIC FEATURES OF WASHINGTON

TOPOGRAPHIC FEATURES

The location of the State of Washington on the windward coast in mid-latitudes is such that the climatic elements combine to produce a predominantly marine-type climate west of the Cascade Mountains, while east of the Cascades, the climate possesses both continental and marine characteristics. Considering its northerly latitude, 46° to 49°, Washington's climate at lower elevations is relatively mild

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There are several climatic controls, which have a definite influence on the climate; (a) terrain, (b) Pacific Ocean, and (c) semi-permanent high and low pressure regions located over the North Pacific Ocean. The effects of these various controls combine to produce significantly different climate conditions within relatively short distances.

Washington’s western boundary is the Pacific Ocean. The seasonal change in the temperature of the ocean is less than the seasonal change in the temperature of the land, thus the ocean is warmer in winter and cooler in summer than the adjoining land surfaces. The average temperature of the water along the coast and in the Strait of Juan de Fuca ranges from 45° in January to 53° F in July; however, during the summer, some of the shallow bays and protected coves are five to ten degrees warmer.

There are two ranges of mountains parallel to the coast and approximately perpendicular to the prevailing direction of moist air moving inland from over the ocean. The first orographic lifting and major release of moisture occurs along the western slope of the coastal range-The Olympic Mountains. The second area of heavy orographic precipitation is along the windward slopes of the Cascade Mountains, which includes the Baker River drainage basin. The Cascade Mountains, 90 to 125 miles inland and 4,000 to above 10,000 feet in elevation, are a topographic and climatic barrier separating the state into eastern and western Washington. The higher, wider and more rugged sections are in the northern part of the state, known as the North Cascades. This is the region that encompasses the Baker River drainage. Some of the highest isolated volcanic peaks are Mt. Rainier (14,411 ft.), Mt. Adams (12,307 ft.) and Mt. Baker (10,730 ft.). The Baker River drainage is situated along the southeast slopes of Mt. Baker, and therefore is greatly influenced by the volcanic peak and its effects on the local climate and weather.

Mount Baker (10,778 feet) is an ice-clad volcano in the North Cascades of Washington about 30 miles due east of the city of Bellingham. After Mount Rainier, it is the most heavily glaciated of the Cascade volcanoes: the volume of snow and ice on Mount Baker (about 1.8 cubic kilometers; 0.43 cubic miles) is greater than that of all the other Cascades volcanoes (except Rainier) combined. Isolated ridges of lava and hydrothermally altered rock, especially in the area of Sherman Crater, are exposed between glaciers on the upper flanks of the volcano: the lower flanks are steep and heavily vegetated

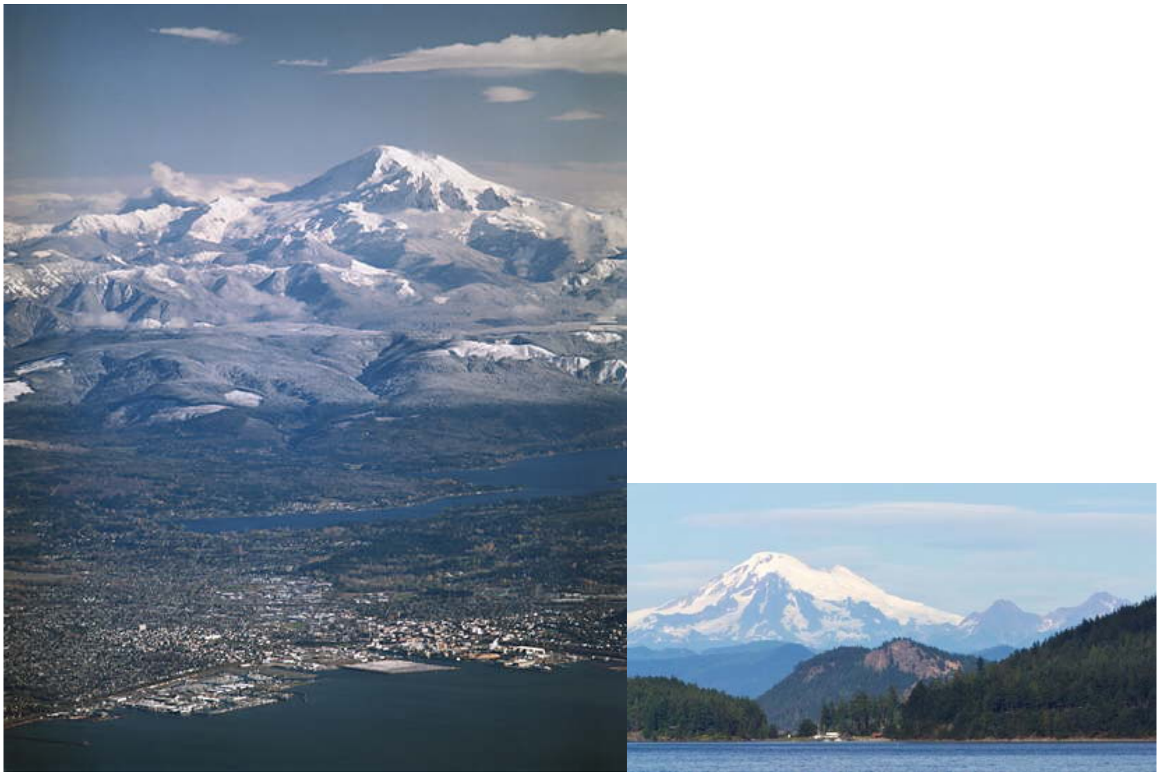


Fig. 1-Mt Baker and surrounding topography

Photo Courtesy of:
http://images.google.com

Photo Courtesy of:
http://www.ics.uci.edu

CLIMATIC FEATURES

The location and intensity of the semi-permanent high and low-pressure areas over the North Pacific Ocean have a definite influence on the climate. Air circulates in a clockwise direction around the semi-permanent high-pressure cell and in a counter-clockwise direction around the semi-permanent low-pressure cell. From the late spring through late summer, the low-pressure cell becomes weak and moves north of the Aleutian Islands. At the same time, the high-pressure area to the southwest strengthens and spreads over most of the North Pacific Ocean. A circulation of air around the high-pressure center brings a prevailing westerly and northwesterly flow of comparatively dry, cool and stable air into the Pacific Northwest. As the air moves inland, it becomes warmer and drier which results in a dry season beginning in the late spring and reaching a peak in mid-summer.

In the fall and winter, the Aleutian low-pressure center intensifies and moves southward, generally over the Gulf of Alaska, reaching a maximum intensity in midwinter. At the same time, the high-pressure area becomes weaker and moves southward. A circulation of air around these two pressure centers over the ocean brings prevailing southwesterly and westerly atmospheric flow into the Pacific Northwest. This air mass from over the ocean is moist and near the temperature of the water. Condensation occurs as the air moves inland over the cooler land and rises along the windward slopes of the mountains. The result is a wet season beginning in October, reaching a peak in winter, and then gradually decreasing in the spring.

CLIMATE REGIONS

The climate of Washington is highly variable, ranging from temperate rainforest, to deserts and sand, to glaciated volcanic peaks. The area's precipitation follows a distinct pattern, with a distinct wet season from October through April and relatively drier conditions from May through September. During the wet season, a modified maritime polar airmass dominates the region with steady rain developing every couple of days as approaching low pressure centers moving out of the Gulf of Alaska follow the polar jet stream into the region. Following frontal passage, cool and blustery conditions with showers dominate for the next 12-24 hours. Snow levels often rise to around three to four thousand feet ahead of these storms, then drop to one to two thousand feet with the cold air advection. This allows extensive snowpacks to develop in the Baker River drainage, often reaching over 100 inches from December through April. Snow water content is high, with a 10:1 ratio or lower common throughout winter and into spring. Therefore, large amounts of water are stored throughout winter and released in spring and summer, adding greatly to the amount of water available for hydrologic runoff and keeping the area green through the relatively dry summer and early fall. The heavy snowfall and cool summer temperatures allow permanent snowfields to remain at many locations above five thousand feet in the region and most peaks above seven thousand feet are glaciated. Figure 2 below shows the wide variety of precipitation patterns that affect the state of Washington.

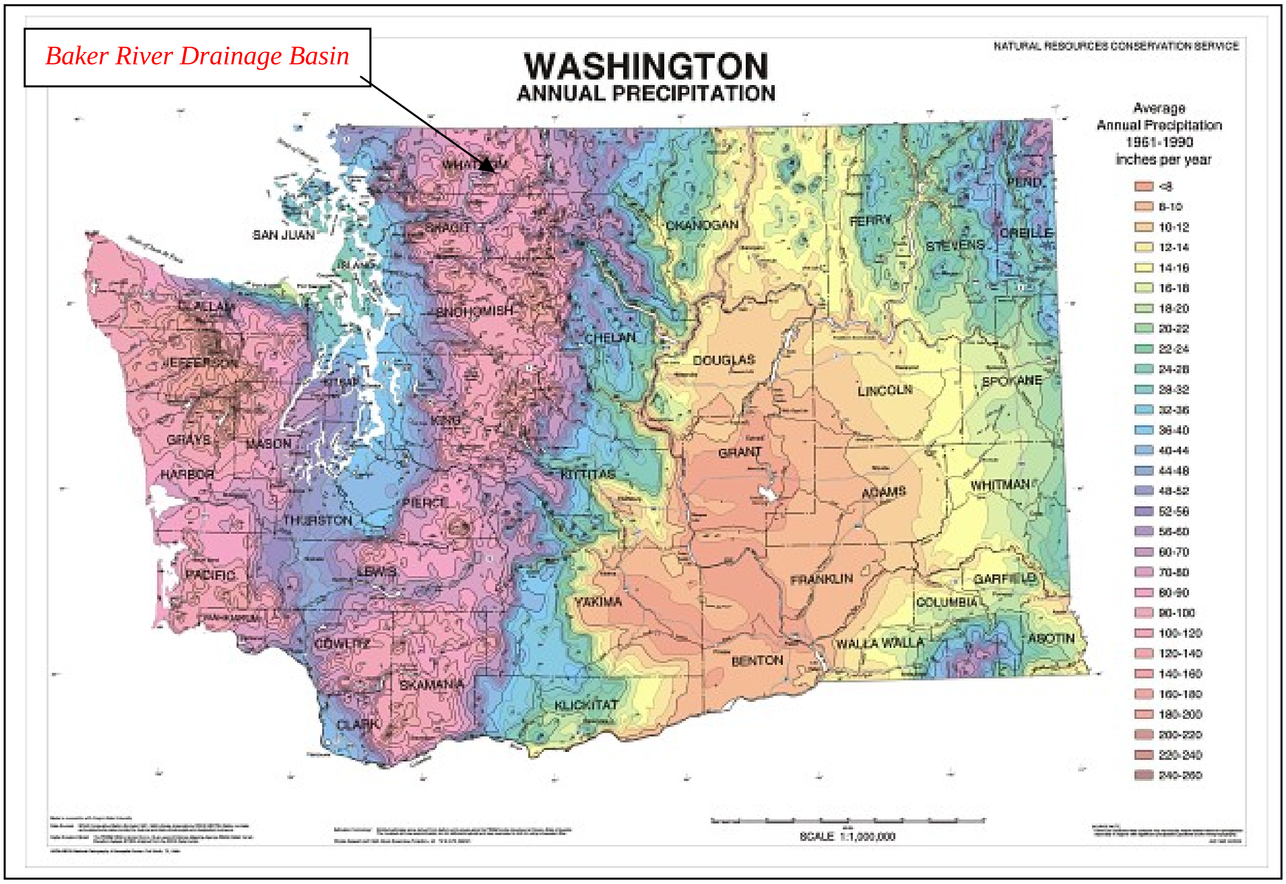


Figure 2 Washington Annual Precipitation, inches

WESTERN WASHINGTON

West of the Cascade Mountains, summers are cool and comparatively dry and winters are mild, wet, and cloudy. The average number of clear or only partly cloudy days each month varies from four to eight in winter, eight to 15 in spring and fall, and 15 to 20 in summer. The percent of possible sunshine received each month ranges from approximately 25 percent in winter to 60 percent in summer. In the interior valleys, measurable rainfall is recorded on 150 days each year and on 190 days in the mountains and along the coast. Thunderstorms over the lower elevations occur on four to eight days each year and over the mountains on seven to 15 days. Damaging hailstorms rarely, if ever, occur in most localities of western Washington. During July and August, the driest months, it is not unusual for two to four weeks to pass with only a few showers; however, in December and January, the wettest months, precipitation is frequently recorded on 20 to 25 days or more each month. Annual precipitation ranges from just less than 20 inches in an area northeast of the Olympic Mountains around Sequim to over 150 inches along the southwestern slopes of Olympic Mountains. Snowfall is light over the lower elevations but increases dramatically with elevation, becoming heavy in the mountains above 3000 feet. In fact, the two highest recorded yearly snowfalls have occurred in the Cascade Mountains. The old world record was set at Paradise Ranger Station, when 1122 inches accumulated during the winter of 1971-72. Then during the 1998-1999 season an amazing 1140 inches of snow fell at Mt. Baker Ski Resort. This became the new world record, and more importantly is a location that has a direct influence on our study basin.

The Baker River region is dominated by a west-southwesterly flow, which often transports moisture from the Pacific Ocean and steers strong areas of low pressure into the region with rain, wind, and winter snow. The heaviest precipitation occurs from the late fall through early spring timeframe. Rainfall resulting from moisture flowing into the region is enhanced by orographic lift as it rises from sea level around the Puget Sound less than 50 miles to the west to over ten thousand feet along the slopes of Mt. Baker. Several re-occurring climate systems also play a role in the region’s climate. The El Nino-La Nina cycle (ENSO) influences the precipitation and temperatures in the region, with a generally higher amount of moisture expected during El Nino events and lower amounts expected during La Nina events. Also, the phase of the Pacific Decadel Oscillation plays a role in the frequency and strength of storms moving in from the Gulf of Alaska. Other factors such as the phase of the Pacific North America pattern and the western pacific typhoon activity often play a role.

During the wet season, rainfall is usually light to moderate intensity and continuous over a period of time rather than heavy downpours for brief periods. Maximum rainfall intensities in one out of ten years are: .6 to 1.0 inch in one hour; 1.0 to 2.5 inches in three hours; 1.5 to 5.0 inches in six hours; and 2.0 to 7.0 inches in 12 hours. The heavier intensities occur along the windward slopes of the mountains. Rainfall and potential flooding events are often enhanced during the winter months when the prevailing winds flow in from the southwest, transporting copious amounts of tropical moisture into western Washington. This phenomenon is often referred to as the “Pineapple Express.” Figure 4 below represents typical satellite imagery associated with this phenomenon. This combination of warm, moist air producing heavy rain on top of melting snow often results in serious flooding.

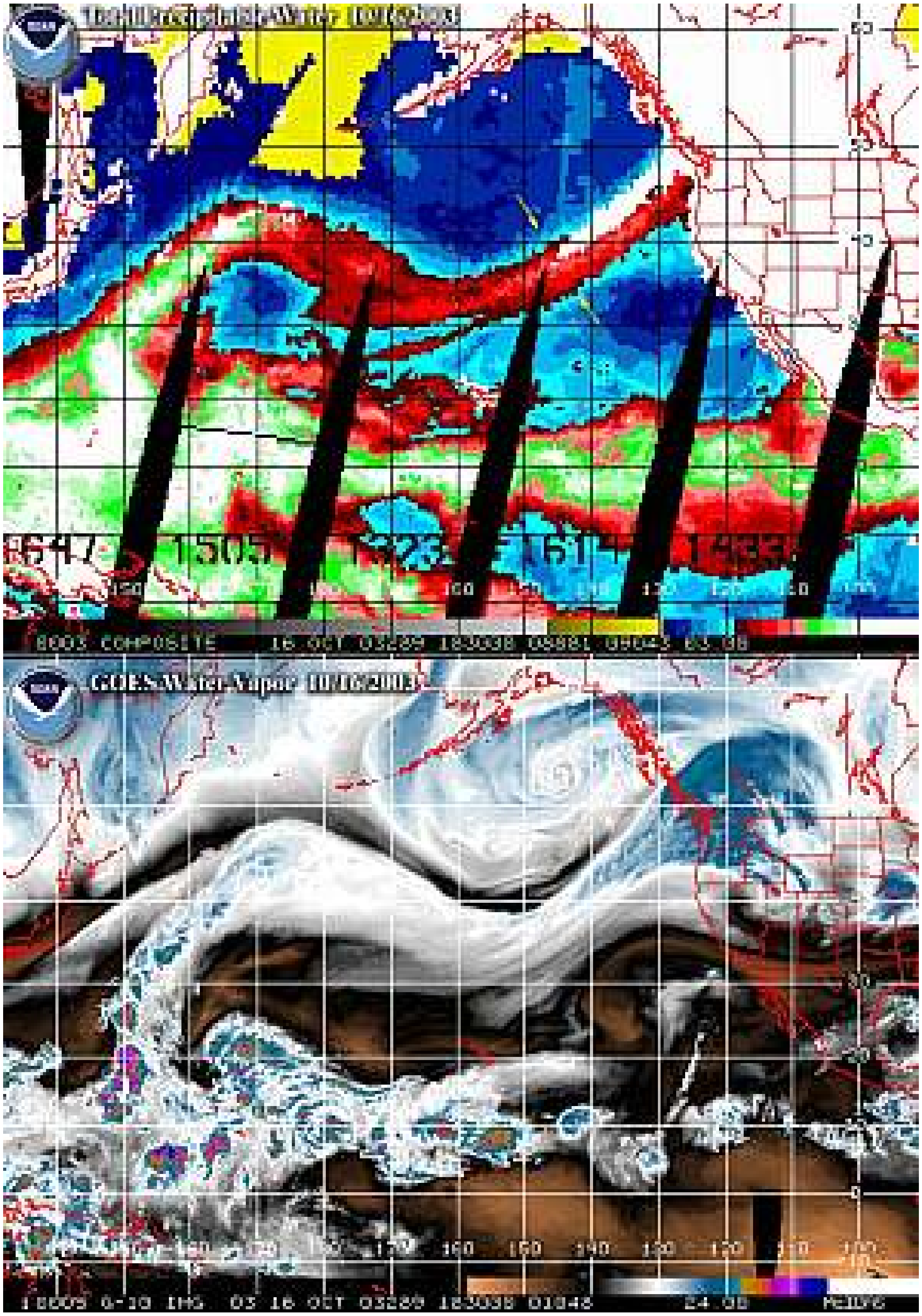


Figure 4 Example of the Pineapple Express as seen from satellite imagery. Top image-Perceptible Water, notice the Subtropical Jet with higher value aimed directly at the Washington Coast. Bottom Image-Water Vapor, again a large plume of moisture is slamming into Washington and southern British Columbia

On October 20th 2003, the track of the “Pineapple Express” slammed directly into northwestern Washington. Sea-Tac Airport, south of Seattle, set the all-time, 24-hour rainfall record with 5.02 inches (126.5 mm), and it was only third on the list of rainfall records set that day. At Shelton, 7.20 inches (181.4 mm) fell, and Hoquiam received 5.39 inches (135.8 mm). Five other stations recorded record daily rainfalls for October including the communities of Bellingham, Port Angeles and Olympia. The heavy rainfall combined with melting snow in the Cascade Mountains to produce severe flooding on many rivers of western Washington. For example, the Skagit River, about 60 miles north of Seattle, crested at a record 42.2 feet - more than 14 feet above flood stage. The flooding of the river forced more than 3,000 Skagit County residents out of their homes. Figures 5 below shows the results of this record flooding event and are typical of “Pineapple Express” heavy rain events that often affect western Washington from October through February.

Figure 5 Flooding near Hamilton, WA and flood water rushing over the Baker Dam

Flooding From October 2003 Event, photos courtesy of http://emd.wa.gov/emdimages/03-

During the latter half of the summer and early fall, the lower valleys are sometimes filled with fog or low clouds, while at the same time, the higher elevations are sunny. This occurs as an inversion sets up with cool, moist air trapped below relatively warmer air above. The cool surface temperatures of the adjacent Pacific Ocean and Puget Sound play a key role by “chilling” the lower layers of the atmosphere and strengthening this inversion, especially in stagnant weather conditions.

The strongest winds are generally from the south or southwest and occur during the late fall and winter in association with intense areas of low pressure moving southward from the Gulf of Alaska. Strong pressure gradients winds from the north/northeast occur a few times per year as well when continental polar air masses slide south over the region and cold dense air rushes south out of the Fraser River Canyon in southwestern British Columbia. The winds can be sustained over 40 mph and are often accompanied by sub-freezing temperatures, snow, and freezing rain. Generally, the Arctic Air intrusions do not make it farther than 100 miles or so south of the Canadian border, but they do have a direct affect on our study area. Finally, easterly winds also occur at the outlets of the major passes through the Cascades, such as Stevens and Snoqualmie Passes. These occur when an area of high pressure sets up over Eastern Washington and the Northern Rockies. As an area of low pressure approaches the Washington coastline, the pressure gradient force increases; cold air spills through the passes, and accelerates as it descends to the Puget Sound Lowlands. In the interior valleys, wind velocities can be expected to reach 40 to 50 mph each winter and 75 to 90 mph once in 50 years.

The mean daily relative humidity in January varies from about 87 percent in the early morning to 78 percent in the late afternoon. In July, it ranges from 85 percent to 47 percent. During periods of easterly winds, the relative humidity occasionally drops to 25 percent or lower.

In order to describe the climate of western Washington in more detain, the area has been divided into five regions.

PUGET SOUND-LOWLANDS

This area includes a narrow strip of land along the west side of Puget Sound southward from the Strait of Juan de Fuca to the vicinity of Centralia and Chehalis and a somewhat wider strip along the east side of the Sound extending northward to the Canadian Border. Variations in the temperature, length of the growing season, fog, rainfall, and snowfall are due to such factors as distance from the Puget Sound, elevation, and channeling of air from over the ocean through the Strait of Juan de Fuca and the Chehalis River valley.

The prevailing direction of the wind is south to southwest during the wet season and northwest in summer. The average wind velocity is less than 10 mph. Although this is the most densely populated and industrialized area in the state, there is sufficient wind most of the year to disperse air pollutants released into the atmosphere. Air pollution is usually most noticeable in the late fall and winter season, under conditions of clear skies, light wind and sharp temperature inversions. These conditions usually only persist for a few days before weather systems move through removing the pollution by wind and rain.

Annual precipitation ranges from 32 to 35 inches from the Canadian Border to Seattle, then gradually increases to 45 inches in the vicinity of Centralia. The winter season snowfall ranges from 10 to 20 inches. Both rainfall and snowfall increase with only slight increases in elevation and distance from the Puget Sound. Snow generally melts rather quickly and depths seldom exceed six to 15 inches. The greatest snow depth recorded in Seattle is 29 inches. Most of this area is near the eastern edge of the “rain shadow” of the Olympic Mountains.

The average January maximum temperature ranges from 41° to 45° F and minimum temperatures from 28° to 32° F. With an increase in distance from the moderating influences of the Puget Sound, winter temperatures decrease and summer temperatures increase. Minimum temperatures ranging from 0° to -10° F have been recorded; however, temperatures seldom drop lower than 10° to 15° F. During July, the average maximum temperature ranges from 73° F near the Canadian Border to 78° F in the vicinity of Olympia, and the minimum temperature is near 50° F. Maximum temperatures have reached 100° F; however, in an average summer, 90° or higher is only recorded on three to five days. The growing season is from the latter half of April until the middle of October.

EAST OLYMPIC-CASCADE FOOTHILLS

This area includes foothills along the eastern slope of the Olympic Mountains, foothills along the western slope of the Cascade Mountains and the valley separating these ridges from the vicinity of Chehalis to the Columbia River. This, along with the Cascade Mountains-West (next section), encompasses the Baker River Drainage Basin. The easterly movement of moist air from over the ocean produces down slope winds in foothills along the eastern slope of the Coastal Range and upslope winds in the foothills along the western slope of the Cascade Mountains. Precipitation is heavier along the windward slopes than in the valley or along the lee slopes. The average annual precipitation ranges form 40 inches in the lower valleys near the Columbia River to 90 inches at stations 800 to 1,000 feet above sea level along the western slope of the Cascade Range. Annual snowfall increases from less than 10 inches in the lower valleys to 50 inches at elevations 500 to 800 feet. Figures 6 through 8 display the monthly precipitation for several climate stations located within or near the Baker River drainage basin. Notice the strong seasonality in the precipitation patterns, with the majority of the yearly precipitation occurring from October through March.

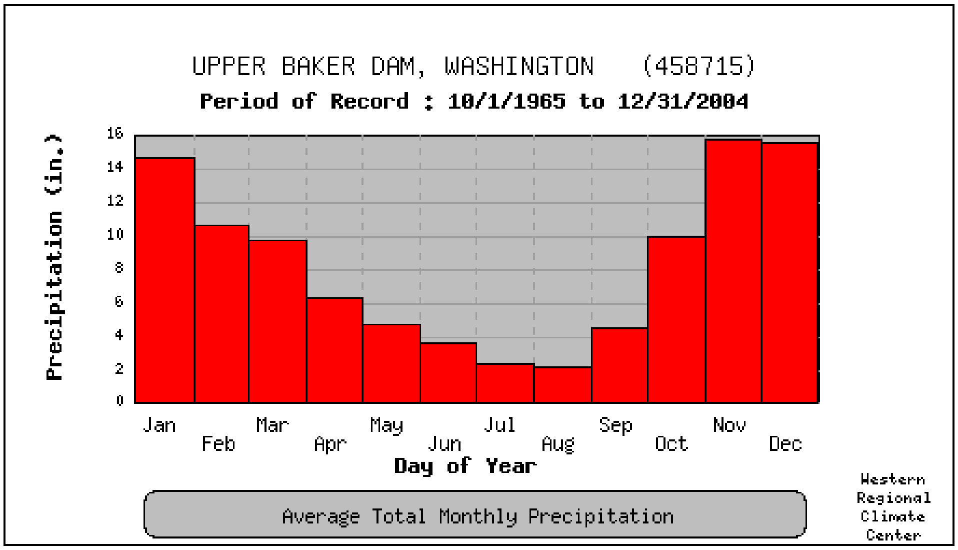


Figure 6 Upper Baker Dam Monthly Precipitation Histogram

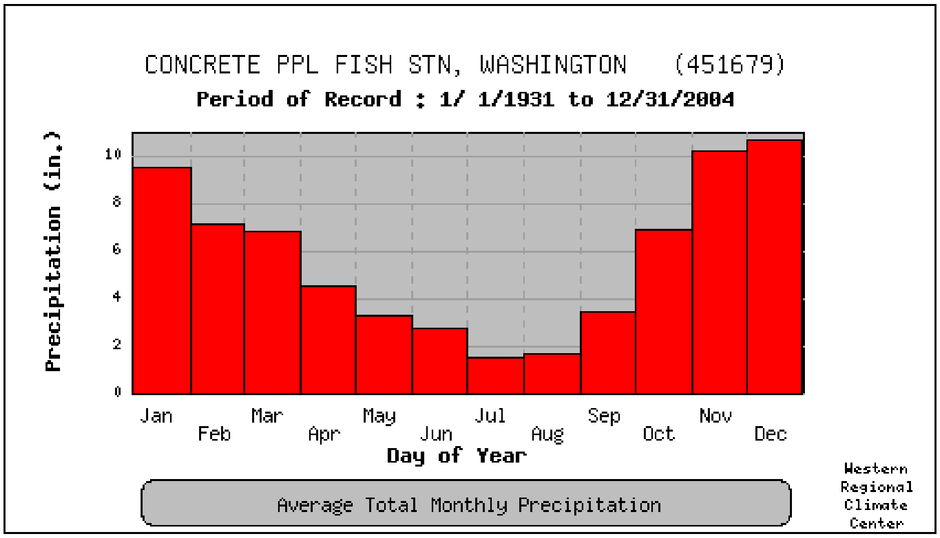


Figure 7 Concrete Monthly Precipitation Histogram

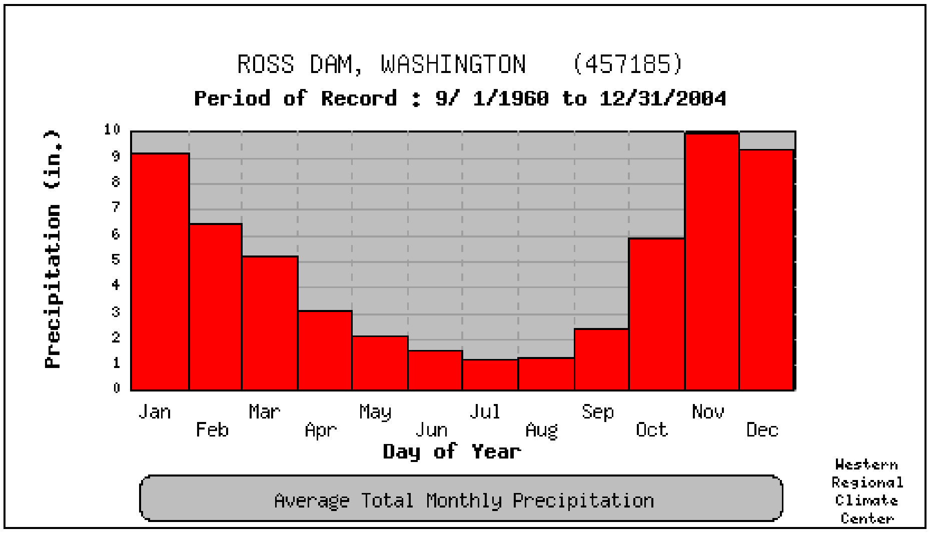


Figure 8 Ross Dam Monthly Precipitation Histogram

In January the average maximum temperature ranges from 38° to 45° F, and the minimum from 25° to 32° F. Minimum temperatures have dropped to between 0° and -15° F; however, minimum temperatures lower than 5° to 10° F occur infrequently. In July the average maximum temperature ranges from 75° to 80° F and the minimum is near 50° F. Maximum temperature have reached 100 ° to 105° F; however, it is unusual for afternoon temperatures to exceed 90° on more than eight to 15 days in the summer season. The hottest weather occurs during periods of dry easterly winds. The average date of the last freezing temperature in the spring ranges from the middle of April in the warmer valleys to the middle of May in the colder localities. In the fall freezing temperatures can be expected after the middle of October. Below Figures 9 to 11 display the yearly temperature ranges expected a several climate stations location within or near the Baker River drainage basin.

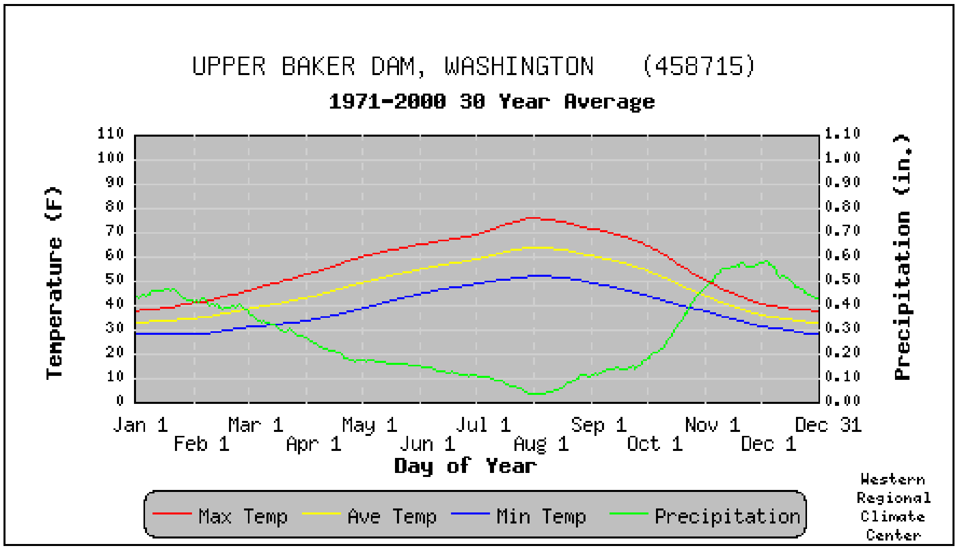


Figure 9 Upper Baker Dam Yearly Climate Trend

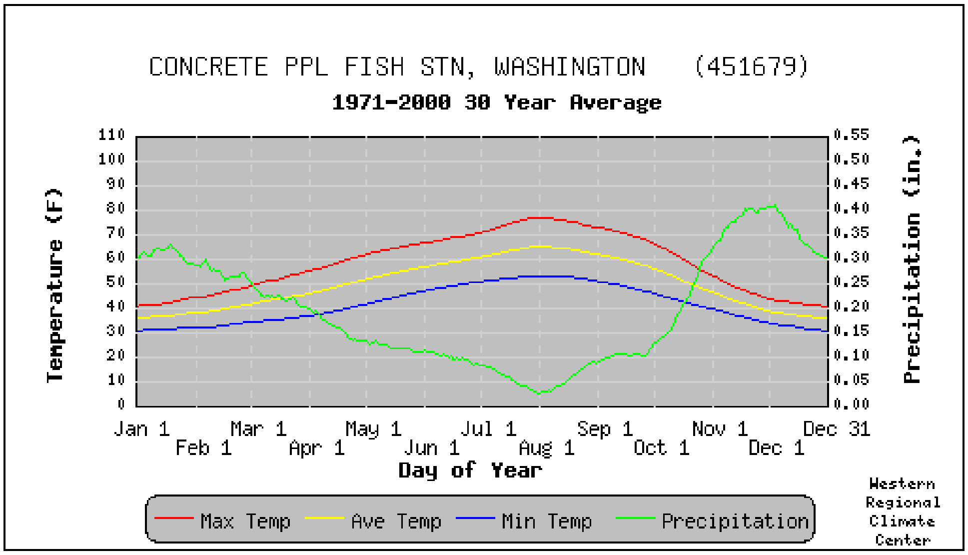


Figure 10 Concrete Yearly Climate Trend

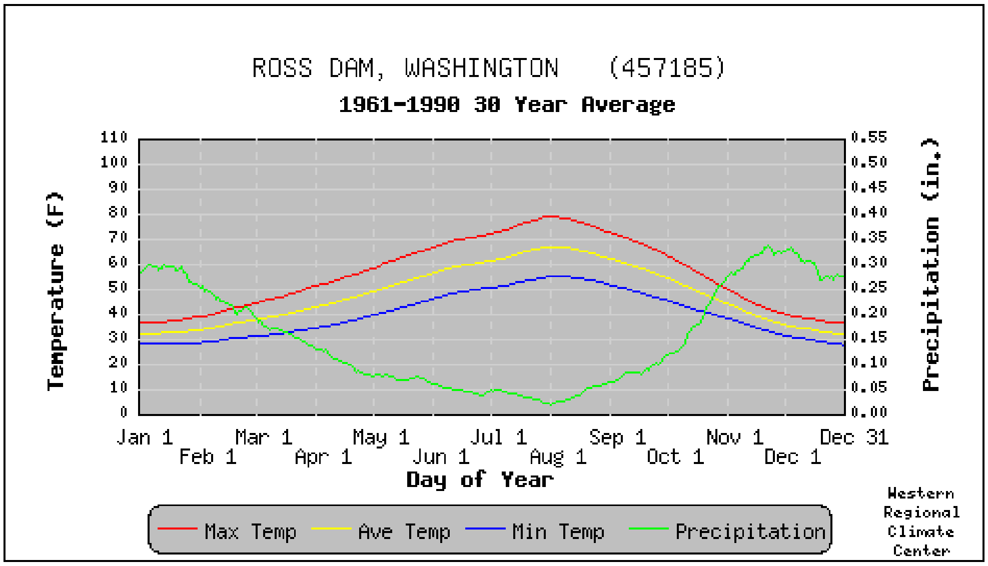


Figure 11 Ross Dam Yearly Climate Trend

This region is also affected by a unique weather phenomena, locally referred to as the Puget Sound Convergence Zone (PSCZ), see Figure 12. This weather pattern sets up when winds reaching the northwest Washington Coastline are predominantly from a west/northwest direction. The wind flow is then forced to split around the Olympic Mountains, flowing through the Strait of Juan de Fuca and the Chehalis Gap, and colliding over the north central section of the Puget Sound. The air is then forced to rise, condensing the moisture, cooling the air column, and producing brief periods of heavy rain or snow, while the rest of the region is relatively dry and calm. The PSCZ occurs most frequently from the south side of the San Juan Islands south to just north of Seattle. It also extends eastward to the crest of the Cascade Mountains, producing very high snowfall amounts over a short time period in the regions it affects.

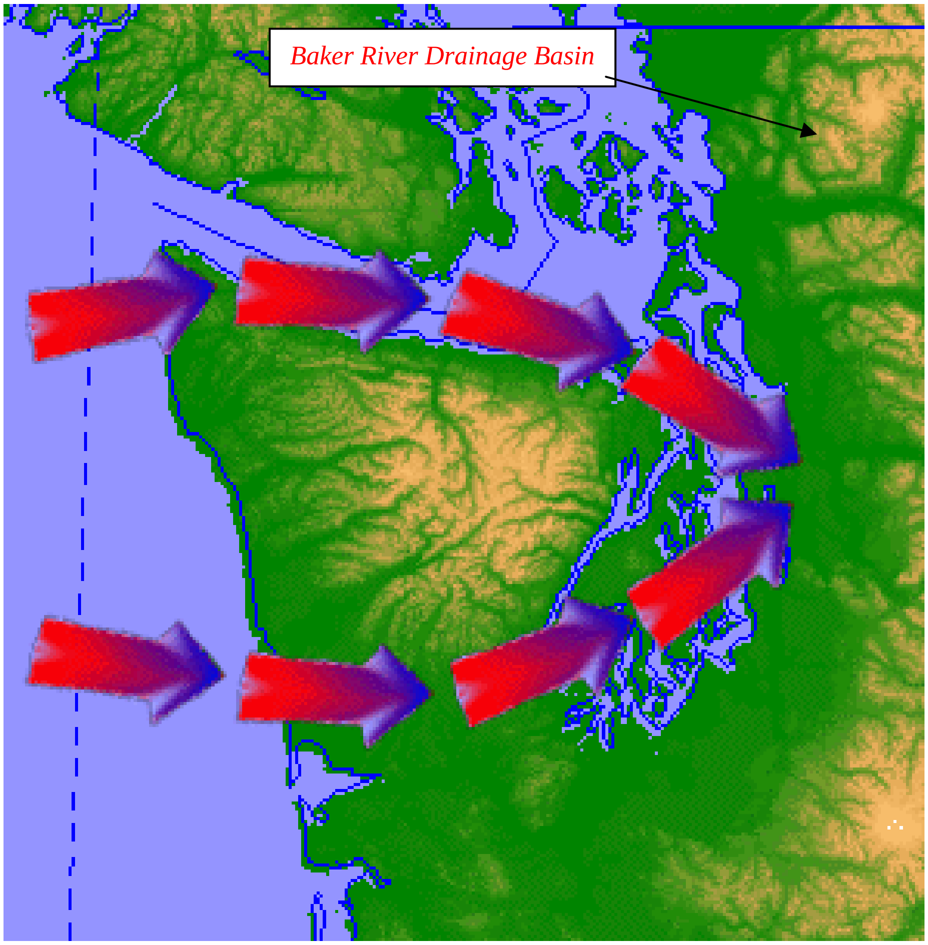


Figure 12 Typical wind flow associated with the development of the Puget Sound Convergence Zone. West/Northwesterly winds following the passage of a cold front are forced to flow around the Olympic Mountains, through the Strait of Juan de Fuca on the north and the Chehalis gap to the south. These winds then converge over the Puget Sound. This Mesoscale phenomena often produces localized region of heavy rain, snow, and/or thunderstorms over sections of the Puget Sound and western foothills of the Cascade Mountains.

CASCADE MOUNTAINS-WEST

This area includes the western slope of the Cascade Range from an elevation of approximately 1,000 feet to the divide and extends from the Columbia River to the Canadian Border. Orographic lifting of the moisture-laden southwesterly and westerly winds results in heavy precipitation in this area. The annual precipitation ranges from 60 to 120 inches with locally higher amounts. Indications are that the heaviest precipitation probably occurs along the slopes of east-west mountain valleys, which become narrower as the elevation increases along the windward slopes of the Cascades. This includes the valley draining the Baker River into the Skagit River. Annual precipitation in some of the wetter areas has reached 140 inches in about one out of ten years.

The average winter season snowfall ranges from 50 to 75 inches in the lower elevations, gradually increasing with elevation to between 400 and 600 inches at 4,000 to 5,500 feet. Some of the greatest seasonal snowfalls and snow depths in the world have been recorded on the slopes of Mt. Rainer and Mt.Baker. These and other high peaks above 7,000 remain snowcapped throughout the summer and contain the vast majority of the contiguous United State's glaciers. Snowfall usually begins in the higher elevations in September, gradually working down to 3,000 feet by the last of October. The snowline in midwinter varies from 1,500 to 2,000 feet above sea level. Although snowfall continues until late spring, the maximum depth is usually reached during the first half of March through the beginning of April. At this season of the year, snow depths above 3,000 feet range from 10 to 25 feet. The density of the snow pack increases from approximately 30 percent water the first of December to 45 percent water in March.

The average January maximum temperature ranges from 40° F in the lower elevations to 30° F at the 5,500-foot elevation. Minimum temperatures range from 30° F in the lower elevations to 20° F in the higher elevations. Minimum temperatures from 0° to -17° F have been recorded in the higher elevations. Above 4,000 feet, minimum temperatures occasionally drop below freezing in midsummer. In general, the temperature decreases approximately 3° F with each 1,000 feet increase in elevation.

RIVERS

The Columbia River, draining approximately 259,000 square miles in the Pacific Northwest and second only to the Mississippi River in volume flow, enters near the northeastern corner of the State and flows in a semi-circular pattern through eastern Washington. Before reaching the Pacific Ocean, it forms most of the boundary between Washington and Oregon, draining all of eastern Washington and the western slope of the Cascade Mountains between Mt. Rainier and the southern border. In addition to providing water for vast irrigation and hydroelectric projects, the Columbia River is a navigable stream for ocean vessels to ports at Vancouver and Portland and for river barges into eastern Washington. Principal tributaries of the Columbia in Washington include the Pend Oreille, Spokane, Snake and Cowlitz Rivers.

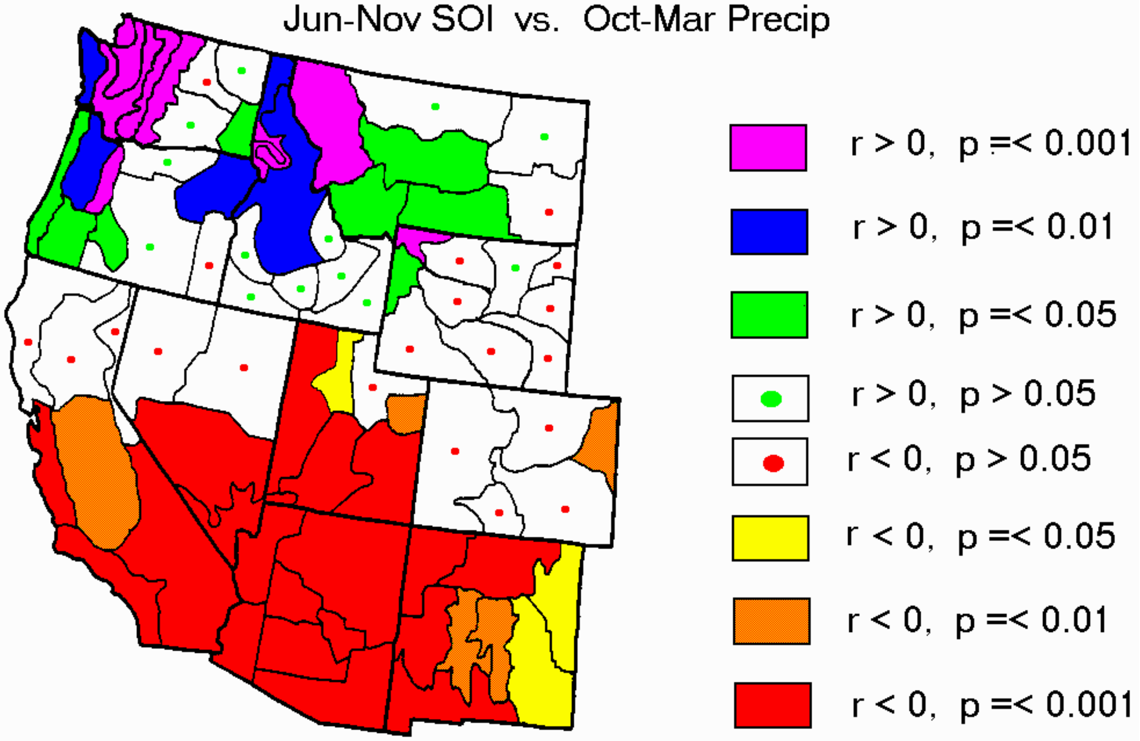
Although some overflow may be expected in Washington in most years, severe flooding occurs infrequently. In recent years, the most severe flooding in the Columbia River basin occurred in 1948 and 1950, while some of the other notable flood years have been 1894, 1897, 1913, 1916, 1928 and 1933. In the Columbia River basin in eastern Washington, winter floods are rare. They may occur at times, however, especially in local areas as a result of a combination of moderate snow cover, warm southerly winds and heavy rains. Annual peak flows occur in the spring and early summer as the winter snow pack melts.

In western Washington, the Snoqualmie, Skagit, Stillaguamish, Chehalis and other streams drain into Puget Sound, the Strait of Juan de Fuca and the Pacific Ocean. There are two periods of high flow in the streams of western Washington, especially in the Puget Sound region. One occurs during the winter months coinciding with the periods of maximum precipitation, and the other in the spring or early summer caused by the seasonal rise in temperature with the resultant melting of snow accumulations in the higher elevations augmented at times by rainfall. The Baker River drains flows into the Skagit River and empties into the Puget Sound at Skagit Bay. Severe flooding along this route occurs around the towns of Concrete, Hamilton, Lyman, Sedro Wooley, Burlington, Mount Vernon, and Fir Island. In recent years, some of the worst flooding on record has taken place. November 1990, November 1995, February 1996, and October 2003 are in the top five high water events in both Concrete and Mount Vernon. Other major flood events in western Washington occurred in 1909, 1917, 1921, 1932, 1933, 1934, 1951, 1959, 1971, 1972, 1975, 1979, and 1986.

THE ENSO CYCLE

Another significant factor influencing the annual precipitation in our study region is the El Nino-La Nina (ENSO) cycle (see http://www.pmel.noaa.gov/tao/elnino/nino-home.html for a complete description). Years of above average precipitation and colder than average temperatures, especially from October through March, have been significantly correlated with La Nina episodes. El Nino years are strongly correlated with warmer than average temperatures and slightly drier than normal precipitation. However, occasionally during El Nino years, a combination of modified maritime tropical air masses (higher than normal levels of moisture and warmer than normal temperatures) moves into the region from the southwest. This leads to flooding situations on many of the rivers that drain the west side of the Cascades. A common scenario sets up where a late fall or early winter snowfall is followed by rapidly rising snow levels and heavy rain. This combination of melting snowpack and heavy rain leads to widespread flooding and is responsible for some of the worst flooding events on record. During La Nina years, the climate of the Baker River drainage basin is significantly correlated with colder and wetter than normal conditions, along with deeper than normal snowpack. The winter of 1998-1999 is a great example of this, when a record setting 1140 inches of snow accumulated during a single season in which a La Nina developed during the preceding summer months and strengthened through the winter and into the spring of 1999.
(http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml)

Correlation:
Jun-Nov SOI vs. Oct-Mar Precip



Updated from Redmond and Koch (1991). Winters of 1933/34 - 1994/95.
Reddish: El Nino associated with wet winters, La Nina with dry winters.
Bluish/greenish: El Nino associated with dry winters, La Nina with wet winters.

Redmond, K.T., and R.W. Koch, 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resources Research, 27(9), 2381-2399.

This is an important factor to monitor, as seasonal forecasts can be generated based on the occurrence of El Nino, La Nina, or neutral conditions helping hydrologists and residents plan for better chance of above normal precipitation and possible flooding/run-off problems.

SIGNIFICANT STORM EVENTS IN HMR 57

A thorough investigation of HMR 57 was conducted to identify extreme rainfall events appropriate for transpositioning to the Baker River drainage basin. Each storm presented and described in HMR 57 was scrutinized to determine if it occurred over a geographic and climatic region similar to the topography and climate of the Baker River drainage basin. Ten storms were identified; seven general storms and three local storms (see the table below). The three local storms were eliminated from further consideration because the amount of precipitation and duration of the events were not significant enough to be considered driver storms for the Baker River Drainage Basin.

General Storms

Storm Name/Number from HMR 57	Date	Storm Center Location
Wind River, Wa #38	11/18-22/1921	45.47 N 121.87 W
Silverton, Wa #40	12/9-12/1921	48.01 N 121.53 W
Quinault, Wa #80	1/20-25/1935	47.47 N 123.71 W
Valsetz, Or #88	12/26-30/1937	44.91 N 123.63 W
North Cascade, Wa #165	1/14-17/1974	48.19 N 121.05 W
Aberdeen, Wa #174	11/30-12/2/1975	47.61 N 123.73 W
Seymour Falls, BC	1/14-15/1961	49.43 N 122.97 W

Local Storms

Storm Name	Date	Storm Center Location
Aberdeen, Wa	5/28/1982	47.27 N 123.70 W
Castle Rock, Wa	8/8/1963	46.27 N 122.92 W
Skykomish, Wa	5/25/1945	47.36 N 121.36 W

USE OF THE HYSPLIT MODEL FOR STORM MOISTURE INFLOW VECTOR DETERMINATION

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model was developed in a joint effort between the National Oceanic and Atmospheric Administration (NOAA) and Australia's Bureau of Meteorology. HYSPLIT has been extensively tested in a series of long-range tracer studies and in a variety of opportunistic studies of smoke from fires. The field tests in which these tracers were used covered much of the eastern USA. The Cross Appalachians Tracer Experiment (CAPTEX) was conducted in 1983, following some initial tests in 1980. The larger-scale Across North America Tracer Experiment (ANATEX) was conducted in 1987. These field studies were conducted by the Air Resources Laboratory (ARL), under sponsorship of the Department of Defense, and the Department of Energy. Following the success of these field evaluations, HYSPLIT has been adopted as the standard dispersion forecasting tool used by the National Weather Service.

The model is a complete system for computing parcel trajectories to complex dispersion and deposition simulations using either puff or particle approaches. Gridded meteorological data, on one of three conformal (Polar, Lambert, Mercator, latitude-longitude grid) map projections, are required at regular time intervals. Calculations may be performed sequentially or concurrently on multiple meteorological grids, usually specified from fine to coarse resolution.
Parcel trajectories are calculated by assuming either a Gaussian or Top-Hat horizontal distribution within a puff or from the dispersal of a fixed number of particles. An alternate approach combines

both puff and particle methods by assuming a puff distribution in the horizontal and particle dispersion in the vertical direction.

The routine meteorological data fields required for the calculations may be obtained from existing archives or from forecast model outputs already formatted for input to HYSPLIT. In addition, several different pre-processor programs are provided to convert NOAA, NCAR (National Center for Atmospheric Research) re-analysis, or ECMWF (European Centre for Medium-range Weather Forecasts) model output fields to a format compatible for direct importation into the model.

The model runs on archived datasets that can be downloaded and includes the following: FNL: 1997 – Current, ETA 40km: 2004 – Current, ETA 80km: 1997 – 2004, NGM: 1991-1997, NCEP/NCAR Reanalysis: 1948 – 2004. All of these datasets contain basic fields such as the u- and v- wind components, temperature, and humidity. However, the archives differ from each other because of the horizontal and vertical resolution, as well as in the specific fields provided by NCEP.

The model includes a module to set up a trajectory, air concentration, or deposition simulation. The model package contains a graphical program that generates multi-color or black and white publication quality graphics that displays the model results. The trajectory module of the model allows the user to enter the model simulation parameters including: starting time of the calculation; starting location in terms of latitude, longitude, height (AGL), the run-time or duration of the trajectory (3hrs to 48 hours) calculation, calculation time steps (1hr to 12hrs) and the name and location of the meteorological model data. Trajectories can be modeled forward or backward. A backward trajectory starts from the trajectory termination point and proceeds downwind.

The following are some of the main features of the HYSPLIT model:

Trajectories

- Single or multiple (space or time) simultaneous trajectories
- Optional grid of initial starting locations
- Computations forward or backward in time
- Default vertical motion using omega field
- Other motion options: isentropic, isosigma, isobaric, isopycnic
- Trajectory ensemble option using meteorological variations
- Output of meteorological variables along a trajectory

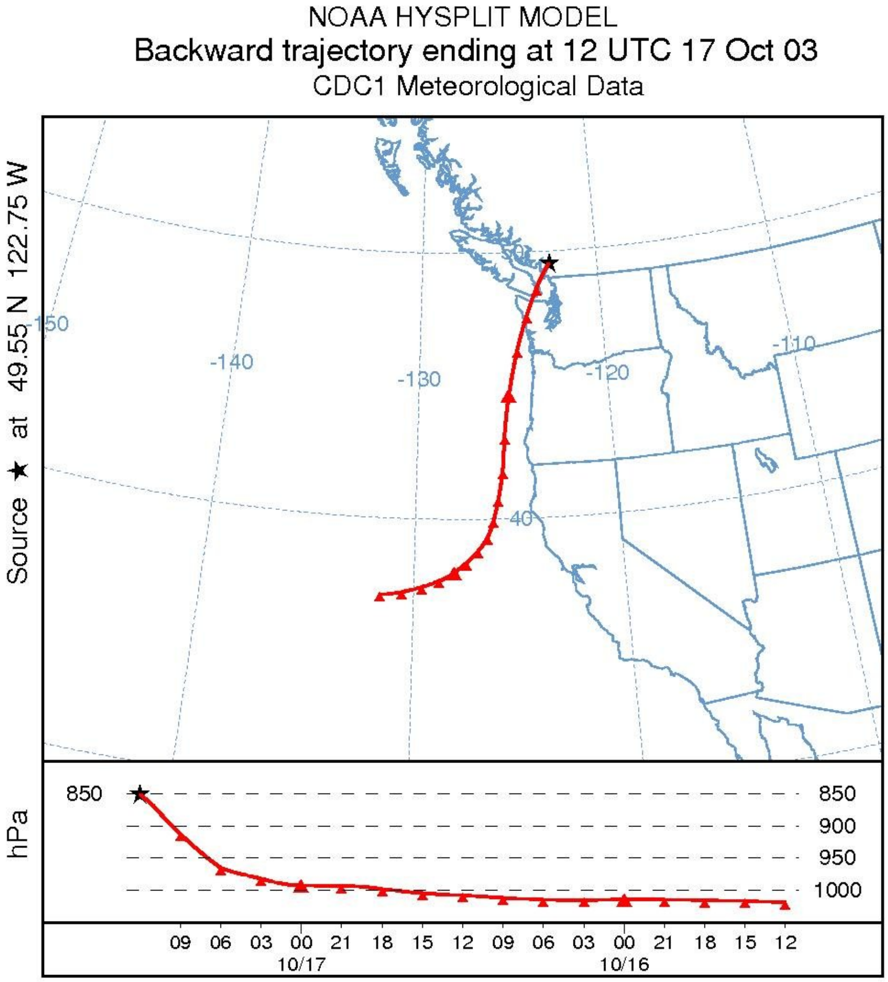
Meteorology

- Model can run with multiple nested input data grids
- Links to ARL and NCEP meteorological data server
- GUI integrated GRIB decoding for NAM, GFS, and ECMWF data
- Access to forecasts and archives including NCAR/NCEP reanalysis
- Additional software to convert MM5, RAMS, COAMPS, and other data
- Utility programs to display and manipulate meteorological data
- Model restart from particle position files for plume initialization
- Converters to many other formats: GIF, GrADS, ArcView, Vis5D - (GIS Exportation)

An additional module associated with the model allows vertical profile calculations for a point defined by the user. Variables included in the vertical profile include height above sea level, pressure level, temperature, relative humidity, wind direction, wind speed, and the u and v components of the wind.

The HYSPLIT model was used for each of the storm analysis. Surface, 925mb (approximately 3,000 feet), and 850mb (approximately 5,000 feet) trajectories were run. AWA constructed the storm moisture inflow vector using subjective combinations of the various trajectories. For some storms, a 700mb (approximately 10,000 feet) trajectory was also used.

Baker WA - Storm Center - 850 mb NCEP

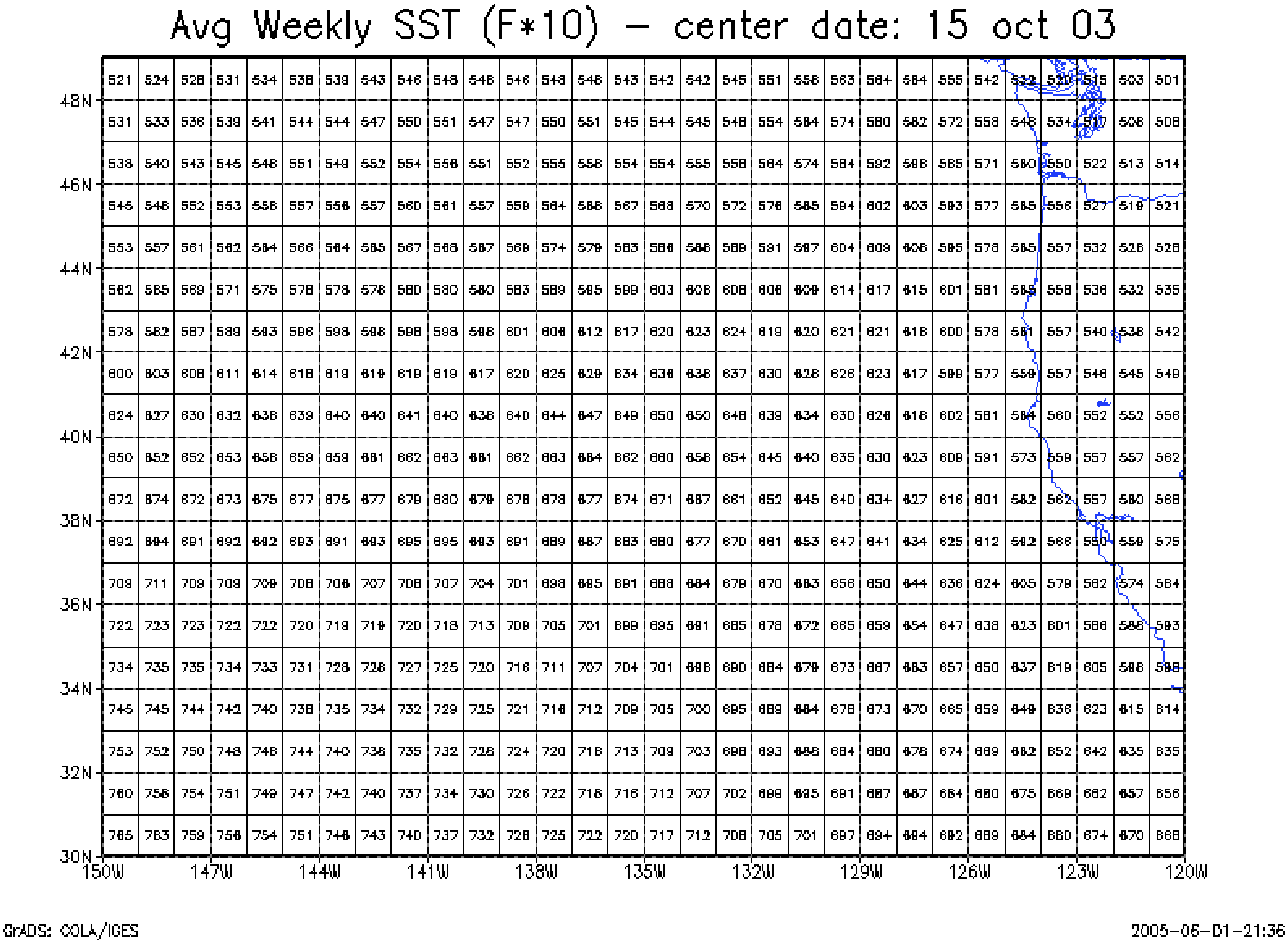


Example of a HYSPLIT trajectory

Determination of the Storm SST and Maximum SST

SST grids over the northern Pacific Ocean were obtained for each storm period. The storm moisture inflow vector (constructed using HYSPLIT) was overlaid on the SST grid and the upwind trajectory was followed until the SST values changed less than one degree F over one degree latitude or longitude. This technique was developed for site-specific PMP studies in the northeastern US where the inflow trajectories were over the Atlantic Ocean. The purpose of this criteria is to identify the ocean region where the SSTs become somewhat homogeneous, and then assuming that it is this region over the ocean that is the source region for the atmospheric moisture that is ultimately advected into the storm, producing the observed extreme rainfall. The location of the selected SST is identified as the storm SST location and the vector connecting this location with the rainfall center is the storm moisture inflow vector.

The two sigma SST (the SST value that is two standard deviations warmer than the mean SST) at this location is used as the maximum SST for the maximization calculations. The standard procedure of selecting the two sigma SST two weeks earlier than the date of the storm event is used in the determination of the maximum SST. For example, if the storm occurred on October 15, the two sigma SST value for October 1 would be selected.



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531	533	536	539	541	544	544	547	550	551	547	547	550	551	545	544	545	548	554	584	574	580	582	572	558	548	534	517	508	508
538	540	543	545	548	551	549	552	554	558	551	552	555	558	554	554	555	558	564	574	584	592	588	585	571	580	550	522	513	514
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553	557	561	562	564	566	564	565	567	568	567	569	574	579	583	586	586	589	591	587	604	609	606	595	578	585	557	532	526	528
562	565	569	571	575	578	578	576	580	580	580	583	589	585	599	603	606	608	606	609	614	617	615	601	581	585	558	538	532	535
578	582	587	589	593	596	598	596	598	598	596	601	606	612	617	620	623	624	619	620	621	621	618	600	578	581	557	540	538	542
600	603	608	611	614	618	619	619	619	619	617	620	625	629	634	638	636	637	630	626	626	623	617	599	577	559	557	548	545	548
624	627	630	632	636	639	640	640	641	640	638	640	644	647	649	650	650	648	639	634	630	628	618	602	581	564	560	552	552	556
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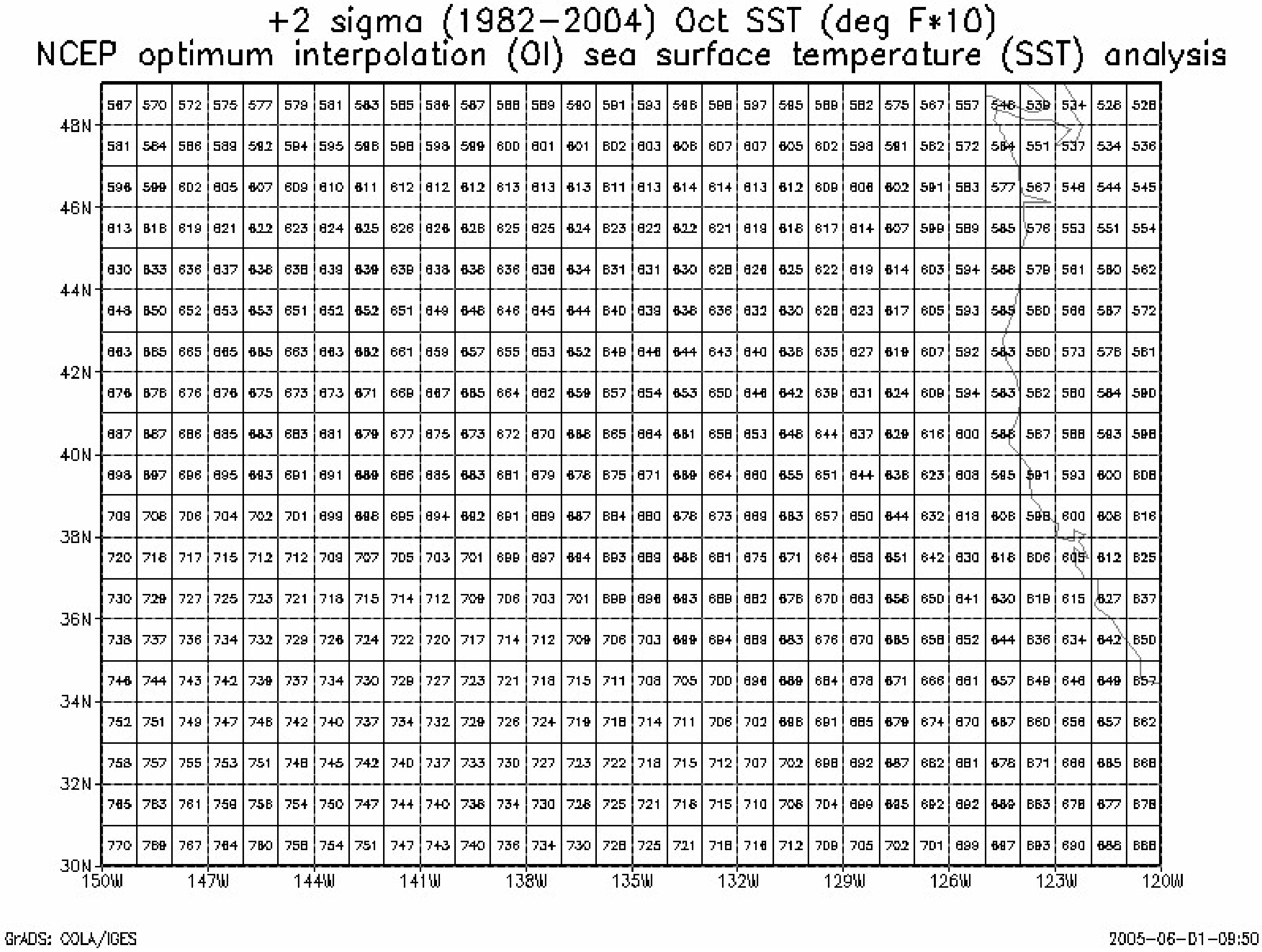
672	674	672	673	675	677	675	677	679	680	679	678	678	677	674	671	667	661	652	645	640	634	627	616	601	582	562	557	560	568
692	694	691	692	692	693	691	693	695	695	693	691	689	687	683	680	677	670	661	653	647	641	634	625	612	582	566	550	559	575
709	711	709	709	709	708	708	707	708	707	704	701	698	695	691	688	684	679	670	663	656	650	644	636	624	605	579	582	574	584
722	723	723	722	722	720	719	719	720	718	713	709	705	701	699	695	691	685	678	672	665	659	654	647	638	623	601	588	586	593
734	735	735	734	733	731	728	726	727	725	720	716	711	707	704	701	696	690	684	679	673	667	663	657	650	637	619	605	596	598
745	745	744	742	740	738	735	734	732	729	725	721	716	712	709	705	700	695	689	684	678	673	670	665	659	649	636	623	615	614
753	752	750	748	746	744	740	738	735	732	728	724	720	716	713	709	703	698	693	686	684	680	676	674	669	662	652	642	635	635
760	758	754	751	749	747	742	740	737	734	730	726	722	718	716	712	707	702	698	695	691	687	687	684	680	675	669	662	657	656
765	763	759	756	754	751	748	743	740	737	732	728	725	722	720	717	712	708	705	701	697	694	694	692	689	684	680	674	670	668

Example of a Storm SST Grid



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581	584	586	589	592	594	595	596	598	598	599	600	601	601	602	603	606	607	607	605	602	598	591	582	572	564	551	537	534	536
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613	616	619	621	622	623	624	625	626	626	626	625	625	624	623	622	622	621	619	618	617	614	607	599	589	585	576	553	551	554
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663	665	665	665	665	663	663	662	661	659	657	655	653	652	649	646	644	643	640	636	635	627	619	607	592	583	560	573	576	561
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687	687	686	685	683	683	681	679	677	675	673	672	670	668	665	664	661	658	653	648	644	637	629	616	600	586	567	588	583	598
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752	751	749	747	746	742	740	737	734	732	729	726	724	719	718	714	711	706	702	696	691	685	679	674	670	667	660	656	657	662
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770	769	767	764	760	758	754	751	747	743	740	736	734	730	728	725	721	718	716	712	709	705	702	701	699	697	693	690	686	688

Example of a Two Sigma SST Grid

In-Place Storm Maximization

Data from each of the identified storms was placed into a storm adjustment spreadsheet. Storm location, duration, elevation, moisture availability, topographical enhancement/depletion, total storm precipitation, and other elements were incorporated into the storm adjustment spreadsheet. From these data, an adjusted DAD table was developed based on the DAD provided for each storm (except the Seymour Falls, British Columbia storms) in Appendix 2 of HMR 57 and the in-place maximization factor from HMR 57 table 2.1. The storm centers were located on the General Storm Probable Maximum Precipitation (PMP) Index Maps provided as part of the HMR 57 report. The HMR 57 PMP values for the storm locations were incorporated into the storm adjustment spreadsheets. In developing the HMR 57 PMP table for each storm, the adjustment factors found in HMR 57 tables 2.1 and 15.1 were used and the depth-area curves from Figure 15.10 were used to determine areal variations in the PMP values. For each storm, the ratio of the in-place maximized storm rainfall values to the HMR 57 PMP values has been computed for each area size and duration.

The average ratios of the in-place maximized storm rainfall values to the HMR 57 PMP values for the 200 and 500 square mile area sizes were computed for all durations and are listed in the following table. The results indicate an average ratio of approximately 0.54. This means that the average in-place maximized storm rainfall is only 54% of the PMP values at the storm locations. For these locations, procedures in the development of the HMR 57 PMP values increased the extreme rainfall values to values much larger than the in-place maximized rainfall values provided by the storm analyses. Increases in the in-place maximized storm rainfall values in the development of PMP values are expected but usually are on the order of 5-20%, so that the final PMP values at the largest storms locations are about 5-20% higher than the maximized storm rainfall values. For the storms in the table, the HMR 57 PMP values are, on average, almost twice the maximized rainfall amounts.

Storm Name	HMR 57 Storm Number	Date	Lat	Lon	Ratio of Maximized Storm Rainfall to HMR 57 PMP (all Hrs at 200 & 500 mi2)
Wind River, Washington	**38**	**11/18-22/1921**	**45.47 N**	**121.87 W**	**0.44**
Silverton, Washington	**40**	**12/9-12/1921**	**48.01 N**	**121.53 W**	**0.52**
Quinault, Washington	**80**	**1/20-25/1935**	**47.47 N**	**123.71 W**	**0.85**
Valsetz, Oregon	**88**	**12/26-30/1937**	**44.91 N**	**123.63 W**	**0.57**
North Cascade, Washington	**165**	**1/14-17/1974**	**40.33 N**	**124.10 W**	**0.33**
Aberdeen 20NNE, Washington	**179**	**11/30-12/2/1975**	**47.61 N**	**123.73 W**	**0.38**
Kirby, OR	***126***	***10/26-29/1950***	***41.87 N***	***123.97 W***	***0.58***
Illahe, OR	***149***	***11/21-24/1961***	***42.17 N***	***123.93 W***	***0.44***

There are a couple of concerns about the results shown in the table. The analysis of the Seymour Fall storms is not included and could make a significant difference in the conclusion drawn from the ratios. Storm #80 was inconsistent with the other storms with only a 15% difference between the in-place maximized storm values and the PMP values for the storm location.

The Seymour Falls storm is listed in HMR 57 as the controlling storm for the Baker River drainage basin region in Figure 7.3 of that report. Hence, its transpositioned maximized storm values are probably greater than the in-place values for the other storms. The maximized values from storm #80 is 1.62, much higher than is expected for a major storm. The initial evaluation indicates that the storm representative SST of 55 degrees F is several degrees cooler than the mean SST for the location storm representative SST location. This is highly suspicious since extreme rainfall storms historically have been associated with SSTs that are significantly warmer than the mean SSTs. Plus its transpositioning to the western slopes of the Cascades (if that was what was done in HMR 57) is questionable.

The October 17, 2003 storm has now been evaluated as part of this study. Results are provided in Technical Memo 9. An in-place maximization factor of 1.10 was determined using SSTs. The center of this storm is in Canada so direct comparisons of the in-place maximized rainfall values with HMR 57 PMP values is not possible. However, assuming the topographic effects associated with the storm are similar to those at the Baker River drainage basin, the storm was transpositioned to the Baker River drainage basin location. The transposition factor is 1.00 since the storm center was relative close to the Baker River drainage basin and the two sigma SST at the storm representative SST inflow vector transposition location was almost identical (less than 0.5 degree F) to the SST at the storm representative SST location. Comparison of the transpositioned maximized rainfall amounts for the 200 and 500 square mile area sizes for all durations shows a ratio of the maximized in-place storm rainfall values to HMR 57 PMP values for the Baker River drainage basin location of 0.62. This comparison indicates that the October 17, 2003 storm was larger relative to HMR 57 PMP values that all of the other HMR 57 storms with the exception of storm #80. Its relative magnitude compared with Seymour Falls is not yet known.

The preliminary conclusion based on the ratios of maximized rainfall to HMR 57 PMP values is that site-specific considerations applied to the Baker River drainage basin could potentially produce site-specific PMP values that are on the order of 25% lower than those published in HMR 57. However, the Seymour Fall storm must be evaluated for a final conclusion and recommendation to be made. AWA is continuing it efforts to acquire the required information either from NWS or Environment Canada.

STORM MAXIMIZATION USING SEA SURFACE TEMPERATURES VS SOUNDING PRECIPITABLE WATER DATA

The BOC requested that a comparison of precipitable water values derived from SSTs and atmospheric soundings be made for storm affecting the Pacific Northwest. An analysis of six storms has been completed. Because of the lack of Sea Surface Temperature (SST) data for the HMR 57 storms, more recent storms were used for comparing the precipitable water (PW) values derived from using SSTs and PW derived from atmospheric sounding data. The dates of the storm used in this analysis are as follows:

October 22, 2003
October 17, 2003
November 28, 1995
November 23, 1990
November 10, 1990
November 10, 1989

The comparison used these events since they were associated with large rainfall storms. The HYSPLIT model was used with the National Center for Environmental Prediction (NCEP) re-analysis data to determine the inflow moisture vector for each storm. SST data from the National Center for Atmospheric Research (NCAR) was used to determine the storm representative SST and the two sigma SST values used for storm maximization. Sounding data from Quillayute, Washington was used to determine the sounding PW values. Storm maximization used the 100-year sounding PW values for Quillayute provided by the Oregon Climate Center.

Comparisons were made between the PW values determined using the storm SSTs together with the saturated atmosphere assumption and PW determined from the Quillayute sounding data. Additionally, a comparison was made between the in-place storm maximization factors computed with the SST PW values for each storm and with the sounding PW values for each storm. The results are listed below:

Storm Date	SST PW	Sounding PW	2 sigma SST PW	Sounding 100-yr PW	SST Max	Sounding Max
October 22, 2003	**1.68**	**1.24**	**1.86**	**1.35**	**1.11**	**1.09**
October 17, 2003	**1.91**	**1.25**	**2.10**	**1.48**	**1.10**	**1.18**
November 28, 1995	**2.25**	**1.11**	**2.54**	**1.35**	**1.13**	**1.22**
November 23, 1990	**1.35**	**0.90**	**1.49**	**1.34**	**1.10**	**1.49**
November 10, 1990	**1.86**	**1.23**	**2.05**	**1.31**	**1.10**	**1.07**
November 10, 1989	**1.42**	**1.29**	**1.64**	**1.31**	**1.15**	**1.02**

The sounding PW is consistently lower than the SST PW for these storms. This is reasonable since moisture is depleted in the lower levels of the atmosphere as the air mass approaches the north-western coast of the US either because of the colder underlying SSTs immediately off of the coastline or because the low level trajectories have a southerly component and the air mass passes over portions of northern California and Oregon before arriving in Washington. The maximization factors are reasonably close except for the later November storm of 1990 with the SST maximization factors being slightly larger. The very low sounding PW in the late November 1990 storm accounts for the very high sounding maximization factor for that storm.

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 9

OCTOBER 2003 STORM ANALYSIS AND SUPPLEMENTARY STORM ANALYSES FOR CALIBRATION EVENTS

Applied Weather Associates
August 16, 2005
Revised March 10, 2006

(FINAL)

INTRODUCTION

This memo summarizes the October 14-17, 2003 storm analyses completed using the Applied Weather Associates Storm Precipitation Analysis System (SPAS). It was recognized that several large rainfall events have occurred since the HMR 57 storm analyses were completed. The Board of Consultants (BOC) recommended that the October 14-17, 2003, storm be analyzed so it could be compared with the largest storms included in HMR 57 that could have affected the PMP values for the Baker River drainage basin. This comparison is provided in Technical Memorandum No. 8.

The analysis included extensive data mining that identified available rainfall data for the storm. Sources for these data included the following:

National Climatic Data Center (NCDC)
Environment Canada
Interagency Remote Automated Weather Stations (RAWS)
NRCS Snotel
Automatic Snow Pillow (ASP) Data from The Government of British Columbia
and the RIVER FORECAST CENTRE
Mountain Weather Data Network
The Weather Underground
University of Utah MesoWest and the NOAA/FSL MADIS
NOAA's Climate Reference Network (CRN)

A complete depth-area-duration analyses and hourly rainfall fields in gridded GIS files were developed. Hourly NexRad maps were used to provide additional timing information for regions that lacked adequate hourly rainfall data. Additionally, a storm inflow wind vector and maximization factor was determined using the HYSPLIT trajectory model

STORM PRECIPITATION ANALYSIS SYSTEM (SPAS) DESCRIPTION
(From *HydroReview*, In Press)

Introduction

Applied Weather Associates, LLC and Metstat, Inc have teamed to develop a rainfall analysis software package named Storm Precipitation Analysis System (SPAS) that analyzes rainfall associated with extreme storms. Using digital precipitation data with Geographical Information Systems (GIS), detailed rainfall analyses provide high spatial resolution hourly rainfall fields that accurately quantify the spatial and temporal distribution of storm rainfall over watersheds. The analyzed rainfall fields can be used to produce hourly rainfall amounts over user defined watersheds and sub-watersheds. The availability of detailed rainfall information allows for runoff model calibration and verification with much improved precision and reliability. (Rudolph et al, 2004) The spatial characteristics of the hourly rainfall fields can be retained or average rainfall amounts over watersheds can be provided. Additionally, the analyzed rainfall fields provide the information required to produce storm depth-area-duration (DAD) tables. These analyses provide rainfall depths over standardized areas sizes and durations. Hence extreme storm rainfall can be compared to determine which storms produced the greatest rainfall amounts over various area sizes and durations. The rainfall associated with recent storms can be directly compared with historic storms that occurred over the same climate region. These analyses are required for storm climatology updates used in site-specific probable maximum precipitation (PMP) studies.

The Weather Bureau (currently the National Weather Service, or NWS) and the US Army Corps of Engineers routinely performed detailed storm rainfall analyses until the 1950s. Since then, only a few selected storms have been analyzed. SPAS applies the same basic approach used by the Weather Bureau and the US Army Corps of Engineers, thereby achieving a level of consistency between the newly analyzed storms and the historic storms previously analyzed, but also applies several enhancements. (Tomlinson and Parzybok, 2004). SPAS has been rigorously tested, both with a theoretical storm where the rainfall rates and spatial distribution are known exactly and with historic storms that have been previously analyzed by the Weather Bureau. SPAS analyses have also been completed for several relatively recent extreme rainfall storms, including Hurricane Floyd (September 13-17, 1999) for which results are presented in this paper.

SPAS analysis results for several extreme rainfall storms have been incorporated into updated technology applications for PMP and probable maximum flood (PMF) analyses. (Rudolph, et al, 2004) SPAS output for Hurricane Floyd has been used in a FERC approved site-specific PMP study in New York. In that study for the Great Sacandaga Lake drainage basin, extreme rainfall storms were identified, some of which were used in HMR 51. DADs for later storm events had not been produced. Two rainfall centers were analyzed using SPAS and incorporated into the site-specific PMP study. The study results provided reduction of 10% to 50% from the generalized HMR 51 PMP values (25% for the 1,000 square mile area size and 72 hour duration that most impacted the site-specific study). (Tomlinson, et al, 2003)

Background

The Weather Bureau and Corps of Engineers produced many storm studies for extreme rainfall events that occurred during the first half of the last century. The DADs from these studies were used to compare rainfall events and were used in Hydrometeorological Reports (HMRs) to determine PMP rainfall amounts. Objective procedures were used in these analyses augmented with subjective judgment by qualified hydrometeorologists. The SPAS analysis incorporates earlier procedures while providing updated techniques along with GIS to improve the quality and speed of the analyses. (World Meteorological Organization, 1986)

With SPAS, storms analyses (including storm-centered DADs and mass curves) can be efficiently completed much quicker and with more detail than historic analyses. In the past, a detailed analysis of a storm's precipitation required a great deal of manual labor, hence making it time consuming and prone to human errors. SPAS is a largely automated system, yet it provides flexibility and enhancements over the old storm analysis procedure. In the past, it was time and cost prohibitive to produce hourly precipitation maps, therefore assumptions had to be made in the computations of the DAD results. SPAS, however, does not have to make as many assumptions since it has the ability to better resolve the storm's precipitation through the use of GIS algorithms and individual hourly precipitation grids. Table 1 compares the procedures used historically by the Weather Bureau and SPAS.

Topic	***Weather Bureau***	***SPAS***
Timing of daily stations	Mimics the hourly distribution of the nearest single hourly station	Uses nearby hourly stations
"Pseudo" data	Did not use a systematic procedure for including ancillary information	Various options to account for complex terrain, unique meteorological conditions or other ancillary information
Base map options	100-year 24-hour precipitation frequency map, elevation or no base map	Multiple, high resolution base map options
DAD calculations	Based on a hand-analyzed total storm, isohyetal map	Based on high-resolution hourly GIS-created precipitation grids
Automation	None	Largely automated
Reproducibility	Largely not reproducible	Reproducible

Table 1 Comparison between the Weather Bureau storm analysis method and SPAS.

Methodology and Technical Details

One of the most significant strengths of SPAS is its ability to convert daily measured precipitation into hourly precipitation – known as timing - utilizing several nearby hourly stations. In the past, timing of daily measured data was accomplished by associating each daily station with a single nearby hourly station and distributing the daily precipitation exactly the same as that hourly station. (World Meteorological Organization, 1969 and Shands, 1946) SPAS, however, uses several (user defined) spatially weighted hourly stations to time each of the daily stations, thereby allowing the hourly precipitation distribution to be unique at each daily station.

The transformation of daily data into hourly precipitation depths is a spatially-based approach which utilizes the percent of hourly precipitation for each hour at the hourly gauges. Because the percentages typically have a high degree of spatial autocorrelation, the spatial interpolation carries skill in predicting the percentages among hourly stations (i.e. at daily stations). The end result is a percental grid for each hour of the storm, which are then used to create simulated hourly data for daily station data. Percental values are sequentially extracted from the hourly percental grids and converted into estimated hourly precipitation values for the daily station as illustrated in Figure 1.

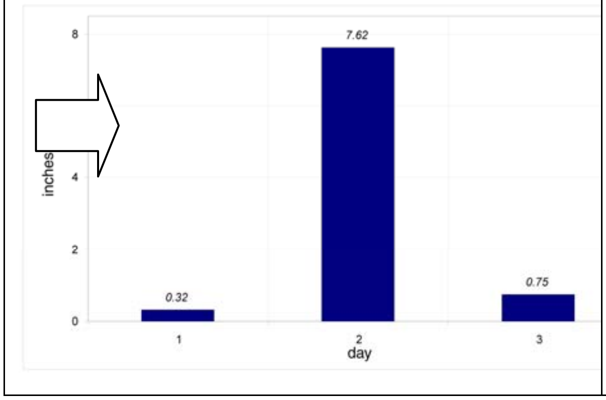
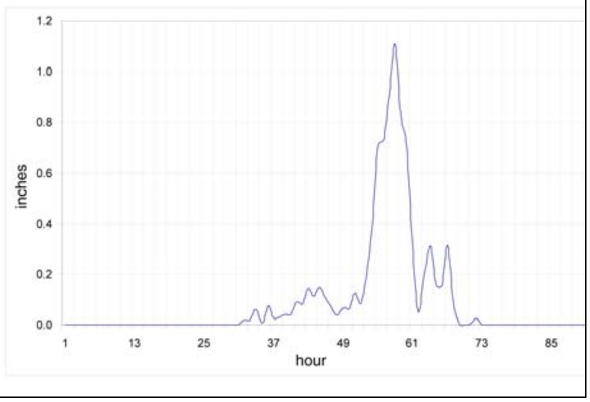
Observed daily precipitation (Daily station)	**Converted to →**	**Estimated hourly precipitation**
	➔	

Figure 1 An illustration of how SPAS converts three days of daily precipitation into estimated hourly amounts.

Plots of the incrementally accumulated precipitation data (known as mass curves) are created for each daily station and then combined into a single plot with other nearby stations for evaluation (see Figure 2). This allows immediate evaluation of the magnitude and temporal characteristics of each station as compared to its neighbors. This is one of several on-going quality control procedures that insure accurate results from SPAS.

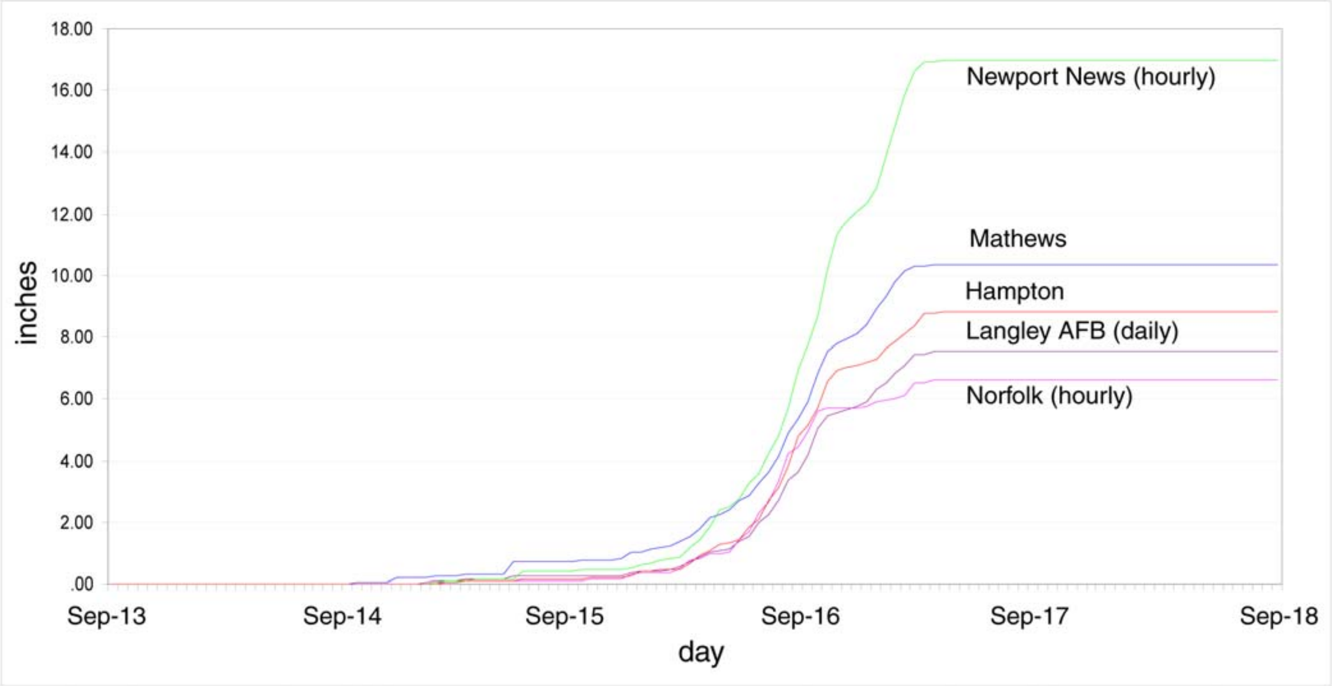


Figure 2 Storm center mass curve for precipitation associated with Hurricane Floyd (September 13-17, 1999) in northeastern Virginia.

To assist in defining the spatial variations of the rainfall fields, the use of "base maps" can be implemented. The spatial patterns of the base maps aid in the interpolation between points of hourly precipitation estimates. The use of a Next Generation Radar (NEXRAD) estimated precipitation has allowed SPAS to better resolve the relative magnitude and spatial details of storm precipitation; however gauge data is basis for the actual precipitation depths. SPAS base map options include:

- Elevation - Digital Elevation Model (DEM)
- Mean monthly precipitation - Parameter-elevation Regressions on Independent Slopes Model (PRISM)(Daly, et. al, 1997)
- Precipitation frequency grids – e.g. NOAA Atlas 14 (Bonnin, 2004) or TP-40 (Hershfield, 1961)
- Mean annual precipitation – PRISM (Daly, et. al, 1997)
- Total monthly precipitation – PRISM (Daly, et. al, 1997)
- Next Generation Radar (NEXRAD) estimated precipitation

Once the hourly precipitation grids are quality controlled and finalized, any subset of hours during the storm can be summed together, displayed and analyzed. Additionally, any analyzed rainfall field (each hour, summation of several hours or total storm duration) can be clipped to user defined watershed boundaries with explicit rainfall amounts over that watershed provided (either spatially distributed or averaged).

Runoff Model Calibration and Validation

SPAS was used for runoff model calibration and validation for a study in Wisconsin. (Rudolph et al, 2004) After completing a storm search using station data to identify the most extreme historic rainfall events over the basin being studied, stream gauge data availability was evaluated to identify the most appropriate storms for use in runoff model calibration and validation. Hourly rainfall analyses were completed, explicitly providing hourly rainfall amounts within the basin boundaries for each hour during the storm period, making calibration possible. For example, the detailed high spatial resolution hourly precipitation allowed for the volume of rainfall that fell directly over open water to be accurately determined as well as the hourly volume of rainfall that fell over regions of the watershed with varying soil types, infiltration rates and lag times. Calibration of the model was greatly improved using the high spatial and temporal resolution rainfall analyses. For this particular study, the detailed rainfall information allowed the modelers to determine that almost all of the runoff from the watershed was provided by rainfall directly over open water. This level of calibration and runoff evaluation was made possible using the SPAS rainfall analyses results together with GIS analysis of the watershed characteristics to better define the topography of the watershed. "The use of GIS analysis did not introduce new or untested hydrologic techniques. It simply solved practical problems that had dogged the analysis of the watershed for years – indeterminate topography and lack of rainfall data – adding value to an otherwise conventional PMF analysis." (Rudolph et al, 2004)

Storm Depth-Area-Duration (DAD) Analyses

Storm DAD analyses are the best means for comparing the magnitude of extreme rainfall storms. The Weather Bureau and the Corps of Engineers routinely performed detailed storm rainfall analyses during the first half of the last century, however since then, only a few selected storms have been analyzed. The DADs from these studies were used in Hydrometeorological Reports (HMRs) to determine PMP rainfall amounts. Objective procedures were used in these analyses augmented with subjective judgment by qualified hydrometeorologists. The SPAS analysis incorporates earlier procedures while providing updated techniques along with powerful GIS capabilities to improve the quality, speed and accuracy of the analyses. (World Meteorological Organization, 1986)

The hourly precipitation grids serve as the basis for the computation of DAD statistics in SPAS. (See Figure 3 and Table 3) The SPAS DAD functionality has been rigorously tested both with a theoretical storm where the rainfall rates and spatial distributions are known exactly and with historic storms that have been previously analyzed by the Weather Bureau. The DAD process, by nature, is computationally intensive, hence forcing time-saving assumptions in storm studies conducted by the Weather Bureau (see Table 1). SPAS, however utilizes today's computer power and GIS algorithms to compute precise and perhaps more accurate DAD analyses.

SPAS utilizes the same general method for determining the storm-centered depth-area statistics as the World Meteorological Organization's Manual for Depth-Area-Duration Analysis of Storm Precipitation. (World Meteorological Organization, 1969) However, SPAS does not make the assumption that the hourly storm precipitation pattern is constant as dictated by a manually analyzed total storm isohyetal map but rather it changes from hour to hour throughout the storm.

In real storm cases, the SPAS DAD results were generally within +/-5% of the published Weather Bureau results for the Westfield, MA, storm of 1955 and Ritter, IA, storm of 1953. (U.S. Army Corps of Engineers, 1953 and 1955) These results confirm the reproducibility of not only the storm-centered DAD results, but also the spatial and temporal characteristics of the storm precipitation.

Area	**Duration (hours)**					
(mi^2)	**3**	**6**	**12**	**24**	**48**	**72**
1	3.5	6.4	9.8	15.3	16.4	16.6
10	3.4	6.3	9.5	15.0	16.0	16.2
100	3.0	5.7	8.7	13.6	14.7	14.9
200	2.9	5.4	8.4	12.8	14.0	14.2
500	2.7	5.0	7.9	12.0	13.2	13.4
1000	2.5	4.8	7.6	11.6	12.7	12.9
5000	2.1	3.8	6.5	9.8	11.1	11.2
10000	1.7	3.1	5.6	8.4	9.6	9.7
20000	1.1	2.0	3.7	5.7	6.6	6.7

Table 3 Storm-centered D-A-D table for the northeastern Virginia rainfall from hurricane Floyd (September 13-17, 1999).

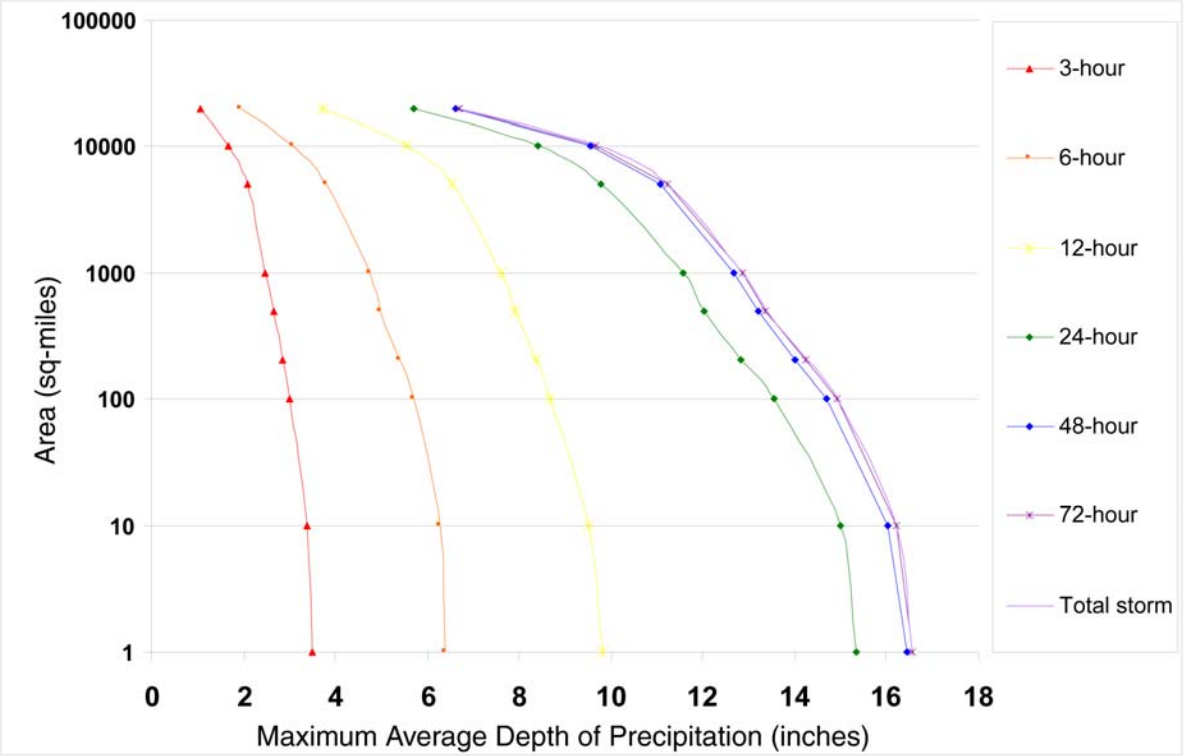
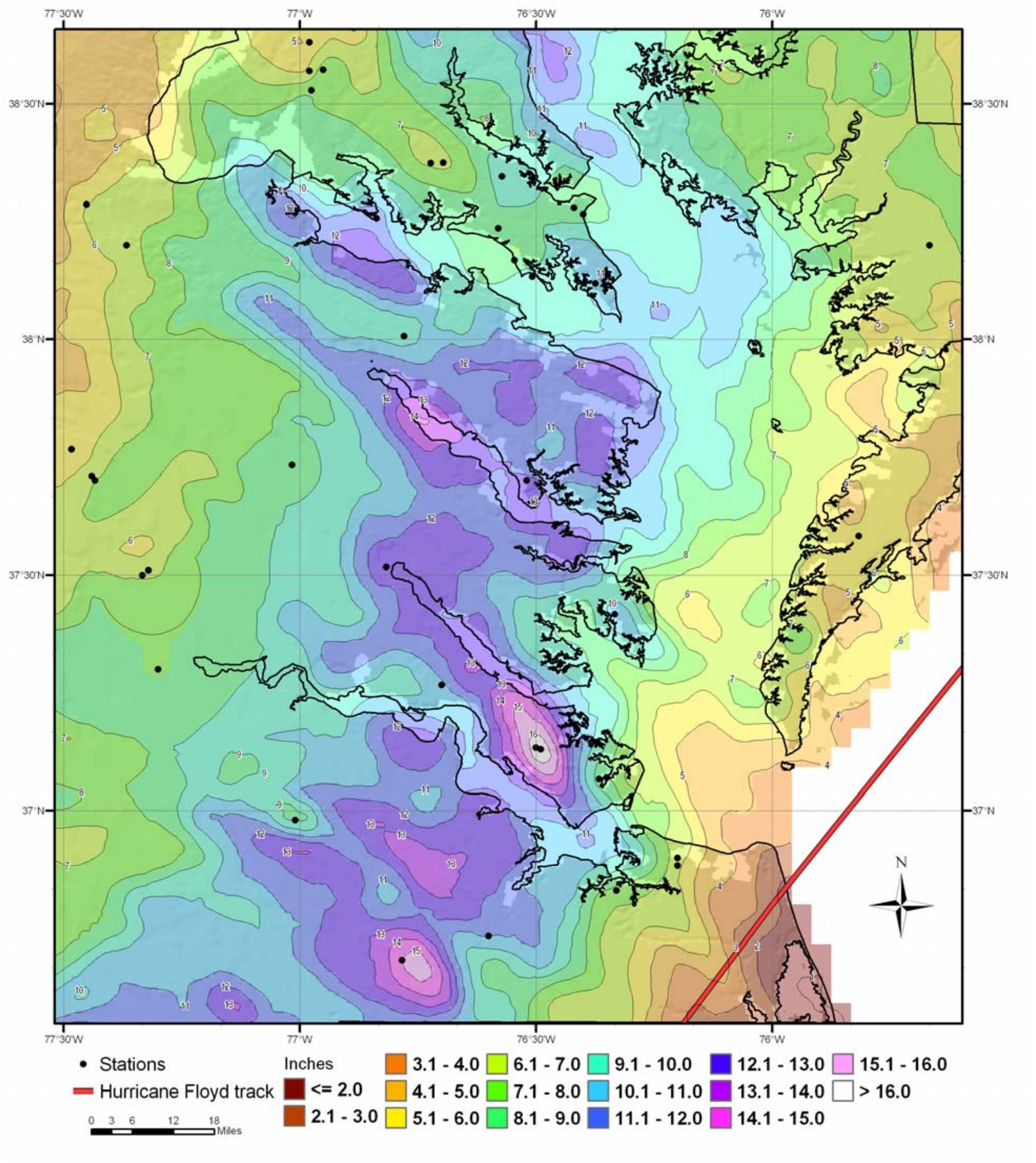


Figure 3 Storm-centered D-A plot associated with the northeastern Virginia rainfall from hurricane Floyd (September 13-17, 1999)



TWP 2/8/05

Figure 4 Total storm precipitation (inches) in northeastern Virginia during the period September 13-17, 1999 (hurricane Floyd) created by SPAS.

SPAS SUMMARY

SPAS is based on the sound foundation of the storm analysis procedure used by the Weather Bureau, thereby providing consistency between storms previously analyzed and those analyzed by SPAS. However, SPAS computes more precise and perhaps more accurate results by using a more sophisticated timing algorithm, a variety of base maps, a wider variety of data, fewer assumptions and more effective quality control measures. Although largely automated, SPAS has been designed to be flexible such that it can be utilized for any storm situation and account for unique meteorological conditions. And lastly, SPAS produces reproducible results and uses less subjectivity than previous storm analysis studies.

Currently SPAS is optimized to be a post-storm analysis tool, however there is growing interest in developing a near real-time or real-time version. Such a version would provide hydrologic engineers and decision maker's important detailed information about real time rainfall events.

SPAS provides an analysis tool for analyzing storm rainfall patterns with much improved spatial and temporal resolution that has historically been available for use in runoff model calibration and validation. The improved spatial data enables variations in soils types, infiltration rates and lag times to be associated with detailed rainfall rain rates and volumes. Additionally the hourly rainfall analyses allow for improvement in runoff timing.

There is an extremely large backlog of extreme rainfall storm analyses that should be completed. With rare exception, extreme rainfall storms that have occurred in the last 50 years have not been analyzed. Without storm DADs, comparison of rainfall amounts from extreme rainfall storms for various area sizes and durations is not possible. The storm data bases in most of the current HMRs are significantly out of date. For example, the most recent storm used in HMR 51 occurred in 1972. (Schreiner and Riedel, 1978) Using SPAS, this backlog in storm analyses can be addressed. Equally important, storm analyses could be provided in near real-time, utilizing rainfall observations that are not included in official archives and providing emergency managers with some measure of how extreme the storm rainfall amounts over various area sizes and for various durations when compared to other storms, published return frequency values and published PMP values.

SPAS STORM ANALYSIS RESULTS

Date: October 14-17, 2003

Domain: 51N 125W to 46.5N 199.5W

Duration: 96 hours, 1 AM PDT Oct 14, 2003 through midnight October 17, 2003

Base map: For consistency with the SPAS-lite runs on the calibration events, the 100-yr 24-hr precipitation grid was used for consistency and because the other options, including mean annual precipitation, mean October precipitation and no base map, caused elevated storm totals where average annual (or monthly) precipitation may be high but not representative of storm-caused precipitation.

Storm center: Approximately 70 miles northwest of the Baker Basin. The interpolated storm center precipitation of 18.22” is defined as a result of the base map and influence of the nearby Disappointment Lake pseudo station. The highest observed rainfall in the DAD domain was 12.12” at BUNTZEN BAY, BC. The lowest precip was 0” at several east-central Washington locations.

Spatial resolution: 1 min 15 sec or about 2-km, same as the base map.

Station Data:

331 stations:

- 95 Daily
- 80 Hourly
- 15 Hourly pseudos (timing only)
- 139 Daily supplemental (unknown observation time)
- 2 Daily pseudos

Daily Pseudos

Due to lack of observed data, a critical pseudo station was placed near the storm center in the mountains of southwestern British Columbia. This station is critical because it’s relationship to the base map will drive the estimated maximum storm precipitation. The daily pseudo station was placed at Disappointment Lake (49.55N/122.75W), elevation 3412 feet. This location was chosen because between 1994 and 1999 daily weather observations were made at an Automatic Snow Pillow (ASP) site here; site number 1D18P. Although the ASP was inactive during the October 2003 storm, inferences could be made between its precipitation and other stations during similar storms during the period 1994-1999. Three methods were used to estimate the Oct 15-17, 2003 total precipitation of 14.55 inches at Disappointment Lake. Remarkably the all of the methods and rationales resulted in similar amounts, thereby establishing confidence in the final estimate.

1) The closest reporting station to Disappointment Lake during the October 2003 storm was Buntzen Bay, BC, which reported 12.12 inches of precipitation during the period October 15-17, 2003. During a similar storm in 1994 (Nov 6-8), Disappointment Lake received about 20% more precipitation than Buntzen Bay, which would imply Disappointment Lake received about 14.54 inches (12.12 * 1.20) during the October 2003 storm. Other storms

were considered, but the analysis was constrained by a lack of quality data at Disappointment Lake and similar storm events.

2) Another estimation approach utilized the gridded 100-year 24-hour precipitation estimates. The percentage of the 100-year 24-hour storm the October 2003 storm represented. Using the 3 nearest stations to Disappointment Lake, the average ratio was about 1.138. In other words, the October 2003 storm was 13.8% higher than the 100-year 24-hour event. The 100-year 24-hour precipitation estimate at Disappointment Lake is 13.75 inches, so this would suggest the October 2003 storm dropped 15.65 inches (13.75 * 1.138).

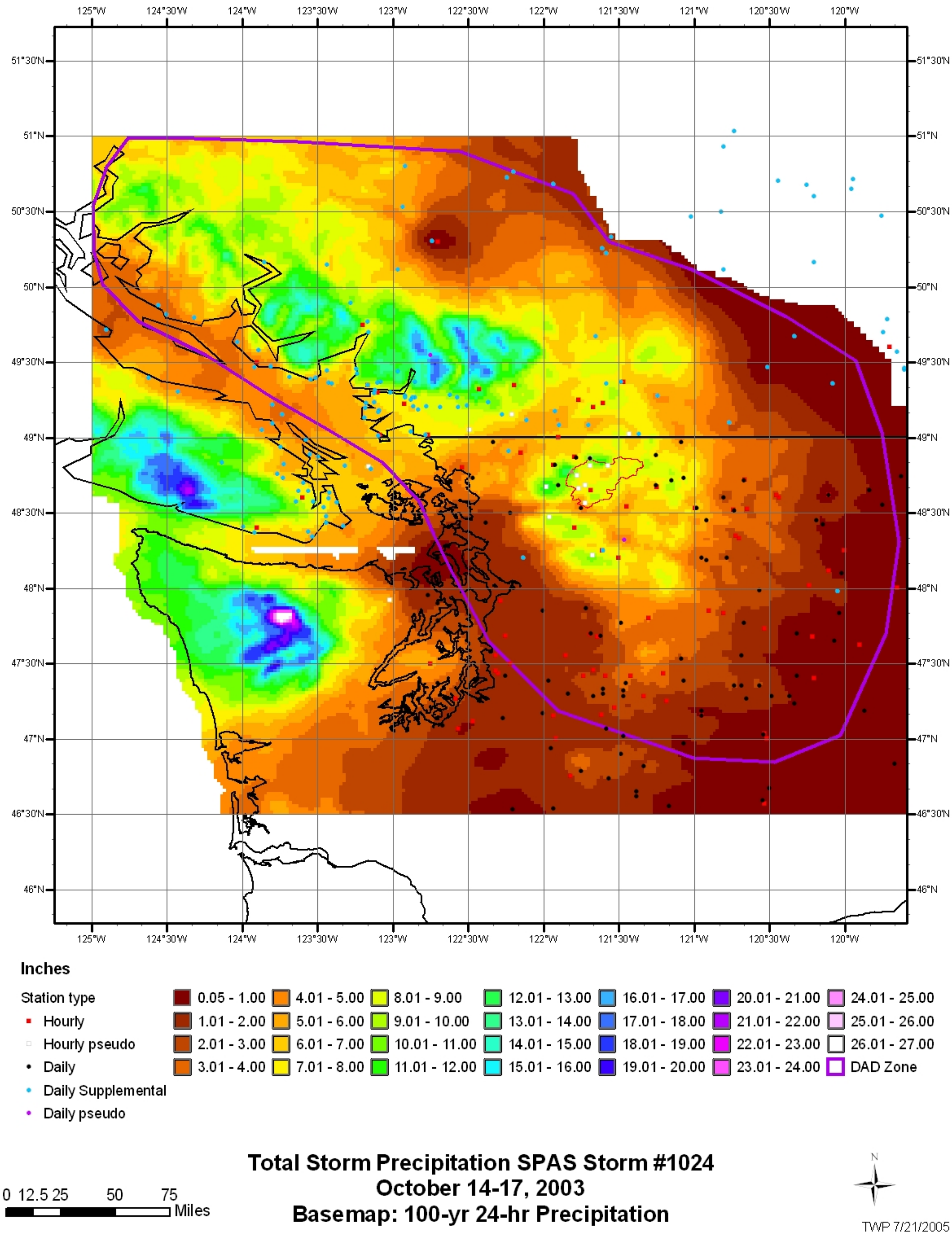
3) Although severe beam blockage and overshooting prevented direct use of radar data at Disappointment Lake, inferences were made from radar echoes extending up the valley's south of Disappointment Lake. Canadian radar estimated 6-7 inches of rainfall in the valley's, however radar was only representing about 33% of the observed precipitation at stations north of the radar site. This would suggest the valley's received 19-21 inches of precipitation, which is consistent with the storm center estimated rainfall of 18.2 inches about 5 miles southeast of Disappointment Lake. Bottom line, the 14.55 inch value at Disappointment Lake strongly influenced the storm center precipitation which is appropriate for this event.

Hourly Radar-based Psuedos

Six radar-based pseudo hourly stations were created in the Baker basin and used for timing only. Nine additional radar-based pseudo hourly stations were placed outside of the basin where hourly data was otherwise not available.

Final Isopluvial Map

(Area Used in the DAD Analysis is Outlined in Purple on the Map)

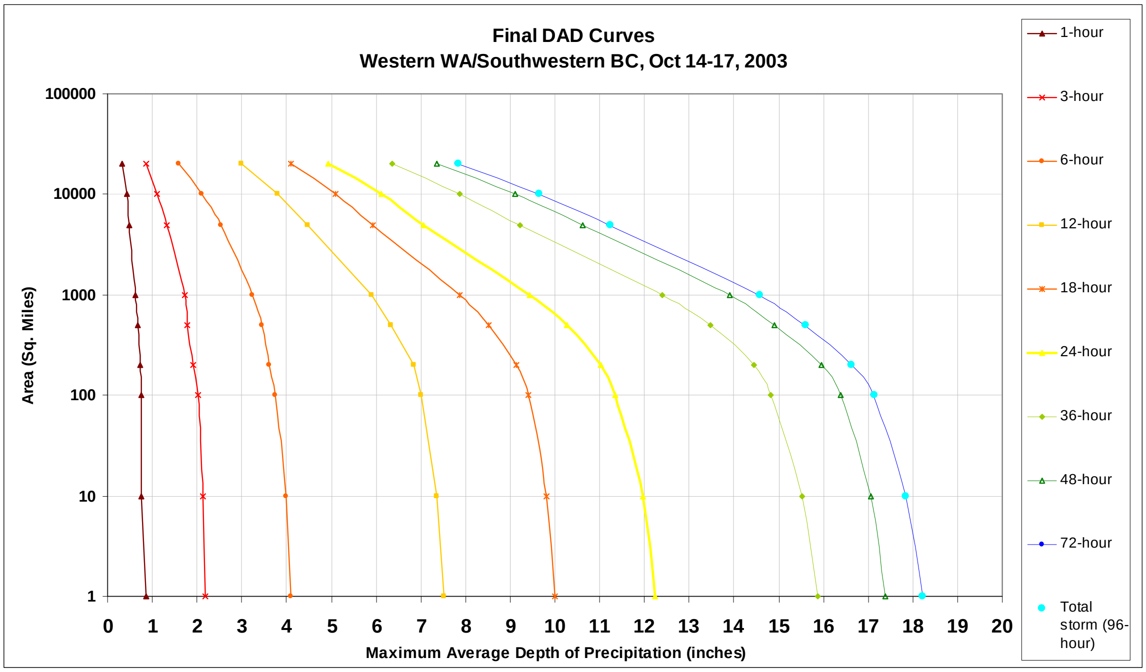


Total Storm Precipitation SPAS Storm #1024
October 14-17, 2003
Basemap: 100-yr 24-hr Precipitation

TWP 7/21/2005

DAD Results

Depth-Area Curves



Depth-Area-Duration Table

MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)

	Duration (hours)										
Area in Sq. Mi.	1	3	6	12	18	24	36	48	72	96	total
1.000	0.9	2.2	4.1	7.5	10.0	12.3	15.9	17.4	18.2	18.2	18.2
10.000	0.8	2.1	4.0	7.4	9.8	12.0	15.5	17.1	17.8	17.8	17.9
100.000	0.8	2.0	3.7	7.0	9.4	11.4	14.8	16.4	17.1	17.1	17.1
200.000	0.7	1.9	3.6	6.8	9.2	11.0	14.4	16.0	16.6	16.6	16.6
500.000	0.7	1.8	3.4	6.3	8.5	10.3	13.5	14.9	15.6	15.6	15.6
1000.000	0.6	1.7	3.2	5.9	7.9	9.4	12.4	13.9	14.6	14.6	14.6
5000.000	0.5	1.3	2.5	4.5	5.9	7.1	9.2	10.6	11.2	11.2	11.3
10000.000	0.4	1.1	2.1	3.8	5.1	6.1	7.9	9.1	9.6	9.7	9.7
20000.000	0.3	0.9	1.6	3.0	4.1	4.9	6.4	7.4	7.8	7.9	7.9

STATIONS USED IN THE OCTOBER 2003 STORM ANALYSIS

ID	Name	St	Lat	Lon	Elev	Inches	Type
451233	CEDAR LAKE	WA	47.4167	-121.7333	1562	2.50	H
451400	CHIEF JOSEPH	WA	48.0000	-119.6500	820	0.50	H
452384	EASTON	WA	47.2500	-121.1833	2172	1.50	H
452505	ELLENSBURG	WA	47.0000	-120.5167	1631	0.20	H
452614	EPHRATA FAA	WA	47.3000	-119.5333	1273	0.14	H
454446	LAKE WENATCH	WA	47.8333	-120.8000	1972	2.70	H
454764	LONGMIRE RAI	WA	46.7500	-121.8167	2762	1.70	H
455133	MAZAMA 2 W	WA	48.6000	-120.4333	2182	1.80	H
455704	MUD MOUNTAIN	WA	47.1500	-121.9333	1312	1.10	H
455876	NOOKSACK SAL	WA	48.9000	-122.1500	410	4.50	H
456892	RAINIER CARB	WA	47.0000	-121.9167	1722	1.10	H
457470	SEATTLE SAND	WA	47.6833	-122.2500	60	1.51	H
457473	SEATTLE TACO	WA	47.4333	-122.3000	384	1.52	H
457773	SNOQUALMIE F	WA	47.5500	-121.8500	430	1.40	H
457781	SNOQUALMIE P	WA	47.4167	-121.4167	3022	3.50	H
458009	STAMPEDE PAS	WA	47.2833	-121.3333	3958	2.27	H
458059	STEHEKIN 4 N	WA	48.3333	-120.7000	1152	2.40	H
458715	UPPER BAKER	WA	48.6500	-121.6833	689	8.70	H
459082	WENATCHEE PA	WA	47.4000	-120.2000	1229	0.26	H
459465	YAKIMA WSO A	WA	46.5667	-120.5333	1063	0.17	H
21A31S	WELLS CREEK SNOTEL	WA	48.8700	-121.7900	4200	5.93	H
21A36S	MF NOOKSACK SNOTEL	WA	48.8200	-121.9300	4980	9.49	H
20A05S	HARTS PASS SNOTEL	WA	48.7200	-120.6600	6500	3.50	H
20A09S	RAINY PASS SNOTEL	WA	48.5200	-120.7400	4780	4.16	H
20A07S	THUNDER BASIN SNOTEL	WA	48.5300	-120.9900	4200	6.65	H
KBLI	BELLINGHAM	WA	48.7994	-122.5392	157	3.46	H
KPWT	BREMERTON NTNL	WA	47.5000	-122.7500	482	5.62	H
KELN	ELLENSBURG	WA	47.0333	-120.5333	1702	0.21	H
KEPH	EPHRATA	WA	47.3000	-119.5167	1256	0.14	H
KPAE	EVERETT	WA	47.9167	-122.2833	590	1.16	H
KGRF	FORT LEWIS/GRAY	WA	47.0667	-122.5667	301	0.73	H
KOMK	OMAK	WA	48.4667	-119.5167	1295	0.55	H
KRNT	RENTON	WA	47.5000	-122.2167	68	1.30	H
KBFI	SEATTLE/BOEING	WA	47.5500	-122.3167	13	1.87	H
KSEA	SEATTLE/METRO	WA	47.4500	-122.3167	446	1.43	H

KTIW	TACOMA	WA	47.2667	-122.5833	291	2.34	H
KTCM	TACOMA/MC CHORD	WA	47.1167	-122.4667	321	0.84	H
1B65C	Finney Creek Concrete 10S RAWS	WA	48.4028	-121.7903	1900	9.29	H
07E84	Gold Hill RAWS	WA	48.2000	-121.5000	3020	8.14	H
1C0CC	KIDNEY CREEK RAWS	WA	49.0000	-121.9000	3000	6.11	H
4739C	Marblemount RAWS	WA	48.5394	-121.4461	357	5.21	H
JNLQ2	JONES LAKE INTAKE FSL	BC	49.2310	-121.6020	-999	7.98	H
TLRW1	SOUTH FORK TOLT RES FSL	WA	47.6939	-121.6877	1765	0.80	H
TLFW1	TOLT RAWS	WA	47.6772	-121.6419	3800	1.26	H
451992	Darrington 21 NNE CRN	WA	48.6740	-121.2460	510	4.78	H
GOFW1	Mt Baker FSL RAWS PSEUDO	WA	48.8630	-121.6900	5400	10.93	HP
CWRQ2	CHILLIWACK RIVER FSL PSEUDO	BC	49.0210	-121.4310	-999	5.47	HP
CMFW1	Camp 4 RAWS	WA	48.0181	-120.2342	3600	1.23	H
CPPW1	CLE ELUM FSL	WA	47.4310	-121.2010	3170	3.84	H
DIFW1	DOUGLAS INGRAM RIDGE RAWS	WA	48.1156	-120.1031	3560	1.04	H
99999	DOUGLAS RAWS	WA	47.6200	-119.8980	2530	0.46	H
99999	DRY CREEK RAWS	WA	47.7330	-120.5330	3480	0.92	H
ERAW1	ENTIAT RAWS	WA	47.6744	-120.2108	796	0.43	H
99999	FIRE TRAINING ACADEMY RAWS	WA	47.4536	-121.6658	1570	1.27	H
FBFW1	FIRST BUTTE RAWS	WA	48.6172	-120.1075	5509	0.84	H
GWFW1	GREENWATER RAWS	WA	47.1556	-121.6114	2490	1.10	H
99999	JOHNSON RIDGE RAWS	WA	47.8000	-121.3000	2000	4.21	H
LEFW1	LEECHER RAWS	WA	48.2510	-120.0019	5019	0.28	H
LSFW1	LESTER RAWS	WA	47.2083	-121.5250	1615	2.71	H
MZAW1	MAZAMA 2nw FSL	WA	48.6170	-120.4520	2193	3.84	H
GARW1	NORTH BEND 11se FSL	WA	47.4170	-121.5840	1515	2.59	H
99999	STEHEKIN RAWS	WA	48.3469	-120.7203	1230	2.43	H
PEFW1	PEOH POINT	WA	47.1522	-120.9467	4020	0.94	H
99999	VIEWPOINT RAWS	WA	47.8500	-120.9000	3760	3.37	H
WPFW1	WASHINGTON PASS RAWS	WA	48.5253	-120.6472	5460	1.83	H
CWZA	AGASSIZ	BC	49.2500	-121.7670	49	7.83	H
CYHE	HOPE AIRPORT	BC	49.3670	-121.4670	127	6.86	H
CWMM	PITT MEADOWS	BC	49.2000	-121.6670	16	8.68	H
CWWK	WHITE ROCK	BC	49.0167	-122.7670	49	7.39	H
CWHC	Vancouver Harbour WX UNDERGROUND	BC	49.3000	-123.1000	7	6.53	H
CWWA	W Vancouver WX UNDERGROUND	BC	49.3500	-123.1643	583	7.60	H
71780	Sheringham Point WX UNDERGROUND	BC	48.4000	-123.9000	69	7.81	H

IBCMADEI1	Madeira Park WX UNDERGROUND	BC	49.5000	-123.9000	130	3.09	H
CWKH	Malahat WX UNDERGROUND	BC	48.6000	-123.6000	1201	8.23	H
CWUS	SUMMERLAND	BC	49.6000	-119.7000	1490	0.59	H
PSEUDO1	RADAR PSEUDO 1 IN BASIN	WA	48.6601	-121.7660	3428	6.76	HP
PSEUDO2	RADAR PSEUDO 2 IN BASIN	WA	48.7487	-121.7756	4878	4.19	HP
PSEUDO3	RADAR PSEUDO 3 IN BASIN	WA	48.8113	-121.6887	2516	4.89	HP
PSEUDO4	RADAR PSEUDO 4 IN BASIN	WA	48.8104	-121.5679	5400	2.91	HP
PSEUDO5	RADAR PSEUDO 5 IN BASIN	WA	48.6801	-121.7191	1397	5.15	HP
PSEUDO6	RADAR PSEUDO 6 IN BASIN	WA	48.5657	-121.7191	600	2.86	HP
PSEUDO1o	RADAR PSEUDO 1 OUT BASIN	WA	48.6742	-121.9826	3756	11.59	HP
PSEUDO2o	RADAR PSEUDO 2 OUT BASIN	WA	48.4711	-121.9616	2641	10.02	HP
PSEUDO4o	RADAR PSEUDO 4 OUT BASIN	WA	48.2189	-121.6744	5085	7.19	HP
PSEUDO5o	RADAR PSEUDO 5 OUT BASIN	BC	49.0524	-122.4869	-9999	6.36	HP
PSEUDO6o	RADAR 6 OUT BASIN	BC	49.3186	-122.4239	-9999	9.85	H
PSEUDO7o	RADAR 7 OUT BASIN	BC	49.3466	-122.1927	-9999	8.34	H
PSEUDO8o	RADAR PSEUDO 8 OUT BASIN	BC	49.1505	-122.2067	-9999	6.56	HP
PSEUDO9o	RADAR PSEUDO 9 OUT BASIN	WA	48.8073	-123.1593	-9999	6.03	HP
PSEUDO10o	PSEUDO RADAR 10 OUT BASIN	WA	47.9177	-123.0192	2709	5.76	HP
IBCNEWW1	NEW WESTMINSTER WX UNDERGROUND	BC	49.2210	-122.9220	236	7.88	H
IBCPEMB1	PEMBERTON WX UNDERGROUND	BC	50.3000	-122.7000	669	0.32	H
IBCSQUA1	SQUAMISH AIRPORT WX UNDERGROUND	BC	49.7480	-123.2000	194	9.97	H
IBCTSAW1	TSAWWASSEN WX UNDERGROUND	BC	49.0170	-123.0830	100	8.49	H
KWADARRI1	DARRINGTON WXUNDERGROUND	WA	48.2500	-121.6100	549	9.09	H
450456	BARING	WA	47.7667	-121.4833	771	4.88	D
450872	BREMERTON NA	WA	47.5500	-122.6333	10	4.81	D
450945	BUCKLEY 1 NE	WA	47.1667	-122.0000	689	1.13	D
451350	CHELAN	WA	47.8333	-120.0333	1120	0.81	D
451414	CHIMACUM 4 S	WA	47.9500	-122.7667	249	0.88	D
451484	CLEARBROOK	WA	48.9667	-122.3333	59	4.68	D
451783	COUPEVILLE 1	WA	48.2000	-122.7000	49	0.30	D
452157	DIABLO DAM	WA	48.7167	-121.1500	889	8.15	D
452507	ELLENSBURG N	WA	47.0294	-120.5386	1705	0.10	D
452563	ENTIAT FISH	WA	47.7000	-120.3167	960	0.54	D
452675	EVERETT	WA	48.0000	-122.2000	120	1.00	D
452952	FORT LEWIS G	WA	47.0875	-122.6669	299	1.81	D
453730	HOLDEN VILLA	WA	48.2000	-120.7833	3220	2.76	D
454486	LANDSBURG	WA	47.3833	-121.9667	541	1.38	D

455224	MC MILLIN RE	WA	47.1333	-122.2667	581	1.20	D
455678	MOUNT VERNON	WA	48.4333	-122.3833	10	1.14	D
455840	NEWHALEM	WA	48.6833	-121.2500	531	7.90	D
456096	OLGA 2 SE	WA	48.6167	-122.8000	79	3.40	D
456123	OMAK 2 NW	WA	48.4333	-119.5333	1228	0.53	D
456295	PALMER 3 SE	WA	47.3000	-121.8333	902	1.61	D
456534	PLAIN	WA	47.7667	-120.6667	1801	1.53	D
456678	PORT TOWNSEN	WA	48.1000	-122.7667	66	0.41	D
456880	QUINCY 3 S	WA	47.1833	-119.8667	1260	0.15	D
456896	RAINIER OHAN	WA	46.7333	-121.5667	1932	1.98	D
456909	RANDLE 1 E	WA	46.5333	-121.9333	951	1.01	D
457185	ROSS DAM	WA	48.7333	-121.0667	1236	7.68	D
457507	SEDRO WOOLLE	WA	48.5000	-122.2167	59	1.58	D
457522	SELAH 2 NE	WA	46.6722	-120.4994	1120	0.23	D
457727	SMYRNA	WA	46.8333	-119.6667	561	0.19	D
458034	STARTUP 1 E	WA	47.8667	-121.7167	171	1.38	D
458278	TACOMA 1	WA	47.2500	-122.4167	25	1.95	D
459021	WAUNA 3 SW M	WA	47.3667	-122.7000	20	3.71	D
459074	WENATCHEE	WA	47.4167	-120.3167	630	0.41	D
459376	WINTHROP 1 W	WA	48.4500	-120.1833	1762	1.11	D
459463	YAKIMA NO 2	WA	46.5897	-120.5414	1150	0.18	D
450566	BELLINGHAM K	WA	48.7333	-122.4667	300	4.49	D
451504	CLE ELUM	WA	47.1833	-120.9500	1920	0.95	D
451666	CONCONULLY	WA	48.5500	-119.7500	2320	0.90	D
451679	CONCRETE PPL	WA	48.5333	-121.7500	195	2.90	D
454169	KENT	WA	47.4167	-122.2500	30	1.51	D
454572	LEAVENWORTH	WA	47.5500	-120.6833	1128	1.27	D
455326	METHOW	WA	48.1000	-120.0167	1150	0.68	D
455525	MONROE	WA	47.8500	-122.0000	120	1.54	D
458059	STEHEKIN 4NW	WA	47.3500	-120.7333	1270	2.41	D
458508	TOLT SOUTH F	WA	47.7000	-121.6833	2000	0.69	D
459012	WATERVILLE	WA	47.6500	-120.0667	2620	0.35	D
ANEW1	AENEAS RAWS	WA	48.7431	-119.6222	5185	0.15	D
FBFW1	FIRST BUTTE RAWS	WA	48.6172	-120.1075	5509	0.84	D
KOSW1	KOSMOS RAWS	WA	46.5278	-122.2014	2100	0.00	D
KMFW1	KRAMER RAWS	WA	48.2733	-119.5233	2720	0.45	D
GOFW1	MOUNT BAKER RAWS	WA	48.8625	-121.6894	6500	11.53	D

NCSW1	NCSB RAWS	WA	48.4253	-120.1408	1697	0.84	D
OMAW	OMAK RAWS	WA	48.4025	-119.5761	1697	0.34	D
PEFW1	PEOH POINT RAWS	WA	47.1522	-120.9467	4020	0.81	D
RXSW1	REX RIVER RAWS	WA	47.3300	-121.6000	3999	2.50	D
MEFW1	SAWMILL FLATS RAWS	WA	46.9686	-121.0686	3500	0.54	D
FWFW1	SWAUK RAWS	WA	47.2667	-120.6500	3773	0.89	D
TKSW1	TINKHAM CREEK RAWS	WA	47.3200	-121.4700	3071	2.90	D
21B48S	ALPINE MEADOWS SNOTEL	WA	47.7833	-122.7000	3500	2.41	D
21A01S	BEAVER PASS SNOTEL	WA	48.8833	-121.2500	3670	7.00	D
20B02S	BLEWETT PASS SNOTEL	WA	47.3500	-120.6833	4270	1.60	D
21C38S	BUMPING RIDGE SNOTEL	WA	46.8167	-121.3333	4970	2.08	D
21B13S	CORRAL PASS SNOTEL	WA	47.0167	-121.4667	6000	1.30	D
21B42S	COUGAR MOUNTAIN SNOTEL	WA	47.2833	-121.6667	3200	2.30	D
21A32S	ELBOW LAKE SNOTEL	WA	48.6833	-121.9000	3300	11.40	D
21B04S	FISH LAKE SNOTEL	WA	47.5333	-121.0833	5000	2.70	D
21C10S	GREEN LAKE SNOTEL	WA	46.5500	-121.1667	5840	0.60	D
20B11S	GROUSE CAMP SNOTEL	WA	47.2833	-120.4833	5300	1.00	D
20A05S	HARTS PASS SNOTEL	WA	48.7167	-120.6667	6600	2.90	D
21B62S	HUCKLEBERRY C SNOTEL	WA	47.0667	-121.5833	2200	1.10	D
20A23S	LYMAN LAKE SNOTEL	WA	48.1833	-120.9167	4970	3.50	D
21B59S	MEADOWS PASS SNOTEL	WA	47.2833	-121.4667	3500	2.60	D
20A40S	MINERS RIDGE SNOTEL	WA	48.2000	-120.9500	6270	2.60	D
21C17S	MORSE LAKE SNOTEL	WA	46.9000	-121.4833	5120	3.10	D
21B21S	MOUNT GARDNER SNOTEL	WA	47.3500	-120.5667	3000	2.51	D
21C40S	MOWICH SNOTEL	WA	46.9333	-121.9500	3150	0.90	D
21B55S	OLALLIE MEADOW SNOTEL	WA	47.3667	-121.4500	4270	3.40	D
21C35S	PARADISE SNOTEL	WA	46.7833	-121.7500	5120	3.10	D
20A12S	PARK CREEK RDG SNOTEL	WA	48.4500	-120.9167	4480	5.50	D
21C33S	PIGTAIL PEAK SNOTEL	WA	46.6167	-121.3833	5980	1.40	D
20B24S	POPE RIDGE SNOTEL	WA	47.9833	-120.5667	3200	2.60	D
20A09S	RAINY PASS SNOTEL	WA	48.5167	-120.7333	4780	3.90	D
21B17S	REX RIVER SNOTEL	WA	47.3000	-121.6000	4000	2.50	D
19A02S	SALMON MEADOWS SNOTEL	WA	48.6500	-119.8333	4500	1.00	D
21B51S	SASSE RIDGE SNOTEL	WA	47.3833	-121.0667	4200	2.60	D
21B60S	SKOOKUM CREEK SNOTEL	WA	47.6833	-121.6167	3920	2.40	D
20A07S	THUNDER BASIN SNOTEL	WA	48.5333	-120.9833	4200	6.20	D
20B25S	TROUGH SNOTEL	WA	47.2333	-120.3333	5300	0.80	D

20B07S	UPPER WHEELER SNOTEL	WA	47.2800	-120.3667	440	1.10	D
21A31S	WELLS CREEK SNOTEL	WA	48.8667	-121.7833	4200	4.80	D
21C28S	WHITE PASS ES SNOTEL	WA	46.6500	-121.3833	4500	1.20	D
21A35S	HOZOMEEN CAMP SNOTEL	WA	48.9667	-121.0833	1650	5.00	D
21A36S	MF NOOKSACK SNOTEL	WA	48.8200	-121.9200	4980	7.80	D
20A41S	SWAMP CREEK SNOTEL	WA	48.6000	-120.8000	4000	1.50	D
KWAPORTL3	PORT LUDLOW WXUNDERGROUND	WA	47.9000	-122.7000	-9999	2.21	D
TR757	CHELAN PORTABLE RAWS	WA	47.9781	-120.0439	3580	1.46	S
450257	ARLINGTON	WA	48.2000	-122.1333	102	1.84	S
SUMAS	SUMAS CANAL	BC	49.1130	-122.1100	-9999	5.68	S
YYXX	ABBOTSFORD	BC	49.0253	-121.3630	190	7.07	S
OKANA	OKANAGAN CENTRE	BC	50.0562	-119.4620	-9999	0.76	S
WINFI	WINFIELD	BC	50.0367	-119.4160	-9999	1.14	S
COQUI	COQUITLAM COMO LAKE	BC	49.2666	-122.8500	525	8.45	S
MILL	MILL BAY 1 SOUTHWEST	BC	48.6447	-123.5580	-9999	7.49	S
NORTHC	NORTH COWICHAN	BC	48.8247	-123.7200	-9999	4.85	S
LIONS	LIONS BAY	BC	49.4533	-123.2390	-9999	7.10	S
YWKV	HOPE SLIDE	BC	49.2791	-121.2380	2210	4.73	S
YYHE	HOPE	BC	49.3670	-121.4830	128	6.93	S
NORTHV4	NORTH VANCOUVER WHARVES	BC	49.3139	-123.1190	-9999	8.50	S
VANCOH	VANCOUVER HARBOUR CS	BC	49.2956	-123.1220	-9999	8.66	S
CWWA	WEST VANCOUVER	BC	49.3500	-123.1667	583	7.44	S
ROBCR	ROBERTS CREEK	BC	49.4000	-123.6833	4	8.65	S
1012040	COWICHAN LAKE FOREST	BC	48.8333	-124.1333	177	10.98	S
1126150	PENDICTON EC	BC	49.4500	-119.6000	1129	0.58	S
1106CL2	PORT MOODY GLENAYRE EC	BC	49.2670	-122.8670	427	9.02	S
BUNTZ	BUNTZEN BAY	BC	49.3670	-122.8500	33	12.12	S
BURNA	BURNABY SIMON FRASER UNIV	BC	49.2769	-122.9190	-9999	8.58	S
BURQU	BURQUITLAM VANCOUVER GOLF	BC	49.2517	-122.8770	-9999	8.76	S
CHILL1	CHILLIWACK RIVER HATCHERY	BC	49.0830	-121.7000	-9999	4.97	S
CHILL2	CHILLIWACK	BC	49.1728	-121.9240	-9999	5.94	S
DOUGL	DOUGLAS LAKE	BC	50.1648	-120.2000	-9999	0.17	S
HANEYE	HANEY EAST	BC	49.2000	-122.5670	-9999	8.85	S
HANEY	HANEY UBC RF ADMIN	BC	49.2650	-122.5730	-9999	9.82	S
HEDLE	HEDLEY	BC	49.3572	-120.0770	-9999	0.40	S
JELLI	JELLICOE	BC	49.6730	-120.3330	-9999	0.71	S
KELOWQ	KELOWNA QUAILS GATE	BC	49.8420	-119.5740	-9999	0.59	S

1101158	BURNABY SIMON FRASER UNIV EC	BC	49.2670	-122.9170	1200	8.59	S
KELOW	KELOWNA UA	BC	49.8830	-119.4830	-9999	0.48	S
LAIDL	LAIDLAW	BC	49.3565	-121.5800	-9999	8.44	S
MAPLE	MAPLE RIDGE KANAKA CREEK	BC	49.2110	-122.5070	-9999	9.94	S
MISSI	MISSION WEST ABBEY	BC	49.1530	-122.2710	-9999	8.56	S
N VANC	N VANCOUVER SEYMOUR HATCHERY	BC	49.4372	-122.9670	-9999	10.40	S
OLIVESTP	OLIVER STP	BC	49.1792	-119.5450	-9999	0.34	S
OLIVE	OLIVER	BC	49.1658	-119.5640	-9999	0.26	S
PEACHG	PEACHLAND GREAT A RANCH	BC	49.7003	-119.7410	-9999	0.69	S
PEACH	PEACHLAND	BC	49.7830	-119.7170	-9999	0.74	S
YYYF	PENTICTON A	BC	49.4631	-119.6020	1129	0.65	S
YWMM	PITT MEADOWS CAMPBELL SCIENCE	BC	49.2000	-122.6830	16	8.77	S
YWMM	PITT POLDER	BC	49.2830	-122.6170	16	9.78	S
SARDI	SARDIS	BC	49.0819	-121.8950	-9999	5.18	S
STAVE	STAVE FALLS	BC	49.2330	-122.3670	-9999	11.11	S
YWUS	SUMMERLAND CS	BC	49.5670	-119.6500	1490	0.72	S
SURREYG	SURREY GUILDFORD	BC	49.1875	-122.8310	-9999	7.22	S
SURREYT	SURREY TYNELEAD B	BC	49.2053	-122.7760	-9999	9.78	S
YWWK	WHITE ROCK CAMPBELL SCIENTIFIC	BC	49.0183	-122.7830	43	7.38	S
BOWEN	BOWEN ISLAND	BC	49.3658	-123.4260	-9999	5.86	S
CENTR	CENTRAL SAANICH ISLAND VIEW	BC	48.5710	-123.3730	-9999	6.52	S
CHEMA	CHEMAINUS	BC	48.9353	-123.7420	-9999	6.65	S
DELTA	DELTA TSAWWASSEN BEACH	BC	49.0110	-123.0930	-9999	6.42	S
DUNCANG	DUNCAN GLENORA	BC	48.7560	-123.7650	-9999	6.84	S
DUNCANK	DUNCAN KELVIN CREEK	BC	48.7328	-123.7260	-9999	6.74	S
ENTRA	ENTRANCE ISLAND	BC	49.2167	-123.8000	-9999	3.83	S
ESQUI	ESQUIMALT HARBOUR	BC	48.4320	-123.4390	-9999	6.00	S
GALIA	GALIANO NORTH	BC	48.9853	-123.5740	-9999	4.56	S
GAMBI	GAMBIER HARBOUR	BC	49.4431	-123.4330	-9999	7.86	S
GANGE	GANGES MANSELL ROAD	BC	48.8720	-123.4970	-9999	6.18	S
GIBSO	GIBSONS	BC	49.3975	-123.5120	-9999	5.45	S
GIBSOG	GIBSONS GOWER POINT	BC	49.3858	-123.5410	-9999	5.70	S
HOWE	HOWE SOUND STRACHEN CREEK	BC	49.4210	-123.2340	-9999	8.94	S
MALAH	MALAHAT	BC	48.5750	-123.5300	-9999	8.31	S
METCH	METCHOSIN	BC	48.3740	-123.5610	-9999	6.87	S
NANAI	NANAIMO	BC	49.0520	-123.8700	-9999	4.87	S
NORTHP	NORTH PENDER ISLAND	BC	48.8130	-123.3170	-9999	6.53	S

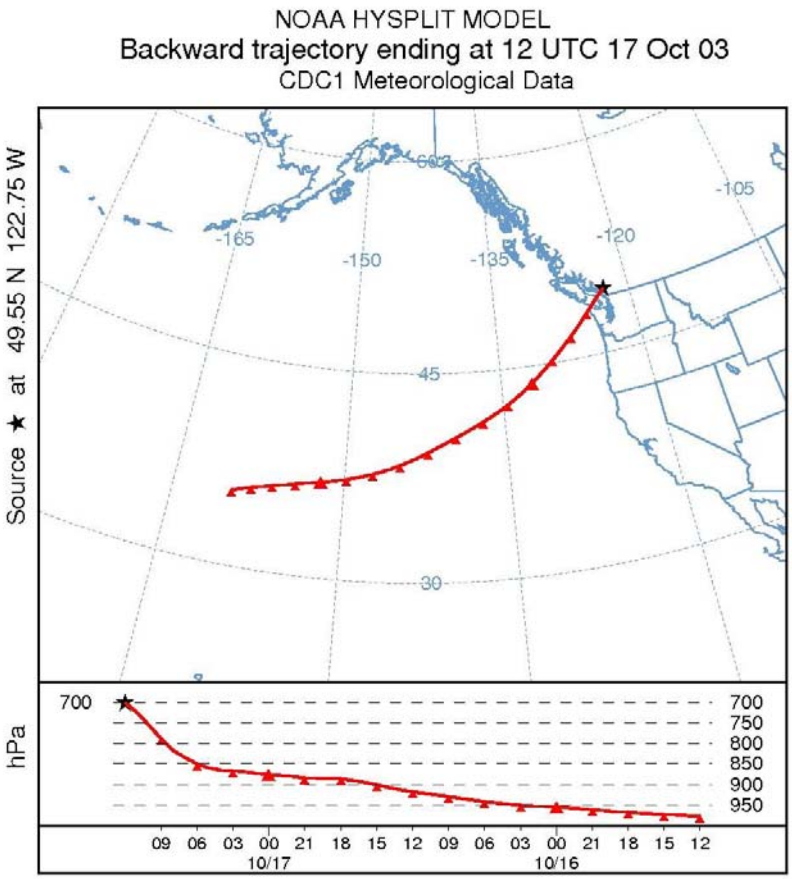
NORTHV1	NO. VANCOUVER GROUSE MTN RESORT	BC	49.3681	-123.0810	-9999	12.42	S
NORTHV2	NORTH VANCOUVER SECOND NARROWS	BC	49.2981	-123.0150	-9999	7.99	S
NORTHV3	NORTH VANCOUVER SONORA DRIVE	BC	49.3625	-123.0980	-9999	8.79	S
RICHMD	RICHMOND DALLYN ROAD	BC	49.1792	-123.0870	-9999	6.98	S
RICHMN	RICHMOND NATURE PARK	BC	49.1706	-123.0930	-9999	6.64	S
SAANI	SAANICHTON MOUNT NEWTON	BC	48.5975	-123.4270	-9999	7.28	S
SALTS	SALTSPRING ST MARYS L	BC	48.8880	-123.5470	-9999	5.38	S
SATUR	SATURNA CAPMON	BC	48.7920	-123.1430	-9999	6.18	S
SECHE	SECHELT 5 WEST	BC	49.4742	-123.8060	-9999	4.69	S
SHAWN	SHAWNIGON LAKE	BC	48.6472	-123.6270	-9999	7.84	S
SOOKE	SOOKE LAKE NORTH	BC	48.5756	-123.6400	-9999	8.26	S
SQUAMSTP	SQUAMISH STP CENTRAL	BC	49.6983	-123.1600	-9999	7.59	S
SQUAMU	SQUAMISH UPPER	BC	49.8958	-123.2810	-9999	9.88	S
STEVE	STEVESTON	BC	49.1306	-123.1890	-9999	6.37	S
VANCOI	VANCOUVER INTERNATIONAL AIRPORT	BC	49.1950	-123.1820	-9999	6.05	S
VANCOO	VANCOUVER OAKRIDGE	BC	49.2347	-123.1200	-9999	7.23	S
VANCOS	VANCOUVER SOUTHLANDS	BC	49.2275	-123.1780	-9999	5.27	S
VICTOR	VICTORIA FRANCIS PARK	BC	48.4764	-123.4430	-9999	6.92	S
2G03P	BLACKWALL PEAK ASP	BC	49.1000	-120.7670	-999	3.01	S
SZKQ2	SPUZZUM CREEK ASP	BC	49.6710	-121.6520	-999	6.33	S
1C18P	Mission Ridge ASP	BC	50.7667	-122.2000	6070	2.41	S
1C12P	Green Mountain ASP	BC	50.8000	-122.9167	5840	6.18	S
1D06P	Tenquille Lake ASP	BC	50.5333	-122.9333	5512	5.82	S
3A25P	Upper Squamish River ASP	BC	50.1500	-123.4333	4396	6.97	S
CYQQ	comox	BC	49.7167	-124.9000	78	2.65	S
PORTR	PORT RENFREW	BC	48.5500	-124.4167	-999	15.37	S
CYPW	POWELL RIVER AIRPORT	BC	49.8167	-124.5000	426	3.62	S
CWSP	SHERINGHAM	BC	48.3667	-123.9167	68	7.88	S
CYYJ	VICTORIA INTERNATIONAL AIRPORT	BC	48.6333	-123.4167	62	7.15	S
CWAE	WHISTLER	BC	50.1167	-122.9667	2158	5.85	S
BOWEN	BOWEN ISLAND SUNSET PARK	BC	49.3603	-123.4020	427	6.52	S
CELIS	CELISTA	BC	50.9556	-119.3790	1690	1.33	S
COOMB	COOMBS	BC	49.3064	-124.4270	322	5.04	S
CRISS	CRISS CREEK	BC	51.0333	-120.7330	368	0.48	S
GABRI	GABRIOLA ISLAND	BC	49.1539	-123.7340	151	2.96	S
HIGHL	HIGHLAND VALLEY LORNEX	BC	50.4667	-121.0170	416	1.19	S
CYKA	KAMLOOPS AIRPORT	BC	50.7022	-120.4420	1133	0.18	S

KAMLOP	KAMLOOPS PRATT ROAD	BC	50.6000	-120.2000	2100	0.34	S
KAMLOV	KAMLOOPS VALLEY VIEW	BC	50.6750	-120.2530	1138	0.13	S
CYLW	KELOWNA AIRPORT	BC	49.9561	-119.3780	1409	0.67	S
KELOW	KELOWNA MWSO	BC	49.9500	-119.4000	1496	0.67	S
LILLO	LILLOOET	BC	50.6841	-121.9330	912	1.28	S
LOGAN	LOGAN LAKE	BC	50.5000	-120.8170	361	0.75	S
LOISR	LOIS RIVER DAM	BC	49.7953	-124.3180	515	5.10	S
LYTTO2	LYTTON 2	BC	50.2569	-121.6080	571	2.62	S
CWLY	LYTTON	BC	50.2244	-121.5820	738	3.57	S
LYTTOB	LYTTON BOTANIE VALLEY	BC	50.3288	-121.5490	2395	1.62	S
MALIB	MALIBU JERVIS INLET	BC	50.1647	-123.8530	25	6.99	S
MERRI	MERRITT STP	BC	50.1142	-120.8010	1998	1.18	S
CWMR	MERRY ISLAND	BC	49.4667	-123.9170	25	5.13	S
MONTE	MONTE CREEK	BC	50.6531	-119.9540	1152	0.18	S
CWGP	PEMBERTON AIRPORT	BC	50.3025	-122.7380	670	0.27	S
PENDE	PENDER HARBOUR	BC	49.6344	-124.0320	210	3.96	S
PINAN	PINANTAN LAKE	BC	50.7161	-119.9450	3150	0.45	S
POINT	POINT NO POINT	BC	48.4058	-123.9910	82	9.31	S
POWEL	POWELL RIVER	BC	49.8761	-124.5540	170	2.99	S
YWPR	PRINCTON CS	BC	49.4675	-120.5120	2296	0.61	S
QUALI	QUALICUM FISH RESEARCH	BC	49.3942	-124.6180	25	5.75	S
REDLA	RED LAKE	BC	50.9333	-120.8000	3937	0.60	S
SAANI	SAANICHTON CDA	BC	48.6978	-123.5940	200	7.21	S
SHALA	SHALATH	BC	50.7283	-122.2410	800	2.26	S
CWSK	SQUAMISH	BC	49.7667	-123.1667	196	10.06	S
STUAR	STUART CHANNEL BOAT HARBOUR	BC	49.0908	-123.7990	46	4.32	S
SURRE	SURREY KWANTHEN PARK	BC	49.2089	-122.8600	256	4.32	S
VICTOG	VICTORIA GONZALES CS	BC	48.4134	-123.3250	229	4.13	S
VICTOH	VICTORIA HARTLAND CS	BC	48.5338	-123.4590	506	8.39	S
WESTW	WESTWOLD	BC	50.4696	-119.7510	2001	0.28	S
WHITE	WHITE ROCK OCEAN PARK	BC	49.0417	-122.8790	150	7.98	S
WILLI	WILLIAM ROAD	BC	48.3397	-123.5320	40	4.56	S
WOODF	WOODFIBRE	BC	49.5811	-123.8890	11	7.20	S
KWACONCR2	CONCRETE WXUNDERGROUND PSEUDO	WA	48.3200	-121.4600	250	3.82	SP
1D18P	Disappointment Lake PSEUDO	BC	49.5500	-122.7500	3412	14.55	SP
451992	DARRINGTON R	WA	48.2500	-121.6000	551	7.15	S
4739C	Sumas RAWS	WA	48.9100	-122.2320	3000	5.00	S

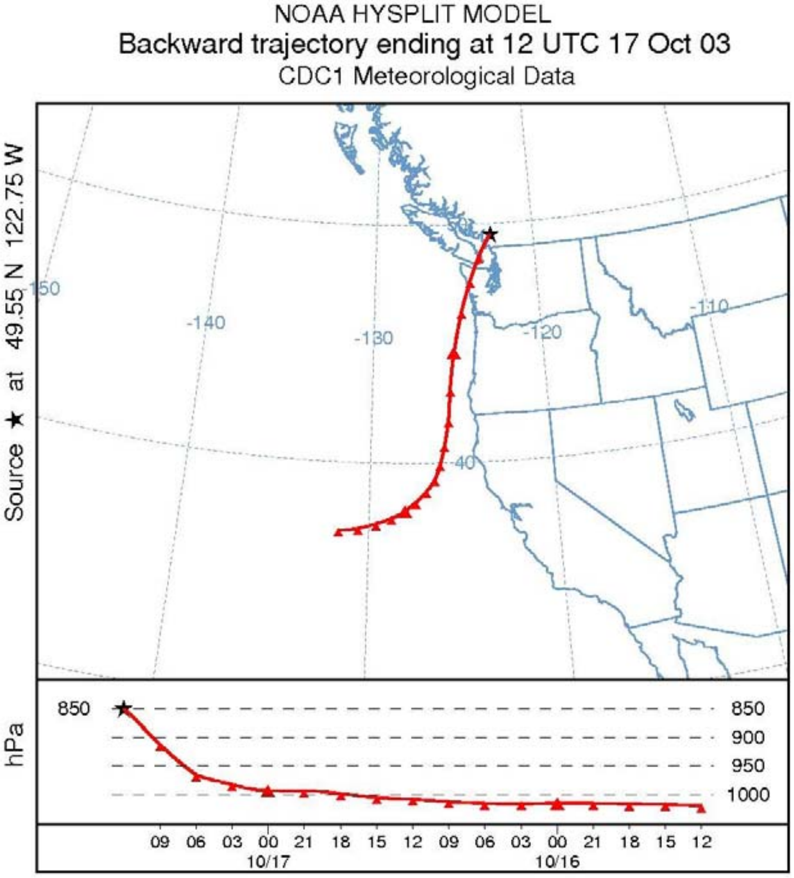
MAXIMIZATION FACTOR FOR THE OCTOBER 2003 STORM

The HYSPLIT model trajectory (described in Technical Memo 8) was used to determine the moisture inflow vector for the October, 2003, storm. The inflow vector was determined primarily using the 700 mb and 850 mb trajectories shown below. The 925 mb trajectory was not from over the Pacific Ocean and did not influence the determination of the storm moisture inflow vector.

Baker WA - Storm Center - 700 mb NCEP

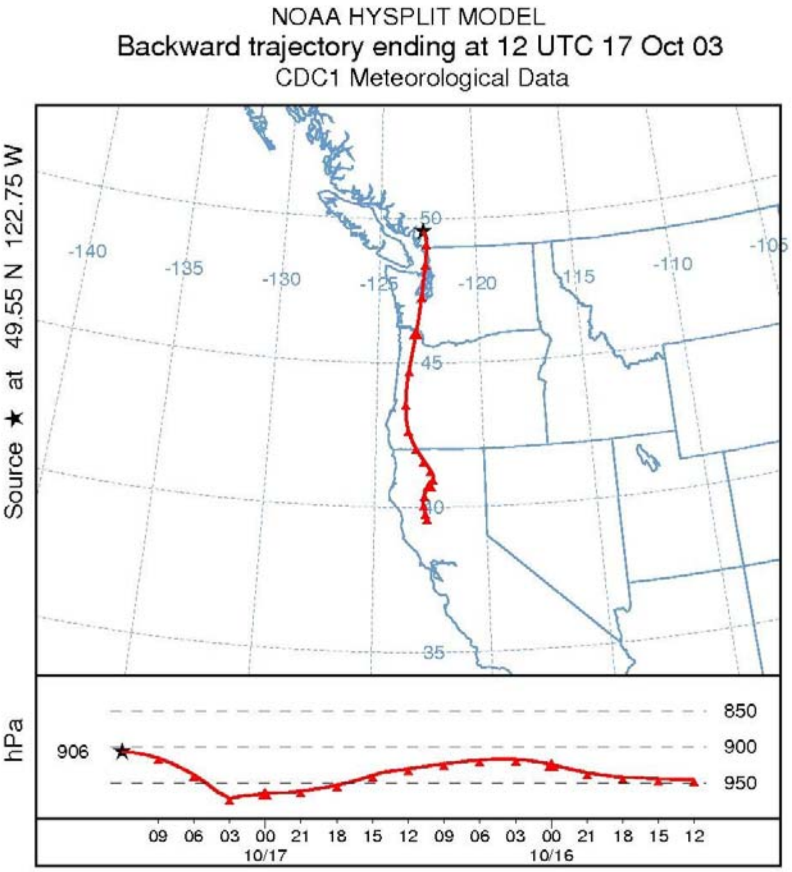


Baker WA - Storm Center - 850 mb NCEP



NOAA HYSPLIT MODEL
Backward trajectory ending at 12 UTC 17 Oct 03
CDC1 Meteorological Data

Baker WA - Storm Center - 925 mb NCEP



The sea surface temperature (SST) selected for the storm representative SST was 66.5 degrees F at 39 N, 125 W. The moisture inflow vector is Southwest @ 920 miles. The two sigma SST at that location for October 1 (two weeks towards the warm season from the date of the storm) is 68.5 degrees F. Using the precipitable water associated with a saturated atmosphere with these surface temperatures, an in-place maximization factor of 1.10 was computed.

An in-place maximization factor was also computed using maximum precipitable water from the Quillayute soundings for the period of two days before the storm through the storm period together with the 100-year precipitable water value for the Quillayute soundings. The maximum precipitable water for the storm period was 3.18 centimeters (Oct 17, 00Z) and the 100-year value for October is 3.48 centimeters, yielding a maximization factor of 1.09. Applying the two week temporal transposition towards September, the 100-year value is 3.75 centimeters and the maximization factor is 1.18. This value is in general agreement with the 1.10 maximization factor determined using the SST approach.

The comparison of this storm with the largest of the HMR 57 storms is provided in Technical Memo 8. The maximum analyzed point rainfall was also compared with the 100-year value. The highest rainfall in the storm analysis occurred at 122.71W, 49.49N. The 24-hour total was 12.3 inchesand the 72-hour total 18.2 inches. The 100-year 24-hour value at this location is 15.01 inches.

SUPPLEMENTARY STORM ANALYSES FOR CALIBRATION EVENTS

INITIAL STORM ANALYSES

SPAS-lite, a limited domain SPAS storm analysis, was used to establish temporal and general spatial characteristics for the five calibration events. Between 9 and 13 stations in the immediate vicinity of the Baker Basin were used in these analyses; The 1995 SPAS-lite run utilized two radar-based pseudo hourly stations as well which were used to resolve the temporal characteristics of the storm, but not the magnitude. Fortunately, the Upper Baker Dam COOP site was operating during each of the calibration events and provided key information for SPAS-lite. SNOTEL and RAWS data were also used. The 100-year 24-hour base map was chosen for all five SPAS-lite runs because it provided the best representation of an extreme event and resolved the precipitation variability across the complex terrain. Although much of the data for the SPAS-lite runs was observed outside the basin, the SPAS technology (described above) provided sufficient confidence in the spatial interpolation for extraction of hourly precipitation at each sub-basin centroid; this information was later combined with a total storm precipitation grid to compute average hourly precipitation depths over the sub-basins.

STORM ANALYSES WITH UPDATED 100-YEAR 24-HOUR BASE MAP AND NEXRAD PSEUDO STATIONS

The BOC provided an updated 100-year 24-hour map for Washington that was incorporated as the base map in the SPAS-lite analyses. Additionally, for the 1995 and 2003 storms, hourly rainfall values at 11 pseudo stations were computed using NEXRAD data at the 1.32 and 1.36 elevation scan angles. The following discussions provide information on how the NEXRAD data were used to compute the pseudo station rainfall values.

NEXRAD RAINFALL ESTIMATION PROCESS

Radar has been in use by meteorologists since the 1960’s to estimate rainfall depth. In general, most current radar-derived rainfall techniques rely an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the equation (1) below:

$$Z = A\,R^{b} \qquad (1)$$

Where Z is the radar reflectivity, measured in units of dBZ, R is the rainfall rate, A is the “multiplicative coefficient” and b is the “power coefficient”. Both A and b are directly related to the drop size diameter (DSD) within a cloud (Martner et al 2005).

The National Weather Service (NWS) utilizes these algorithms to estimate rainfall through the use of their network of Doppler radars located across the United States. A standard default Z-R algorithm of $Z = 300R^{1.4}$ is the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD and air mass characteristics across the United States (Dickens 2003). Other factors include occultation or blockage of the radar beam due to terrain features, range effects, which is when the radar beam passes through an elevation too high in the cloud to observe the main precipitation portion of the cloud.

Using the technique described above, NEXRAD rainfall depth and temporal distribution estimates were determined for multiple points located within the Baker River drainage basin and for points located in the proximity of the basin for two rainfall events. The first event occurred in November 1995 and the other event occurred in October 2003.

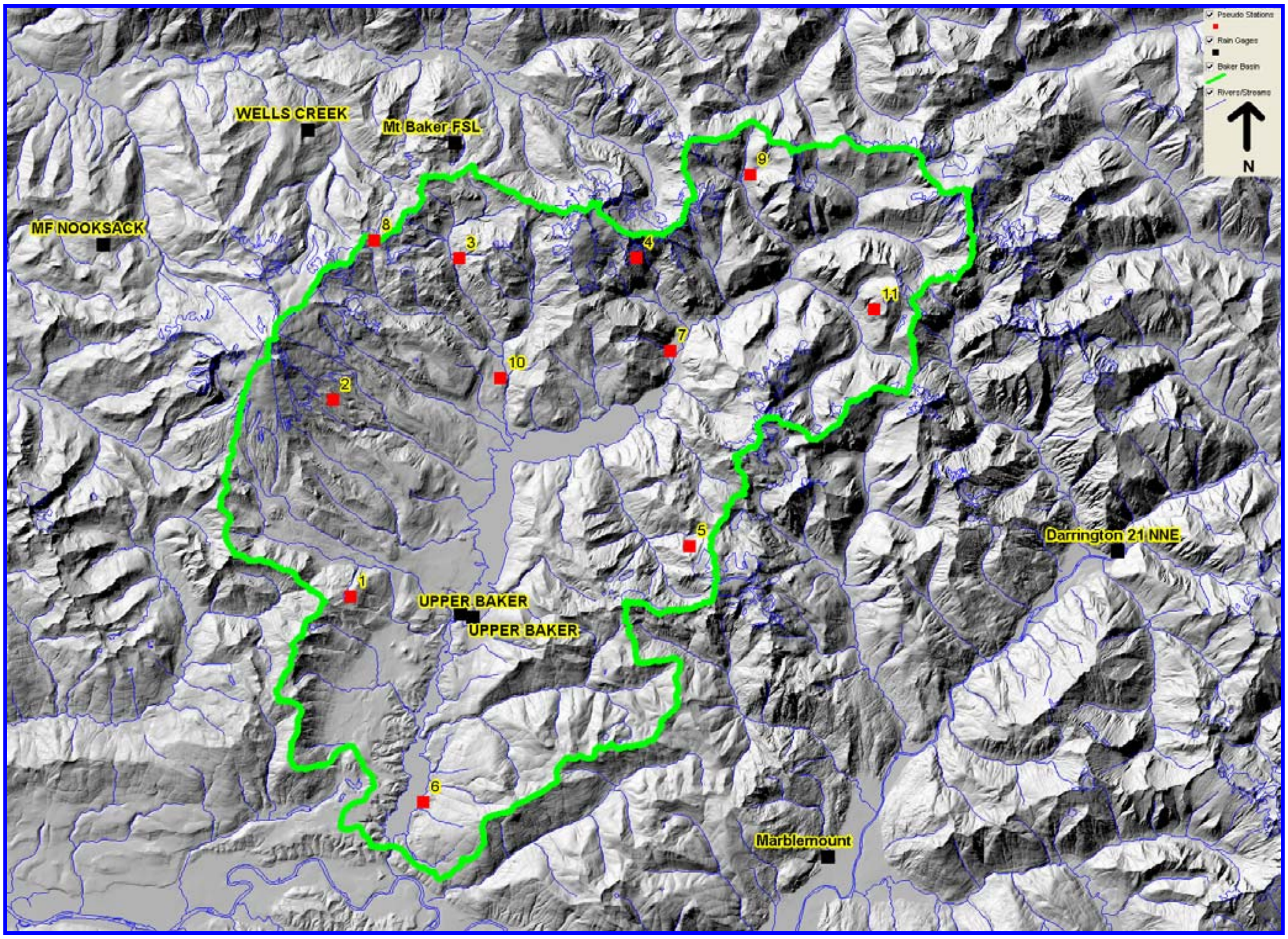
The lowest beam angle of the KATX radar had 40% or less beam power over the entire basin. The decision was made to use the second lowest beam angle to relate Z to R.

The procedure that was utilized to estimate the rainfall is described in the following steps:

1. Surface rainfall observations taken within and in the proximity of the basin were obtained from multiple sources for the two rainfall events. A Geographic Information System (GIS) layer containing the locations of these rainfall observations was created using GIS software.

2. NWS KATX Doppler radar (Seattle, Washington) Level II data was obtained for both rainfall events from the National Climatic Data Center (NCDC). KATX Level II Base Reflectivity data, 1.32 and 1.36 degree beam angle, 124 km range, data resolution of 1 degree x 1.0 km (polar coordinates) and 0.50 dBZ data bin resolution was extracted from the Level II dataset. During the November 1995 event KATX was operating in Volume Coverage Pattern (VCP) 21 mode, which produces the base reflectivity information at a

temporal resolution of 6 minutes. During the October 2003 event KATX was operating in VCP 21 mode as well, but changed over to the VCP 11 mode about 30 hours into the event. VCP 11 mode produces the base reflectivity information at a temporal resolution of 5 minutes.



Baker River drainage basin, rainfall observation locations and the virtual rain gage locations.

3. An occultation correction scheme was applied to each radar data bin located within and in the proximity of the basin. The correction scheme resulted in the addition of dBZ values in increments of 1 to depending on the amount of beam power of the radar data bins (Fulton et. el, 1998).

Occultation (%)	Reflectivity correction (dBZ)
0-10, >60	0
11-29	+1
30-43	+2
44-55	+3
56-60	+4

Occultation correction factors.

4. The polar coordinate base reflectivity data (Z) was converted into Cartesian coordinate ESRI ASCII II Grid GIS files and combined with the rainfall observations GIS layer. The grid cells within the GIS grid have a resolution of approximately 1.00 km^2. GIS Scripts were used to determine base reflectivity values (Z) over each rainfall observation location and for 11 points located within the basin for each radar time step.

5. A range correction scheme that had been determined through research performed by the United States Bureau of Reclamation across the Pacific Northwest was applied to each radar data bin located over the points located within and outside the basin. The range correction factor (CF) used was: $1.00000 - 0.00500r + 0.0001428r^2$, where r is the range (distance in km) from the radar (Hartzell and Super, 2000). The range correction corrects for rainfall underestimates due to the radar beam not observing the main precipitation portion of the cloud.

6. Multiple Z-R algorithms most commonly used across the Pacific Northwest were used to convert radar reflectivity (Z) to rainfall (R). Point rainfall depth estimates were produced for the rainfall observation locations located within the basin and in the proximity of the basin (Figure x). A manual “best fit” Z-R algorithm was then determined by applying additional Z-R algorithms until the total estimated point rainfall depths at the rain observation locations had the best agreement with the observed total rainfall depths at the rain observation locations.

7. The “best fit” Z-R algorithm was then used to estimate rainfall depths at 11 points located within the basin. Hourly rainfall depth estimates were produced for these 11 points. The points were treated as virtual rain gage observations that were imported into SPAS model runs.

KATX OCCULTATION PROCEDURE

A procedure was carried out to determine the amount (percentage) of radar beam blockage (occultation) that the closest and the most representative National Weather Service Doppler radar (NEXRAD) was experiencing over the Baker River drainage basin for two heavy rainfall events. The radar is located in Seattle Washington (KATX), about 87km from the center of the basin. The purpose of this effort was to determine if there was sufficient radar beam energy (greater than 40 percent energy of the beams total energy) to detect precipitation falling into the basin. The procedure that was used was developed by Dr. Scott Shipley a professor at George Mason University, Ira Graffman with the National Weather Service and Robert Saffle a scientist with Mitretek Systems. (Shipley et al. 2003)

The technical approach of this procedure was to estimate radar beam occultation on a bin-by-bin basis. Radar bins are 1 degree x 1 km areas (polar coordinates) contained within radials that extend 230 km beyond the radar. The radar bins contain data derived by the radar’s beam energy. The radar beam contains 360 radials with each radial containing 230 data bins.

Radar data bin centroid locations and the height of the bin centroid above the radar were determined using a software program created by Dr. Shipley called NEX2SHP. The program produces point polygon shapefiles for input into the occultation process procedure.

The occultation procedure was performed through the following steps using ESRI’s ArcView by:

1. **Generate theoretical radar coverage pattern –** The radar beam pattern is generated as centroids and are joined to a digital elevation model (DEM).

2. **Merge radar and terrain database –** The radar beam height difference is calculated with respect to local terrain elevation and /or man-made obstacles.

3. **Calculation of beam obstruction cross section –** The radar beam pattern model is used to estimate percentage of the beam occulted by terrain features and/or man made objects along each the path of each radial.

4. **Interpret obstruction pattern –** Determination of the theoretical performance limit using an occultation threshold level of 60 % or greater (beam power greater than 40%).

The procedure was performed for the lowest beam angle of the KATX radar (0.5 degrees) by Dr. Shipley and it was determined that the beam energy was less then 40% (occultation of 60% or greater) over the entire basin due to occultation due to terrain features downstream of the basin.

The procedure was then performed by AWA for the second lowest beam angles of the KATX radar (1.36 degrees and 1.32 degrees) that were being used for a heavy rainfall event that occurred in November 1995 and another event that occurred in October 2003. Through this procedure it was determined that the occultation for the 1.36 and 1.32 radar beam angles was less than 60% over the entire basin. The radar beam power over the basin varied from 41% to 100%. The reductions in beam power were due to occultation caused by terrain features upstream of the basin.

Images were produced that contained the percentage of power (%) for each radar data bin located over the basin for both the lowest radar beam angle (0.5 degrees) and the second lowest radar beam angles (1.32 degrees and 1.36 degrees).

Using this same procedure the height of each radar data bin above sea level (MSL) was determined. Images were produced that contained the height of each radar data bin above sea level (MSL) located over the basin for both the lowest radar beam angle (0.5 degrees) and the second lowest radar beam angles (1.32 degrees and 1.36 degrees).

HOURLY TEMPERATURE SERIES

The snowmelt modeling required hourly temperatures at Upper Baker Dam. However, Upper Baker Dam only reports daily maximum and daily minimum temperatures so an algorithm was developed to estimate a serially complete hourly temperature profile at Upper Baker Dam. The algorithm uses a known temperature profile at a nearby, representative station; Stampede Pass, Washington, was used. Each hourly temperature at Stampede Pass was converted into a value that represented the percent of the total daily temperature range (maximum minus minimum). Starting at the hour in which Stampede Pass recorded its lowest temperature, the Upper Baker temperature was assumed to have also been at its minimum for the day. For subsequent hours, the percent change of range was applied to each hour using the previously estimated Upper Baker temperature. This was done until the maximum temperature was reached at Upper Baker (and Stampede Pass), then a new temperature range was computed and the process repeated. Fortunately, the observation forms from Upper Baker Dam indicated the temperature at the time of observation, so this always provided a single known hourly temperature at Upper Baker Dam. If the algorithm did not correctly estimate this temperature, then manual modifications were made to the temperature profile to ensure continuity.

STORM LAPSE RATE ANALYSES

Atmospheric lapse rates were calculated for five (5) heavy rainfall events. These events included the following:

1. November 5 – 11, 1989
2. November 7 – 14, 1990
3. November 21 – 26, 1990
4. November 26 – 30, 1995
5. October 15 – 17, 2003

Lapse rates were calculated by creating a “composite” atmospheric sounding constructed using average values observed by radiosondes launched at the Quillayute, WA (KUIL, 47 57 00, 124 33 00, 56 m). KUIL radiosondes are launched twice a day at 12 UTC and 00 UTC. Three consecutive KUIL radiosonde observations (i.e. 12 UTC, 00 UTC and 12 UTC) taken around the time period that the heaviest rainfall associated with each heavy rainfall event was observed in and around the Baker River basin and were used to construct the “composite” soundings.

Atmospheric variables were determined every 50 mb from 1000 mb to 600 mb. The atmospheric variables included pressure levels (ft-msl), temperature (degrees F), wind direction (degrees) and wind speed (mph).

Lapse rates (degrees F/1000 ft) were calculated every 50 mb and were averaged together to determine the 1000 mb to 600 mb layer lapse rate for each of the five heavy rainfall events. Each of the soundings along with the composite sounding results was provided to Tetra Tech for use in their hydrologic model calibrations.

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 10

ANTECEDENT AND COINCIDENT CONDITIONS FOR PMF ANALYSIS

Tetra Tech, Inc.
March 13, 2006

(FINAL)

INTRODUCTION

This memo summarizes the approach for determining antecedent watershed conditions for the Baker River watershed and antecedent project conditions for Upper Baker Dam and Lower Baker Dam prior to the occurrence of the PMP event. Additionally, coincident meteorological conditions during the PMP event are also presented.

The following categories are discussed in this technical memorandum:

- Antecedent storm and initial reservoir elevations
- Base flow coincident with the PMP
- Antecedent snowpack conditions, including snow water equivalent and snow density
- Antecedent precipitation
- Air temperatures coincident with the PMP
- Wind speeds coincident with the PMP

Where appropriate, the specific values that will be input into the hydrologic or reservoir routing model are presented. For some of the categories, the amount of input data is large and not easily summarized, in which case a sufficient portion of the input data is presented or an example of the input data is presented. For some categories, iterative methods are proposed for determining the critical antecedent conditions (snowpack conditions for instance), in which case the procedure is summarized and examples of the information that will be used to identify critical conditions are presented.

ANTECEDENT STORM AND INITIAL RESERVOIR ELEVATIONS

FERC (2001) states that it is advisable to determine if a water resources agency has conducted special regional studies related to antecedent storms in determining a reasonable starting elevation in the reservoir(s) prior to the occurrence of the PMF. If such a study has been conducted, the results should be considered for application in the PMF study. In the absence of antecedent storm information, FERC (2001) recommends the following four approaches that can be considered as alternatives in developing antecedent conditions relative to the reservoir elevations:

1. Assume the reservoir surface is at a predefined annual maximum level, which for many hydroelectric projects is defined as the annual maximum normal operating level.
2. Use an operating rule curve to identify the reservoir surface corresponding to the maximum storage level for the season of the controlling PMP. For this method, a 100-year, 24 hour storm is assumed to end three days prior to the PMP. The runoff hydrograph associated with the 100-year event is routed through the reservoir using established project operating rule curves.
3. Use a wet-year rule curve to establish the antecedent reservoir level. The average of the five consecutive, highest wet-year reservoir levels occurring during the season of the critical PMP is taken to be the antecedent condition.
4. Analyze historical extreme floods and antecedent storms for the region and develop a storm that could reasonably be expected to occur antecedent to the PMP.

In 1989, the Washington State Department of Ecology conducted a study entitled "*Characteristics of Extreme Precipitation Events in Washington State*" (Schaefer 1989) which included an investigation into the meteorological conditions that prevailed in the 14 day time period prior to the occurrence of historical extreme storms.

The results of the antecedent storm investigation revealed that extreme storms are not typically preceded by an unusual storm. A review of the characteristics of these antecedent events indicated that precipitation events antecedent to extreme storms are of a magnitude which occur numerous times (10 to 20 times) during any given year. Based on the results of the investigation, the selection of antecedent conditions (antecedent precipitation, soil moisture, and initial reservoir levels) prior to an extreme event can be reasonably made by considering the seasonality of the extreme storm and the historical record of pertinent data.

Therefore, combining the findings of Schaefer (1989) and the recommendations made in FERC (2001), the approach that is proposed for determination of initial reservoir elevations at Upper Baker Dam and Lower Baker dam is comprised of three methods. Methods 1 and 2 will be used to establish how sensitive the assumed initial water surface elevation is in determining the resulting PMF hydrograph and maximum reservoir water surface elevation. Once this is complete, then Method 3 will then be used to develop the initial conditions used for the study.

Method 1 - Use the Baker Lake Flood Control Rule Curve in Conjunction with the Interim Protection Plan (IPP)

Upper Baker Dam provides up to 74,000 acre-feet of federally authorized flood control volume according to the rule curve shown in Figure 1. Based on the findings of Schaefer (1989), which indicate that extreme storms are not typically preceded by unusually large storm events, it is not unreasonable to assume that the reservoir elevation in Baker Lake prior to the occurrence of the PMP would be at the normal flood control elevation as indicated in Figure 1 for the months of October through March if the PMP was not preceded by an extreme storm. Under Method 1, the initial reservoir elevation in Baker Lake at the start of the PMP will be assumed equal to the top of the flood control pool (727.8 feet NAVD88) for the months outside of the flood control season.

Under the recently enacted Interim Protection Plan (IPP), Puget Sound Energy (PSE) provides up to a total of 115,000 acre-feet of flood control storage that is allocated between the two reservoirs for the months of October through December. This includes the federally authorized 74,000 acre-feet of flood control storage that is provided at Upper Baker Dam. The remaining 41,000 acre feet can be provided in either reservoir. However, to provide more than 29,000 acre-feet at Lower Baker would require that Lake Shannon be drawn down below the crest of the spillway, which is only a likely scenario during dry years as project releases for elevations less than the crest of the spillway are limited by the 4,500 cfs powerhouse capacity at Lower Baker Dam. Therefore, the assumption for Method 1 is that Lake Shannon is capable of being drawn down to the spillway crest elevation (428.55 feet NAVD 88) at the beginning of the PMF under normal operating procedures for the months of October through December. The draw down schedule would follow that for Upper Baker (Figure 1) with provision of the 29,000 acre-feet during the months of November and December. For all other months Lake Shannon will be conservatively assumed at the normal full pool elevation of 442.4 feet NAVD 88.

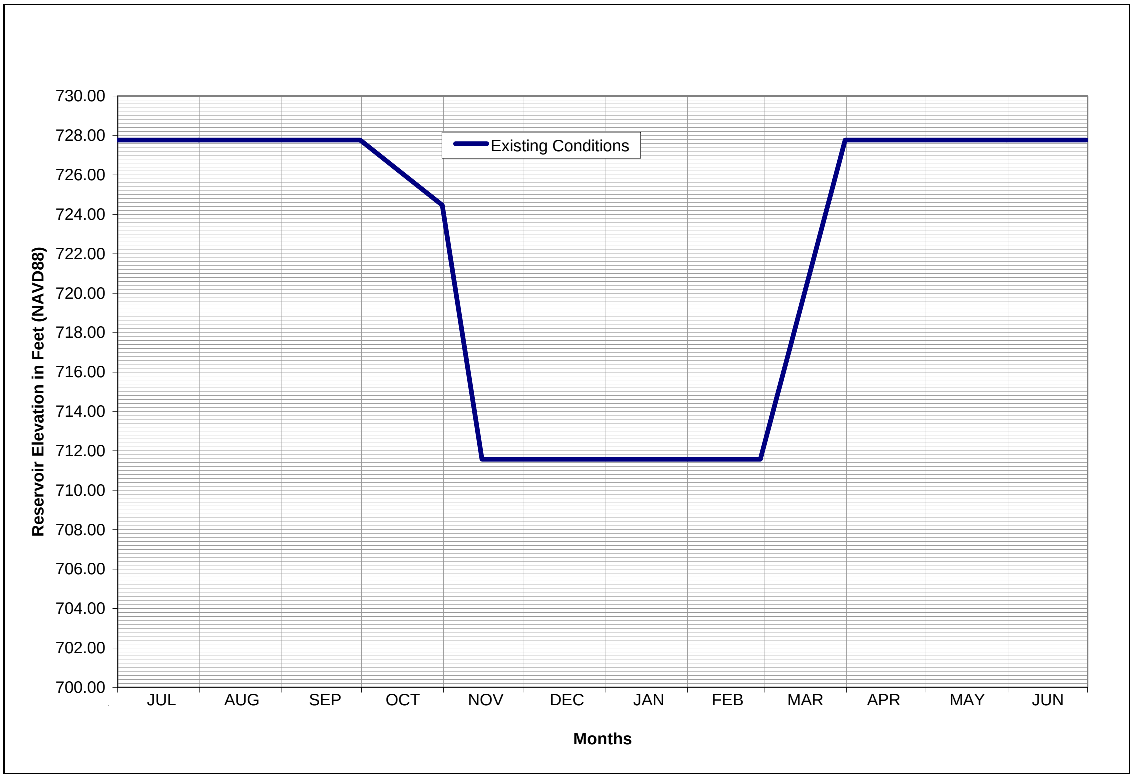


Figure 1. Flood Control Rule Curve for Baker Lake (NAVD88 Datum)

Method 1 is partially predicated on the assumption that the flood control volume in Upper Baker reservoir can be reestablished quickly after an extreme event. To validate this assumption, the project conditions subsequent to the extreme events used in the watershed model calibration were analyzed. A computation was made of the number of days that it took to draw down Upper Baker reservoir after the precipitation event had ceased. The results are summarized in Table 1. This was done for each of the calibration events that occurred during the flood control season, and as such the OCT 03 event was not included.

Table 1.
Upper Baker Reservoir Draw Down Following Historical Extreme Storm Events

Storm Event	Day and Time Precipitation Event Ended	Day and Time Upper Baker Reservoir was at Flood Control Elevation	Number of Hours / Days to Drawdown
NOV 89	11/10/89 1200 hrs	11/16/89 0300 hrs	135 hrs / 5.6 days
NOV 90 (1)	11/14/90 0100 hrs	11/22/90 0200 hrs	193 hrs / 8.0 days
NOV 90 (2)	11/24/90 1500 hrs	12/7/90	approx. 13 days
NOV 95 (1)	11/8/95 1400 hrs	11/19/95 2100 hrs	271 hrs / 11.3 days
NOV 95 (2)	11/29/95 1200 hrs	12/03/95 2000 hrs	104 hrs / 4.3 days

Note: Hourly reservoir elevation data not available for NOV 90 (2) event, so day and time that Upper Baker reservoir was at Flood Control was based on mean daily data

On average, it took 8.4 days for Upper Baker reservoir to be drawn back down to the 711.6 foot (NAVD 88) flood control elevation. This may be a slight overestimate of the elapsed time for several reasons. First off, reservoir evacuation at the Baker River project typically begins soon after the main stem Skagit River has crested (USACE 2000), which in most cases would occur after the time the precipitation event had ended. Secondly, evacuation during the events included in Table 1 may have proceeded somewhat conservatively so as to prevent increased flood problems in the Skagit River valley. According to USACE (2000), rapid evacuation could be authorized if “weather conditions threaten renewed flooding”, which would indicate that evacuation of the reservoir could have been conducted quicker if conditions indicated another extreme event was soon to follow.

It therefore does not seem unreasonable to assume that on the average, Upper Baker reservoir would be back to flood control elevation in a time period less than 8.4 days, based on the analysis of extreme events, and perhaps even quicker after less extreme events.

Method 2 – Assume Both Reservoirs are at Maximum Elevation

In Method 2 both reservoirs will be set at the statistically determined maximum value for the month of interest. These initial reservoir elevations correspond to the maximum monthly mean daily reservoir elevations as summarized in Tables 2 and 3 for the period of record from 1977 to the present. For most months, this maximum value is equal to the top of the flood control pool for Upper Baker Dam and the normal full pool for Lower Baker Dam. This method assumes that the effect of any antecedent storm is accounted for with the high reservoir elevation and is consistent with the first approach proposed in Section 8-9.2.1 of FERC (2001).

Method 3 – Use a Probabilistic Assessment of Historical Mean Daily Reservoir Elevations

Once the upper and lower bounds of the initial reservoir elevation have been tested in Methods 1 and 2, it will be known how sensitive the routed PMF hydrograph is to assumed initial reservoir elevation. Method 3 will then be used to develop a historically based, yet sufficiently conservative estimate of the initial reservoir elevations for each month using historical mean daily reservoir elevation data for Upper Baker and Lower Baker Dams.

A probabilistic analysis of historical mean daily reservoir elevations at both Upper Baker and Lower Baker dams will provide the basis for this estimate. Mean daily reservoir elevation data were compiled and statistically analyzed. Only data from 1977 to the present was included in the analysis since this is the time period when the full 74,000 acre-feet of flood control volume has been provided at Upper Baker Dam.

Maximum mean daily reservoir elevations were determined by month for both reservoirs for the 29 year partial period of record. The data were compiled in Excel and standard statistics were computed for each month. The results of the analysis are included in Tables 2 and 3.

For each month, the 29 values were then ranked using the Cunnane plotting position formula and probability plots were developed. An example plot for the month of November for Upper Baker Dam is included as Figure 2. It is proposed that for Method 3, a conservative value of 0.80 be assumed for the non-exceedance probability value for determining the initial reservoir elevations.

Table 2.
Statistical Analysis of Mean Daily Reservoir Elevations (feet) at Baker Lake, by Month, 1977 to 2005

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
Maximum	727.9	726.6	727.3	727.2	723.3	718.3	727.0	727.5	727.7	728.0	727.8	727.6
Minimum	713.6	703.0	695.0	695.6	683.1	682.1	683.4	695.4	719.3	723.5	722.7	718.5
Mean	723.4	717.9	709.9	707.4	702.2	703.0	705.5	718.6	725.7	726.9	726.3	725.2
Standard Deviation	4.08	6.32	6.73	7.95	9.39	10.01	11.99	9.39	2.29	0.93	1.43	2.45

Elevations reference NAVD 88 Datum
Top of Flood Pool = 727.8 feet
Bottom Elevation of Flood Control Pool = 711.6 feet
Crest Elevation of Spillway = 697.8 feet

Table 3.
Statistical Analysis of Mean Daily Reservoir Elevations (feet) at Lake Shannon, by Month, 1977 to 2005

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
Maximum	442.3	442.3	442.3	442.3	441.5	439.5	441.5	442.22	442.33	442.4	442.4	442.4
Minimum	412.0	424.6	426.7	418.6	396.2	401.5	407.4	410.91	417.04	437.4	430.3	408.9
Mean	437.8	438.6	437.5	432.9	426.8	422.5	422.4	428.11	436.83	441.1	439.8	436.8
Standard Deviation	6.81	4.70	4.41	6.24	12.71	12.03	10.85	9.78	7.78	1.37	3.29	8.69

Elevations reference NAVD 88 Datum
Normal Full Pool = 442.4 feet
Crest Elevation of Spillway = 428.6 feet

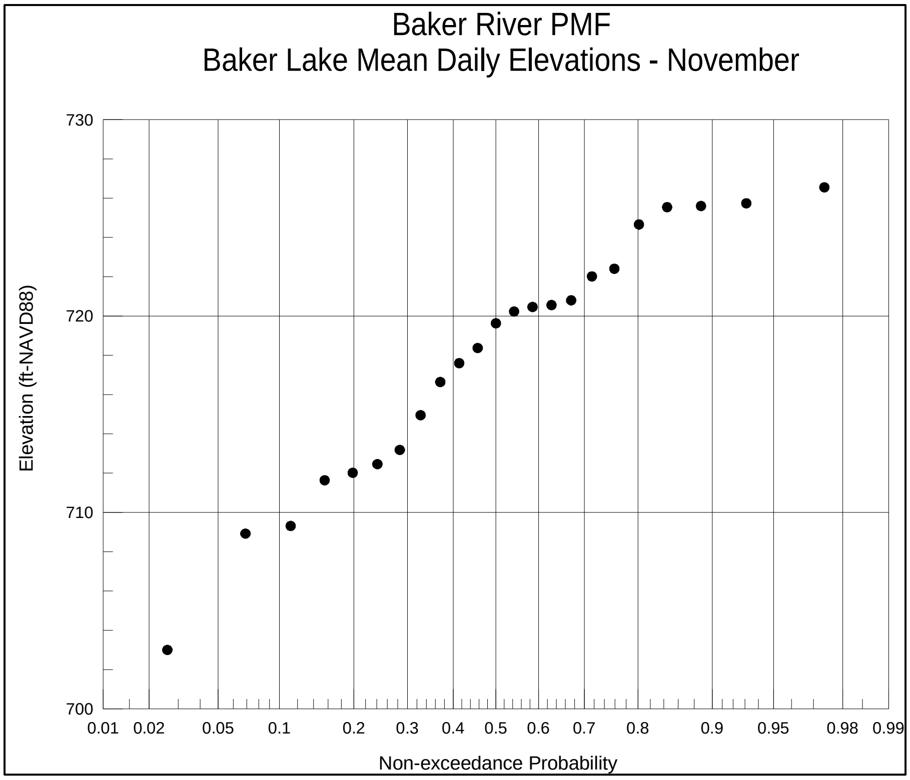


Figure 2. Magnitude Frequency Relationship for Maximum Mean Daily Reservoir Elevations at Upper Baker Dam for the Month of November

BASE FLOW COINCIDENT WITH PMP

As per Section 8-9.4 of FERC (2001), the base flow at the start of the PMP event was determined by computing the average monthly flow for the critical PMF season as recorded at the Baker

River at Concrete Gage (USGS 12193500). The computed baseflow values were allocated based on the ratio of drainage area of the Upper Baker portion of the watershed and the Lower Baker portion of the watershed to the total watershed area.

Table 4 summarizes the average monthly flow rate for the total watershed as determined for the Baker River at Concrete Gage (USGS 12193500). Also included in Table 4 is the approximate magnitude of the computed base flow for both the Upper Baker portion of the watershed (218.8 mi^2) and the Lower Baker portion of the watershed (83.9 mi^2).

Table 4.
Baker River Watershed, Upper Baker Tributary Area and Lower Baker Tributary Area
Base Flow Rate (cfs) Coincident with PMP

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
Total	2,490	3,353	2,883	2,737	2,485	2,101	1,974	2,774	3,716	3,274	2,116	1,823
UB	1,790	2,411	2,073	1,968	1,787	1,511	1,419	1,995	2,672	2,354	1,521	1,311
LB	700	942	810	769	698	590	555	779	1,044	920	595	512

UB = Upper Baker Tributary Area
LB = Lower Baker Tributary Area

ANTECEDENT SNOWPACK CONDITIONS

The determination of the antecedent snowpack conditions, which include snow water equivalent (SWE) and density (SD), will require iterative execution of the hydrologic model to determine reasonable critical conditions for the months of interest. These iterations will be performed after the model calibration and verification have been performed and accepted. This section presents the methodologies proposed to develop the antecedent snowpack conditions and analysis of data that will support the development of the antecedent snowpack conditions.

It is proposed that the determination of antecedent conditions relative to the snow water equivalent in the snowpack be conducted based on a probabilistic methodology and that the determination of antecedent conditions relative to the snowpack density be conducted using typical, or average, conditions.

Snow Water Equivalent

Observations of snowpack depth, snow water equivalent, and snowpack density were collected at each of the nine snow course stations in the watershed dating from 1959 through the late 1970's. This nearly twenty years of collected data provided Puget Sound Energy (PSE) with information regarding average snow density and the range of snow density for each month of the season.

Subsequent to the late 1970's, only snowpack depth was measured based on observed snow depth at the aerial markers. Estimates of snow water equivalent and snow density were then made using the historical record of snow density and were adjusted to account for antecedent precipitation.

Snowpack conditions for the end-of-October and the end-of-November are not available from field observations. In lieu of field data for these two months, model output from PSE's Hydrologic Forecast Analysis Model (HFAM) was used (Hydrocomp 2000). The HFAM model has been shown to correlate fairly well with observed winter snowpack conditions (personal communication Netik 2005) and therefore provided a reasonable source of information for snowpack conditions for the end-of-October time period and the end-of-November time period.

The general methodology for determining antecedent snow water equivalent conditions for the PMF study will involve the process of iteratively searching for a collection of snow water equivalent magnitudes at the various zones of elevation and mean annual precipitation that will yield the greatest volumetric runoff contribution to the PMF hydrograph. As the basis for this methodology, snow water equivalent values will be determined for each combination of zone of elevation and mean annual precipitation that corresponds with a common exceedance probability. Varying magnitudes of exceedance probability will be tested to determine the critical exceedance probability. It is anticipated that there will be a point in this iterative method where a snowpack associated with a higher non-exceedance probability (i.e. a deeper pack with higher snow water equivalent) will not result in significantly more runoff volume from the basin. Additionally, it is possible that a larger pack could actually reduce the runoff due to the ability to store precipitation during the process of snowpack ripening. As such, a deeper pack (such as the 100-year return period snowpack) may not actually produce the critical runoff volume.

The following steps summarize the method that will be used to determine the critical antecedent snow water equivalent conditions prior to the onset of the PMP events for each of the months included in the analysis:

1. End-of-month magnitude-frequency relationships were developed for snow water equivalent for each of the nine snow course station within the basin, using either historical measurements or HFAM model output. Historical observations were used for the end-of-month plots for the months of December through May and HFAM model output was used to develop end-of-month plots for October and November. The magnitude frequency estimates were developed for the conditions when snow was on the ground. Snow-free conditions were not included in the analysis. Figure 3 shows an example of such a magnitude frequency relationship.
2. For the month of interest, an initial value of the non-exceedance probability will be assumed
3. The snow water equivalent associated with this non-exceedance probability will be determined for each snow course station from magnitude frequency plots.
4. The nine snow course stations range in elevation between 2,100 feet and 5,800 feet, and each is located within a different zone of mean annual precipitation. Therefore, the predicted values of snow water equivalent will be normalized to a common value of mean annual precipitation. The median value of the lowest mean annual precipitation zone (67

inches) will be used to normalize the computed snow water equivalent values, resulting in elevation as being the independent variable.

5. The normalized snow water equivalent values will then be plotted versus elevation and the data points will be fit to a logarithmic relationship. An example of such a plot is shown as Figure 4 for the 0.80 non-exceedance probability for the end-of-December time period.
6. Using the plot of normalized snow water equivalent versus elevation, the magnitude of snow water equivalent will be determined for all zones of mean annual precipitation and elevation.
7. The hydrologic model will then be run for the 72-hour duration general storm PMP to quantify the magnitude of runoff contribution from the snowpack.
8. Increasing values of non-exceedance probability (i.e. deeper and wetter snowpacks) will be incrementally tested until the critical non-exceedance probability is identified for the month of interest. The critical non-exceedance probability may be different for different months.

This approach is a technically sound approach that is consistent with the intentions of Section 8-9.2.2 of FERC (2001) which state that the assumed snow water equivalent should be that which could reasonably be expected to occur antecedent to the PMP. FERC (2001) also states in Section 8-9.2.2 that “if snowpack is apt to exist in at least part of the drainage basin in the season when the critical PMP would occur, an antecedent 100-year snowpack should be assumed to exist at the time when the PMP occurs”. The above approach will identify whether the 100-year snowpack is indeed the critical snowpack.

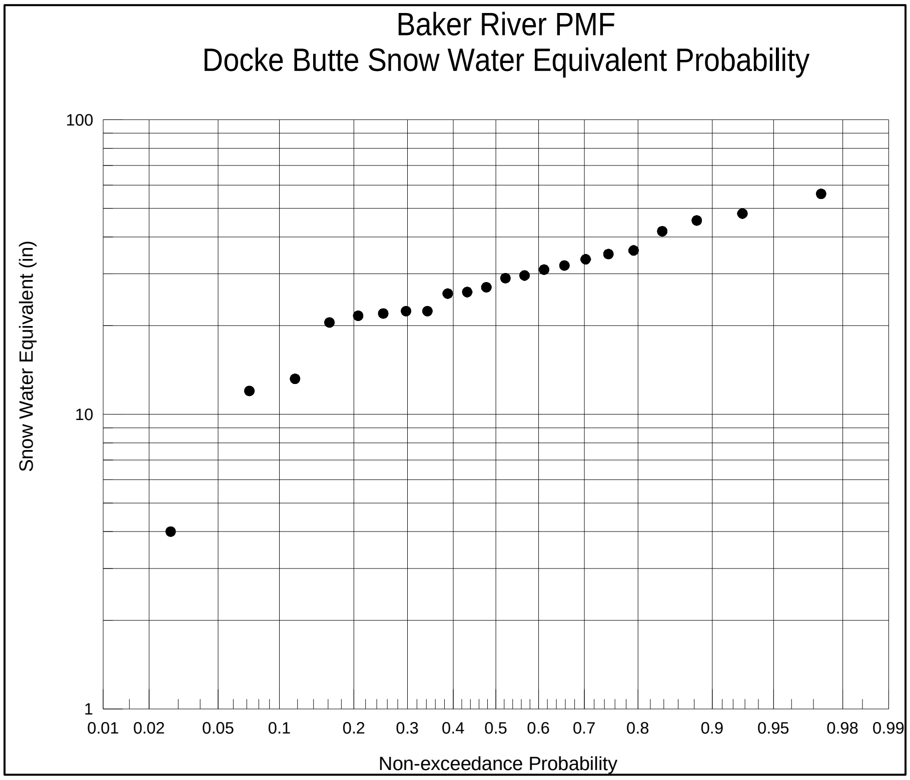


Figure 3. SWE Magnitude Frequency Relationship for End-of-December at Dock Butte Snow Course Station

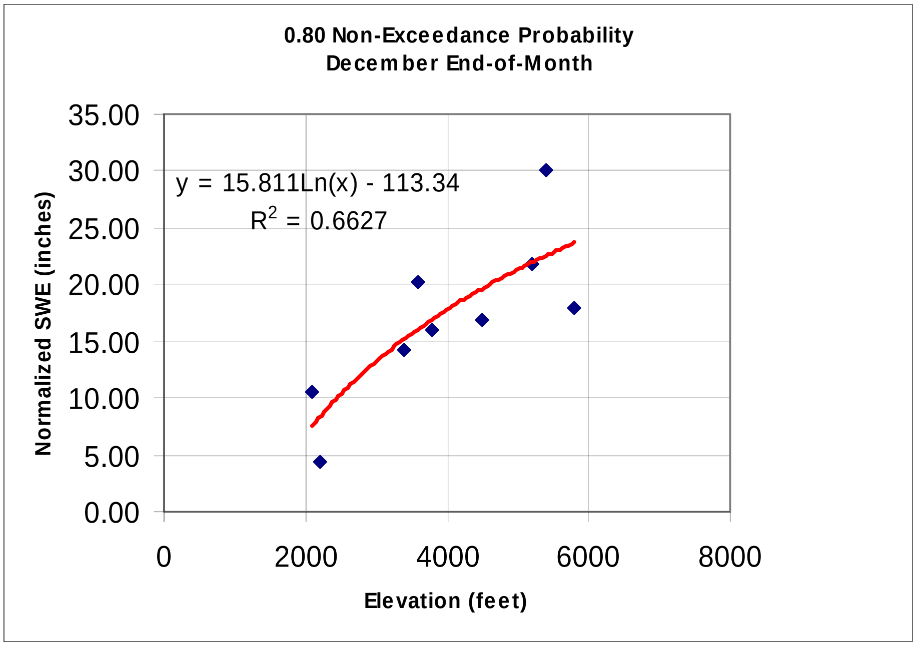


Figure 4. December End-of-Month Snow Water Equivalent Associated with 0.80 Non-Exceedance Probability

Snowpack Density

As previously mentioned, snowpack density observations were made at each of the nine snow course stations in the watershed for the first twenty years of the snow course program. Subsequent to the first twenty years, snowpack density on a given observation day was based on the historical record of snow density with adjustments to account for antecedent meteorological conditions. Observations were recorded starting at the end of December and continuing until the end of May.

HFAM model output was initially considered to be used to augment the snow course observations to include the end-of-October time period and the end-of-November time period. However, it was found that the snowpack densities that were output from the HFAM model for the end of October and end of November time periods were problematic and in many cases unrealistically high. Therefore HFAM model output for the end-of-October and end-of-November time periods was not included in the snowpack density analysis.

The general methodology for determining antecedent snowpack density for the PMF analysis will be to use mean values of the end-of-month snow density as the basis for determining the variation in snowpack density throughout the watershed. Table 5 summarizes the end-of-month snowpack density at each of the snow course stations.

For each end-of-month time period, the average snowpack density was plotted against station elevation, using the information from the snow course stations. A 2nd order polynomial trend line was fit to the data as shown in Figure 5. As seen in Table 4 and Figure 5, snowpack density appears to be independent of elevation, but does appear to vary seasonally. Therefore the density of the antecedent snowpack will be computed as the mean value of the nine snow course stations for the month of interest, resulting in an estimate of snowpack density that will not vary according to elevation. For the months of October and November, the computed mean value for December will be used.

Table 5.
Average End-of-Month Snowpack Density (in/in)

	Snow course Station and Elevation (in feet)								
Month	Rocky Creek 2,100	SF Thunder 2,200	Schreibers Meadow 3,400	Marten Lake 3,600	Dock Butte 3,800	Watson Lake 4,500	Easy Pass 5,200	Jasper Pass 5,400	Mt Blum 5,800
OCT	---	---	---	---	---	---	---	---	---
NOV	---	---	---	---	---	---	---	---	---
DEC	0.35	0.34	0.37	0.35	0.36	0.35	0.36	0.34	0.35
JAN	0.39	0.39	0.39	0.39	0.40	0.39	0.38	0.39	0.38
FEB	0.41	0.38	0.42	0.41	0.42	0.41	0.42	0.41	0.41
MAR	0.44	0.39	0.44	0.43	0.43	0.42	0.43	0.42	0.42
APR	0.48	0.50	0.49	0.48	0.48	0.47	0.47	0.47	0.47
MAY	0.55	n/a	0.54	0.56	0.54	0.54	0.55	0.55	0.55

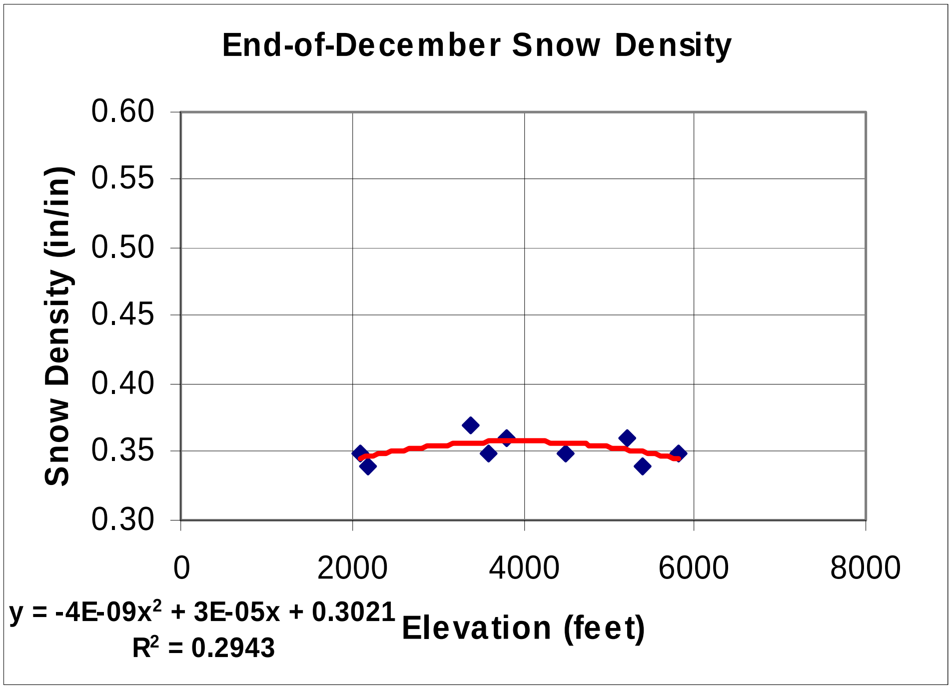


Figure 5. Snowpack Density vs. Elevation for End-of-January

ANTECEDENT PRECIPITATION

It will be assumed that the initial soil moisture conditions prior to the occurrence of the PMP event will result from a typical water year. This will result in near saturated conditions for the soils in the watershed for the late fall months and for the winter months. Initial soil moisture conditions at the onset of the PMP will be computed using soil moisture budgeting algorithms within the hydrologic model. Input to the soil moisture budgeting algorithm includes average values of the cumulative end-of-month precipitation for each of the eight zones of mean annual precipitation in the hydrologic model, as determined from an analysis of the historical precipitation record at the Upper Baker Dam precipitation station.

The proposed methodology for determining antecedent precipitation for input to the soil moisture budgeting algorithm is as follows:

1. Compute monthly precipitation for the Upper Baker Dam gaging station for each year of the period of record.
2. Rearrange the monthly precipitation values to represent cumulative end-of-month precipitation using October 1st (the start of the water year) as the starting point.
3. Compute average values of the cumulative end of month precipitation for each month of the water year. Table 6 summarizes these values.
4. The Upper Baker Dam precipitation gage is located within Mean Annual Precipitation (MAP) Zone 3 of the hydrologic model. The median value of the mean annual precipitation for this zone is 102”. Therefore, the cumulative values presented in Table 5 will be adjusted to all other zones of mean annual precipitation using a ratio of the mean annual precipitation for the MAP zone to the mean annual precipitation at the Upper Baker Dam precipitation gage.

The final product is average values of the cumulative end-of-month precipitation for each of the eight zones of mean annual precipitation.

Table 6.
Average Values of the Cumulative End-of-Month Precipitation at Upper Baker Dam for the Period of Record (inches)

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
9.94	25.41	40.86	55.40	66.42	76.15	82.65	87.54	91.29	93.88	96.20	100.75

Notes: Cumulative precipitation based on data from WY1966 through WY2004.

AIR TEMPERATURES COINCIDENT WITH PMP

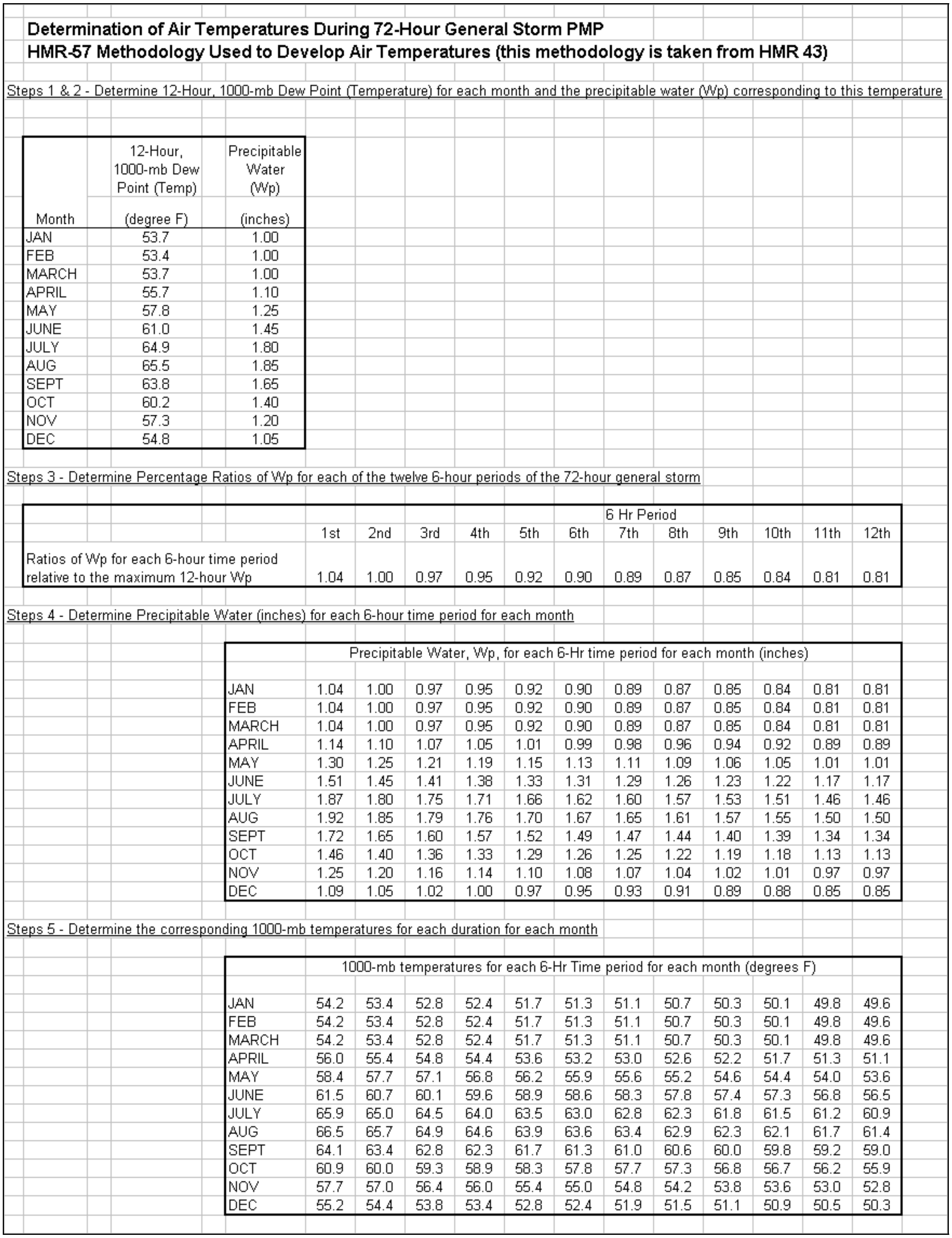
The methodology outlined in HMR 57 for deriving air temperatures coincident with the PMP was followed. This methodology was originally presented in HMR 43 and is based on the assumption of a saturated pseudo-adiabatic atmosphere and the use of 12-hour maximum persisting dewpoints temperatures.

The methodology is summarized in the following steps:

1. Obtain 12-hour maximum persisting 1000-mb dew point temperature for each month from monthly isotemperature mapping
2. Determine the corresponding magnitude of precipitable water (Wp) associated with each of the monthly 12-hour maximum persisting 1000-mb dewpoint temperatures
3. Determine the durational variation of Wp (relative to the maximum 12-hour value of Wp) throughout the course of the 72 hour storm duration. This is done for each of the 6-hour segments.
4. Compute the absolute value of Wp for each of the 6-hour segments
5. Determine the magnitude of the 1000-mb dewpoint temperature corresponding for each of the 6-hour segments.

The results of applying this method to the Baker River project site are summarized in Figure 6.

The final two steps for determining the air temperature time sequence for the 72 hour duration general storm include rearranging the air temperatures shown at the bottom of Figure 6 to conform to the temporal distribution of the PMP. The highest 6-hour duration air temperature would occur during the highest 6-hour period of rainfall and the lowest 6-hour duration air temperature would occur during the lowest 6-hour period of rainfall. Finally, the air temperature time series would then be adjusted for elevation. For the Baker River watershed, there are eight elevation zones, and therefore, the 1000-mb air temperature time series would be adjusted to the median value of each of the elevation zones. A constant lapse rate of 2.6 degrees per 1,000 feet will be used to adjust air temperature to higher elevations, as per HMR 57 guidelines. This lapse rate is consistent with the lapse rates used in the Baker River watershed model calibration that were computed from radiosonde data (Tetra Tech 2006). For the four storm events that were included in the calibration, the computed lapse rate from approximately sea level to the freezing elevation ranged between 1.9 and 2.9 degrees per 1,000 feet.



Determination of Air Temperatures During 72-Hour General Storm PMP
HMR-57 Methodology Used to Develop Air Temperatures (this methodology is taken from HMR 43)

Steps 1 & 2 - Determine 12-Hour, 1000-mb Dew Point (Temperature) for each month and the precipitable water (Wp) corresponding to this temperature

Month	12-Hour, 1000-mb Dew Point (Temp) (degree F)	Precipitable Water (Wp) (inches)
JAN	53.7	1.00
FEB	53.4	1.00
MARCH	53.7	1.00
APRIL	55.7	1.10
MAY	57.8	1.25
JUNE	61.0	1.45
JULY	64.9	1.80
AUG	65.5	1.85
SEPT	63.8	1.65
OCT	60.2	1.40
NOV	57.3	1.20
DEC	54.8	1.05

Steps 3 - Determine Percentage Ratios of Wp for each of the twelve 6-hour periods of the 72-hour general storm

	6 Hr Period											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
Ratios of Wp for each 6-hour time period relative to the maximum 12-hour Wp	1.04	1.00	0.97	0.95	0.92	0.90	0.89	0.87	0.85	0.84	0.81	0.81

Steps 4 - Determine Precipitable Water (inches) for each 6-hour time period for each month

	Precipitable Water, Wp, for each 6-Hr time period for each month (inches)											
JAN	1.04	1.00	0.97	0.95	0.92	0.90	0.89	0.87	0.85	0.84	0.81	0.81
FEB	1.04	1.00	0.97	0.95	0.92	0.90	0.89	0.87	0.85	0.84	0.81	0.81
MARCH	1.04	1.00	0.97	0.95	0.92	0.90	0.89	0.87	0.85	0.84	0.81	0.81
APRIL	1.14	1.10	1.07	1.05	1.01	0.99	0.98	0.96	0.94	0.92	0.89	0.89
MAY	1.30	1.25	1.21	1.19	1.15	1.13	1.11	1.09	1.06	1.05	1.01	1.01
JUNE	1.51	1.45	1.41	1.38	1.33	1.31	1.29	1.26	1.23	1.22	1.17	1.17
JULY	1.87	1.80	1.75	1.71	1.66	1.62	1.60	1.57	1.53	1.51	1.46	1.46
AUG	1.92	1.85	1.79	1.76	1.70	1.67	1.65	1.61	1.57	1.55	1.50	1.50
SEPT	1.72	1.65	1.60	1.57	1.52	1.49	1.47	1.44	1.40	1.39	1.34	1.34
OCT	1.46	1.40	1.36	1.33	1.29	1.26	1.25	1.22	1.19	1.18	1.13	1.13
NOV	1.25	1.20	1.16	1.14	1.10	1.08	1.07	1.04	1.02	1.01	0.97	0.97
DEC	1.09	1.05	1.02	1.00	0.97	0.95	0.93	0.91	0.89	0.88	0.85	0.85

Steps 5 - Determine the corresponding 1000-mb temperatures for each duration for each month

	1000-mb temperatures for each 6-Hr Time period for each month (degrees F)											
JAN	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
FEB	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
MARCH	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
APRIL	56.0	55.4	54.8	54.4	53.6	53.2	53.0	52.6	52.2	51.7	51.3	51.1
MAY	58.4	57.7	57.1	56.8	56.2	55.9	55.6	55.2	54.6	54.4	54.0	53.6
JUNE	61.5	60.7	60.1	59.6	58.9	58.6	58.3	57.8	57.4	57.3	56.8	56.5
JULY	65.9	65.0	64.5	64.0	63.5	63.0	62.8	62.3	61.8	61.5	61.2	60.9
AUG	66.5	65.7	64.9	64.6	63.9	63.6	63.4	62.9	62.3	62.1	61.7	61.4
SEPT	64.1	63.4	62.8	62.3	61.7	61.3	61.0	60.6	60.0	59.8	59.2	59.0
OCT	60.9	60.0	59.3	58.9	58.3	57.8	57.7	57.3	56.8	56.7	56.2	55.9
NOV	57.7	57.0	56.4	56.0	55.4	55.0	54.8	54.2	53.8	53.6	53.0	52.8
DEC	55.2	54.4	53.8	53.4	52.8	52.4	51.9	51.5	51.1	50.9	50.5	50.3

Figure 6. Determination of 1000-mb Air Temperatures

WIND SPEEDS COINCIDENT WITH PMP

Wind speeds for each month were determined using the methodology outlined in HMR 57.

The methodology is summarized in the following steps:

1. Convert the basin average elevation to pressure using the pressure-height relationship in Figure 15.33 in HMR 57.
2. Determine the January maximum free-air wind speed associated with the basin average elevation for the 1-hour duration. For the Baker River basin, this value was computed as 80 knots.
3. Determine the seasonal (monthly) variation of the January maximum free-air wind speed (expressed as a percent of the January value) using the seasonal variation figure in HMR 57.
4. Multiply the seasonal variation percentage from Step 3 by the January maximum free-air wind speed to obtain the maximum free-air wind speed for each month.
5. Obtain the durational adjustment factors
6. Multiply the maximum 1-hour wind speeds from Step 4 by the duration adjustment factors from Step 5 to wind speeds for each of the 6-hour durations of the 72-hour storm.

Table 7 summarizes the anemometer-level wind speeds for each 6 hour time period for each month. As per HMR57 these wind speeds will be rearranged to conform to the temporal distribution of the PMP. The highest 6-hour duration wind speeds would occur during the highest 6-hour period of rainfall and the lowest 6-hour duration wind speeds would occur during the lowest 6-hour period of rainfall.

Table 7.
Monthly Anemometer-Level Wind Speeds (knots) for
Each 6-Hour Time Period Coincident with the PMP

Month	6-Hour Time Period Increments											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
OCT	43	39	35	33	30	29	27	25	24	24	23	23
NOV	49	44	40	37	35	33	31	29	28	27	26	26
DEC	52	48	43	40	38	35	33	31	30	30	29	28
JAN	55	50	46	43	40	37	35	33	32	31	30	29
FEB	52	48	43	40	38	35	33	31	30	30	29	28
MAR	49	44	40	37	35	33	31	29	28	27	26	26
APR	41	38	34	32	30	28	26	25	24	23	23	22
MAY	36	33	30	28	26	24	23	21	21	20	20	19
JUN	30	27	25	23	21	20	19	18	17	17	16	16
JUL	28	25	23	21	20	19	17	17	16	16	15	15
AUG	28	26	23	22	20	19	18	17	16	16	15	15
SEPT	28	25	23	21	20	19	17	17	16	16	15	15

SUMMARY

Baker River watershed conditions and Upper Baker Dam and Lower Baker Dam project conditions antecedent to the PMP event were presented. Additionally, coincident meteorological conditions during the PMP event were also presented. The following categories were included in this memo:

- Initial Reservoir Elevations - Three methods were proposed for determining initial reservoir elevations in the two reservoirs. Two of the methods were included to determine the sensitivity of the assumption on the PMF.
- Base Flow – The base flow during the PMF will be equal to the Baker River average monthly flow for the critical PMF season
- Antecedent Snowpack Conditions – A methodology for determining the snowpack conditions antecedent to the PMP was proposed, based on an iterative execution of the hydrologic model to determine reasonable critical conditions for the months of interest
- Antecedent Precipitation – It was proposed that the initial soil moisture conditions prior to the occurrence of the PMP event will result from a typical water year
- Air Temperatures Coincident with the PMP – The methodology outlined in HMR 57 for deriving air temperatures coincident with the PMP was utilized.
- Wind Speeds Coincident with the PMP – The methodology outlined in HMR 57 for deriving wind speeds coincident with the PMP was utilized.

REFERENCES

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

Hydrocomp, Inc. 2000. *Baker River Watershed Model – Final Project Report*. Prepared for Puget Sound Energy by Hydrocomp, Inc.

Netik, Irena. Personal Communication via Email. March 31st, 2005.

Schaefer M.G. 1989. *Characteristics of Extreme Precipitation Events in Washington State*. Washington State Department of Ecology, Water Resources Program, 89-51.

Tetra Tech, Inc. 2006. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 7 Revision No. 1 – Model Calibration and Verification.* Technical Memorandum prepared for Puget Sound Energy dated March 15, 2006.

United States Army Corps of Engineers (USACE). 2000. *Baker River Project Water Control Manual.* Seattle District US Army Corps of Engineers.

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 11

PMF RESULTS AND GLOBAL SENSITIVITY ANALYSIS

Tetra Tech, Inc.
June 20, 2006
Revised December 29, 2006
Revised March 19, 2007
Revised May 11, 2007

(FINAL)

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1 INTRODUCTION

This technical memorandum describes and documents the development of inflow and outflow PMF hydrographs for Upper Baker and Lower Baker reservoirs, resulting from the probable maximum precipitation (PMP) and the associated antecedent conditions. The work was performed as part of the Baker River Project Part 12 PMP/PMF Study. The PMF analysis documented in this technical memorandum was essentially conducted in three steps, using FERC engineering guidelines (FERC 1993, FERC 2001) and methodologies outlined in *Hydrometeorological Report No. 57* (HMR-57; NWS 1994) throughout.

The first step utilized a deterministic approach to develop an initial estimate of the PMF. According to FERC guidelines, in the deterministic approach, "a flood hydrograph is generated by modeling the physical atmospheric and drainage basin hydrologic and hydraulic processes. The approach attempts to represent the most severe combination of meteorologic and hydrologic conditions considered reasonably possible for a given drainage basin" (FERC 1993). In application to the Baker River project, seasonal PMP volumes were derived in accordance with the standard methodologies outlined in HMR-57. The coincident and antecedent meteorologic and hydrologic conditions were then identified and a range of discrete values for each condition were selected for analysis. The hydrologic and reservoir routing model were then executed, and the model results were reviewed so as to identify the most conservative results from the discreet model runs that were executed. Throughout this technical memorandum, these results are referred to as the initial PMF results, which are characterized as a combined product of conservative, yet reasonable, estimates of the coincident and antecedent meteorologic and hydrologic conditions.

The initial PMF inflow hydrographs were developed for each reservoir using the calibrated hydrologic model for the Baker River watershed (Tetra Tech 2006a). Outflow hydrographs were developed using the HEC-5 flood control simulation model developed for the Skagit River watershed by the Seattle District Corps of Engineers.

After completion of the initial PMF analysis, the results were presented to the Board of Consultants (BOC) on June 27, 2006. Upon review of the results, the BOC pointed out the possibility of compounding conservatism that is inherent when assuming conservative estimates for each of the coincident and antecedent meteorologic and hydrologic conditions. A global sensitivity analysis (GSA) was recommended to evaluate the level of conservatism inherent in the initial estimate of PMF and to evaluate the effect of the various hydrometeorological input parameters on flood response (inflow hydrographs) and on reservoir response (outflow hydrographs). A GSA was conducted instead of a more traditional single-variable sensitivity analysis in order to more thoroughly evaluate the range of parameter values and to preserve the dependencies that physically exist between parameters. For example, a strong correlation has been shown to exist between antecedent snow water equivalent and antecedent precipitation, and the GSA maintains this dependency. The concept of the GSA is explained in detail in Section 7. The objectives of the GSA were as follows:

- Identify the parameters to which flood response and reservoir response are most sensitive;
- Qualitatively evaluate each identified parameter's influence on model output and develop a relative ranking of parameter sensitivity;
- Develop a probabilistic characterization of the range of PMP produced floods that are possible for the various combinations of hydrometeorological input parameters;
- Provide guidance in the selection of antecedent and coincident conditions that represent a conservative yet reasonable parameter set for the final PMF.

The probabilistic characterization that was produced from the GSA was used to evaluate the reasonableness or conversely the conservativeness of the initial PMF results relative to the range of PMP produced flood magnitudes that are possible. Since the initial PMF results were based on conservative estimates for each of the coincident and antecedent meteorologic and hydrologic conditions, it was found that the initial PMF was indeed characterized by compounding conservatism resulting in an overly conservative estimate of the PMF. Therefore, alternative magnitudes for specific values of hydrometeorological input parameters were proposed to minimize this conservatism. Consistency with FERC engineering guidance and historical data was maintained in selecting the final set of input parameters.

The final step was to run the hydrologic model and reservoir routing model using the final set of input parameters. The probabilistic characterization that was produced from the GSA was again used to evaluate the conservativeness of the final PMF results relative to the range of PMP produced flood magnitudes that are possible.

The supporting information and analyses for each of these steps is presented in distinct sections of this technical memorandum. The sections are summarized as follows:

- Section 2 – Development of the probable maximum precipitation (PMP)
- Section 3 – Antecedent and coincident conditions for the initial PMF analysis
- Section 4 – Hydrologic modeling of the PMP event to produce the initial PMF inflow hydrographs
- Section 5 – Reservoir routing analysis for the initial PMF inflow hydrographs
- Section 6 – Presentation of initial PMF results
- Section 7 – Global sensitivity analysis, recommendations for final modeling parameters and presentation of the final PMF results based on the recommended parameters

2 PMP

Seasonal PMP volumes were derived in accordance with the standard methodology outlined in *Hydrometeorological Report No. 57* (HMR-57; NWS 1994). The details regarding the derivation of the seasonal PMP volumes relative to the Baker River watershed are presented in Tetra Tech (2006b).

HMR-57 uses areal reduction factors to convert the 10-mi^2 index PMP estimate to a corresponding PMP estimate for the drainage basin of interest. The 298.7 mi^2 Baker River watershed can be subdivided into two separate drainage areas, each of which is tributary to one of the two reservoirs. The drainage area tributary to the Upper Baker reservoir is 214.8 mi^2 and the drainage area that is locally tributary to the Lower Baker reservoir is 83.9 mi^2. As documented in Tetra Tech (2006b), areal reduction factors for the 298.7 mi^2 watershed were determined in accordance with computation procedures outlined in HMR-57, which represented the condition of the general storm centered over the watershed.

Areal reduction factors were also computed for the 214.8 mi^2 tributary area upstream of Upper Baker Dam, to represent a condition where the general storm is centered over the Upper Baker tributary area. Likewise, areal reduction factors were determined for the 83.9 mi^2 Lower Baker tributary area, to represent the condition where the general storm is centered over the Lower Baker tributary area.

2.1 SPATIAL DISTRIBUTION

The Baker River watershed is subdivided into sixteen subbasins in the hydrologic model. It was therefore necessary to compute subbasin average seasonal PMP volumes for each of the subbasins. FERC (2001) recommends several options for spatial distribution of the PMP in watersheds where orographic influence is strong, such as is the case for the Baker River watershed. Options include isohyetal maps developed from historical storm events, from mean annual precipitation studies, or from 50-year or longer return period precipitation studies.

As originally proposed in Tetra Tech (2006b), the 100-year 24-hour precipitation map developed by Schaefer et al. (2006) was used as the base map to spatially distribute the basin average PMP volumes throughout the watershed. The resolution of the grid system in this base map is 30 arc-seconds, which represents a nominal resolution of 800 meters. The methodology used to determine the subbasin average PMP volumes for each season and each of the three general storm centering scenarios is described in Tetra Tech (2006b).

The 100-year, 24-hour precipitation map was used to compute 100-year, 24-hour precipitation depths for the entire watershed (298.7 mi^2), the Upper Baker portion of the watershed (214.8 mi^2) and the Lower Baker portion of the watershed (83.9 mi^2). These values were computed as 9.87 inches, 10.01 inches and 9.51 inches, respectively. Figure 1 shows the distribution of the 100-year precipitation in the Baker River watershed.

The ratio of the seasonal PMP to the 100-year precipitation was computed for each general storm centering scenario. Each grid in the 100-year map was multiplied by the computed ratio. The ratios ranged from 1.42 for the summer months to 3.29 for the Nov-Feb winter season. The final step was to compute the subbasin average precipitation values for each season and storm centering scenario.

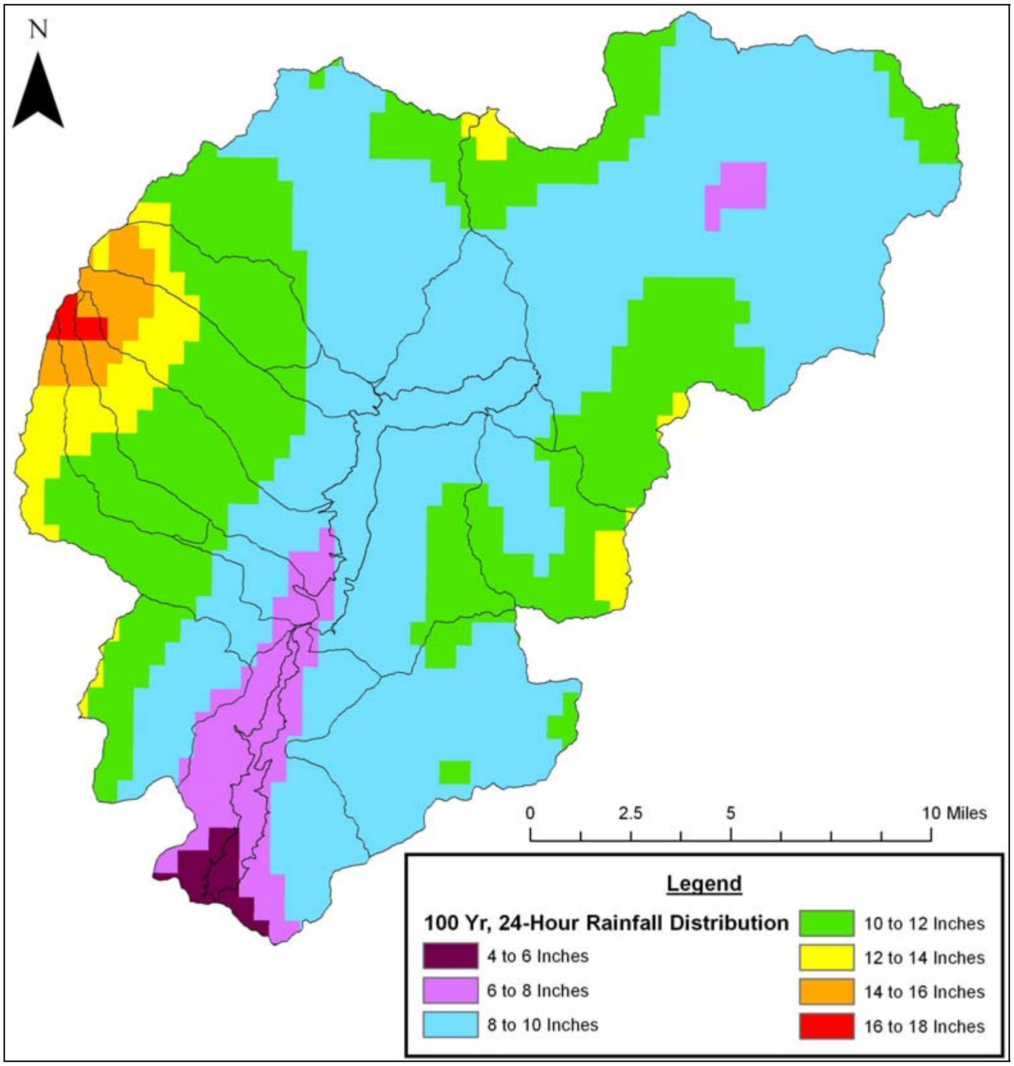


Figure 1. 100-Year 24-Hour Precipitation Distribution for Baker River Watershed

2.2 TEMPORAL DISTRIBUTION

For the temporal distribution of the PMP, FERC (2001) recommends that the peak 6-hour period of rainfall be placed between the half and two-thirds point of the storm and that the remaining 6-hour increments be arranged in alternating descending order on each side of the peak. This approach would result in temporal patterns with the peak intensity placed between hour 36 and hour 48 of the 72-hour duration general storm. FERC (2001) further recommends that reference should be made to the appropriate HMR or site specific studies. Temporal distribution of the PMP is addressed in HMR-57 in the form of guidelines that can be used to construct temporal patterns. It is left to the analyst to determine "which sequence will provide the temporal distribution most critical to the specific drainage of interest".

In lieu of guidance provided in NWS (1994) and FERC (2001), temporal distributions of the subbasin average PMP volumes were developed in accordance with guidance presented in Schaefer (1989). Schaefer (1989) presents a frequency based characterization of historical storm events in the State of Washington and proposes a frequency based methodology that can be used to develop temporal patterns of synthetic storm events, such as the PMP. The details of how the methodologies presented in Schaefer (1989) were applied to this analysis are documented in Tetra Tech (2006b). In summary, three temporal patterns were considered in the analysis, the primary difference between each of the three being the time of occurrence within the 72-hour general storm of the high intensity 1-hour segment. The time of occurrence of the high intensity segment is a frequency characteristic of extreme storms (Schaefer 1989) and can be associated with an exceedance probability. The three different temporal patterns are characterized as follows:

- High intensity segment occurs at hour 33 of elapsed time. This is associated with the 50% exceedance probability (EP).
- High intensity segment occurs at hour 46 of elapsed time. This is associated with the 20% EP.
- High intensity segment occurs at hour 58 of elapsed time. This is associated with the 5% EP.

Figures 2 through 4 present the incremental precipitation distributions for each of the three temporal patterns that were included in the analysis. The three temporal patterns that were included in the analysis, combined with the three potential storm centering scenarios that were considered, resulted in nine candidate PMP distributions for each season. Each of the nine candidate PMP distributions was input into the watershed model, which allowed for comparisons to be made regarding the effect of the assumed temporal and spatial distributions.

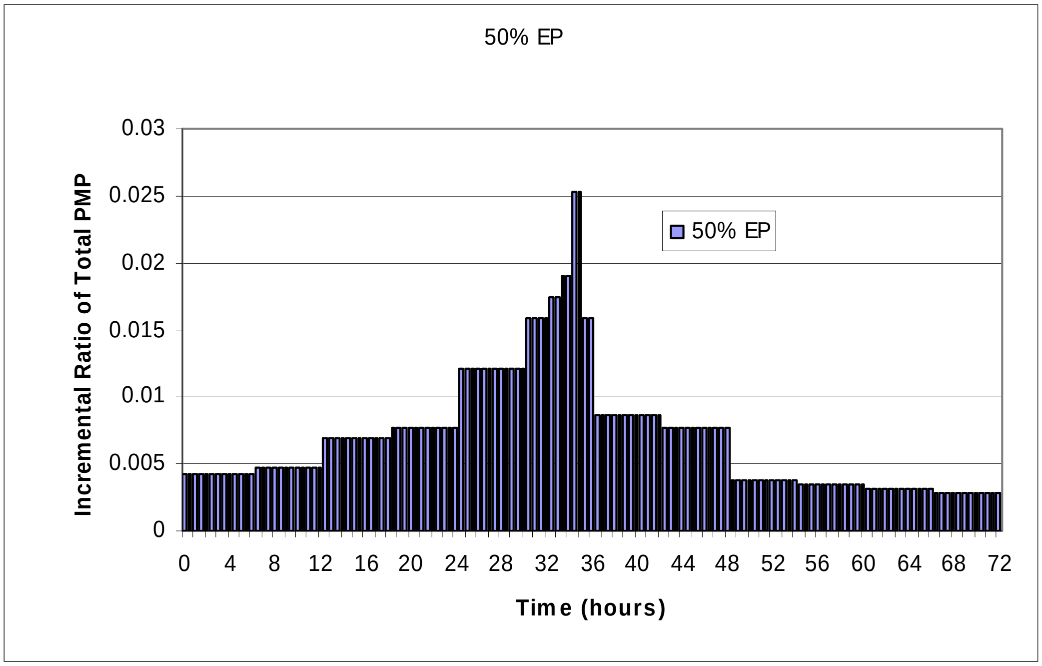


Figure 2. Hyetograph of the 50% Exceedance Probability Temporal Pattern

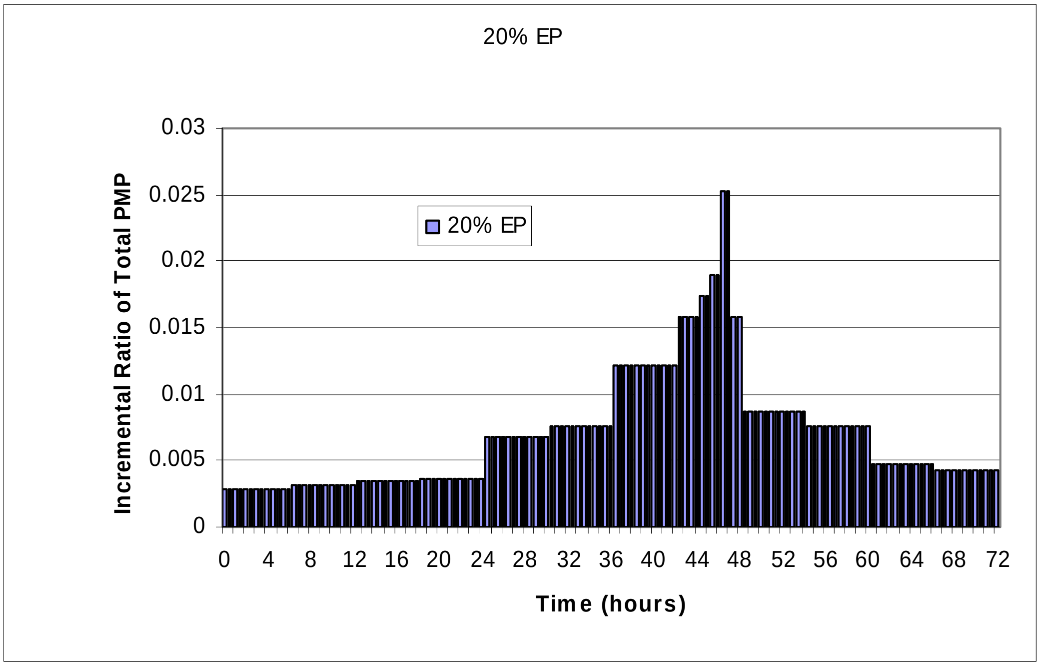


Figure 3. Hyetograph of the 20% Exceedance Probability Temporal Pattern

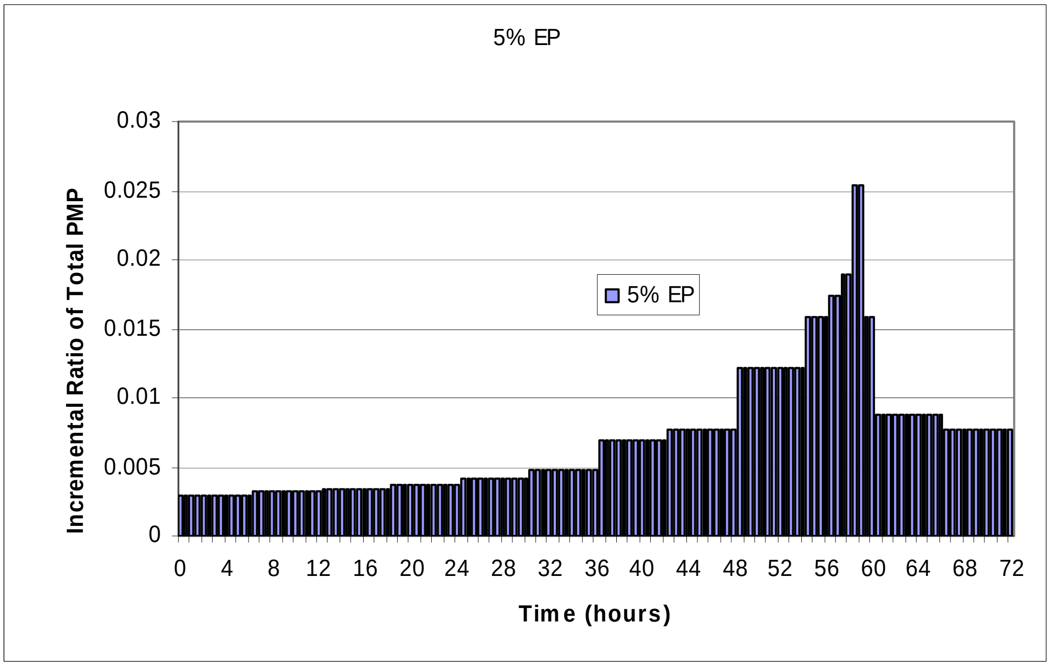


Figure 4. Hyetograph of the 5% Exceedance Probability Temporal Pattern

3 ANTECEDENT/COINCIDENT CONDITIONS FOR INITIAL PMF ANALYSIS

Seasonal antecedent and coincident hydrologic and meteorological conditions were developed for input into the watershed model. A previously issued technical memorandum (Tetra Tech 2006c) presented the derivation of the antecedent and coincident hydrologic and meteorological conditions and the supporting analysis for this information. This section primarily summarizes the results of Tetra Tech (2006c) but does add detail for clarification in several areas, most notably involving the analysis used to determine antecedent snowpack conditions.

3.1 RESERVOIR ELEVATION

FERC (2001) addresses the issue of what reservoir level is reasonable to assume as the starting elevation when routing the inflow PMF. Four approaches are recommended:

1. Use the annual maximum reservoir elevation, which should be defined as the annual maximum normal operating level for most hydroelectric projects.
2. Use an operating rule curve to identify the maximum reservoir elevation corresponding to each season. Assume that the 100-year, 24-hour storm ends three days prior to the PMP. The reservoir elevation at the beginning of inflow from the PMP is taken as the antecedent reservoir elevation.
3. Use the average of the five consecutive, highest wet-year reservoir levels occurring for each season (month).
4. Analyze historical extreme floods and antecedent storms of the region and develop a storm that could reasonably be expected to occur antecedent to the PMP.

Upper Baker reservoir currently provides up to 74,000 acre-feet of federally authorized flood control and operates according to the flood control rule curve (USACE 2000) shown in Figure 5. For the initial PMF analysis, the antecedent reservoir elevation at Upper Baker Dam, at the onset of the PMP event, was assumed to be equal to the minimum flood control pool elevation consistent with this flood control rule curve. Analysis of records for five extreme storms (Tetra Tech 2006c) had concluded that the Upper Baker reservoir was capable of being drawn back down to the rule curve elevation within an average of 8 days of cresting. Therefore, it was reasonable to assume that Upper Baker would be operating at the elevations specified in Figure 5 at the onset of the PMP event.

Lower Baker does not provide flood control. Therefore, for Lower Baker, the reservoir was assumed to be operating at normal full pool elevation (442.35 feet NAVD88).

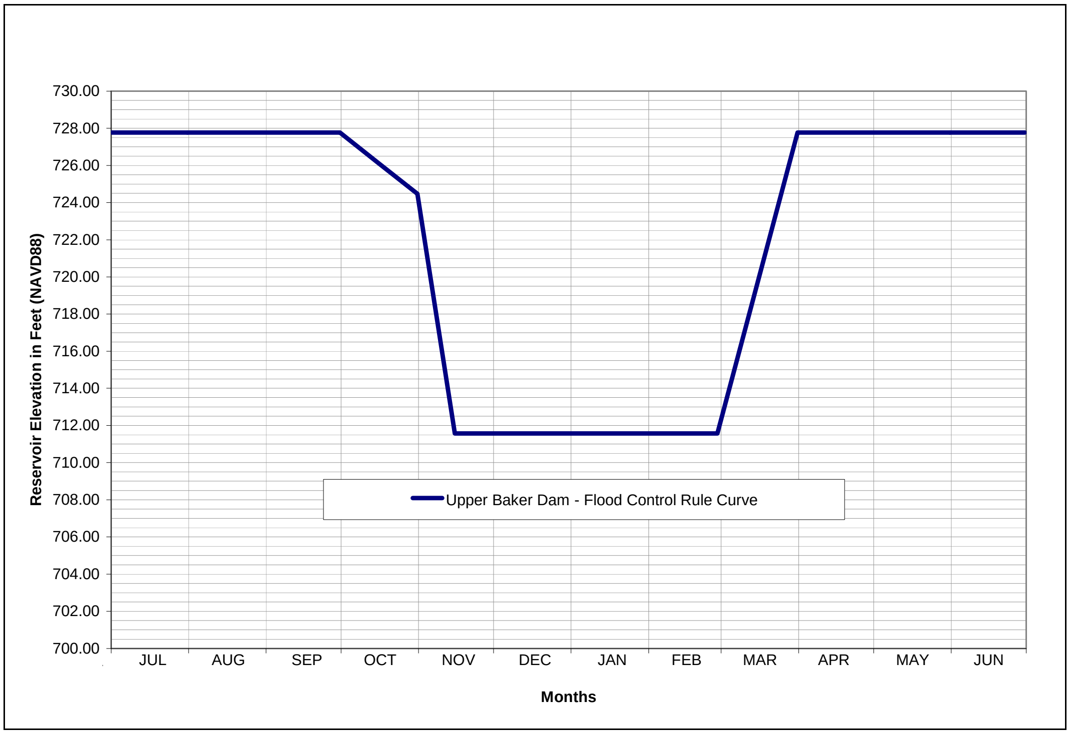


Figure 5. Flood Control Rule Curve for Upper Baker Dam (from USACE 2000)

3.2 BASE FLOW

FERC (2001) recommends that average monthly flow be used as the base flow coincident with the occurrence of the PMP. This recommendation is consistent with the guidance that antecedent conditions represent reasonable meteorologic conditions and was adopted for this analysis. Monthly base flow estimates for Upper and Lower Baker were previously documented and summarized in Tetra Tech (2006c). They are reprinted in this memorandum in Table 1.

	Table 1. Seasonal Base Flow Rate (cubic feet/second (cfs)) Coincident with PMP											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
Total	2,490	3,353	2,883	2,737	2,485	2,101	1,974	2,774	3,716	3,274	2,116	1,823
Upper Baker Tributary Area	1,790	2,411	2,073	1,968	1,787	1,511	1,419	1,995	2,672	2,354	1,521	1,311
Lower Baker Tributary Area	700	942	810	769	698	590	555	779	1,044	920	595	512

3.3 SNOWPACK DENSITY

FERC (2001) does not provide guidance for determining reasonable values for antecedent snowpack density. Therefore, it was assumed that mean end-of-month values for snowpack density would be representative of reasonable hydrologic conditions in the watershed.

Mean values of the end-of-month snowpack density were computed for the period of record of each of the nine snow course stations. As concluded in Tetra Tech (2006c), the snowpack density was found to be independent of elevation, but was found to vary seasonally. The mean end-of-month snowpack densities for each snow course station are summarized in Table 2.

The snowpack density antecedent to the PMP event for each month was computed as the average of the mean end-of-month values for all nine snow course stations. The only exception was for those months where the computed density was greater than the model's threshold (yield) density of 0.40 in/in. For those months, the antecedent density was set to 0.40 in/in.

The values of the antecedent snowpack density for each month in the PMF analysis are summarized at the far right column of Table 2. As seen in Table 2, the snowpack density for the months of October through January is less than the model's threshold density of 0.40 in/in. As such, the snowpack will not yield snowmelt until it has ripened to the threshold density. For the remaining months, the antecedent snowpack density is greater than the threshold density, thereby allowing for immediate snowmelt from the pack at the onset of the PMP event.

Table 2. Mean Value of End-of-Month Snowpack Density (in/in)

	Snow Course Station and Elevation (in feet)									
Month	Rocky Creek 2,100	SF Thunder 2,200	Schreibers Meadow 3,400	Marten Lake 3,600	Dock Butte 3,800	Watson Lake 4,500	Easy Pass 5,200	Jasper Pass 5,400	Mt Blum 5,800	PMF
OCT	---	---	---	---	---	---	---	---	---	0.35
NOV	---	---	---	---	---	---	---	---	---	0.35
DEC	0.35	0.34	0.37	0.35	0.36	0.35	0.36	0.34	0.35	0.35
JAN	0.39	0.39	0.39	0.39	0.40	0.39	0.38	0.39	0.38	0.39
FEB	0.41	0.38	0.42	0.41	0.42	0.41	0.42	0.41	0.41	0.40
MAR	0.44	0.39	0.44	0.43	0.43	0.42	0.43	0.42	0.42	0.40
APR	0.48	0.50	0.49	0.48	0.48	0.47	0.47	0.47	0.47	0.40
MAY	0.55	n/a	0.54	0.56	0.54	0.54	0.55	0.55	0.55	0.40

3.4 SNOWPACK WATER CONTENT

FERC (2001) states that if “snowpack is apt to exist in at least part of the drainage basin in the season when the critical PMP would occur, an antecedent 100-year snowpack should be assumed to exist at the time when the PMP occurs”. The spirit of this guidance is based on the assumption that the 100-year snowpack would produce a reasonably conservative condition for snowmelt during the PMP, without requiring consideration of even more extreme conditions. Since the hydrologic model of the Baker River watershed includes snowpack density as an input parameter, it was recognized that snowpacks with a high probability of occurrence may actually produce more conservative results due to the phenomenon of snowpack ripening. Therefore, for the initial PMF analysis, the determination of the water content of the snowpack antecedent to the PMP event was conducted using an iterative execution of the hydrologic model to determine the most conservative conditions for each season.

The objective of this methodology was to use a frequency based approach to determine the antecedent conditions that would result in the highest volume of snowmelt for the 72-hour duration general storm. The general methodology involved the process of iteratively searching for a collection of snow water equivalent magnitudes, at the various zones of elevation and mean annual precipitation, that yielded the greatest volumetric runoff contribution to the PMF hydrograph. As the basis for this methodology, snow water equivalent (SWE) values were determined for each combination of zone of elevation and mean annual precipitation that corresponds with a common non-exceedance probability. Varying magnitudes of non-exceedance probability were tested to determine the non-exceedance probability associated with the highest volume of snowmelt. It was anticipated that there would be a point in this method where a snowpack associated with a higher non-exceedance probability (i.e. a deeper pack with higher snow water equivalent) would not result in significantly more runoff volume from the basin. Additionally, it was considered a possibility that a larger snowpack would actually reduce the runoff due to the ability to store precipitation during the process of snowpack ripening. As such, a deeper pack (such as the 99% non-exceedance snowpack) may actually produce less runoff volume than a shallower snowpack (such as the 50% non-exceedance snowpack).

End-of-month magnitude frequency relationships were first developed for each of the snow course stations for each of the months of the snow season (end-of-October through end-of-May). This analysis relied upon Hydrologic Forecasting and Analysis Model (HFAM) output for the end-of-October and end-of-November periods and the 45-year data record of snow observations for the remaining months. The data were organized by month. Zero values for missing or non-reported data were differentiated from zero values for snow-free conditions. Zero values associated with snow-free conditions were incorporated into the frequency analysis as explained below. Missing or non-reported values only acted to shorten the period of record. With the exception of the two lowest elevation snow course stations, Rocky Creek and South Fork Thunder Creek, snow is present at all snow course stations from the end-of-December through the end-of-May (Barnes 2006). A mixed distribution model was used to describe the probability of distribution of snow water equivalent as described in Equation 1.

$$F(x) = \Theta + (1 - \Theta)G(x) \qquad \text{Equation (1)}$$

where,

$F(x) =$ the cumulative distribution function for snow water equivalent (SWE)

$\Theta =$ the frequency of snow-free ground computed as the ratio of the number of snow-free data values to the total number of data values

$G(x) =$ the cumulative distribution function for SWE when the ground is snow covered

The two parameter Log-Normal distribution was used to determine the cumulative distribution function for SWE when the ground was snow covered (non-zero data points). The Cunnane non-parametric plotting position formula was used to estimate the non-exceedance probability associated with each SWE value as described in Equation 2. Examples of the non-exceedance probability plots are shown in Figures 6 and 7. Figure 6 is an example where there were no snow-free conditions during the period of record, and Figure 7 is an example where there were three snow-free values out of 39 total values.

$$G(x) = 1 - \left(\frac{i - \phi}{N + 1 - 2\phi} \right) \qquad \text{Equation (2)}$$

where,

$G(x) =$ the non-exceedance probability

$N =$ the total number of non-zero SWE data points

$i =$ the relative rank of the data ordered from largest to smallest

$\phi =$ 0.40

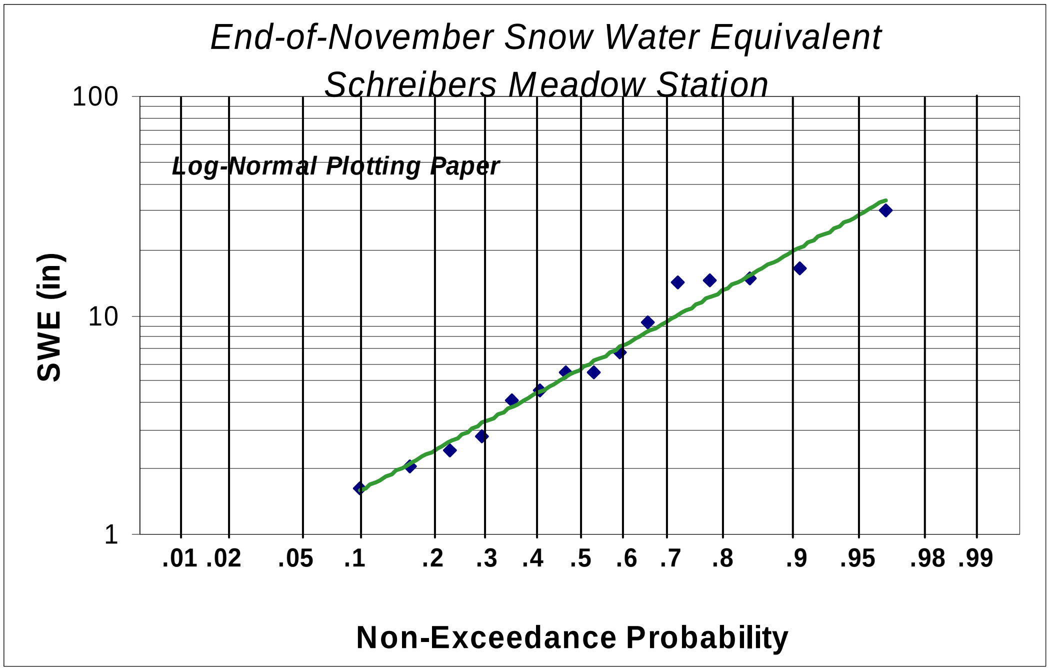


Figure 6. Example Snow Water Equivalent Probability Plot with No Zero Values

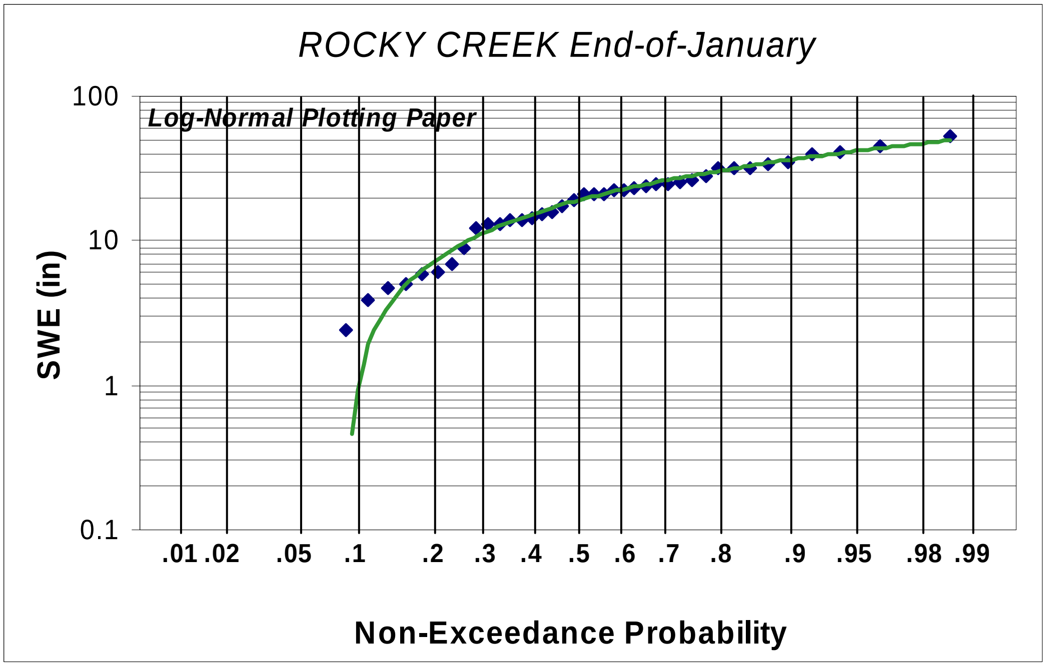


Figure 7. Example Snow Water Equivalent Probability Plot with Zero Values

To determine the most conservative snowpack conditions for a given month, an initial value of the non-exceedance probability was assumed. The starting condition in all cases was the 0.50 non-exceedance probability, which is equivalent to a 2-year return period. The SWE associated with this non-exceedance probability value was computed at each of the nine snow course stations using the non-exceedance probability plots. The resulting SWE values were then normalized to a common value of mean annual precipitation, resulting in the elevation of the snow course station as the independent variable. The normalized SWE values were then plotted versus elevation, resulting in a plot such as the one shown in Figure 8. This figure illustrates normalized SWE versus elevation for the 95% non-exceedance probability snowpack conditions for the end-of-November period. The equation of the line through the points was then used to compute the SWE value for each elevation zone and mean annual precipitation zone in the hydrologic model, resulting in spatial allocation of SWE that is physically consistent with the historical data.

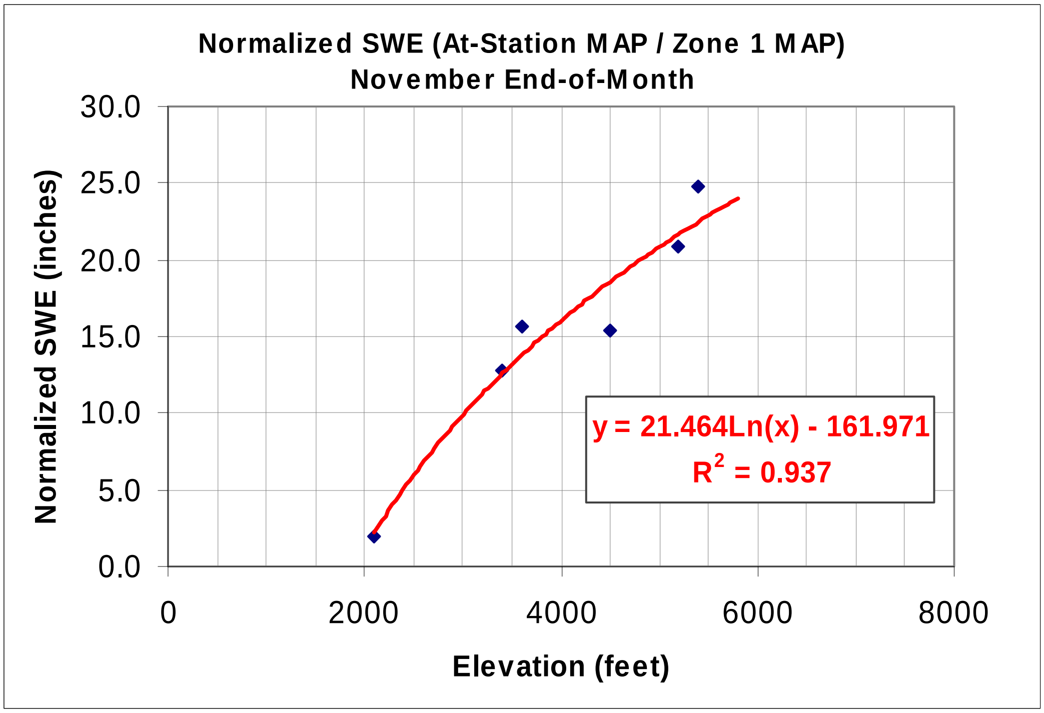


Figure 8. Normalized SWE versus Elevation for the 95% Non-Exceedance Snowpack Condition for the Month of November

The hydrologic model was run first assuming antecedent snowpack conditions associated with the 50% non-exceedance probability, and the resulting runoff volume was recorded. The process was repeated for the 80% non-exceedance probability, and on up to the 99% non-exceedance probability for each month. The recorded runoff volumes were reviewed to determine at which point in the process the runoff volume actually began to decrease with increasing snowpack depth. The non-exceedance probability snowpack condition that produced the largest snowmelt volume was assigned to be the antecedent PMF conditions. For each model run, all other hydrometeorological input parameters were set at fixed values. The general storm was centered over the entire watershed and the temporal pattern with the high intensity segment occurring at hour 33 (50% EP) was used.

Table 3 summarizes the results of this iterative analysis. The results presented in this table illustrate that for those months which had packs that were characterized with densities below the yield point, shallower snowpack conditions were found to result in the highest runoff volume. Deeper packs simply allowed for precipitation to initially be used to ripen the pack, thus reducing the overall snowmelt volume. October was a unique situation where full melt-out of the snowpack occurred regardless of the depth. Therefore, the 99% non-exceedance snowpack produced the highest magnitude of snowmelt volume for October.

Table 3. Non-Exceedance Probability of Antecedent Snowpack Yielding the Largest Snowmelt Volume, by Month	
Month	**Snowpack Non-Exceedance Probability**
October	99 %
November	90 %
December	50 %
January	90 %
February	90 %
March	99 %
April	99 %
May	99%
June - September	n/a

3.5 ANTECEDENT PRECIPITATION

FERC (2001) does not provide guidance for determining reasonable values for antecedent precipitation. Therefore, soil moisture conditions antecedent to the PMP event were assumed to be the product of a typical water year. This assumption resulted in near saturated conditions for the watershed soils for the late fall months and for the winter months. Initial soil moisture conditions at the onset of the PMP were computed using soil moisture budgeting algorithms within the hydrologic model. Input to the soil moisture budgeting algorithm includes average values of the cumulative end-of-month precipitation for each of the eight zones of mean annual precipitation (MAP zones) in the hydrologic model, as determined from an analysis of the historical precipitation record at the Upper Baker Dam precipitation station. Table 4 presents the average values of the cumulative end-of-month precipitation as recorded at Upper Baker Dam. These values were then adjusted to the eight MAP zones in the hydrologic model using a ratio of the mean annual precipitation for the MAP zone to the mean annual precipitation at the Upper Baker precipitation gage. The results are summarized in Table 5.

Table 4. Average Values of the Cumulative End-of-Month Precipitation (inches) at Upper Baker Dam for the Period of Record

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
9.94	25.41	40.86	55.40	66.42	76.15	82.65	87.54	91.29	93.88	96.20	100.75

Notes: Cumulative precipitation based on data from WY1966 through WY2004.

Table 5. Cumulative End-of-Month Precipitation (inches) for a given Mean Annual Precipitation Zone Coincident with PMF

MAP ZONE	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	6.53	16.69	26.84	36.39	43.63	50.02	54.29	57.50	59.97	61.67	63.19	66.18
2	8.38	21.42	34.45	46.71	56.00	64.20	69.69	73.81	76.97	79.15	81.11	84.95
3	9.94	25.41	40.86	55.40	66.42	76.15	82.65	87.54	91.29	93.88	96.20	100.75
4	10.91	27.90	44.87	60.83	72.93	83.62	90.75	96.12	100.24	103.08	105.63	110.63
5	11.89	30.39	48.87	66.26	79.44	91.08	98.86	104.70	109.19	112.29	115.06	120.50
6	13.64	34.88	56.08	76.04	91.16	104.52	113.44	120.15	125.30	128.85	132.04	138.28
7	15.20	38.86	62.49	84.73	101.58	116.46	126.41	133.88	139.62	143.58	147.13	154.09
8	18.32	46.83	75.31	102.11	122.42	140.35	152.34	161.35	168.26	173.03	177.31	185.70

3.6 AIR TEMPERATURE

The methodology outlined in HMR-57 (NWS 1994) for deriving air temperatures coincident with the PMP was followed. This methodology was originally presented in HMR-43 (NWS 1966) and is based on the assumption of a saturated pseudo-adiabatic atmosphere and the use of 12-hour maximum persisting dew point temperatures. Tetra Tech (2006c) presents the detailed application of this methodology to the Baker River Basin and Table 6 summarizes the resulting un-ordered air temperature values for the six hour increments of the 72-hour duration PMP.

The air temperatures in Table 6 were then re-ordered to conform to the temporal distribution of the PMP. The highest 6-hour duration air temperature corresponds with the highest 6-hour period of rainfall and the lowest 6-hour duration air temperature would occur during the lowest 6-hour period of rainfall.

The final step was to adjust the 1000-mb air temperature time series for elevation. For the Baker River watershed, there are eight elevation zones, and therefore, the 1000-mb air temperature time series were adjusted to the median elevation of each of zone. Figure 15.32 in NWS (1994) was used to adjust the air temperature time series. The lapse rates used in this study ranged between 2.45 and 3.10 degrees per 1,000 feet for elevations less than 4,000 feet and between 2.52 and 3.18 for elevations between 4,000 feet and 8,000 feet. These lapse rates are consistent with the lapse rates used in the Baker River watershed model calibration that were computed from radiosonde data (Tetra Tech 2006a). For the four storm events that were included in the calibration, the computed lapse rate from approximately sea level to the freezing elevation ranged between 1.9 and 2.9 degrees per 1,000 feet

Antecedent temperatures for the 72-hour time period prior to the PMP event were computed based on guidance presented in Figure 15.13 of NWS (1994). This figure is included in this memorandum as Figure 9.

Table 6. 1000-mb Temperatures (°F) for Each 6-Hour Time Increment Coincident with the PMP

Month	Ranked Air Temperatures for Each 6-Hour Time Increment											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
JAN	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
FEB	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
MARCH	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
APRIL	56.0	55.4	54.8	54.4	53.6	53.2	53.0	52.6	52.2	51.7	51.3	51.1
MAY	58.4	57.7	57.1	56.8	56.2	55.9	55.6	55.2	54.6	54.4	54.0	53.6
JUNE	61.5	60.7	60.1	59.6	58.9	58.6	58.3	57.8	57.4	57.3	56.8	56.5
JULY	65.9	65.0	64.5	64.0	63.5	63.0	62.8	62.3	61.8	61.5	61.2	60.9
AUG	66.5	65.7	64.9	64.6	63.9	63.6	63.4	62.9	62.3	62.1	61.7	61.4
SEPT	64.1	63.4	62.8	62.3	61.7	61.3	61.0	60.6	60.0	59.8	59.2	59.0
OCT	60.9	60.0	59.3	58.9	58.3	57.8	57.7	57.3	56.8	56.7	56.2	55.9
NOV	57.7	57.0	56.4	56.0	55.4	55.0	54.8	54.2	53.8	53.6	53.0	52.8
DEC	55.2	54.4	53.8	53.4	52.8	52.4	51.9	51.5	51.1	50.9	50.5	50.3

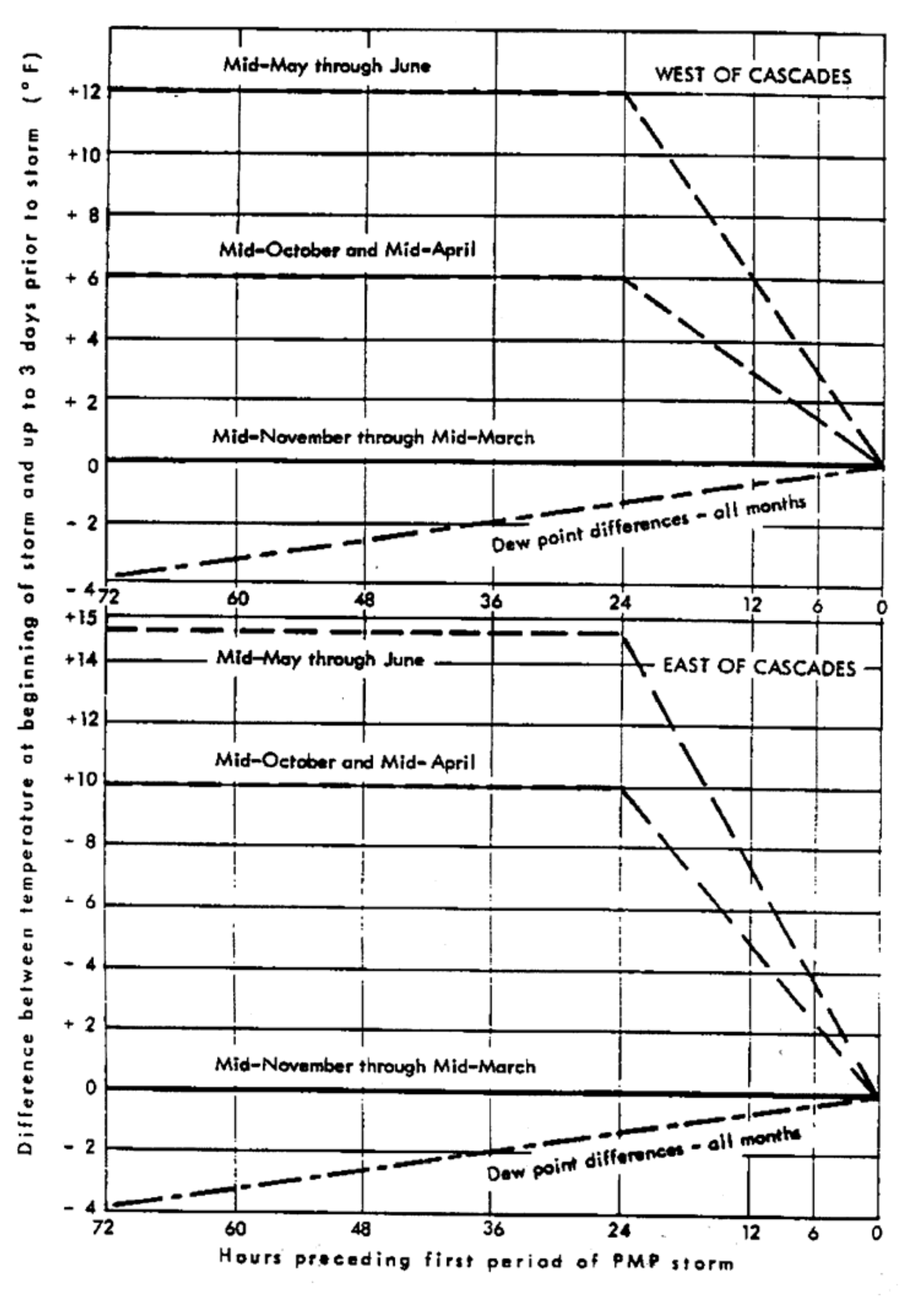


Figure 9. Temporal Distribution of Temperatures Prior to the PMP Storm (From NWS 1994)

3.7 WIND SPEED

The methodology outlined in HMR-57 (NWS 1994) for deriving wind speeds coincident with the PMP was followed. Tetra Tech (2006c) presents the detailed application of this methodology to the Baker River Basin and Table 7 summarizes the resulting un-ordered wind speed values for each of the six hour increments of the 72-hour duration PMP event. As documented in Tetra Tech (2006c), the wind speeds shown in Table 7 include a basin average reduction factor of 0.75 that was used to convert the free air wind speeds to anemometer level wind speeds. Standard procedures in NWS (1994) allow for a greater reduction for sheltered portions of the drainage and a lesser reduction for exposed portions of the drainage. Since the Baker River watershed is characterized by both sheltered and exposed conditions, the 0.75 reduction factor was chosen to represent the basin average conditions.

The wind speeds in Table 7 were then re-ordered to conform to the temporal distribution of the PMP. The highest 6-hour duration wind speed was set to correspond with the highest 6-hour period of rainfall and the lowest 6-hour duration wind speed was set to correspond with the lowest 6-hour period of rainfall.

Antecedent wind speeds for the 72-hour time period prior to the PMP event were computed based on guidance presented NWS (1994). According to this guidance, the minimum wind speed in the time series was assumed to persist for the 72-hour time period prior to the PMP event.

Table 7. Monthly Anemometer-Level Wind Speeds (mph) for Each 6-Hour Time Period Coincident with the PMP

Month	Ranked Wind Speeds for Each 6-Hour Time Increment											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
OCT	49	45	40	38	35	33	31	29	28	28	27	26
NOV	56	51	46	43	40	38	35	33	32	32	30	30
DEC	60	55	50	47	43	41	38	36	35	34	33	32
JAN	63	58	52	49	46	43	40	38	37	36	35	34
FEB	60	55	50	47	43	41	38	36	35	34	33	32
MAR	56	51	46	43	40	38	35	33	32	32	30	30
APR	48	43	39	37	34	32	30	28	27	27	26	25
MAY	41	38	34	32	30	28	26	25	24	23	22	22
JUN	34	31	28	26	25	23	22	20	20	19	19	18
JUL	32	29	26	24	23	21	20	19	18	18	17	17
AUG	32	30	27	25	23	22	20	19	19	18	18	17
SEPT	32	29	26	24	23	21	20	19	18	18	17	17

4 INITIAL PMF ANALYSIS AND INFLOW HYDROGRAPHS

The calibrated hydrologic model was used to simulate the PMP event and to produce inflow hydrographs to the Upper Baker reservoir and the Lower Baker reservoir for each season and for each storm centering scenario. Also, as described previously, three temporal distributions of the PMP were evaluated. The unique naming convention system was used for the input and output files. The system is described below:

XXX_Y_ZZ.extension

Where,

XXX = the month (i.e. **OCT**, **NOV**, **DEC** etc...)
Y = the general storm centering scenario (E=**E**ntire watershed, U=**U**pper, and L=**L**ower)
Z = exceedance probability associated with the timing of the high intensity segment (**05** = 5% exceedance probability, **20**=20% exceedance probability, and **50**=50% exceedance probability)

For each month, nine PMF models were run. The results were then reviewed to determine the combined centering scenario and temporal distribution that resulted in the most conservative result for each month.

4.1 ADJUSTMENT OF UNIT HYDROGRAPH PERIOD OF RISE

The unit hydrograph method for transformation of precipitation excess to runoff is based on an assumption that the watershed response is linearly related to the effective precipitation input. In reality, the watershed response becomes shorter with increasing precipitation intensity and flows, due to higher channel velocities, which in turn cause shorter travel times. Since precipitation intensities and the resulting runoff flow rates associated with the PMP event are significantly greater in magnitude than intensities and flows that have been recorded in the basin, the response time of the calibrated unit hydrograph is typically adjusted to account for this phenomenon. FERC (2001) and USACE (1991) provide very general guidance on this issue.

A method was developed to quantify the shortening of the watershed response associated with PMP-level precipitation intensities. Reduction of the period of rise was determined from calibration of a kinematic wave theory (KWT) based HEC-1 model to the historical November 90(1) storm event (unit hydrograph based model). Parameters in the KWT model that are dependent on physical characteristics of the watershed, such as channel width, slope, and hydraulic roughness for each subbasin were adjusted until the model matched both the timing and the magnitude of the hydrographs determined for the historical November 90(1) storm event. Five of the subbasins were included in this analysis (Park Creek, Swift Creek, Baker River, Sulphur Creek and Thunder Creek) Figures 10 and 11 show the comparison of the kinematic wave and unit hydrograph calibration for Park and Thunder Creek, respectively.

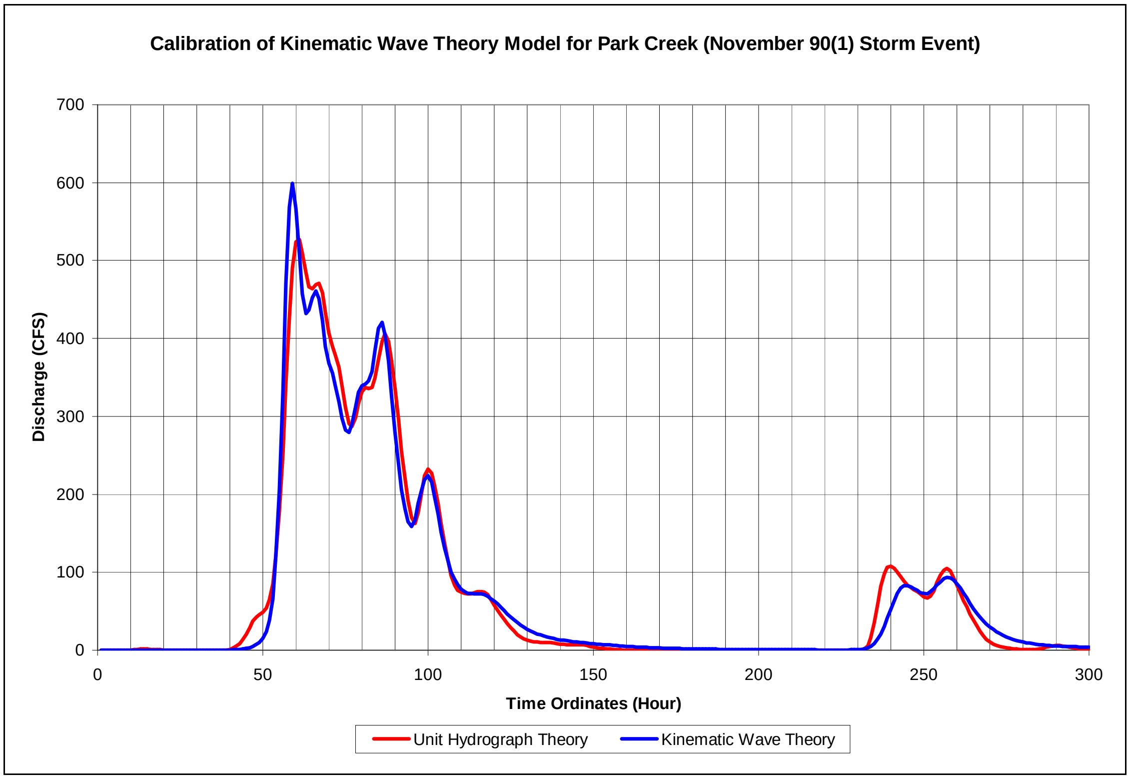


Figure 10. Comparison of Kinematic Wave and Unit Hydrograph Based Models for Park Creek

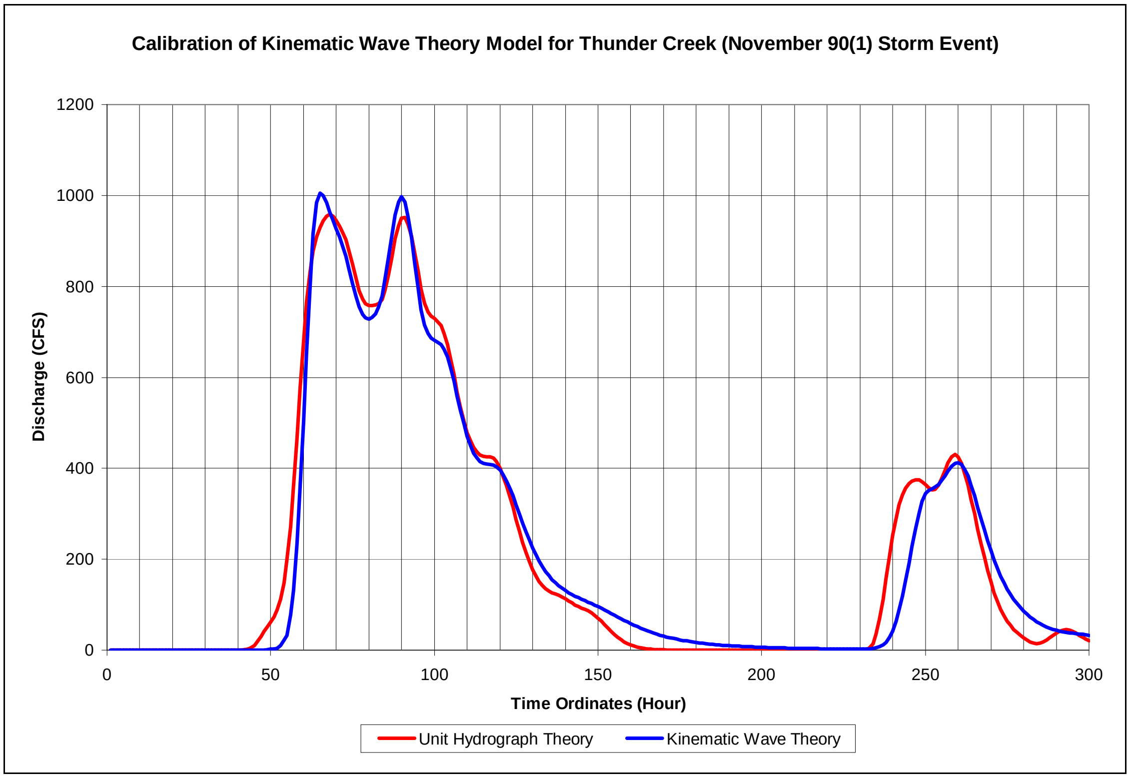


Figure 11. Comparison of Kinematic Wave and Unit Hydrograph Based Models for Thunder Creek

Using the calibrated KWT model, typical PMP rainfall intensities associated with the month of June (0.086 in/hr) and the month of November (0.335 in/hr) were applied and held constant for the entire duration of the simulation. The resulting hydrographs were compared with results from a model simulation using a typical historical rainfall intensity seen in the November 90(1) storm event (0.049 in/hr). The higher rainfall intensities associated with the PMP produced a shorter period of rise, which varied depending on the subbasin. For the June PMP intensity, the period of rise was 6 to 19 percent shorter than was the case for the historical intensity. For the November PMP intensity, the period of rise was 28 to 39 percent shorter.

Initially, an average value of 22 percent was adopted as the global reduction factor for adjusting the calibrated unit hydrograph period of rise values for all subbasins. However, after further consideration, a smaller reduction factor (7 percent) was applied to those subbasins with well developed floodplains and large overbank areas. In those subbasins, increased channel and floodplain velocities associated with higher intensity precipitation would likely be mitigated by the attenuating effect of the floodplain. This smaller reduction factor was applied to Subbasins 5, 6, 7, and 8 in the Upper Baker tributary area and Subbasins 11 and 15 in the Lower Baker tributary area. The 22 percent reduction factor was applied to all other subbasins. These reduction factors are consistent with guidance presented in FERC (2001) and USACE (1991). FERC (2001) guidance is fairly general and states that “lag times should be adjusted to account for PMF conditions,” while USACE (1991) states more specifically that “reservoir inflow hydrographs for IDF (inflow design flood) determinations should be peaked 25 to 50 percent to account for the fact that unit hydrographs are usually derived from smaller floods.” Table 8 summarizes the calibrated and PMF adjusted period of rise values for each of the Baker River watershed subbasins.

The unit hydrograph peaking factor values were not changed from those that were established during model calibration, because the reduced unit hydrograph period of rise values, as summarized in Table 8, have the secondary effect of increasing the peak discharge of the unit hydrographs.

Table 8. Reduced Period of Rise Used for the PMF Storm		
Sub-Basin	**Calibrated Period of Rise (Min)**	**Reduced Period of Rise (Min)**
UPPER BAKER SUBBASINS		
1	240	180
2	180	150
3	180	150
4	180	150
5	270	240
6	180	150
7	360	330
8	180	150
9	--	--
LOWER BAKER SUBBASINS		
10	180	150
11	180	150
12	300	240
13	210	180
14	150	120
15	240	210
16	--	--
Notes 1. Subbasins 9 and 16 represent the reservoir surfaces		

4.2 PMF INFLOW HYDROGRAPHS

The consideration of three different storm centering scenarios and three different temporal patterns resulted in nine inflow hydrographs for each month for each reservoir. This allowed for an evaluation as to the effects of the assumed centering and temporal distributions on the resulting inflow hydrographs.

An example is presented in Figure 12, which shows the inflow hydrograph into Upper Baker reservoir for the three different centering scenarios, while assuming the same temporal distribution (in this case the distribution associated with the 5% exceedance probability). In this figure, it is seen that the peak of the inflow hydrograph occurs at the same time for each, as expected. The magnitude of the peak, however, does vary. Of the three, the PMP volume associated with the Upper centering is the largest, thereby resulting in slightly higher rainfall intensities and producing a slightly larger peak magnitude.

Another example is presented in Figure 13 which shows the inflow hydrographs into Upper Baker reservoir for the three temporal distributions while assuming the same storm centering scenario (in this case the Upper centering). It is seen that the magnitude of the hydrograph peak is virtually the same for each of the three, regardless of the temporal distribution. This is expected since the hourly precipitation intensities are identical in the 24-hours leading up to the peak intensity. The slight difference in the peak values is attributed to fact that each of the temporal distributions had slightly different precipitation intensities and volumes in the hours before the 24-hour segment leading up to the peak.

One last example is presented in Figure 14, which shows a comparison of the PMF inflow hydrographs for the Upper Baker tributary area and the Lower Baker tributary area (both total and local). This figure illustrates the relative magnitude of the two hydrographs, assuming the same centering scenario (Upper) and temporal pattern (5% exceedance probability). This figure also illustrates the total inflow hydrograph to Lower Baker reservoir, which is the combination of the local PMF inflow from the Lower Baker tributary area and the PMF outflow from Upper Baker Dam.

Tables 9 and 10 present a tabular summary of the PMF inflow hydrographs by month, for the Upper Baker and Lower Baker tributary areas, respectively. These tables summarize the largest inflow volumes and largest peak flow rates for each of the months, using the results of the nine models run for each month. The tables also identify the associated storm centering scenario and temporal distribution that produced these results. Certain patterns are evident the tables. As seen in Figure 12, the U_05 model typically results in the highest peak inflow for the Upper Baker tributary area. Likewise, the L_05 model typically results in the highest peak inflow for the Lower Baker tributary area.

The largest inflow volumes for the Upper Baker tributary area are obviously associated with the Upper centering models, and likewise the largest inflow volumes for the local Lower Baker tributary area are produced when the storm is centered in Lower Baker. From month to month, however, the tables indicate that the controlling model scenario for inflow volume varies among the three temporal distributions, with no consistent pattern. In actuality, the inflow volume is not sensitive to the assumed temporal pattern. For a given storm centering scenario, the difference in magnitude in the inflow volume between the three temporal distributions is generally less than 1 percent.

Based on the results shown in Tables 9 and 10, the Upper Baker and Lower Baker inflow hydrographs for the month of November have the highest peaks and volumes when compared to the other months. Therefore, before proceeding with the reservoir routing analysis, it appears that the November month is the leading candidate for producing the critical PMF hydrograph. Because of this possibility, Table 11 presents a summary of key hydrologic inputs and outputs associated with the hydrologic model for the month of November. The months of October and December are included as well. All the results in Table 11 use the output from the U_05 models. The values presented in this table are basin average values for the 214.80 square-mile Upper Baker portion of the watershed and the 83.88 square-mile Lower Baker portion of the watershed.

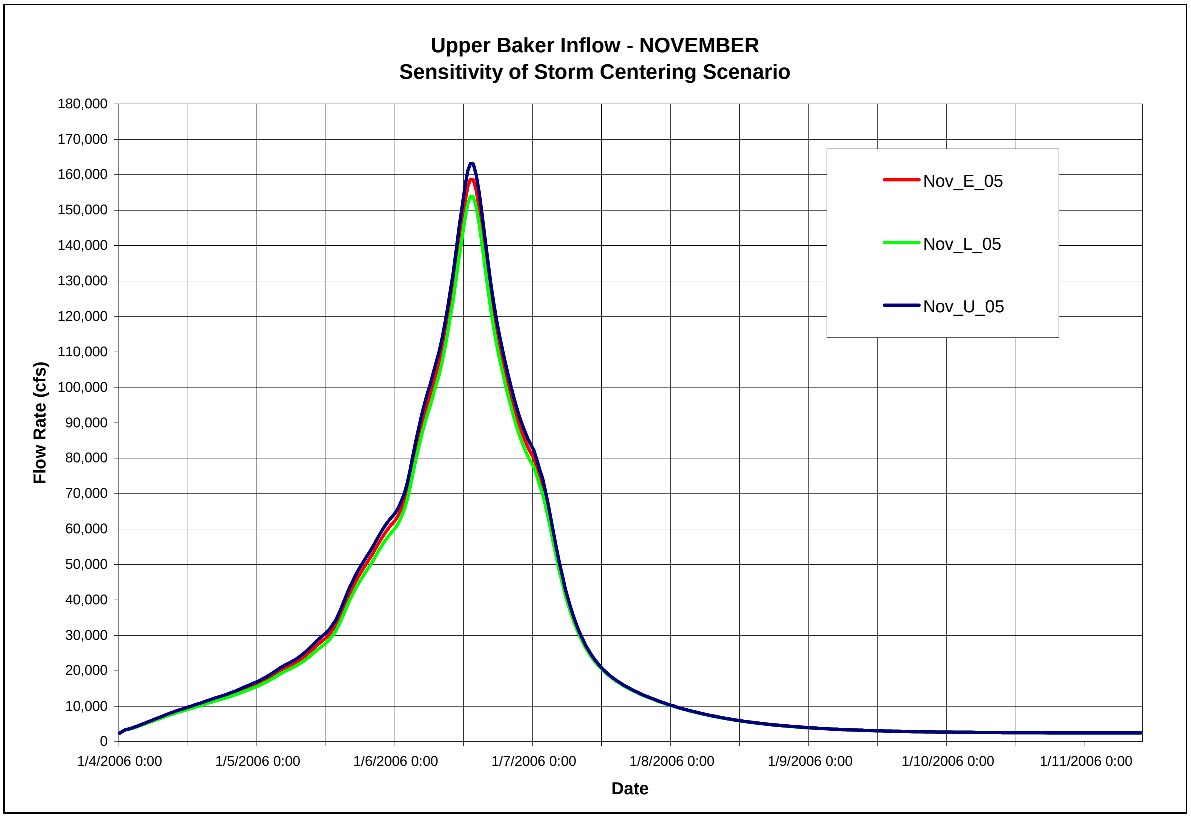


Figure 12. Sensitivity of Storm Centering Scenario on Inflow Hydrograph to Upper Baker

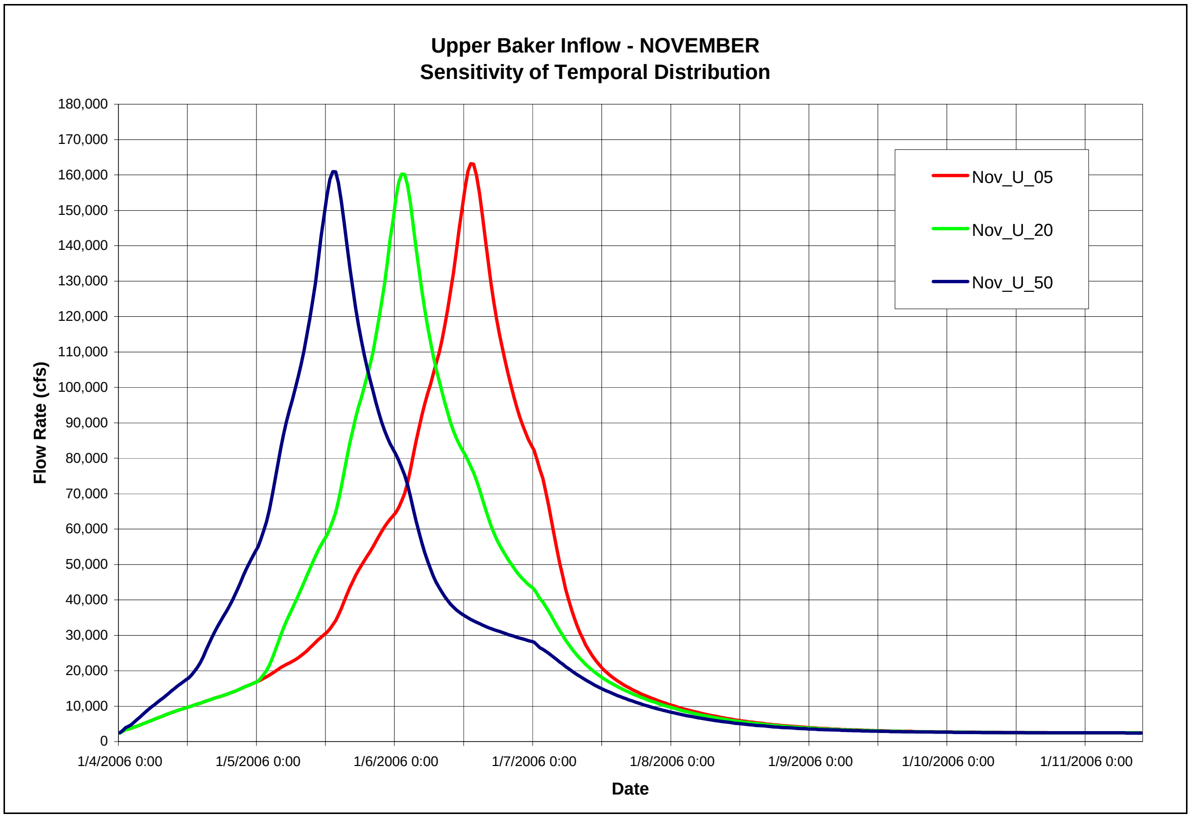


Figure 13. Sensitivity of Storm Temporal Distribution on Inflow Hydrograph to Upper Baker

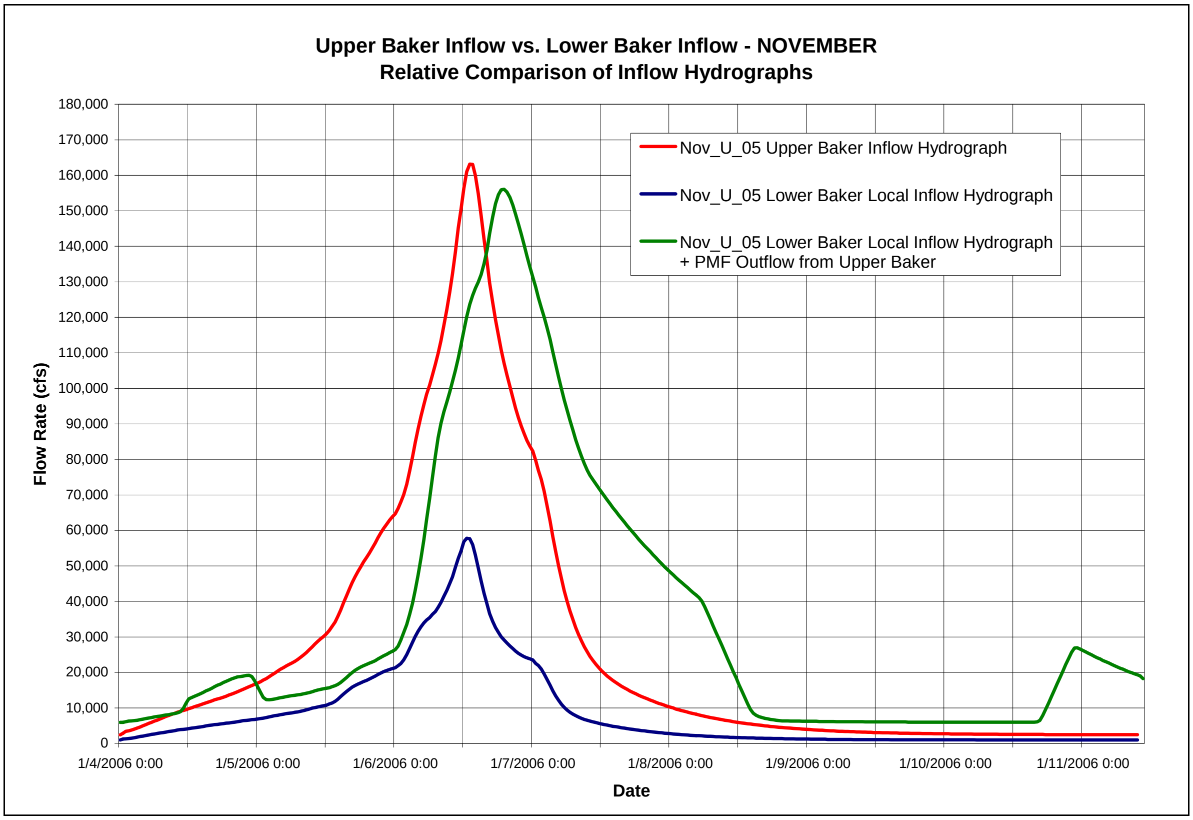


Figure 14. Comparison of Upper Baker and Lower Baker PMF Inflow Hydrographs

Table 9. Summary of Maximum Peak Flow Rate and Inflow Volume by Month for Local Inflow Hydrographs to Upper Baker Reservoir

Month	Maximum Peak Flow Rate (cfs)	Controlling Model Scenario	Maximum Inflow Volume (acre-feet)	Controlling Model Scenario
October	139,300	U-05	345,900	U-20
November	**163,200**	**U-05**	**392,000**	**U-50**
December	155,600	U-05	368,500	U-50
January	152,400	U-50	356,700	U-50
February	150,800	U-05	342,700	U-20
March	105,000	U-50	247,500	U-50
April	103,500	U-05	242,600	U-50
May	109,300	U-05	273,700	U-50
June	73,800	U-05	183,700	U-20
July	46,900	U-05	123,200	U-20
August	45,700	U-05	110,000	U-05
September	78,500	U-05	157,700	U-05

Table 10. Summary of Maximum Peak Flow Rate and Inflow Volume by Month for Local Inflow Hydrographs to Lower Baker Reservoir				
Month	**Maximum Peak Flow Rate (cfs)**	**Controlling Model Scenario**	**Maximum Inflow Volume (acre-feet)**	**Controlling Model Scenario**
October	54,800	L-05	118,800	L-20
November	**67,200**	**L-05**	**146,900**	**L-50**
December	65,400	L-05	139,700	L-50
January	65,900	L-05	140,900	L-50
February	65,700	L-05	136,900	L-05
March	44,900	L-05	94,000	L-20
April	42,700	L-05	88,600	L-20
May	43,900	L-05	95,400	L-20
June	31,100	L-05	66,700	L-20
July	19,800	L-05	43,200	L-05
August	19,100	L-05	37,200	L-05
September	34,100	L-05	59,900	L-05

Table 11. Key Hydrologic Inputs and Outputs for PMF Inflow Hydrographs, Expressed in Inches

	OCT		**NOV**		**DEC**	
	Upper Baker	**Lower Baker**	**Upper Baker**	**Lower Baker**	**Upper Baker**	**Lower Baker**
INPUTS						
Rain	30.11	25.97	32.79	28.40	31.98	28.20
Snow	0.00	0.00	0.18	0.06	0.99	0.26
Total Precipitation (inches)	30.11	25.97	32.98	28.46	32.98	28.46
Initial Snow Water Equivalent	10.13	5.30	22.24	12.28	21.16	12.08
Final Snow Water Equivalent	1.90	0.61	16.18	7.00	18.78	8.79
Snowpack Yield (inches)	8.22	4.68	6.05	5.28	2.38	3.30
Total Moisture Input (inches)	38.33	30.65	39.03	33.74	35.36	31.76
OUTPUTS						
Base Flow	2.30	2.30	3.10	3.10	2.66	2.67
Surface Runoff	16.52	11.29	20.64	16.15	19.28	15.28
Interflow Runoff	11.84	9.38	10.90	9.51	10.44	9.15
Total Runoff (inches)	30.66	22.98	34.64	28.77	32.39	27.10

Notes:
1. Results using U_05 model output

5 ROUTING OF INITIAL PMF INFLOW HYDROGRAPHS

The local Upper Baker and Lower Baker inflow hydrographs were then routed through the reservoirs to determine the resulting peak reservoir elevations and outflow rates.

5.1 METHODOLOGY

The USACE HEC-5 model (USACE-HEC 1998) was used to route the inflow hydrographs through the reservoir system and to determine the outflow hydrographs for both the Upper Baker and Lower Baker reservoirs. Outflows from both reservoirs are controlled by gated spillways. At Upper Baker, each of the three spillways is controlled by a 25' by 30' radial gate. During flood events that occur during the flood control season (November 1st through March 1st), outflows from the reservoir are determined by the Baker River Water Control Manual (USACE 2000). For Lower Baker, twenty three vertical lift gates control outflows from the reservoir. There is currently no flood control operation at Lower Baker and the reservoir is typically operated to pass inflows as quickly as possible. Dam schematics are provided in Attachment A.

5.2 RATING CURVES

Existing published spillway discharge rating curves for both Upper Baker Dam and Lower Baker Dam were reviewed. According to the plant manual for Upper Baker Dam, the Upper Baker Dam rating curve is based "essentially on results of model tests." Therefore, the rating curve was used as published. However, since the published rating curve only extended to an elevation two feet below the top of the dam, it was necessary to extend the free capacity discharge curve so as to include weir flow over the top of the dam and weir flow over West Pass Dike. Table 12 summarizes the controlling elevations in the Upper Baker Dam rating curve and Figure 15 graphically illustrates the rating curve.

Table 12. Upper Baker Dam Controlling Elevations

Flow Condition			Elevation		Flow Depth Over Spillway (feet)	
Gated Free Spill	**Weir Flow**	**Controlling Structure**	**(feet) NGVD29**	**(feet) NAVD88**		**Reference**
		Spillway Crest	694.00	697.77	0.00	Plate 2-3 (USACE 2000)
X		Bottom of unremovable gates	718.00	721.77	24.00	Drawing No. 9548-FH-39A
X	X	Top of wall east abutment	732.00	735.77	38.00	Plate 2-3 (USACE 2000)
X	X	Top of roadway	732.00	735.77	38.00	Plate 2-3 (USACE 2000)
X	X	Top of wall west abutment	732.00	735.77	38.00	Plate 2-3 (USACE 2000)
X	X	Top of West Pass dike	734.00	737.77	40.00	Plate 2-4 (USACE 2000)

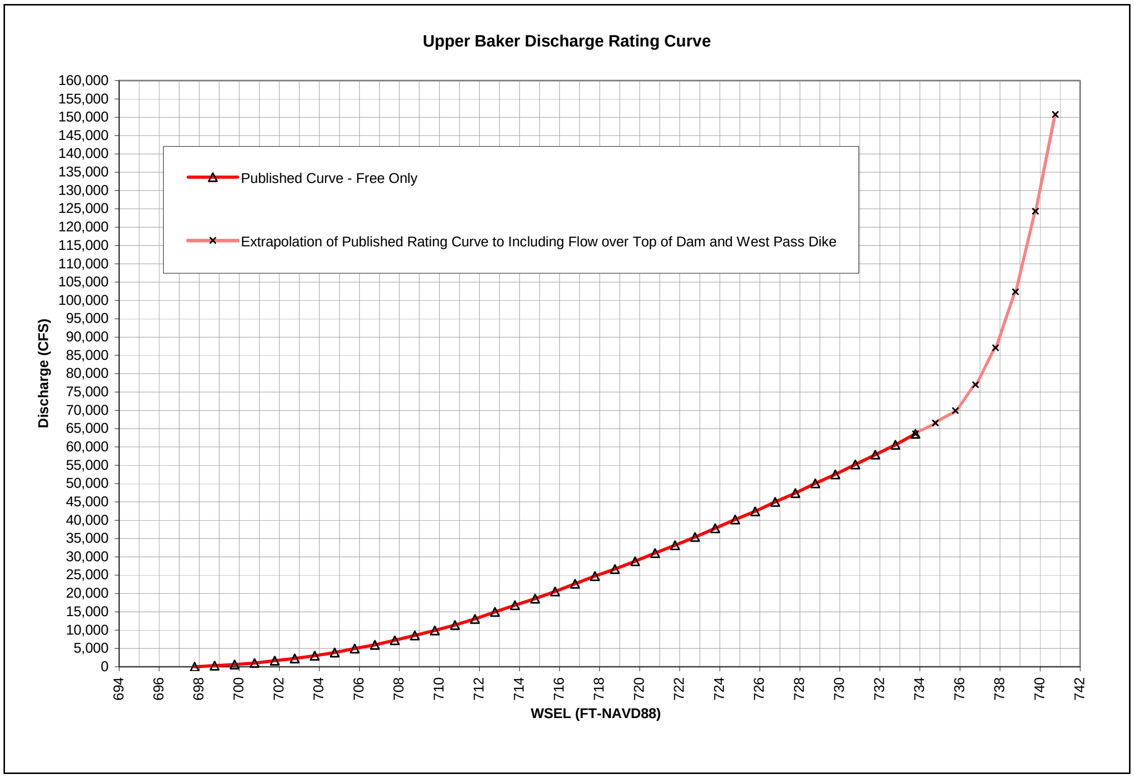


Figure 15. Upper Baker Spillway Discharge Rating Curve Used for Routing Analysis

For the Lower Baker Dam rating curve, an independent analysis was performed to verify the published curves and to incorporate new topographic survey data for the dam (PSE 2005), which describe features that impact the published rating curve. A vertically faced rock outcrop that is located just upstream of the west abutment likely causes local contraction of approach flows and acts to reduce the effective weir length of the west non-overflow section. Immediately upstream of the east abutment, the headgate building likely has a similar effect on the approach flows to the east non-overflow section.

Lower Baker's rating curve is based on a series of controlling elevations, which are summarized in Table 13. Free discharge of the spillways was calculated using Equation 3 until elevation 439.08 ft-NAVD88, at which point the fixed vertical slide gates (1 and 2) begin acting under submerged conditions. Free discharge over the spillways incorporated a variable coefficient of discharge, C_d, which was calculated based on the hydraulic head over the spillway and varied from 3.10 to 4.22. Adjustments to C_d were based on Figure 34 of *Engineering Monograph 9* (Bradley 1952). To account for the reduction in conveyance through the spillway bays caused from both piers and abutment constriction, an effective length was calculated using Equation 4. A blunt nose pier (Type I) was assumed for all piers, with a corresponding coefficient of pier contraction, Kp, determined using Chart 111-5 from USACE (1987). A 0.10 value for the coefficient of abutment contraction, Ka, was determined from Sheet III-3/1 (USACE 1987).

Table 13. Lower Baker Dam Controlling Elevations								
Flow Condition					**Elevation**		**Flow Depth Over Spillway (ft)**	
Gated Free Spill	**Submerged Orifice**	**Weir – Submerged**	**Weir - Broad Crested**	**Controlling Structure**	**ft (NGVD29)**	**ft (NAVD88)**		**Reference**
X				Spillway Crest	424.87	428.62	0.00	(MWH 2004)
X	**X**			Bottom of unremovable gates when fully open (Gates 1 & 2)	435.33	439.08	10.46	(MWH 2004)
X	**X**			Bottom of unremovable gate when fully open (Gate 23)	436.87	440.62	12.00	(MWH 2004)
X	**X**			Bottom of unremovable gates when fully open (Gates 3 - 10)	440.37	444.12	15.50	(MWH 2004)
X	**X**	**X**		Top of wall east abutment	440.82	444.57	15.95	2005 Survey
X	**X**	**X**	**X**	Top of wall above head gates near east abutment	440.84	444.59	15.97	2005 Survey
X	**X**	**X**	**X**	Top of wall west abutment	441.39	445.14	16.52	2005 Survey
X	**X**	**X**	**X**	Transition from submerged weir to broad-crested weir at west abutment	443.98	447.73	19.11	Calculated
X	**X**		**X**	Bottom of gate opening for removable gates (Gates 11 through 22)	445.51	449.26	20.64	(MWH 2004)
	X		**X**	Top Deck of Dam	446.89	450.64	22.02	2005 Survey
	X		**X**	Top of wall above Gates 3 – 23	449.77	453.52	24.90	2005 Survey
	X		**X**	Top of unremovable gates (Gates 1 & 2)	449.83	453.58	24.96	(MWH 2004)
	X		**X**	Top of unremovable gate (Gate 23)	451.37	455.12	26.50	(MWH 2004)
	X		**X**	Top of unremovable gates (Gates 3 - 10)	454.57	458.32	29.70	(MWH 2004)
	X		**X**	Top of wall west abutment above Gates 1 & 2	453.16	456.91	28.29	2005 Survey

$$Q_{Free} = C_d L_{Eff} H^{3/2} \qquad \text{(Equation 3)}$$

$$L_{Eff} = L - 2(NK_p + K_a)H \qquad \text{(Equation 4)}$$

where,

C_d = Coefficient of Discharge
L_{Eff} = Effective Discharge Length, ft
L = Length of Spillway, ft
N = Number of piers
K_p = Coefficient of Pier Contraction (HDC Chart 111-5)
K_a = Coefficient of Abutment Contraction
H = Discharge Head, ft

Starting at elevation 439.08 ft-NAVD88, the flow through spillway bays 1 and 2 behaves as orifice flow because the gates cannot be removed. By elevation 449.26 ft-NAVD88, the flow through all spillway bays behaves as orifice flow. Submerged orifice flow was calculated using a standard orifice equation with a constant discharge coefficient (Equation 5). It has been suggested that little variance in the discharge coefficient exists for heads greater than 5 feet (Brater & King 1976), as is the case at Lower Baker Dam. A constant coefficient of 0.64 was assumed based on the curved sill (crest of the ogee) (Zipparro & Hasen, 1993).

$$Q_{Orifice} = C_d A\sqrt{2g\bar{h}} \qquad \text{(Equation 5)}$$

where,

A = Apparent Opening Area, ft^2
G = Gravitational Constant, 32.2 ft/s^2
$\bar{h}$ = Hydraulic Head from Center of Apparent Opening, ft

At elevation 444.57 ft-NAVD88, flows begin overtopping the east non-overflow section of the dam. Flow over this section was assumed to act under submerged weir flow caused by the interaction of the upstream and downstream parapet walls. A submerged weir equation (Brater and King 1976) (Equation 6) was used until the elevation at which the tailwater effect caused by the downstream parapet wall was found to be minimal. A broad crested weir equation was used for all subsequent elevations (Equation 7). A coefficient of discharge of 2.63 was assumed constant for all broad crested weir flow. Adjustments to the rating curve were made to account for the effect of the headgate building on the approach flow.

$$\frac{Q}{Q_1} = \left[1 - \left(\frac{H_2}{H_1}\right)^{1.5}\right]^{0.385} \qquad \text{(Equation 6)}$$

where,

Q = Discharge over submerged weir, cubic feet per second (cfs)
Q = Discharge at the head, H1 computed from the free discharge weir equation, cfs
H_2 = head on the downstream side of the submerged weir, feet
H_1 = head on the upstream side of the submerged weir, feet

$$Q_{Broad} = KLH^{3/2} \qquad \text{(Equation 7)}$$

where,

K = Coefficient of Discharge
L = weir length, feet
H = Depth of flow over weir

Weir flow over the west non-overflow section of the dam begins at elevation 445.14 ft-NAVD88. A similar approach used for the east non-overflow section with flow characteristics transitioning to a broad crested weir at elevation 447.73 ft-NAVD88. Flows over the mid section of the dam, above the vertical slide gates, were computed using a broad crested weir equation starting at elevation 453.52 ft-NAVD88 (Equation 7).

The resulting spillway discharge rating curve used for routing flows through Lower Baker Dam is shown in Figure 16, which also includes the currently published rating curve for Lower Baker Dam.

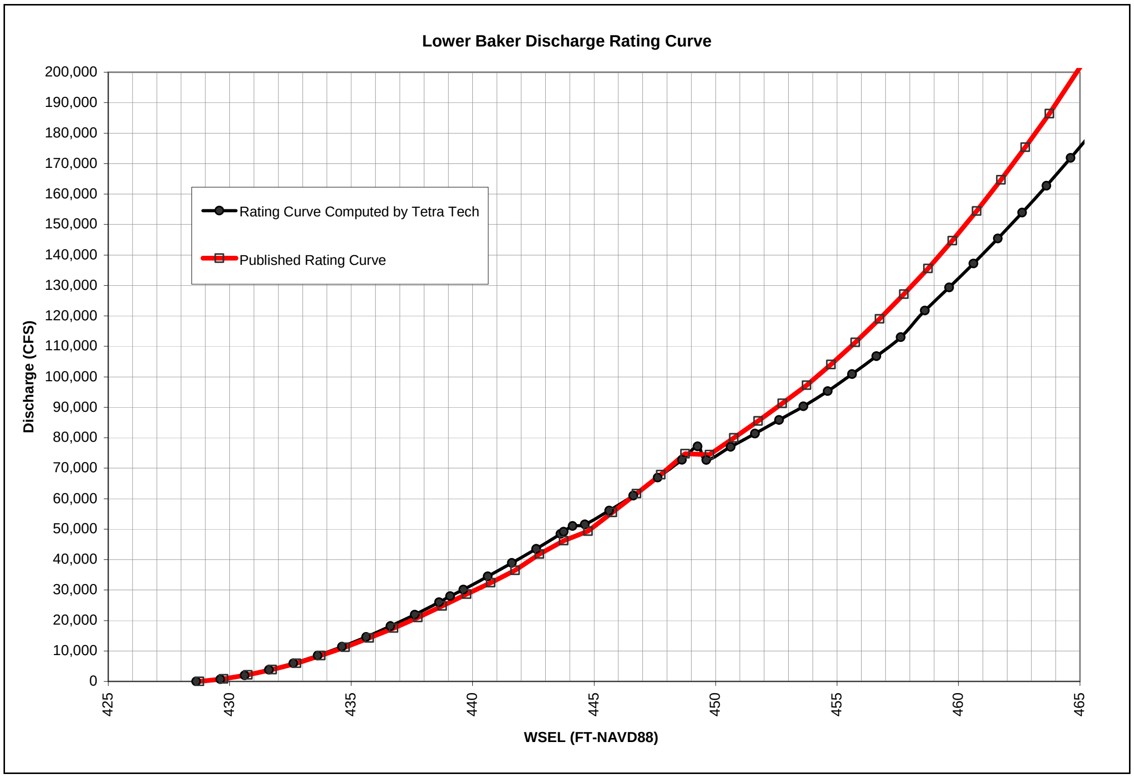


Figure 16. Existing and Revised Lower Baker Spillway Discharge Rating Curve

5.3 RESERVOIR ROUTING RESULTS

The use of the HEC-5 model allows for the simulation of the Baker River project under flood control scenarios for the flood control season, defined as extending between November 1st and March 1st. During this period, up to 74,000 acre-feet of federally authorized flood control volume is provided at Upper Baker Dam. When a large precipitation event occurs, Upper Baker Dam is operated to reduce flood damages in the Skagit River valley. Assuming a starting condition in the reservoir at the minimum flood control pool elevation of 711.70 feet NAVD88, the operation of Upper Baker Dam during such an event is summarized as follows:

- When the minimum flood control pool is reached on a rising flood, Puget Sound Energy (PSE) must coordinate with the National Weather Service Reservoir Control Center (NWS-RCC) to determine whether to begin passing inflow to maintain the pool elevation or to begin active flood control storage. In either event, the minimum discharge from Upper Baker must be increased to the mandatory 5,000 cfs minimum flow rate.
- An Official Flood Control Notice (OFCN) is issued by the NWS-RCC when the natural (unregulated) main stem Skagit River flow rate at Concrete is forecast to reach 90,000 cfs on a rising flood within eight hours.
- When an OFCN is issued, the releases from Upper Baker Dam are immediately reduced to the minimum mandatory discharge of 5,000 cfs. If the powerhouse is unable to release the entire minimum discharge, the remaining amount is released through the spillways.
- Minimum releases are maintained until the flood crest has occurred at Concrete or until higher discharges are required by the Special Gate Regulation Schedule (SGRS). Outflows are then determined from the SGRS.
- Maintain releases according to the SGRS until the reservoir rises to maximum surcharge pool elevation of 730.77 feet NAVD88. If inflows continue to rise, the spill gates must be opened to provide spillway free flow.

Since the issuance of a OFCN is based on flow conditions on the main stem Skagit River, it was necessary to develop boundary conditions in the main stem Skagit River. A 500-year return period flood event was therefore assumed to be occurring coincident with the PMF event in the Baker River watershed. The Seattle District USACE provided the necessary inflow design hydrographs for this condition (Perkins 2006).

In addition to routing the inflow hydrographs assuming operation of the Upper Baker Dam according to the flood control operation schedule in USACE (2000), the inflow hydrographs were also routed assuming spillway free flow immediately after the OFCN would be issued. This scenario assumed that the flood control operation steps would not occur and that Upper Baker Dam would release flows at the capacity of the spillway soon after the OFCN is issued.

The November inflow hydrographs were considered first because they are characterized by the highest peak flow rates and the largest volumes, and therefore are likely to produce the critical PMF hydrograph. The November inflow hydrographs for the nine combinations of temporal distributions and storm centering scenarios were routed through the Baker River project using the HEC-5 reservoir operation model. Table 14 summarizes the outflow hydrograph results, assuming that Upper Baker Dam was operated strictly in accordance with the flood control operation procedures outlined in USACE (2000). Table 15 summarizes the outflow hydrograph results assuming free spillway discharge immediately after the issuance of an OFCN. In both of these tables, the overtopping elevation at Upper Baker is 735.77 feet (NAVD88), which represents the top of the dam. The overtopping elevation at Lower Baker Dam is 444.57 feet (NAVD88), which represents the overtopping elevation at the east non-overflow section of the dam.

Table 14. Reservoir Routing Summary for NOVEMBER Inflow Hydrographs – With Flood Control Operation

	Model Scenario	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. Pool Elev. (ft NAVD88)	Overtopping (ft)
UPPER CENTERING					
Upper Baker Reservoir	U_05	163,200	126,100	739.84	**4.07**
	U_20	160,300	109,300	739.08	**3.31**
	U_50	160,900	107,100	738.99	**3.22**
Lower Baker Reservoir	U_05	156,100	136,700	460.56	**15.99**
	U_20	136,200	120,800	458.49	**13.92**
	U_50	133,600	118,900	458.24	**13.67**
ENTIRE WATERSHED CENTERING					
Upper Baker Reservoir	E_05	158,700	119,200	739.54	**3.77**
	E_20	155,800	102,200	738.76	**2.99**
	E_50	156,500	100,400	738.64	**2.87**
Lower Baker Reservoir	E_05	150,900	133,700	460.18	**15.61**
	E_20	130,600	118,300	458.16	**13.59**
	E_50	128,400	116,300	457.89	**13.32**
LOWER CENTERING					
Upper Baker Reservoir	L_05	153,800	111,800	739.20	**3.43**
	L_20	150,900	95,900	738.34	**2.57**
	L_50	151,600	94,000	738.23	**2.46**
Lower Baker Reservoir	L_05	145,500	130,900	459.81	**15.24**
	L_20	126,200	115,800	457.83	**13.26**
	L_50	123,800	113,800	457.55	**12.98**

Table 15. Reservoir Routing Summary for NOVEMBER Inflow Hydrographs – With Spillway Free Flow

	Model Scenario	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. Pool Elev. (ft NAVD88)	Overtopping (ft)
UPPER CENTERING					
Upper Baker Reservoir	U_05	163,200	103,100	738.80	**3.03**
	U_20	160,300	89,600	737.94	**2.17**
	U_50	160,900	88,400	737.86	**2.09**
Lower Baker Reservoir	U_05	128,800	117,400	458.04	**13.47**
	U_20	113,300	104,300	456.19	**11.62**
	U_50	111,900	103,000	455.97	**11.40**
ENTIRE WATERSHED CENTERING					
Upper Baker Reservoir	E_05	158,700	96,500	738.39	**2.62**
	E_20	155,800	83,700	737.44	**1.67**
	E_50	156,500	82,900	737.36	**1.59**
Lower Baker Reservoir	E_05	123,600	114,200	457.61	**13.04**
	E_20	110,000	102,000	455.79	**11.22**
	E_50	109,000	100,700	455.57	**11.00**
LOWER CENTERING					
Upper Baker Reservoir	L_05	153,800	89,100	737.91	**2.14**
	L_20	150,900	77,800	736.86	**1.09**
	L_50	151,600	77,000	736.77	**1.00**
Lower Baker Reservoir	L_05	120,000	110,900	457.18	**12.61**
	L_20	113,300	100,000	455.43	**10.86**
	L_50	112,200	98,800	455.23	**10.66**

The inflow hydrographs for the preceding month (October) and the subsequent month (December) were then routed using the HEC-5 model, to verify that the November inflow hydrographs were resulting in the critical conditions. Like the November conditions, the December HEC-5 runs assumed a starting elevation in Upper Baker of 711.57 feet (minimum flood pool) and a starting elevation in Lower Baker of 442.35 feet (normal full pool). The October runs assumed a starting water surface elevation in Upper Baker equal to 725.77 feet (minimum flood pool for October 15) and a starting elevation in Lower Baker of 442.35 (normal full pool). Tables 16 and 17 summarize the results for both months, assuming that Upper Baker Dam was operated strictly in accordance with the flood control operation procedures outlined in USACE (2000).

Table 16. Reservoir Routing Summary for OCTOBER Inflow Hydrographs - With Flood Control Operation

	Model Scenario	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. Pool Elev. (ft NAVD88)	Overtopping (ft)
UPPER CENTERING					
Upper Baker Reservoir	U_05	139,300	103,600	738.83	**3.06**
	U_20	138,700	100,200	738.63	**2.86**
	U_50	138,100	101,800	738.74	**2.97**
Lower Baker Reservoir	U_05	125,900	112,700	457.41	**12.84**
	U_20	122,200	109,000	456.92	**12.35**
	U_50	124,300	111,600	457.26	**12.69**
ENTIRE WATERSHED CENTERING					
Upper Baker Reservoir	E_05	134,400	97,300	738.44	**2.67**
	E_20	133,800	94,000	738.23	**2.46**
	E_50	133,200	96,000	738.36	**2.59**
Lower Baker Reservoir	E_05	120,900	109,500	456.99	**12.42**
	E_20	117,300	105,900	456.47	**11.90**
	E_50	119,700	108,700	456.88	**12.31**
LOWER CENTERING					
Upper Baker Reservoir	L_05	131,200	93,300	738.18	**2.41**
	L_20	130,500	90,000	737.97	**2.20**
	L_50	130,000	92,000	738.10	**2.33**
Lower Baker Reservoir	L_05	120,100	109,600	457.00	**12.43**
	L_20	118,500	106,000	456.49	**11.92**
	L_50	119,700	108,900	456.90	**12.33**

Table 17. Reservoir Routing Summary for DECEMBER Inflow Hydrographs – With Flood Control Operation

	Model Scenario	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. Pool Elev. (ft NAVD88)	Overtopping (ft)
UPPER CENTERING					
Upper Baker Reservoir	U_05	155,600	114,400	739.32	**3.55**
	U_20	153,500	99,300	738.57	**2.80**
	U_50	153,600	98,300	738.51	**2.74**
Lower Baker Reservoir	U_05	142,100	125,100	459.06	**14.49**
	U_20	124,400	111,300	457.22	**12.65**
	U_50	123,300	110,300	457.09	**12.52**
ENTIRE WATERSHED CENTERING					
Upper Baker Reservoir	E_05	151,200	107,500	739.01	**3.24**
	E_20	149,200	93,400	738.19	**2.42**
	E_50	149,300	92,500	738.13	**2.36**
Lower Baker Reservoir	E_05	136,700	122,300	458.70	**14.13**
	E_20	120,000	108,700	456.88	**12.31**
	E_50	118,800	107,700	456.74	**12.17**
LOWER CENTERING					
Upper Baker Reservoir	L_05	146,600	100,100	738.62	**2.85**
	L_20	144,500	86,700	737.74	**1.97**
	L_50	144,700	86,100	737.68	**1.91**
Lower Baker Reservoir	L_05	131,400	119,900	458.38	**13.81**
	L_20	121,500	106,500	456.57	**12.00**
	L_50	121,000	105,700	456.44	**11.87**

Conclusions drawn from the results presented in Tables 14 through 17 include the following:

- For all months, the Upper centering scenario controls for both Upper Baker Dam and Lower Baker Dam.
- The month of November produces not only the critical inflow hydrograph (see Tables 9 and 10) but also the critical PMF outflow hydrograph.
- The temporal distribution characterized with the high intensity segment occurring later in the storm (the 5% EP scenario) results in the highest reservoir elevations for both dams. This is attributed to the delay in inflow volume associated with this back-loaded storm. Overtopping depths resulting from this temporal distribution are up to one (1) foot greater than those associated with either the 20%EP or 50%EP distributions.
- In general, the reservoir routing results are relatively insensitive to the assumption of 20% EP or 50% EP temporal distributions. The overtopping depths associated with these two distributions are typically within 0.2 feet of each other.
- In comparing the results in Table 14 against those in Table 15, the sensitivity of the results in regards to how the Upper Baker reservoir is operated is apparent. For the U_05 scenario, if Upper Baker Dam is operated according to the procedures in the water control manual, the maximum reservoir elevation is 4.07 feet above the top of the dam. If the reservoir is operated to maximize outflow during the rising limb of the hydrograph, the maximum reservoir elevation is 3.03 feet above the top of the dam. Assuming free spillway at Upper Baker Dam also has an effect on the results at Lower Baker Dam, reducing the overtopping depth from 15.99 feet to 13.47 feet.

Several figures are included to summarize the results. Figures 17 and 18 illustrate the Baker Project inflow hydrographs, outflow hydrographs and reservoir elevations associated with the U_05 model, assuming flood control operation. As seen in Figure 17, the outflow from Upper Baker Dam is reduced to the mandatory minimum flow rate of 5,000 cfs and maintained for nearly 24 hours. This is triggered by the unregulated 90,000 cfs flow conditions in the Skagit River at Concrete. Outflow begins to increase above mandatory minimum at hour 48 when outflows are determined from the SGRS. This occurs when the reservoir has risen to an elevation of approximately 722 feet, roughly 6 feet below top of flood pool. When the reservoir pool elevation reaches the maximum surcharge elevation (730.77 feet), the spillway gates are fully opened to maximize outflow. Figure 18 shows Lower Baker capable of passing the inflow for nearly the first 50 hours of the inflow hydrograph. From this point on, the inflow rate exceeds the spillway capacity.

Figures 19 and 20 illustrate the Baker Project inflow hydrographs, outflow hydrographs and reservoir elevations associated with the U_05 model, assuming free spillway discharge soon after the OFCN is issued. As seen in Figure 19, with the exception of a short period of time (about six hours) where the outflows are reduced to the mandatory minimum 5,000 cfs flow rate, the computed outflows are equal to the spillway capacity for the duration of the rising limb of the inflow hydrograph.

Finally, Figures 21 and 22 present a comparison of the reservoir elevations resulting from the U_05, U_20, and U_50 models for Upper Baker and Lower Baker respectively. These figures use the flood control operation output and illustrate the duration of overtopping for each of the temporal distributions.

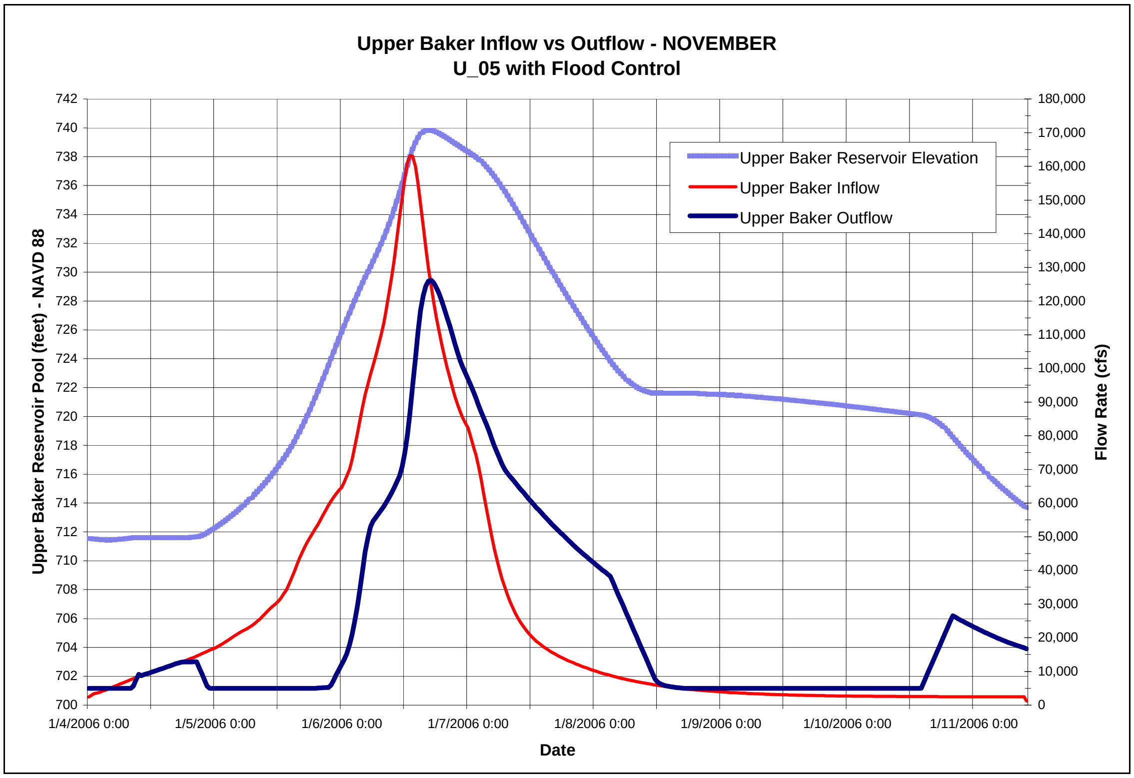


Figure 17. NOVEMBER Flood Routing Results for Upper Baker for U_05 with Flood Control

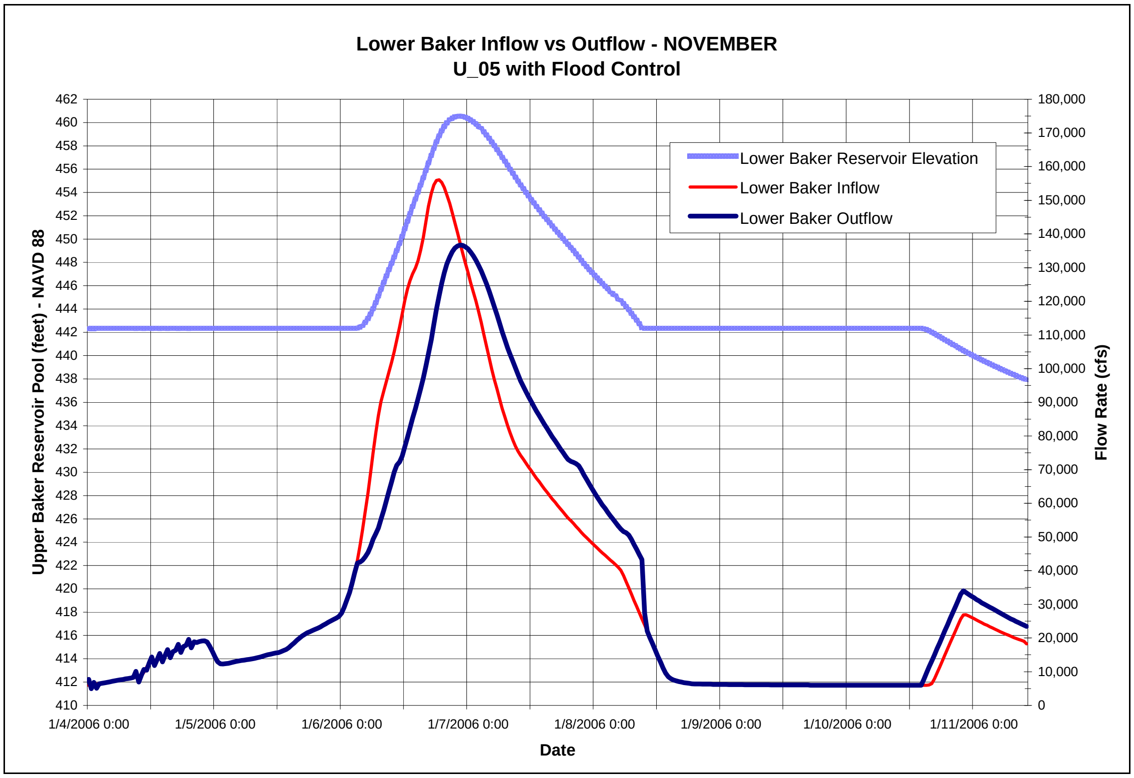


Figure 18. NOVEMBER Flood Routing Results for Lower Baker for U_05 with Flood Control

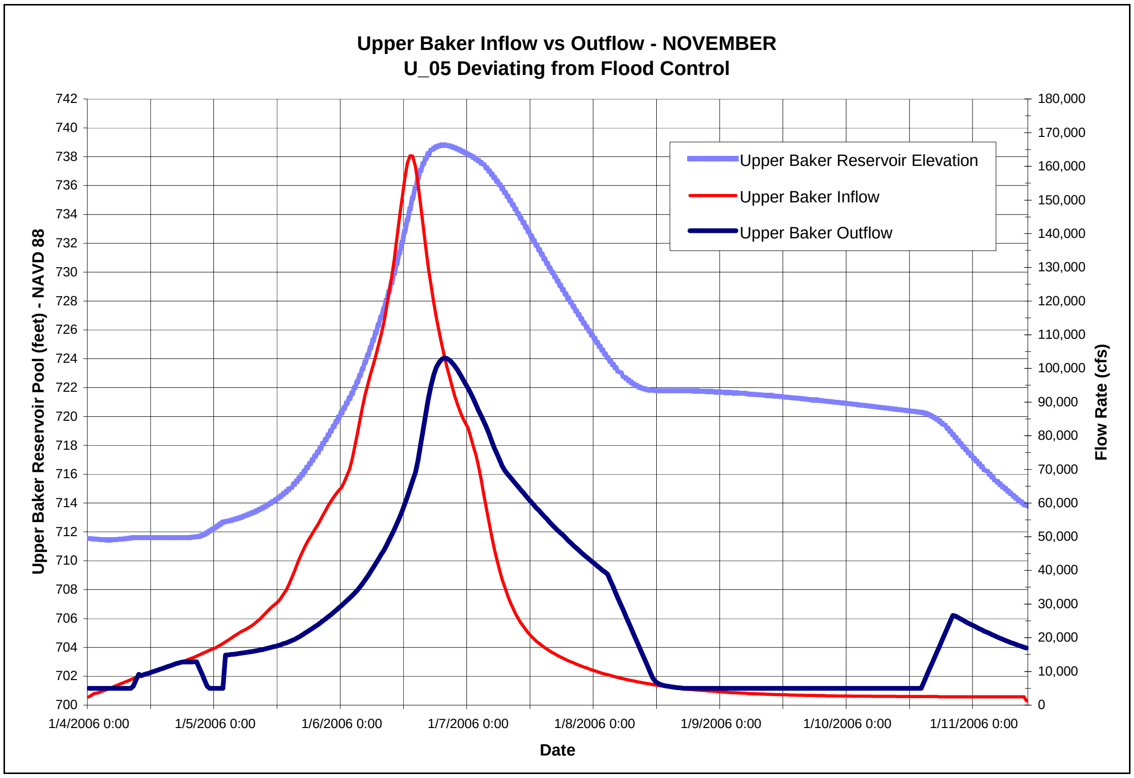


Figure 19. NOVEMBER Flood Routing Results for Upper Baker for U_05 with Free Discharge

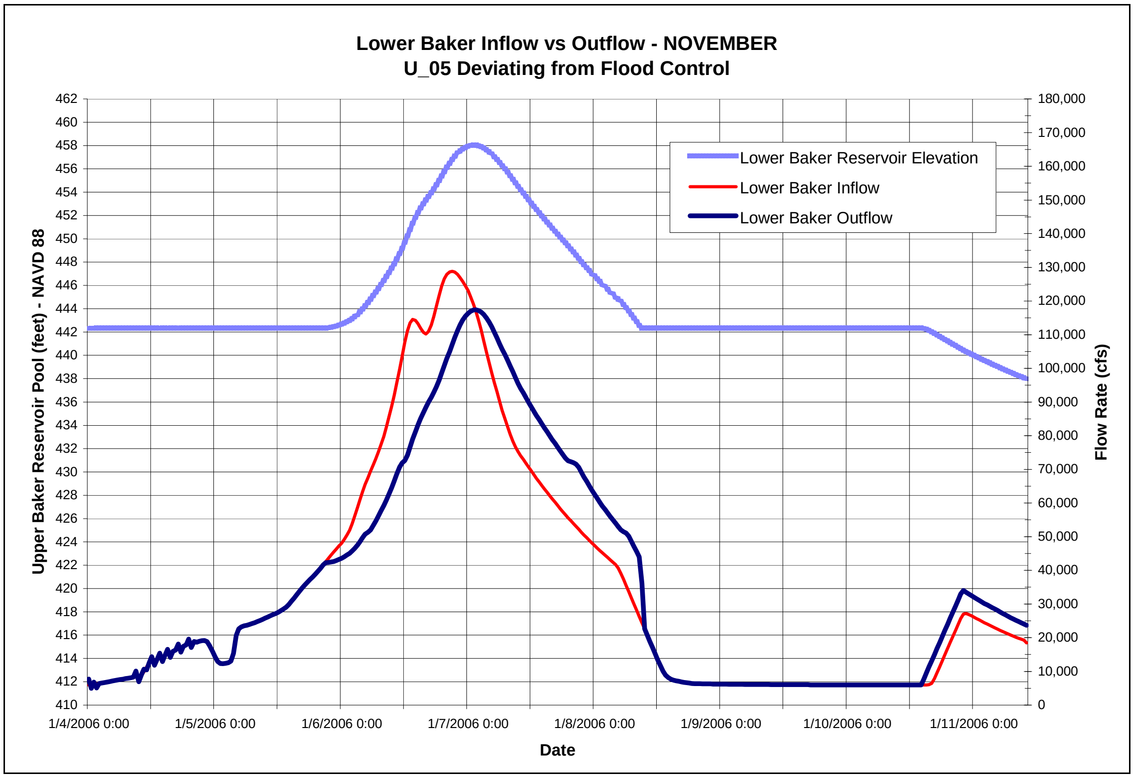


Figure 20. NOVEMBER Flood Routing Results for Lower Baker for U_05 with Free Discharge

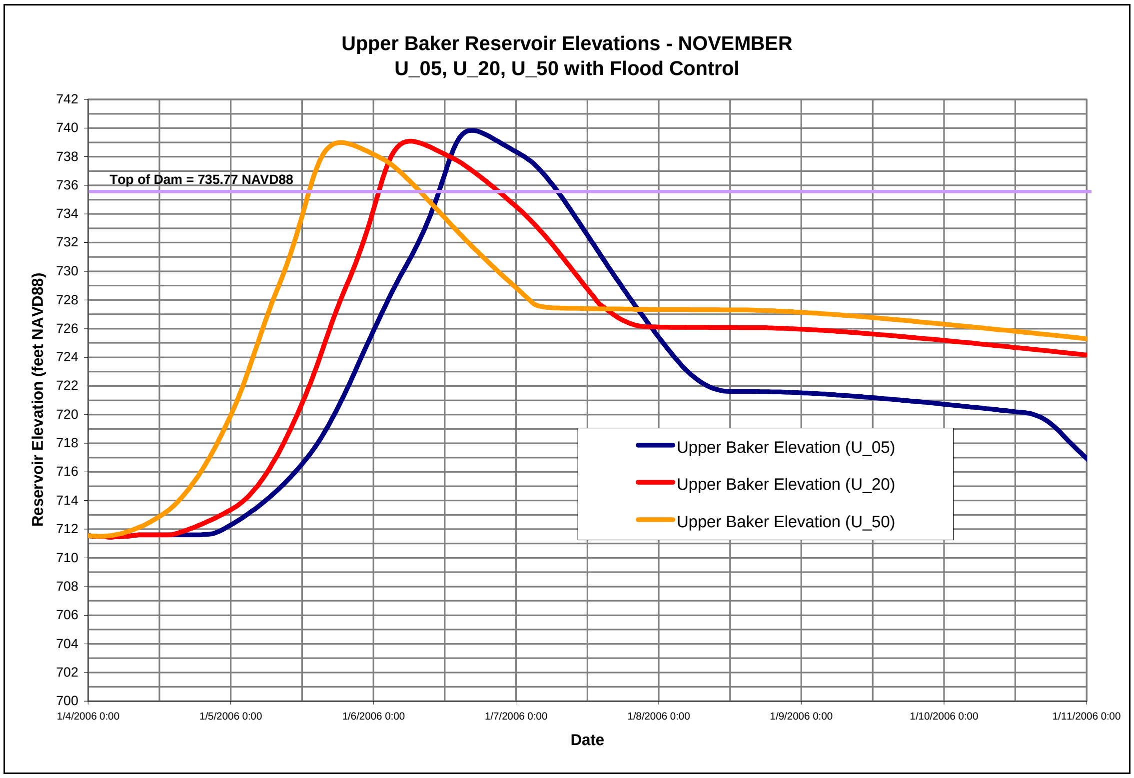


Figure 21. NOVEMBER Upper Baker Reservoir Elevations for Three Temporal Distributions

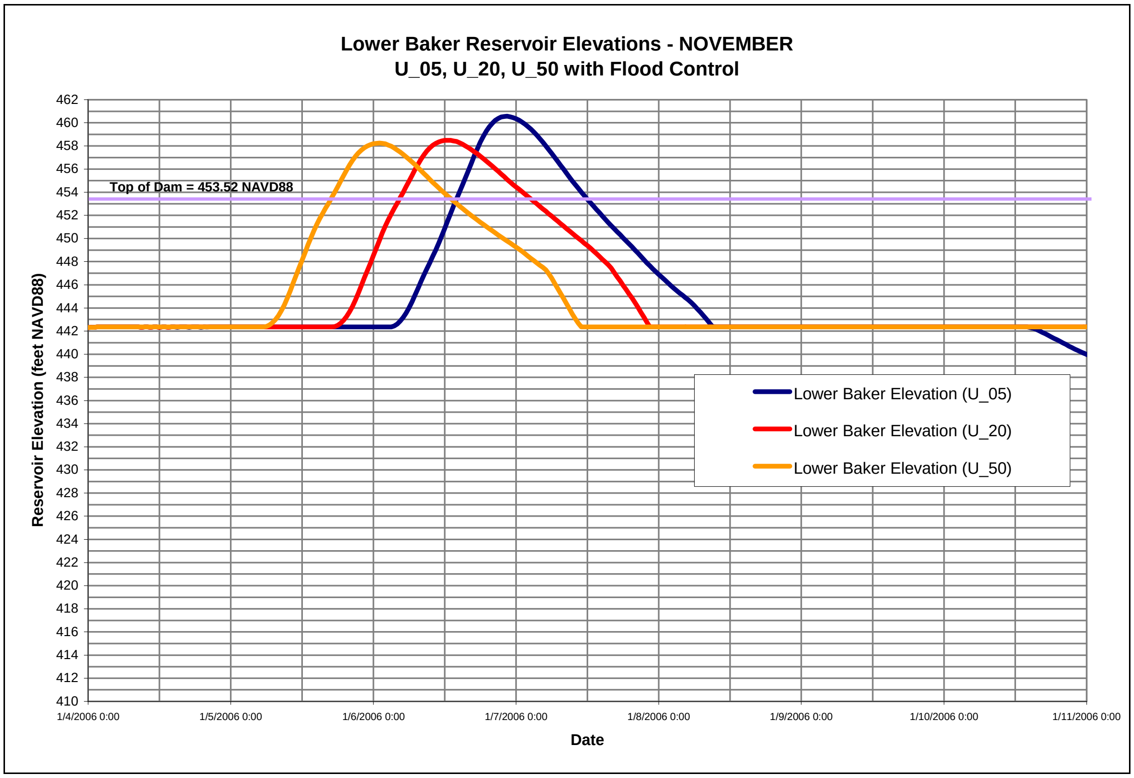


Figure 22. NOVEMBER Lower Baker Reservoir Elevations for Three Temporal Distributions

6 SUMMARY OF INITIAL PMF RESULTS

This section presents the initial results of the PMF study. The initial results presented are derived from conservative, yet reasonable estimates for the magnitude of each hydrometeorologic input parameter, as described in the previous sections. It is recognized that combining multiple parameters that are based on conservative assumptions may lead to extremely unlikely and highly conservative results due to compounding conservatism. The GSA, presented later in Section 7, assesses the ultimate effect of combining conservative parameter values and provides the framework for a final recommended set of parameter values for defining the PMF which are considered reasonable.

6.1 INITIAL PMF PARAMETERS

Table 18 summarizes the antecedent and coincident hydrometeorological conditions used for the initial PMF results, based on the tables presented in Section 5.3. The following sections briefly summarize the basis for the selection of these conditions.

The magnitudes of the air temperature and wind speed were essentially fixed in the analysis. The air temperature and wind speed magnitudes were developed from methods presented in HMR-57 and were documented in Tetra Tech (2006c). However, the sequential ordering of the air temperature and wind speed time series was established to correspond with the storm temporal pattern. This re-ordering process was explained previously in Sections 3.6 and 3.7. Therefore, the air temperature and wind speed parameters are not included in the following discussion.

Table 18. Summary of Hydrometeorological Inputs for Initial PMF Results

Input Parameter	**Value used for Initial PMF Determination**
Seasonality of Occurrence	November
Centering of Storm	Upper
Storm Temporal Pattern	5% exceedance probability
Antecedent Precipitation	25.4 inches at key precipitation station [a]
Antecedent Snow Water Equivalent	90% non-exceedance probability = 20.3 inches at key snow course station [b]
Antecedent Snowpack Density	0.352 [c]
Antecedent Reservoir Elevation Lower Baker	442.35 feet NAVD88
Antecedent Reservoir Elevation Upper Baker	711.57 feet NAVD88
Air Temperatures	Determined from HMR-57
Wind Speeds	Determined from HMR-57

a. Mean end-of-November value at key precipitation station (Upper Baker Dam)
b. Schreibers Meadow is the key snow course station
c. Average value determined from historical record

6.1.1 Seasonality of Occurrence

Inflow hydrographs were developed for all months. Based on the routing analysis of the October, November, and December inflow hydrographs, it was clear that the antecedent and coincident conditions for November combined with the November PMP produced the most critical results for the PMF study for both Upper Baker and Lower Baker Dams.

6.1.2 Storm Centering

Using the methodology in HMR-57, three centering scenarios were considered in the initial PMF analysis. All other input parameters considered equal, the upper centering scenario, in which the general storm was centered in the portion of the watershed upstream of Upper Baker Dam, was found to produce the highest magnitude of inflow results for both Upper Baker Dam and the Lower Baker Dam, in terms of peak runoff and runoff volume. The upper centering scenario was also consistently associated with the highest peak reservoir elevations for both reservoirs.

6.1.3 Storm Temporal Pattern

Three storm temporal patterns were included in the initial portion of the PMF study, representing mid-loaded and back-loaded storm patterns. The most back-loaded storm pattern, with the 1-hour peak intensity at hour 58 (the 5% exceedance probability), was found to produce the highest magnitude of PMF results for both Upper and Lower Baker Dams. This was especially true for the routed results.

6.1.4 Antecedent Precipitation

Soil moisture conditions antecedent to the PMP event were assumed to be the product of a typical water year. This assumption resulted in near saturated conditions for the soils in the watershed. This assumption was reasonable and, because the soils were near saturated, was the most conservative assumption.

6.1.5 Antecedent Snow Water Equivalent

Antecedent snowpack conditions that were determined to provide the largest magnitude of snowmelt volume were found to be associated with non-exceedance probabilities of less than 99% for months early in the snow season (November through February). For all other months where snow accumulation is possible, the snowpack associated with the 99% non-exceedance probability was determined to provide the largest magnitude of snowmelt volume. Early season snowpacks in the Baker River watershed are historically characterized by snowpack densities less than the 0.40 in/in yield density. Therefore, during simulation of the PMP, precipitation falling on these early season snowpacks was initially absorbed by the snowpack as the snowpack “ripened” to the yield density. Deeper snowpacks, such as the 99% non-exceedance snowpack, were found to have the capability to absorb more precipitation and delay the snowmelt response sufficiently that the snowmelt volume was less than that associated with a shallower snowpack.

For the month of November, the maximum snowmelt condition was determined to be associated with a 90% non-exceedance probability, which produced 103,270 acre-feet of snowmelt volume; nearly 30 percent more than the 80,050 acre-feet associated with the 99% non-exceedance probability snowpack.

6.1.6 Antecedent Snowpack Density

Mean values for the end-of-month snowpack density were used for all of the PMF runs. The range of the historical snowpack density values was very narrow, and it was felt that average conditions were reasonable and not overly conservative.

6.1.7 Antecedent Reservoir Elevation

The end-of-month antecedent reservoir elevation at Upper Baker Dam was set to be equal to the minimum flood control pool elevation (711.57 feet NAVD88), per USACE (2000). The end-of-month antecedent reservoir elevation at Lower Baker Dam was assumed to be equal to the normal full pool elevation (442.35 feet NAVD88). Review of historical end-of-month data showed that the reservoir levels were typically at or below these values. The exception was after extreme storm events. A review of five flood events in November indicated that Upper Baker reservoir was on average drawn back down to flood control elevation within 8 days of the end of the precipitation event. Therefore, it was felt that the flood control elevation in the Upper Baker reservoir and the normal full pool elevation in the Lower Baker reservoir were reasonable values for the antecedent conditions.

6.2 RESULTS

The antecedent/coincident conditions summarized above produced a PMF simulation with 4.07 feet of overtopping at the Upper Baker Dam and 15.99 feet of overtopping at the Lower Baker Dam. These represent the initial PMF results, selected from the family of model simulations summarized in Section 5.3 (see Table 14).

Table 19 summarizes the overtopping depths for the initial PMF results. This table compares the maximum PMF pool elevation of 739.84 feet (NAVD88) and 460.56 feet (NAVD88) for Upper Baker and Lower Baker reservoirs, respectively, against the elevations of various features of the two dams.

Table 19. Overtopping Depths for Initial PMF Results

	Critical PMF Reservoir Elevation (ft-NAVD88)	Elevation of Feature (ft-NAVD88)	Overtopping Depth (feet)
UPPER BAKER DAM			
Top of Dam	739.84	735.77	**4.07**
Top of West Pass Dike		737.77	**2.07**
LOWER BAKER DAM			
Top of Wall – East Abutment	460.56	444.57	**15.99**
Top of Wall – West Abutment		445.14	**15.42**
Top Deck of Dam		450.64	**9.92**
Top of Parapet Wall		453.52	**7.04**

As a point of comparison, the most recently published PMF study for the Baker River Project (Hydrocomp 1969) calculated a maximum pool elevation of 729.9 feet NGVD29 (733.67 feet NAVD88) at the Upper Baker reservoir and 446.8 feet NGVD29 (450.55 feet NAVD88) at the Lower Baker reservoir. The Hydrocomp study, which used HMR-43 to derive the PMP depth duration curves, concluded that the PMF would not overtop Upper Baker Dam. This study also concluded that overtopping of the abutment sections (east and west) would occur at Lower Baker, but that overtopping of the top deck would not occur.

7 GLOBAL SENSITIVITY ANALYSIS

The Federal Energy Regulatory Commission defines the PMF as follows:

> “the flood that may be expected from the most severe
> combination of critical meteorological and hydrologic
> conditions that are reasonably possible in the drainage basin
> under study” (FERC 1993).

The initial PMF results presented in Section 6 are based on the most critical combination of conditions identified for this study. Several of the selected input values used for the development of the initial PMF model are based on conditions that are less likely to occur than average conditions. This is a reasonable approach for individual parameter selection, considering the definition of a PMF. However, the conservatism inherent in each of these inputs is compounding, so as to possibly produce a set of conditions for modeling the PMF that is extremely unlikely and beyond being considered “reasonably possible”.

A global sensitivity analysis (GSA) was performed to address the excessive conservatism resulting from the use of multiple conservative inputs. The GSA considered the likelihood of parameters actually having a selected value. Like a traditional one-at-time sensitivity analysis, the GSA allows for the determination of each parameter’s influence on the inflow and outflow hydrographs. However, unlike the traditional sensitivity analysis, the GSA also preserves dependencies among specific input parameters. For example, antecedent snowpack magnitudes are correlated to antecedent precipitation, and this dependency is maintained in the GSA. In addition, the probability, or likelihood, that a specific magnitude of antecedent precipitation would occur was defined by a probability distribution developed using the historical record. The methodology used to conduct the GSA is presented in the next section.

7.1 GLOBAL SENSITIVITY ANALYSIS METHODOLOGY

The GSA involved running the hydrologic model for 10,000 combinations of the following hydrometeorological inputs:

- Seasonality of occurrence
- Storm centering
- Storm temporal pattern
- Antecedent precipitation
- Antecedent snow water equivalent
- Antecedent snowpack density
- Antecedent reservoir elevation in Upper Baker
- Antecedent reservoir elevation in Lower Baker.

The 10,000 combinations of inputs were generated using a Monte Carlo sampling procedure that selects a value for each parameter from user-defined probability distributions, while maintaining the dependencies that exist among the specific input parameters. Due to the allowance for these dependencies, the sampling procedure maintains a certain logic in terms of which parameters are sampled before others and which parameters can be sampled independently of all others. Figure 23 uses a flow chart to illustrate the procedure that was used in sampling the input parameters. The procedure starts at the far left of the flow chart and proceeds to the right. The procedure is repeated, in the case of the Baker River analysis, 10,000 times.

The Monte Carlo procedure samples each of the probability density functions based on a computer-generated random number. For the Baker River PMF analysis, this process was repeated 10,000 times to generate 10,000 input parameter sets.

Once the 10,000 parameter sets were generated, the Stochastic Event Flood Model (SEFM) was used to determine antecedent soil moisture deficits, to compute snowmelt and snow accumulation, to conduct infiltration computations, and to generate and export 10,000 HEC-1 input files. Each HEC-1 input file contained a precipitation excess time series, unit hydrograph, and interflow hydrograph for each subbasin. The HEC-1 models were then executed in batch-mode and output was used to populate HEC-5 reservoir routing model input files. The 10,000 HEC-5 reservoir routing models were executed in batch-mode, and output was organized into an Excel spreadsheet. Output was generated for both the Upper Baker reservoir and the Lower Baker reservoir. For each of the 10,000 simulations, the Excel spreadsheet contained the sampled value for each input parameter, the maximum value of the reservoir inflow hydrograph, the maximum value of the outflow hydrograph, and the maximum reservoir elevations The spreadsheet format allowed the simulations to be sorted in order to generate graphs showing the model's sensitivity to a specific input parameter and histograms of model output that can be used to evaluate the conservatism of the initial PMF results.

The following section discusses the model inputs and the probability distributions and sampling methods used in the GSA.

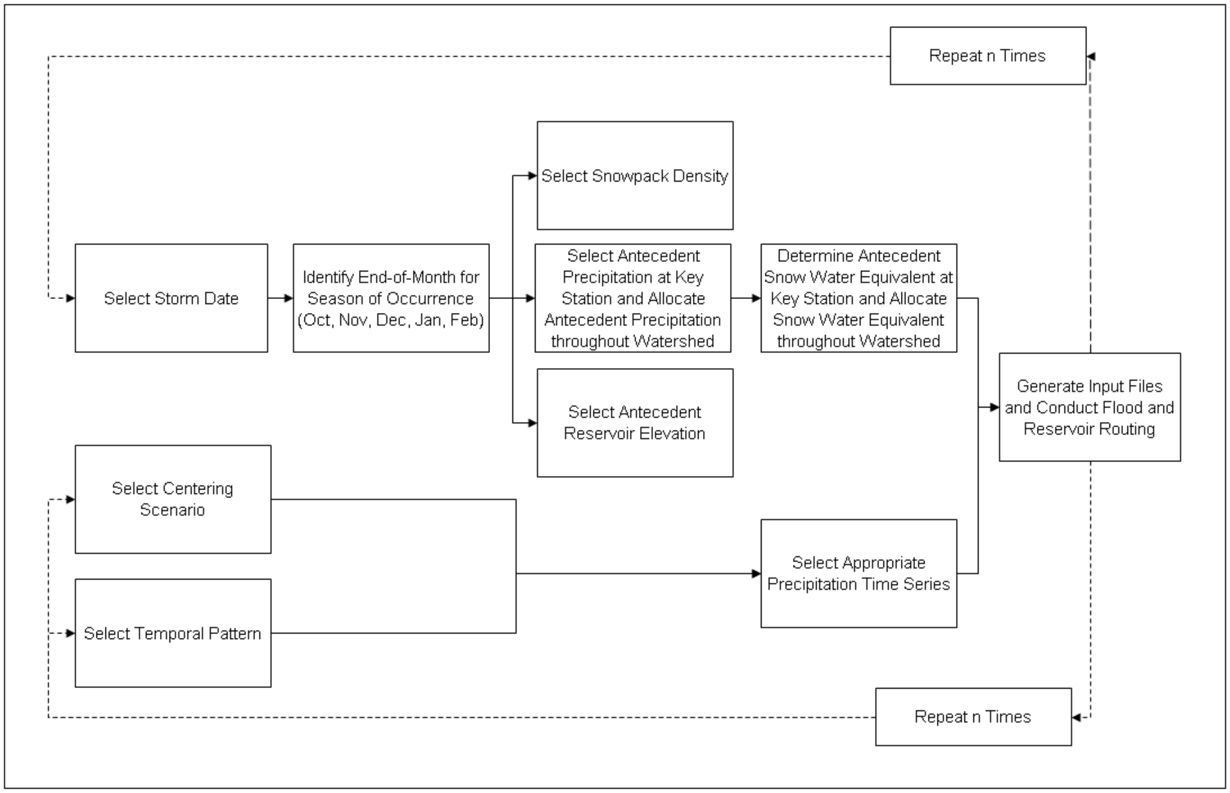


Figure 23. Flow Chart for Hydrometeorological Input Parameter Monte Carlo Sampling Procedure

7.2 INPUT PARAMETERS AND PARAMETER DISTRIBUTIONS

In order to conduct the GSA, it was necessary to first define the probability distribution for each parameter. The probability distributions allow the Monte Carlo sampling procedure to reflect the likelihood of each parameter value. For each parameter, data from the historical record was fit to a specific probability distribution. The SEFM User Manual (MGS 2004) was used to provide general guidance for selecting the distribution appropriate for each parameter. Distributions for each parameter were chosen by visually verifying that the distribution adequately described the data.

Even though the distributions are based on historical data, several factors can contribute to parameter uncertainty. Table 20 presents a qualitative assessment of the relative uncertainty in parameter estimation. The assessment considered several factors, including the length of the period of record for the data, the source of the data, and the resolution of the data.

Table 20. Relative Magnitude of Parameter Uncertainty in the Global Sensitivity Analysis

Input Parameter	Relative Magnitude of Parameter Uncertainty	Comments
Seasonality of Occurrence	Low	Seasonality distribution was based on a seasonality analysis conducted by Schaefer et al (2002) using a database of over 200 historical extreme storms in western Washington.
Centering of Storm	Moderate	The storm centering scenarios for this study were derived using HMR-57 depth-area-duration data that were developed from a sample of 18 extreme storms that occurred in orographic terrain.
Storm Temporal Pattern	Low	Temporal distribution was based on a probabilistic analysis conducted by Schaefer (1989) using a database of over 250 historical extreme storms in Washington State.
Antecedent Precipitation	Low	40 years of record at Upper Baker Dam. Included statistical data from 8 other stations in developing the distribution for antecedent precipitation
Antecedent Snow Water Equivalent	Moderate	Included data from nine snow course stations. However, SWE was not directly measured at the snow course stations and the period of records ranged from 27 to 46 years. It was necessary to supplement the data with HFAM model output for the end-of-October and end-of-November periods.
Antecedent Snowpack Density	High	Snowpack density was not directly measured and historical data was supplemented with HFAM model output
Antecedent Reservoir Elevation Lower Baker	Moderate	End-of-period values were used in the sampling procedure. Only the data from 1980 to the present (27 years) were used since this period most accurately reflects the current flood control operation at Upper Baker Dam.
Antecedent Reservoir Elevation Upper Baker	Moderate	End-of-period values were used in the sampling procedure. Only the data from 1980 to the present (27 years) were used since this period most accurately reflects the current flood control operation at Upper Baker Dam.

The GSA used correlation analyses to maintain model input parameter dependencies such as the correlation between antecedent snow water equivalent and antecedent precipitation. All other factors being equal, heavier snowpacks occur during wet years (higher antecedent precipitation), and lighter snowpacks occur during dry years (lower antecedent precipitation). Historical precipitation and snow water equivalent data were analyzed to determine the relationship between the two parameters. The Monte Carlo sampling procedure was used to select specific values of antecedent precipitation, and the snow water equivalent value was then computed from the equation describing the correlation. Table 21 summarizes the parameter dependencies that were maintained in the GSA.

The remainder of this section provides a brief discussion of the input parameters that were included in the GSA. This discussion includes details regarding the probability distributions used to describe the variability of each parameter.

Table 21. Hydrometeorological Input Parameter Dependencies for Global Sensitivity Analysis

Input Parameter	Dependencies	Comments
Seasonality of Occurrence	Independent	
Centering of Storm	Independent	Three storm centering scenarios were included
Storm Temporal Pattern	Independent	Seven temporal patterns were included
Antecedent Precipitation	Seasonality of Occurrence	
Antecedent Snow Water Equivalent	Seasonality of Occurrence & Antecedent Precipitation	
Antecedent Snowpack Density	Seasonality of Occurrence	Initial consideration was given to making dependent on antecedent precipitation or snowpack depth
Antecedent Reservoir Elevation Lower Baker	Seasonality of Occurrence	Initial consideration was given to making dependent on Upper Baker reservoir elevation or antecedent precipitation
Antecedent Reservoir Elevation Upper Baker	Seasonality of Occurrence	Initial consideration was given to making dependent antecedent precipitation

7.2.1 Seasonality of Occurrence

The seasonal relationship of PMP in the Baker River watershed was determined according to methodologies in HMR-57 (NWS 1994) and was documented in Tetra Tech (2006b). Figure 24 illustrates the results. As seen in this figure, the months of October through February, inclusive, are capable of producing PMP that is equal to 100 percent of the all-season index PMP value (October is included because HMR-57 assumes 100 percent PMP anytime the seasonal reduction factor is greater than 90%). All the other months of the year are capable of producing PMP that is less than 70 percent of the all-season index PMP. Only the months that are capable of producing 100 percent PMP were included in the GSA analysis.

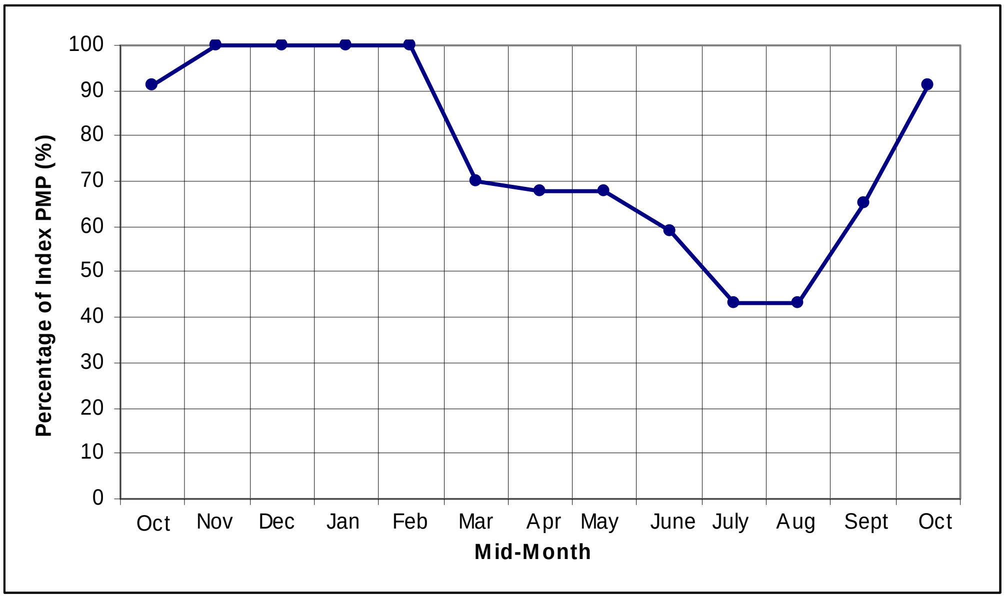


Figure 24. Seasonality of PMP

Seasonality of PMP occurrence was assumed to be equal to the seasonality of extreme storm occurrence in Western Washington. Seasonality of extreme storm occurrence in the mountains of Western Washington has been described by a twice-monthly probability distribution from a precipitation study by Schaefer et al. (2006). This study documents storm characteristics, including month of occurrence, for 53 historical extreme storms in the mountains of Western Washington. Table 22 lists the twice-monthly probability values for each month. Probability of occurrence was assigned for the first half and the second half of each month. As seen in this table, the month of November has the highest probability of occurrence for extreme storms. Figure 25 is the probability histogram for seasonality and Figure 26 is the cumulative probability distribution for seasonality.

Table 22. Twice Monthly Probabilities for Seasonal Occurrence of Extreme Storms

	Monthly Period									
	Oct16 – Nov15		Nov16 – Dec15		Dec16 – Jan15		Jan16 – Feb15		Feb16 – Mar15	
Twice Monthly Probability	0.070	0.130	0.210	0.140	0.110	0.100	0.090	0.080	0.070	0.000
End-of-Month Probability	0.200		0.350		0.210		0.170		0.070	

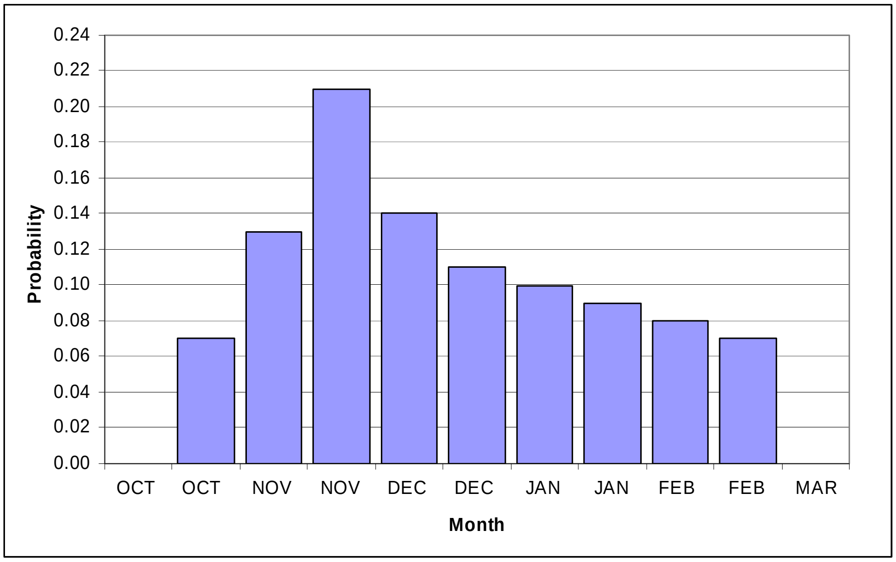


Figure 25. Probability Histogram for Seasonality of Extreme Storms

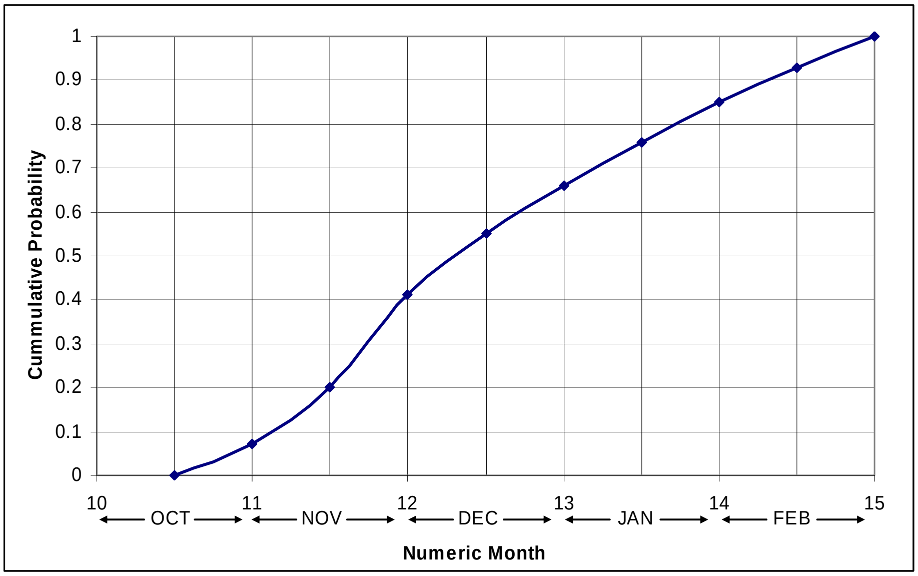


Figure 26. Cumulative Probability for Seasonality of Extreme Storms

The SEFM model uses procedures that conduct watershed modeling based on end-of-month hydrometeorological input conditions. The first step in the stochastic simulation is for the model to employ Monte Carlo sampling procedures to identify an event date, based on the twice-monthly probability distributions in Table 22. The model then identifies the end-of-month for that date. For example, if the Monte Carlo sampling generates a storm date between October 15th and November 15th, then the end-of-October hydrometeorological input data is chosen for the PMP occurrence.

7.2.2 Storm Centering

Three storm centering scenarios have been investigated for the general storm PMP in the Baker River watershed (Tetra Tech 2006b):

1. Upper Centering – General storm is centered over the 214.8 mi^2 Upper Baker tributary area
2. Entire Centering – General storm is centered over the entire 298.7 mi^2 watershed

3. Lower Centering – General storm is centered over the 83.9 mi^2 Lower Baker tributary area.

For the GSA, all centering scenarios were assumed to have equal probability of occurrence, as shown in Table 23. The storm centering scenario input parameter was sampled independently of all other hydrometeorological input parameters.

Table 23. Probabilities for Storm Centering Scenario

Upper Centering	Entire Watershed Centering	Lower Centering
0.33	0.33	0.33

7.2.3 Storm Temporal Pattern

Variability in the temporal distribution of the PMP precipitation was initially considered only as a function of the time of occurrence of the maximum intensity segment within the 72-hour duration PMP event. The initial PMF results included consideration of three temporal distributions developed using methodologies in Schaefer (1989). For the GSA, the number of storm temporal patterns was expanded to seven. The primary differentiator between each pattern was again, the time of occurrence of the maximum rainfall intensity.

The exceedance probabilities for the maximum intensity segment are 0.95, 0.90, 0.80, 0.50, 0.20, 0.10 and 0.05, which were determined by fitting historical storm data to the four-parameter Beta distribution (Schaefer 1989). As seen in Table 24, the time of occurrence of the maximum intensity segment for these exceedance probabilities ranges between 10.4 hours and 57.8 hours of cumulative time. These temporal patterns describe front-loaded storms, mid-loaded storms, and back-loaded storms. In application to 72-hour duration general storms, front-loaded storms are characterized by a peak intensity occurring in the first tri-sector (within the first 24 hours), mid-loaded storms are characterized by a peak intensity occurring within the second tri-sector, and back-loaded storms are characterized by a peak intensity occurring within the last tri-sector (within the last 24 hours).

Since the temporal pattern sampling in the GSA was not conducted over a continuous range of values, it was necessary to develop an estimate of the probability of occurrence for each of the discrete storm temporal patterns. The discrete probability of occurrence of each temporal pattern was approximated by assuming a normal distribution and the results are summarized in Table 24. Figure 27 shows the probability histogram for the storm temporal patterns.

Monte Carlo sampling of the storm temporal patterns for the GSA was based on the probabilities assigned to each storm pattern. The temporal pattern was sampled independently of all other hydrometeorological input parameters.

The temporal variations in air temperature and wind speed during the PMP event were assumed to be consistent with the temporal variation in precipitation for the selected storm pattern. The highest 6-hour duration air temperatures and wind speeds were assumed to coincide with the 6-hour period of highest precipitation, and the lowest 6-hour duration air temperatures and wind speeds were assumed to coincide with the 6-hour period of lowest precipitation. This is consistent with the guidance for developing coincident air temperature and wind speed time series in HMR-43 (NWS 1966) and HMR-57 (NWS 1994). Tetra Tech (2006c) included a detailed application of the HMR-57 methodology for deriving air temperatures and wind speeds coincident to the PMP. The 6-hour duration air temperature and wind speed values that were presented in Section 3 of this technical memorandum were re-ordered to conform to the seven temporal distributions used in the GSA.

Table 24. Probability of Occurrence for the Seven Precipitation Temporal Patterns

Storm Temporal Pattern Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Time of Occurrence of Maximum Rainfall Intensity (hours)	10.4	14.3	20.1	33.3	47.0	53.4	57.8
Exceedance Probability for Maximum Intensity Segment	0.95	0.90	0.80	0.50	0.20	0.10	0.05
Probability of Occurrence of Storm Temporal Pattern	0.075	0.075	0.200	0.300	0.200	0.075	0.075

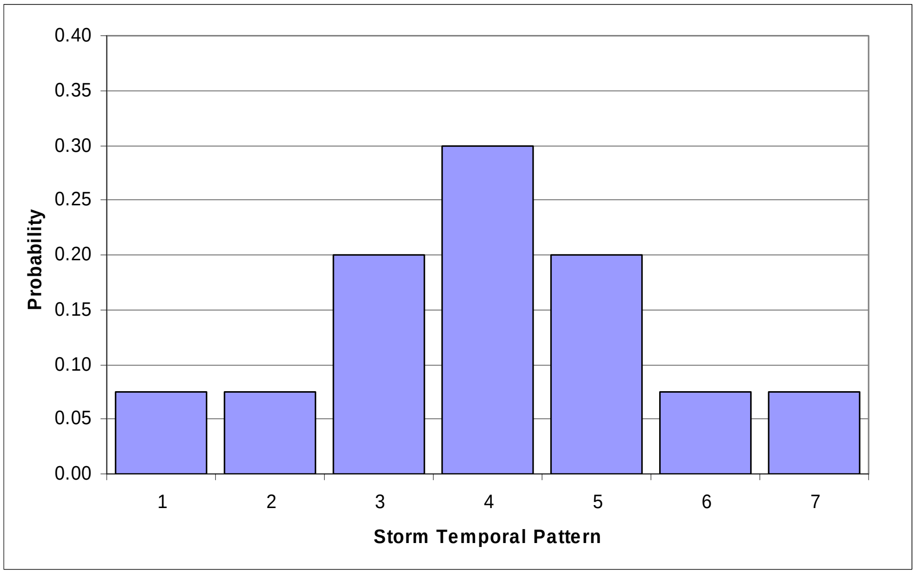


Figure 27. Probability Histogram for Storm Temporal Patterns

7.2.4 Antecedent Precipitation

Antecedent precipitation is defined as the cumulative precipitation that has occurred from October 1st to the end-of-month selected for a given simulation. By including antecedent precipitation as a variable in the GSA, the range of possible antecedent soil moisture conditions—dry to saturated—was considered. Antecedent snowpack also is correlated to antecedent precipitation in the SEFM, so including antecedent precipitation as a variable allowed for consideration of the range of antecedent snowpack conditions.

For the GSA, it was necessary to fit a distribution to end-of-month antecedent precipitation data at a key precipitation station, which was defined as the Upper Baker Dam precipitation station. The three-parameter Gamma distribution was used for describing the historical data. This distribution function is defined by the sample mean, the sample coefficient of variation, and the sample coefficient of skewness.

The Gamma distribution parameters were determined for each end-of-month period at the Upper Baker Dam precipitation station. The end-of-month sample statistics are summarized in Table 25 for the station period of record (1965 to 2005). Figure 28 shows the end-of-November antecedent precipitation data fit to the Gamma distribution, and Table 26 summarizes the values of mean annual precipitation for specific non-exceedance probabilities.

Table 25. Sample Statistics for End-of-Month Antecedent Precipitation at Upper Baker Dam Station

Month	Sample Mean (inches)	Sample Coefficient of Variation	Sample Coefficient of Skewness
OCT	9.94	0.64	0.93
NOV	25.41	0.38	0.55
DEC	40.86	0.30	0.47
JAN	55.65	0.27	0.14
FEB	66.69	0.26	0.09
MAR	76.42	0.25	0.26
APR	82.91	0.23	0.37
MAY	87.80	0.22	0.46
JUN	91.55	0.21	0.46
JUL	94.14	0.21	0.49
AUG	96.46	0.21	0.50
SEP	101.01	0.20	0.50

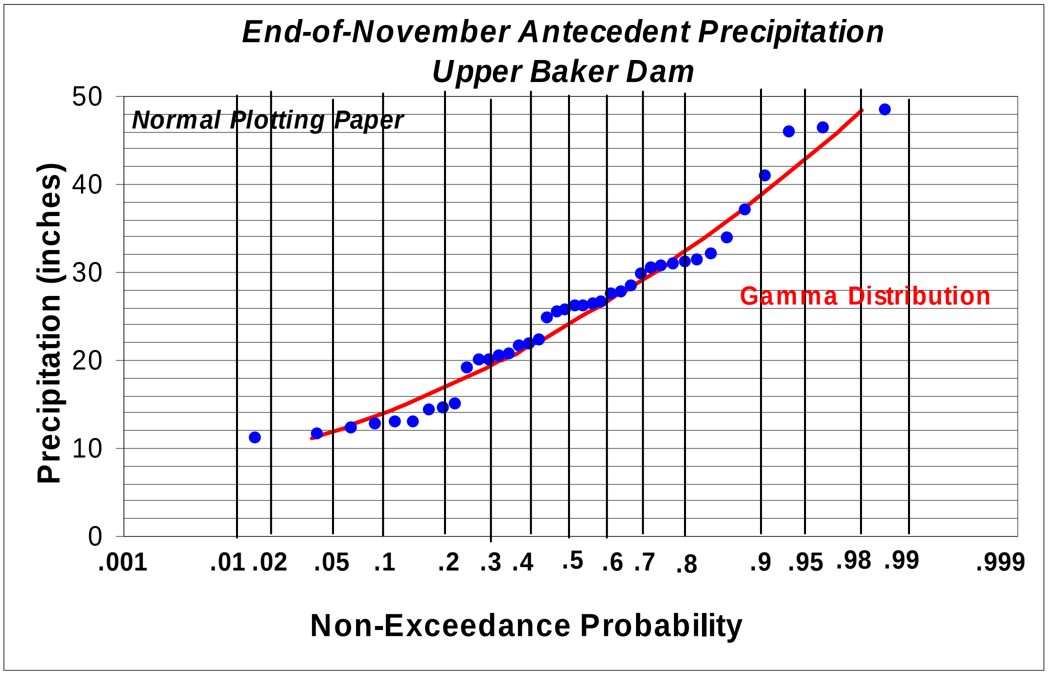


Figure 28. Gamma Distribution Fitted to End-of-November Antecedent Precipitation for Upper Baker Precipitation Station (Key Precipitation Station)

Table 26. Non-Exceedance Probabilities for End-of-November Antecedent Precipitation for Upper Baker Precipitation Station Using Gamma Distribution

Non-Exceedance Probability	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
Antecedent Precipitation (inches)	6.58	11.84	14.05	16.99	24.21	33.02	38.49	43.54	53.73

The coefficient of variation and the coefficient of skewness are subject to greater sampling variability than is the case for mean annual precipitation. To account for this variability, Gamma distribution parameters were determined for eight supplemental precipitation stations in the region (Table 27). The sample coefficient of variation for all nine of the stations (including the key precipitation station) were then plotted against the station values of mean annual precipitation to obtain smoothed plots that illustrated the variability of this parameter with station mean annual precipitation and with season. Figure 29 shows an example plot that illustrates the variability in the coefficient of variation among the stations for the end-of-November period. The Mount Baker Lodge station was not included in the analysis due to insufficient data.

Estimation of the coefficient of skewness is subject to even higher sampling variability than is the case for the coefficient of variability. For this reason, the coefficient of skewness was estimated on a seasonal basis rather than using a regressional analysis with mean annual precipitation as was done for the coefficient of variation. Figure 30 illustrates the trend line used to estimate the coefficient of skewness for each season using sample values of the coefficient of skewness from the stations listed in Table 27. Again, the Mount Baker Lodge station was not included in the analysis due to insufficient data.

Table 27. Precipitation Stations Used in Antecedent Precipitation Analysis

Station Name	Station ID	Mean Annual Precipitation at Station [a]	Station Elevation (feet)
Cedar Lake	45-1233	97.8	1560
Concrete PPL Fish Station	45-1679	50.8	195
Darrington Ranger Station	45-1992	86.5	550
Diablo Dam	45-2157	78.9	891
Mount Baker Lodge	45-5663	113.2	4150
Newhalem	45-5840	74.4	525
Ross Dam	45-7185	61.4	1236
Stampede Pass	45-8009	84.3	3958
Upper Baker Dam (key station)	45-8715	96.4	690

a. Determined from mapping provided by OCS (2005)

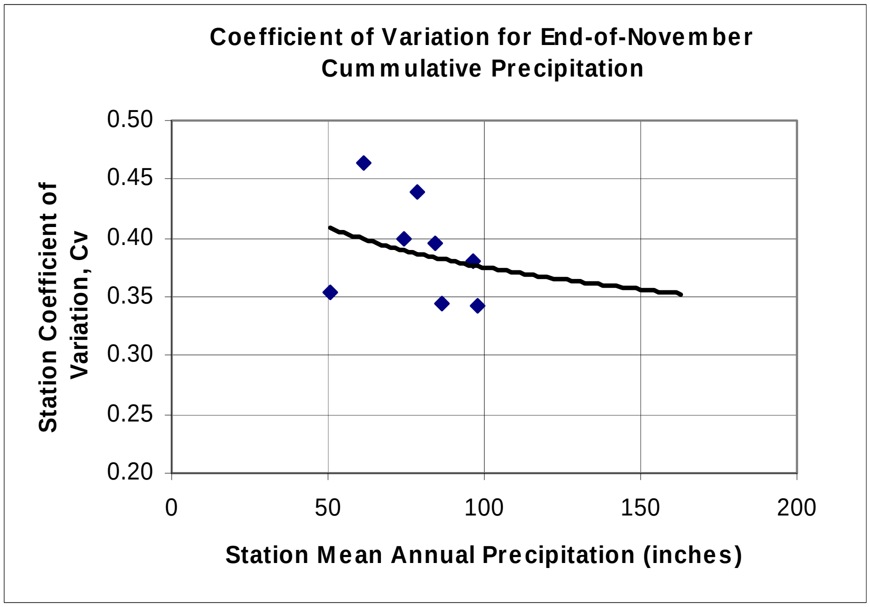


Figure 29. Relationship of Coefficient of Variation to Station Mean Annual Precipitation for End-of-November

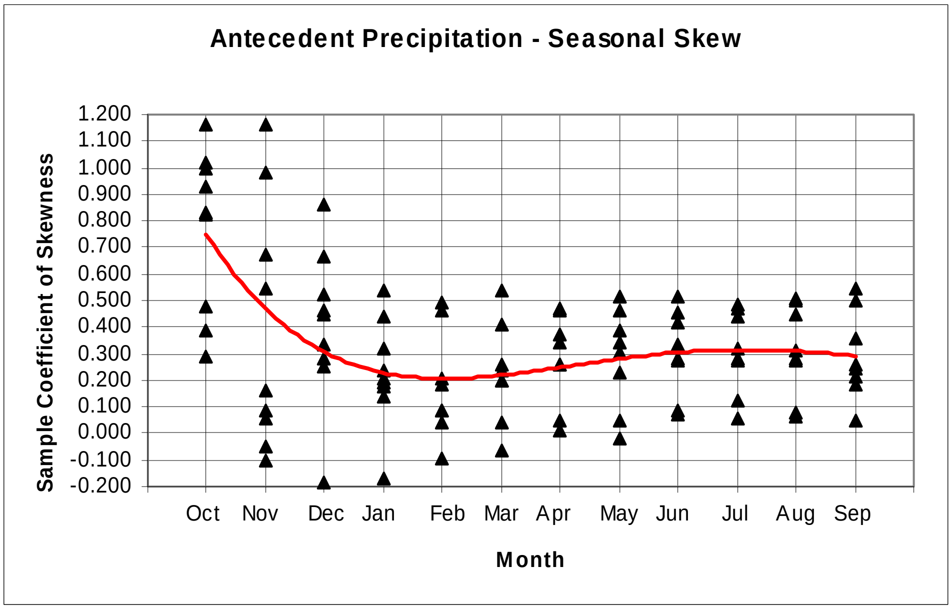


Figure 30. Seasonal Relationship of Coefficient of Skewness

Estimates of the distribution parameters were then determined for each zone of mean annual precipitation in the Baker River Watershed, using the regression analysis as exemplified in Figure 29 for developing estimates for the coefficient of variation and using the seasonal relationship exemplified in Figure 30 for developing estimates for the coefficient of skewness. It is noted that the sampling variability exhibited in both of these figures is fairly large; therefore, additional references were used to verify that the resulting estimates of the coefficients of variation and coefficients of skewness were consistent with recent regional studies. The two references were WSDOE (1993) and Schaefer et al (1999). WSDOE (1993) presents the results of a state-wide regional precipitation analysis conducted for the State of Washington, including the determination of estimates of coefficient of variation as a function of station mean annual precipitation.

As part of a stochastic model for the Keechelus Watershed, Schaefer et al (1999) includes the results of an antecedent precipitation analysis conducted for the Keechelus Watershed in the Cascade Mountain Range in the State of Washington. Review of both references concluded that the behavior of the regional estimates of the coefficients of variation and skewness for the Baker River Watershed were consistent with other regional studies. The values of the coefficients of variation and skewness are largest and most variable in the early portion of the water-year due to the small number of months that are included in the multi-month analysis of the data. The values rapidly decrease in magnitude as the water-year progresses through to September as more and more months are considered in the multi-month analysis of the data.

As an example, Table 28 summarizes the final distribution parameters that were developed for Mean Annual Precipitation Zone 3 (102 inches of mean annual precipitation) of the Baker River Watershed. The typical seasonal trend of the magnitudes of the coefficient of variation and coefficient of skewness is exemplified.

Table 28. Three Parameter Gamma Distribution Parameters for MAP Zone 3

Month	Mean (inches)	Coefficient of Variation	Coefficient of Skewness
OCT	10.04	0.57	0.75
NOV	24.36	0.37	0.45
DEC	39.15	0.29	0.32
JAN	51.39	0.25	0.25
FEB	60.76	0.24	0.21
MAR	74.57	0.23	0.21
APR	81.85	0.21	0.23
MAY	87.18	0.20	0.28
JUN	91.31	0.19	0.33
JUL	93.65	0.19	0.32
AUG	96.08	0.19	0.28
SEP	100.81	0.18	0.30

For the GSA, Monte Carlo sampling was used to determine antecedent precipitation values for the selected end-of-month for each MAP zone. This was accomplished as follows:

- The value of antecedent precipitation for the key precipitation station was determined using Monte Carlo sampling procedures and the three-parameter Gamma distribution that was fitted to the data at the key precipitation station (see Table 25 and Figure 28).
- The non-exceedance probability associated with the selected antecedent precipitation value at the key precipitation station was computed.
- The computed non-exceedance probability was used to determine the values of antecedent precipitation for each MAP zone, using the Gamma distributions for each zone (see Table 28).

7.2.5 Antecedent Snow Water Equivalent

The initial PMF results were developed using an incremental methodology to identify the non-exceedance probability for antecedent snowpack conditions that would result in the largest volume of snowmelt runoff. This approach identified the most conservative antecedent snowpack conditions in terms of runoff produced.

For the GSA, antecedent snow water equivalent was instead correlated to antecedent precipitation. A key snow course station (Schreibers Meadow) was used together with the key precipitation station (Upper Baker Dam) to establish a correlation between end-of-month antecedent precipitation and end-of-month antecedent snow water equivalent. For a selected value of antecedent precipitation, a corresponding value of snow water equivalent was computed. The non-exceedance probability associated with the computed snow water equivalent value was determined from a Log-Normal distribution developed from the historical record at the key snow course station. Snow water equivalent was then spatially distributed throughout the watershed based on Log-Normal distributions developed for each of the snow course stations in the watershed. Input for spatial allocation of snow water equivalent therefore included the following:

- Correlation relationship between the key snow course station and the key precipitation station. This relationship allowed for computation of end-of-month snow water equivalent for a selected value of end-of-month antecedent precipitation.
- Magnitude-frequency relationships for snow water equivalent at each snow course station in the watershed.

The Schreibers Meadow snow course station receives approximately 153 inches of precipitation annually, and is located at elevation 3,400 feet, which is approximately the median elevation of the watershed. Logarithmic correlation between antecedent precipitation at the key station and corresponding snow water equivalent at the key snow course station was determined for each end-of-month period. Figure 31 illustrates this relationship for the end-of-February period. From this graph, the y-intercept, slope and correlation coefficient describe the relationship between the two key stations and were input into the model.

The results of the correlation analysis, as shown in Figure 31, were used in the GSA to preserve the deterministic (dependent) component of the relationship between antecedent precipitation and snow water equivalent while at the same time preserving the natural variability in the relationship. The natural variability in the relationship is principally due to the variability in atmospheric conditions, during the specific time of year, that determine whether precipitation falls as liquid precipitation or as snow. Especially early in the winter season, large fluctuations in air temperature and freezing level cause high variability in the relationship between antecedent precipitation and snow water equivalent. Therefore, in the context of the GSA, a high correlation coefficient is not necessarily superior to a low correlation coefficient since the natural variability in the relationship is preserved.

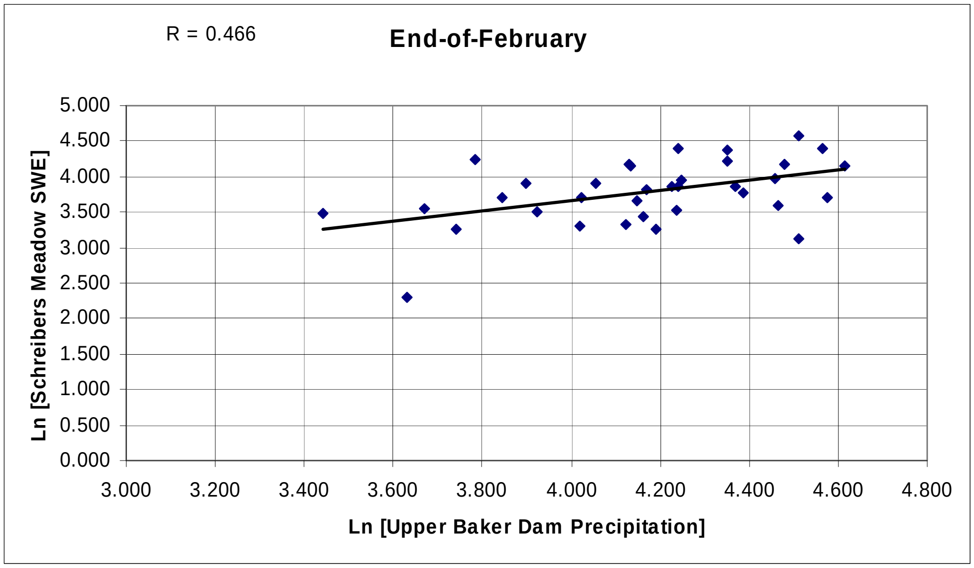


Figure 31. Logarithmic Correlation Between Antecedent Precipitation and Snow Water Equivalent

For the snowpack spatial allocation, snow water equivalent end-of-month data at each of the nine snow course stations in the watershed were analyzed and fit to a mixed distribution model. The mixed distribution model consists of a frequency of snow-free ground term (theta) and the two-parameter Log-Normal distribution that describes the data for when snow is on the ground. The distribution parameters that describe the Log-Normal distribution are the sample mean and the sample standard deviation. This at-station analysis was conducted for the initial phase of the PMF analysis and is described in Section 3.4. Figure 32 illustrates the Log-Normal distribution for the end-of-November data for the key snow course station and Table 29 summarizes snow water equivalent values for specific non-exceedance probabilities.

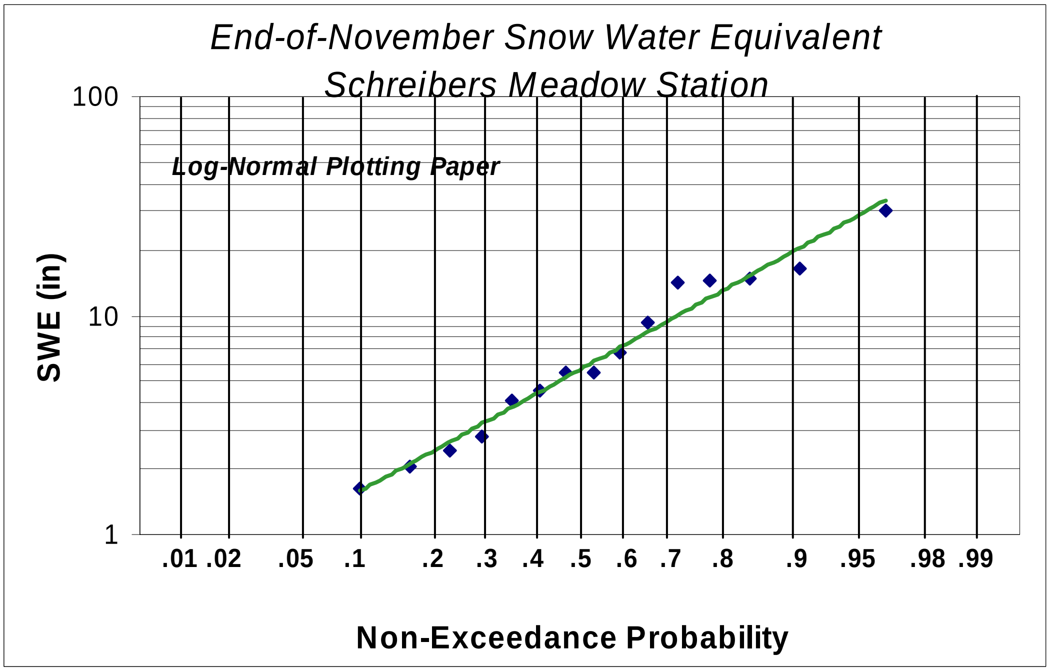


Figure 32. Log-Normal Distribution Fitted to End-of-November Snow Water Equivalent Data for Schreibers Meadow Station (Key Snow Course Station)

Table 29. Non-Exceedance Probabilities for End-of-November Snow Water Equivalent for Schreibers Meadow Snow Course Station Using Log-Normal Distribution

Non-Exceedance Probability	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
Antecedent Snow Water Equivalent (inches)	0.56	1.10	1.58	2.45	5.66	13.07	20.25	29.06	57.22

Using the results of the at-station analysis of end-of-month snow water equivalent, the three parameters in the mixed distribution model were plotted versus station elevation. This allowed for the development of regression relationships to describe the variability of each distribution parameters with elevation. These relationships were then used to estimate the values of the three distribution parameters applicable to elevation zone for each end-of-month. Figure 33 shows an example of such a plot, illustrating the variation in the frequency of snow-free ground for the end-of-October period.

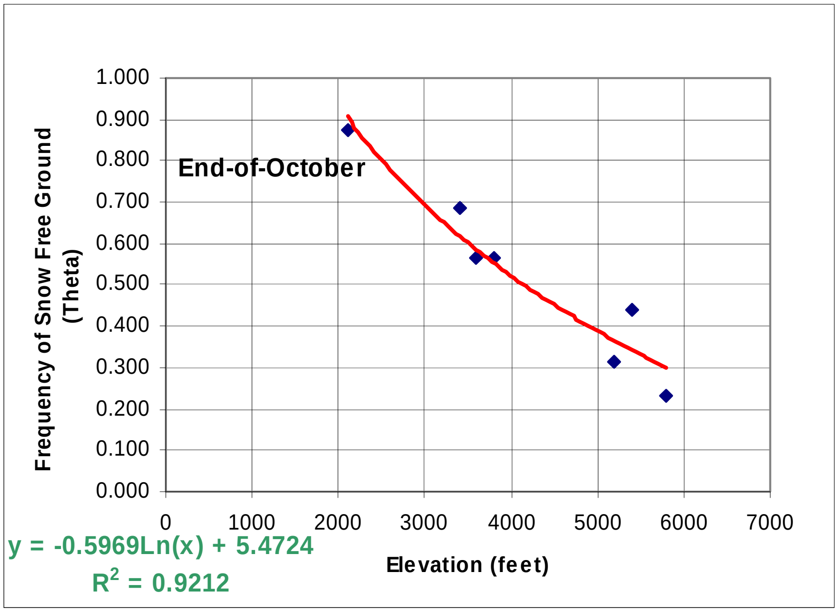


Figure 33. Regression Relationship for Frequency of Snow-Free Ground Term (Theta)

For the GSA, the model proceeded through the following steps to spatially allocate antecedent snow water equivalent for each model simulation (MGS 2004):

1. A value of antecedent precipitation at the key precipitation station was selected using Monte Carlo sampling.
2. The value of snow water equivalent was computed for the key snow course station using the logarithmic correlation between antecedent precipitation at the key precipitation station and snow water equivalent at the key snow course station (Figure 31).
3. The non-exceedance probability associated with the computed value of snow water equivalent was estimated based on the Log-Normal distribution and the estimated values of the sample mean and sample standard deviation (Figure 32).

4. The mixing parameter and the log normal distribution parameters (sample mean and sample standard deviation) are determined from the regression relationships with elevation for the elevation of the key snow course station (Figure 33).
5. The value of the non-exceedance probability at the key snowpack station is used together with the frequency of snow-free ground parameter and the Log-Normal distribution parameters to allocate snow water equivalent within each hydrologic runoff unit (HRU) in the model.

The result of this process was to allocate snow water equivalent throughout the watershed by using an equal value of non-exceedance probability for all locations. Spatial variability of antecedent snow water equivalent was accounted for through the use of sample statistics from nine snow course stations in the watershed. Therefore, snow water equivalent was allocated throughout each of the zones of elevation and mean annual precipitation. In this manner, the process used in the GSA for allocating snow water equivalent was consistent with the process used to allocate snow water equivalent for the initial development of the PMF (Section 3.4).

7.2.6 Antecedent Snowpack Density

For the GSA, three methods were initially considered to describe the seasonal and topographical variability of snowpack density:

- Correlate snowpack density to antecedent precipitation.
- Correlate snowpack density to snowpack depth or snow water equivalent
- Fit the historical monthly snowpack data to a four-parameter Beta distribution to allow independent sampling of the value of snowpack density.

Correlation of end-of-month snowpack density to end-of-month antecedent precipitation was investigated at each of the nine snow course stations for each of the months included in the GSA. It was found that there was consistently poor correlation, as illustrated in Figure 34. This poor correlation is attributable to the cycle of snowpack melt and accumulation during the early winter season, when complete melt-off of the snowpack may occur at any point in time.

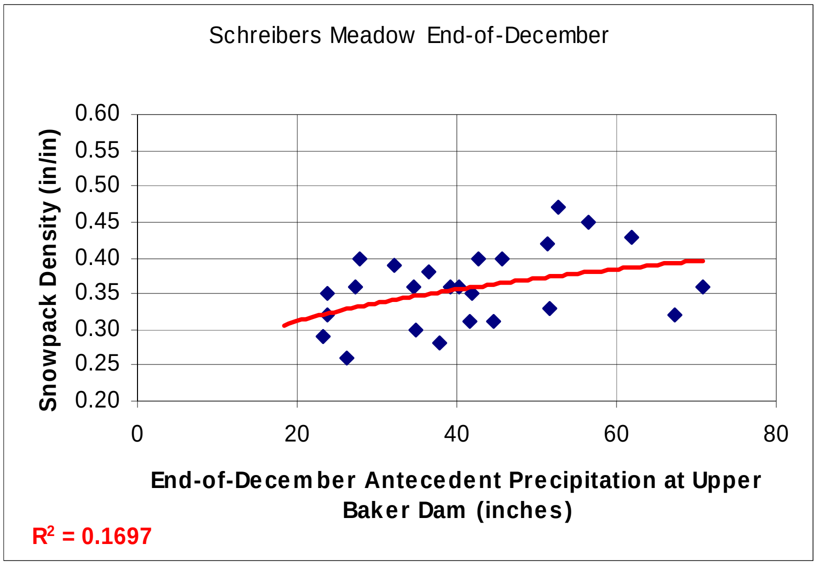


Figure 34. Correlation of End-of-Month Antecedent Precipitation with End-of-Month Snowpack Density

Correlation of end-of-month snowpack density to end-of-month snow water equivalent was investigated at each of the nine snow course stations for each of the months included in the GSA. Again, it was found that there was consistently poor correlation, as seen for example in Figure 35. The cyclic melt and accumulation of the snowpack during the early winter season is a factor in the poor correlation.

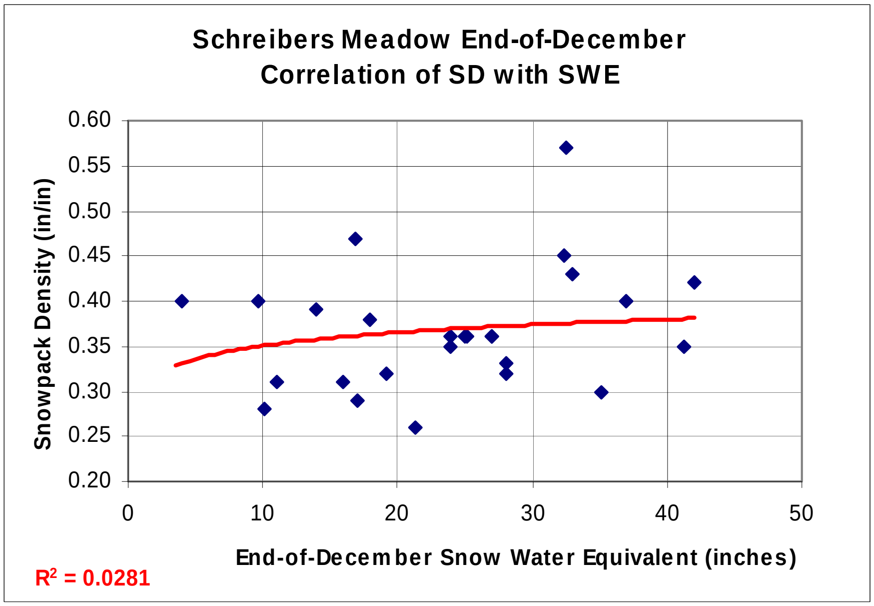


Figure 35. Correlation of End-of-Month Snow Water Equivalent with End-of-Month Snowpack Density

Due to the poor statistical correlation with antecedent precipitation and snow water equivalent, end-of-month snowpack density was treated as an independent variable in the GSA. The Schreibers Meadow snow course station end-of-month data was fit to the four-parameter Beta distribution for each of the five months. The Schreibers Meadow station was used because it is the key snow course station used in allocation of snow water equivalent. By plotting the historical end-of-month snow pack density data in the form of frequency histograms, it was concluded that the Beta distribution provided a reasonable fit to the data for each of the five months. Figure 36 compares the frequency histogram for the end-of-November data to the data using the four-parameter Beta distribution. Figure 37 illustrates how the historical data fits the Beta distribution, and Table 30 summarizes snowpack density values for specific non-exceedance probabilities.

The end-of-month snowpack density input parameter was selected independently of all other input parameters except seasonality of occurrence. Once the Monte Carlo sampling procedure established a month for a given simulation, a second Monte Carlo sampling procedure was used to select a value for the end-of-month snowpack density using the four-parameter Beta distribution that was fit to the end-of-month data (see Figure 37). The snowpack density value that was selected was assumed to be representative of all zones of the watershed, regardless of elevation and magnitude of mean annual precipitation. This assumption was based on previous determination that there is minor variability in snowpack density with topography and mean annual precipitation (Tetra Tech 2006c).

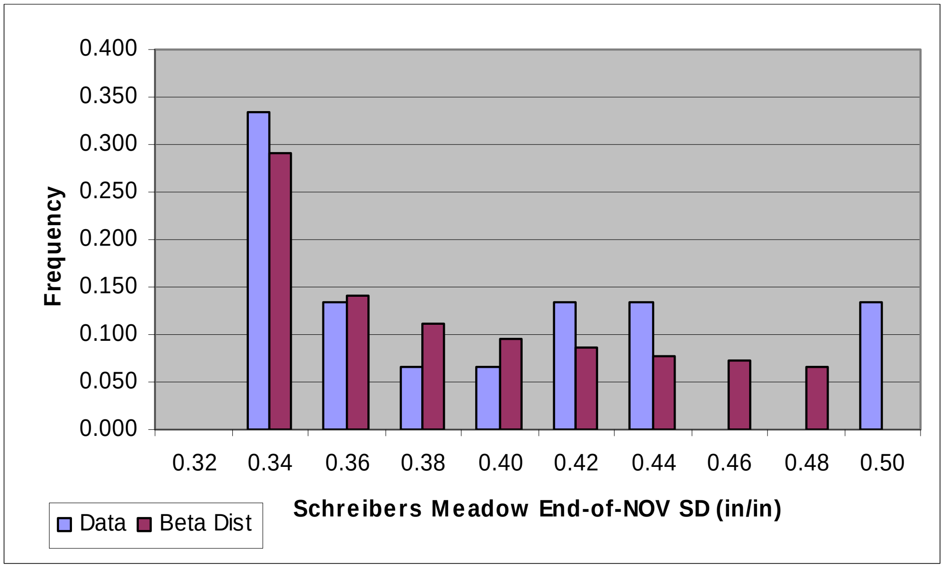


Figure 36. Frequency Histogram for End-of-November Antecedent Snowpack Density at Schreibers Meadow Snow Course Station.

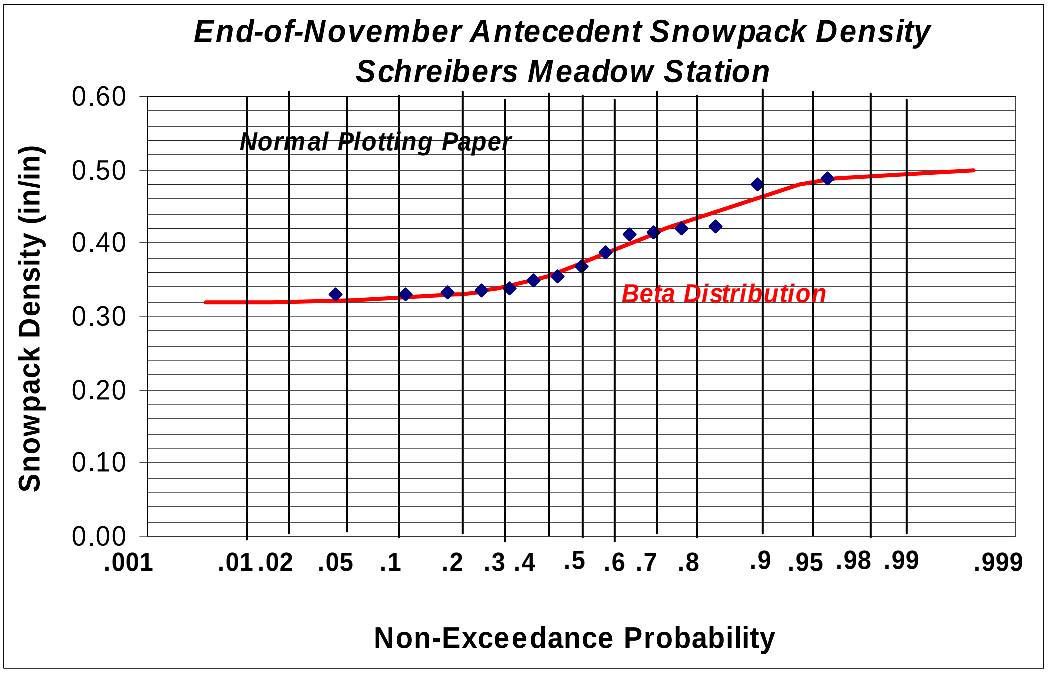


Figure 37. Probability Plot for End-of-November Antecedent Snowpack Density at Schreibers Meadow Snow Course Station

Table 30. Non-Exceedance Probabilities for End-of-November Antecedent Snowpack Density for Schreibers Meadow Snow Course Station

Non-Exceedance Probability	0.01	0.05	0.10	0.20	0.50	0.80	0.90	0.95	0.99
Antecedent Snowpack Density (inches per inch)	0.32	0.32	0.32	0.33	0.37	0.44	0.470	0.48	0.50

7.2.7 Antecedent Reservoir Elevations

For the GSA, three methods were initially considered to describe the seasonal variability of antecedent reservoir elevation:

- Correlate both Upper Baker and Lower Baker antecedent reservoir elevations to antecedent precipitation at Upper Baker Dam
- Fit the historical end-of-month antecedent reservoir elevation data to a four-parameter Beta distribution to allow independent sampling of the reservoir elevations
- Use a resampling methodology, in which the antecedent reservoir elevation is randomly selected from the historical data set, with each value having an equal probability of occurrence.

Correlation of end-of-month antecedent reservoir elevation to antecedent precipitation was investigated for both reservoirs. Due to the controlled nature of Upper Baker and Lower Baker reservoirs during the winter months, it was anticipated that correlation between reservoir elevation and antecedent precipitation would be very weak for elevations above the spillway elevation and that correlation might improve for reservoir elevations lower than the spillway elevations. It was found, however, that correlation was very weak for both conditions.

Consideration was then given to fitting the historical data to the four-parameter Beta distribution for independent sampling. However, this was deemed inappropriate, again due to the controlled nature of the two reservoirs. During the months of November through February, Upper Baker is operated as a flood control facility and PSE attempts to maintain the reservoir elevations at both Upper Baker and Lower Baker at set operational levels.

Finally, a resampling methodology was determined to be the most appropriate. The resampling methodology uses standard Monte Carlo sampling procedures to randomly select a value from a database of historical values. Instead of fitting the data to a probability distribution (as was done for all other parameters in the GSA), all values were defined as being equally likely.

Input to the resampling methodology required that end-of-month reservoir elevation data be compiled for both Upper Baker Dam and Lower Baker Dam. The data from 1980 to the present was used because this period reflects the current flood control operation conditions at Upper Baker Dam. From October 1st through March 31st, PSE operates Upper Baker Dam as a flood control facility in accordance with the flood control rule curve shown previously as Figure 5. As seen in this figure, reservoir elevation drawdown is quite rapid between November 1st and November 15th, and the standard end of month reservoir elevation resampling procedure is too long of a time period to adequately capture this rapidly changing condition. Therefore, the resampling procedure was modified to include two shorter resampling periods between November 1st and November 15th. Table 31 summarizes the reservoir resampling periods used in the GSA, and their relation to the event date selected in the Monte Carlo sampling procedure. As seen in this table, a Monte Carlo generated storm date between November 1st and November 15th still uses end of October hydrometeorological input data (as explained in Section 7.2.1) but uses either Nov 4th or November 11th reservoir elevation data.

Table 31. Sampling Periods for Reservoir Resampling Methodology

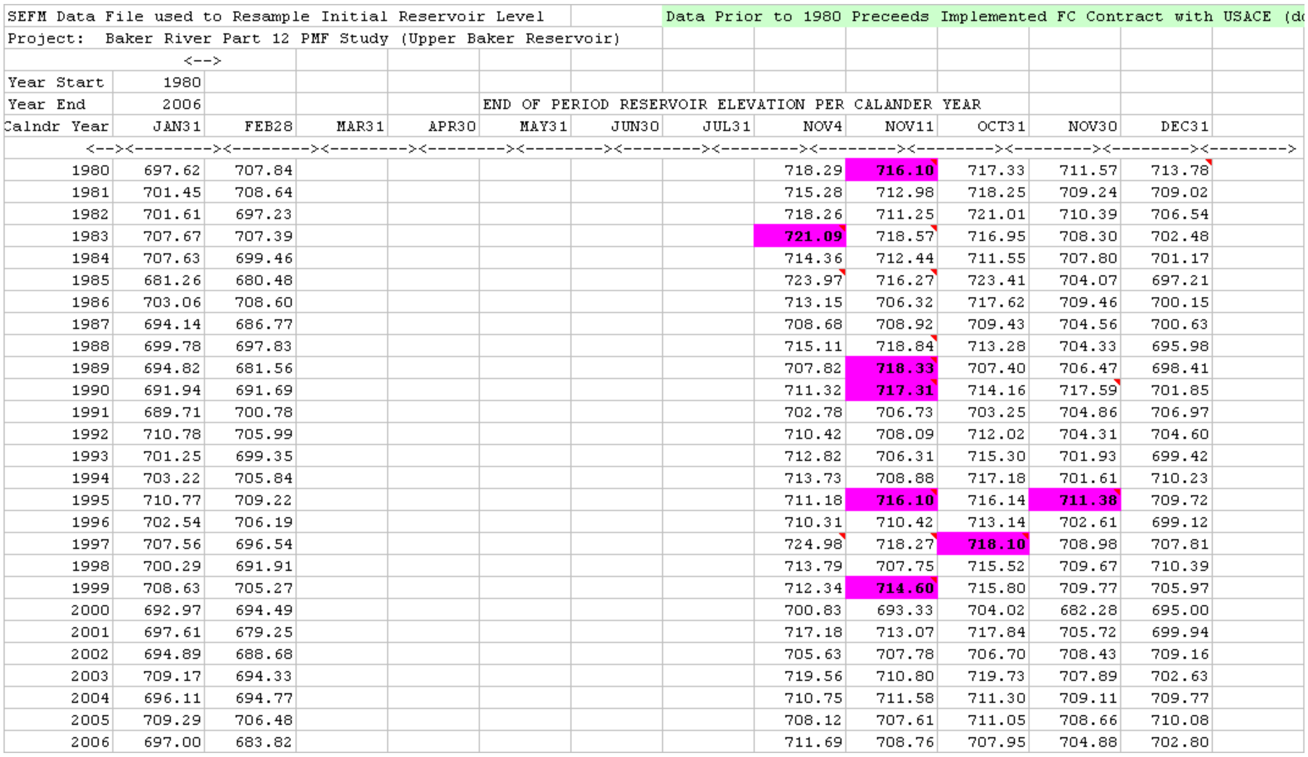
Monte Carlo Generated Storm Date	Corresponding Date for Hydrometeorological Input Data	Corresponding Date for Antecedent Reservoir Elevation
Oct 16 - Oct 31	End of October	Oct 31
Nov 1 – Nov 7	End of October	Nov 4
Nov 8 – Nov 15	End of October	Nov 11
Nov 16 – Dec 15	End of November	Nov 30
Dec 16 – Jan 15	End of December	Dec 31
Jan 16 – Feb 15	End of January	Jan 31
Feb 16 – Feb 28	End of February	Feb 28

The database of end-of-period reservoir elevations used in the GSA should be representative of reservoir conditions that would expected antecedent to the occurrence of PMP. However, in some instances, the end of period reservoir elevation at Upper Baker was actually the result of an ongoing flood event. For instance, the end of November reservoir elevation in 1995 was 722.34 feet (NAVD88), nearly eleven feet above the target flood control elevation for that time of year. This high reservoir elevation was on account of the fact that Upper Baker Dam was in flood control operation due to the extreme precipitation event that occurred during the last three days of this month. Since this value can not be considered representative of reservoir conditions that would expected antecedent to the occurrence of PMP, it was replaced with a reservoir elevation on the recession limb of the flood event at an elapsed time of three days after the end of the precipitation event – a period of time that represents the elapsed period between historical precipitation events. This three day period also corresponds with guidance provided in FERC (2001) for establishing an antecedent reservoir elevation following the occurrence of a 100-year precipitation event.

This same approach was used for all end-of-period reservoir elevations that were found to be above the target flood control elevation due to an ongoing flood event. End-of-period reservoir elevations that were above the target flood control elevation for reasons other than a concurrent precipitation event were not replaced. Figures 38 and 39 summarize the end-of-period reservoir elevation database for the October through February time period, and reflect the changes made to the historical data. The shaded values in Figure 38 are those that were changed according to the procedure described in the previous paragraph.

Figures 40 through 47 are probability plots of the reservoir elevation data for the end-of-October period, the two periods in early November, and the end-of-November period. These four periods had the highest number of instances of Upper Baker reservoir values that were greater than that allowed by the flood control rule curve.

In application to the GSA, the end-of-period antecedent reservoir elevation was selected independently of all other input parameters except seasonality of occurrence. Once a month was selected, the resampling methodology was employed to randomly select a calendar year for the corresponding antecedent reservoir elevations.



SEFM Data File used to Resample Initial Reservoir Level

Data Prior to 1980 Preceeds Implemented FC Contract with USACE (d

Project: Baker River Part 12 PMF Study (Upper Baker Reservoir)

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Year Start 1980

Year End 2006

END OF PERIOD RESERVOIR ELEVATION PER CALANDER YEAR

Calndr Year	JAN31	FEB28	MAR31	APR30	MAY31	JUN30	JUL31	NOV4	NOV11	OCT31	NOV30	DEC31
<-->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->
1980	697.62	707.84						718.29	**716.10**	717.33	711.57	713.78
1981	701.45	708.64						715.28	712.98	718.25	709.24	709.02
1982	701.61	697.23						718.26	711.25	721.01	710.39	706.54
1983	707.67	707.39						**721.09**	718.57	716.95	708.30	702.48
1984	707.63	699.46						714.36	712.44	711.55	707.80	701.17
1985	681.26	680.48						723.97	716.27	723.41	704.07	697.21
1986	703.06	708.60						713.15	706.32	717.62	709.46	700.15
1987	694.14	686.77						708.68	708.92	709.43	704.56	700.63
1988	699.78	697.83						715.11	718.84	713.28	704.33	695.98
1989	694.82	681.56						707.82	**718.33**	707.40	706.47	698.41
1990	691.94	691.69						711.32	**717.31**	714.16	717.59	701.85
1991	689.71	700.78						702.78	706.73	703.25	704.86	706.97
1992	710.78	705.99						710.42	708.09	712.02	704.31	704.60
1993	701.25	699.35						712.82	706.31	715.30	701.93	699.42
1994	703.22	705.84						713.73	708.88	717.18	701.61	710.23
1995	710.77	709.22						711.18	**716.10**	716.14	**711.38**	709.72
1996	702.54	706.19						710.31	710.42	713.14	702.61	699.12
1997	707.56	696.54						724.98	718.27	**718.10**	708.98	707.81
1998	700.29	691.91						713.79	707.75	715.52	709.67	710.39
1999	708.63	705.27						712.34	**714.60**	715.80	709.77	705.97
2000	692.97	694.49						700.83	693.33	704.02	682.28	695.00
2001	697.61	679.25						717.18	713.07	717.84	705.72	699.94
2002	694.89	688.68						705.63	707.78	706.70	708.43	709.16
2003	709.17	694.33						719.56	710.80	719.73	707.89	702.63
2004	696.11	694.77						710.75	711.58	711.30	709.11	709.77
2005	709.29	706.48						708.12	707.61	711.05	708.66	710.08
2006	697.00	683.82						711.69	708.76	707.95	704.88	702.80

Figure 38. End-of-Period Reservoir Elevation Data – Upper Baker Reservoir

SEFM Data File used to Resample Initial Reservoir Level

Data Prior to 1980 Preceeds Implemented FC Contract with USACE (d

Project: Baker River Part 12 PMF Study (Lower Baker Reservoir)

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Year Start 1980

Year End 2006

END OF PERIOD RESERVOIR ELEVATION PER CALANDER YEAR

Calndr Year	JAN31	FEB28	MAR31	APR30	MAY31	JUN30	JUL31	NOV4	NOV11	OCT31	NOV30	DEC31
<-->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->	<-------->
1980	428.95	432.47						439.09	442.30	436.51	440.18	441.95
1981	427.75	430.80						436.60	430.43	435.62	434.09	434.17
1982	426.99	435.22						440.23	436.45	439.36	434.16	430.43
1983	431.40	439.77						441.51	441.67	438.71	438.07	433.32
1984	436.54	421.16						437.05	437.50	437.88	437.18	432.24
1985	419.52	401.51						441.05	442.12	442.21	429.97	419.71
1986	431.02	431.32						439.06	437.15	439.33	439.40	428.29
1987	394.09	393.59						428.56	429.02	428.71	427.75	427.64
1988	421.70	419.30						438.41	439.80	438.46	438.38	413.20
1989	409.21	395.44						429.51	441.86	426.87	437.64	422.42
1990	422.42	404.62						439.28	442.20	438.88	441.98	429.87
1991	406.95	423.02						431.67	432.69	433.83	436.36	429.87
1992	430.26	403.43						435.10	436.51	435.70	433.45	423.83
1993	422.62	402.83						430.87	433.80	428.78	434.66	430.05
1994	427.16	424.65						437.63	433.96	437.52	433.24	439.47
1995	436.16	438.87						434.13	441.51	432.28	441.39	434.24
1996	428.67	407.92						428.64	425.75	429.88	423.05	401.93
1997	437.17	411.36						435.44	441.01	434.12	437.01	436.35
1998	430.90	431.13						439.25	437.87	437.59	440.24	440.88
1999	436.77	433.02						437.94	441.84	434.19	432.90	430.47
2000	415.55	411.45						405.72	400.06	406.47	385.14	384.12
2001	389.86	374.32						441.35	438.19	440.76	439.94	431.70
2002	428.20	435.55						413.63	415.79	412.01	424.07	430.22
2003	441.10	429.08						416.76	416.35	427.94	423.86	421.62
2004	410.74	392.59						430.45	422.75	424.47	432.86	426.70
2005	430.08	434.75						424.19	419.41	418.99	422.29	438.61
2006	428.30	387.31						435.37	432.47	438.09	426.63	436.08

Figure 39. End-of-Period Reservoir Elevation Data – Lower Baker Reservoir

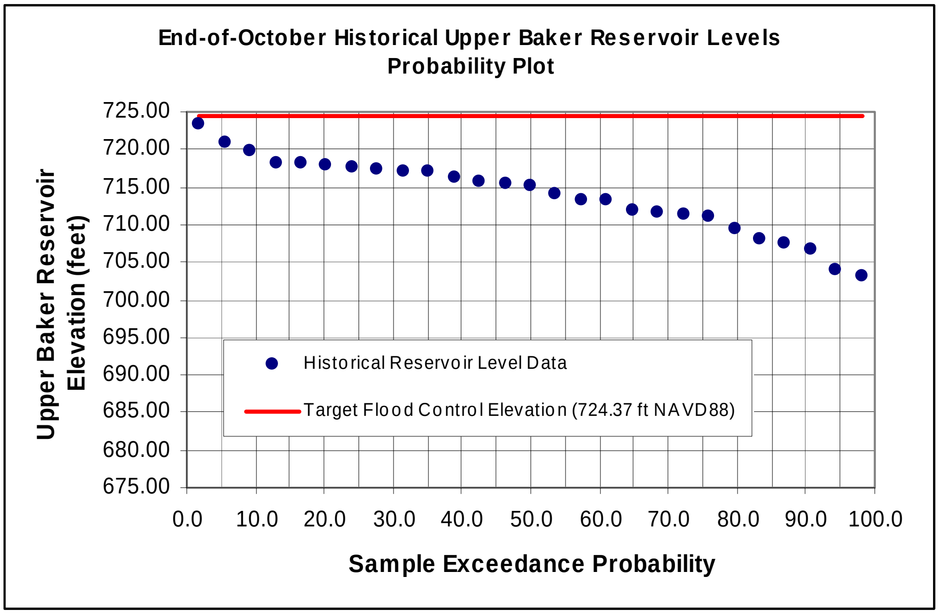


Figure 40. Probability Plot of End-of-October Reservoir Elevation Data for Upper Baker Dam

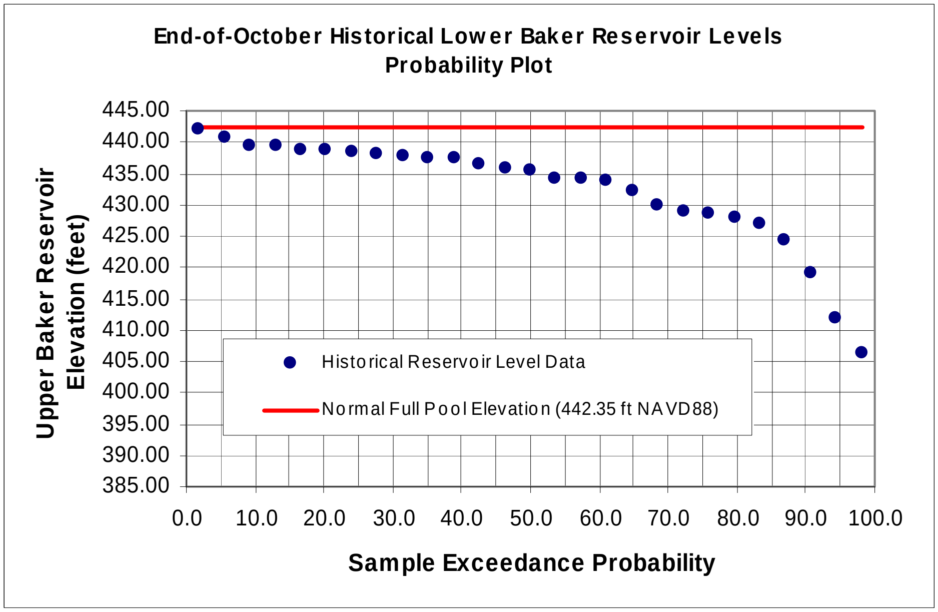


Figure 41. Probability Plot of End-of-October Reservoir Elevation Data for Lower Baker Dam

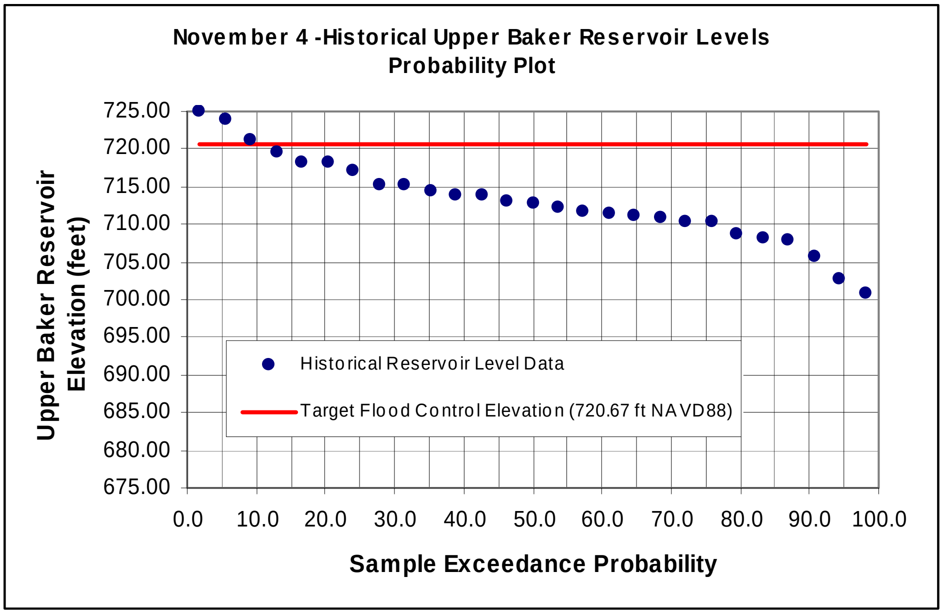


Figure 42. Probability Plot of November 4th Reservoir Elevation Data for Upper Baker Dam

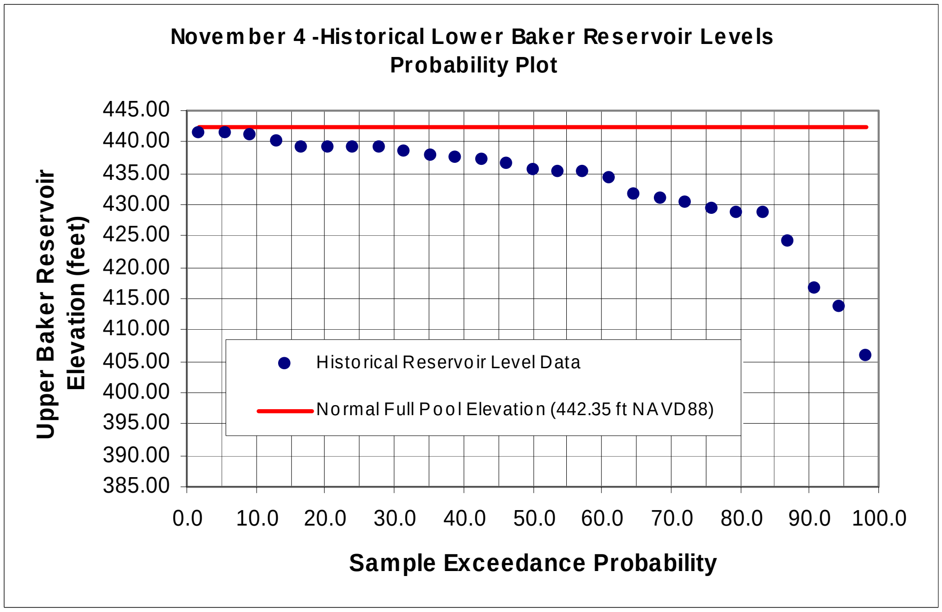


Figure 43. Probability Plot of November 4th Reservoir Elevation Data for Lower Baker Dam

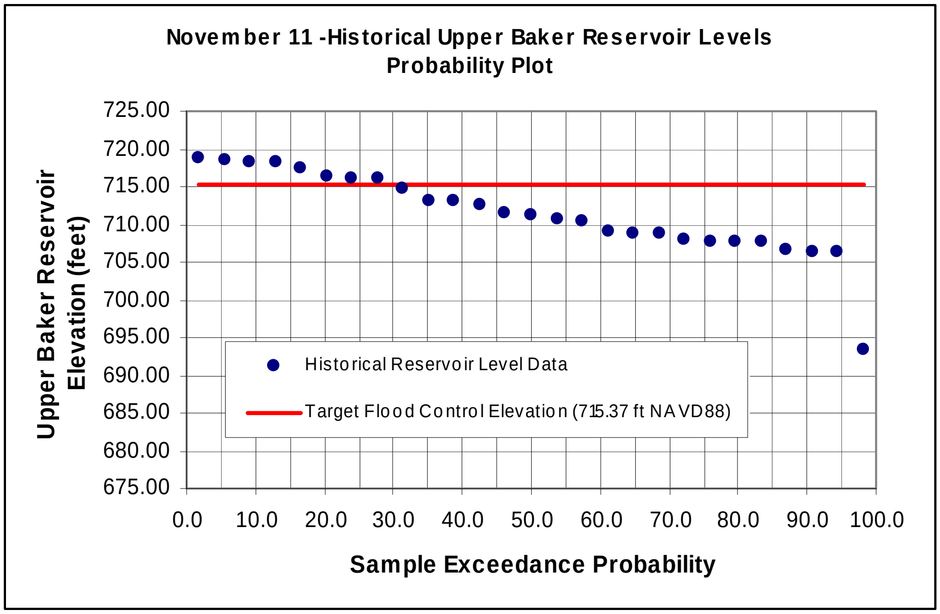


Figure 44. Probability Plot of November 11th Reservoir Elevation Data for Upper Baker Dam

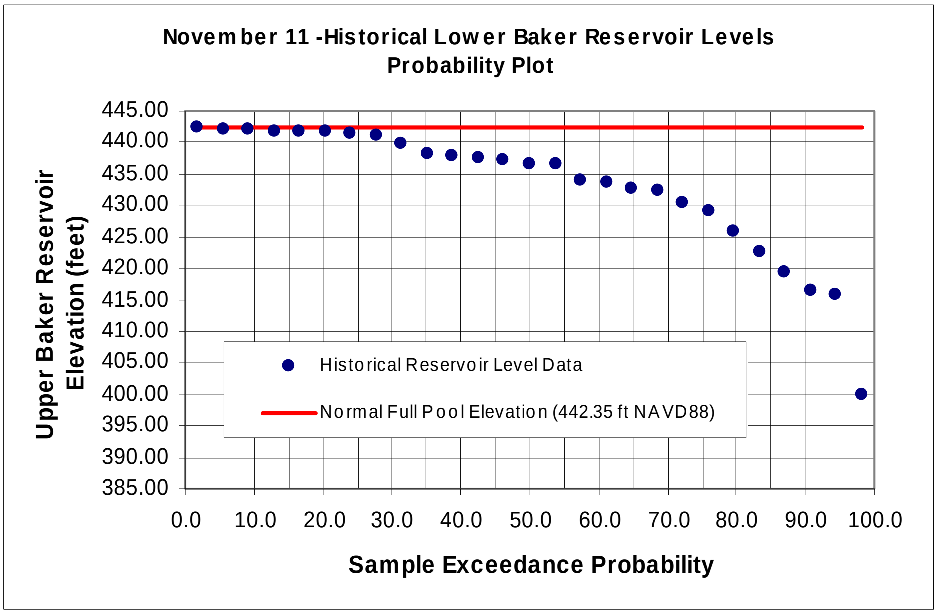


Figure 45. Probability Plot of November 11th Reservoir Elevation Data for Lower Baker Dam

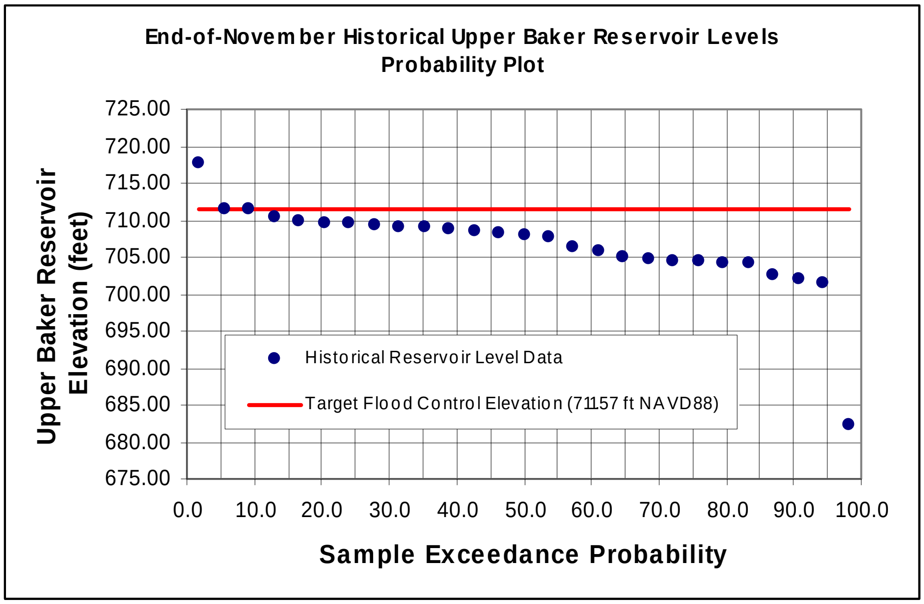


Figure 46. Probability Plot of End-of-November Reservoir Elevation Data for Upper Baker Dam

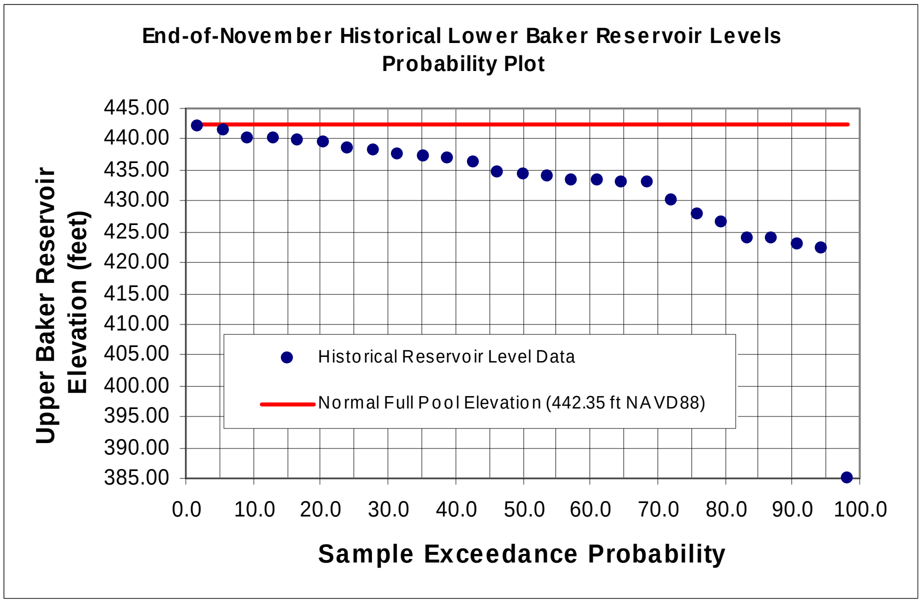


Figure 47. Probability Plot of End-of-November Reservoir Elevation Data for Lower Baker Dam

7.3 FLOOD RESPONSE AND RESERVOIR RESPONSE SENSITIVITY

The GSA model output was reviewed to allow for the evaluation of the sensitivity of flood response and reservoir response to changes in the magnitude of each model input parameter. Scatter-plots were used as the primary tool for this evaluation. Scatter-plots were created by plotting the results of the 10,000 model simulations generated from the GSA. The value of the input parameter was plotted as the independent variable on the x-axis and the model output parameter was plotted as the dependent variable on the y-axis. Scatter-plots were developed for each of the model input parameters included in the GSA. Output parameters used to evaluate model sensitivity included peak inflow, peak outflow and maximum reservoir elevation. Figures 48 and 49 are examples of the scatter-plots that were used to evaluate the sensitivity of the maximum Upper Baker reservoir elevation to changes in snow water equivalent and changes in assumed temporal pattern, respectively. For those input parameters that were sampled from a continuous distribution, such as antecedent snow water equivalent, the scatter-plots are represented as a continuous array of points, as is shown in Figure 48. For those input parameters that were sampled from a limited number of discrete conditions, such as was the case for the temporal pattern parameter, the scatter-plots are represented as a distinct number of "columns" of points, as is shown in Figure 49. For those scatter-plots which were generated from discrete sampling conditions, sample statistics were computed for each "column" of points to illustrate the central tendency and a measure of the variability of the set of points represented in each "column". The 25th percentile value, the median value, and the 75th percentile value of each column of points was computed and are indicted on the scatter-plots as horizontal dashes.

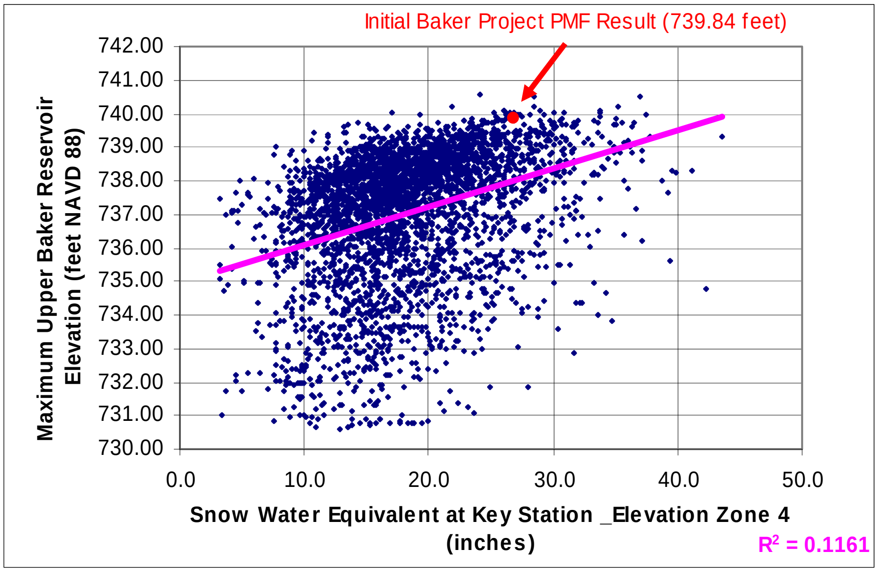


Figure 48. Example Scatter-plot –Snow Water Equivalent Parameter

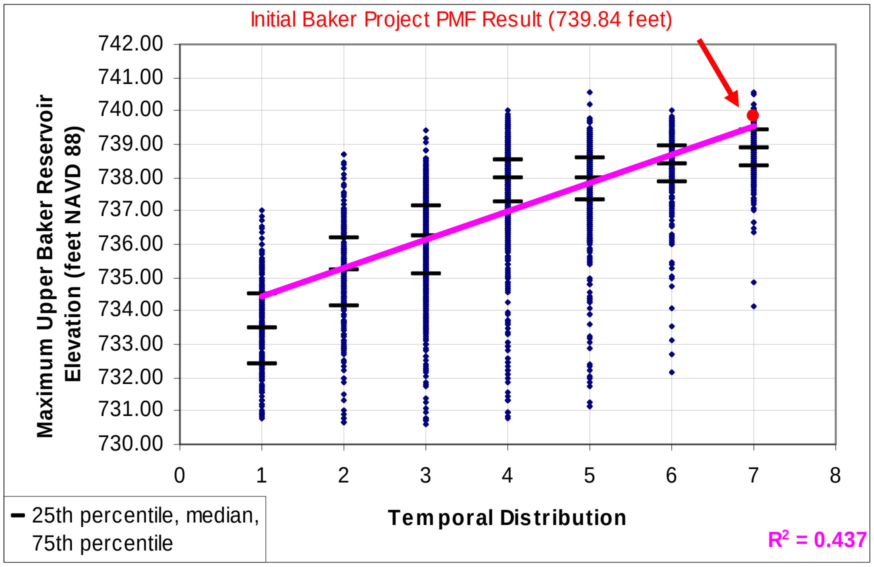


Figure 49. Example Scatter-plot –Temporal Pattern Parameter

Standard linear correlation was used to fit trend lines to the model output in each scatter-plot. A flatter trend line is typically indicative of a lower degree of model sensitivity and a steeper trend line is indicative of a higher degree of sensitivity. The degree of scatter about the trend line represents variability in the model output that is not explained by the variability in the model input parameter. A high degree of scatter indicates that other model input parameters are influencing the model output more than the variation in input parameter depicted in the plot. The coefficient of determination (R^2) was used to quantify this variability explained by the model input.

The input parameters were ranked relative to one another, in terms of model sensitivity, using a subjective evaluation of the scatter-plots. Since the R^2 value is a quantitative measure of the variability in model output that is explained by the input parameter plotted on the x-axis, the R^2 value was used as the primary measure in assessing model sensitivity for each of the input parameters. An input parameter which had a high R^2 value was identified as a highly sensitive input parameter relative to the other input parameters. In instances where model output was clearly non-linear, the sensitivity ranking was supplemented with a qualitative judgment of model sensitivity using non-linear trend lines. This additional qualitative evaluation was use for the temporal pattern, seasonality of occurrence, and antecedent reservoir elevation input parameters.

Evaluation of the model sensitivity to the seasonality of occurrence parameter was made by plotting month of occurrence (input parameter) versus model output for all 10,000 model simulations. Evaluation of model sensitivity to all other input parameters used only the November simulations, of which there were 3,581. Including only the November simulations eliminated the influence of the seasonality of occurrence parameter on the model output. The November subset of simulations was chosen because the initial PMF analysis had identified the month of November as the critical month for PMF.

Table 32 presents a summary of the findings of the GSA, which includes a qualitative evaluation of the model sensitivity to each input parameter. Flood response sensitivity is a measure of the SEFM watershed model sensitivity to variation in a given parameter and was evaluated by developing scatter-plots of peak inflow magnitude versus the corresponding input parameter value. Reservoir response sensitivity is a measure of the HEC-5 reservoir operation model sensitivity to variation in a given parameter and was evaluated by developing scatter-plots of peak reservoir elevation versus the corresponding input parameter value.

Table 32. Flood and Reservoir Response Sensitivity to Hydrometeorological Inputs

Input Parameter	Flood Response Sensitivity	Reservoir Response Sensitivity
Seasonality of Occurrence	Moderate	Moderate
Centering of Storm	Low	Low
Storm Temporal Pattern	Moderate	**High**
Antecedent Precipitation	Moderate	Moderate
Antecedent Snow Water Equivalent	**High**	**High**
Antecedent Snowpack Density	Low	Low
Antecedent Reservoir Elevation Lower Baker	n/a	Low
Antecedent Reservoir Elevation Upper Baker	n/a	Moderate

The following sections describe the sensitivity of the models to variation in each of the input parameters included in the GSA. The input parameters to which flood response and/or reservoir response are most sensitive, as shown in Table 32, are discussed first.

7.3.1 Antecedent Snow Water Equivalent

Flood response and reservoir response were determined to have a relatively high sensitivity to variation in magnitude of antecedent snow water equivalent. Figures 50 through 53 illustrate the sensitivity of the model results to antecedent snow water equivalent. These figures present the results of the GSA only for the month of November, which in effect eliminates the seasonal influence on the model results.

Figures 50 and 51 illustrate the sensitivity of flood response (Upper Baker inflow and Lower Baker inflow, respectively) to the magnitude of antecedent snow water equivalent. The results indicate model sensitivity through the entire range of antecedent snow water equivalent values. These November results indicate that increasingly deeper snowpacks are capable of melting out, thereby resulting in increasing magnitudes of peak runoff. It was anticipated that there would be a leveling off or slight reduction in the magnitude of peak runoff for deeper snowpacks, as the capability of the hydrometeorological conditions to melt the snowpack were maximized. The scatter-plots of Figures 50 and 51 do not entirely substantiate this, which could be partially attributed to the small number of model runs with snowpacks greater than 30 inches. The degree of scatter about the trend line is greater for the Lower Baker inflow results (Figure 51) than for the Upper Baker inflow results (Figure 50). This is quantitatively measured by the value of R^2, which is smaller for the Lower Baker results. The higher degree of scatter in the Lower Baker peak inflow results indicates that other model input parameters are having a higher degree of influence on the results than is the case for the Upper Baker peak inflow results.

Figures 52 and 53 illustrate the sensitivity of reservoir response (Upper Baker reservoir and Lower Baker reservoir, respectively) to the magnitude of antecedent snow water equivalent.

The relatively high values of the R^2 parameter and the strong upward slope of the trend lines, compared to many of the scatter-plots presented in the remaining sections of this memorandum, indicate a higher degree of model sensitivity to snow water equivalent.

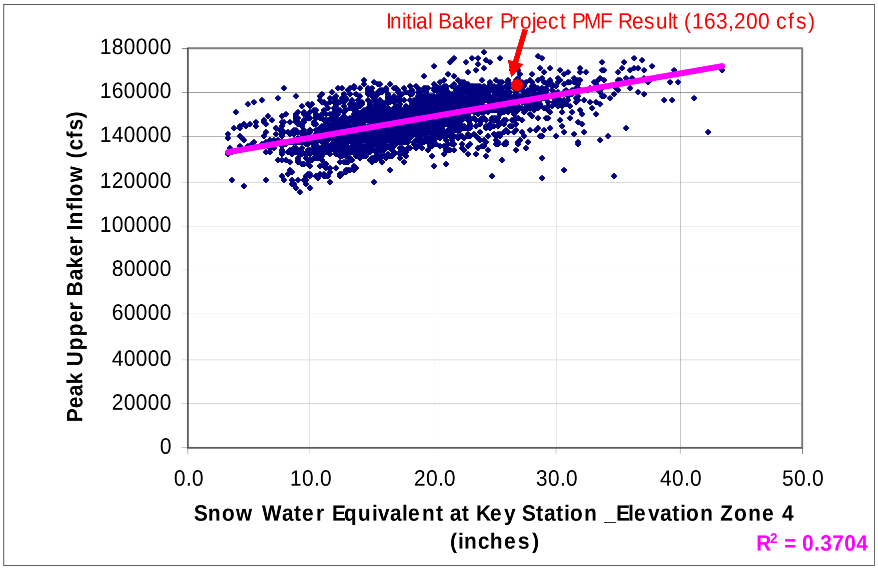


Figure 50. Sensitivity of Upper Baker Peak Inflow to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

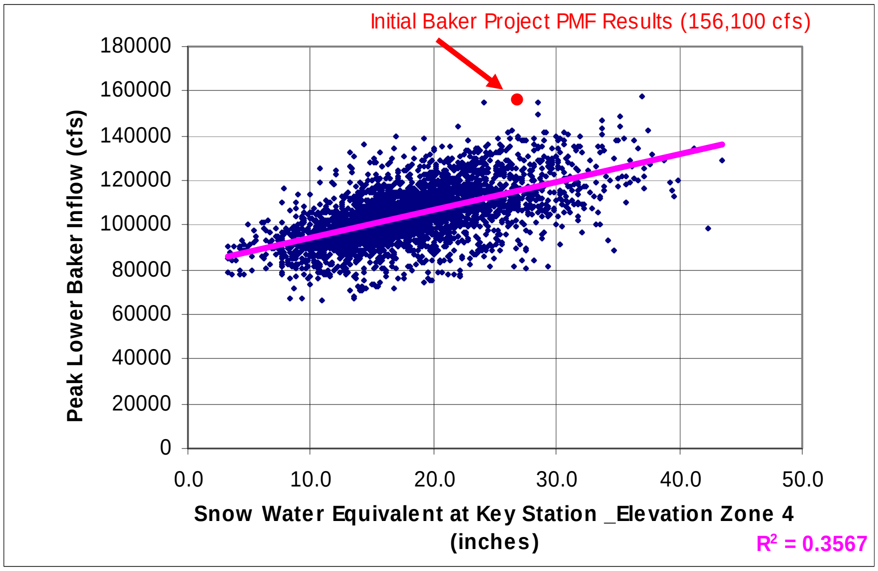


Figure 51. Sensitivity of Lower Baker Peak Inflow to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

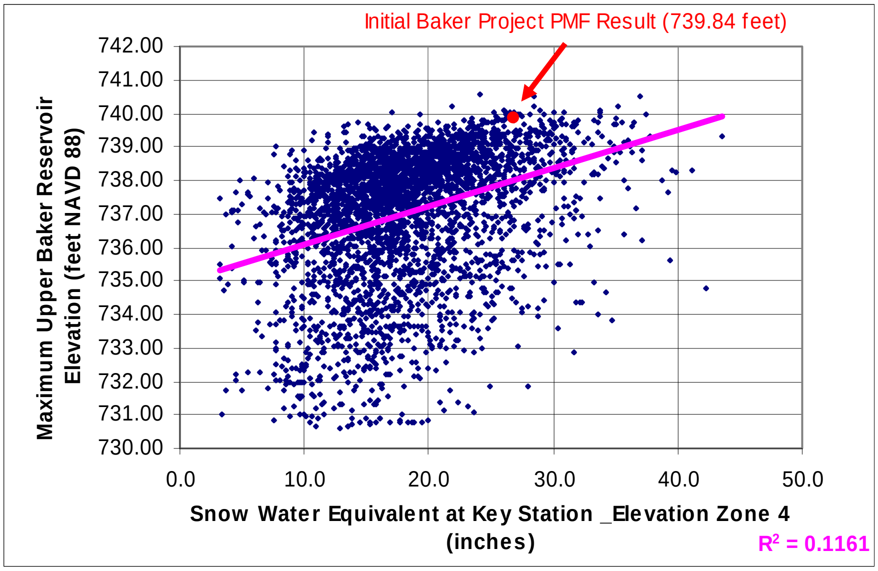


Figure 52. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

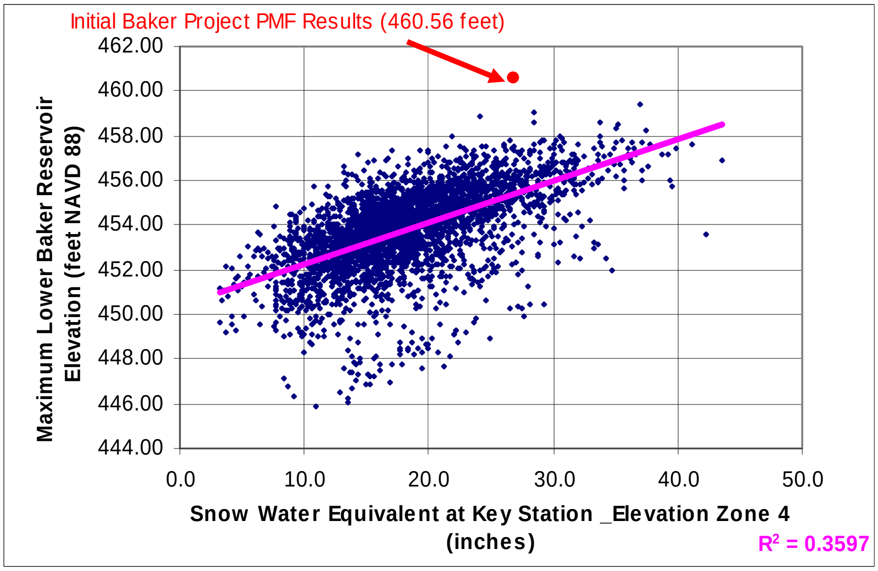


Figure 53. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

7.3.2 Storm Temporal Pattern

Flood response was determined to be moderately sensitive to the temporal pattern of the storm and reservoir response was determined to be highly sensitive to temporal pattern of the storm. Figures 54 and 55 illustrate the sensitivity of the model results to the temporal pattern. These figures present the results of the GSA only for the month of November, which in effect takes out some of the seasonal influence on the model results.

Seven temporal patterns—including mid-loaded, front-loaded and back-loaded—were evaluated for the GSA. The primary difference was the timing of the highest intensity segment, which ranged from hour 10

(Pattern No. 1) to hour 58 (Pattern No. 7). Temporal Pattern No. 1 was the most front-loaded of the seven and Temporal Pattern No. 7 was the most back-loaded. Temporal Patterns No. 4 and No. 5 represent mid-loaded storm patterns, with the peak intensity during the middle one-third of the 72-hour storm duration.

The analysis generally showed that the back-loaded temporal patterns produce the largest peak inflows, the highest reservoir elevations, and the largest peak outflows. For the Upper Baker peak inflow (Figure 54), the front-loaded temporal patterns (patterns 1 and 2) produce lower peak flows because the peak precipitation intensity occurs before 100 percent of the basin is contributing to the total runoff, before the soils are completely saturated, and/or before the snowpack is fully yielding.

The model sensitivity to temporal pattern is significantly more pronounced when considering reservoir response (Figure 55). Back-loaded storm patterns produce a large surge of inflow volume in the latter portion of the storm after earlier portions of the storm have partially filled much of the available reservoir storage. As seen in Figure 55, the most back-loaded patterns produce a clear cluster of higher model output values, as illustrated by lesser degree of variability in the model output for these back-loaded patterns. As such, the back-loaded temporal patterns poses the greatest potential for producing high reservoir levels.

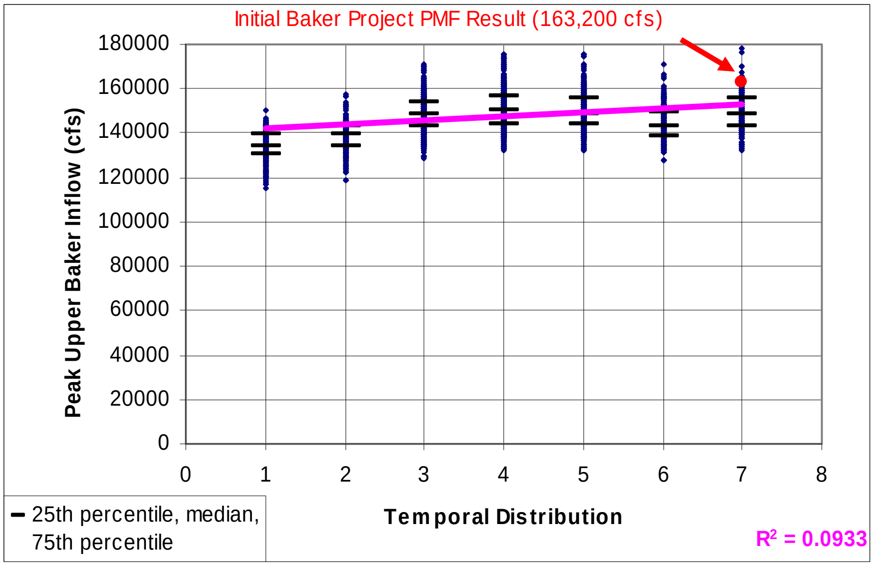


Figure 54. Sensitivity of Upper Baker Peak Inflow to PMP Temporal Pattern for END-OF-NOVEMBER Results Only

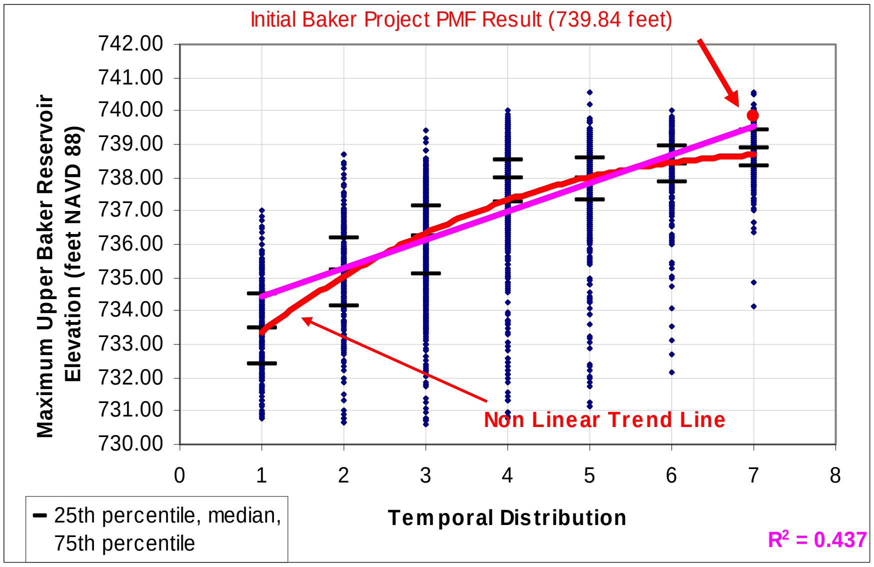


Figure 55. Sensitivity of Upper Baker Peak Reservoir Elevation to PMP Temporal Pattern for END-OF-NOVEMBER Results Only

7.3.3 Seasonality of Occurrence

Flood response, represented by peak inflow, was determined to be moderately sensitive to the seasonality of occurrence, and reservoir response was also determined to be moderately sensitive to seasonality of occurrence. The conclusion that the model is at least moderately sensitive to this parameter is not surprising since many of the other input parameters are dependent on the seasonality of occurrence. The strength of the sensitivity is illustrated in Figures 56 and 57. Figure 56 shows the sensitivity of the flood response (in this case, peak Upper Baker inflow) and Figure 57 shows the sensitivity of the reservoir response (in this case, peak Upper Baker reservoir elevation).

As seen in Figure 56, the month of November produced the single highest value of peak inflow into the Upper Baker reservoir and the month of October produced the second single highest; however, the subset of October results had much more variability than the subset of any other month, as seen visually in Figure 56 and as quantified by the standard deviation. The mean value of the November subset of results was the highest of all months (147,438 cfs) while the December subset had the second highest mean value of all months (145,164 cfs). The October subset had the lowest mean value of the months that were included in the GSA (134,828 cfs).

In terms of flood response, the months of October and November are clearly most capable of producing the highest peak inflows of all months. Since all months were assumed to be capable of producing 100 percent PMP (precipitation was equal for all months), the question is why October and November are capable of producing the largest peak inflow rates. Available snow water equivalent in the snowpack is expected to be greater later in the season (i.e. in December and January and February). Since available moisture in the watershed during the PMP (precipitation input plus snow water equivalent) tends to be higher for the later winter months, the only explanation is that the October and November average air temperatures are high enough to produce more snowmelt and less snowfall than is the case for any of the later months. The average air temperatures for the November simulations were above freezing for all elevation zones. For the December, January and February simulations, the average air temperatures were above freezing for all but the two highest elevation zones.

As seen in Figure 57, the month of November produced the single highest value of peak Upper Baker reservoir elevation and the month of October produced the second highest; however, the subset of October results had much more variability and a lower mean value than the subset of November results. The November results are characterized as having the least amount of variability as compared to the other months, as measured by the standard deviation of the results and also by the difference between the 25th and the 75th percentiles.

The mean value of the November subset of results in Figure 57 was the highest of all months (737.04 feet) and the October subset had the second highest mean value of all months (736.00 feet). The February subset had the lowest mean value of the months that were included in the GSA (733.87 feet). To further illustrate the trend of the model results in Figure 57, a third order polynomial trend line was fit to the data. This non-linear trend line passes approximately through the mean monthly model values. The trend for lower reservoir elevations for the months of December, January and February as compared to October and November is due to the combined effect of lower antecedent reservoir elevations and cooler air temperatures.

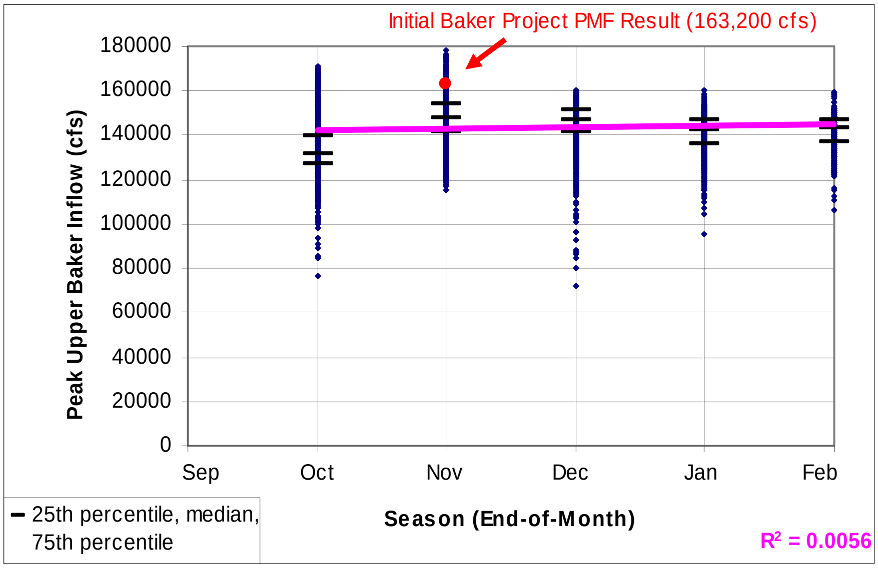


Figure 56. Sensitivity of Upper Baker Peak Inflow to Seasonality of Occurrence

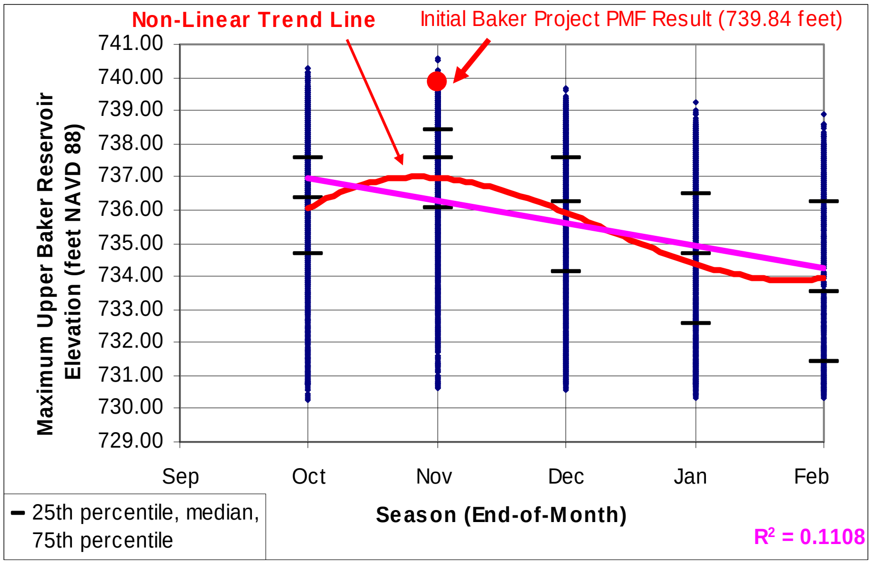


Figure 57. Sensitivity of Upper Baker Peak Reservoir Elevation to Seasonality of Occurrence

7.3.4 Antecedent Precipitation

Flood response and reservoir response were both determined to have a moderate sensitivity to antecedent precipitation. Figures 58 through 61 illustrate the sensitivity of the model results to antecedent precipitation for the month of November.

Antecedent precipitation represents the cumulative rainfall during the water year prior to the onset of the PMP event. As the winter season progresses, soils in the watershed become more and more saturated as cumulative precipitation increases. During wet water years, the soils become saturated earlier in the season. When an extreme precipitation event occurs under these conditions, the saturated soils allow for the immediate conversion of precipitation to runoff. During drier water years, the soils are not yet saturated and when an extreme precipitation event occurs, soil moisture deficits must be satisfied before runoff is produced. Therefore, all other things equal, it is expected that higher runoff volumes, and possibly higher peak runoff rates, would be expected during wet water years than dry water years.

Figures 58 through 61 show the trend of higher model output for higher of end-of-November antecedent precipitation. Compared to the previously identified highly sensitive parameters (snow water equivalent, storm temporal pattern, and seasonality), the degree of scatter, especially for the reservoir response model results, is significant (as measured by the relatively small value of R^2). This indicates that the variability in model output is explained less by the variability in antecedent precipitation and more by other model input parameters. However, the clear upward slope of the trend lines in all four figures does indicate that the magnitude of antecedent precipitation does influence the model output. For the November simulations, watershed soils were typically entirely saturated for antecedent precipitation values greater than approximately 10 inches.

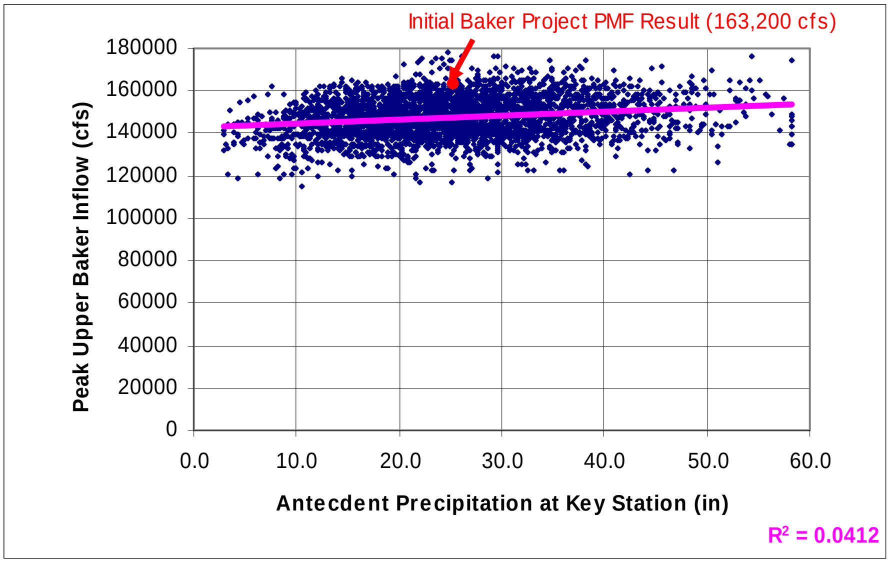


Figure 58. Sensitivity of Upper Baker Peak Inflow to Antecedent Precipitation for END-OF-NOVEMBER Results Only

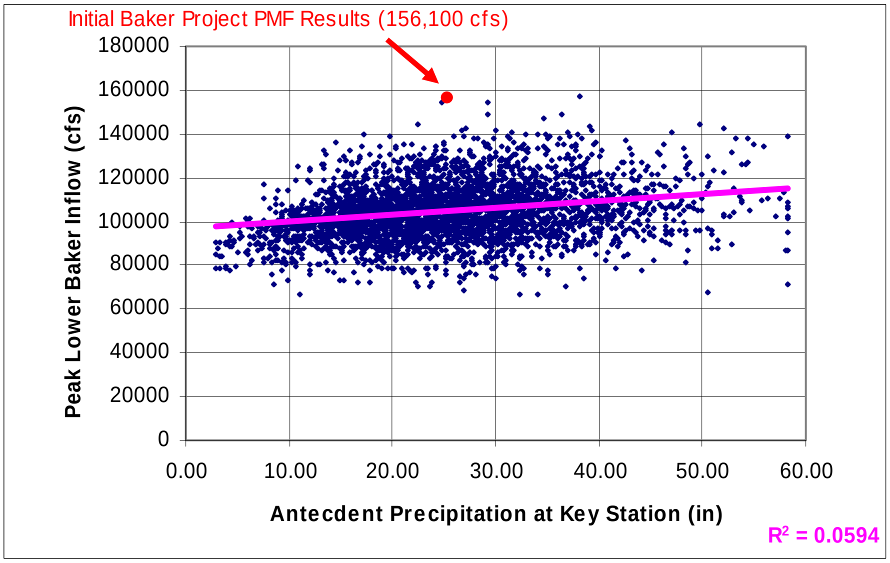


Figure 59. Sensitivity of Lower Baker Peak Inflow to Antecedent Precipitation for END-OF-NOVEMBER Results Only

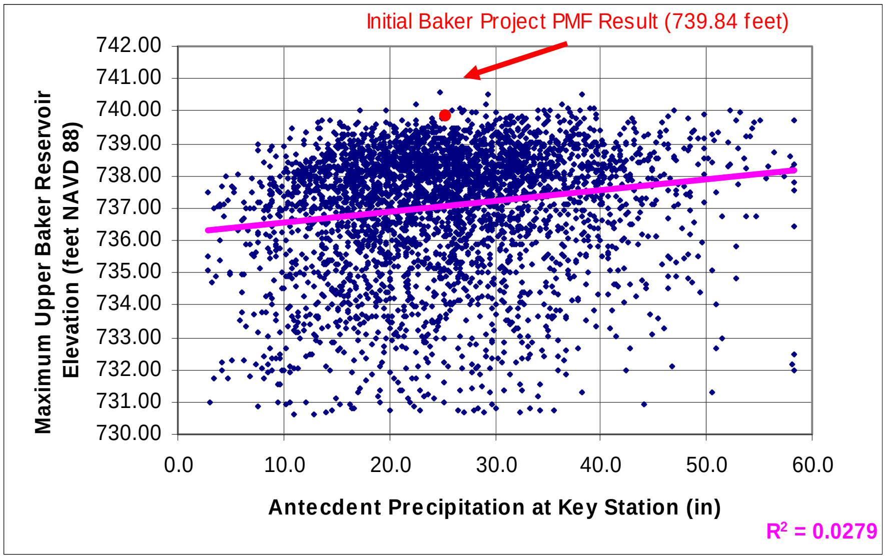


Figure 60. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Precipitation for END-OF-NOVEMBER Results Only

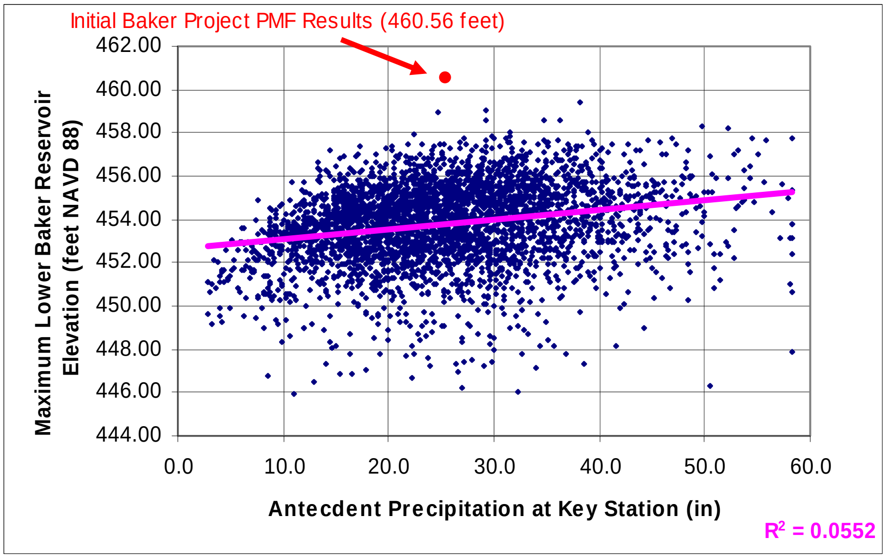


Figure 61. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Precipitation for END-OF-NOVEMBER Results Only

7.3.5 Antecedent Reservoir Elevation

It is expected that reservoir response should be sensitive to variation in antecedent reservoir elevation magnitude. Lower antecedent reservoir elevations allow for larger reservoir volumes that are available to manage the incoming PMF volume. Therefore, all other inputs being equal lower antecedent reservoir elevations should result in lower peak reservoir elevations after routing the PMF hydrograph. This trend was found to be more pronounced for Upper Baker reservoir routing results than for Lower Baker reservoir routing results. This makes sense because typical antecedent reservoir conditions leave significantly more volume available for managing inflow volume in Upper Baker than in Lower Baker. Additionally, Lower Baker is not currently managed for flood control and essentially operates as a run-of-river facility, passing inflow volume as quickly as allowed by the spillway capacity.

Figure 62 shows the sensitivity of the peak Upper Baker reservoir elevation to antecedent reservoir elevation. The sensitivity of this parameter for antecedent elevations greater than 710 feet is illustrated by the generally denser clusters of higher peak reservoir elevations. But for antecedent elevations between 701 feet and 710 feet, it does not appear that the model is extremely sensitive to the antecedent reservoir elevation value. It is also noted that regardless of the antecedent reservoir elevation, there were occurrences where the peak reservoir elevation exceeded 739.8 feet (4 feet of overtopping). This leads to the conclusion that the combined effect of the other hydrometeorological parameters is capable of producing high peak reservoir values, regardless of the antecedent reservoir elevation. Based on the results of the sensitivity analysis presented thus far, the assumed temporal pattern and the magnitude of antecedent snow water equivalent are influencing the results more so than the antecedent reservoir elevation.

Figure 63 shows the sensitivity of the peak Lower Baker reservoir elevation to antecedent conditions in that reservoir. With the exception of the highest initial reservoir elevation, the results are not clearly sensitive to the initial conditions in the reservoir. This is because there is limited storage volume available in Lower Baker before overtopping begins. For the lowest end-of-November antecedent reservoir elevation included in the analysis, there is only 57,000 acre-feet of storage volume available before overtopping of the parapet wall occurs. For the November simulations, the 72-hour PMF inflow volume to Lower Baker is nearly an order of magnitude greater than the volume typically available in the reservoir. This is in contrast to the condition at the Upper Baker reservoir where the 72-hour PMF inflow volume is no more than three times greater than the volume typically available in the reservoir before overtopping occurs.

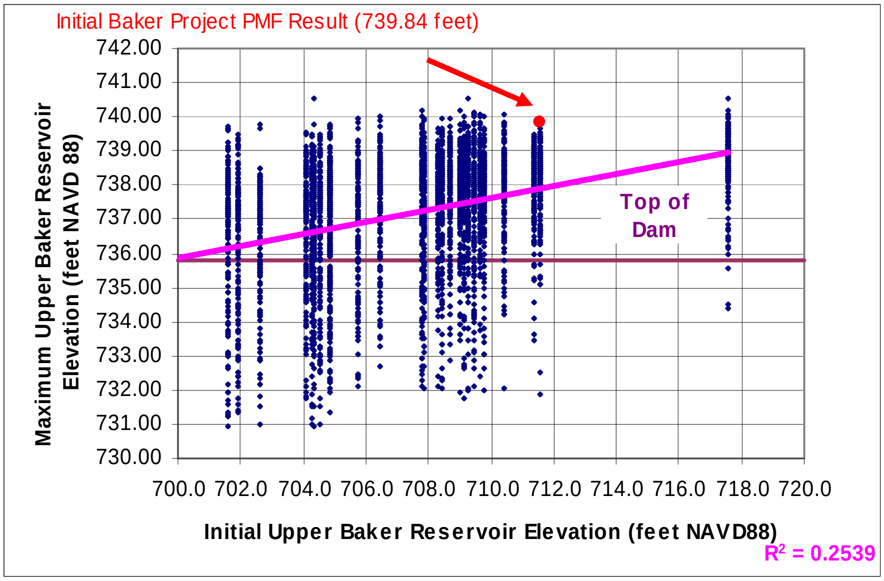


Figure 62. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Reservoir Elevation for END-OF-NOVEMBER Results Only

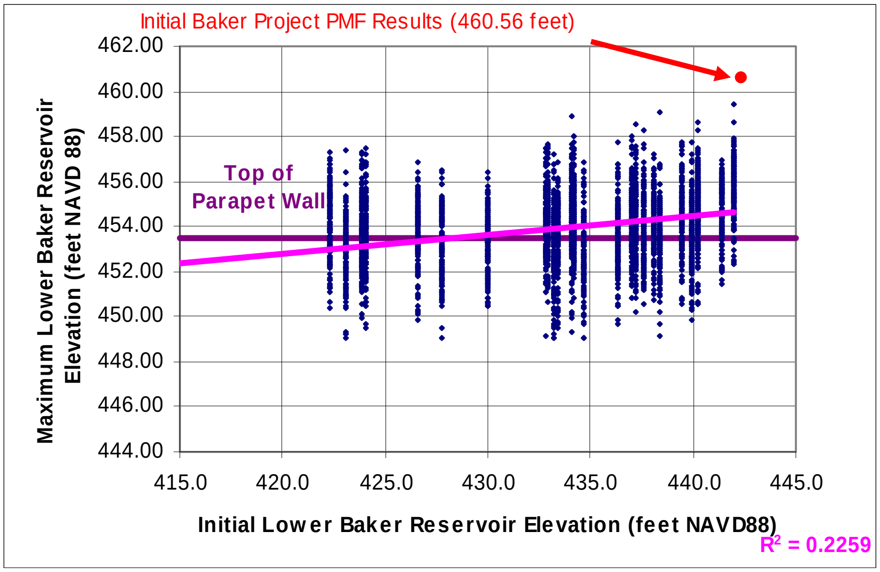


Figure 63. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Reservoir Elevation for END-OF-NOVEMBER Results Only

7.3.6 Centering of Storm

Modeled flood and reservoir response were found to have a relatively low degree of sensitivity to the centering of the general storm PMP. Figures 64 through 66 illustrate the sensitivity of the model results to general storm centering. These figures present results only for November, which in effect eliminates the seasonal influence on the model results.

These figures illustrate a general trend toward higher peak inflow rates and higher peak reservoir elevations for the upper centering scenario for both reservoirs. These results were expected for Upper Baker (Figures 64 and 65) because the upper centering scenario places a relatively higher precipitation volume in the portion of the watershed upstream of Upper Baker Dam. It is interesting, however, that the plot of Lower Baker peak reservoir elevations (Figure 66) also indicates higher peak reservoir elevations for the upper centering scenario, despite the fact that the lower centering scenario places a higher precipitation depth in the portion of the watershed downstream of Upper Baker Dam. This is at least partially explained by the fact that more than 70 percent of the entire watershed is upstream of Upper Baker Dam. Therefore, regardless of which of the three centering scenarios is assumed, runoff volume from the Upper Baker portion of the watershed sufficiently overwhelms the runoff volume generated by the local tributary area between the two dams.

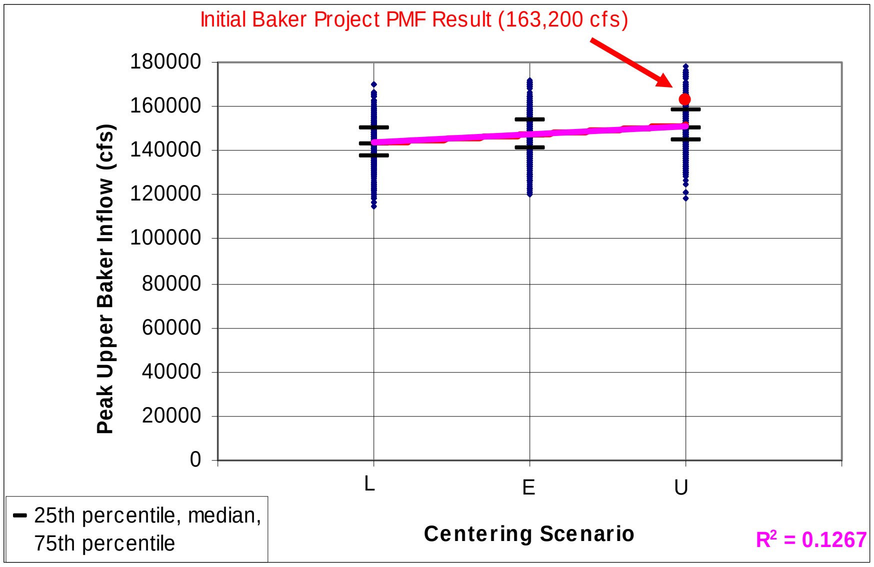


Figure 64. Sensitivity of Upper Baker Peak Inflow to General Storm Centering Scenario for END-OF-NOVEMBER Results Only

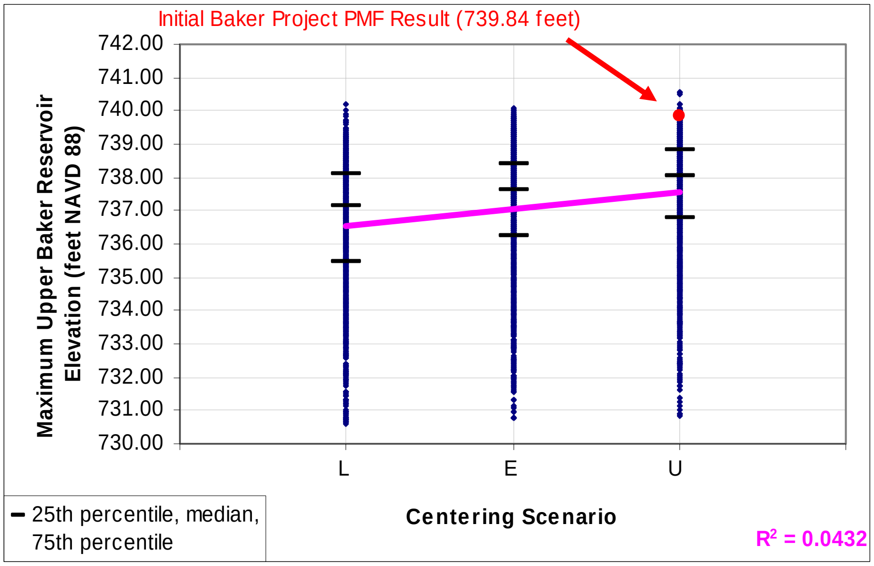


Figure 65. Sensitivity of Upper Baker Peak Reservoir Elevation to General Storm Centering Scenario for END-OF-NOVEMBER Results Only

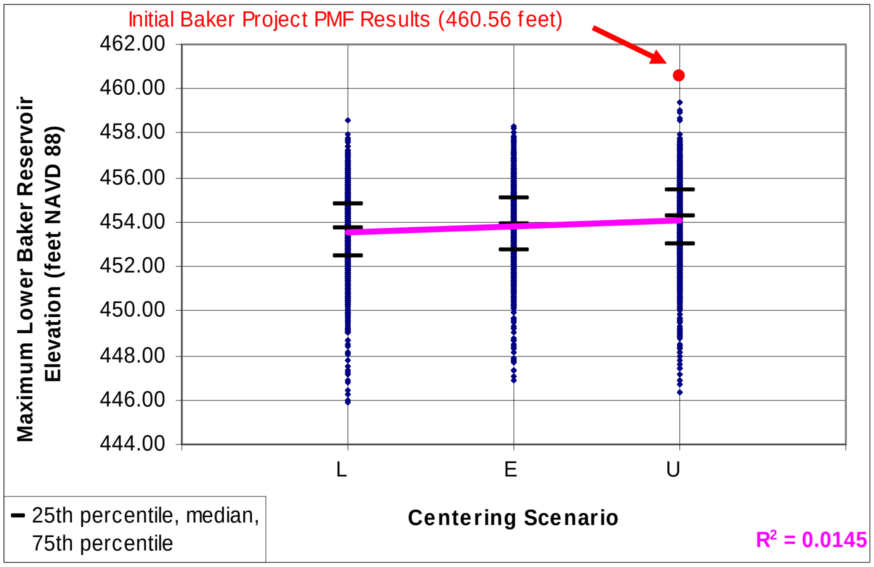


Figure 66. Sensitivity of Lower Baker Peak Reservoir Elevation to General Storm Centering Scenario for END-OF-NOVEMBER Results Only

7.3.7 Antecedent Snowpack Density

Flood response and reservoir response were determined to have a very low degree of sensitivity to antecedent snowpack density. Figures 67 through 69 illustrate the sensitivity of the model results for November to antecedent snowpack density. The high degree of scatter in the plots and the flat trend line indicate the low degree of model sensitivity to this parameter.

This is slightly contrary to the expectation that higher values of initial density would produce higher runoff volumes, which in turn would result in higher values of peak reservoir elevation. This expectation is based on the concept that a denser snowpack would not be able to absorb as much precipitation and would yield snowmelt throughout the simulation. The reasons that the results do not entirely substantiate this expectation are two-fold:

- The historical record of end-of-November snowpack densities indicated values only as low as 0.32 and as high as 0.50. Therefore, regardless of the snowpack density value selected by the Monte Carlo procedure, the antecedent snowpacks quickly reached yield density (0.40) and began producing snowmelt early in the simulation.
- The median value of the end-of-November snowpack density was 0.37. Therefore 50 percent of the simulations used antecedent densities equal to or greater than 0.37, and nearly 40 percent of the November simulations started with antecedent snowpack densities equal to or greater than yield density (0.40).

The narrow sampling range of snowpack densities, coupled with the fact that the median value was virtually equal to the yield density, essentially eliminated snowpack density as an influential parameter in the GSA.

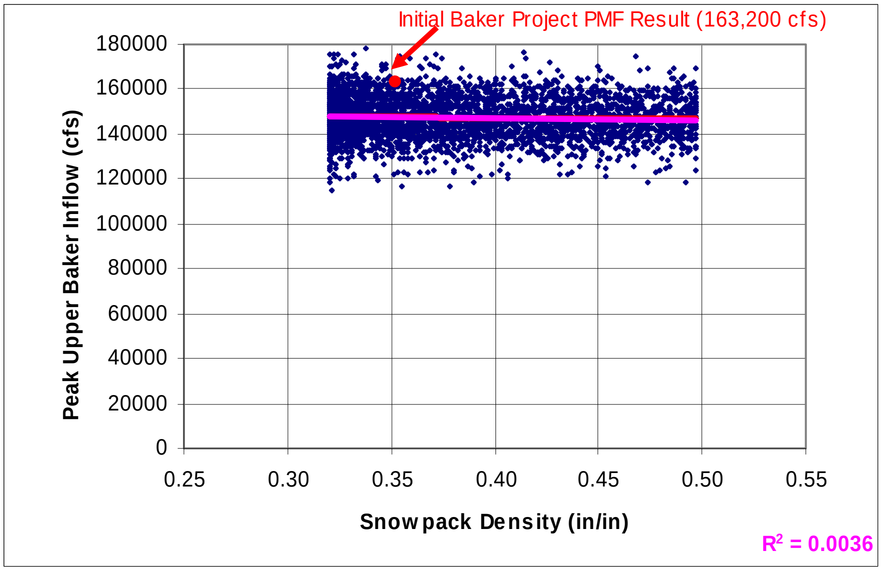


Figure 67. Sensitivity of Upper Baker Peak Inflow to Antecedent Snowpack Density for END-OF-NOVEMBER Results Only

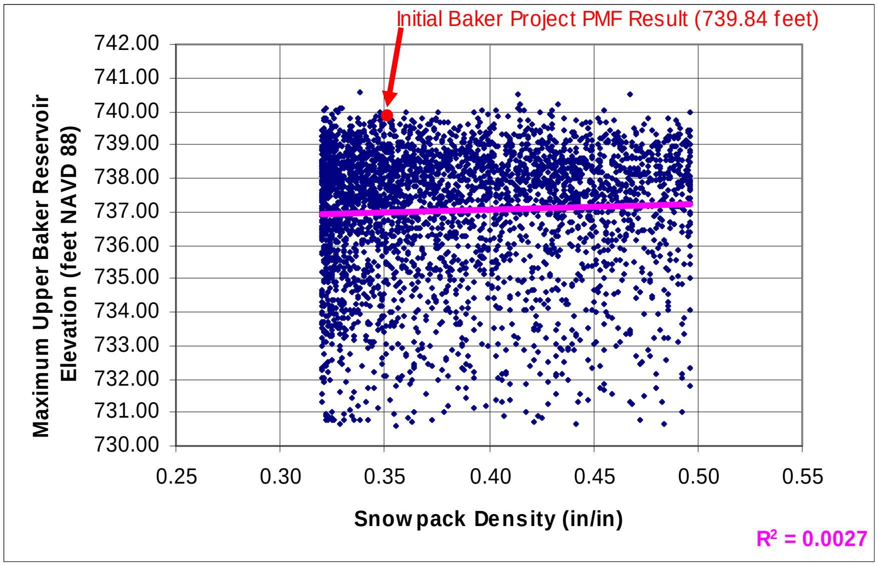


Figure 68. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Snowpack Density for END-OF-NOVEMBER Results Only

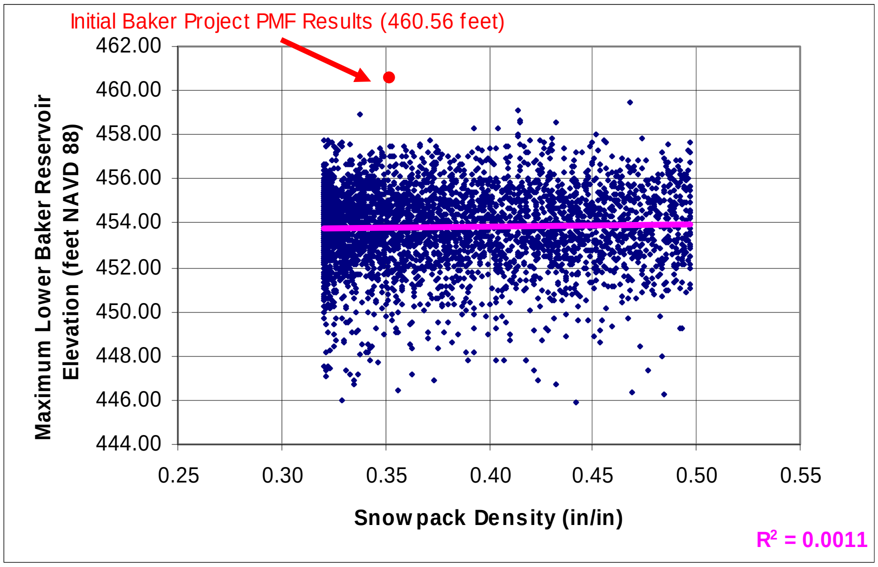


Figure 69. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Snowpack Density for END-OF-NOVEMBER Results Only

7.3.8 Sensitivity Results Summary

The findings of the GSA provided significant insight to the hydrologic response of the Upper Baker and Lower Baker watersheds to variation in the magnitude of the hydrometeorological input parameters. This insight allowed for a subjective evaluation of flood response and reservoir response sensitivity to variation in magnitude of specific input parameters. Scatter-plots of the multi-thousand model simulations were used for this evaluation. For each specific model output (i.e. peak reservoir elevation, peak inflow, or peak outflow), the set of scatter-plots for all of the input parameters were compared against one another. The degree of scatter about the linear trend line (as indicated by the value of R^2) was the quantitative measure used to identify those parameters that had the strongest influence on the model output and to rank the parameters relative to one another. This was supplemented with qualitative judgment of sensitivity in those instances where the behavior of model output for a given input parameter was clearly non-linear.

The analysis found that the model response was most sensitive to antecedent snow water equivalent, storm temporal pattern, and seasonality of occurrence. Therefore, these parameters warrant the most scrutiny when evaluating the initial PMF results for the Baker River Project.

The analysis determined that the model response was not sensitive to antecedent snowpack density. This conclusion is important because antecedent snowpack density was identified as having a higher magnitude of uncertainty than the other input parameters. Since the model response was not sensitive to the value of antecedent snowpack density, the uncertainty in this particular parameter did not contribute to a high degree of uncertainty in the model results.

Table 33 summarizes the relative magnitudes of parameter uncertainty and the relative magnitudes of flood and reservoir response sensitivity for each of the input parameters included in the GSA.

Table 33. Parameter Uncertainty and Flood and Reservoir Response Sensitivity to Hydrometeorological Inputs

Input Parameter	**Relative Magnitude of Parameter Uncertainty**	**Flood Response Sensitivity**	**Reservoir Response Sensitivity**
Seasonality of Occurrence	Low	Moderate	Moderate
Centering of Storm	Moderate	Low	Low
Storm Temporal Pattern	Low	Moderate	**High**
Antecedent Precipitation	Low	Moderate	Moderate
Antecedent Snow Water Equivalent	Moderate	**High**	**High**
Antecedent Snowpack Density	High	Low	Low
Antecedent Reservoir Elevation Lower Baker	Moderate	n/a	Low
Antecedent Reservoir Elevation Upper Baker	Moderate	n/a	Moderate

7.4 PROBABILISTIC CHARACTERIZATION OF RESULTS

As part of the GSA, 10,000 model simulations were conducted while allowing all hydrometeorological input parameters to be sampled from user input distributions. Each simulation assumed 100 percent PMP. As presented in the previous section, this sampling methodology allowed for an evaluation of which parameters the hydrologic and reservoir routing models were most sensitive to. The results of the GSA also provided a framework for developing a probabilistic characterization of the range of inflow and outflow flood magnitudes possible assuming 100 percent PMP. This probabilistic characterization is in turn used to evaluate the conservatism of the initial PMF results.

The results of the 10,000 simulations were plotted as histograms and non-exceedance probability curves to illustrate the distribution of peak inflow, peak outflow, and peak reservoir elevation. The results were also sorted by season, which allowed for the development of season specific histograms and non-exceedance probability curves. This memorandum has documented the fact that the month of November is clearly the critical month for the PMF. Therefore the November season histograms and non-exceedance curves are presented in this section. Out of the 10,000 model simulations that were conducted for the GSA, 3,581 were November simulations.

7.4.1 Upper Baker Results

Figures 70 through 72 present the frequency histograms for the Upper Baker GSA results, using all 10,000 of the GSA simulations. The initial PMF results, from Section 6, are indicated by red arrows. It is evident that the initial PMF results for Upper Baker are at the upper end of the histograms, but do not exceed the highest of the 10,000 simulations. Other observations include the following:

- 187 of the 10,000 simulations resulted in an Upper Baker peak inflow greater than the initial PMF result (see Figure 70). This means that the initial PMF inflow result is greater than the result for 98.1% of the 10,000 GSA simulations. Of these 187 simulations, 66% were November simulations and 34% were October simulations.
- 50 of the 10,000 simulations resulted in an Upper Baker maximum reservoir elevation greater than the initial PMF result (see Figure 72). This means that the initial PMF reservoir elevation result is greater than 99.5% of the 10,000 GSA simulations. Of these 50 simulations, 60% were November simulations and 40% were October simulations.

Figures 73 and 74 compare the initial PMF results to the subset of GSA simulations for November, using the peak reservoir elevation as the flood characteristic of interest. The percent non-exceedance curve is an alternative way of illustrating the results shown in the frequency histogram and provides a clearer perspective on the relative conservatism of the initial PMF results. Together, these two figures show that 30 of the 3,581 November simulations were greater than the initial PMF results. The initial PMF results are therefore greater than 99.2% of the November simulations.

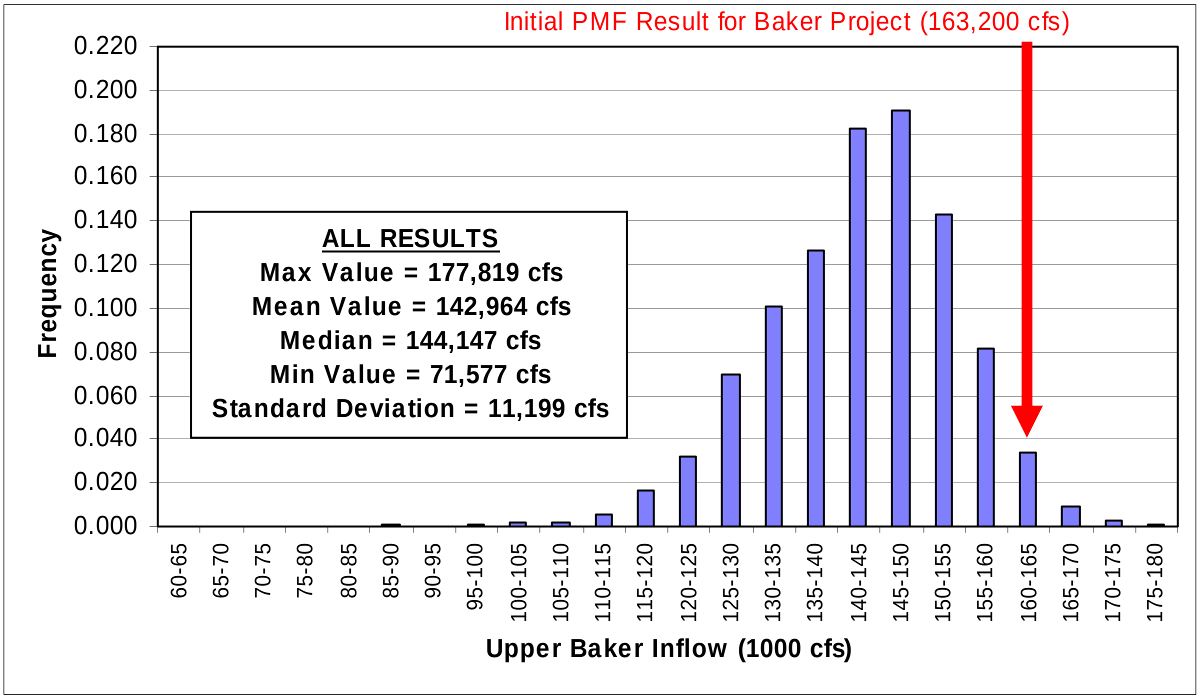


Figure 70. Frequency Histogram of Upper Baker Peak Inflows Produced by PMP – All Results

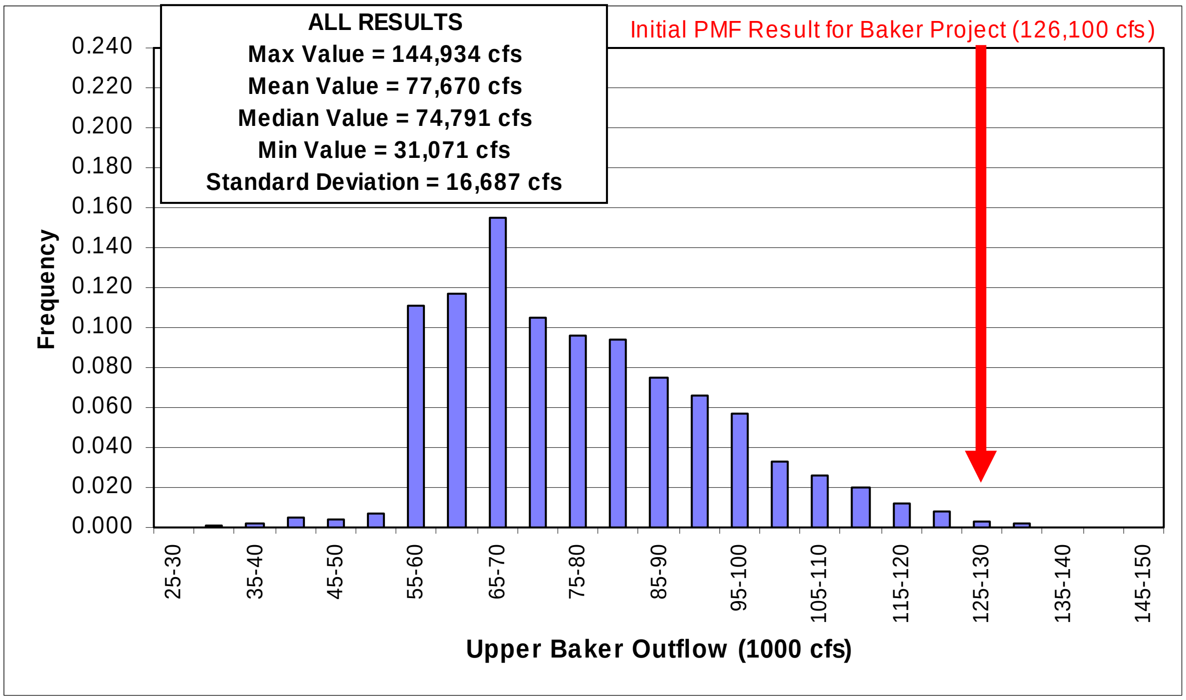


Figure 71. Frequency Histogram of Upper Baker Peak Outflows Produced by PMP – All Results

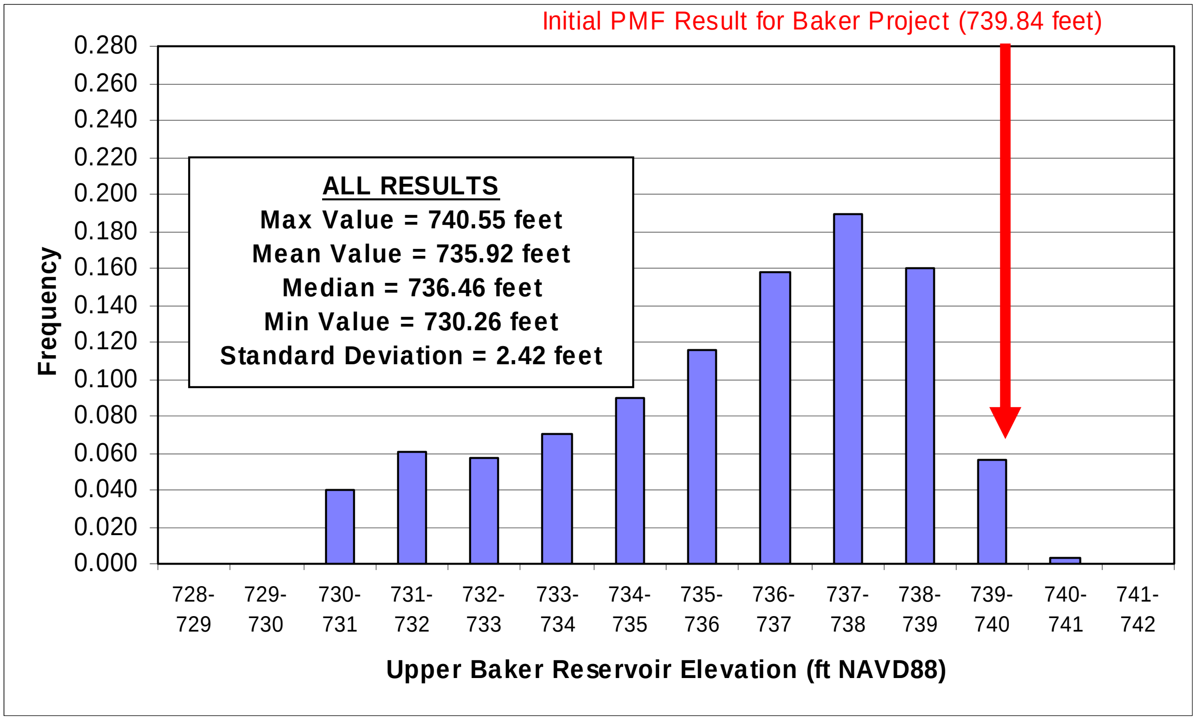


Figure 72. Frequency Histogram of Upper Baker Peak Reservoir Elevations Produced by PMP – All Results

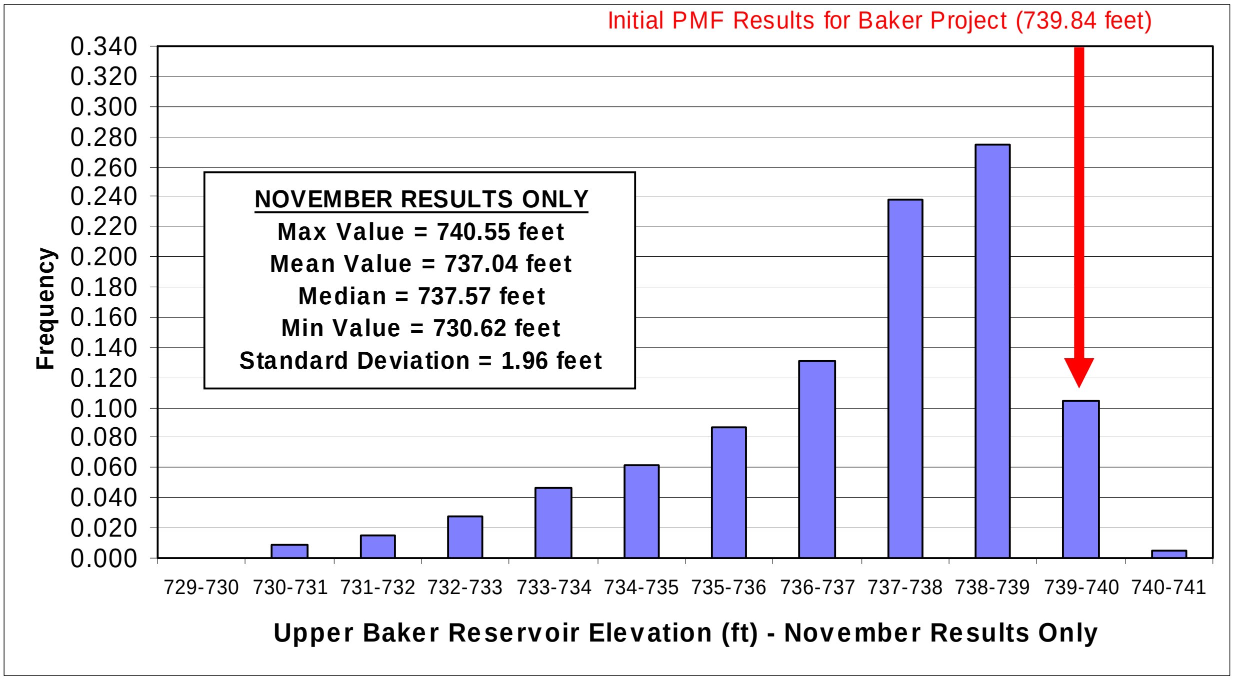


Figure 73. Frequency Histogram of Upper Baker Peak Reservoir Elevations Produced by November PMP

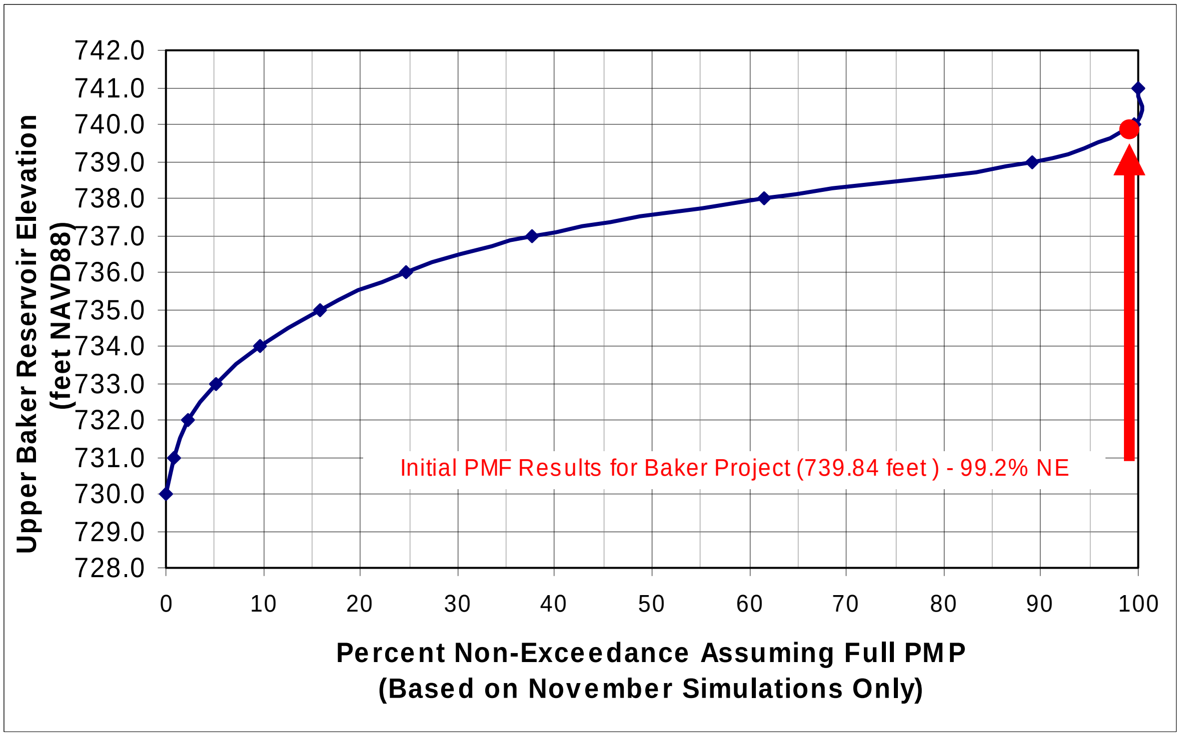


Figure 74. Percent Non-Exceedance for Upper Baker Peak Reservoir Elevations – November Results Only

7.4.2 Lower Baker Results

Figures 75 through 77 present the same frequency histograms for the Lower Baker results as were previously presented for the Upper Baker results. As seen in these figures, the initial PMF results for peak inflow, peak reservoir elevation and peak outflow (indicated by the red arrows) are greater than the results for all 10,000 model simulations. The combination of the various hydrometeorological input parameters for the initial Lower Baker PMF produced a result that none of the other 10,000 combinations could exceed. Several compounding factors contribute to this result:

- The GSA simulations reflect the historical distribution of Upper Baker end-of-month reservoir elevations, with approximately 85 percent of the 10,000 simulations and approximately 92 percent of the November simulations using sampled antecedent Upper Baker reservoir elevations lower than the 711.57 foot value that was assumed for the initial PMF simulation. With so many of the GSA simulations using antecedent reservoir elevations less than 711.57 feet, this had the effect of reduced magnitudes of outflow volume and peak outflow from Upper Baker into Lower Baker.
- All of the GSA simulations used sampled antecedent Lower Baker reservoir elevations that were less than the 442.35 foot initial reservoir elevation (normal full pool) that was assumed for the initial PMF simulation. The historical end-of-November Lower Baker reservoir elevations ranged between 385.14 feet and 441.98 feet. The median Lower Baker antecedent reservoir elevation of the 10,000 simulations was 432.24 feet, more than 10 feet below normal full pool elevation. The use of antecedent reservoir elevations that were less than the 442.35 foot elevation resulted in lower peak outflow and lower overtopping depths relative to the initial PMF results.
- Consistent with the historical data, the GSA included a significant number of simulations with little or no snow on the ground, especially for October and November. The initial PMF simulation assumed the most conservative conditions for antecedent snowpack, which placed the results at the upper end of the non-exceedance curve, and the large number of simulations with little or no snow on the ground shifts the initial results even higher on that curve. This affects the GSA results for Upper Baker as well, but the Lower Baker portion of the watershed has more low elevation coverage, so this phenomenon affects inflow to Lower Baker more than inflow to Upper Baker.

Figures 78 and 79 show the Lower Baker frequency histogram and a non-exceedance probability curve for the 3,581 November GSA simulation results for maximum reservoir elevation. These charts show that the peak reservoir elevation for the initial Lower Baker PMF simulation is roughly 1.1 feet greater than the largest of the November GSA simulations.

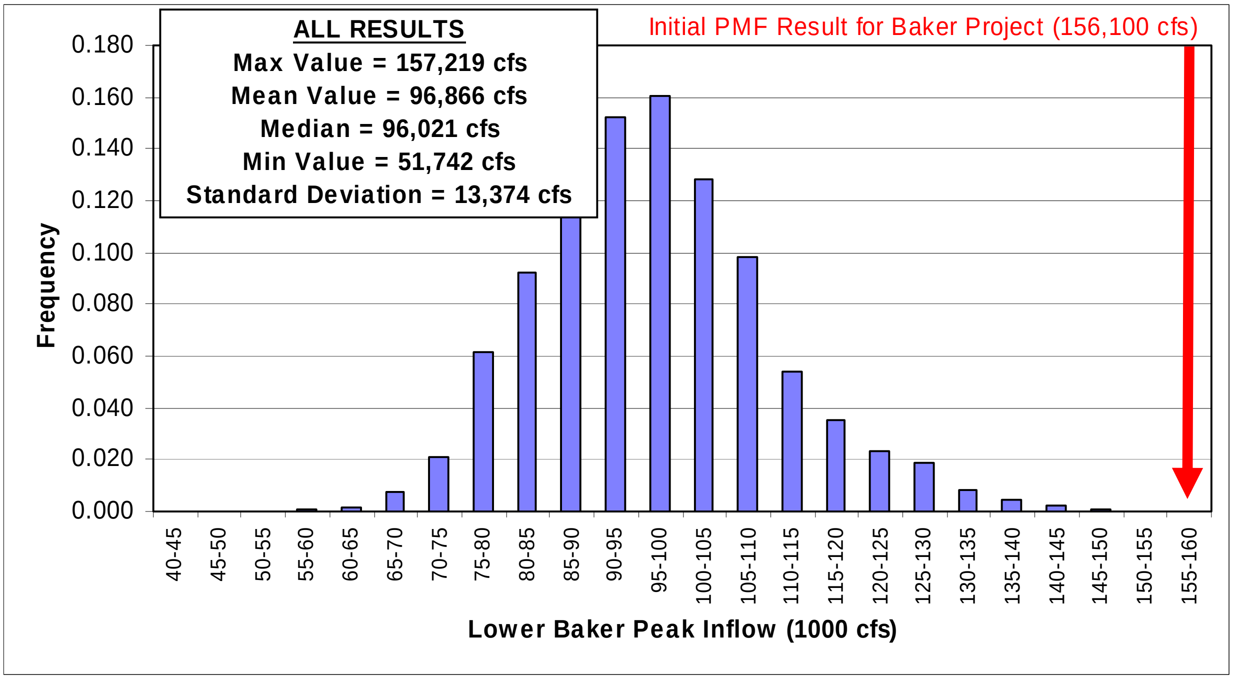


Figure 75. Frequency Histogram of Lower Baker Peak Inflows Produced by PMP – All Results

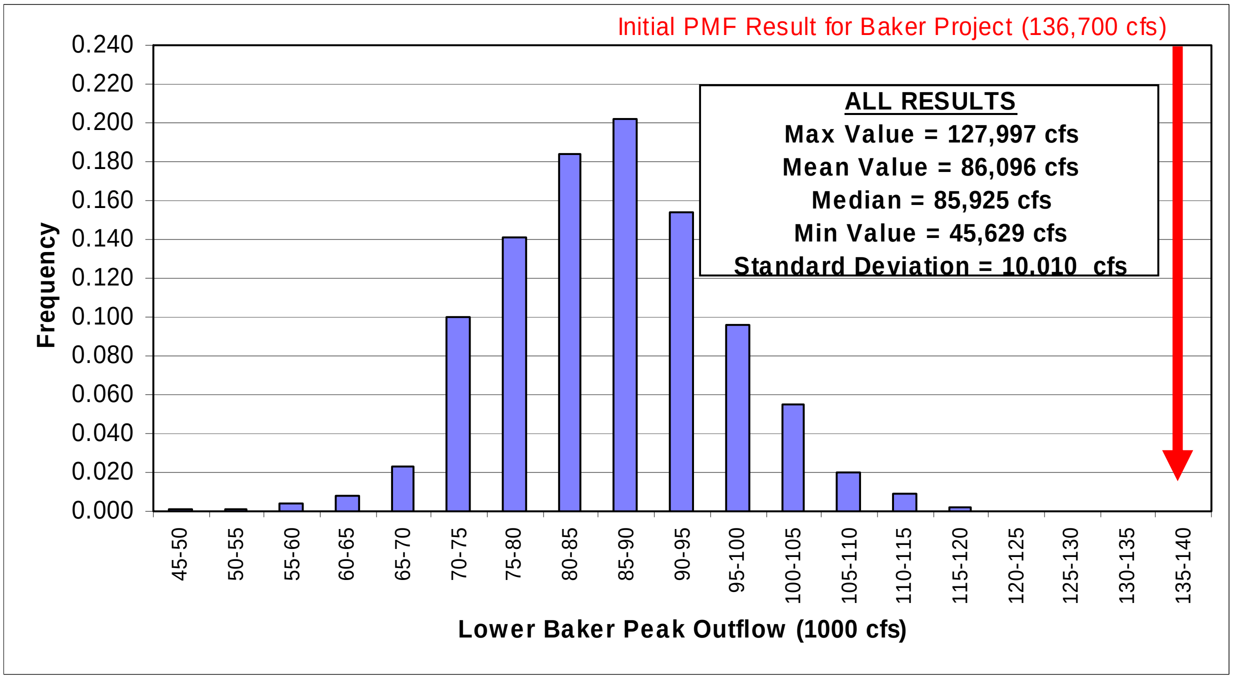


Figure 76. Frequency Histogram of Lower Baker Peak Outflows Produced by PMP – All Results

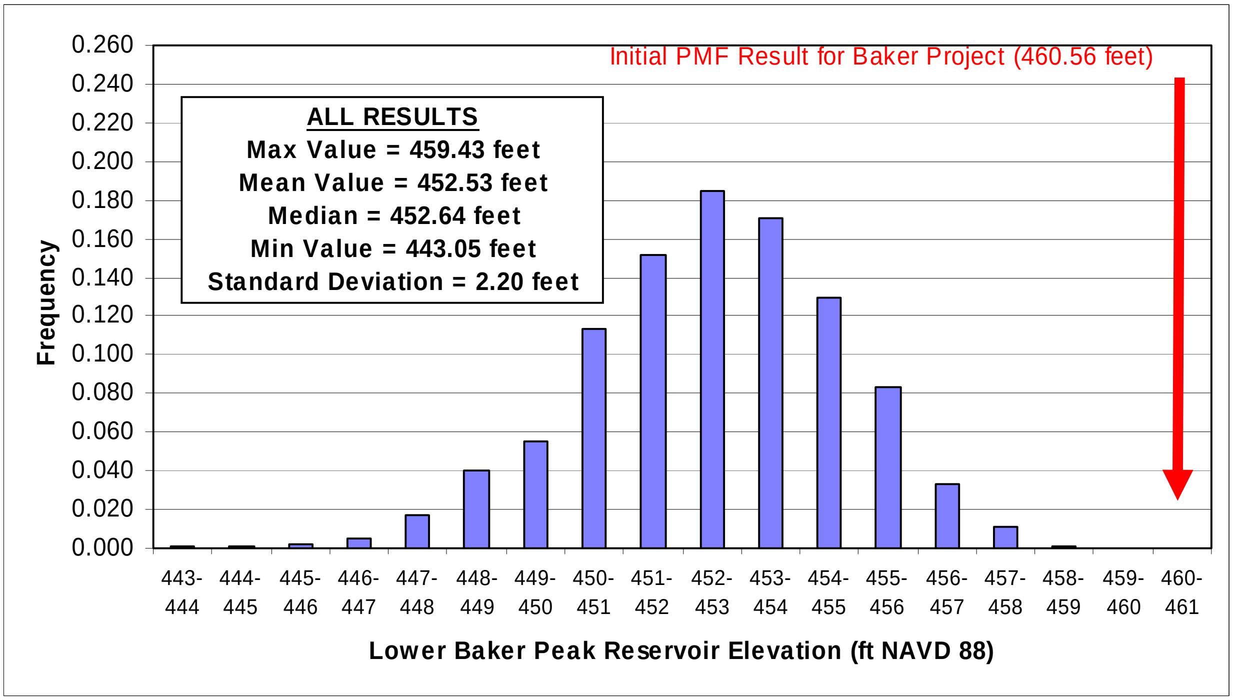


Figure 77. Frequency Histogram of Lower Baker Peak Reservoir Elevations Produced by PMP – All Results

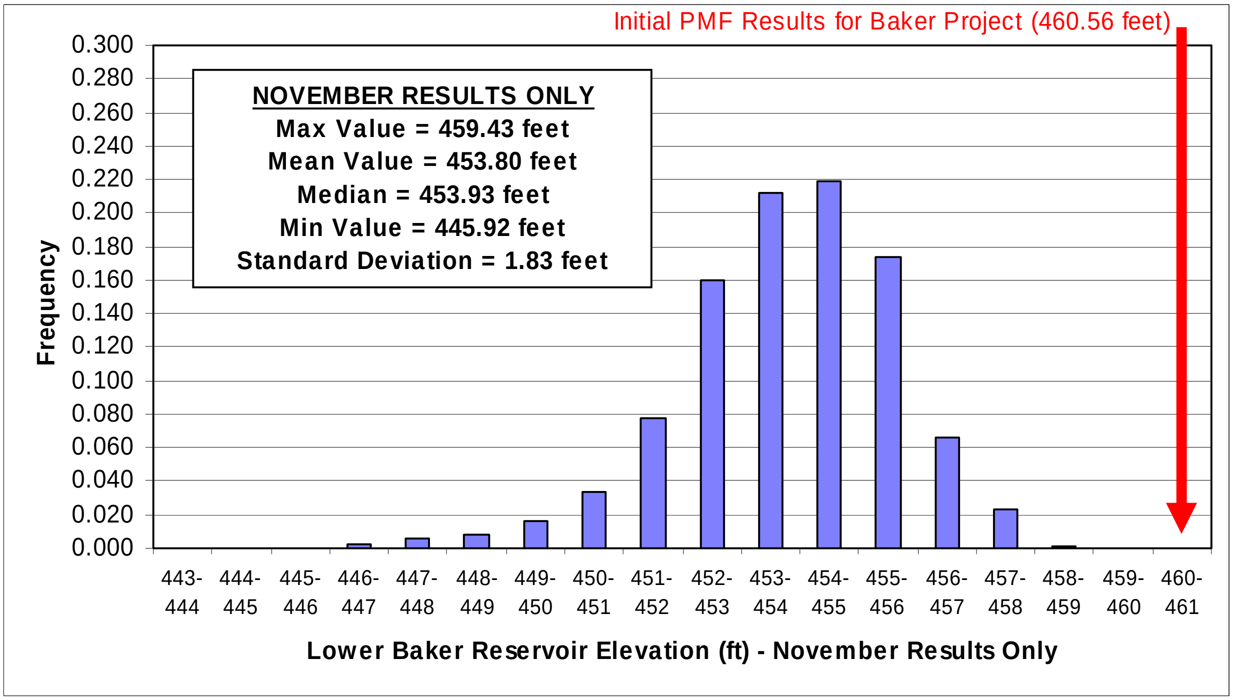


Figure 78. Frequency Histogram of Lower Baker Peak Reservoir Elevations Produced by November PMP

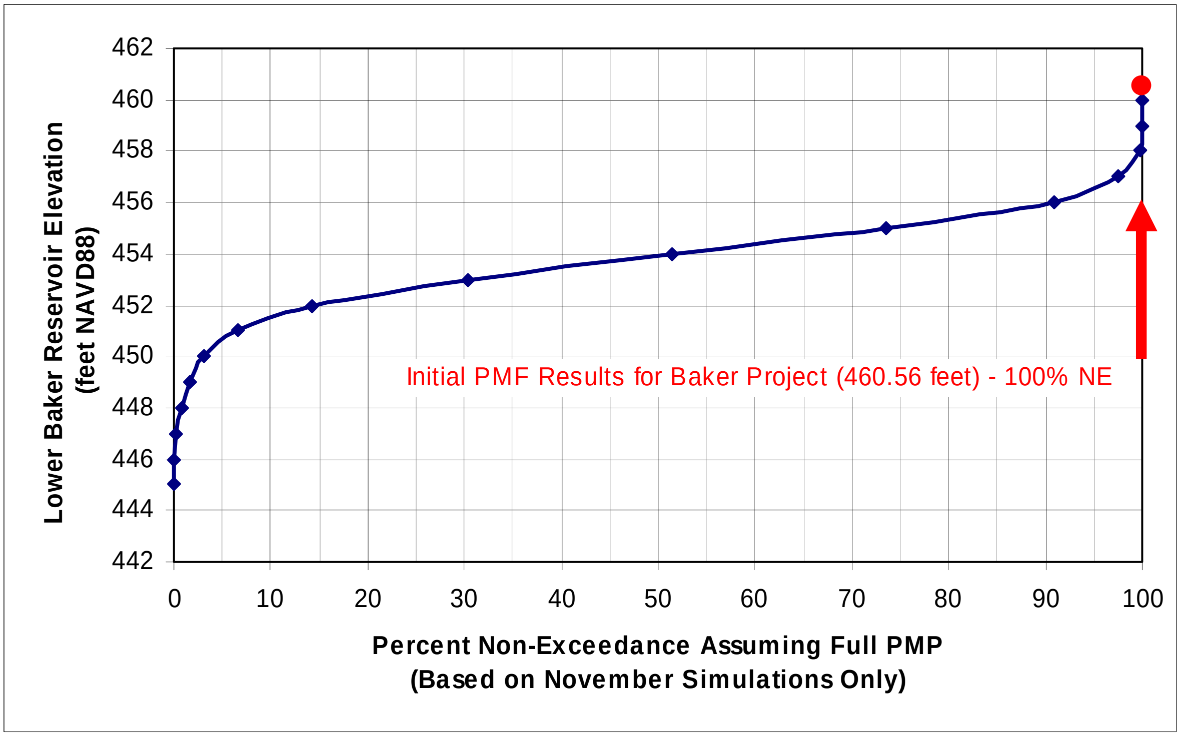


Figure 79. Percent Non-Exceedance for Lower Baker Peak Reservoir Elevations – November Results Only

7.4.3 Conclusions

The frequency histograms and the non-exceedance probability curves presented in this section were used to evaluate the initial PMF results relative to the range of results from the GSA. All of the 10,000 GSA simulations used 100 percent PMP as input, so the peak inflows and the peak outflows generated by these simulations are associated with extremely rare storm events. The results of the GSA illustrate that there are numerous combinations of hydrometeorological input parameter values that can result in high peak inflow and peak reservoir elevations, particularly for the end-of-October and end-of-November time periods. The results of the GSA also illustrate that the selected values for the hydrometeorological input parameters for the initial PMF simulation were such that the initial result are characterized with a high level of conservatism.

The frequency histograms for Upper Baker indicate that the initial PMF results are in the top 1 to 2 percent of 10,000 model simulations conducted for the GSA, establishing them as clearly conservative model results. The fact that the initial PMF results for Lower Baker exceed the entire range of GSA simulated results indicates an excessively high degree of conservatism.

Hydrometeorological input values used in the initial PMF analysis were based on the most conservative estimate that was considered reasonable so as to produce a conservative estimate of the PMF. However, the comparison to the GSA results indicates that the conservatism in the individual parameter estimates is compounding in such a way as to result in an overly conservative estimate of the PMF. It is therefore recommended that the basis for selecting the magnitude of some hydrometeorological input parameters be revisited, using the results of the GSA to guide which parameters should be revisited.

7.5 FINAL PMF CONCLUSIONS AND RECOMMENDATIONS

Table 33 identified the relative ranking of the parameters to which the hydrologic and reservoir routing models were sensitive. Seasonality of occurrence, temporal pattern, and antecedent snow water equivalent were identified as the three parameters that were found to have the most influence on the flood and reservoir routing model results. Therefore, the values of these three input parameters used to develop the initial estimate of PMF were considered first for potential modification. FERC engineering guidance (FERC 2001) was considered during the process of reviewing these parameters for potential modification. The following sections provide the rationale for changes recommended to the initial input parameters to develop the parameter set for the final PMF simulation.

7.5.1 Seasonality

It cannot be justified to use a month other than November for the critical PMF. The analysis conducted for the initial PMF determined that November was the critical month, and the results of the GSA substantiated this determination. The GSA results indicated that the November simulations produced the highest peak inflow rates and maximum reservoir elevations of all months considered, for both Upper Baker and Lower Baker. **Therefore, it is recommended that the November season remain as the basis for the final PMF analysis.**

7.5.2 Centering

Regarding the spatial distribution of the general storm PMP, FERC (2001) states that “dependence must be placed on patterns produced by historical storms, mean annual precipitation patterns, or 50-year or longer return period precipitation patterns such as those found in NOAA Atlas 2” for PMF studies for western states where orographic influence is predominant. The FERC guidance does not explicitly address general storm centering. However, HMR-57 indirectly addresses the issue of general storm centering through the use of areal reduction factors, which provide a means of reducing the 10-mi^2 PMP index estimates to basin average estimates.

For this study, spatial allocation of the PMP was based on the 100-year 24-hour precipitation map developed by Schaefer et al. (2006). Three centering scenarios were investigated because the two dams subdivide the watershed into two distinct tributary areas. The areal reduction factors presented in HMR-57 were used to center the general storm over the entire Baker River watershed, the portion of the watershed upstream of Upper Baker Dam and the portion of the watershed between the Upper Baker and Lower Baker Dams.

The results of the initial PMF analysis determined that model runs which assumed the upper centering scenario were found to produce the highest magnitude of inflow results for both Upper Baker Dam and the Lower Baker Dam, in terms of peak runoff and runoff volume, and the highest peak reservoir elevations for both reservoirs. This conclusion was substantiated through the GSA. The upper centering scenario is consistent with the nature of historical distribution of precipitation which favors the upper portion of the watershed. Additionally, the upper centering is the only logical choice for Upper Baker Dam. **Therefore, it is recommended that the upper centering scenario remain as the basis for the final PMF analysis for both Upper Baker and Lower Baker Dams.**

7.5.3 Storm Temporal Pattern

The initial PMF results were based on a back-loaded storm event that had the peak 1-hour intensity occurring at hour 58 of the 72-hour duration storm event. The non-exceedance probability associated with the time of occurrence of this peak intensity is 5% (Schaefer 1989), meaning that 95% of extreme storms typically have peak intensities occurring prior to hour 58. The results of the GSA indicated that back-loaded storms consistently produced the highest reservoir elevations, due to the delayed timing of the inflow volume (see Figure 55).

FERC guidance (FERC 2001) recommends that the peak 6-hour period of rainfall be placed between the half and two-thirds point of the storm's temporal sequence. For a 72 hour duration storm, this would result in the peak intensity falling between hour 36 and hour 48. Two of the seven temporal patterns included in the GSA fall within this recommendation: Temporal Pattern 4 has the peak 1-hour intensity at hour 33 (50 percent exceedance probability); and Temporal Pattern 5 has the peak 1-hour intensity at hour 47 (20 percent exceedance probability). **Temporal Pattern 5 produced the most severe results of the temporal distributions that fall within the FERC guidance and is therefore recommended as the temporal pattern for use in the final PMF analysis.**

7.5.4 Antecedent Precipitation

FERC guidance indicates that the conditions antecedent to the occurrence of the PMP should represent reasonable meteorological conditions. For the initial PMF results, the magnitude of antecedent precipitation was equivalent to average conditions. These average conditions resulted in near saturation of the soils in the watershed, which is typical of the soil conditions during the winter season. **Therefore the assumption made for the initial PMF of average antecedent precipitation is recommended for the final PMF.**

7.5.5 Antecedent Snow Water Equivalent

The initial PMF results were based on an iterative procedure that sought to identify the snow water equivalent conditions for each month that maximized snowmelt runoff volume and therefore represented the most severe condition, for a select general storm centering scenario and a select temporal pattern (see Section 3.4). The initial PMF analysis for the month of November determined that this corresponded with a snowpack that had a 90% non-exceedance probability (see Table 3), although the 80% non-exceedance probability snowpack produced fairly similar results. This iterative procedure is consistent with the intent of the guidance provided in FERC (2001) due to the fact that the objective was to maximize the snowmelt contribution to watershed runoff. In the FERC guidance, a 100-year return period snowpack is recommended for antecedent conditions, which would guarantee a maximization of snowmelt runoff since the snowmelt methodology included in the FERC guidance does not include the effect of snowpack ripening. For the Baker project, however, the effect of snowpack ripening is accounted for.

In support of the final PMF, single runs of the hydrologic model were again conducted, with varying magnitudes of snow water equivalent. For these runs, the specific storm centering scenario (Upper) and temporal pattern (Temporal Pattern 5) recommended for the final PMF were assumed. Table 34 summarizes the starting and ending snowpack conditions and the total change in snow water equivalent for each model run. As was determined in the initial PMF analysis, the critical snowpack was between a 80% and 90% non-exceedance probability. All results in Table 34 are for the November model.

Table 34. Final Results of Iterative Snow Water Equivalent Model Runs for Entire Baker River Watershed – November Results

Snowpack Non-Exceedance Probability	Starting Snow Water Equivalent (Ac-Ft)	Ending Snow Water Equivalent (Ac-Ft)	Change in Snow Water Equivalent (Ac-ft)
33.3 %	119,340	48,540	70,800
50 %	150,150	70,940	79,210
66.7 %	189,770	101,540	88,230
80 %	**241,510**	**146,380**	**95,130**
90 %	309,680	216,740	92,940
95 %	381,830	295,340	86,490
98 %	485,800	408,570	77,230
99 %	572,010	502,440	69,570

Referring to the results in Table 34, it is seen that the 50% non-exceedance probability snowpack is still capable of yielding a high volume of runoff relative to the 80% non-exceedance probability snowpack. The model results indicated that the 50% non-exceedance snowpack was melted out in it's entirety for the lowest four elevation zones (less than 3,700 feet), while portions of the 80% non-exceedance snowpack remained as low as 2,700 feet at the end of the simulation. By definition, the 50% non-exceedance snowpack has a higher probability of occurring in a given year as compared to the 80% non-exceedance. Therefore, even though the 50% non-exceedance snowpack produces approximately 17% less runoff than the critical 80% non-exceedance snowpack, it has a significantly increased likelihood of occurrence. **Therefore, it is recommended that some of the conservatism inherent in the initial PMF results be reduced by assuming antecedent snowpack conditions consistent with the 50% non-exceedance snowpack for the final PMF.**

The selection of the 50% non-exceedance snowpack to represent antecedent conditions for the PMF was made within the context of the entire set of hydrometeorological input parameters with the goal of minimizing the compounding conservatism that was inherent in the initial PMF analysis. The selection of this particular antecedent snowpack condition represents a reasonable condition based on the likelihood of occurrence and at the same time it maintains a degree of conservatism as compared to deeper snowpack conditions.

7.5.6 Antecedent Snowpack Density

FERC guidance does not include discussion of antecedent snowpack density. The initial PMF results were based on an average value for snowpack density based on historical snow course station data. Given the guidance that antecedent conditions should represent reasonable meteorological conditions (FERC 2001) the average snowpack density condition is a justifiable assumption. **Therefore the assumption made for the initial PMF of average snowpack density of 35% is recommended for the final PMF.**

7.5.7 Antecedent Reservoir Elevation

FERC (2001) recommends four approaches for identifying a reasonable antecedent reservoir condition, and they were listed previously in Section 3.1. The antecedent reservoir conditions used for the initial PMF results were based on the Upper Baker Dam flood control rule curve in the *Baker River Water Control Manual* (USACE 2000) and the assumption that the Lower Baker reservoir would be at the normal full pool elevation. This initial choice for the antecedent reservoir elevation condition was based on a review of the historical end-of-month data, including a review of the time period required to draw the Upper Baker reservoir down to the flood control pool elevation following extreme precipitation events (Tetra Tech 2006c). After review of the data, it was concluded that the assumption of flood control elevation at Upper Baker and normal full pool elevation at Lower Baker was reasonable.

The GSA allowed for a thorough investigation of the range of possible antecedent reservoir elevations based on the historical end-of-month data. Lower Baker results illustrated a low degree of sensitivity to the starting condition because of the limited amount of volume in the reservoir. Upper Baker results illustrated a slightly greater degree of sensitivity to the starting condition in the upper reservoir, but not enough to justify changing the assumption that was the basis for the initial PMF results. **Therefore the assumption made for the initial PMF of normal full pool elevation at Lower Baker and minimum flood control pool elevation at Upper Baker is recommended for the final PMF.**

7.5.8 Final Recommended PMF

Table 35 summarizes the values of the hydrometeorological input parameters recommended for the final PMF model. The only changes from input used for the initial PMF results are for storm temporal pattern and antecedent snow water equivalent. The temporal pattern was changed from Temporal Pattern 7 to Temporal Pattern 5, which shifted the peak rainfall intensity from hour 58 to hour 47. The antecedent snowpack conditions were changed from the 90% non-exceedance probability to the 50% non-exceedance probability.

Table 35. Summary of Hydrometeorological Inputs for Final PMF Results

Input Parameter	Value Used for Final PMF Determination
Seasonality of Occurrence	November
Centering of Storm	Upper
Storm Temporal Pattern	20% exceedance probability (peak intensity at hour 47)
Antecedent Precipitation	25.4 inches at key precipitation station [a]
Antecedent Snow Water Equivalent	50% non-exceedance probability = 5.7 inches at key snow course station [b]
Antecedent Snowpack Density	0.352 [c]
Antecedent Reservoir Elevation Lower Baker	442.35 feet NAVD88
Antecedent Reservoir Elevation Upper Baker	711.57 feet NAVD88
Air Temperatures	Determined from HMR-57
Wind Speeds	Determined from HMR-57

a. Mean end-of-November value at key precipitation station (Upper Baker Dam)
b. Schreibers Meadow is the key snow course station
c. Average value determined from historical record

Using the values of the hydrometeorological input parameters listed in Table 35, the hydrologic model was run to develop the inflow PMF hydrographs, and the reservoir routing model was run to develop the outflow hydrographs. Table 36 summarizes the results of the final recommended PMF model relative to the results of the initial PMF model.

Table 36. Comparison of Initial and Final PMF Model Results

	Model Scenario	**Peak Inflow (cfs)**	**Peak Outflow (cfs)**	**Max. Pool Elev. (ft NAVD88)**	**Depth of Overtopping (ft)**
Upper Baker Reservoir	U_05 10-yr snowpack INITIAL PMF	163,200	126,100	739.84	**4.07**
	U_20 2-yr snowpack **FINAL PMF**	157,800	111,500	739.19	**3.42**
Lower Baker Reservoir	U_05 10-yr snowpack INITIAL PMF	156,100	136,700	460.56	**15.99**
	U_20 2-yr snowpack **FINAL PMF**	136,800	120,300	458.43	**13.86**

Table 37 presents a summary of key hydrologic inputs and outputs for the final PMF model simulation. The values presented in this table are basin average values for the 214.80 square-mile Upper Baker portion of the watershed and the 83.88 square-mile Lower Baker portion of the watershed. During the PMF simulation, most of the precipitation fell as liquid precipitation. During the first 24-hours of the event, however, precipitation fell as snow within Elevation Zone 8 due to the fact that air temperatures in this elevation zone were less than 32 degrees F during for this period of time. Basin average snowmelt in the Upper Baker portion of the watershed was 5.35 inches and basin average snowmelt in the Lower Baker portion of the watershed was 4.02 inches. Watershed-wide, nearly 70 percent of the snowmelt occurred within the mid-elevation HRU's, located between elevation 3200 feet and elevation 5000 feet (Elevation Zones 4 and 5), where the antecedent snowpack in these mid-elevation HRU's was melted out in it's entirety.

Table 38 summarizes the snowmelt by elevation zone. As seen in this table, there was no antecedent snowpack in the lowest two elevation zones and therefore no snowmelt contribution. The procedure used to allocate SWE was based on using physical data supplemented by HFAM hydrologic model output for nine snowcourse stations in the watershed (refer to Section 3.4). For the 50% non-exceedance conditions for the end-of-November period, SWE within these two lower elevations was determined to be zero. Figure 80 illustrates the spatial allocation of the 50% non-exceedance antecedent SWE for the end-of-November PMF conditions.

Table 37. Key Hydrologic Inputs and Outputs for Final PMF Inflow Hydrographs, Expressed in Inches		
	Upper Baker	**Lower Baker**
INPUTS		
Rain	32.79	28.40
Snow	0.18	0.06
Total Precipitation (inches)	32.98	28.46
Initial Snow Water Equivalent	10.90	5.65
Final Snow Water Equivalent	5.55	1.63
Snowpack Yield (inches)	5.35	4.02
Total Moisture Input (inches)	38.33	32.48
OUTPUTS		
Base Flow	3.10	3.10
Surface Runoff	19.49	14.59
Interflow Runoff	12.00	9.60
Total Runoff (inches)	34.59	27.29

Notes:

1. Results for Final PMF Model (NOV_U_20 with 50% non-exceedance probability snow water equivalent conditions

Table 38. Summary of Snowmelt by Elevation Zone, Expressed in Inches

Elevation Zone	Area (sq miles)	Antecedent SWE (inches)	Ending SWE (inches)	Snowmelt (inches)
1	48.77	0.00	0.00	0.00
2	39.95	0.00	0.00	0.00
3	49.80	3.49	0.00	3.49
4	65.04	10.69	0.03	10.66
5	43.80	16.21	6.63	9.58
6	27.81	20.64	13.21	7.43
7	15.63	25.32	19.61	5.71
8	7.88	33.79	46.20	-12.41

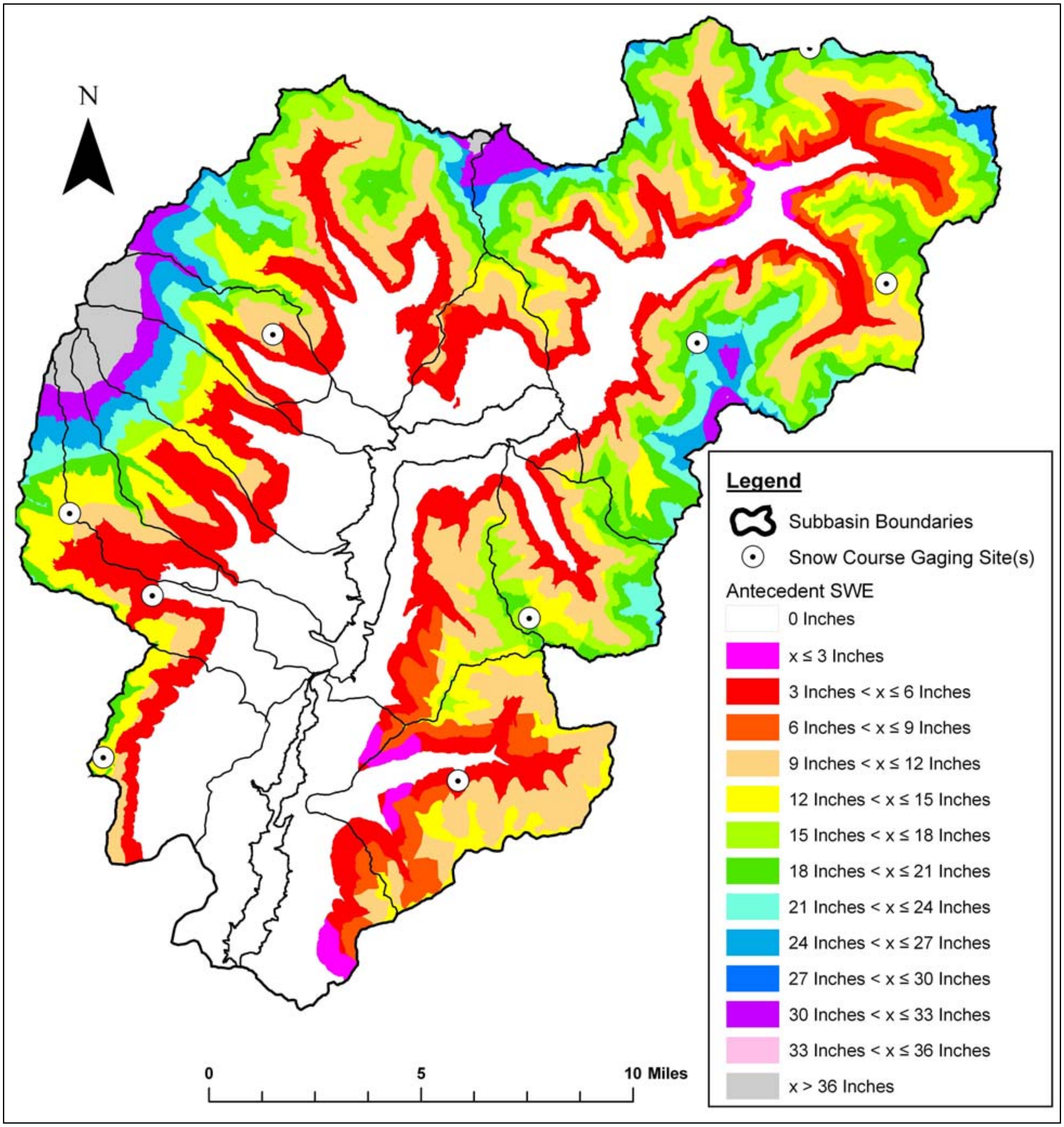


Figure 80. Spatial Distribution of Antecedent Snowpack for Final PMF Determination

Figure 81 illustrates the inflow hydrograph and outflow hydrograph for Upper Baker Dam and Figure 82 illustrates the inflow hydrograph and outflow hydrograph for Lower Baker Dam.

Figures 83 through 86 present frequency histograms and non-exceedance curves of the Upper Baker GSA results and include the initial and final PMF results as well. Figures 87 through 90 present frequency histograms and non-exceedance curves of the Lower Baker GSA results and include the initial and final PMF results as well. As seen in these figures, revising the initial assumption for the storm temporal pattern and antecedent snow water equivalent resulted in shifting the final PMF results slightly to the left on the non-exceedance curves.

The magnitudes of the hydrometeorological input parameters that were used to generate the final PMF results are consistent with FERC guidance and with methods presented in HMR-57. Referencing Figures 84 and 86, the final recommended PMF results for Upper Baker are approximately equivalent to the 93% non-exceedance value and the 96% non-exceedance value for the peak inflow rate and the peak reservoir elevation, respectively, when compared with the 10,000 simulations produced by the GSA. The Lower Baker final PMF results are slightly more conservative at values of 99% and 99.9% non-exceedance for the peak inflow rate and the peak reservoir elevation, respectively. Therefore, the adopted final PMF represents a conservative yet realistic estimation of the PMF, based on a thorough investigation of the range of hydrometeorological input values for the Baker River watershed.

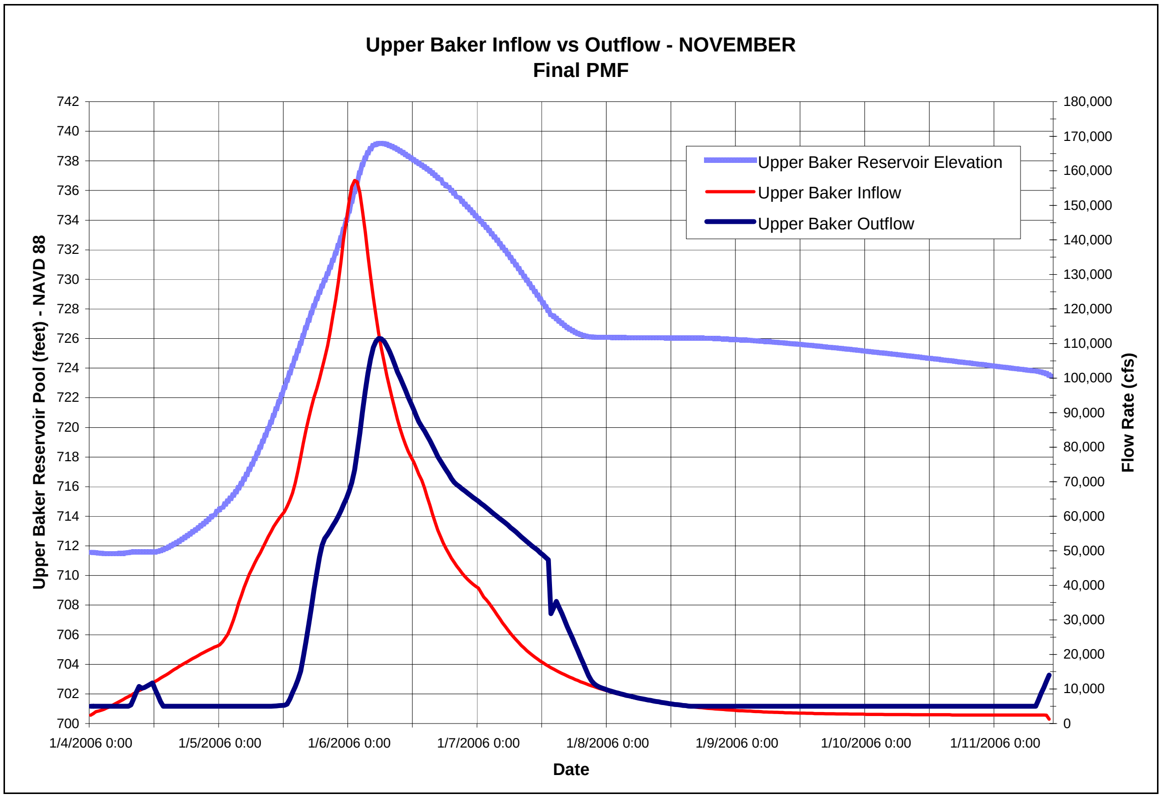


Figure 81. Final Upper Baker PMF – Inflow Hydrograph and Outflow Hydrograph

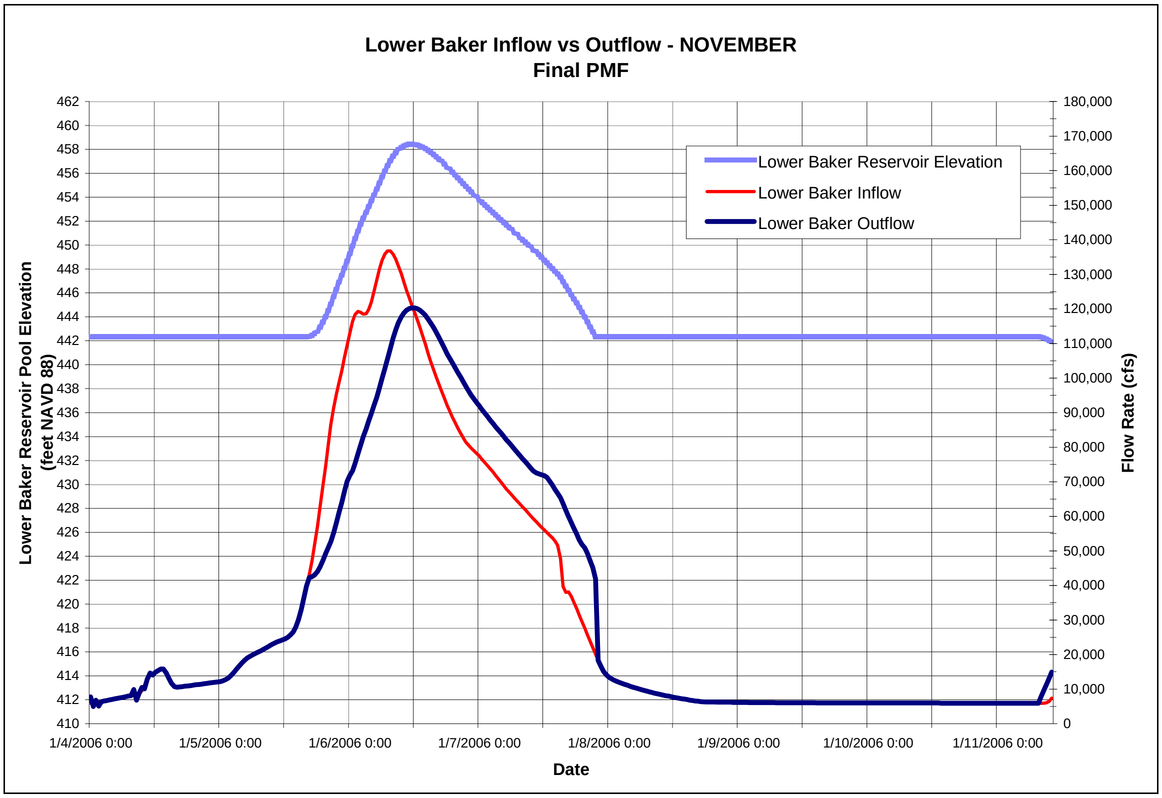


Figure 82. Final Lower Baker PMF – Inflow Hydrograph and Outflow Hydrograph

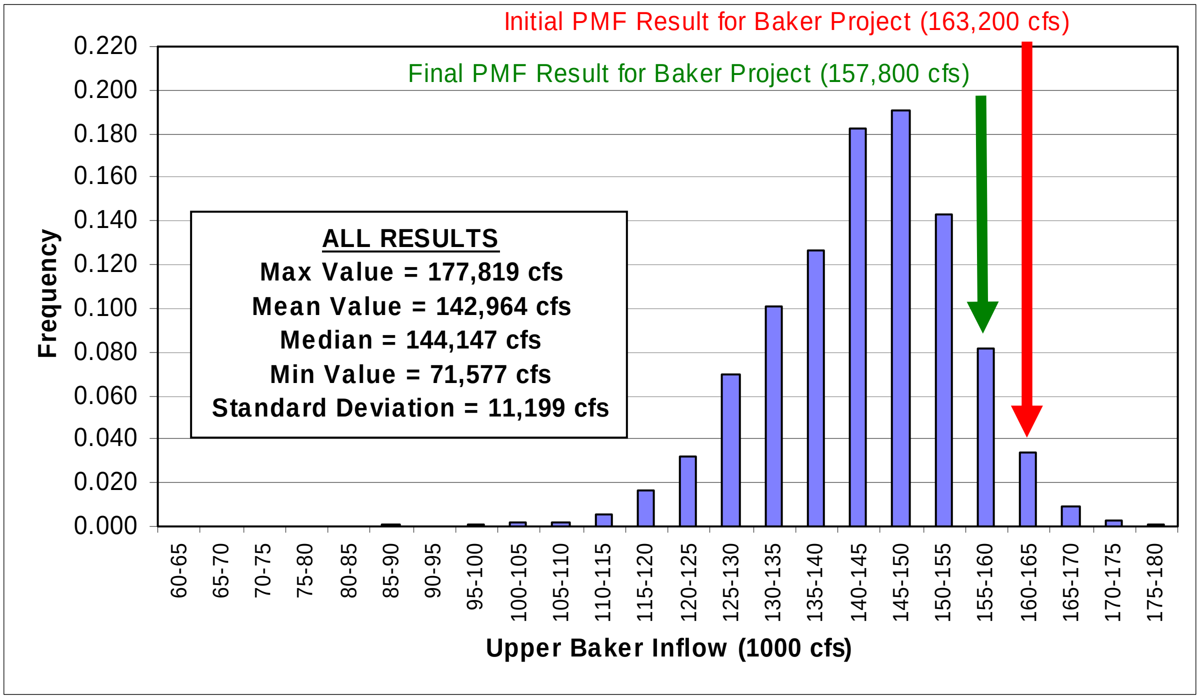


Figure 83. Frequency Histogram of Upper Baker Peak Inflow Rates Produced by PMP – All Results Including Final PMF

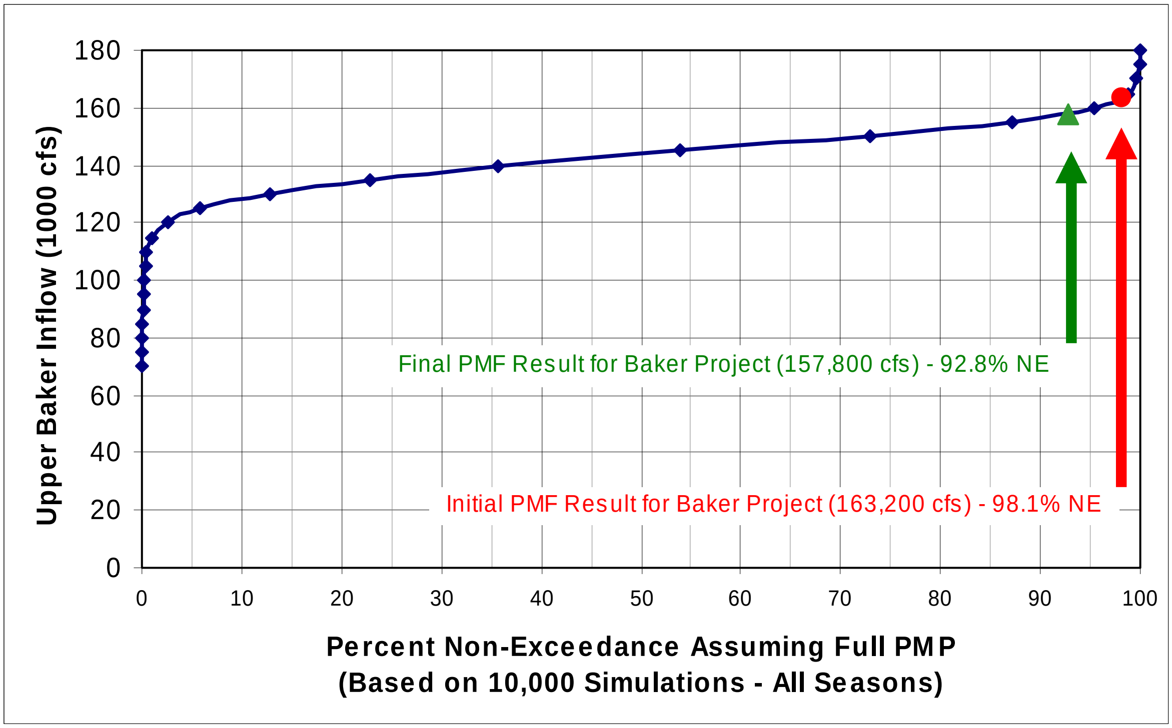


Figure 84. Percent Non-Exceedance for Upper Baker Peak Inflow Rates – All Results Including Final PMF

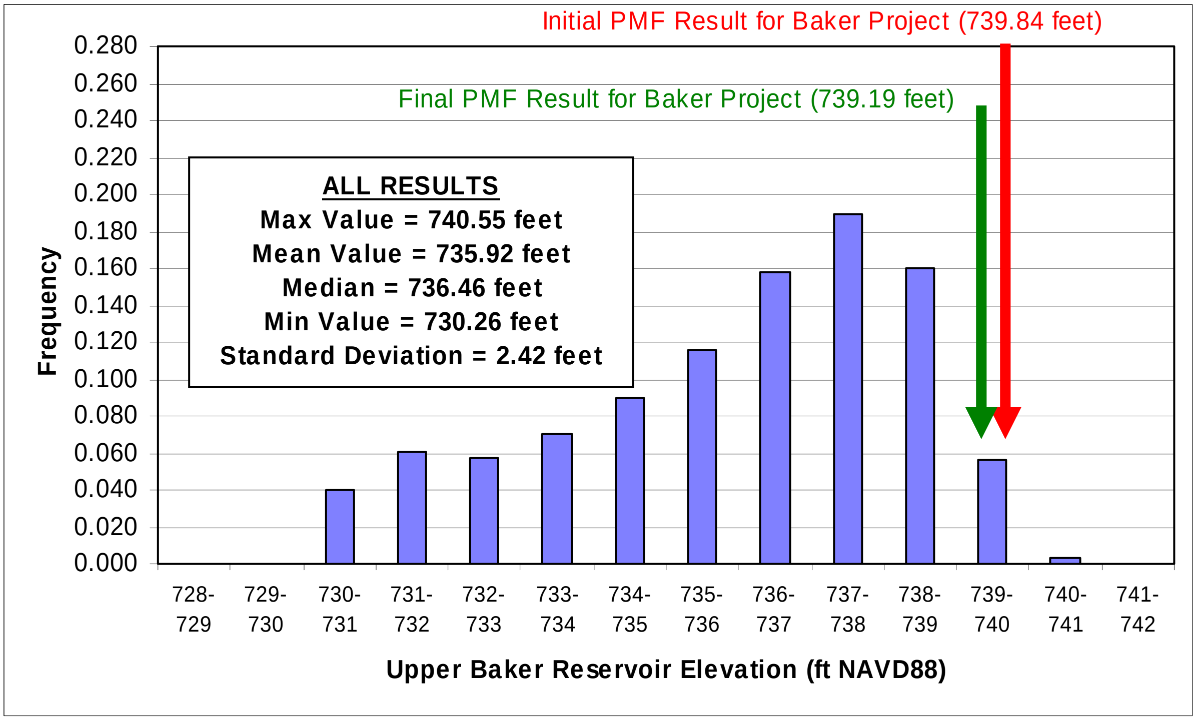


Figure 85. Frequency Histogram of Upper Baker Peak Reservoir Elevations Produced by PMP – All Results Including Final PMF

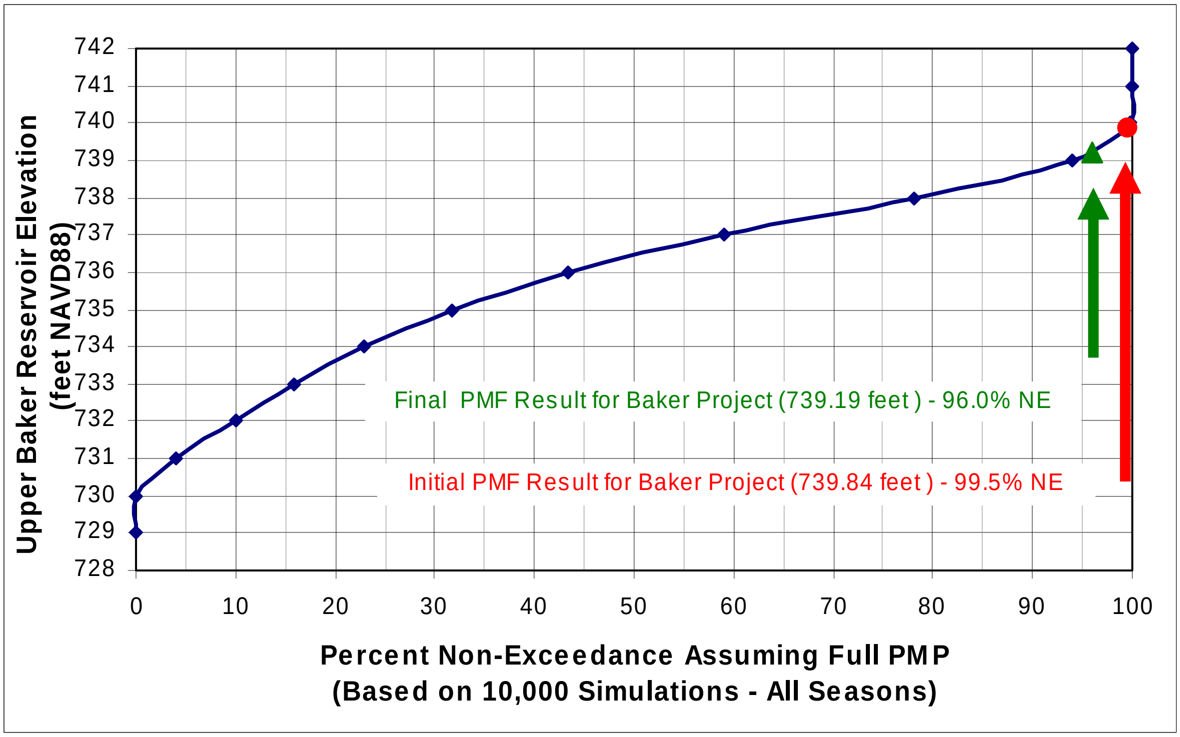


Figure 86. Percent Non-Exceedance for Upper Baker Peak Reservoir Elevations – All Results Including Final PMF

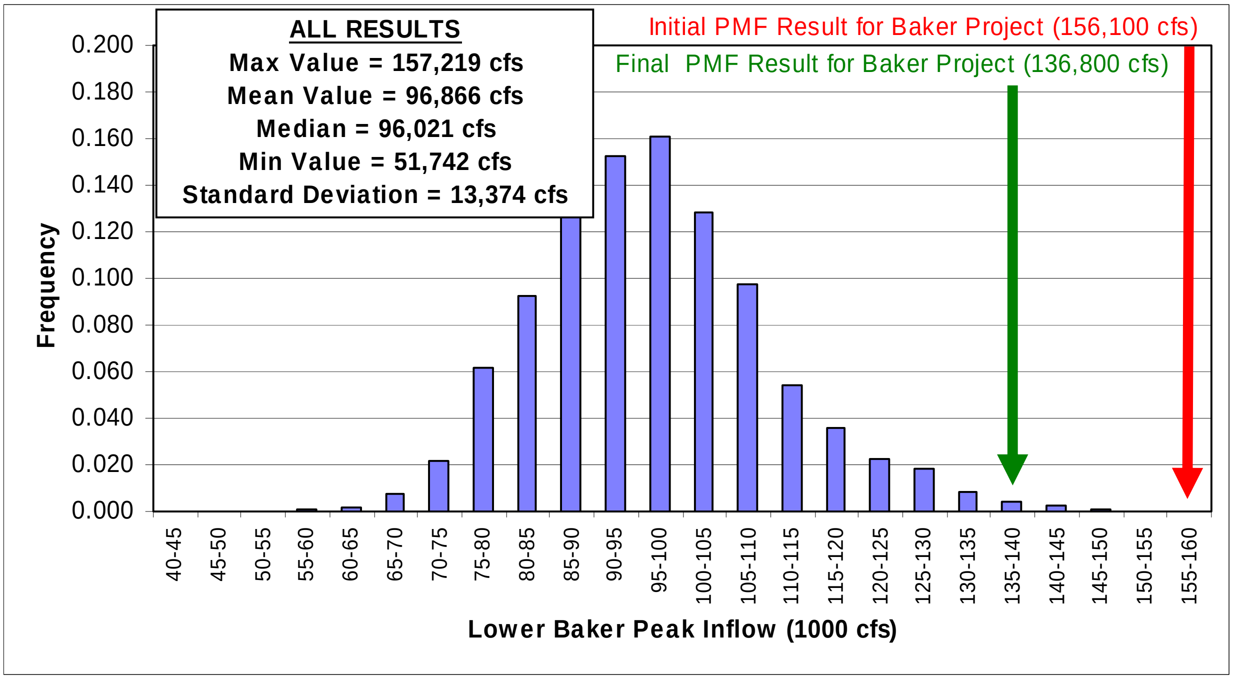


Figure 87. Frequency Histogram of Lower Baker Peak Inflow Rates Produced by PMP – All Results Including Final PMF

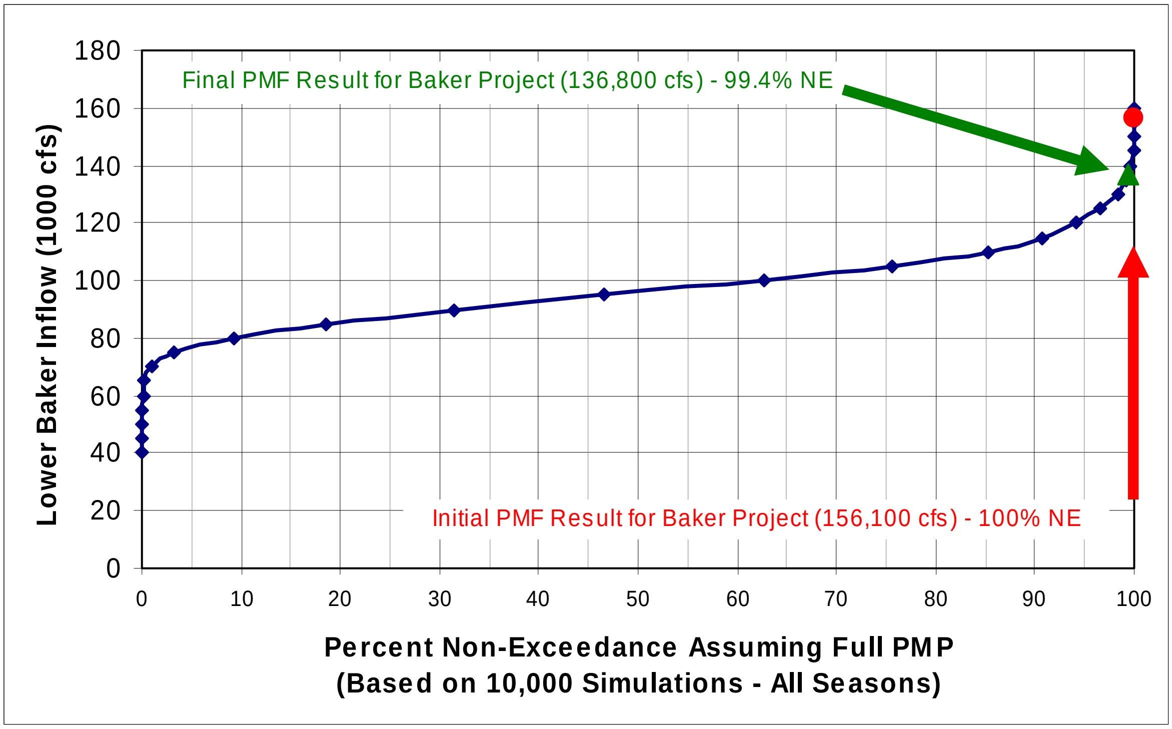


Figure 88. Percent Non-Exceedance for Lower Baker Peak Inflow Rates – All Results Including Final PMF

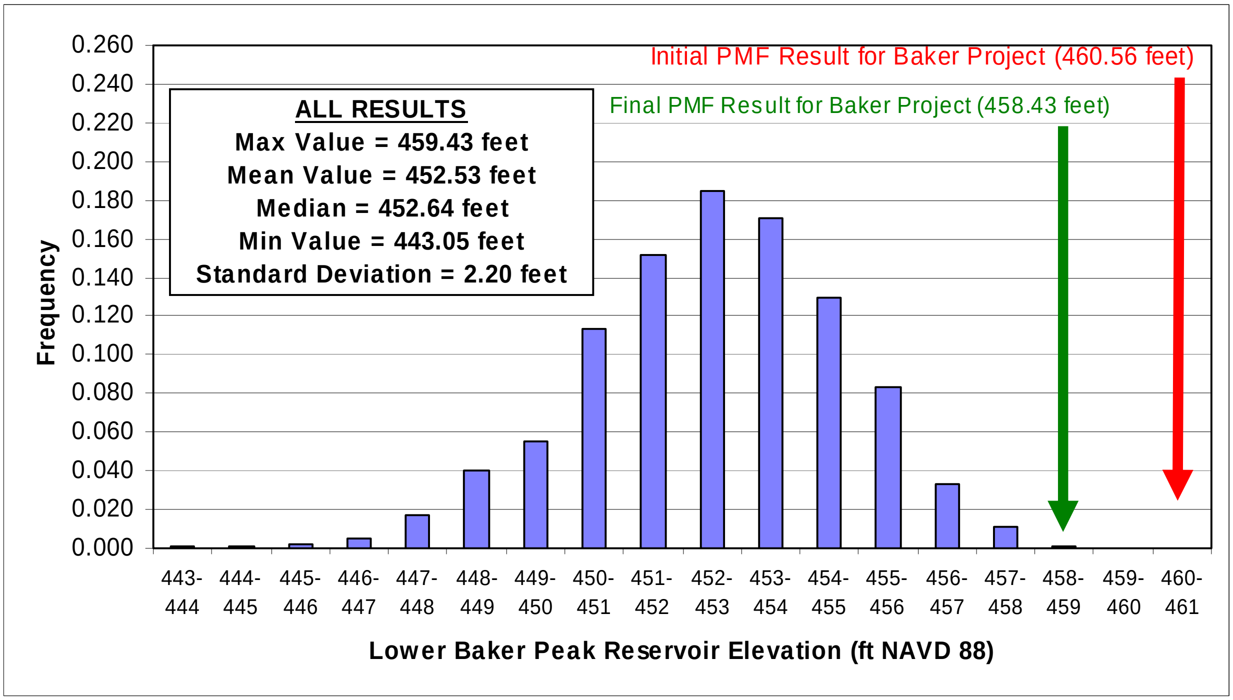


Figure 89. Frequency Histogram of Lower Baker Peak Reservoir Elevations Produced by PMP – All Results Including Final PMF

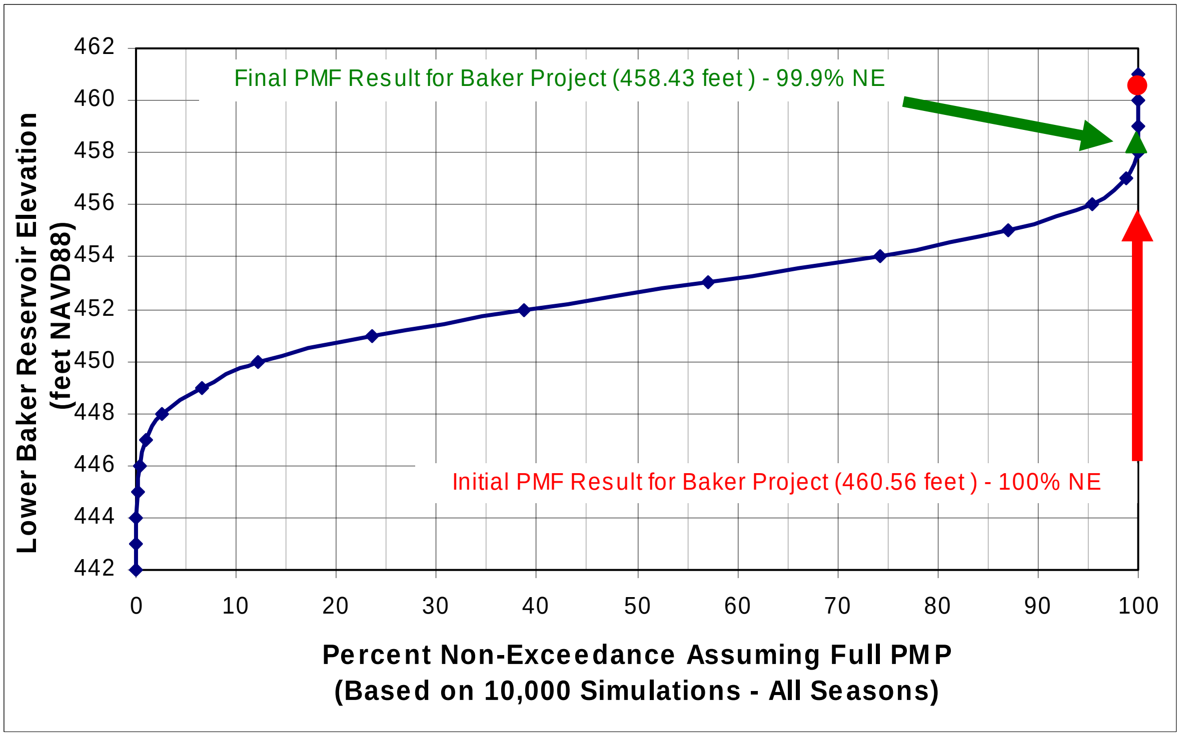


Figure 90. Percent Non-Exceedance for Lower Baker Peak Reservoir Elevations – All Results Including Final PMF

8 REFERENCES

Barnes, Robert. 2006. Personal Communication. March 3rd, 2006.

Brater, E.F., King H.W. 1976. Handbook of Hydraulics. 6th Edition. McGraw-Hill: New York.

Bradley, J.N. 1952. *Discharge Coefficients for Irregular Overfall Spillways*. Engineering Monograph No. 9, USBR March 1952

Federal Energy Regulatory Commission (FERC). 1993. *Engineering Guidelines for the Evaluation of Hydropower Project. Chapter II – Selecting and Accommodating Inflow Design Floods for Dams.* October 1993

Federal Energy Regulatory Commission (FERC). 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter VIII – Determination of the Probable Maximum Flood.

MGS Engineering Consultants, Inc (MGS). 2004. *General Storm Stochastic Event Flood Model (SEFM) Technical Support Manual.*

MWH. 2004. *Supporting Technical Information. Baker River Hydroelectric Project Lower Baker Development. FERC Project No. 2150.*

National Weather Service (NWS). 1966. *Probable Maximum Precipitation for the Pacific Northwest. Hydrometeorological Report No. 43.* U.S. Department of Commerce - National Oceanic and Atmospheric Administration, U.S. Weather Bureau.

National Weather Service (NWS). 1994. *Probable Maximum Precipitation – Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages. Hydrometeorological Report No. 57.* U.S. Department of Commerce - National Oceanic and Atmospheric Administration, U.S. Department of Interior – Bureau of Reclamation, U.S. Department of Army – Corps of Engineers.

Oregon Climate Service (OCS). 2005. *Mean Annual Precipitation Mapping for the United States.* Provided to Tetra Tech via email from George Taylor from the Oregon Climate Service.

Puget Sound Energy (PSE). 2005. *Topographic Survey of Lower Baker Dam Conducted by Leonard, Boudinot & Skodje Inc*. Survey Conducted in June 2005. Set of Five Sheets.

Schaefer MG. 1989. *Characteristics of Extreme Precipitation Events in Washington State*. Washington State Department of Ecology, Water Resources Program, 89-51.

Schaefer MG. 2006. *Recommendations for Probabilistic Inputs for Global Sensitivity Analysis at Baker River Project.* Technical Memorandum prepared by Mel Schaefer on July 21 2006. MGS Engineering Consultants.

Schaefer MG and Barker BL. 1999. *Stochastic Modeling of Extreme Floods for Keechelus Dam.* Prepared by MGS Engineering Consultants. September 1999

Schaefer M.G., Barker B.L., Taylor G.H., Wallis J.R. 2002. *Regional Precipitation-Frequency Analysis and Spatial Mapping for 24-Hour and 2-Hour Durations in Western Washington.* Prepared for Washington State Department of Transportation (WSDOT), March 2002.

Schaefer M.G., Barker B.L., Taylor G.H., Wallis J.R. 2006. *Regional Precipitation-Frequency Analysis and Spatial Mapping for 24-Hour and 2-Hour Durations in Eastern Washington.* Prepared for Washington State Department of Transportation (WSDOT).

Tetra Tech, Inc. 2006a. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 7 – Model Calibration and Verification.* Technical Memorandum prepared for Puget Sound Energy. Revision Date June 20 2006.

Tetra Tech, Inc. 2006b. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 6 – Determination of Probable Maximum Precipitation Using HMR-57.* Technical Memorandum prepared for Puget Sound Energy. Revision Date March 13, 2006.

Tetra Tech, Inc. 2006c. *Baker River Project Part 12 PMP/PMF Study – Technical Memorandum No. 10 – Antecedent and Coincident Conditions for PMF Analysis.* Technical Memorandum prepared for Puget Sound Energy. March 2006.

Tetra Tech, Inc. 2006d. *Technical Memorandum – Response to BOC Meeting 3 Comments.* Technical Memorandum prepared for Puget Sound Energy. Revision Date April 24, 2006.

United States Army Corps of Engineers (USACE), 1987. *Hydraulic Design Criteria*. Revision Date October 1987.

United States Army Corps of Engineers (USACE), 1991. *Inflow Design Floods for Dams and Reservoirs. Engineering Regulation 1110-8-2.*March 1 1991.

United States Army Corps of Engineers (USACE). 2000. *Baker River Project, Baker River, Washington. Water Control Manual.* June 2000.

United States Army Corps of Engineers Hydrologic Engineering Center (USACE-HEC). 1998. *HEC-5 Simulation of Flood Control and Conservation Systems. Users Manual Version 8.0.* October 1998.

Washington State Department of Ecology (WSDOE). 1993. *Dam Safety Guidelines Technical Note 3: Design Storm Construction*. April 1993. 92-55G.

Zipparro V.J., Hasen H. 1993. Davis Handbook of Applied Hydraulics. 4th Edition. McGraw-Hill: New York.

ATTACHMENT A – DAM SCHEMATICS

LOWER BAKER DAM SCHEMATIC

UPPER BAKER DAM SCHEMATIC

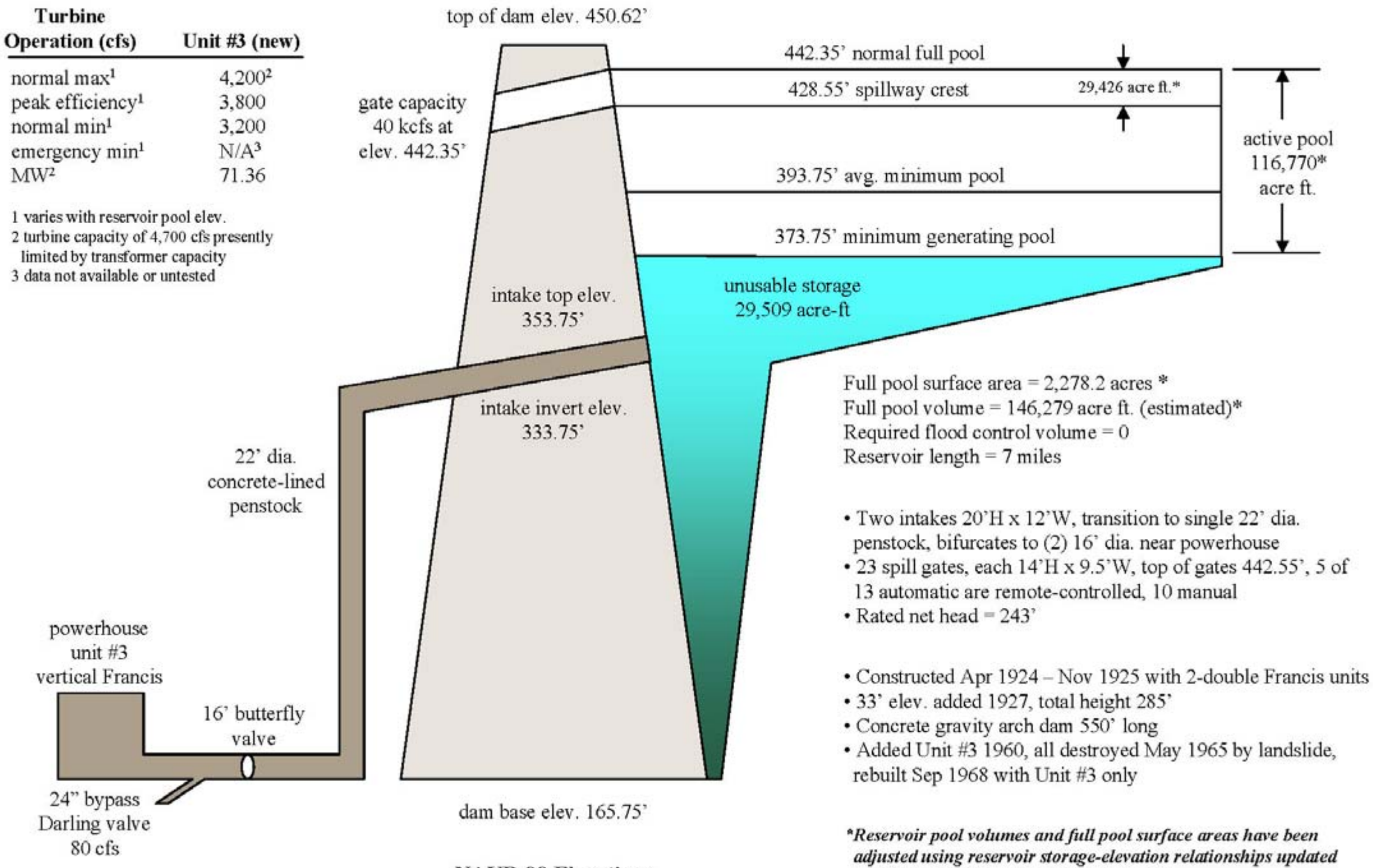
WEST PASS DIKE SCHEMATIC

Lower Baker Dam

Section View - Not to Scale

Turbine Operation (cfs)	Unit #3 (new)
normal max[1]	4,200[2]
peak efficiency[1]	3,800
normal min[1]	3,200
emergency min[1]	N/A[3]
MW[2]	71.36

1 varies with reservoir pool elev.
2 turbine capacity of 4,700 cfs presently limited by transformer capacity
3 data not available or untested



Full pool surface area = 2,278.2 acres *
Full pool volume = 146,279 acre ft. (estimated)*
Required flood control volume = 0
Reservoir length = 7 miles

- Two intakes 20'H x 12'W, transition to single 22' dia. penstock, bifurcates to (2) 16' dia. near powerhouse
- 23 spill gates, each 14'H x 9.5'W, top of gates 442.55', 5 of 13 automatic are remote-controlled, 10 manual
- Rated net head = 243'

- Constructed Apr 1924 – Nov 1925 with 2-double Francis units
- 33' elev. added 1927, total height 285'
- Concrete gravity arch dam 550' long
- Added Unit #3 1960, all destroyed May 1965 by landslide, rebuilt Sep 1968 with Unit #3 only

Reservoir pool volumes and full pool surface areas have been adjusted using reservoir storage-elevation relationships updated as of May 2003 based on 2001 survey data.

NAVD 88 Elevations

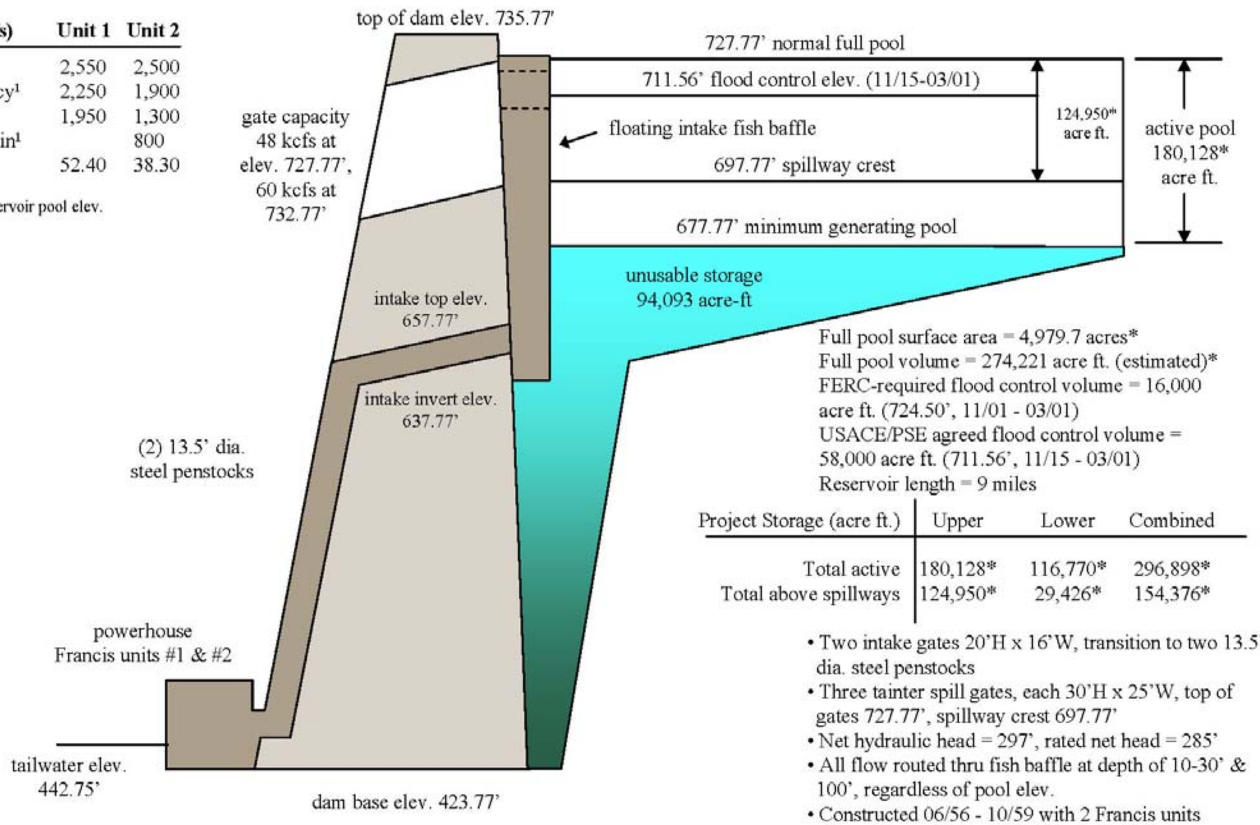
Filename: dams schematics_new elevations_ 092603

Upper Baker Dam

Section View - Not to Scale

Turbine Operation (cfs)	Unit 1	Unit 2
normal max¹	2,550	2,500
peak efficiency¹	2,250	1,900
normal min¹	1,950	1,300
emergency min¹		800
MW	52.40	38.30

1 varies with reservoir pool elev.



Full pool surface area = 4,979.7 acres*
Full pool volume = 274,221 acre ft. (estimated)*
FERC-required flood control volume = 16,000 acre ft. (724.50', 11/01 - 03/01)
USACE/PSE agreed flood control volume = 58,000 acre ft. (711.56', 11/15 - 03/01)
Reservoir length = 9 miles

Project Storage (acre ft.)	Upper	Lower	Combined
Total active	180,128*	116,770*	296,898*
Total above spillways	124,950*	29,426*	154,376*

- Two intake gates 20'H x 16'W, transition to two 13.5' dia. steel penstocks
- Three tainter spill gates, each 30'H x 25'W, top of gates 727.77', spillway crest 697.77'
- Net hydraulic head = 297', rated net head = 285'
- All flow routed thru fish baffle at depth of 10-30' & 100', regardless of pool elev.
- Constructed 06/56 - 10/59 with 2 Francis units
- Concrete gravity dam 1200' long, 312' high
- 12' roadway at elev. 735.77'

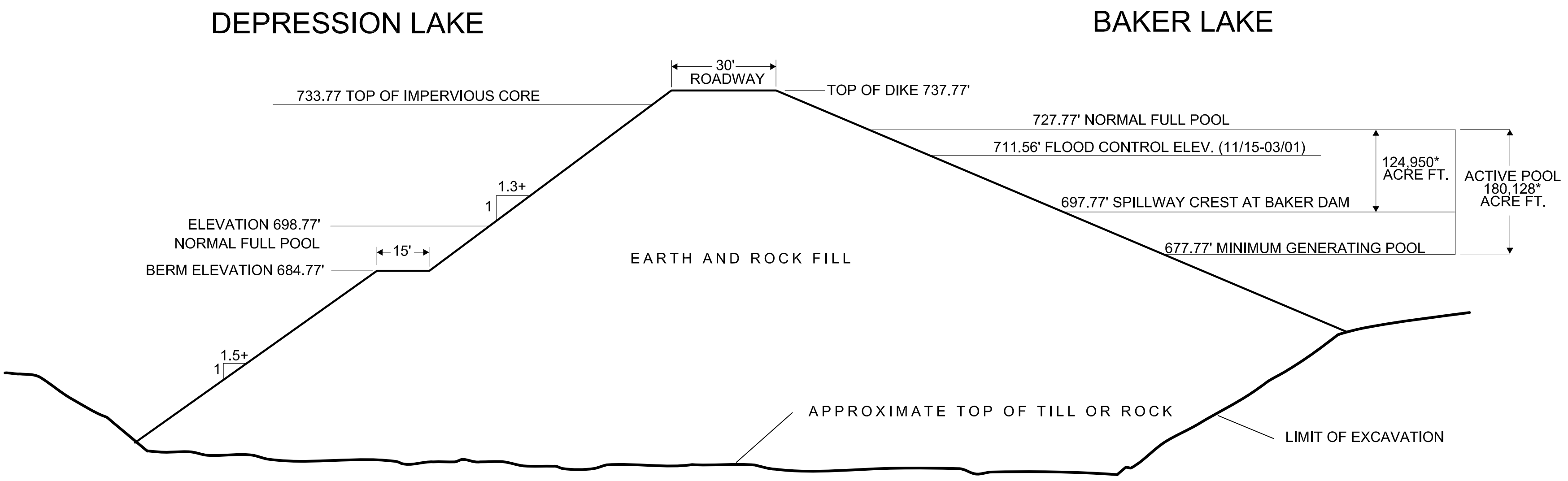
NAVD 88 Elevations

**** Reservoir pool volumes and full pool surface areas have been adjusted using reservoir storage-elevation relationships updated as of May 2003 based on 2001 survey data.***

Filename: dams schematics_new elevations_092603

PUGET SOUND ENERGY
ENERGY PRODUCTION

WEST PASS DIKE



FULL POOL SURFACE AREA = 4,979.7 ACRES*
FULL POOL VOLUME = 274,221 ACRE FT. (ESTIMATED)*
FERC - REQUIRED FLOOD CONTROL VOLUME = 16,000 ACRE FT.
(724.50', 11/01 - 03/01)
USACE/PSE AGREED FLOOD CONTROL VOLUME = 58,000 ACRE FT.
(711.56', 11/15 - 03/01)
RESERVOUR LENGTH 9 MILES (BAKER LAKE)

PROJECT STORAGE (ACRE FT.)	UPPER	LOWER	COMBINED
TOTAL ACTIVE	180,128*	116,770*	296,898*
TOTAL ABOVE SPILLWAYS	124,950*	29,426*	154,376*

* RESERVOIR POOL VOLUMES AND FULL POOL SURFACE AREAS HAVE BEEN ADJUSTED USING RESERVOIR STORAGE-ELEVATION RELATIONSHIPS UPDATED AS OF MAY 2003 BASED ON 2001 SURVEY DATA.

WEST PASS DIKE: 1200 FEET LONG - 115 FEET HIGH

NAVD 88 ELEVATION DATUM

BAKER RIVER PROJECT PART 12 PMP/PMF STUDY

TECHNICAL MEMORANDUM NO. 12 - DRAFT

TEMPERATURE, WIND AND SYNOPTIC DATA ANALYSIS FOR USE IN BAKER RIVER PROJECT PMF STUDY

Applied Weather Associates
Tetra Tech, Inc.
March 20, 2007

(FINAL)

DEVELOPMENT OF HOURLY AIR TEMPERATURE TIME SERIES

Objective

To develop a 144-hour duration air temperature time series that represents conditions in the Baker River watershed during extreme precipitation events for each of the months of October through February, inclusive. To attain this objective, the first step was to develop 144-hour duration air temperature time series for each hour during specific extreme precipitation events that have affected the Upper Baker watershed. For each month, six extreme precipitation events were identified to include in this analysis. The precipitation events are summarized in the appendix of this memo. The 144-hour period extends from 72 hours prior to the start of the heaviest precipitation to the end of the 72 hour precipitation event. Hourly temperatures at the Upper Baker (id 45-8715) cooperative station were based on the observed temperature at the observation time, daily maximum and minimum temperature along with known hourly temperatures at Bellingham, WA (KBLI) and Whidbey Island Naval Air Station (KNUW) when KBLI data was unavailable for storms in January 1965 and 1972 and February of 1972. If Upper Baker observation data were not available, the Upper Baker River (id 45-8718) cooperative station data were used. See Figure 1 below for reference locations.

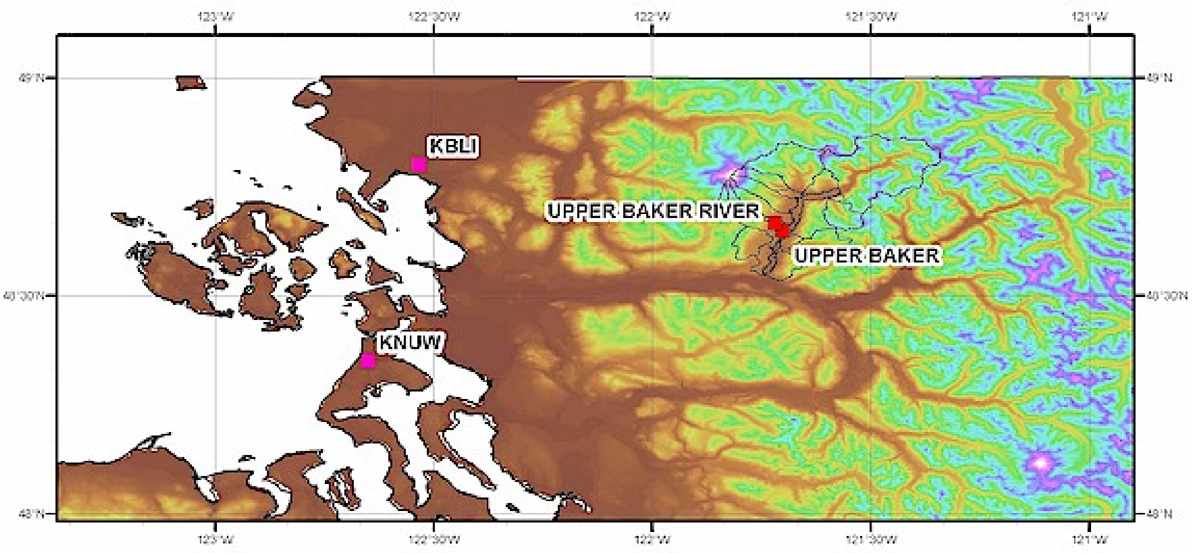


Figure 1. Reference Map with Hourly Temperature Reporting Stations Noted

Methods

Observation forms for Upper Baker station and temperature data from Bellingham, WA (reference station) climate station were downloaded for the time periods of interest.

At a distance of 40 miles, Bellingham was the closest station with reliable hourly data for most of the storms and is upwind of Upper Baker. The Whidbey Island Naval Air Station, approximately 48 miles from Upper Baker, hourly data were used if the Bellingham record was incomplete (See Table 1).

Table 1. Study Station Information

	Bellingham	**Whidbey Island Naval Air Station**	**Upper Baker**	**Upper Baker River**
Station ID	KBLI	KNUW	45-8715	45-8718
Latitude/Longitude	48.8000/-122.5333	48.3500/-122.6667	48.65/-121.6833	48.6667/-121.7167
Elevation (feet)	164	33	689	850

Spreadsheets were created for hourly temperatures and the recorded time adjusted from GMT to LST. The hourly temperature data were split into 24-hour groups that started on the observed time (~8 am) determined from the Upper Baker observation form. For each 24-hour group, the maximum and minimum temperatures were determined from the reference station. The daily maximum and minimum temperatures were offset one day (previous) to account for temperature measurement methods. The time at which the reference station reached its maximum and minimum values were used to determine the time when the maximum and minimum temperatures occurred at Upper Baker. The observation time temperature from Upper Baker was placed at the observation time (~8 am).

Wherever a co-located temperature occurred (observation time, daily maximum, and daily minimum), a difference in temperature (delta t) was calculated. The number of hourly time intervals between calculated delta t values and the difference between the delta t values were used to calculate a delta t ratio for each hour within that delta t interval. This process was repeated for every delta t interval. If the Bellingham hourly temperatures were constant, the delta t values remained constant instead of applying the hourly ratio estimate. After each delta t value the reference station's temperature was subtracted from the final delta t value to arrive at an estimate for Upper Baker. This method created an estimated hourly temperature profile for the Upper Baker station.

The adjusted hourly temperature data for Upper Baker was plotted and analyzed several ways in order to determine if any trends or patterns could be identified and ultimately to deliver a representative temperature at each hour of the 144-hour period. All the analysis was completed in the Microsoft Excel software. The data was analyzed and graphed in six different categories. A simple line graph was completed for each storm's adjusted temperature for each of the 144-hours. All temperatures for each hour for each storm in each individual month were summed and averaged. This produced an average temperature at each hour for a given month. This data was again represented with a line graph. Next, the temperature data was analyzed by taking the lowest temperature during the 144-hour period and determining each hour's difference (delta T) from that value and again using a line graph to visually represent the data. All hours for each storm for each month were summed and averaged to give a complete picture for each month. Finally, this same process was completed for delta T from the warmest temperature of each 144-hour period for each storm.

Once these analyses and graphs were completed, each was scrutinized for inconsistencies, errors, and/or emissions. Any obvious trends during the 144-hour period were discussed for significance in relation to modeling of an ideal temperature series through time for each month.

Problems and Assumptions

It was assumed that the process of using the Bellingham hourly temperature observations along with the maximum and minimum recorded temperature at the Upper Baker station was the most appropriate process to determine the hourly temperatures at Upper Baker. Further, it was assumed that choosing the top six storms for each of the months represented a large enough sample to produce a reliable data set from which to develop the temperature series.

Another assumption was that the hour when Bellingham recorded its maximum (or minimum) temperature was the same hour as when Upper Baker reached its maximum (or minimum) temperature. Occasionally the maximum (or minimum) temperature would occur at the time of observation, and in some cases the maximum (or minimum) temperature was different than the observation time temperature. In these cases, the convention was to enter the observation time temperature since it was the only known hourly temperature at Upper Baker. This occasionally did cause the maximum (or minimum) temperature to be unfaithful to the actual recorded maximum (or minimum) temperature at Upper Baker. In most cases however, the difference was quite small (within 2-4 degrees).

Other than a few missing hourly temperatures at Bellingham, the station had a complete hourly temperature record most storm events. The Bellingham data were not used for January 1965, January 1972 and February 1972. For these periods, the Whidbey Island Naval Air Station temperature data were used. Estimated hourly temperature where developed based on the temperature trend for the few missing hours.

Output

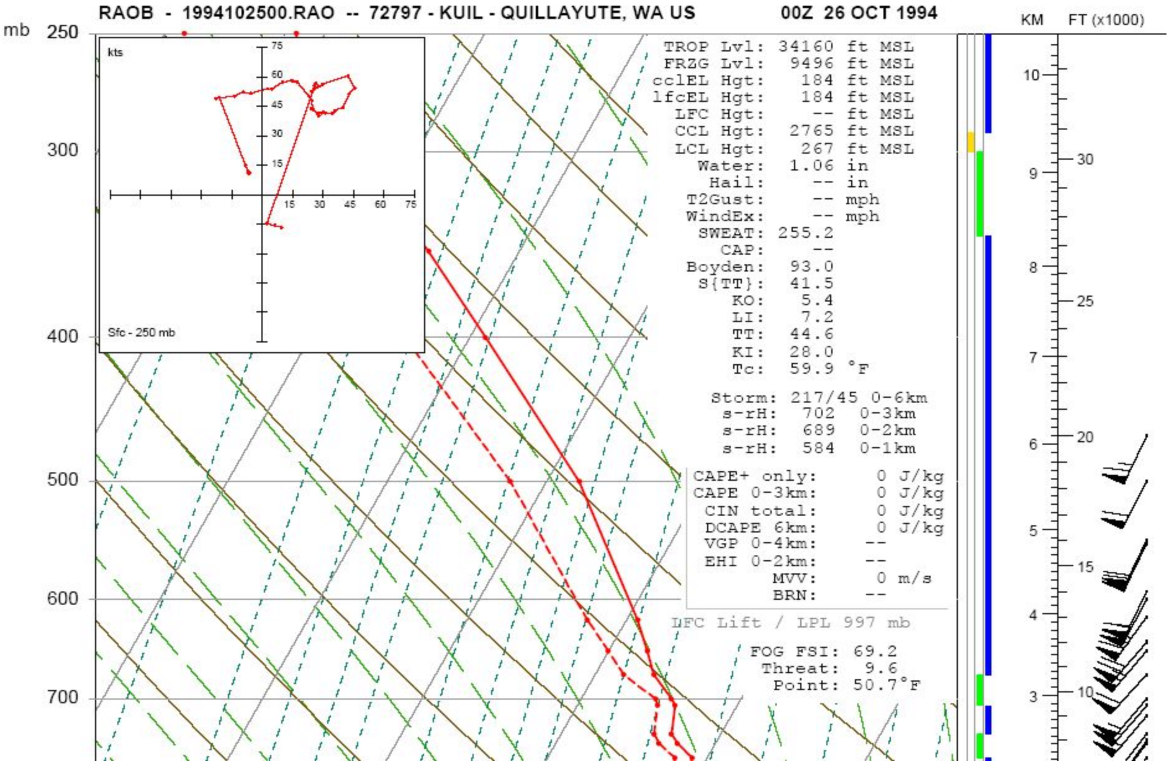
All of the data and graphs were developed in an Excel spreadsheet format. A separate workbook was devoted to each month, and each workbook contains several tabs including the raw temperature data and derived Upper Baker temperature data, a graph of the Upper Baker derived temperature for all storms, a graph of the delta T from the coldest temperature for all storms, a graph of the delta T from the warmest temperature for all storms, a graph for the average temperature for all storms, a graph of the average delta T from the coldest for all storms, and a graph of the average delta T from the warmest temperature for all storms,

The final product was a 144-hour duration air temperature time series that represents conditions in the Baker River watershed during extreme precipitation events for each month of October through February, inclusive. The monthly plots are included in the appendix of this memo. Included in each monthly plot is the representative air temperature time series for each month, the time series of hourly maximum air temperature values for all of the storms, and the time series of hourly minimum air temperature values for all of the storms. The intermediary products describe in the preceding paragraph can also be provided upon request.

DEVELOPMENT OF HOURLY FREEZING LEVEL TIME SERIES

Objective

To develop a 144-hour duration freezing level time series that represents conditions in the Baker River watershed during extreme precipitation events for each of the months of October through February, inclusive. To attain this objective, the first step was to develop 144-hour duration freezing level time series for each hour during specific extreme precipitation events that have affected the Upper Baker watershed. For each month, six extreme precipitation events were identified to include in this analysis. The precipitation events are summarized in the appendix of this memo. The 144-hour period extended from 72 hours prior to the start of the heaviest precipitation to the end of the 72 hour event. Hourly freezing levels at the Upper Baker (id 45-8715) cooperative station were based on the freezing level observed by the twice daily (00z and 12z) soundings from Quillayute, WA (KUIL). The soundings were taken from Tatoosh Island, WA (KTTI) for December 1964, January 1964 and 1965, and Seattle, WA (KSEA) for January 1961. Figure 2 below shows an example sounding as processed from RAOB software with the freezing level noted.



```
    TROP Lvl:  34160 ft MSL
    FRZG Lvl:   9496 ft MSL
   cclEL Hgt:    184 ft MSL
   lfcEL Hgt:    184 ft MSL
     LFC Hgt:     -- ft MSL
     CCL Hgt:   2765 ft MSL
     LCL Hgt:    267 ft MSL
      Water:   1.06 in
       Hail:     -- in
     T2Gust:     -- mph
     WindEx:     -- mph
      SWEAT:  255.2
        CAP:     --
     Boyden:   93.0
     S{TT}:   41.5
        KO:    5.4
        LI:    7.2
        TT:   44.6
        KI:   28.0
        Tc:   59.9 °F

      Storm: 217/45 0-6km
      s-rH:   702   0-3km
      s-rH:   689   0-2km
      s-rH:   584   0-1km

 CAPE+ only:       0 J/kg
 CAPE 0-3km:       0 J/kg
  CIN total:       0 J/kg
  DCAPE 6km:       0 J/kg
  VGP 0-4km:      --
  EHI 0-2km:      --
        MVV:       0 m/s
        BRN:      --

LFC Lift / LPL 997 mb

     FOG FSI: 69.2
      Threat:  9.6
       Point: 50.7°F
```

Figure 2. Example Sounding with Freezing Level noted

Methods

The freezing level data for each 144-hour storm period was taken from the twice daily soundings. Therefore, for each 144-hour storm period, 12 freezing level data points were taken. Once these data points were placed along the appropriate hour of the 144-hour storm period, each were plotted and analyzed several ways in order to determine if any trends or patterns could be identified and ultimately to deliver a representative freezing level at each hour of the 144-hour period. The 12 data points were connected using a simple trendline in order to analyze the changes over the 144-hour period. Along with this graph, the maximum and minimum value was also potted and connected with the similar trendline. All freezing levels for each of the six storms for each month were then summed and averaged and subsequently plotted as an average freezing level for all storms for each month.

In order to derive the value for each of the intervening 11 hours between the data points, each of the month's average freezing level graphs were split into two 72 hour periods. To connect the data points, a 6th order polynomial equation was applied through the Excel software in order to properly distribute the values across the intervening 11 hour time period. A hand analyses was then completed on each of the graphs for each of the months in order to derive the freezing level value at each of the 144-hours for each month.

Once these analyses and graphs were completed, each was scrutinized for inconsistencies, errors, and/or emissions. Any obvious trends during the 144-hour period were discussed for significance in relation to modeling of an ideal freezing level series through time for each month.

Problems and Assumptions

The best available data source that contains free atmosphere freezing level information for the storms in questions are atmospheric soundings. Unfortunately, these soundings are taken only twice daily (00z and 12z) and the sounding stations are widely spaced across the country (there are only two in the state of Washington-Quillayute and Spokane). This requires two assumptions to be made; first that the freezing level recorded from the Quillayute sounding (~140 southwest of Upper Baker) represents the same air mass and freezing level as would be found at the same hour over Upper Baker and two that the intervening 11 hours between known data points can be represented and derived using a 6th order polynomial to connect each data point. Fortunately, freezing levels do not change as rapidly both spatially and temporally as temperatures and other weather parameters, and therefore it is reasonable to assume that the data derived from the Quillayute sounding does represent the Upper Baker location.

Output

All of the data and graphs were developed in an Excel spreadsheet format. A separate workbook was devoted to each month, and each workbook contains several tabs including the raw freezing level data and a graph comparing it to the hourly temperature data, a graph of the Upper Baker freezing level for all storms connected with a simple trendline, a graph of the average freezing level for all storms along with the maximum and minimum freezing level, again connected with a simple trendline. A separate set of Excel files contains the two 72-hour periods for each month with the average freezing level connected with a 6th order polynomial.

The final product was a 144-hour duration freezing level time series that represents conditions in the Baker River watershed during extreme precipitation events for each month of October through February, inclusive. The monthly plots are included in the appendix of this memo. Included in each monthly plot is the representative freezing level time series for each month, the time series of twice-daily maximum freezing level values for all of the storms, and the time series of twice-daily minimum freezing level values for all of the storms. The intermediary products describe in the preceding paragraph can also be provided upon request.

DEVELOPMENT OF HOURLY WIND SPEED TIME SERIES

Objective

To develop a 144-hour duration wind speed time series that represents conditions in the Baker River watershed during extreme precipitation events for each of the months of October through February, inclusive. To attain this objective, the first step was to develop 144-hour duration wind speed time series for each hour during specific extreme precipitation events that have affected the Upper Baker watershed. For each month, six extreme precipitation events were identified to include in this analysis. The precipitation events are summarized in the appendix of this memo. Estimates of hourly wind speeds over the Baker River watershed were based on the hourly wind speed at Bellingham, WA (KBLI) and the 00z and 12z RAOB radiosonde data at Quillayute, WA (KUIL, 72797). If Quillayute observation data were not available, the Tatoosh Island (TTI, 72798) or Seattle (SEA, 72793) RAOB data were used. Tatoosh Island observation data were used for December 1964 and January 1964 and 1965 storms. Seattle data were used for the January 1961 storm.

Methods

Downloaded RAOB data for Quillayute station and wind speed data from Bellingham, WA (reference station) climate station for the time periods of interest.

At a distance of 40 miles, Bellingham was the closest station with reliable hourly data for most of the storms and is upwind of Upper Baker. The Quillayute radiosonde data were collected approximately 140 miles from Upper Baker, Tatoosh Island radiosonde data were collected approximately 140 miles from Upper Baker, and the Seattle radiosonde data were collected approximately 88 miles from Upper Baker. Refer to Table 2 and Figure 3 for station information and station location.

Table 2. Station Information

	Bellingham	Upper Baker	Quillayute	Tatoosh Island	Seattle
Station ID	KBLI	45-8715	KUIL	TTI	SEA
Latitude/Longitude	48.8000/-122.5333	48.65/-121.6833	47.95/-124.55	48.38/-124.73	47.45/-122.30
Elevation (feet)	164	689	204	105	406

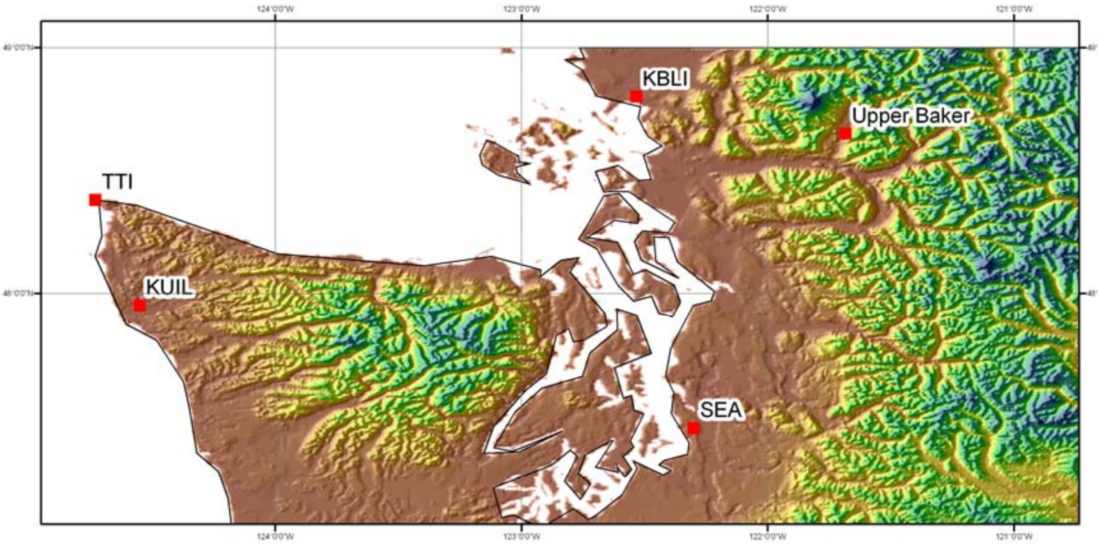


Figure 3. Reference Map

Spreadsheets were created for hourly wind speed and the recorded time adjusted from GMT to LST. The same 144-hour time periods used for the hourly temperature data were used for the wind speed data. The daily 00z and 12z wind speed data for 1000 mb (~ 360 ft), 900 mb (~ 3,000 ft), and 850 mb (~ 5,000 ft) obtained from the RAOB radiosonde data were entered into the spreadsheet for each storm of interest. Wind speed data obtained from the Bellingham hourly station were used to determine the average wind speed profile for the 144-hours of interest for each study month (three storm events for each month at the Bellingham station were selected to determine the average wind speed).

An average wind speed ratio for 00z and 12z was derived by calculating the average wind speed for each storm period at the 00z and 12z time step and dividing by the derived average monthly Bellingham wind speed. The 00z and 12z time step ratios were used as anchor points. The number of hourly time intervals between calculated anchor points (12 hrs) and the difference between the 00z and 12z ratios were used to calculate a delta ratio for each hour within that time interval. This process was repeated for every 12 hour time interval. This process created a complete one hour time series of wind speed ratios for each storm. A five hour average wind speed ratio was calculated to smooth the data. Hourly wind speed time series at 1000 mb, 900 mb, and 850 mb were derived by multiplying the Bellingham wind speed by the derived five hour smoothed wind speed ratio. An additional five hour smoothing factor was applied to the final wind speed profiles.

The 900 mb (approx 3,000 feet) and 850 mb (approximately 5,000 feet) smoothed wind speed profiles were adjusted to the PSU/NCAR mesoscale model (MM5) data. The University of Washington provided MM5 wind speed data (850 mb) for 00z and 12z times during the storm periods where available. An adjustment factor was determined for each month and was used to adjust the 900 mb and 850 mb five hour smoothed wind speed profiles. This adjustment factor reduced the free atmosphere wind speeds to those that are representative of Upper Baker wind speeds.

Problems and Assumptions

The 5hr smoothing average did not provide a wind speed ratio estimate for 10 hours (1-10) at the beginning of the time series and 4 hours (142-145) at the end of the time series. An assumed constant wind speed ratio equal to the last known value was used to fill in the missing hours.

Other than a few missing hourly wind speeds at Bellingham, the station had a complete hourly wind speed record. Estimated hourly wind speed where developed based on the wind speed trend for the handful of missing hours.

Output

All of the data and graphs were organized in an Excel spreadsheet format. A separate workbook was devoted to each month, and each workbook contains several tabs that include the raw wind speed data, and graphs of average wind speed at 1000 mb, 900 mb, and 850 mb.

The final product was a 144-hour duration wind speed time series that represents conditions in the Baker River watershed during extreme precipitation events for each month of October through February, inclusive. The monthly plots are included in the appendix of this memo. The intermediary products describe in the preceding paragraph can also be provided upon request.

UPPER BAKER SYNOPTIC STORM DEVELOPMENT

Objective

To analyze the synoptic weather conditions that occurred during each storm's 144 hour period for each month to determine what constraints can be applied when modeling the synoptic storm environment.

Methods

In order to determine and quantify the synoptic storm environment associated with each storm for each month several data sources were consulted and analyzed. These included the daily weather maps archive (Figure 4), the NCEP reanalysis archives, and the Plymouth State weather archive (Figure 5). At each of these locations, data were gathered which represented different layers of the atmosphere as varying times during the 144 hour storm period. A surface analysis and 500mb analysis were available at 24-hour intervals. These daily data were analyzed via a storm matrix where significant features were noted and discussed. These features included such variables as locations of fronts, location of high and low pressure, surface wind speeds and direction, surface temperatures, surface dewpoint temperatures, rainfall amounts, 500mb wind speeds and direction, 500mb high and low pressure areas, and 500mb temperatures. All parameters were further analyzed to see how they had changed since the previous maps.

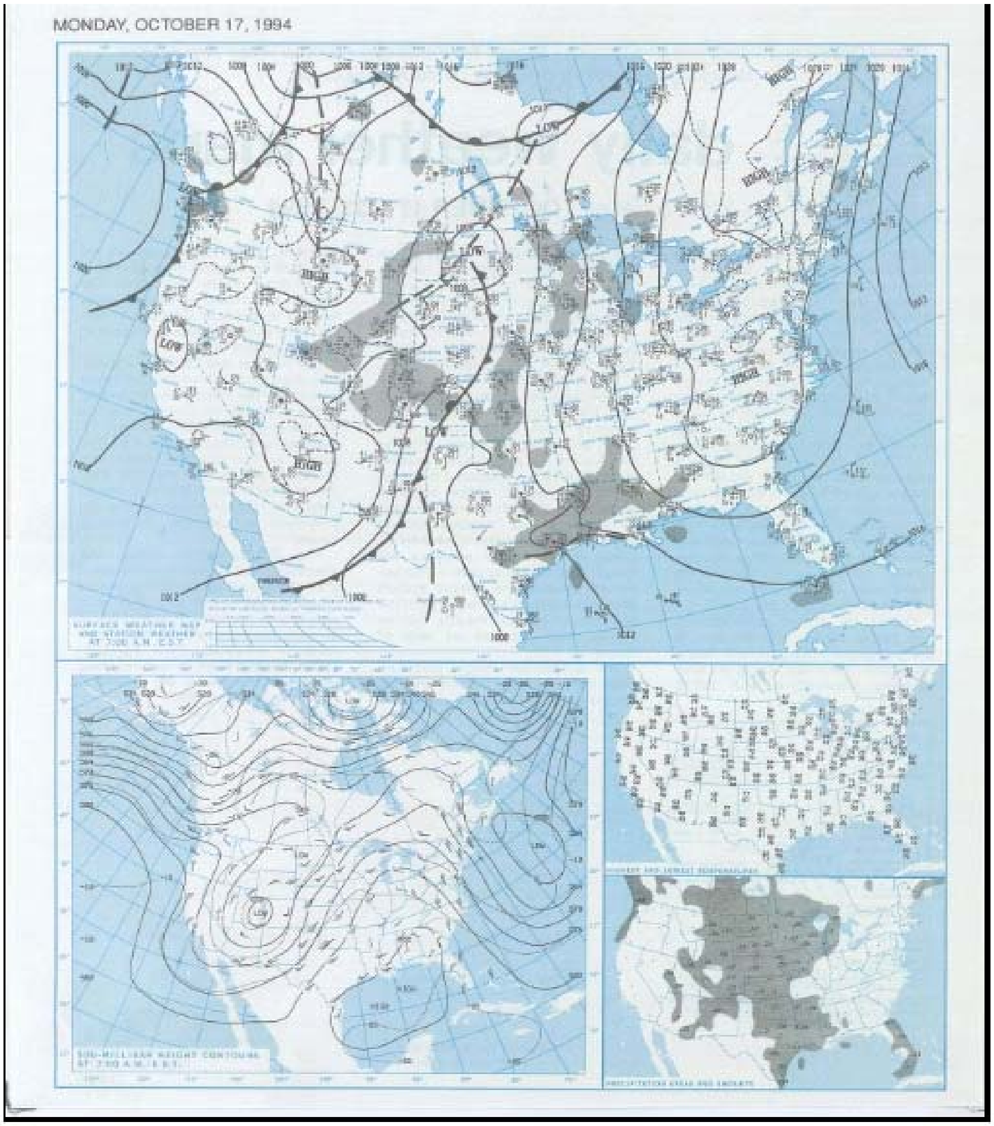


Figure 4. Example Daily Weather Map Used for Synoptic Evaluation

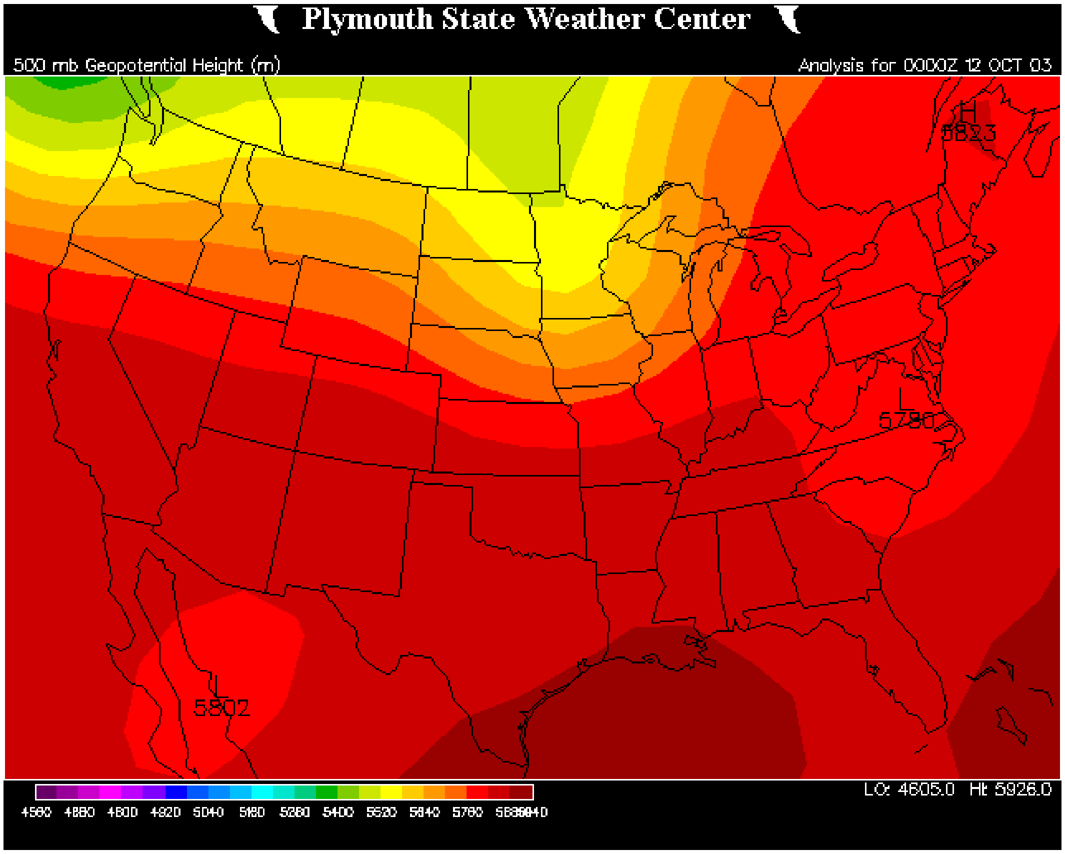
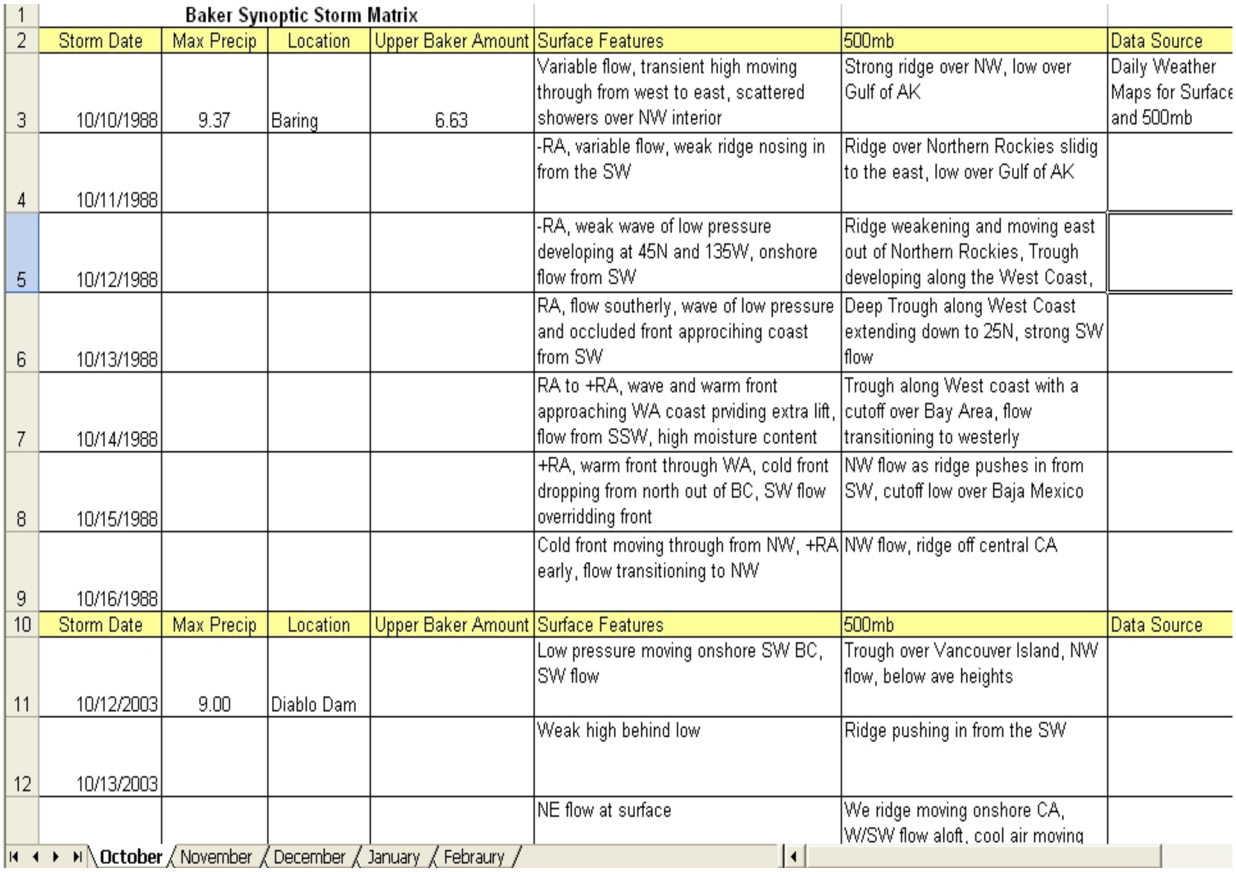


Figure 5. Example 500mb Weather Map Used for Synoptic Evaluation

A detailed write up of each storm for each month was completed once this storm matrix was finalized (Figure 6). From these write-ups, similarities of each storm's synoptic characteristics were evaluated and noted. These included descriptions regarding the conditions during the onset of the heaviest precipitation, the antecedent conditions, the movement of fronts and changes in wind speed and direction over time, and the conditions once the heaviest precipitation had ended. Also noted were the source regions for the large amounts of moisture which produced the extreme rainfalls.

After completing the storm analysis, extensive discussion took place to analyze how well the synoptic environment matched the previously analyzed temperature and freezing level data. The final product contained the constraints to be used for each month when modeling extreme precipitation events.



1		Baker Synoptic Storm Matrix					
2	Storm Date	Max Precip	Location	Upper Baker Amount	Surface Features	500mb	Data Source
3	10/10/1988	9.37	Baring	6.63	Variable flow, transient high moving through from west to east, scattered showers over NW interior	Strong ridge over NW, low over Gulf of AK	Daily Weather Maps for Surface and 500mb
4	10/11/1988				-RA, variable flow, weak ridge nosing in from the SW	Ridge over Northern Rockies slidig to the east, low over Gulf of AK	
5	10/12/1988				-RA, weak wave of low pressure developing at 45N and 135W, onshore flow from SW	Ridge weakening and moving east out of Northern Rockies, Trough developing along the West Coast,	
6	10/13/1988				RA, flow southerly, wave of low pressure and occluded front approcihing coast from SW	Deep Trough along West Coast extending down to 25N, strong SW flow	
7	10/14/1988				RA to +RA, wave and warm front approaching WA coast prviding extra lift, flow from SSW, high moisture content	Trough along West coast with a cutoff over Bay Area, flow transitioning to westerly	
8	10/15/1988				+RA, warm front through WA, cold front dropping from north out of BC, SW flow overridding front	NW flow as ridge pushes in from SW, cutoff low over Baja Mexico	
9	10/16/1988				Cold front moving through from NW, +RA early, flow transitioning to NW	NW flow, ridge off central CA	
10	Storm Date	Max Precip	Location	Upper Baker Amount	Surface Features	500mb	Data Source
11	10/12/2003	9.00	Diablo Dam		Low pressure moving onshore SW BC, SW flow	Trough over Vancouver Island, NW flow, below ave heights	
12	10/13/2003				Weak high behind low	Ridge pushing in from the SW	
					NE flow at surface	We ridge moving onshore CA, W/SW flow aloft, cool air moving	

Figure 6. Example Storm Matrix Used for Synoptic Evaluation

Problems and Assumptions

The Daily Weather Maps were the best source of synoptic information available for the storm periods. However, these were produced at 24 hours intervals, representing a snapshot of the weather conditions at 12z. Changes in the weather pattern which may have impacted the study region during the intervening 23 hours could be missed. For storms that occurred in the 1960's and 1970's, some of the analyses represented on the maps themselves may have been inaccurate or incomplete since at that time the scientific community's understanding of fronts and use of satellite imagery was limited.   AWA addressed these situations using our expertise in understanding how fronts, highs, and lows move and interact through space and time along the West coast and in the Pacific Northwest. Moreover, because the synoptic weather pattern changes generally do not vary significantly over time periods less than 24 hours for large scale events, AWA feels all major parameters and constraints were captured and evaluated by using the available data sets.

Output

The storm matrix data that were developed for the synoptic evaluation are contained in Excel spreadsheet format and the synoptic evaluation and write up for each storm for each month are contained on Word documents. Each of the monthly synoptic storm write ups contains a section detailing the storm characteristics for that month, a detailed analysis of each storm for that month, the storm type for each storm, and the storm constraints for each storm. This detailed information can be provided upon request.

REFERENCES

Higgins, R.W., J.-K.E. Schemm, W. Shi, and A. Leetmaa, 1996. *Extreme Precipitation Events in the Western United States Related Tropical Forcing*. Journal of Climate, 13 (4), 793-820.

Hydrometeorological Report No. 57, Probable Maximum Precipitation Pacific Northwest States, Hansen, E.M., Fenn, D.D, Corrigan, P., Vogel, J.L., Schriener, L.C., Stodt, R.W., NWS, October 1994

Kalnay et al.,The NCEP/NCAR 40-year reanalysis project, Bull. Amer. Meteor. Soc., 77, 437-470, 1996.

National Climatic Data Center (NCDC), 2003. Data Documentation For Data Set 9956 (DSI-9956) DATSAV3 Global Surface Hourly Data. North Carolina: Asheville.

National Weather Service (NWS). 1966. *Probable Maximum Precipitation for the Pacific Northwest. Hydrometeorological Report No. 43.* U.S. Department of Commerce - National Oceanic and Atmospheric Administration, U.S. Weather Bureau.

National Weather Service (NWS). 1994. *Probable Maximum Precipitation – Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages. Hydrometeorological Report No. 57.* U.S. Department of Commerce - National Oceanic and Atmospheric Administration, U.S Department of Interior – Bureau of Reclamation, U.S. Department of Army – Corps of Engineers.

NCDC TD14 and TD3280 U.S. Surface Airway Hourly Observations, continuing from 1938(1948). ds470.0 dataset. Accessed at http://dss.ucar.edu/datasets/ds470.0/.

NORTH AMERICAN REGIONAL REANALYSIS: A long-term, consistent, high-resolution climate dataset for the North American domain, as a major improvement upon the earlier global reanalysis datasets in both resolution and accuracy, Fedor Mesinger et. al, submitted to BAMS 2004.

NOAA Central Library U.S. Daily Weather Maps Project, http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html

Oregon Climate Service (OCS). 2005. *Mean Annual Precipitation Mapping for the United States.* Provided to Tetra Tech via email from George Taylor from the Oregon Climate Service.

Palecki, M.A. et al., *Storm Precipitation in the United States. Part I: Meteorological Characteristics*, Journal of Applied Meteorology, vol. 44, p 933-946, June 2005.

Pennsylvania State University and National Center for Atmospheric Research numerical model (MM5). MM5 Community Model. Accessed at http://box.mmm.ucar.edu/mm5/.

Plymouth State Weather Center Archived Data, http://vortex.plymouth.edu/u-make.html

Radiosonde Database Access (RAOB) and FSL/NCDC Radiosonde Data Archive 1998-2006. Accessed at http://raob.fsl.noaa.gov/.

Radiosonde Database Access (RAOB) and FSL/NCDC Radiosonde Data Archive 1946-1997. Accessed by CD-ROM archive

RAOB Sounding data for Quillayute, WA, Tatoosh Island, WA (December 1964 and January 1964 and 1965), and Seattle, WA (January 1961).

Schaefer, M.G., 1989. *Characteristics of Extreme Precipitation Events in Washington State*. Washington State, Department of Ecology, Water resources Program, 109 pp.

TDL U.S. and Canada Surface Hourly Observations, Daily 1976 Dec-cont. ds472.0 dataset. Accessed at http://dss.ucar.edu/datasets/ds472.0/.

APPENDICES

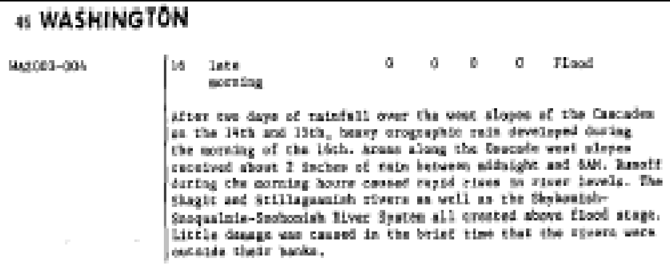
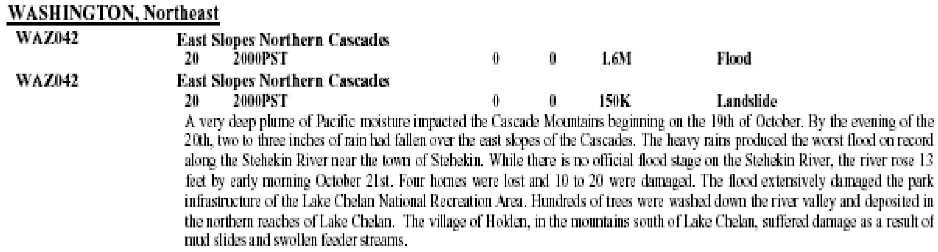
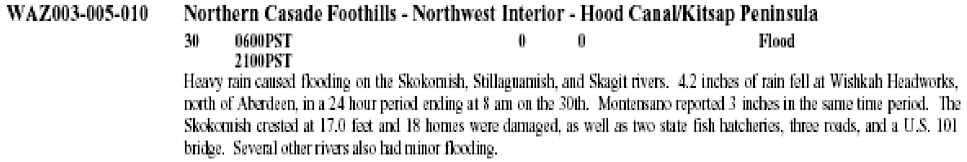
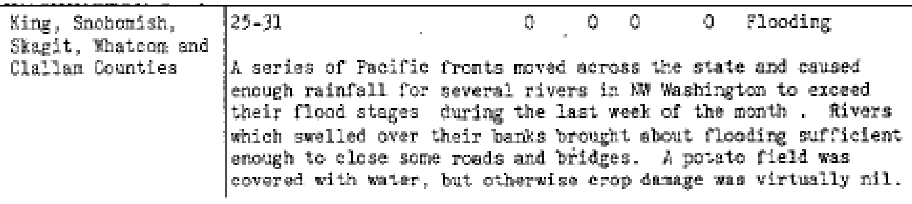
Storm Database

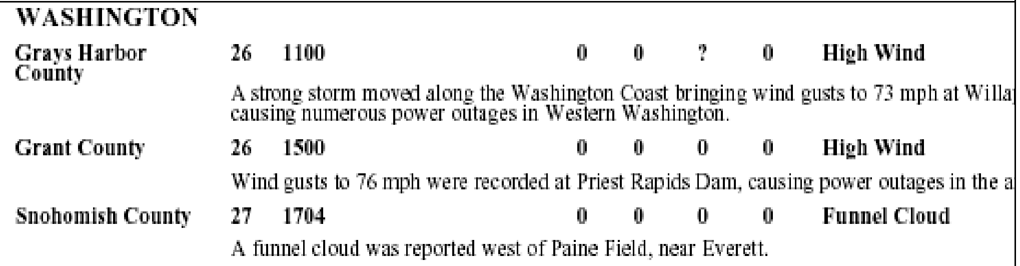
Monthly Air Temperature Time Series Plots

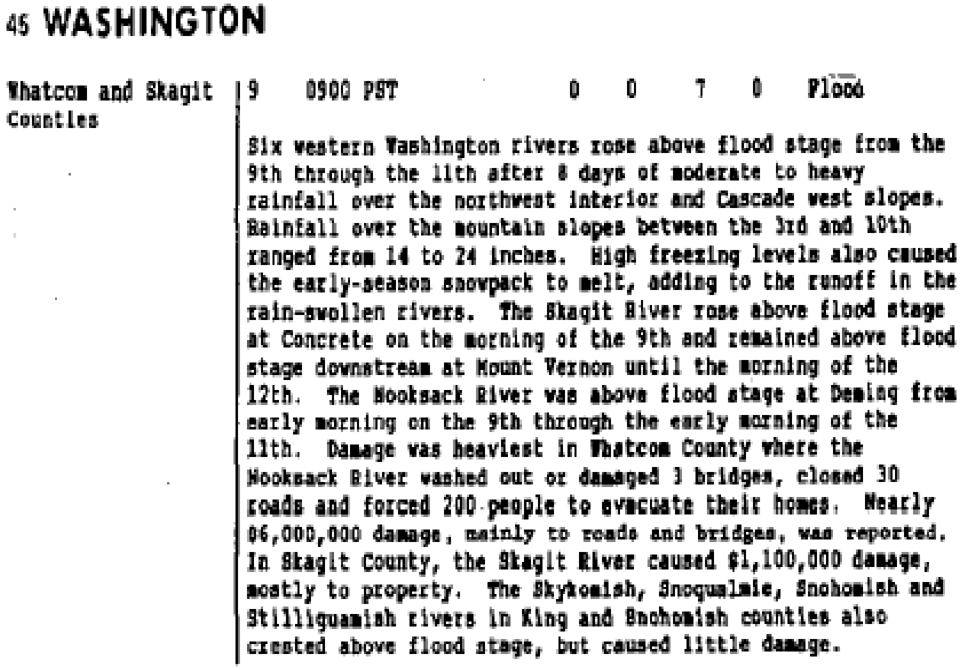
Monthly Freezing Level Time Series Plots

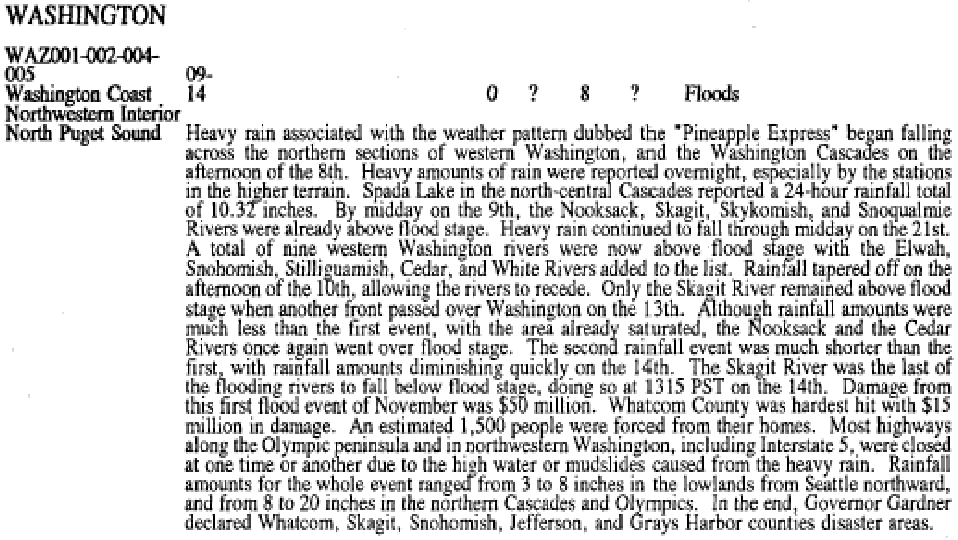
Monthly Wind Speed Time Series Plots

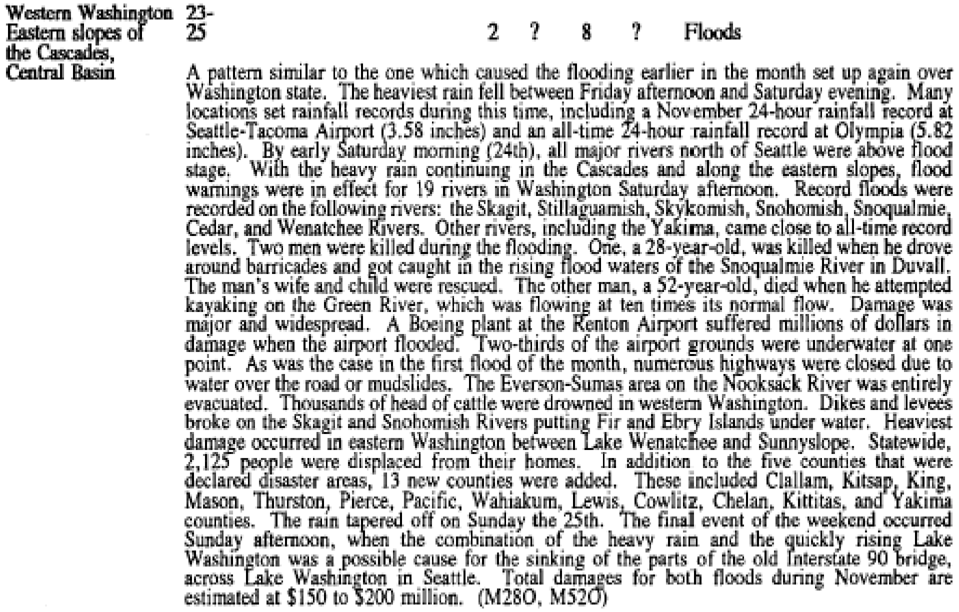
OCTOBER Extreme Precipitation Events Washington Cascades – 1948-2005

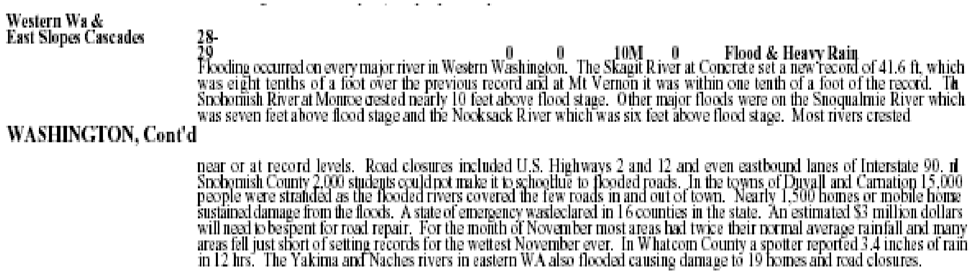
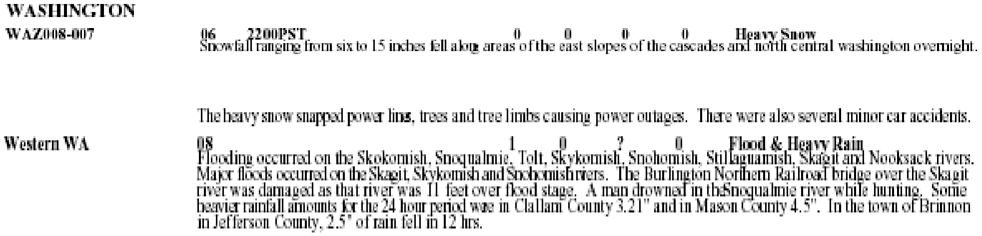
Storm Dates	Gage Location	Max. 3 day Precipitation	Mel Schaefer Report	In “Tropical Forcing” Paper	Storm Data
10/14/1988 – 10/16/1988	Baring	9.37	no	no	 45 WASHINGTON WAZ003-004 16 late morning 0 0 0 0 Flood After two days of rainfall over the west slopes of the Cascades on the 14th and 15th, heavy orographic rain developed during the morning of the 16th. Areas along the Cascade west slopes received about 2 inches of rain between midnight and 8AM. Runoff during the morning hours caused rapid rises in river levels. The Skagit and Stillaguamish rivers as well as the Skykomish-Snoqualmie-Snohomish River System all crested above flood stage. Little damage was caused in the brief time that the rivers were outside their banks.
10/16/2003 – 10/18/2003	Diablo Dam	9.00	no	no	 WASHINGTON, Northeast WAZ042 East Slopes Northern Cascades 20 2000PST 0 0 1.6M Flood WAZ042 East Slopes Northern Cascades 20 2000PST 0 0 150K Landslide A very deep plume of Pacific moisture impacted the Cascade Mountains beginning on the 19th of October. By the evening of the 20th, two to three inches of rain had fallen over the east slopes of the Cascades. The heavy rains produced the worst flood on record along the Stehekin River near the town of Stehekin. While there is no official flood stage on the Stehekin River, the river rose 13 feet by early morning October 21st. Four homes were lost and 10 to 20 were damaged. The flood extensively damaged the park infrastructure of the Lake Chelan National Recreation Area. Hundreds of trees were washed down the river valley and deposited in the northern reaches of Lake Chelan. The village of Holden, in the mountains south of Lake Chelan, suffered damage as a result of mud slides and swollen feeder streams.
10/30/1997 – 11/1/1997	Petersons RA	8.73	no	no	 WAZ003-005-010 Northern Casade Foothills - Northwest Interior - Hood Canal/Kitsap Peninsula 30 0600PST 0 0 Flood 2100PST Heavy rain caused flooding on the Skokomish, Stillaguamish, and Skagit rivers. 4.2 inches of rain fell at Wishkah Headworks, north of Aberdeen, in a 24 hour period ending at 8 am on the 30th. Montensano reported 3 inches in the same time period. The Skokomish crested at 17.0 feet and 18 homes were damaged, as well as two state fish hatcheries, three roads, and a U.S. 101 bridge. Several other rivers also had minor flooding.
10/24/1985 – 10/26/1985	Baring	8.48	no	no	 King, Snohomish, Skagit, Whatcom and Clallam Counties 25-31 0 0 0 0 Flooding A series of Pacific fronts moved across the state and caused enough rainfall for several rivers in NW Washington to exceed their flood stages during the last week of the month. Rivers which swelled over their banks brought about flooding sufficient enough to close some roads and bridges. A potato field was covered with water, but otherwise crop damage was virtually nil.

10/17/1975 – 10/19/1975	Upper Baker	8.11	no	no	Nothing reported
10/26/1994 – 10/28/1994	Longmire RAI	6.84	no	no	 **WASHINGTON** **Grays Harbor County** **26** **1100** **0** **0** **?** **0** **High Wind** A strong storm moved along the Washington Coast bringing wind gusts to 73 mph at Willa causing numerous power outages in Western Washington. **Grant County** **26** **1500** **0** **0** **0** **0** **High Wind** Wind gusts to 76 mph were recorded at Priest Rapids Dam, causing power outages in the a **Snohomish County** **27** **1704** **0** **0** **0** **0** **Funnel Cloud** A funnel cloud was reported west of Paine Field, near Everett.

NOVEMBER Extreme Precipitation Events Washington Cascades – 1948-2005					
Storm Dates	Gage Location	Max. 3 day Precipitation	Mel Schaefer Report	In “Tropical Forcing” Paper	Storm Data
11/5/1989 – 11/11/1989	Nooksack Sal	8.70	no	no	SPAS #1019  45 WASHINGTON Whatcom and Skagit Counties | 9 0900 PST 0 0 7 0 Flood Six western Washington rivers rose above flood stage from the 9th through the 11th after 8 days of moderate to heavy rainfall over the northwest interior and Cascade west slopes. Rainfall over the mountain slopes between the 3rd and 10th ranged from 14 to 24 inches. High freezing levels also caused the early-season snowpack to melt, adding to the runoff in the rain-swollen rivers. The Skagit River rose above flood stage at Concrete on the morning of the 9th and remained above flood stage downstream at Mount Vernon until the morning of the 12th. The Nooksack River was above flood stage at Deming from early morning on the 9th through the early morning of the 11th. Damage was heaviest in Whatcom County where the Nooksack River washed out or damaged 3 bridges, closed 30 roads and forced 200 people to evacuate their homes. Nearly $6,000,000 damage, mainly to roads and bridges, was reported. In Skagit County, the Skagit River caused $1,100,000 damage, mostly to property. The Skykomish, Snoqualmie, Snohomish and Stilliguamish rivers in King and Snohomish counties also crested above flood stage, but caused little damage.

11/5/1990 – 11/13/1990	Baring	12.58	no	no	SPAS #1020 **WASHINGTON** **WAZ001-002-004-005** 09-14 0 ? 8 ? Floods **Washington Coast** **Northwestern Interior** **North Puget Sound** Heavy rain associated with the weather pattern dubbed the "Pineapple Express" began falling across the northern sections of western Washington, and the Washington Cascades on the afternoon of the 8th. Heavy amounts of rain were reported overnight, especially by the stations in the higher terrain. Spada Lake in the north-central Cascades reported a 24-hour rainfall total of 10.32 inches. By midday on the 9th, the Nooksack, Skagit, Skykomish, and Snoqualmie Rivers were already above flood stage. Heavy rain continued to fall through midday on the 21st. A total of nine western Washington rivers were now above flood stage with the Elwah, Snohomish, Stilliguamish, Cedar, and White Rivers added to the list. Rainfall tapered off on the afternoon of the 10th, allowing the rivers to recede. Only the Skagit River remained above flood stage when another front passed over Washington on the 13th. Although rainfall amounts were much less than the first event, with the area already saturated, the Nooksack and the Cedar Rivers once again went over flood stage. The second rainfall event was much shorter than the first, with rainfall amounts diminishing quickly on the 14th. The Skagit River was the last of the flooding rivers to fall below flood stage, doing so at 1315 PST on the 14th. Damage from this first flood event of November was $50 million. Whatcom County was hardest hit with $15 million in damage. An estimated 1,500 people were forced from their homes. Most highways along the Olympic peninsula and in northwestern Washington, including Interstate 5, were closed at one time or another due to the high water or mudslides caused from the heavy rain. Rainfall amounts for the whole event ranged from 3 to 8 inches in the lowlands from Seattle northward, and from 8 to 20 inches in the northern Cascades and Olympics. In the end, Governor Gardner declared Whatcom, Skagit, Snohomish, Jefferson, and Grays Harbor counties disaster areas.

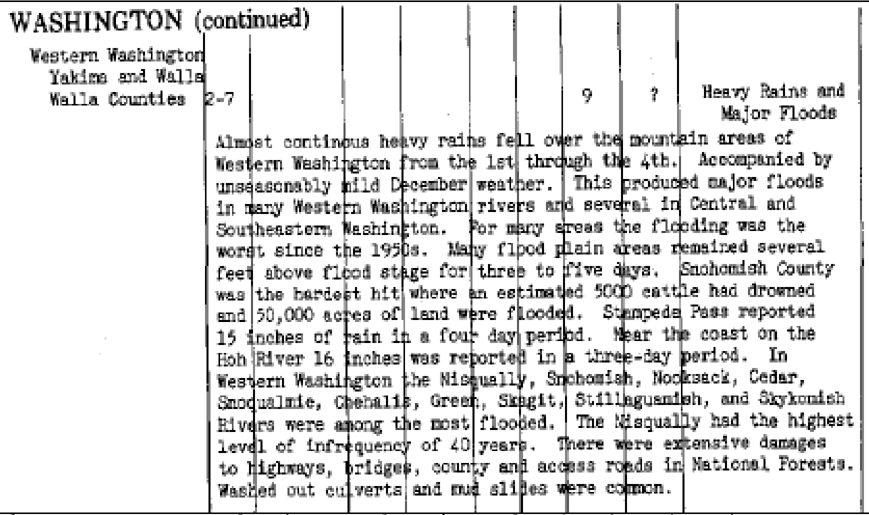
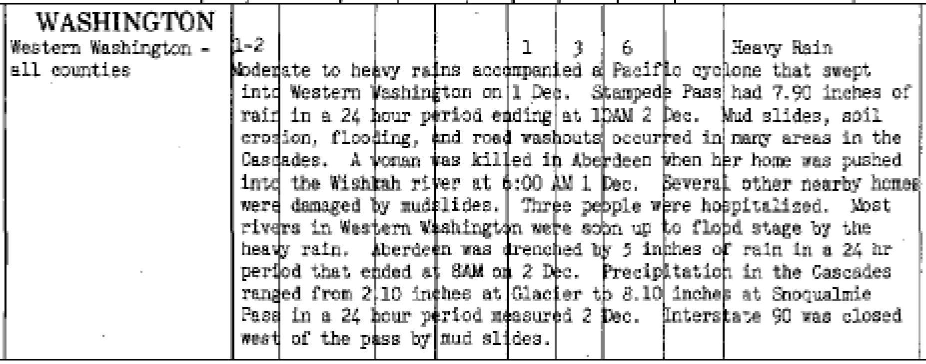
11/18/1990 – 11/25/1990	Baring	15.25	no	no	SPAS #1021  **Western Washington Eastern slopes of the Cascades, Central Basin** 23-25 2 ? 8 ? Floods A pattern similar to the one which caused the flooding earlier in the month set up again over Washington state. The heaviest rain fell between Friday afternoon and Saturday evening. Many locations set rainfall records during this time, including a November 24-hour rainfall record at Seattle-Tacoma Airport (3.58 inches) and an all-time 24-hour rainfall record at Olympia (5.82 inches). By early Saturday morning (24th), all major rivers north of Seattle were above flood stage. With the heavy rain continuing in the Cascades and along the eastern slopes, flood warnings were in effect for 19 rivers in Washington Saturday afternoon. Record floods were recorded on the following rivers: the Skagit, Stillaguamish, Skykomish, Snohomish, Snoqualmie, Cedar, and Wenatchee Rivers. Other rivers, including the Yakima, came close to all-time record levels. Two men were killed during the flooding. One, a 28-year-old, was killed when he drove around barricades and got caught in the rising flood waters of the Snoqualmie River in Duvall. The man's wife and child were rescued. The other man, a 52-year-old, died when he attempted kayaking on the Green River, which was flowing at ten times its normal flow. Damage was major and widespread. A Boeing plant at the Renton Airport suffered millions of dollars in damage when the airport flooded. Two-thirds of the airport grounds were underwater at one point. As was the case in the first flood of the month, numerous highways were closed due to water over the road or mudslides. The Everson-Sumas area on the Nooksack River was entirely evacuated. Thousands of head of cattle were drowned in western Washington. Dikes and levees broke on the Skagit and Snohomish Rivers putting Fir and Ebry Islands under water. Heaviest damage occurred in eastern Washington between Lake Wenatchee and Sunnyslope. Statewide, 2,125 people were displaced from their homes. In addition to the five counties that were declared disaster areas, 13 new counties were added. These included Clallam, Kitsap, King, Mason, Thurston, Pierce, Pacific, Wahiakum, Lewis, Cowlitz, Chelan, Kittitas, and Yakima counties. The rain tapered off on Sunday the 25th. The final event of the weekend occurred Sunday afternoon, when the combination of the heavy rain and the quickly rising Lake Washington was a possible cause for the sinking of the parts of the old Interstate 90 bridge, across Lake Washington in Seattle. Total damages for both floods during November are estimated at $150 to $200 million. (M28O, M52O)

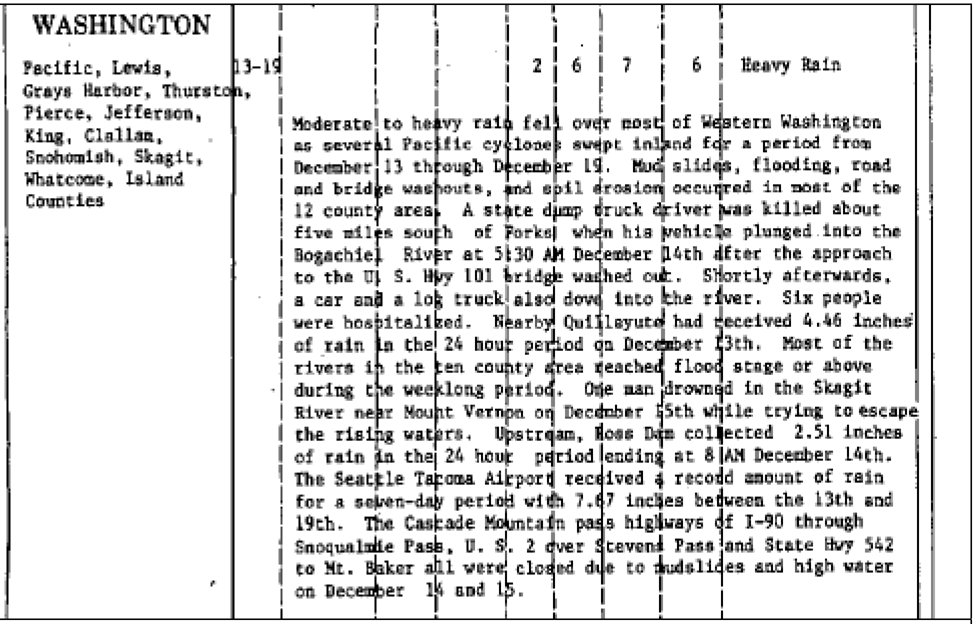
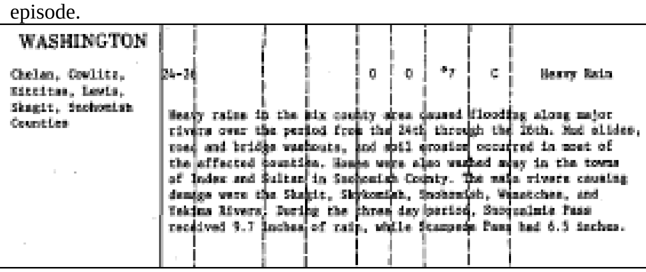
11/24/1995 – 11/30/1995	Snoqualmie Pass	13.50	no	no	SPAS #1022  **Western Wa & East Slopes Cascades** **28-29** **0** **0** **10M** **0** **Flood & Heavy Rain** Flooding occurred on every major river in Western Washington. The Skagit River at Concrete set a new record of 41.6 ft, which was eight tenths of a foot over the previous record and at Mt Vernon it was within one tenth of a foot of the record. Th Snohomish River at Monroe crested nearly 10 feet above flood stage. Other major floods were on the Snoqualmie River which was seven feet above flood stage and the Nooksack River which was six feet above flood stage. Most rivers crested **WASHINGTON, Cont'd** near or at record levels. Road closures included U.S. Highways 2 and 12 and even eastbound lanes of Interstate 90. In Snohomish County 2,000 students could not make it to school due to flooded roads. In the towns of Duvall and Carnation 15,000 people were stranded as the flooded rivers covered the few roads in and out of town. Nearly 1,500 homes or mobile home sustained damage from the floods. A state of emergency was declared in 16 counties in the state. An estimated $3 million dollars will need to be spent for road repair. For the month of November most areas had twice their normal average rainfall and many areas fell just short of setting records for the wettest November ever. In Whatcom County a spotter reported 3.4 inches of rain in 12 hrs. The Yakima and Naches rivers in eastern WA also flooded causing damage to 19 homes and road closures.
11/4/1995 – 11/10/1995	Baring	12.13	no	no	 **WASHINGTON** **WAZ008-007** **06** **2200PST** **0** **0** **0** **0** **Heavy Snow** Snowfall ranging from six to 15 inches fell along areas of the east slopes of the cascades and north central washington overnight. The heavy snow snapped power lines, trees and tree limbs causing power outages. There were also several minor car accidents. **Western WA** **08** **1** **0** **?** **0** **Flood & Heavy Rain** Flooding occurred on the Skokomish, Snoqualmie, Tolt, Skykomish, Snohomish, Stillaguamish, Skagit and Nooksack rivers. Major floods occurred on the Skagit, Skykomish and Snohomish rivers. The Burlington Northern Railroad bridge over the Skagit river was damaged as that river was 11 feet over flood stage. A man drowned in the Snoqualmie river while hunting. Some heavier rainfall amounts for the 24 hour period were in Clallam County 3.21" and in Mason County 4.5". In the town of Brinnon in Jefferson County, 2.5" of rain fell in 12 hrs.

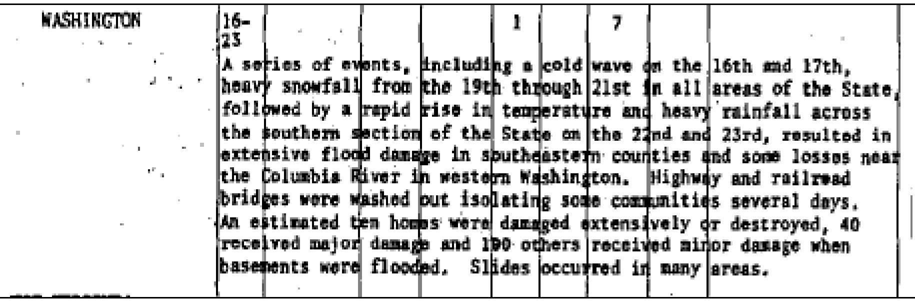
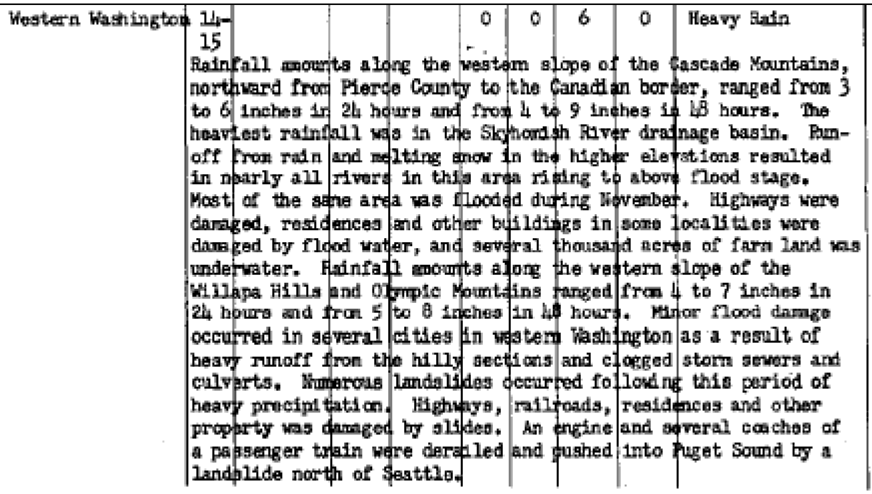
11/13/2003 – 11/19/2003	Baring	10.99	no	no	**WASHINGTON, Northwest WAZ002>007- 010>011-013** **Western Whatcom - Northern Cascade Foothills - Central Cascade Foothills - Northwest Interior – Everett And Vicinity - Seattle Metropolitan Area - Hood Canal/Kitsap Peninsula - Southwest Interior - Eastern Strait Of Juan De Fuca** **Flood 0 0 18 20 0230PST 0330PST** Flooding occurred on the Stillaguamish, Skagit, Snoqualmie, Nooksack, Dungeness, Elwha, Skykomish, Snohomish, Satsop and Tolt rivers. Several home owners had part of their land fall into the Stillaguamish River, threatening their homes. There was also urban and small stream flooding. Numerous roads were closed or barely passable, slowing traffic to a crawl. Seatac airport got record rainfall of 2.04 inches on the 18th, and Bellingham airport got record rainfall of 1.85 inches on the 19th. Several businesses in the Seattle area had water on the ground floor. **Heavy Snow 300K 0 0 19 0400PST** **2100PST** **WAZ006-018 Everett And Vicinity - West Slopes Central Cascades And Passes** A cold front moved south through the area, and unlike normal, it actually dropped the temperatures by almost 20 degrees. After strong, relatively warm south winds, the temperature fell from 55 degrees at midnight to 35 by 8 am. Up to 4 inches of snow fell in Snohomish county. The combination of strong south winds and snowfall, knocked out power to about 12,000 customers. Several schools closed for the day. Later that night, after 16 inches of snow, Interstate 90 at Snoqualmie Pass closed for several hours **Winter Storm 0 0 17** **20 0900PST 1700PST WAZ019>023- 039>040** **West Slopes Southern Cascades And Passes - Southwest Interior - South Coast - Lower Columbia – West Columbia River Gorge - Vancouver Area - Southern Cascade Foothills** Over the three day period a series of strong Pacific storms brought strong winds to the coastal areas, heavy rain and/or snow to most of the CWA. The coastal areas were buffeted by 40 to 50 mph winds. Generous amounts of rain were reported. In 6 hours, Vancouver recorded 1.16 inches and Camas 1.02 inches. In 12 hours, Francis recorded 1.70 inches, Dixie Mt 1.00 inches, and Cougar 0.63 inches. In addition Long Beach reported 2.00 inches in 18 hours, Ocean Park 1.71 inches in 18 hours, and Camas 1.75 in 19 hours. Cold air followed in the wake of the heavy rains bringing a blanket of snow to most of the area. Some of accumulations included 8 inches at Mt Livingston, 5 inches in north Washougal, 4 inches at Camas, 2 inches in east Vancouver, and 1 inch in Longview.

11/15/1985 – 11/21/1985	Snoqualmie Falls	14.50	no	no	Yakima,Kittitas, Chelan and Grant Counties	11 all day 2 ? 0 0 Heavy Snow An intense storm center curved off the Washington Coast and moved east along the Oregon border. The storm slowed just east of the Cascade Mountains and dumped up to four feet of snow east of Mt. Rainier. The storm stranded up to 300 elk hunters, some with horses or mules. Record-breaking cold temperatures added to the danger. One hunter froze to death, not being able to move after falling down an embankment. An elderly couple were stranded in their truck in zero degree weather; the woman died and her husband was rescued in critical condition. Winds blowing up to 50 knots after the storm passed hampered airlift operations.
					Western Washington	21 all day 0 0 0 0 Heavy Snow A winter storm poured out of Canada with snow and very cold air. Six to twelve inches were average totals throughout the Puget Sound area, somewhat less along the Coast and southwest corner of the state. Numerous traffic accidents resulted. A thunderstorm occurred during the snowstorm, northeast of Tacoma. Heavy snow was a more random occurrence east of the Cascades. Yakima and Walla Walla were the worst hit. Up to ten fatalities across the State's highways were blamed on the weather.

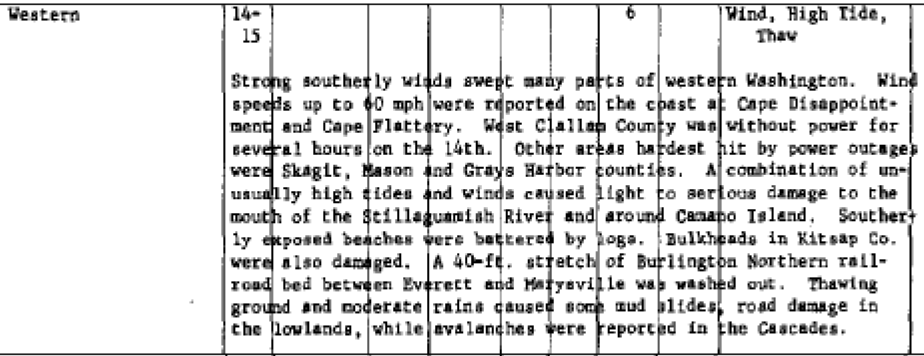
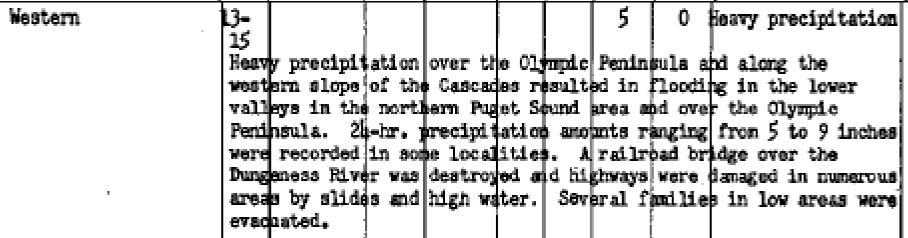
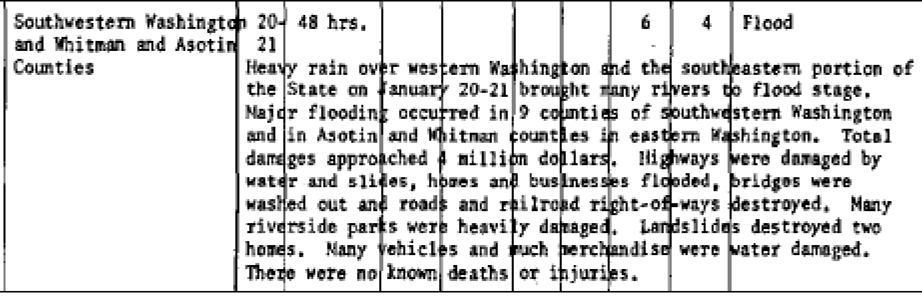
DECEMBER Extreme Precipitation Events Washington Cascades – 1948-2005

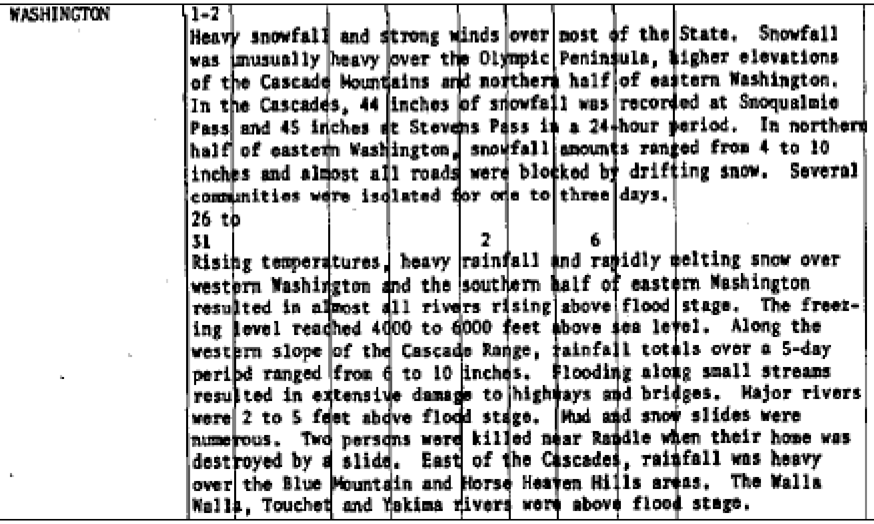
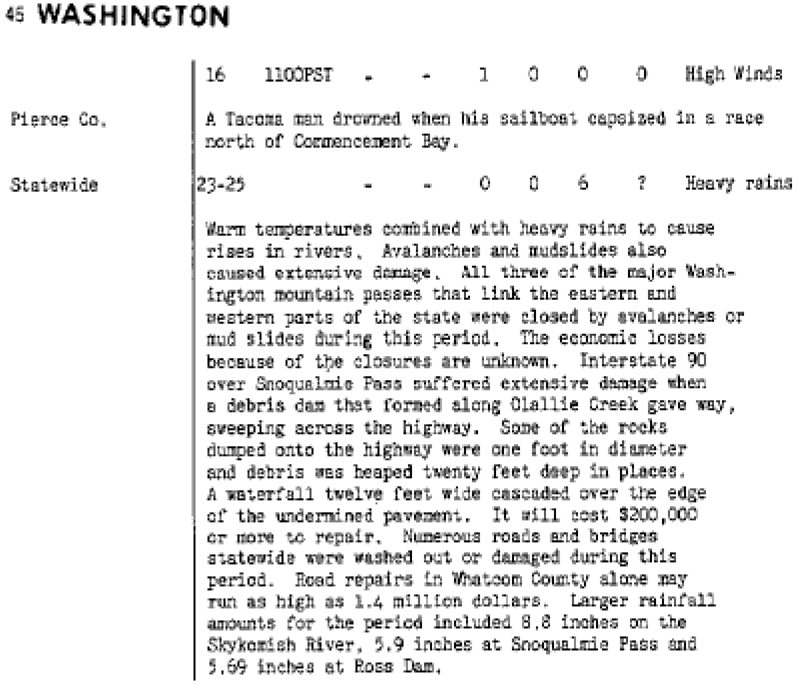
Storm Dates	Gage Location	Max. 3 day Precipitation	Mel Schaefer Report	In "Tropical Forcing" Paper	Storm Data
12/1/1975 – 12/3/1975	Rainier Ohan	25.30	yes	yes	**WASHINGTON** (continued) Western Washington Yakima and Walla Walla Counties 2-7 9 ? Heavy Rains and Major Floods Almost continous heavy rains fell over the mountain areas of Western Washington from the 1st through the 4th. Accompanied by unseasonably mild December weather. This produced major floods in many Western Washington rivers and several in Central and Southeastern Washington. For many areas the flooding was the worst since the 1950s. Many flood plain areas remained several feet above flood stage for three to five days. Snohomish County was the hardest hit where an estimated 5000 cattle had drowned and 50,000 acres of land were flooded. Stampede Pass reported 15 inches of rain in a four day period. Near the coast on the Hoh River 16 inches was reported in a three-day period. In Western Washington the Nisqually, Snohomish, Nooksack, Cedar, Snoqualmie, Chehalis, Green, Skagit, Stillaguamish, and Skykomish Rivers were among the most flooded. The Nisqually had the highest level of infrequency of 40 years. There were extensive damages to highways, bridges, county and access roads in National Forests. Washed out culverts and mud slides were common.
12/1/1977 – 12/3/1977	Stampede Pass	13.03	yes	no	**WASHINGTON** Western Washington - all counties 1-2 1 3 6 Heavy Rain Moderate to heavy rains accompanied a Pacific cyclone that swept into Western Washington on 1 Dec. Stampede Pass had 7.90 inches of rain in a 24 hour period ending at 10AM 2 Dec. Mud slides, soil erosion, flooding, and road washouts occurred in many areas in the Cascades. A woman was killed in Aberdeen when her home was pushed into the Wishkah river at 6:00 AM 1 Dec. Several other nearby homes were damaged by mudslides. Three people were hospitalized. Most rivers in Western Washington were soon up to flood stage by the heavy rain. Aberdeen was drenched by 5 inches of rain in a 24 hr period that ended at 8AM on 2 Dec. Precipitation in the Cascades ranged from 2.10 inches at Glacier to 8.10 inches at Snoqualmie Pass in a 24 hour period measured 2 Dec. Interstate 90 was closed west of the pass by mud slides.

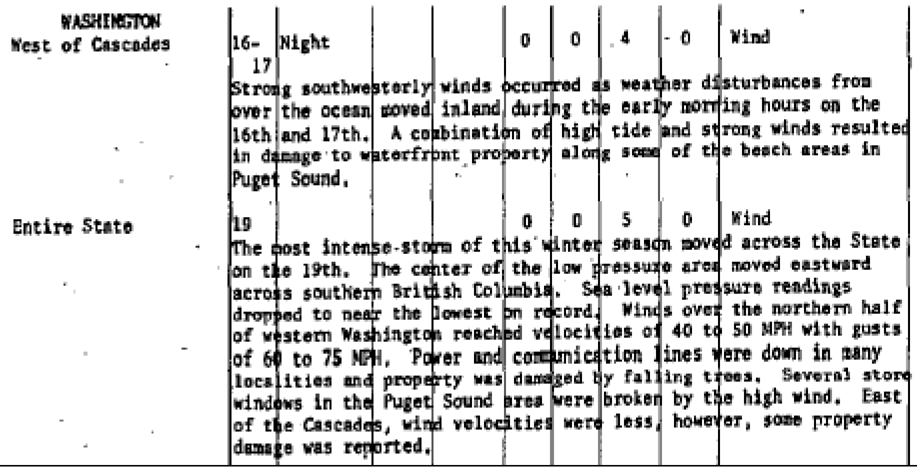
12/13/1979 – 12/15/1979	Baring	10.15	yes	no	WASHINGTON Pacific, Lewis, Grays Harbor, Thurston, Pierce, Jefferson, King, Clallam, Snohomish, Skagit, Whatcome, Island Counties 13-19 2 6 7 6 Heavy Rain Moderate to heavy rain fell over most of Western Washington as several Pacific cyclones swept inland for a period from December 13 through December 19. Mud slides, flooding, road and bridge washouts, and soil erosion occurred in most of the 12 county area. A state dump truck driver was killed about five miles south of Forks when his vehicle plunged into the Bogachiel River at 5:30 AM December 14th after the approach to the U. S. Hwy 101 bridge washed out. Shortly afterwards, a car and a log truck also dove into the river. Six people were hospitalized. Nearby Quillayute had received 4.46 inches of rain in the 24 hour period on December 13th. Most of the rivers in the ten county area reached flood stage or above during the weeklong period. One man drowned in the Skagit River near Mount Vernon on December 15th while trying to escape the rising waters. Upstream, Ross Dam collected 2.51 inches of rain in the 24 hour period ending at 8 AM December 14th. The Seattle Tacoma Airport received a record amount of rain for a seven-day period with 7.67 inches between the 13th and 19th. The Cascade Mountain pass highways of I-90 through Snoqualmie Pass, U. S. 2 over Stevens Pass and State Hwy 542 to Mt. Baker all were closed due to mudslides and high water on December 14 and 15.
12/27/1998 – 12/29/1998	Baring	9.81	no	no	**Heavy Rain 200K Elma 0000PST 2300PST Grays Harbor County** Heavy rain over a two day period caused damage to the Elma High School. The heavy rain also triggered mudslides, one which knocked a house off its foundation in Gig Harbor. SeaTac set a new two month precipitation record after 21.42 inches fell in Nov and Dec of 1998. A Pacific storm on December 27-28 dumped 2 to 5 inches of rain in lowlands and 6 to 10 inches of rain in the Coast Range. This deluge, on top of heavy rain December 25-26, combined with saturated soils and a rapidly melted heavy low elevation snowpack and frozen subsurface soils from the pre-Holiday arctic outbreak to create widespread lowland flooding. The Willapa and Cowlitz River areas were the hardest hit, but fortunately the rain ended December 28 and flood waters receded rapidly Many highways were closed due to slides and washouts, especially along the coast and Coast Range. Fortunately, no deaths or serious injuries were reported during this episode.
12/24/1980 – 12/26/1980	Snoqualmie Pass	9.70	no	no	WASHINGTON Chelan, Cowlitz, Kittitas, Lewis, Skagit, Snohomish Counties 24-26 0 0 7 C Heavy Rain Heavy rains in the six county area caused flooding along major rivers over the period from the 24th through the 26th. Mud slides, road and bridge washouts, and soil erosion occurred in most of the affected counties. Homes were also washed away in the towns of Index and Sultan in Snohomish County. The main rivers causing damage were the Skagit, Skykomish, Snohomish, Wenatchee, and Yakima Rivers. During the three day period, Snoqualmie Pass received 9.7 inches of rain, while Stampede Pass had 6.5 inches.

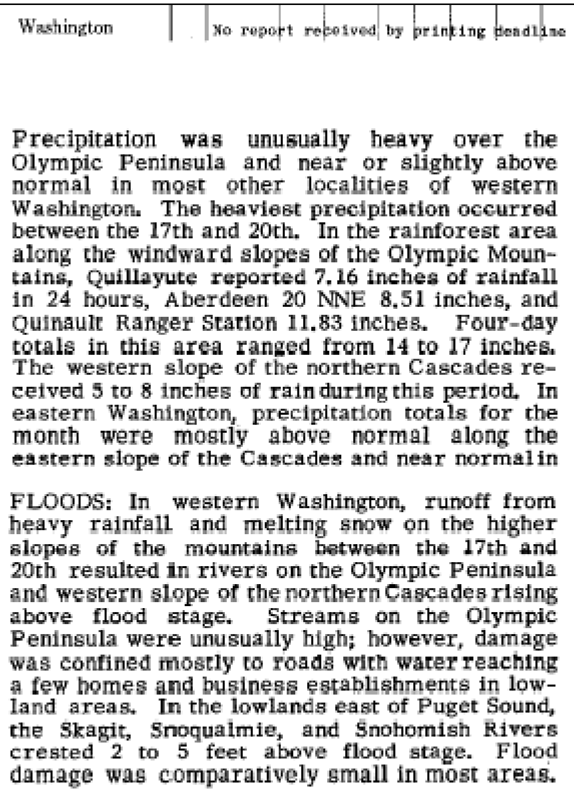
12/21/1964 – 12/23/1964	Satus Pass	9.46	no	yes	 WASHINGTON 16-23 1 7 A series of events, including a cold wave on the 16th and 17th, heavy snowfall from the 19th through 21st in all areas of the State, followed by a rapid rise in temperature and heavy rainfall across the southern section of the State on the 22nd and 23rd, resulted in extensive flood damage in southeastern counties and some losses near the Columbia River in western Washington. Highway and railroad bridges were washed out isolating some communities several days. An estimated ten homes were damaged extensively or destroyed, 40 received major damage and 190 others received minor damage when basements were flooded. Slides occurred in many areas.
Backup Storms Events					
12/8/1956 – 12/10/1956	Grotto	9.26	no	no	Not Available
Did not use because no observation forms reported for Upper Baker					
12/15/1959 – 1217/1959	Grotto	10.11	yes	no	 Western Washington 14-15 0 0 6 0 Heavy Rain Rainfall amounts along the western slope of the Cascade Mountains, northward from Pierce County to the Canadian border, ranged from 3 to 6 inches in 24 hours and from 4 to 9 inches in 48 hours. The heaviest rainfall was in the Skyhomish River drainage basin. Runoff from rain and melting snow in the higher elevations resulted in nearly all rivers in this area rising to above flood stage. Most of the same area was flooded during November. Highways were damaged, residences and other buildings in some localities were damaged by flood water, and several thousand acres of farm land was underwater. Rainfall amounts along the western slope of the Willapa Hills and Olympic Mountains ranged from 4 to 7 inches in 24 hours and from 5 to 8 inches in 48 hours. Minor flood damage occurred in several cities in western Washington as a result of heavy runoff from the hilly sections and clogged storm sewers and culverts. Numerous landslides occurred following this period of heavy precipitation. Highways, railroads, residences and other property was damaged by slides. An engine and several coaches of a passenger train were derailed and pushed into Puget Sound by a landslide north of Seattle.

JANUARY Extreme Precipitation Events Washington Cascades – 1948-2005

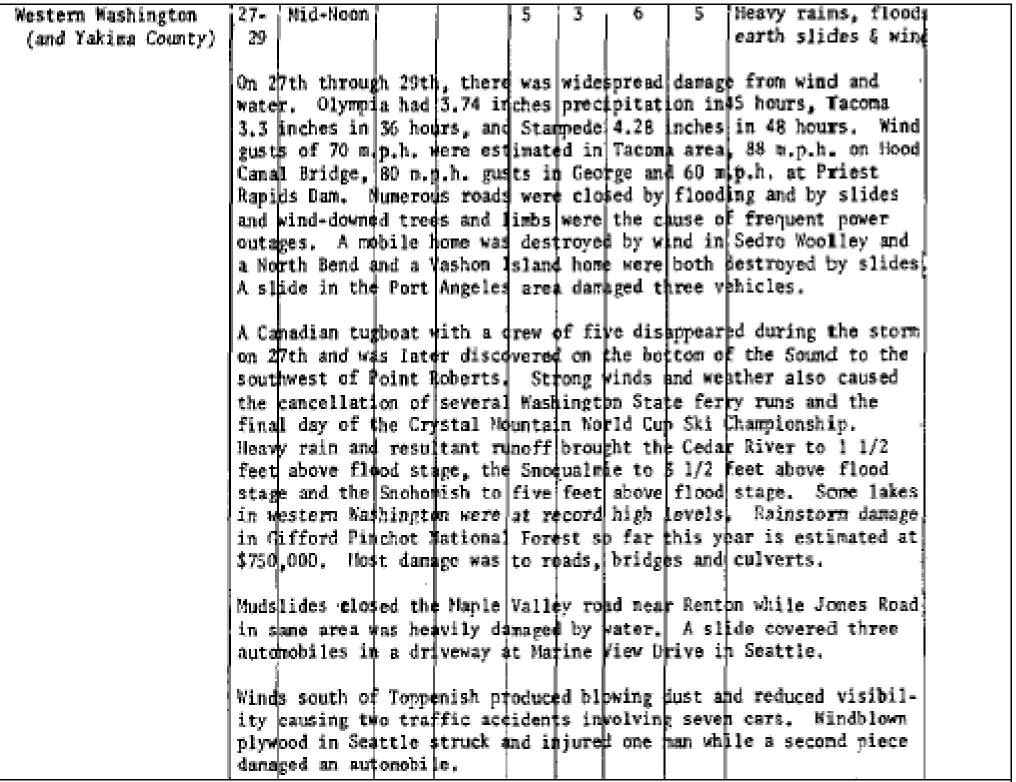
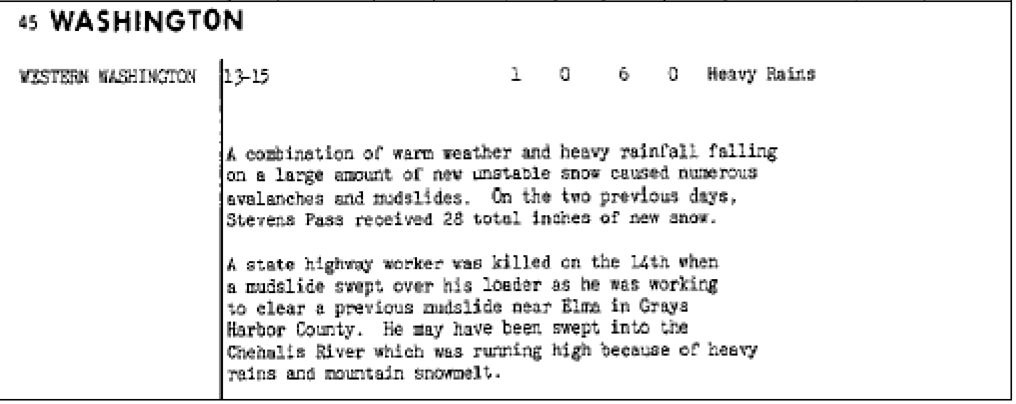
Storm Dates	Gage Location	Max. 3 day Precipitation	Mel Schaefer Report	In "Tropical Forcing" Paper	Storm Data
1/13/1974 – 1/15/1974	Baring	11.42	no	no	 Western 14-15 6 Wind, High Tide, Thaw Strong southerly winds swept many parts of western Washington. Wind speeds up to 60 mph were reported on the coast at Cape Disappointment and Cape Flattery. West Clallam County was without power for several hours on the 14th. Other areas hardest hit by power outages were Skagit, Mason and Grays Harbor counties. A combination of unusually high tides and winds caused light to serious damage to the mouth of the Stillaguamish River and around Camano Island. Southerly exposed beaches were battered by logs. Bulkheads in Kitsap Co. were also damaged. A 40-ft. stretch of Burlington Northern railroad bed between Everett and Marysville was washed out. Thawing ground and moderate rains caused some mud slides, road damage in the lowlands, while avalanches were reported in the Cascades.
1/13/1961 – 1/15/1961	Upper Baker	11.57	no	no	 Western 13-15 5 0 Heavy precipitation Heavy precipitation over the Olympic Peninsula and along the western slope of the Cascades resulted in flooding in the lower valleys in the northern Puget Sound area and over the Olympic Peninsula. 24-hr. precipitation amounts ranging from 5 to 9 inches were recorded in some localities. A railroad bridge over the Dungeness River was destroyed and highways were damaged in numerous areas by slides and high water. Several families in low areas were evacuated.
1/19/1972 – 1/21/1972	Petersons RA	10.81	no	no	 Southwestern Washington and Whitman and Asotin Counties 20-21 48 hrs. 6 4 Flood Heavy rain over western Washington and the southeastern portion of the State on January 20-21 brought many rivers to flood stage. Major flooding occurred in 9 counties of southwestern Washington and in Asotin and Whitman counties in eastern Washington. Total damages approached 4 million dollars. Highways were damaged by water and slides, homes and businesses flooded, bridges were washed out and roads and railroad right-of-ways destroyed. Many riverside parks were heavily damaged. Landslides destroyed two homes. Many vehicles and much merchandise were water damaged. There were no known deaths or injuries.

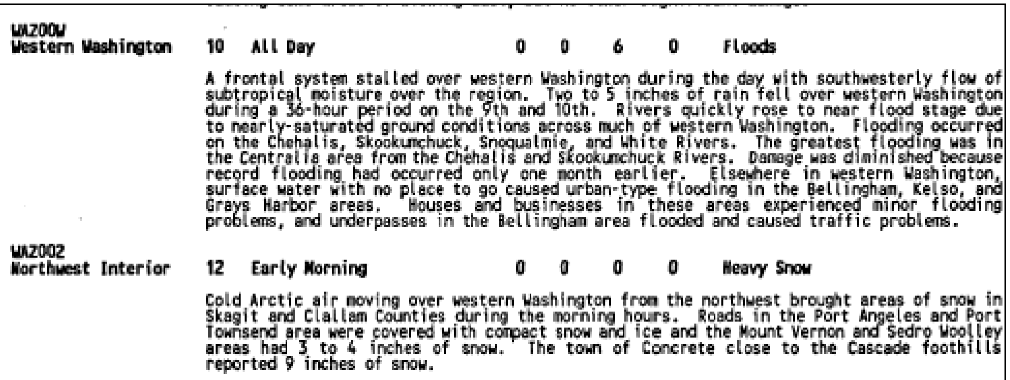
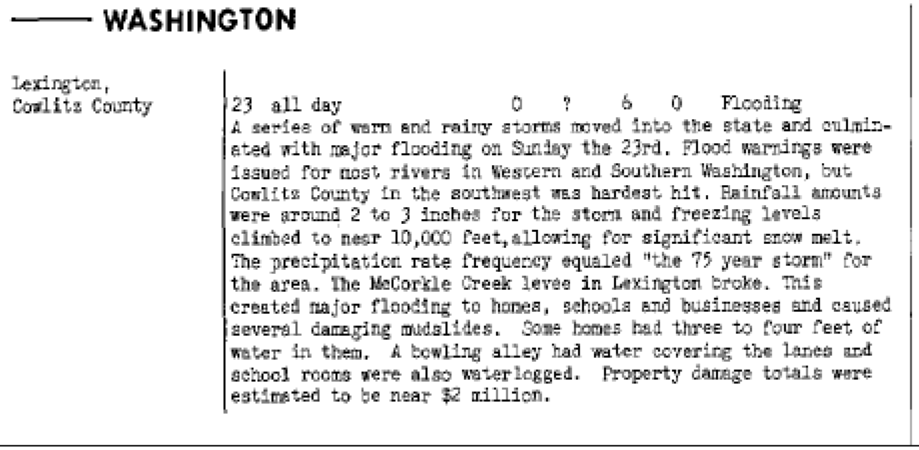
1/27/1965 – 1/29/1965	Snoqualmie Pass	10.02	yes	no	 WASHINGTON 1-2 Heavy snowfall and strong winds over most of the State. Snowfall was unusually heavy over the Olympic Peninsula, higher elevations of the Cascade Mountains and northern half of eastern Washington. In the Cascades, 44 inches of snowfall was recorded at Snoqualmie Pass and 45 inches at Stevens Pass in a 24-hour period. In northern half of eastern Washington, snowfall amounts ranged from 4 to 10 inches and almost all roads were blocked by drifting snow. Several communities were isolated for one to three days. 26 to 31 2 6 Rising temperatures, heavy rainfall and rapidly melting snow over western Washington and the southern half of eastern Washington resulted in almost all rivers rising above flood stage. The freezing level reached 4000 to 6000 feet above sea level. Along the western slope of the Cascade Range, rainfall totals over a 5-day period ranged from 6 to 10 inches. Flooding along small streams resulted in extensive damage to highways and bridges. Major rivers were 2 to 5 feet above flood stage. Mud and snow slides were numerous. Two persons were killed near Randle when their home was destroyed by a slide. East of the Cascades, rainfall was heavy over the Blue Mountain and Horse Heaven Hills areas. The Walla Walla, Touchet and Yakima rivers were above flood stage.
1/23/1982 – 1/25/1982	Lake Wenatch	11.57	yes	yes	 45 WASHINGTON 16 1100PST - - 1 0 0 0 High Winds Pierce Co. A Tacoma man drowned when his sailboat capsized in a race north of Commencement Bay. Statewide 23-25 - - 0 0 6 ? Heavy rains Warm temperatures combined with heavy rains to cause rises in rivers. Avalanches and mudslides also caused extensive damage. All three of the major Washington mountain passes that link the eastern and western parts of the state were closed by avalanches or mud slides during this period. The economic losses because of the closures are unknown. Interstate 90 over Snoqualmie Pass suffered extensive damage when a debris dam that formed along Olallie Creek gave way, sweeping across the highway. Some of the rocks dumped onto the highway were one foot in diameter and debris was heaped twenty feet deep in places. A waterfall twelve feet wide cascaded over the edge of the undermined pavement. It will cost $200,000 or more to repair. Numerous roads and bridges statewide were washed out or damaged during this period. Road repairs in Whatcom County alone may run as high as 1.4 million dollars. Larger rainfall amounts for the period included 8.8 inches on the Skykomish River, 5.9 inches at Snoqualmie Pass and 5.69 inches at Ross Dam.

1/16/1964 – 1/18/1964	Rainier Ohan	8.87	no	no	 **WASHINGTON** West of Cascades 16-17 Night 0 0 4 0 Wind Strong southwesterly winds occurred as weather disturbances from over the ocean moved inland during the early morning hours on the 16th and 17th. A combination of high tide and strong winds resulted in damage to waterfront property along some of the beach areas in Puget Sound. Entire State 19 0 0 5 0 Wind The most intense storm of this winter season moved across the State on the 19th. The center of the low pressure area moved eastward across southern British Columbia. Sea level pressure readings dropped to near the lowest on record. Winds over the northern half of western Washington reached velocities of 40 to 50 MPH with gusts of 60 to 75 MPH. Power and communication lines were down in many localities and property was damaged by falling trees. Several store windows in the Puget Sound area were broken by the high wind. East of the Cascades, wind velocities were less, however, some property damage was reported.

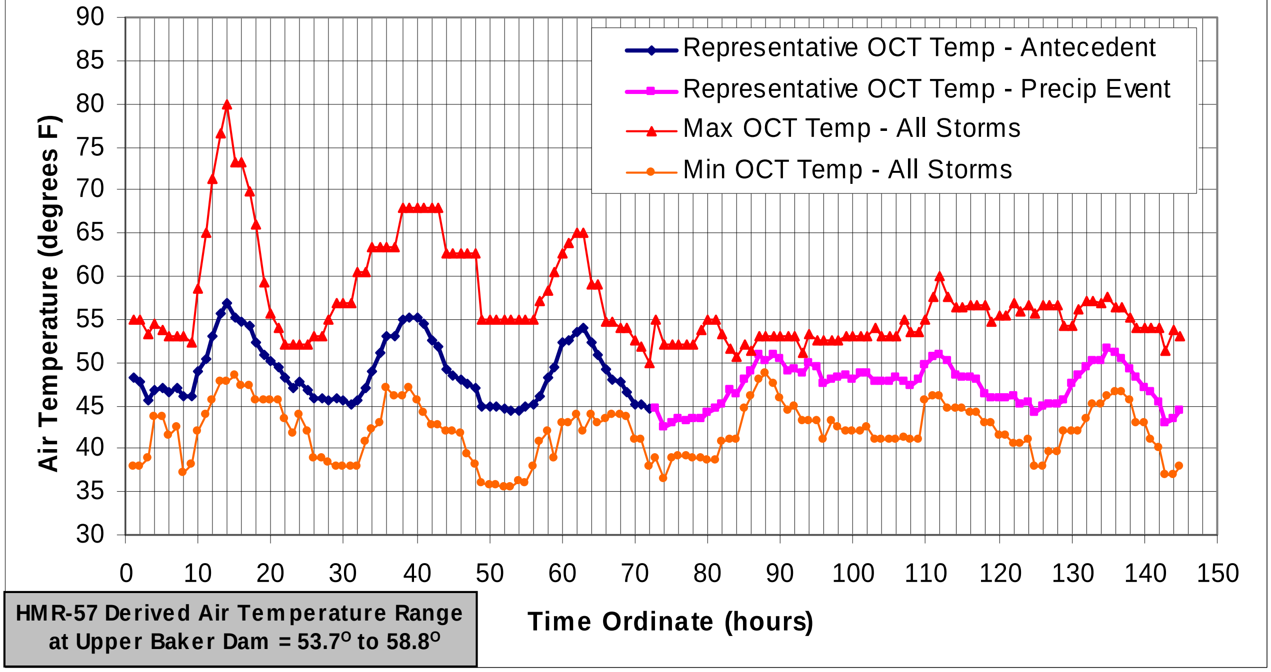
Back Up Event					
1/17/1968 – 1/19/1968	Grotto	7.38	no	yes	 Washington No report received by printing deadline Precipitation was unusually heavy over the Olympic Peninsula and near or slightly above normal in most other localities of western Washington. The heaviest precipitation occurred between the 17th and 20th. In the rainforest area along the windward slopes of the Olympic Mountains, Quillayute reported 7.16 inches of rainfall in 24 hours, Aberdeen 20 NNE 8.51 inches, and Quinault Ranger Station 11.83 inches. Four-day totals in this area ranged from 14 to 17 inches. The western slope of the northern Cascades received 5 to 8 inches of rain during this period. In eastern Washington, precipitation totals for the month were mostly above normal along the eastern slope of the Cascades and near normal in FLOODS: In western Washington, runoff from heavy rainfall and melting snow on the higher slopes of the mountains between the 17th and 20th resulted in rivers on the Olympic Peninsula and western slope of the northern Cascades rising above flood stage. Streams on the Olympic Peninsula were unusually high; however, damage was confined mostly to roads with water reaching a few homes and business establishments in lowland areas. In the lowlands east of Puget Sound, the Skagit, Snoqualmie, and Snohomish Rivers crested 2 to 5 feet above flood stage. Flood damage was comparatively small in most areas.

FEBRUARY Extreme Precipitation Events Washington Cascades – 1948-2005					
Storm Dates	Gage Location	Max. 3 day Precipitation	Mel Schaefer Report	In "Tropical Forcing" Paper	Storm Data
2/8/1996 – 2/10/1996	Cougar 4 SW	13.30	no	yes	**Flood 0 0 07 0000PST** **East Slopes Cascades** Some of the worst flooding in over 60 years took place in Washington from the 7th to the 10th. Damage statewide was estimated at 223 million. In the state the flooding destroyed 100 houses, 400 mobile homes, 7 apt buildings. There was major damage to 795 houses, 507 mobile homes and 115 apartment buildings. Minor damage affected nearly 2000 more residences. Record flooding occurred on several rivers. The Chehalis crested at 74.4 ft nearly 10 ft over flood stage. The Yakima was at 20.8 ft, second all time highest. Cowlitz crested at 32.1 ft, which is about 9 ft above flood stage. The Klickitat was around 18 ft with the old record being almost 17 ft. A state of emergency was declared in 13 counties. Flooding also occurred on the Nisqually, Skookumchuck, Stillaguamish, Skagit, Lewis, Snoqualmie, and Skykomish. In Klickitat County 2000 residents were stranded as all rivers, streams, creeks and ditches were flooded. It was the second largest flood there since 1908. On the east slopes of the cascades all schools were closed on Feb 9th as scores of bridges and 100s of roads were wiped out. I-90 and US 2, both major highways over the Cascades, were closed. It was the second longest closure of Snoqualmie Pass. I-5 was closed at Chehalis as there was 6 to 8 feet over water over the highway. The first 8 days of February had 5 times the normal rainfall. Some 24 hr rainfall amounts: Kent 4.4", Centralia 3.34", Seatac 3.06", Duvall 2.90", Olympia 2.75". Overall it was the wettest winter season ever. The normal precip for Nov-Feb is 21.11 inches the previous record was 30.68" and this year seatac recieved 32.46 inches.
2/21/2002 – 2/23/2002	Upper Baker	10.82	no	no	**Flood 2K 0 0 22 1400PST 2200PST** **WASHINGTON, Northwest** **WAZ005 Northwest Interior** The Stillaguamish reached its highest flood stage in years, flooding several major roads and a couple of neighborhoods.

2/27/1972 – 2/29/1972	Baring	12.21	no	no	 Western Washington (and Yakima County) 27-29 Mid-Noon 5 3 6 5 Heavy rains, flood earth slides & win On 27th through 29th, there was widespread damage from wind and water. Olympia had 3.74 inches precipitation in 45 hours, Tacoma 3.3 inches in 36 hours, and Stampede 4.28 inches in 48 hours. Wind gusts of 70 m.p.h. were estimated in Tacoma area, 88 m.p.h. on Hood Canal Bridge, 80 m.p.h. gusts in George and 60 m.p.h. at Priest Rapids Dam. Numerous roads were closed by flooding and by slides and wind-downed trees and limbs were the cause of frequent power outages. A mobile home was destroyed by wind in Sedro Woolley and a North Bend and a Vashon Island home were both destroyed by slides. A slide in the Port Angeles area damaged three vehicles. A Canadian tugboat with a crew of five disappeared during the storm on 27th and was later discovered on the bottom of the Sound to the southwest of Point Roberts. Strong winds and weather also caused the cancellation of several Washington State ferry runs and the final day of the Crystal Mountain World Cup Ski Championship. Heavy rain and resultant runoff brought the Cedar River to 1 1/2 feet above flood stage, the Snoqualmie to 3 1/2 feet above flood stage and the Snohomish to five feet above flood stage. Some lakes in western Washington were at record high levels. Rainstorm damage in Gifford Pinchot National Forest so far this year is estimated at $750,000. Most damage was to roads, bridges and culverts. Mudslides closed the Maple Valley road near Renton while Jones Road in same area was heavily damaged by water. A slide covered three automobiles in a driveway at Marine View Drive in Seattle. Winds south of Toppenish produced blowing dust and reduced visibility causing two traffic accidents involving seven cars. Windblown plywood in Seattle struck and injured one man while a second piece damaged an automobile.
2/13/1982 – 2/15/1982	Baring	9.93	no	yes	 45 WASHINGTON WESTERN WASHINGTON 13-15 1 0 6 0 Heavy Rains A combination of warm weather and heavy rainfall falling on a large amount of new unstable snow caused numerous avalanches and mudslides. On the two previous days, Stevens Pass received 28 total inches of new snow. A state highway worker was killed on the 14th when a mudslide swept over his loader as he was working to clear a previous mudslide near Elma in Grays Harbor County. He may have been swept into the Chehalis River which was running high because of heavy rains and mountain snowmelt.

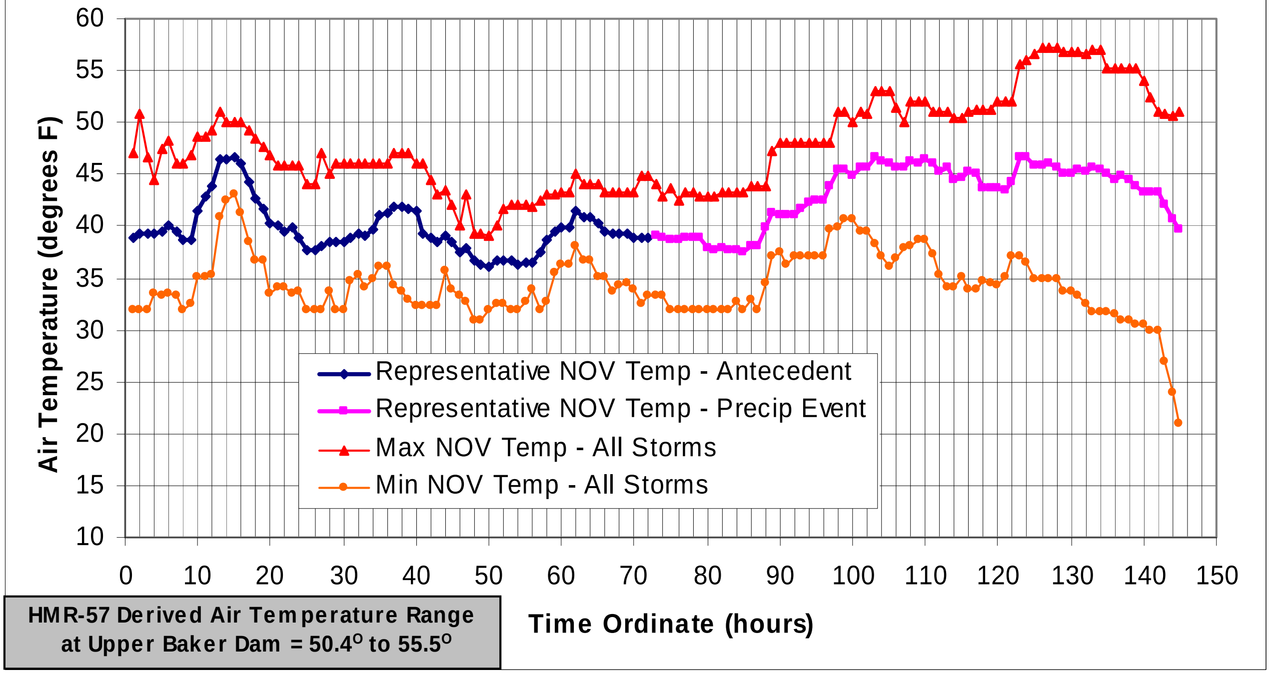
2/9/1990 – 2/11/1990	Nooksack Sal	9.70	no	no	**WA200W** **Western Washington** 10 All Day 0 0 6 0 Floods A frontal system stalled over western Washington during the day with southwesterly flow of subtropical moisture over the region. Two to 5 inches of rain fell over western Washington during a 36-hour period on the 9th and 10th. Rivers quickly rose to near flood stage due to nearly-saturated ground conditions across much of western Washington. Flooding occurred on the Chehalis, Skookumchuck, Snoqualmie, and White Rivers. The greatest flooding was in the Centralia area from the Chehalis and Skookumchuck Rivers. Damage was diminished because record flooding had occurred only one month earlier. Elsewhere in western Washington, surface water with no place to go caused urban-type flooding in the Bellingham, Kelso, and Grays Harbor areas. Houses and businesses in these areas experienced minor flooding problems, and underpasses in the Bellingham area flooded and caused traffic problems. **WA2002** **Northwest Interior** 12 Early Morning 0 0 0 0 Heavy Snow Cold Arctic air moving over western Washington from the northwest brought areas of snow in Skagit and Clallam Counties during the morning hours. Roads in the Port Angeles and Port Townsend area were covered with compact snow and ice and the Mount Vernon and Sedro Woolley areas had 3 to 4 inches of snow. The town of Concrete close to the Cascade foothills reported 9 inches of snow.
2/23/1986 – 2/25/1986	Marblemount	8.50	yes	no	**WASHINGTON** Lexington, Cowlitz County 23 all day 0 ? 6 0 Flooding A series of warm and rainy storms moved into the state and culminated with major flooding on Sunday the 23rd. Flood warnings were issued for most rivers in Western and Southern Washington, but Cowlitz County in the southwest was hardest hit. Rainfall amounts were around 2 to 3 inches for the storm and freezing levels climbed to near 10,000 feet,allowing for significant snow melt. The precipitation rate frequency equaled "the 75 year storm" for the area. The McCorkle Creek levee in Lexington broke. This created major flooding to homes, schools and businesses and caused several damaging mudslides. Some homes had three to four feet of water in them. A bowling alley had water covering the lanes and school rooms were also waterlogged. Property damage totals were estimated to be near $2 million.
Removed Storms					
2/10/1951 – 2/12/1951	Diablo Dam	12.58	yes	no	Not Available
2/6/1955 – 2/8/1955	Skykomish	9.75	no	no	Not Available

Representative OCTOBER Air Temperature Time Series
Upper Baker Dam

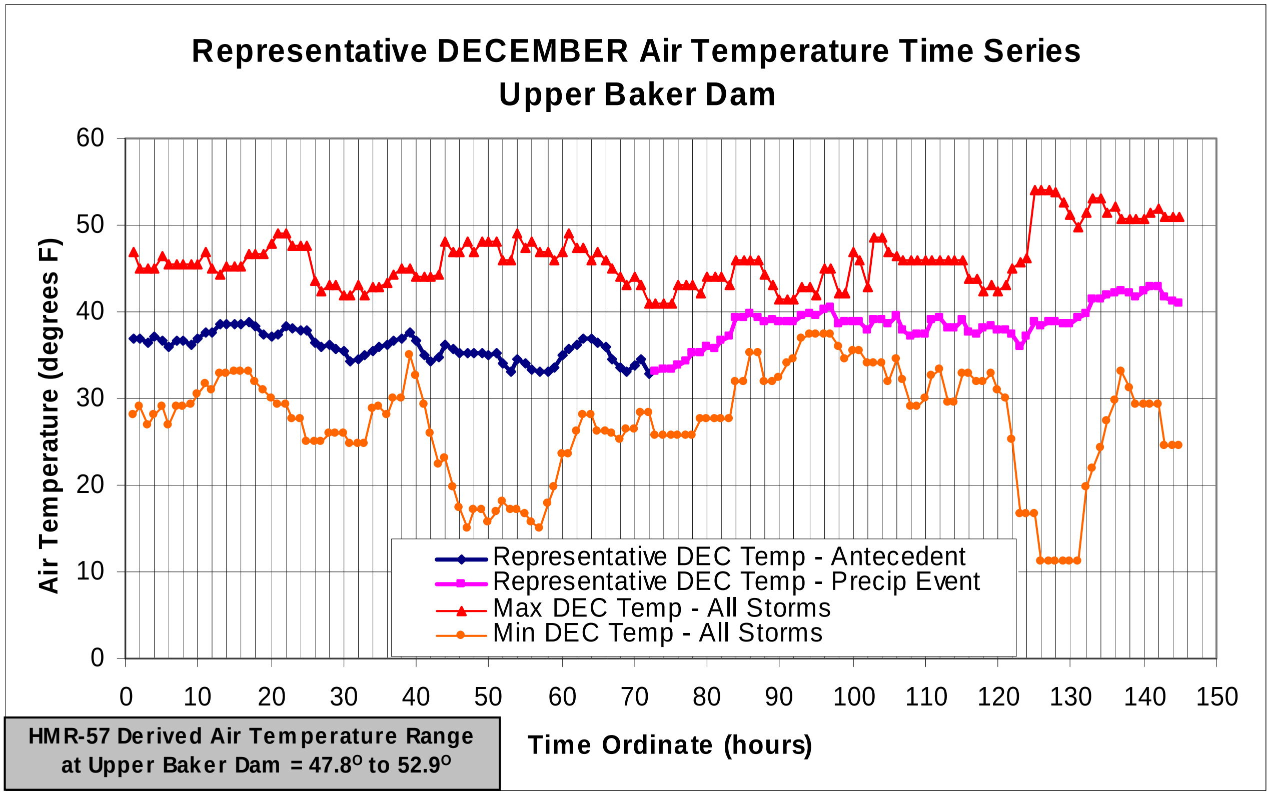


HMR-57 Derived Air Temperature Range at Upper Baker Dam = 53.7° to 58.8°

Representative NOVEMBER Air Temperature Time Series
at Upper Baker Dam

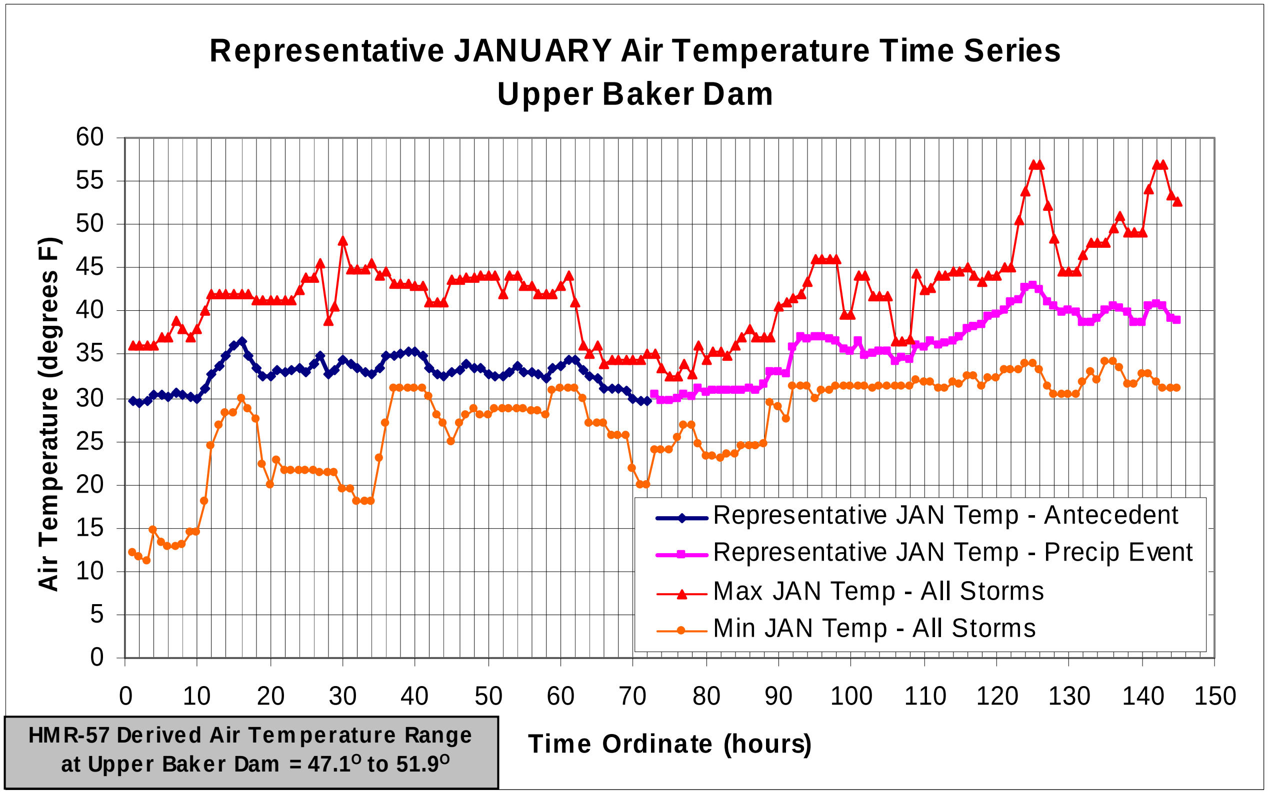


HMR-57 Derived Air Temperature Range at Upper Baker Dam = 50.4° to 55.5°



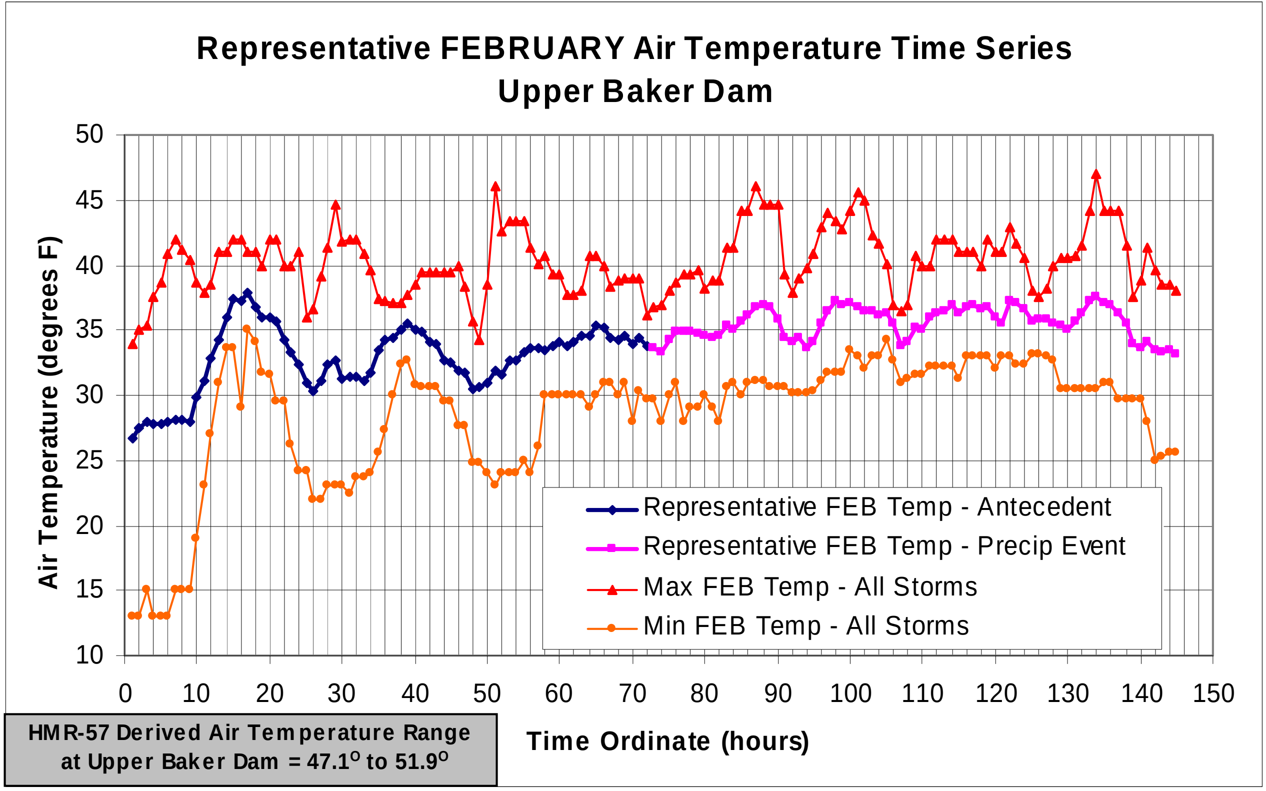
Representative DECEMBER Air Temperature Time Series
Upper Baker Dam

HMR-57 Derived Air Temperature Range
at Upper Baker Dam = 47.8° to 52.9°

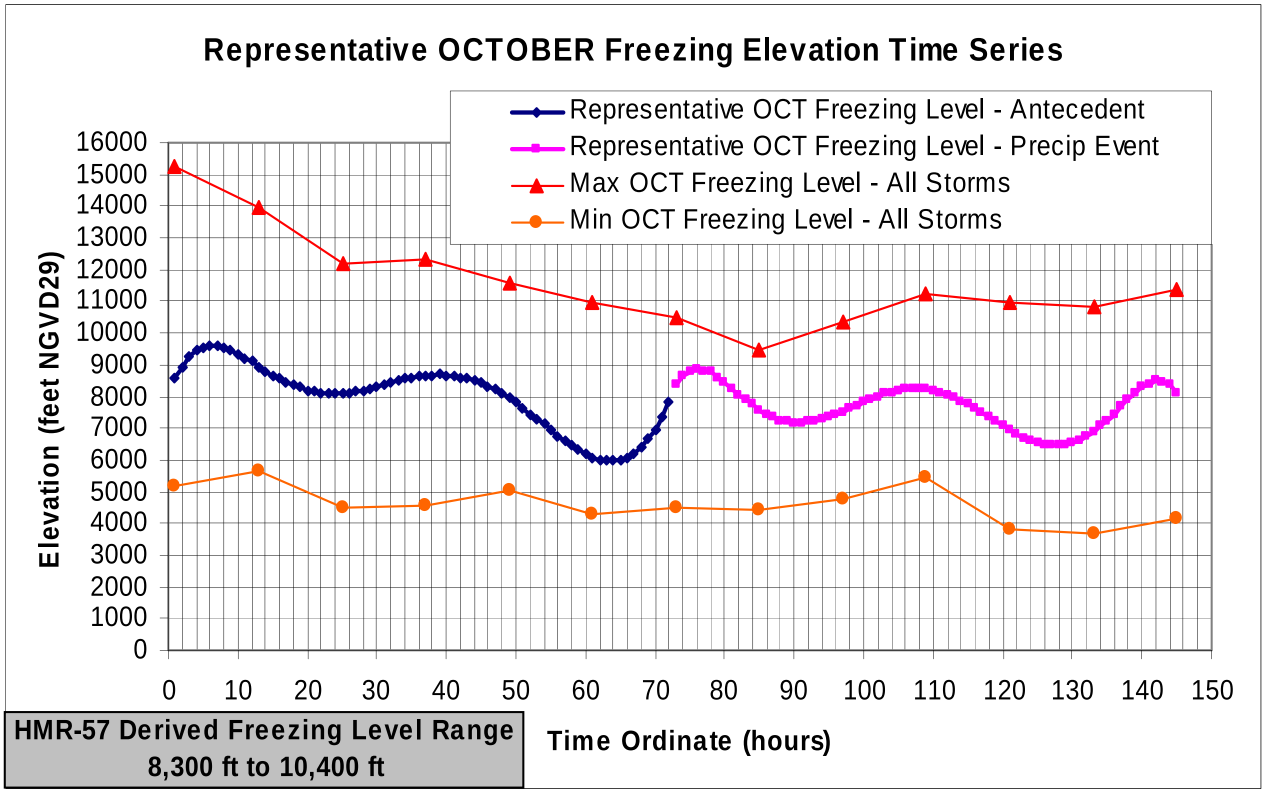


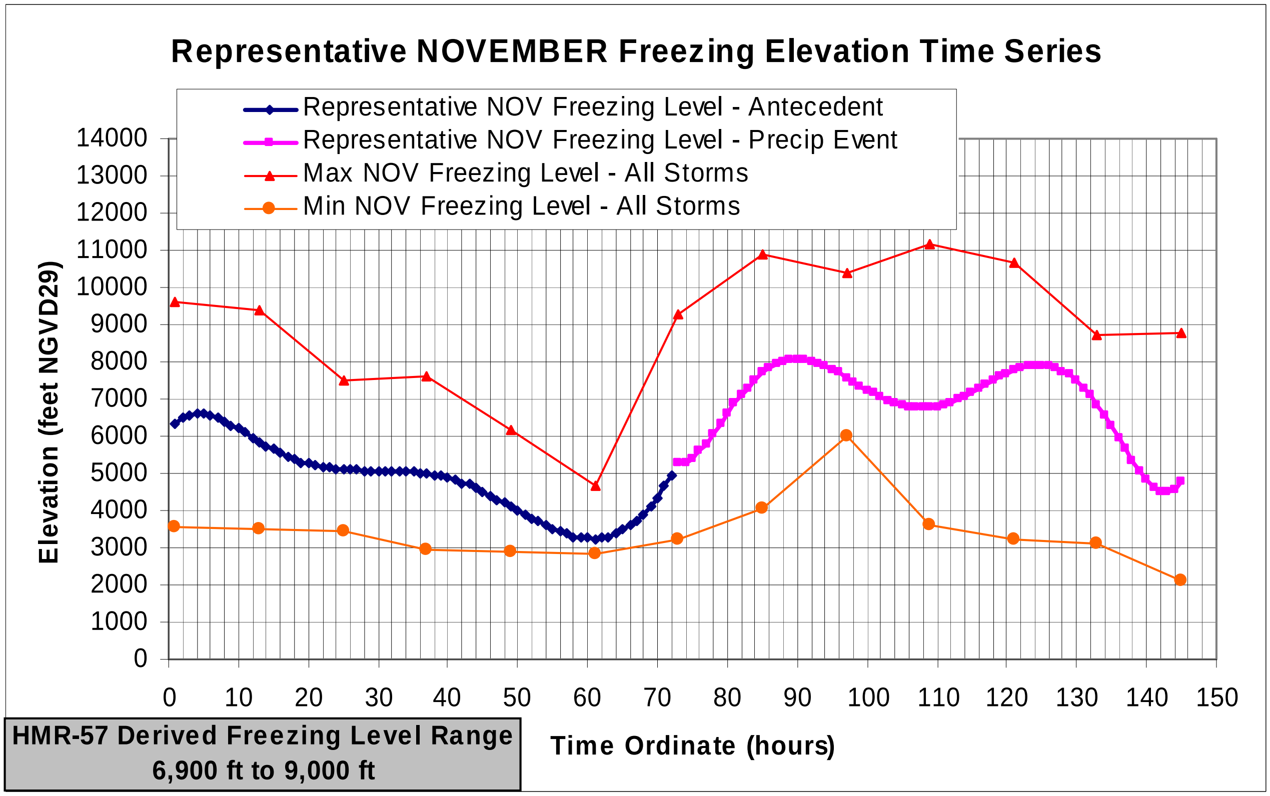
Representative JANUARY Air Temperature Time Series
Upper Baker Dam

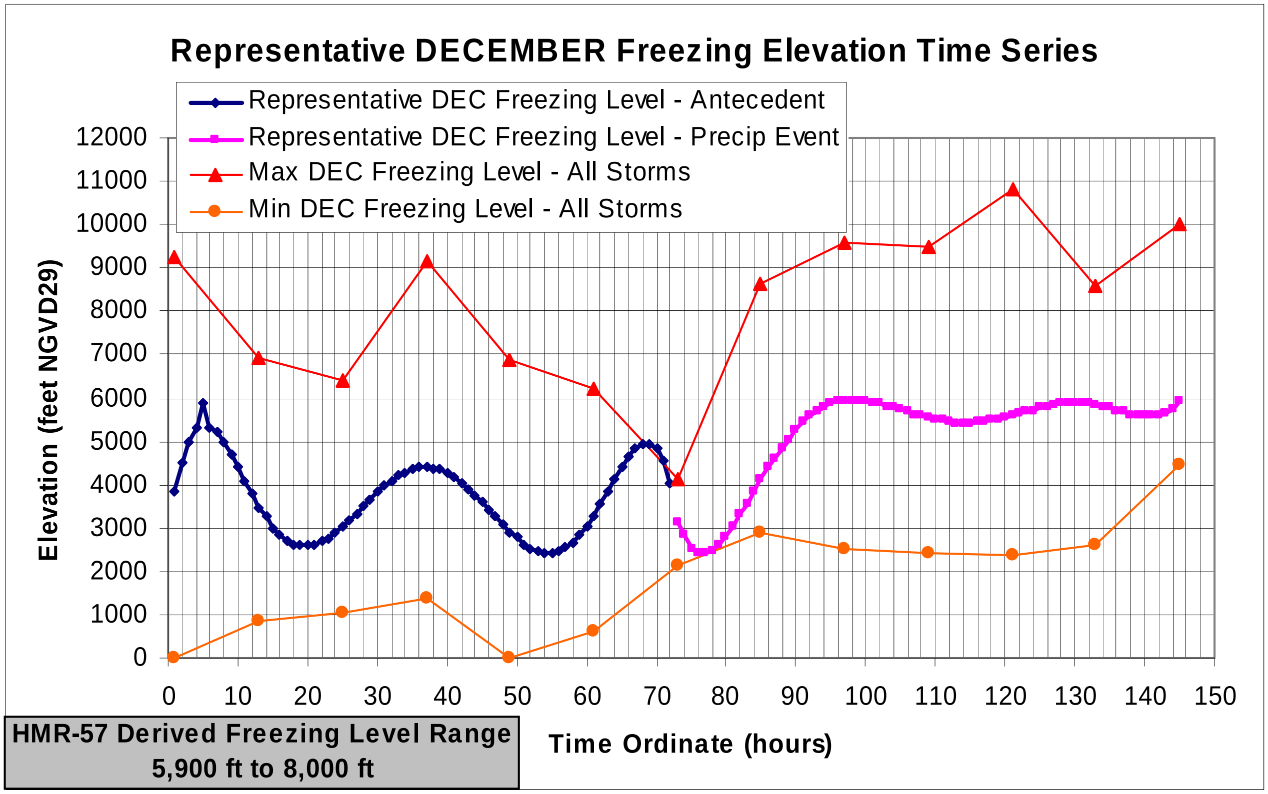
HMR-57 Derived Air Temperature Range
at Upper Baker Dam = 47.1° to 51.9°



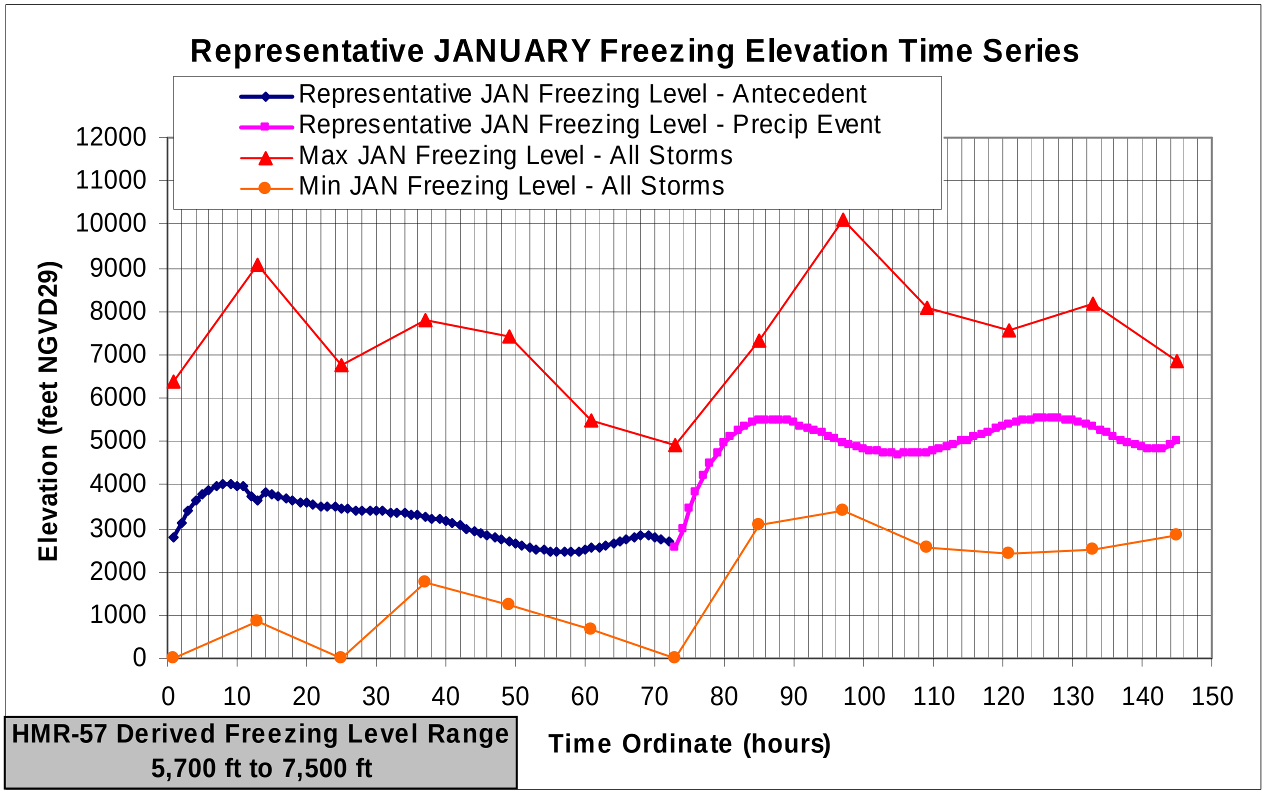
HMR-57 Derived Air Temperature Range at Upper Baker Dam = 47.1^{O} to 51.9^{O}


Representative OCTOBER Freezing Elevation Time Series
Representative OCT Freezing Level - Antecedent
Representative OCT Freezing Level - Precip Event
Max OCT Freezing Level - All Storms
Min OCT Freezing Level - All Storms
Elevation (feet NGVD29)
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time Ordinate (hours)
HMR-57 Derived Freezing Level Range
8,300 ft to 10,400 ft

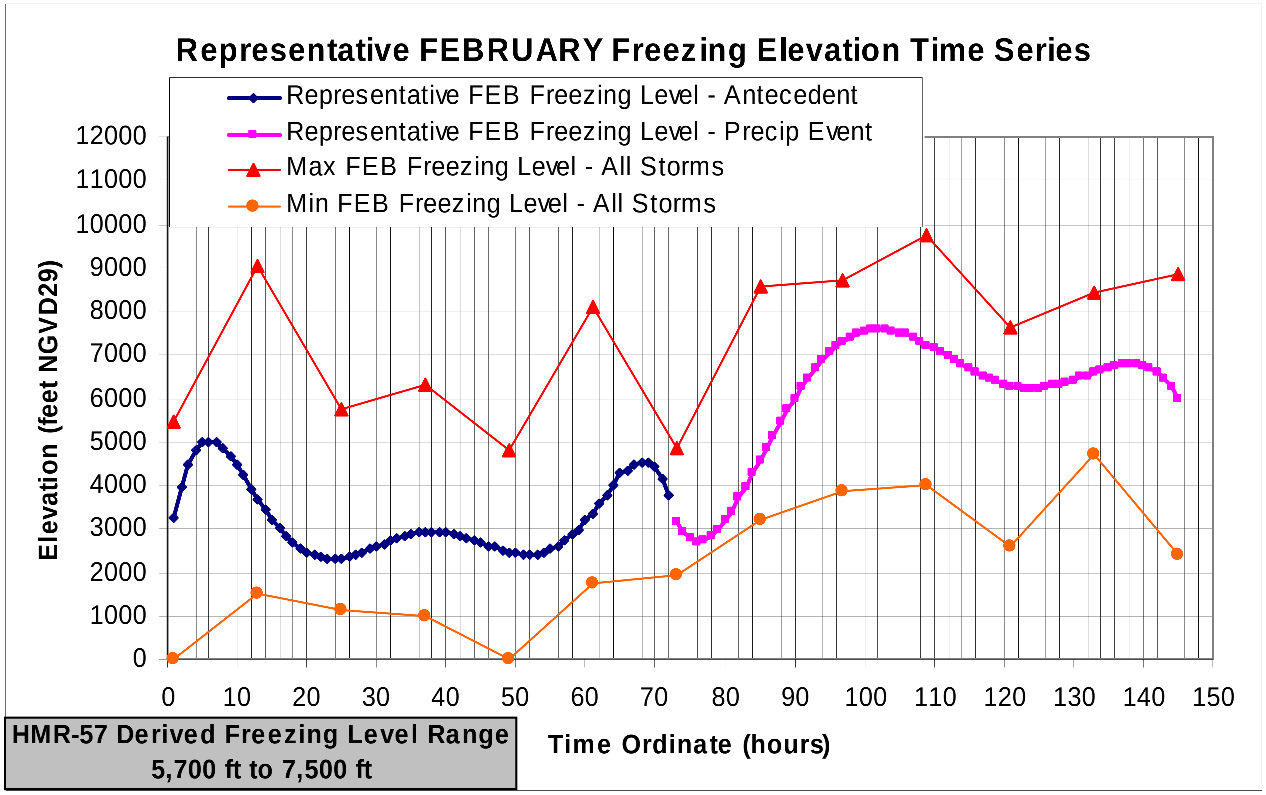

Representative NOVEMBER Freezing Elevation Time Series
Representative NOV Freezing Level - Antecedent
Representative NOV Freezing Level - Precip Event
Max NOV Freezing Level - All Storms
Min NOV Freezing Level - All Storms
Elevation (feet NGVD29)
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Time Ordinate (hours)
HMR-57 Derived Freezing Level Range
6,900 ft to 9,000 ft



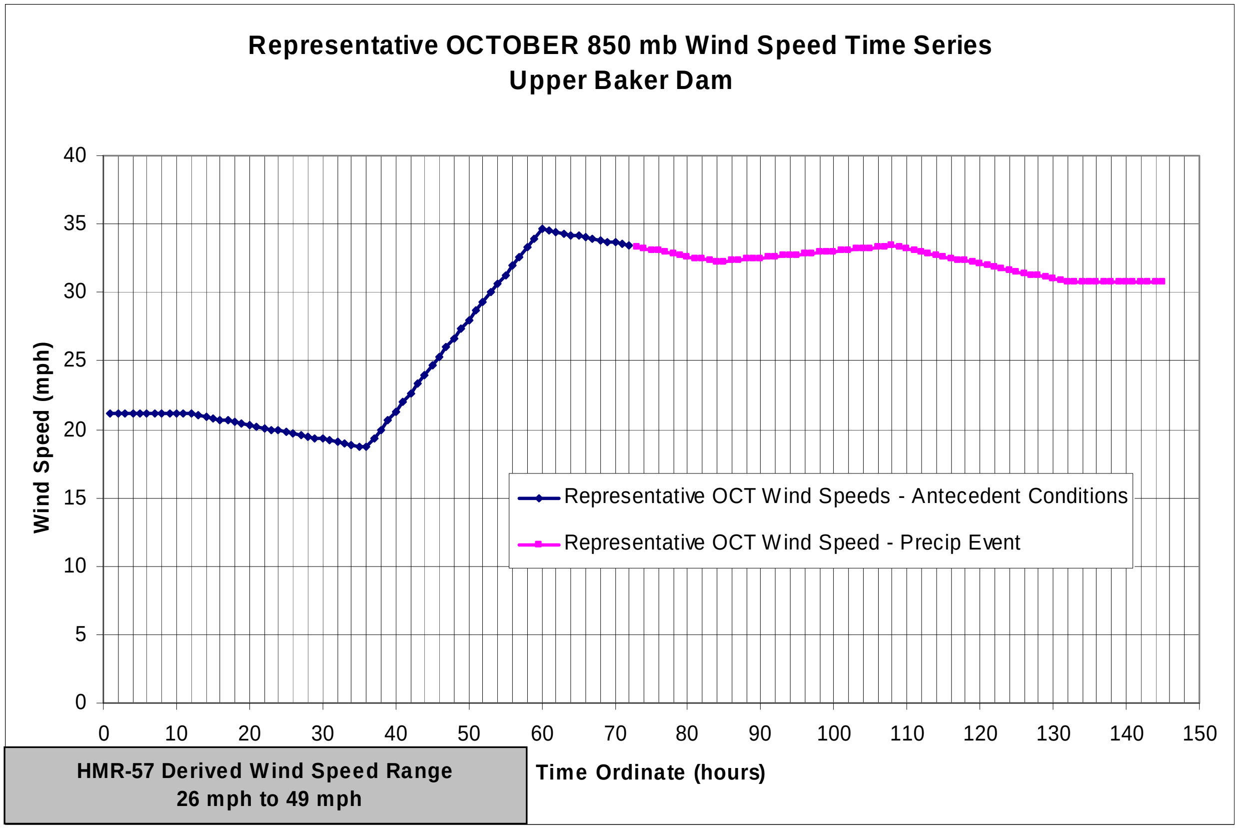
HMR-57 Derived Freezing Level Range
5,900 ft to 8,000 ft



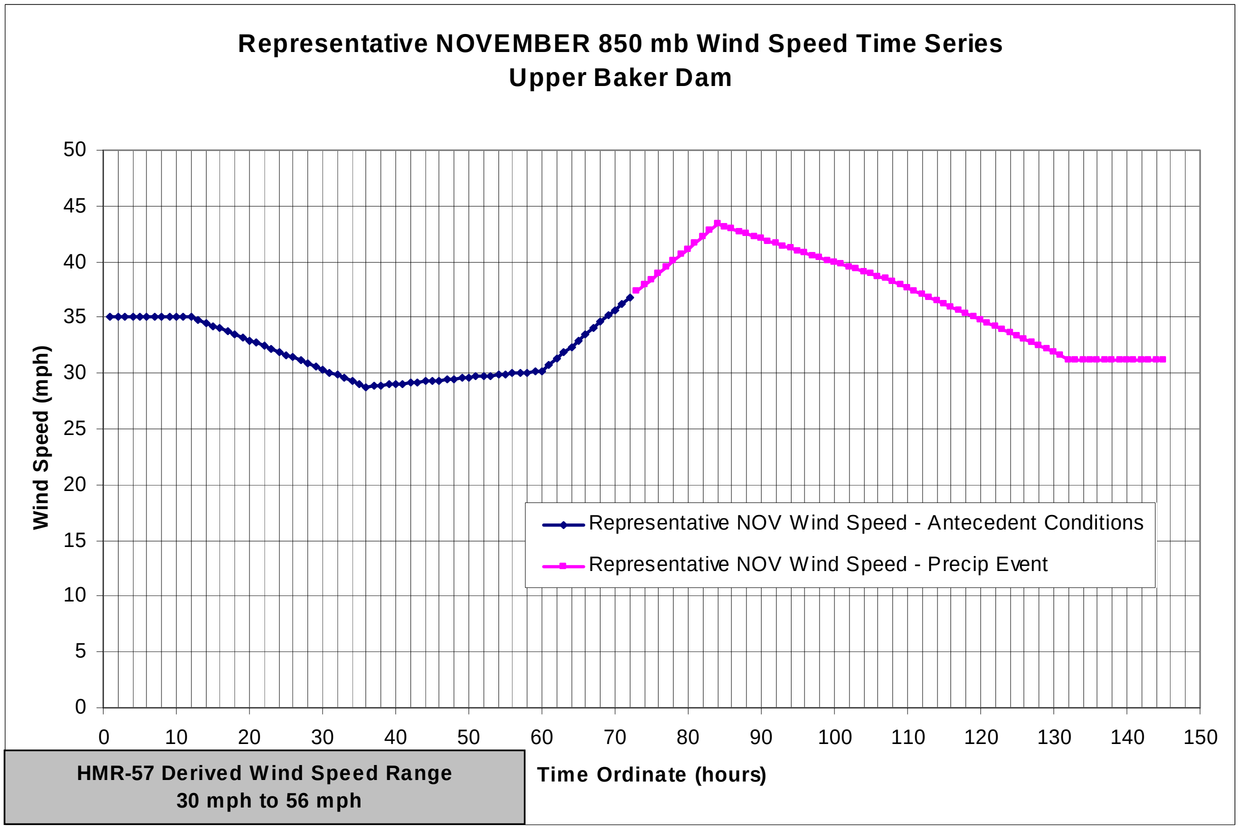
HMR-57 Derived Freezing Level Range
5,700 ft to 7,500 ft



HMR-57 Derived Freezing Level Range
5,700 ft to 7,500 ft

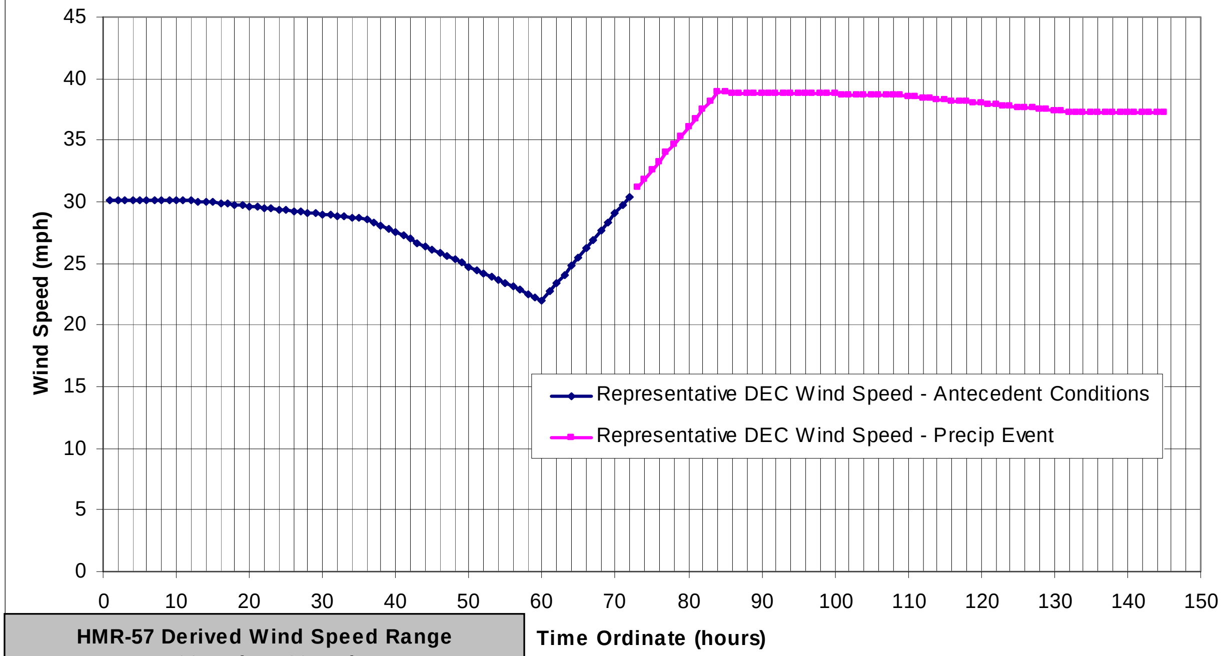

Representative OCTOBER 850 mb Wind Speed Time Series
Upper Baker Dam

HMR-57 Derived Wind Speed Range
26 mph to 49 mph


Representative NOVEMBER 850 mb Wind Speed Time Series
Upper Baker Dam

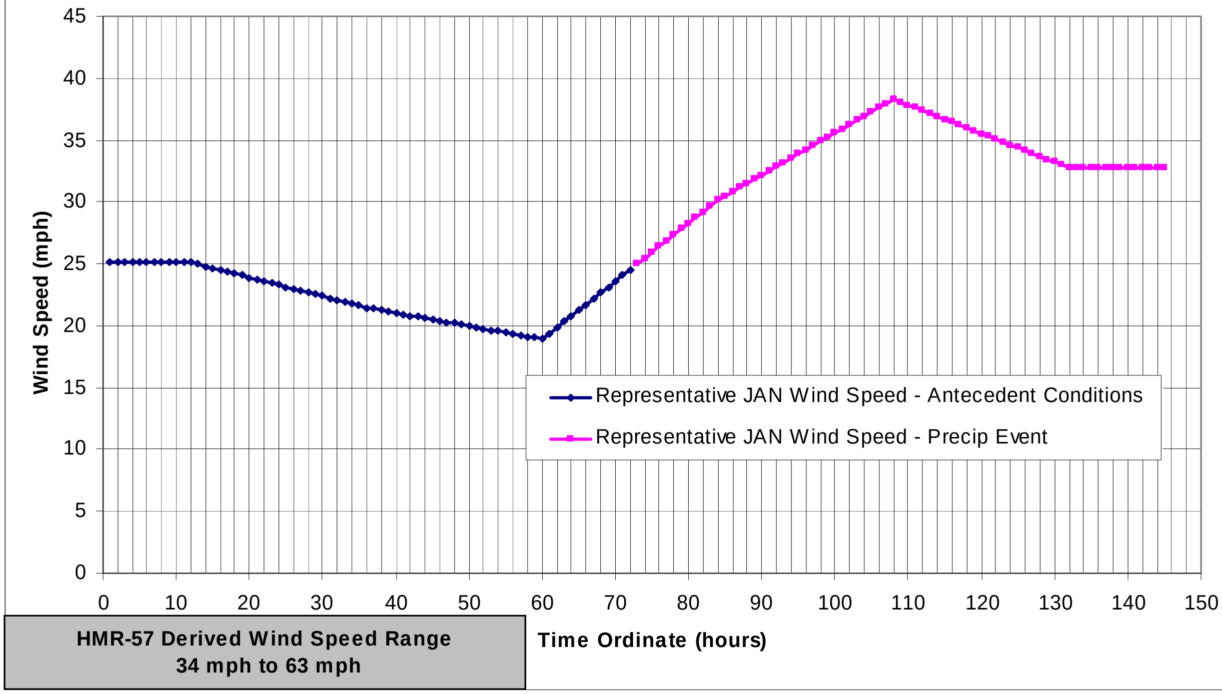
HMR-57 Derived Wind Speed Range
30 mph to 56 mph

Representative DECEMBER 850 mb Wind Speed Time Series
Upper Baker Dam

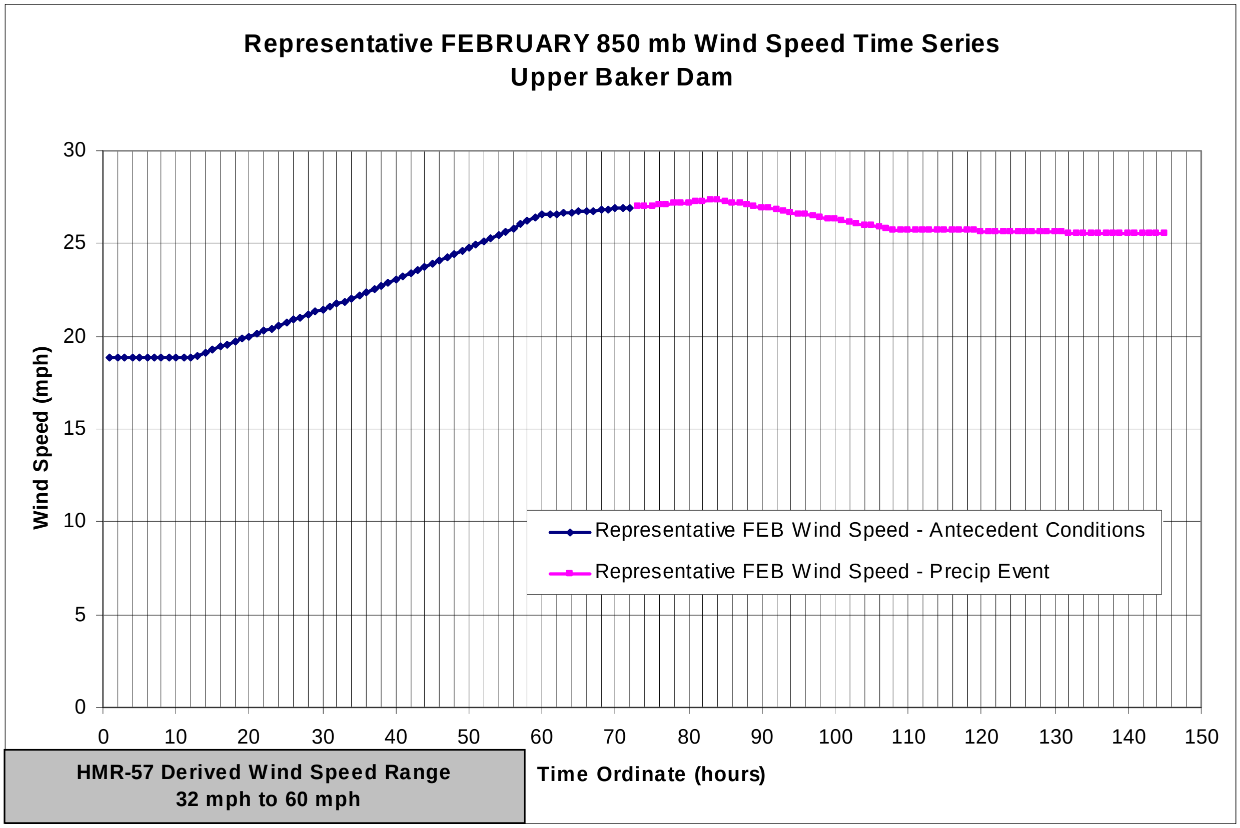


HMR-57 Derived Wind Speed Range
32 mph to 60 mph

Representative JANUARY 850 mb Wind Speed Time Series
Upper Baker Dam



HMR-57 Derived Wind Speed Range
34 mph to 63 mph


Representative FEBRUARY 850 mb Wind Speed Time Series
Upper Baker Dam
Wind Speed (mph)
0
5
10
15
20
25
30
Time Ordinate (hours)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Representative FEB Wind Speed - Antecedent Conditions
Representative FEB Wind Speed - Precip Event
HMR-57 Derived Wind Speed Range
32 mph to 60 mph