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

EXHIBIT C

DRAFT PROBABLE MAXIMUM FLOOD STUDY

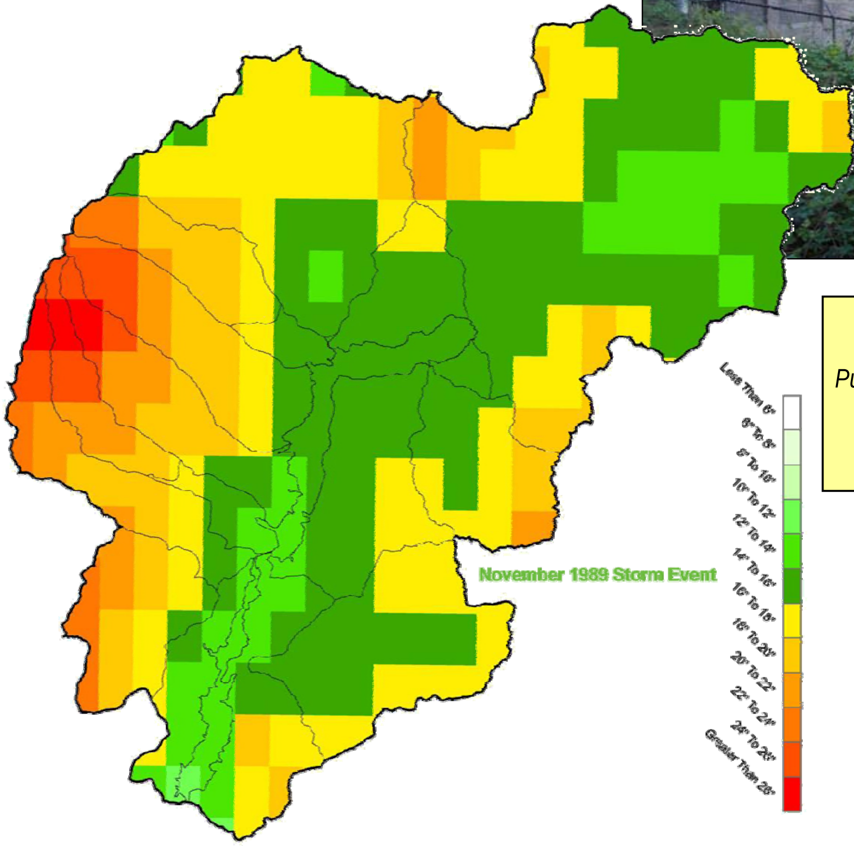
Puget Sound Energy

Baker River Project Part 12 Probable Maximum Flood Study

FERC Project No. 2150

Draft Final Report

December 2007



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Puget Sound Energy

BAKER RIVER PROJECT
PART 12 PROBABLE MAXIMUM FLOOD STUDY

DRAFT FINAL REPORT

DECEMBER 2007

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On the Cover:
Upper Baker Dam (top right); Lower Baker Dam (center); Spatial Distribution of Rainfall for November 1989 Storm Event (bottom left)

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EXECUTIVE SUMMARY

This report presents the findings of a study to update the estimated probable maximum flood (PMF) for Puget Sound Energy's (PSE's) Baker River Hydroelectric Project, using the National Weather Service published Hydrometeorological Report No. 57 (HMR 57), *Probable Maximum Precipitation—Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages* (NWS 1994). The study was conducted under review guidance of Federal Energy Regulatory Commission (FERC) staff and a FERC-approved Board of Consultants.

The primary drivers for this PMF update were recommendations made in the April 4, 2004 Baker River Project Potential Failure Modes Analysis (PFMA) session and subsequently in the Independent Consultant's October 2004 reports (MWH 2004a and MWH 2004b). These recommendations were documented in a letter to Puget Sound Energy (PSE) from FERC (FERC 2004). In this letter, it is stated that "… the Probable Maximum Flood (PMF) study requires updating utilizing current state-of-the-practice analysis methods, the latest Hydrometeorological Report (HMR), and the most recent version of the Division of Dam Safety and Inspections Engineering Guidelines."

The previous PMF study for the Baker River Project was conducted by Hydrocomp International in 1969 (Hydrocomp 1969), which estimated the probably maximum precipitation (PMP) using the National Weather Service's Hydrometeorological Report No. 43 (HMR 43), *Probable Maximum Precipitation for the Pacific Northwest (*NWS 1966). HMR 57 incorporates new storm data and improved analytical procedures for estimating PMP in regions where local climate conditions are influenced by mountainous terrain (known as orographically influenced climate conditions).

PROJECT DESCRIPTION

Unless otherwise noted, all elevations in this report are relative to the NAVD88 geodetic datum. The Baker River Hydroelectric Project is owned and operated by PSE. The project consists of two developments on the Baker River, a tributary to the Skagit River:

- The Lower Baker Development (Figure ES-1) was constructed between April 1924 and November 1925, 1.2 miles upriver of the Baker River's confluence with the Skagit River. It consists of a 285-foot-high, 550-foot-long concrete arch dam (Lower Baker Dam), a reinforced concrete powerhouse structure, a concrete surge tank and facilities for collecting and transporting migratory fish. The dam impounds the 7-mile long Lake Shannon. At the normal full-pool elevation of 442.35 feet (NAVD88), Lake Shannon has a surface area of 2,278 acres and a total volume of 146,279 acre-feet.
- The Upper Baker Development (Figure ES-2) is 9.35 miles upriver of the confluence and was constructed between June 1956 and October 1959. It consists of a 312-foot-high, 1,200-foot-long concrete gravity dam (Upper Baker Dam), an adjacent dike that closes off a low saddle in the topography (West Pass Dike), and a water recovery system that pumps seepage water back into the reservoir (Depression Lake). The dam impounds the 9-mile long Baker Lake. At the normal full-pool elevation of 727.77 feet (NAVD88), Baker Lake has a surface area of 4,980 acres and a total volume of 274,202 acre-feet.

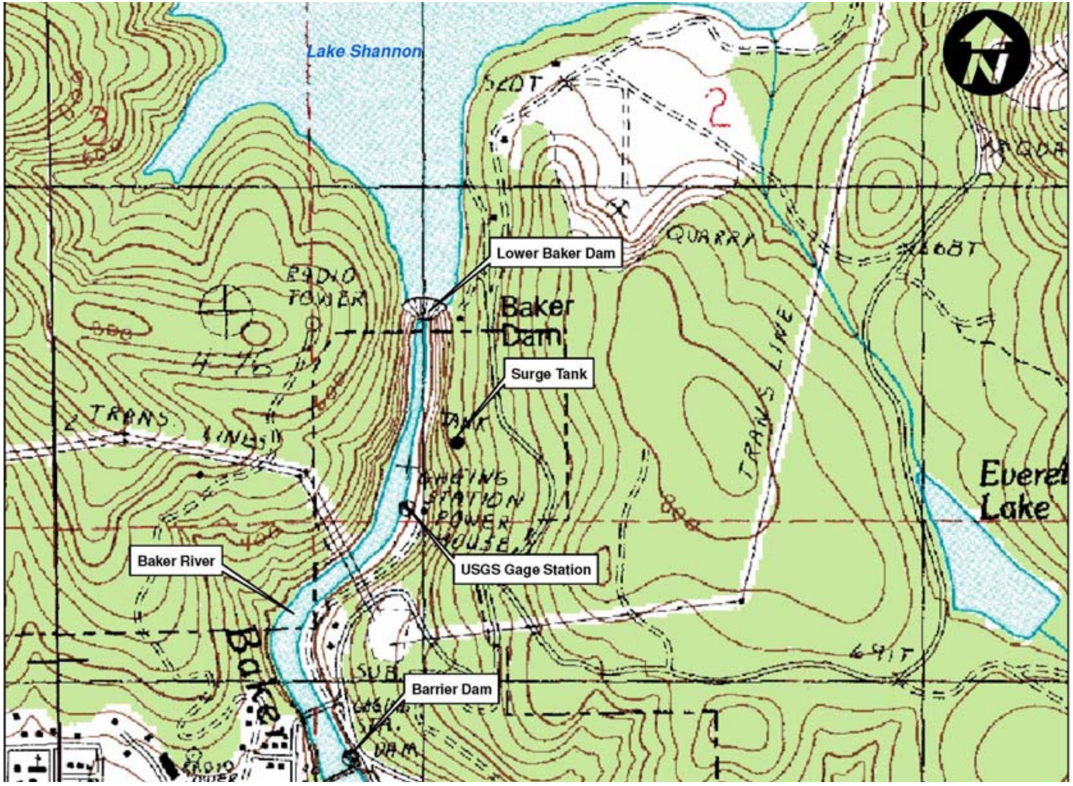

Figure ES-1. Location of Facilities at Lower Baker Development

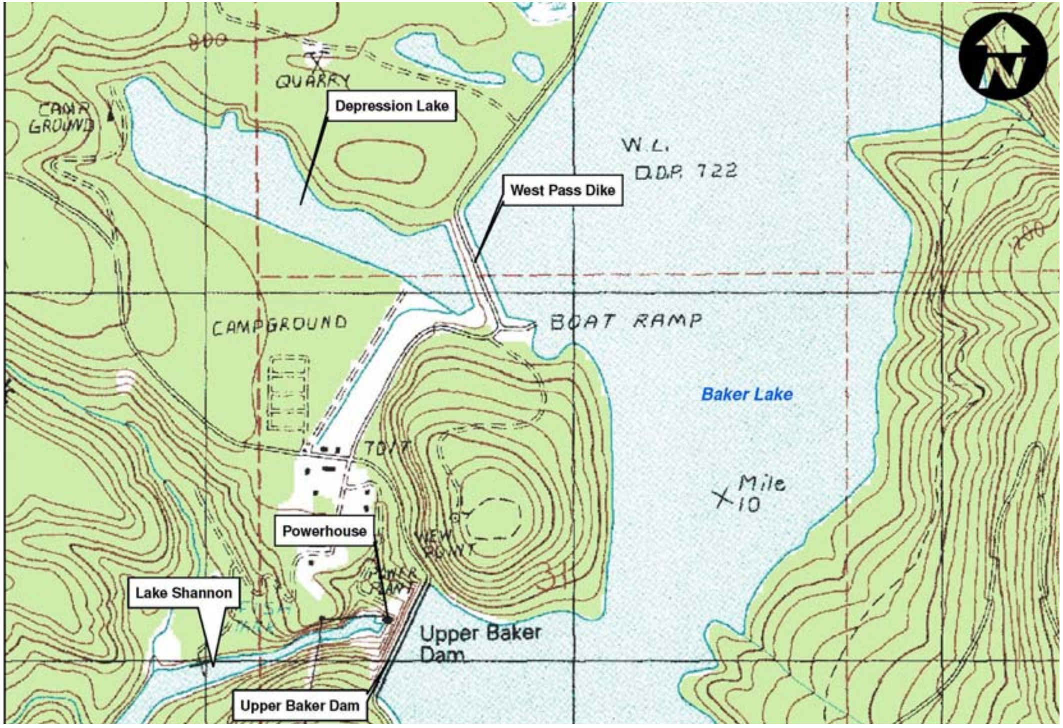

Figure ES-2. Location of Facilities at Upper Baker Development

The Baker River Project is operated to provide for hydroelectric power generation, flood control, recreation and fisheries. Reservoir levels upstream of the two dams fluctuate seasonally to meet the project's objectives:

- During the November through March flood season, Upper Baker Dam is operated at the direction of the Seattle District United States Army Corps of Engineers (USACE) to allocate up to 74,000 acre-feet flood control volume according to the *Baker River Project Water Control Manual* (USACE 2000). The minimum flood control pool elevation of 711.57 feet (NAVD88) must be available by November 15 and must be maintained until March 1. There is no requirement under the current license for flood control storage at Lower Baker.

- Outside the flood control season, the project is operated to meet power, recreational, and fisheries demands. The goal for both reservoirs during this period is to remain as near as possible to the normal full-pool elevation, though in reality both facilities are operated such that the reservoir pool elevation is several feet lower than the normal full-pool level.

WATERSHED DESCRIPTION

The Baker River drains a 298.7-square-mile mountainous watershed. The drainage area above Upper Baker Dam is 214.8 square miles; Lower Baker Dam has a local tributary drainage area of 83.9 square miles. Figure ES-3 shows the Baker River watershed and its two tributary areas.

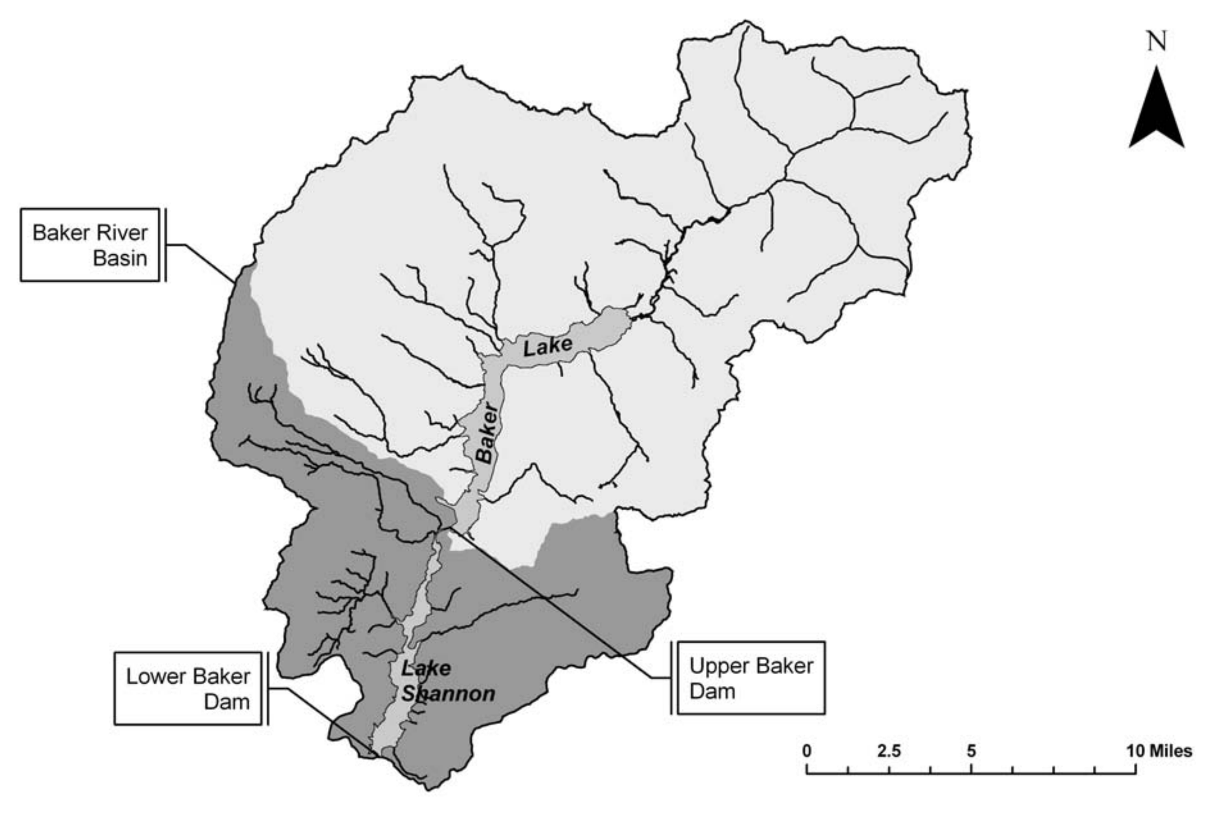

Figure ES-3. Baker River Watershed and Location of Upper Baker and Lower Baker Developments

Following are key features of the watershed relevant for this study:

- The watershed is mountainous, with extreme gradients and an elevation difference of nearly 10,500 feet. The elevation of the low point in the watershed is approximately 170 feet. The most prominent topographical features in the watershed are Mount Baker and Mount Shuksan, with peak elevations of 10,778 feet and 9,131 feet, respectively.
- Geology and soil conditions in the watershed are highly variable due to the influence of Mount Baker, the historical volcanic activity in the watershed, and the residual effects of glacial retreat. Much of the underlying bedrock is highly fractured and weathered and in some instances is extremely conducive to laterally conveying shallow subsurface flows that originate as precipitation in the higher elevations and discharge as springs or reappear as surface flows at the lower elevations.
- Approximately 85 percent of the basin is within Mt. Baker-Snoqualmie National Forest and in the North Cascades National Park. Private and state holdings account for the remainder.
- Over 70 percent of the basin consists of evergreen forest cover, nearly 5 percent is perennial snowfields and glaciers, and nearly 4 percent is the surface of Baker Lake and Lake Shannon.

The major factors that influence the climate in the watershed 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. The Pacific storm season begins in October, and November and December are the wettest months. Mean annual precipitation measured at a precipitation station near Lower Baker Dam is 68.21 inches. Further up in the watershed, the mean annual precipitation at a precipitation station near Upper Baker Dam is 99.63 inches. Snowfall can be extreme in the higher elevations, as evidenced by the world record for annual snowfall of 1,140 inches set on Mount Baker during the 1998-1999 season.

HYDROMETEOROLOGICAL DATA SOURCES

Stream flow and reservoir elevation data were available for this study from PSE records and from the U.S. Geologic Survey (USGS). PSE maintains hourly operation data for each dam, including forebay elevation, turbine discharge, and total spillway discharge. The USGS currently maintains and has historically maintained stream flow and reservoir gaging stations in the Baker River watershed and throughout the greater Skagit River basin.

Historical snowpack data is available primarily from snow course sites monitored by PSE and from Natural Resources Conservation Service (NRCS) SNOTEL sites. There are nine snow course sites in the Baker River watershed where end-of-month readings of snowpack depth are taken from December through May.

The following resources were used for obtaining precipitation data: Puget Sound Energy; National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS); Natural Resources Conservation Service. The only active, long-term hourly precipitation recording station in the Baker River basin is the NOAA station at Upper Baker Dam (Station 458715).

The following data sources were referenced for air temperature data: upper-air data published by NOAA (collected by radiosonde instrumentation mounted on weather balloons); twice-daily air temperature data from NOAA stations in the watershed; hourly air temperature data from NOAA stations outside the watershed.

HYDROLOGIC MODEL

Selection and Watershed Subdivisions

A hydrologic model of the Baker River basin was developed to simulate inflow hydrographs of runoff entering Baker Lake and Lake Shannon in response to extreme precipitation events, including the PMP. The overall model approach included the use of the following software:

- The Storm Precipitation Analysis System (SPAS) to distribute point rainfall measurements to a regularly spaced gridded field
- The Stochastic Event Flood Model (SEFM) to simulate snowpack melt and accumulation and the interflow component of the runoff hydrograph, and to stochastically generate input data for the HEC-1 model
- The U.S. Army Corps of Engineers Hydrologic Engineering Center's HEC-1 model to generate hydrographs from precipitation input
- The Hydrocomp Forecast and Analysis Modeling (HFAM) software to provide supplementary information regarding snowpack conditions.

For the modeling, the Upper Baker tributary area was divided into nine subbasins and the Lower Baker tributary area was divided into seven subbasins. The overall watershed was also divided into the following zones:

- Eight zones of mean annual precipitation
- Eight elevation zones to allow for spatial allocation of the snowpack and to allow for more accurate computation of snowmelt and snow accumulation.
- Ten soil zones, differentiated by soil and bedrock material.

ArcGIS was used to create 253 hydrologic runoff units (HRUs) from the intersections of the soil, elevation and mean annual precipitation zones. Each HRU represents a unique combination of soil type, elevation and mean annual precipitation. The subbasin delineations were then intersected with the HRU delineations, and subbasin-specific HRU area components were tabulated.

The study used the Holtan Loss equation for modeling surface infiltration. Snowmelt was computed in the SEFM using a form of the Bureau of Reclamation's Snow Compaction methodology (USBR 1966). This methodology uses empirical energy budget snowmelt equations similar to those included in HEC-1. A modified form of the Snyder synthetic unit hydrograph method was used for transformation of precipitation excess to surface runoff. Finally, interflow was simulated in the SEFM using a two-stage linear reservoir routing procedure.

Calibration And Verification

The hydrologic model was calibrated and verified by comparing hydrographs produced by the model to inflow hydrographs reconstructed from observed historical data for Baker Lake and Lake Shannon and inflow hydrographs from the Swift Creek and Park Creek USGS gaging stations.

Calibration Approach

Model calibration was conducted using the Generalized Likelihood Uncertainty Estimation (GLUE) procedure (Beven and Binley, 1992). The GLUE procedure allows for the recognition of multiple parameter sets that reasonably replicate the observed conditions, and assigns a likelihood to each parameter set based on an objective measure of the "goodness-of-fit" between the simulated results and the observed conditions (how well the simulated hydrograph matches the observed hydrograph).

The procedure is based on performing multi-thousand model runs with sets of parameter values chosen randomly from within specified parameter ranges. The results of each model run were evaluated using a quantitative measure of the goodness-of-fit between the observed and simulated runoff hydrographs. Parameter sets whose goodness-of-fit failed to achieve a pre-defined threshold value were eliminated, enabling the sampling range for each parameter to be reduced to a narrower range. This process was repeated until the evaluation of the goodness-of-fit could not justify any further narrowing of the sampling ranges. The final step of the calibration process was to generate multi-thousand input parameter sets based on sampling from the final narrowed sampling ranges, using a likelihood measure to identify "behavioral" parameter sets, and then ranking the behavioral parameter sets based on the likelihood measures. The ranked behavioral parameter sets formed the basis for identification of a final calibrated parameter set.

Model calibration and verification proceeded in five phases:

- **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

Storm Events Used for Model Calibration and Verification

Using precipitation data and reservoir inflow information, an analysis was performed to rank storm events since 1949 for use as calibration/verification events. The list was reviewed to ensure that events with the highest precipitation intensities and events that had potential snowmelt contribution to runoff were included at the top of the list. Based on this process, the following events were selected:

- November 8 – 12, 1989
- November 8 – 14, 1990
- November 26 – December 1, 1995
- October 14 – 19, 2003

Input Parameters

The key meteorological input parameters and the sources used to develop values for them were as follows:

- **Precipitation**—Hourly rainfall fields were developed from the precipitation data in and adjacent to the Baker River watershed using the SPAS software. When available, hourly NEXRAD maps were used to provide additional timing information for regions that lacked hourly data.
- **Air Temperature**—Time series of hourly temperatures at the Upper Baker Dam Station were developed from daily records and were supplemented with a known hourly temperature time series at a nearby reference station. Air temperature time series for each elevation zone were adjusted using lapse rates calculated from upper-air radiosonde data.
- **Antecedent Snowpack**—Snow water equivalent and snowpack density were exported from a previously calibrated HFAM model for the first day of each storm event. Using these values from

each of the seven snow course sites, relationships were developed between snow water equivalent, elevation and mean annual precipitation for each storm event used in the calibration.

Estimates of soil, unit hydrograph and interflow parameters are required to describe the hydrologic response of the watershed to each calibration event. The following input parameters were treated as variables in the GLUE calibration procedure, and uniform random sampling was used to search the parameter space of each variable:

- **Maximum soil moisture deficit (S_{max})** – this parameter is a function of the depth and available water capacity of the surface layer antecedent to the onset of precipitation.
- **Minimum infiltration rate (f_c)** – this parameter was assumed to be a function of the hydrologic soil class, and the initial sampling range was based on values published in Maidment (1993).
- **Deep percolation parameter (f_d)** – this parameter allocates runoff between groundwater and interflow and is a function of the bedrock material and texture.
- **Unit hydrograph period of rise (P_r)** – this parameter is a factor of the subbasin lag time, which is defined as the elapsed time from the centroid of the precipitation event that produces runoff to the occurrence of the peak discharge at the subbasin outlet.
- **Unit hydrograph peaking factor (C_p) –** values for this parameter were based on guidance presented in MGS (2004).
- **Upper zone and lower zone interflow storage constants (UZ and LZ) –** these parameters are used to account for the potentially long time delays in the interflow hydrograph attributed to the presence of glaciers, fractured bedrock, and deep volcanic geologic material.

Calibration and Verification Results

Successful aspects of the Baker River watershed model calibration included matching the timing of the hydrograph peaks, reproducing the recession limbs of the hydrographs, and reasonably reproducing the runoff volume. The simulated hydrographs resulted in runoff volumes that were within 15 percent of the observed runoff hydrographs, which is 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 controlling runoff volume in the model. The basin averaged value of the calibrated deep percolation rate was 0.094 in/hr.

The complicating influence of terrain on precipitation patterns in the watershed, combined with the fact that only a single hourly precipitation gage is available within the watershed, presented a challenge in accurately developing spatial and temporal precipitation input. The recorded hourly precipitation data at the only gage in the watershed, which is located at Upper Baker Dam (Elevation 690 feet), is more representative of the precipitation patterns in the lower watershed than in the upper watershed. This is on account of the fact that the gage is a relatively low elevation precipitation gage that is not affected by orographic influences.

The calibrated watershed model developed for the Baker River watershed reasonably replicates the observed runoff hydrographs produced by a set of extreme precipitation events.

RESERVOIR ROUTING MODEL

The Seattle District Corps of Engineers developed a HEC-5 model of the Skagit River basin that includes the Upper and Lower Baker Dams. For the Baker River Project PMF study, the Skagit River HEC-5 model was revised in two ways. The first revision was to update the spillway capacity rating curves based on more current topographic information at Lower Baker Dam, provided by PSE. The second revision was to modify the boundary conditions to include a coincident occurrence of a 500-year return period flood in the main stem Skagit River during the Baker River PMF simulations. The Seattle District provided the necessary inflow design hydrographs for this condition.

PROBABLE MAXIMUM PRECIPITATION

A probable maximum precipitation (PMP) estimate for the Baker River watershed, for input into the calibrated watershed model, was determined using the National Weather Service's *Hydrometeorological Report No. 57* (HMR 57), which defines probable maximum precipitation for the Pacific Northwest states (NWS 1994). HMR 57 recommends that both general and local storm values of PMP be calculated for drainages smaller than 500 square miles, such as the Baker River watershed. The larger of the two estimates is taken to represent the basin PMP.

General Storm PMP

General storm PMP estimates were developed for three storm-centering scenarios: centering over the entire 298.7-square-mile Baker River watershed; centering over the 214.8-square-mile Upper Baker tributary area; and centering over the 83.9-square-mile Lower Baker tributary area. Using procedures from HMR 57, all-season "index" PMP values were estimated for each storm-centering scenario and then adjusted as follows:

- Seasonal Adjustment—Seasonal index maps in HMR 57 were used to estimate seasonal average reduction factors for each month or sequence of months (October, November—February, March, April and May, June, July and August, and September). The seasonal reduction factors were then applied to the all-season index PMP estimate to obtain the seasonal index PMP estimates.
- Depth-Duration Adjustment—HMR 57 presents depth-duration ratios based on climatic subregions of the Pacific Northwest. The Baker River watershed lies within Climatic Subregion 4 (West of the Cascades—Orographic), and the ratios for that subregion were applied to the seasonally adjusted PMP values. Additional ratios for durations not included in HMR 57 were obtained from WDOE (1989).
- Areal Reduction—Areal reduction factors are a function of the size of the drainage area, the duration of the storm event, and whether the drainage area is located within an orographic or a non-orographic subregion. The Baker River watershed lies within an orographic subregion. The appropriate areal reduction factors were applied to the duration-adjusted index PMP values for each duration (1-, 2-, 3-, 6-, 9-, 12-, 24-, 36-, 48-, 60- and 72-hour).

Average seasonal PMP volumes were then computed for each subbasin in the Baker River watershed. Spatial distribution of PMP was determined using 100-year precipitation frequency maps from a study conducted for the Washington State Department of Transportation (Schaefer et al. 2006).

Temporal distributions of the PMP, which define the hour-by-hour intensity of rainfall over the course of the storm event, were developed using a frequency-based methodology presented in WDOE (1989). Three temporal patterns were initially considered in the analysis, the primary difference between them being the time of occurrence within the 72-hour general storm of the high-intensity 1-hour segment:

- High-intensity segment occurs at Hour 33 of elapsed time.
- High-intensity segment occurs at Hour 46 of elapsed time.
- High-intensity segment occurs at Hour 58 of elapsed time.

Local Storm PMP

Local storms are defined in HMR 57 as extreme rainfall events lasting up to 6 hours, covering areas up to 500 square miles, and often occurring independently of any strong wide-area weather feature. In Washington State, local storms are usually a warm-weather feature and are most often observed east of the Cascades (NWS 1994). Local storm PMP values and associated areal reduction factors were determined for the three storm-centering scenarios, as follows:

- Index PMP—HMR 57 gives the basin average, 1-hour duration, 1-square-mile local storm index PMP value as 5.0 inches.
- Adjustment for Duration— Adjustments to the index value for durations less than 1-hour and up to 6 hours, expressed as a percentage of the 1-hour index value, were obtained from HMR 57.
- Adjustment for Basin Area—Areal reduction factors for the total basin, the Upper Baker tributary area and the Lower Baker tributary area were obtained from the depth-area relation in HMR 57, and were applied to the duration-adjusted index values.

Spatial distribution of the local storm PMP was developed using the method presented in HMR 57. This method uses an idealized elliptical storm pattern to estimate the spatial distribution. The pattern is modified by reduction factors that account for reductions due to area and storm duration. The temporal distribution of the local storm was developed with the highest intensity 15-minute segment occurring in the first hour. As per NWS (1994), the subsequent 1-hour segments were arranged in a descending order.

Selection of General or Local Storm for PMF Analysis

Evaluation of the local storm as a PMF candidate was conducted with the conservative assumptions that all precipitation would be converted to runoff, that all runoff would instantaneously enter the reservoirs, and that there would be no releases from the dams during the storm event. For the Upper Baker tributary drainage, the local storm instantaneous runoff volume was computed to be 23,700 acre-feet. Assuming a full pool reservoir elevation of 727.77 feet (NAVD88), input of this runoff volume would cause Baker Lake to rise to elevation 732.43 feet (NAVD88), nearly 3.3 feet below the top of the dam.

Using the calibrated hydrologic model, inflow hydrographs for the general storm were developed for each month for the Upper Baker tributary area and the Lower Baker tributary area. The general storm category was capable of producing more severe conditions than the local storm condition. Therefore, the local storm was not considered any further in the analysis.

COINCIDENT AND ANTECEDENT CONDITIONS FOR INITIAL ANALYSIS

Antecedent and coincident hydrologic and meteorological conditions were developed for input into the watershed model for the initial analysis of the PMF as follows:

- Reservoir Elevation—It was assumed for the initial PMF analysis that the antecedent reservoir elevation (the elevation at the onset of the PMP event) at Upper Baker Dam would be equal to the minimum flood control pool elevation consistent with the flood control rule curve established by the U.S. Army Corps of Engineers. For Lower Baker, the reservoir was assumed to be operating at normal full pool elevation (442.35 feet NAVD88).
- Base flow—Average monthly flow, as recorded at the Baker River at Concrete Gage (USGS 12193500), was used as the base flow coincident with the occurrence of the PMP.
- Snowpack Density and Water Content—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 water content of the snowpack antecedent to the PMP event was determined

using an iterative execution of the hydrologic model to determine the most conservative conditions for each season.

- Antecedent Precipitation—Cumulative antecedent precipitation for the Baker River watershed was estimated using NOAA/NWS Upper Baker Dam precipitation station (Station 458715) data. These values were adjusted to the eight mean annual precipitation zones in the hydrologic model using a ratio of the mean annual precipitation for each zone to the mean annual precipitation at the Upper Baker precipitation gage.
- Air Temperature—Development of antecedent and coincident air temperature time series for the PMF was based on methodologies outlined in HMR 57 (NWS 1994).
- Wind Speed—Development of antecedent and coincident wind speed time series for the PMF was based on the methodologies outlined in HMR 57 (NWS 1994).

PROBABLE MAXIMUM FLOOD HYDROGRAPHS

The calibrated hydrologic model and the reservoir routing model were used to develop the PMF hydrographs for the Upper Baker and Lower Baker reservoirs using the PMP storm events and antecedent conditions described above. The analysis was conducted in three steps:

- Develop an initial estimate of the PMF using an approach that represents the most severe combination of meteorological and hydrologic conditions considered reasonably possible for the drainage basin.
- Perform a global sensitivity analysis to identify the dominant input parameters in the model and to evaluate the level of conservatism inherent in the initial estimate of PMF. Modify specific input parameters as needed to minimize any excessive conservatism.
- Run the hydrologic model and reservoir routing model using the final set of input parameters.

Initial PMF Analysis

For each month, the calibrated hydrologic model was used to produce PMF inflow hydrographs to both the Upper Baker reservoir and the Lower Baker reservoir for nine modeling scenarios. The nine scenarios represent combinations of the three PMP general storm-centering scenarios and the three temporal distributions of PMP. Each model scenario for each month was identified by the naming convention, XXX_Y_ZZ, where:

- XXX = the month (OCT, NOV, DEC, etc.)
- Y = the general storm centering scenario (E=Entire watershed, U=Upper Baker, and L=Lower Baker)
- ZZZ = exceedance probability associated with the timing of the high-intensity segment (05 = 5-percent exceedance probability, 20 = 20-percent exceedance probability, and 50 = 50-percent exceedance probability)

Thus, for example, Model Scenario NOV_U_50 is the November PMP event with storm-centering over the Upper Baker tributary area and a temporal distribution based on the 50-percent exceedance probability for the location of the high intensity segment.

The initial PMF inflow hydrographs were routed through the reservoirs to determine the peak reservoir elevations, depths of overtopping, and outflow rates. The critical condition for both Upper Baker and Lower Baker was found to be the November event with the upper centering scenario and the temporal distribution associated with the 5-percent exceedance probability. Key output results for this event are as follows:

- Upper Baker Reservoir (overtopping occurs when reservoir elevations exceed 735.77 feet (NAVD88), which represents the roadway on the top of the dam):
  - Peak inflow = 163,200 cubic feet per second (cfs)
  - Peak outflow = 126,100 cfs
  - Maximum pool elevation = 739.84 feet (NAVD88)
  - Overtopping = 4.07 feet
- Lower Baker Reservoir (overtopping occurs when reservoir elevations exceed 444.57 feet, which represents the top of the parapet wall at the east non-overflow section of the dam):
  - Peak inflow = 156,100 cfs
  - Peak outflow = 136,700 cfs
  - Maximum pool elevation = 460.56 feet (NAVD88)
  - Overtopping = 15.99 feet

Global Sensitivity Analysis

The initial PMF results were based on the most critical combination of antecedent and coincident conditions identified for this study. Several of the selected input values represent conditions that are less likely to occur than average conditions. This is a reasonable approach for individual parameter selection. However, the conservatism inherent in each of these inputs is compounding, which can lead to a set of modeling conditions for the PMF that is so conservative as to be beyond reasonably possible. A global sensitivity analysis (GSA) (Saltelli et al. 2000) was used to evaluate model sensitivity to changes in input magnitude and to provide the information needed to make objective decisions about the conservatism of the initial estimate of the PMF. The GSA was also performed to evaluate the sensitivity of the hydrologic and reservoir routing models to changes in magnitude in the input parameters. Probability distributions, generated from historical data, were developed for the following input parameters, and 10,000 stochastic simulations of the model were executed:

- 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.

Dependencies among the parameters were maintained by defining the order in which parameters are sampled and which parameters can be sampled independently of all others. The 10,000 input parameter sets were modeled, and scatter plots were generated from the output to evaluate the model sensitivity to changes in input magnitude for each parameter. Standard linear correlation was used to fit trend lines to the data in each scatter-plot and to allow for a quantitative evaluation of the model sensitivity for each parameter.

Table ES-1 summarizes the sensitivity of peak inflow rate and peak reservoir elevation to changes in the input parameters evaluated in the GSA. Also shown in Table ES-1 is a qualitative assessment of the relative uncertainty in parameter estimation, based on the length of the period of record for the data, the source of the data, and the resolution of the data. The analysis found that the model response is most sensitive to antecedent snow water equivalent, storm temporal pattern, and seasonality of occurrence. The analysis showed that the model was not sensitive to antecedent snowpack density.

Table ES-1. Flood and Reservoir Response Sensitivity to Input Parameters, and Input Parameter Uncertainty

Input Parameter	**Peak Inflow Rate Sensitivity**	**Reservoir Elevation Sensitivity**	**Parameter Uncertainty**
Seasonality of Occurrence	Moderate	Moderate	Low
Centering of Storm	Low	Low	Moderate
Storm Temporal Pattern	Moderate	**High**	Low
Antecedent Precipitation	Moderate	Moderate	Low
Antecedent Snow Water Equivalent	**High**	**High**	Moderate
Antecedent Snowpack Density	Low	Low	High
Antecedent Reservoir Elevation Lower Baker	n/a	Low	Moderate
Antecedent Reservoir Elevation Upper Baker	n/a	Moderate	Moderate

The GSA results were also used to develop a probabilistic characterization of the range of inflow and outflow flood magnitudes possible with a PMP event. This probabilistic characterization was 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 following observations were made from this analysis:

- Upper Baker Results:
    - 187 of the 10,000 simulations resulted in an Upper Baker peak inflow greater than the initial PMF result. This means that the initial PMF inflow result is greater than the result for 98.1 percent of the 10,000 GSA simulations.
    - 50 of the 10,000 simulations resulted in an Upper Baker maximum reservoir elevation greater than the initial PMF result. This means that the initial PMF reservoir elevation result is greater than 99.5 percent of the 10,000 GSA simulations.
- Lower Baker Results:
    - For all three output parameters (peak inflow, peak outflow and peak reservoir elevation), the initial PMF results are greater than the results for all 10,000 model simulations.

The frequency histograms for Upper Baker indicate that the initial PMF results are in the top 1 to 2 percent of the 10,000 GSA model simulations, establishing them as clearly conservative. The fact that the initial PMF results for Lower Baker exceed the entire range of GSA results also indicates a high degree of conservatism.

Final PMF Analysis

Table ES-2 summarizes the recommendations for all the input parameters for the final PMF, developed to address the high degree of conservatism of the initial PMF results as identified by the GSA. Table ES-3 compares the results of the final recommended PMF model to the results of the initial PMF model.

Figures ES-4 and ES-5 show the final PMF inflow and outflow hydrographs for Upper Baker and Lower Baker, respectively.

Table ES-2. Summary of Hydrometeorological Inputs for Final PMF

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
Antecedent Snowpack Density	0.352[b]
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. Average value determined from historical record

Table ES-3. Comparison of Initial and Final PMF Model Results

	Model Scenario	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. Pool Elev. (feet NAVD88)	Dam Overtopping Depth (feet)
Upper Baker Development	NOV_U_05, INITIAL PMF INPUTS	163,200	126,100[a]	739.84	**4.07**
	NOV_U_20, FINAL PMF INPUTS	157,800	111,500[a]	739.19	**3.42**
Lower Baker Development	NOV_U_05, INITIAL PMF INPUTS	156,100	136,700	460.56	**15.99**
	NOV_U_20, FINAL PMF INPUTS	136,800	120,300	458.43	**13.86**

a. Peak outflow at the Upper Baker Development includes overtopping of West Pass Dike, which has a top crest elevation of 737.77 feet (NAVD88)

Snowmelt Contribution

A review of the output for the final PMF simulation found that most of the precipitation fell as liquid precipitation throughout the duration of the simulation. However, during the first 24 hours of the event, precipitation fell as snow in the highest of the elevation zones (Elevation Zone 8). Watershed-wide, nearly 70 percent of the snowmelt occurred in the mid-elevations between 3,200 feet and 5,000 feet, where the antecedent snowpack was melted out in its entirety. There was no antecedent snowpack in the lowest two elevation zones and therefore no snowmelt contribution.

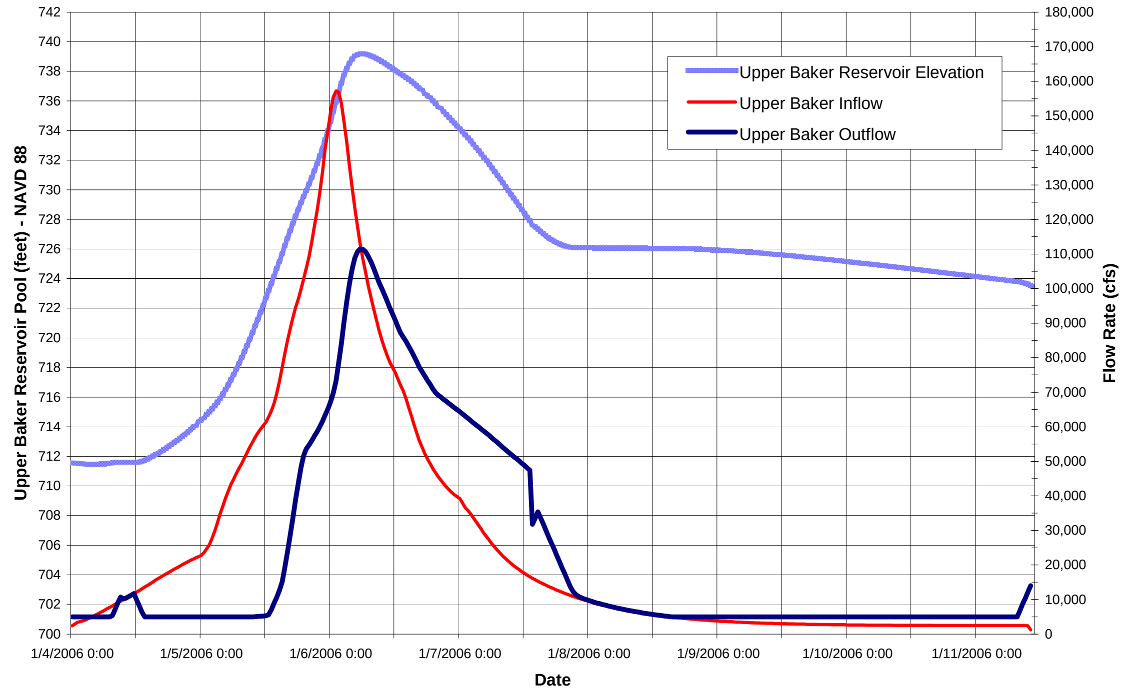

Figure ES-4. Final Upper Baker PMF Inflow and Outflow Hydrographs

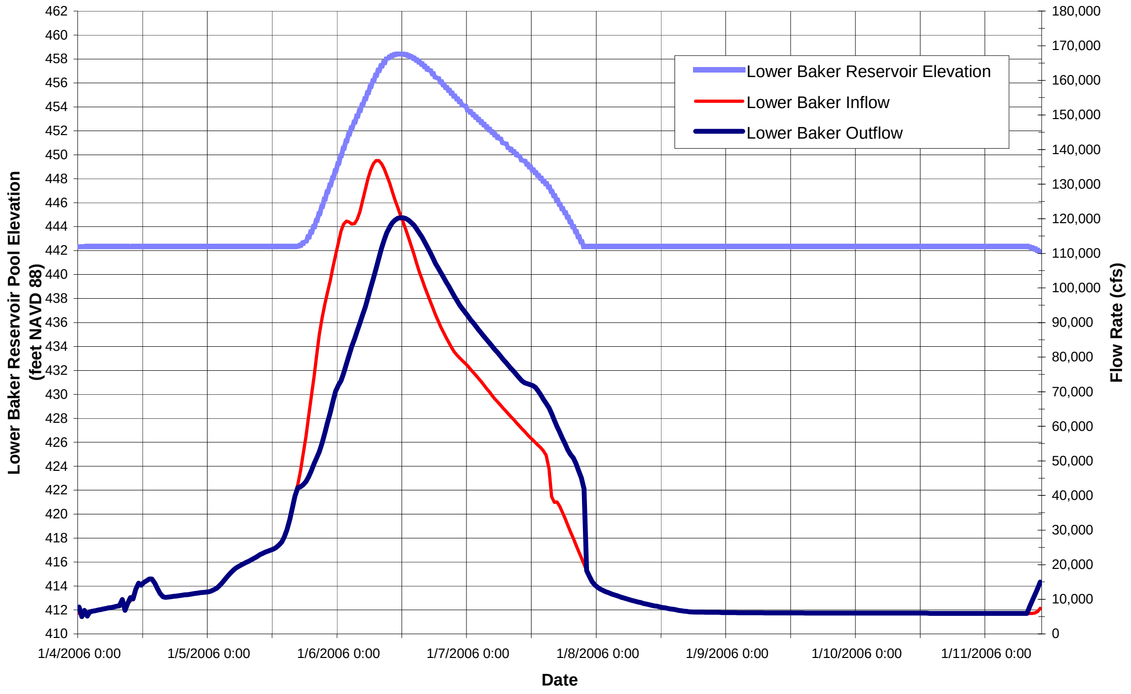

Figure ES-5. Final Lower Baker PMF Inflow and Outflow Hydrographs

Conclusion

The adopted final PMF represents a conservative yet physically realistic estimation of the PMF, based on a thorough investigation of the range of hydrometeorological input values for the Baker River watershed. The following are the key indicators of the appropriateness of the final PMF:

- The magnitudes of the input parameters that were used to generate the final PMF results are consistent with FERC guidance and with methods presented in HMR 57.
- Within the context of the 10,000 PMF simulations generated by the GSA, the final PMF results for Upper Baker are approximately equivalent to the 93-percent non-exceedance value for peak inflow rate and the 96-percent non-exceedance value for peak reservoir elevation.
- Within the context of the 10,000 PMF simulations generated by the GSA, the final PMF results for Lower Baker are slightly more conservative, with values of 99-percent and 99.9-percent non-exceedance for the peak inflow rate and the peak reservoir elevation, respectively.

1. INTRODUCTION

STUDY PURPOSE

This report presents the findings of a study to update the estimated probable maximum flood (PMF) for Puget Sound Energy's Baker River Hydroelectric Project (FERC No. 2150) using the most current available hydrologic and meteorological data and analytical techniques. The estimated PMF represents the design flood hydrograph into the project's reservoirs resulting from the probable maximum precipitation (PMP) event. It is used to determine the maximum reservoir elevation and the maximum rate of outflow at the project's two dams—Upper Baker and Lower Baker. Because the study area is in the northern Cascade Mountain region of the Pacific Northwest, the analysis required consideration of not only the rainfall contribution to the PMF but also the snowmelt contribution.

This updated PMF analysis is part of the Federal Energy Regulatory Commission (FERC) Part 12 Subpart D Independent Safety Inspection Report for the Upper Baker and Lower Baker Developments (MWH 2004a and MWH 2004b). The primary drivers for this PMF update were recommendations made in the April 4, 2004 Baker River Project Potential Failure Modes Analysis (PFMA) session and subsequently in the Independent Consultant's October 2004 reports (MWH 2004a and MWH 2004b). These recommendations were documented in a letter to Puget Sound Energy (PSE) from FERC (FERC 2004). In this letter, it is stated that "… the Probable Maximum Flood (PMF) study requires updating utilizing current state-of-the-practice analysis methods, the latest Hydrometeorological Report (HMR), and the most recent version of the Division of Dam Safety and Inspections Engineering Guidelines".

The previous PMF study for the Baker River Project was conducted by Hydrocomp International in 1969 (Hydrocomp 1969), and estimated the PMP using the National Weather Service's Hydrometeorological Report No. 43 (HMR 43), *Probable Maximum Precipitation for the Pacific Northwest (*NWS 1966). In 1994, the National Weather Service published Hydrometeorological Report No. 57 (HMR 57), *Probable Maximum Precipitation—Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages* (NWS 1994) as a replacement for HMR 43. HMR 57 incorporates new storm data and improved analytical procedures for estimating PMP in regions where local climate conditions are influenced by mountainous terrain (known as orographically influenced climate conditions). HMR 57 is based on a storm database extending through 1975; HMR 43 had been based on a storm database current only through the 1950s.

SCOPE OF WORK

The study was conducted according to guidance presented in HMR 57 and according to FERC's *Engineering Guidelines for the Evaluation of Hydropower Projects* (FERC 1993 and 2001). The analysis was conducted under review guidance of FERC staff and a FERC-approved Board of Consultants (BOC). Following the FERC and HMR 57 guidelines, the study consisted of the following elements:

- Initial data gathering and data acquisition
- Participation in a site visit to the project site
- Estimation of PMP using the updated HMR 57
- Development and calibration of a hydrologic model of the Baker River watershed to simulate inflow hydrographs of runoff entering Baker Lake (the Upper Baker Dam reservoir) and Lake Shannon (the Lower Baker Dam reservoir) in response to storm events

- Development of a reservoir routing model to simulate outflow hydrographs from Baker Lake and Lake Shannon in response to the inflow calculated by the hydrologic model
- Estimation of antecedent and coincident hydrometeorological conditions for the PMF
- Development of initial PMF inflow and outflow hydrographs
- A sensitivity analysis of model input parameters
- Development of final PMF inflow and outflow hydrographs
- Presentation of intermediate results of the analysis at BOC meetings.
- Preparation of a final report summarizing the work effort.

STUDY TEAM

The study was conducted over a 2-year period by the consultant team of Tetra Tech, Inc. and Applied Weather Associates, Inc. under contract with Puget Sound Energy (PSE) and under the review of FERC and the BOC. The members of the BOC, selected by PSE and approved by FERC, included expertise in the fields of hydrology, meteorology, civil works and hydraulics. Table 1-1 identifies the members of the study team.

Table 1-1. Baker River Project PMF Study Team

Team Member	**Title**	**Company**
Wayne Porter	Consulting Engineer and Part 12 Project Manager	PSE
Lloyd Pernela	Manager of Planning and Performance	PSE
Bob Barnes	Water Resource Program Manager	PSE
Paul Wetherbee	Consulting Hydrologist	PSE
Irena Netik	Hydrologist	PSE
Kathy Kimbell	Hydrologist	PSE
David Lord	Senior Civil Engineer	FERC
Ron Wright	Senior Civil Engineer	FERC
Jerry Pierce	Civil Engineer	FERC
Ken Fearon	Senior Civil Engineer	FERC
Bill Fullerton	Project Manager	Tetra Tech
Jay Smith	Senior Project Engineer	Tetra Tech
Justin Nodolf	Civil Engineer	Tetra Tech
Ed Tomlinson	Hydrometeorologist	Applied Weather Associates
Tye Parzybok	GIS Meteorologist	Applied Weather Associates
Bill Kappel	Staff Meteorologist	AWA
Mel Schaefer[a]	Hydrologist	MGS Engineering Consultants
Ron Mason[a]	Hydrologist/Hydraulic Engineer	HDR, Inc
George Taylor[a]	Consulting Meteorologist	Oregon State University

a. Member of the Board of Consultants

The BOC conducted independent review of each phase of the analysis and provided oversight, direction, and guidance to ensure that all assumptions and procedures were justified and consistent with the state-of-the-art of the industry. The consultant team presented status updates to the FERC and the BOC at six technical meetings held at key points in the study process. Technical memorandums were distributed to the BOC and FERC for review prior to the meetings. After each meeting, the BOC prepared a report with comments and recommendations on the analysis presented. Table 1-2 summarizes the technical memorandums that were developed for the Baker River PMF analysis.

Table 1-2. Technical Memorandums Prepared for Baker River PMF Study

No.	Title	Author[a]
1	Data Acquisition	TT
2	Summary of Site Visit Conducted on November 23, 2004	TT
3	Review of FERC Guidelines and Summary of PMF Analysis Procedure	TT
4	Historical Data Analysis	TT
5	Model Recommendation	TT
6	Determination of Probable Maximum Precipitation Using HMR 57	TT
7	Model Calibration and Verification	TT
8	Reconnaissance Level PMP Study and Storm Maximization	AWA
9	October 2003 Storm Analysis and Supplementary Storm Analysis for Calibration Events	AWA
10	Antecedent and Coincident Conditions for PMF Analysis	TT
11	PMF Results and Global Sensitivity Analysis	TT
12	Temperature, Wind and Synoptic Data Analysis	TT and AWA

a. TT = Tetra Tech, Inc.; AWA = Applied Weather Associates, Inc.

ORGANIZATION OF REPORT

This final report is a culmination of the previously prepared technical memorandums, each of which included significant detail to allow a thorough review of the procedures and assumptions applied at each step of the study. This report condenses the previously submitted information, but contains a sufficient amount of the previously submitted information and analyses to provide a full understanding of the procedures used to develop the PMF. Additional detailed information is provided as needed in appendices. The report outline generally follows the "Probable Maximum Flood Study Report Outline for Gaged Basins" included in the FERC engineering guidance (FERC 2001), with modifications as needed to account for new techniques that were used in this study and are not part of the FERC engineering guidelines. The following content is provided:

- Chapter 2 describes the physical and operational features of the Baker River Project and the physical characteristics of the Baker River watershed.
- Chapter 3 describes the selection and initial development of computer models used for the study.
- Chapter 4 describes the calibration and verification of the hydrologic model, including documentation of the input parameters for each historical storm event included in the process. The model was calibrated and verified using a methodology known as Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992).

- Chapter 5 describes the model used to route runoff hydrographs through the Upper and Lower Baker reservoirs.
- Chapter 6 describes development of general storm and local storm estimates of PMP.
- Chapter 7 describes development of antecedent and coincident conditions for the PMF analysis.
- Chapter 8 presents the PMF analysis, including a sensitivity analysis using a Global Sensitivity Analysis (GSA) methodology.

REGULATORY AND ENGINEERING GUIDANCE

The FERC (2001) guidelines provide guidance on important aspects of conducting PMF analysis, including recommendations on procedures to follow and important factors and physical processes to consider. They do not provide rigid criteria or detailed step-by-step procedures for determining PMF. In the introduction to FERC (2001), it is stated that:

> *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.*

Hydrologic Modeling

The following sections identify relevant FERC guidance and performance criteria for hydrologic modeling and how they were applied to the Baker River Project PMF study.

General Approach

- **FERC Guidance—**The FERC procedures are generally applicable for drainage basins up to 10,000 square miles in area. The guidance proposes the unit hydrograph approach as the preferred hydrologic analysis procedure for developing the runoff hydrograph. The Clark, Snyder and Soil Conservation Service (SCS) unit hydrographs are the recommended synthetic unit hydrograph methods.
- **Baker River Project Approach—**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. Consistent with the preference of the guidance, the PMF modeling approach used a form of the Snyder synthetic unit hydrograph methodology. There are no previously developed unit hydrographs specific to the Baker River Basin.

Model Recommendation

- **FERC Guidance—**The guidelines recommend the U.S. Army Corps of Engineers (USACE) HEC-1 model because of its widespread use and acceptance within the engineering industry. The guidelines indicate the potential to use other models developed for specific modeling situations or regions, but indicates that such programs “must be fully documented and verified.”
- **Baker River Project Approach—**Consistent with the guidelines, the study used the HEC-1 model for hydrologic analysis. The study also used the general storm Stochastic Event Flood Model (SEFM) (MGS 2004), a hydrologic model for computing flood frequency relationships. The SEFM model was used for its soil moisture accounting, snowmelt modeling, interflow response modeling and stochastic generation capabilities.

Unit Hydrograph Development

- **FERC Guidance—**The guidelines provide criteria for whether to consider the basin as gaged or ungaged.
- **Baker River Project Approach—**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 proceeded as specified for a gaged basin.

Basin and Subbasin Delineation

- **FERC Guidance—**The guidelines recommend that watersheds be subdivided if they are large and not hydrologically homogeneous or are drained by more than one major tributary. If the reservoir area is "relatively large," it should be considered as a separate subbasin. Subdivisions may also be required to simulate the effects of spatial distribution of precipitation. The guidelines list other criteria for dividing the watershed into subbasins, including the availability of functional stream flow records for tributary subbasins.
- **Baker River Project Approach—**The Baker River watershed was subdivided into 16 subbasins, including a separate delineation for the two reservoirs. The rationale for the delineation was the spatial variability in soil and bedrock characteristics, precipitation volume, and storm temporal distributions. The availability of historical stream flow records for several tributaries justified some further watershed subdivision.

Model Calibration and Verification

- **FERC Guidance—**For gaged watersheds, the guidelines indicate that at least three significant historical storms should be used. The two largest storms should be used for calibration and the third for verification. 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 simulated hydrographs should be calibrated to produce runoff volume and peak discharge similar to the historical data.
- **Baker River Project Approach—**Data sets exist to calibrate the Upper and Lower Baker Basins as gaged watersheds. The study incorporated three precipitation events for model calibration and used a fourth event for model verification. After model verification, this fourth event was then incorporated into the calibration process. All of the events used for calibration and verification occurred in October and November, which corresponds to the critical period for PMP, and three of the four events were rain-on-snow events.

Snowmelt

- **FERC Guidance—**The guidelines state that snowmelt needs to be taken into consideration for calibration storms that occurred while a snowpack was present; the energy budget method is recommended for calculating snowmelt.
- **Baker River Project Approach—**The majority of the largest runoff events were rain-on-snow events. Therefore, snowmelt was included in the calibration process and in the simulation of the PMF. Sufficient data exist to support calibration and application of the snowmelt component and the energy budget method was used for the snowmelt processes.

Loss Rates

- **FERC Guidance—**According to the guidelines, the traditional loss rate method for PMF computations is a basin averaging method using initial and uniform losses. However, the guidelines 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 basin-averaged or distributed mode. Regardless of the method used to compute losses, the hydrologic model must be verified with historical storm data. Resulting parameters should be checked against the expected basin values based on soil types for appropriateness.

- **Baker River Project Approach—**The study used the Holtan Loss equation for modeling surface infiltration. The Holtan Loss equation offers advantages over the uniform loss rate procedure in that it accounts for soil moisture storage capacity, the initial soil moisture content, and the minimum surface infiltration rate. The study also explicitly simulated the interflow runoff component of the runoff hydrograph.

PMP Storm Development

The following sections identify relevant FERC guidance and performance criteria for estimating the PMP and how they were applied to the Baker River Project PMF study.

Storm Volume

- **FERC Guidance—**According to the FERC guidance, the controlling PMF will be produced by the critical PMP that produces the largest routed peak flow from the reservoir. In determining the critical PMP, both the general storm PMP and the local storm PMP should be computed. HMR 57 provides information and procedures for computing PMP storm volumes.
- **Baker River Project Approach—**The area of the Baker River basin is less than 500 square miles, so HMR 57 was used to develop both the general storm PMP and the local storm PMP.

Spatial Distribution

- **FERC Guidance—**According to the guidelines, the PMP needs to be spatially distributed over the basin and then an average developed for the basin or the subbasins. Distribution of the PMP based on historical 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.
- **Baker River Project Approach—**For the study, spatial distribution of the PMP was based on frequency-based climatological mapping, specifically, the 100-year, 24-hour duration mapping developed by Schaefer et al. (2006).

Storm Duration

- **FERC Guidance—**The guidelines indicate that local storms of short duration and high intensity can produce a critical PMF for dams in drainage areas of 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.
- **Baker River Project Approach—**As per HMR 57 guidelines, the local storm PMP was 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. The study assessed whether the local storm PMP can produce the critical PMF.

Temporal Distribution

- **FERC Guidance—**The guidelines recommend placing the 6-hour period with the highest-intensity rainfall between the half and two-thirds point of the storm, with the remaining 6-hour periods alternated in descending order of rainfall intensity 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.

- **Baker River Project Approach—**The study used guidance from HMR 57 to determine PMP temporal distribution. This guidance was supplemented with a detailed regional precipitation developed by Schaefer (WDOE 1989).

Antecedent Conditions

The following sections identify relevant FERC guidance and performance criteria for determining antecedent conditions and how they were applied to the Baker River Project PMF study.

Loss Rates

- **FERC Guidance—** FERC's recommended procedure for loss rates is to assume an initial abstraction with uniform loss thereafter. Loss rates should be assumed to be representative of saturated soils. Initial abstraction may be set to zero unless some condition such as large depression storage justifies initial loss. It is preferred to determine distributed loss rate rather than area-averaged loss rate.

- **Baker River Project Approach—**The Holtan Loss equation was used to simulate soil infiltration processes. The initial abstraction was based on using a soil moisture budget accounting procedure for each month.

Snowpack and Snowmelt

- **FERC Guidance—**The guidelines state that snowpack conditions antecedent to the PMF should be determined from historical records. If total snowpack depth is available, the 100-year snowpack should be assumed over appropriate portions of the basin. 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. Snowmelt during the PMF should be computed with the energy budget method. The temperature sequence and wind speed sequence are provided in HMR 57.

- **Baker River Project Approach—**There is sufficient historical data to estimate appropriate snowpack conditions. A frequency-based analysis was conducted to determine the critical antecedent snowpack condition for the PMF; snowpack was spatially distributed in the watershed based on zones of elevation and mean annual precipitation. This approach to spatial distribution of snowpack provided consistency with observed physical conditions in the watershed. The temperature and wind speed time series were based on guidance in HMR 57.

Reservoir Levels

- **FERC Guidance—**In the absence of any regional study on antecedent storms conducted by a water resource agency, the guidelines indicate the following four procedures to determine a starting reservoir elevation for PMF event:
  - Consider the reservoir at a predetermined annual maximum at the start of the PMF.
  - Assume a 100-year, 24-hour storm occurs three 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 historical extreme floods and antecedent storms for the region.
- **Baker River Project Approach—**Antecedent reservoir levels were based on the operating rule curve for the Baker River Project. The global sensitivity analysis included antecedent reservoir elevation as one of the parameters and used 30 years of historical reservoir data.

PREVIOUS STUDIES

The initial PMF study for the Baker River Project was performed by Hydrocomp International in 1969, using HMR 43 to determine the PMP (Hydrocomp 1969). The authors coordinated with the North Pacific Division of the Corps of Engineers to apply additional reduction factors to the PMP estimates, outside of the procedures of HMR 43. The objective of this PMF study was to develop spillway design floods for both the Upper Baker and Lower Baker dams. The study used the Hydrocomp Simulation Program, a predecessor of the current HSPF modeling software, to model the hydrologic response of the watershed. Hydrographs were generated for each month from October through June.

The study concluded that a December PMP event with a 72-hour duration precipitation depth of 25.8 inches would produce a peak inflow of 118,640 cubic feet per second (cfs) into Baker Lake (the Upper Baker dam reservoir) and a maximum reservoir elevation of 733.57 feet (using the North American Vertical Datum of 1988 (NAVD88)). This elevation provided 2.2 feet of freeboard to the crest of Upper Baker Dam. The December PMP event would produce a peak inflow of 108,250 cfs into Lake Shannon (the Lower Baker dam reservoir) and a maximum reservoir elevation of 450.35 feet (NAVD88). This elevation is above the top of the parapet walls on both abutments, and is 0.30 feet below the top of the dam.

In 1981, PSE conducted a supplemental analysis to the 1969 PMF study in response to concerns identified in a February 1981 letter from FERC (Puget Sound Power and Light Company 1981). It used the inflow hydrographs developed in the 1969 study, but the antecedent reservoir conditions at Upper Baker Dam were revised to provide 74,000 acre-feet of flood control storage. The analysis considered two flood scenarios: a PMF event preceded by a 100-year flood three days earlier; and the PMF event by itself. The analysis concluded that under the first scenario, with Baker Lake constrained to a maximum water surface elevation of 729.0 feet (732.77 feet NAVD88), water surface elevations at Lake Shannon will reach a maximum of 441.9 feet (445.65 feet NAVD88). Under the second scenario, the maximum surface water elevations attained for Baker Lake and Lake Shannon were 728.9 feet and 440.8 feet (732.67 feet NAVD88 and 444.55 feet NAVD88), respectively. The 1981 supplemental analysis was submitted to FERC, but the Hydrocomp (1969) report is still considered the PMF study of record.

2. PROJECT DESCRIPTION

PROJECT AND FACILITY DATA

The Baker River Hydroelectric Project is owned and operated by PSE, an energy company that provides electrical power and natural gas to customers in the Puget Sound region. The project consists of two developments on the Baker River, a tributary to the Skagit River. The Lower Baker Development was constructed between April 1924 and November 1925, upstream of the confluence with the Skagit River at River Mile (RM) 1.2. The Upper Baker Development, located at RM 9.35, was constructed between June 1956 and October 1959. This chapter provides an abridged version of the description of the developments included in the FERC Part 12 Safety Inspection Report (MWH 2004a and 2004b). Appendix A provides schematic representations of Upper Baker Dam and Lower Baker Dam. Figure 2-1 shows the Baker River watershed and the location of the two developments.

Unless otherwise noted, all elevations in this report are relative to the NAVD88 geodetic datum.

Upper Baker Development

The Upper Baker Development consists of a concrete gravity dam (Upper Baker Dam), an adjacent dike that closes off a low saddle in the topography (West Pass Dike), and a water recovery system that pumps seepage water back into the reservoir (Depression Lake). The relative locations of these facilities are shown on Figures 2-2 and 2-3.

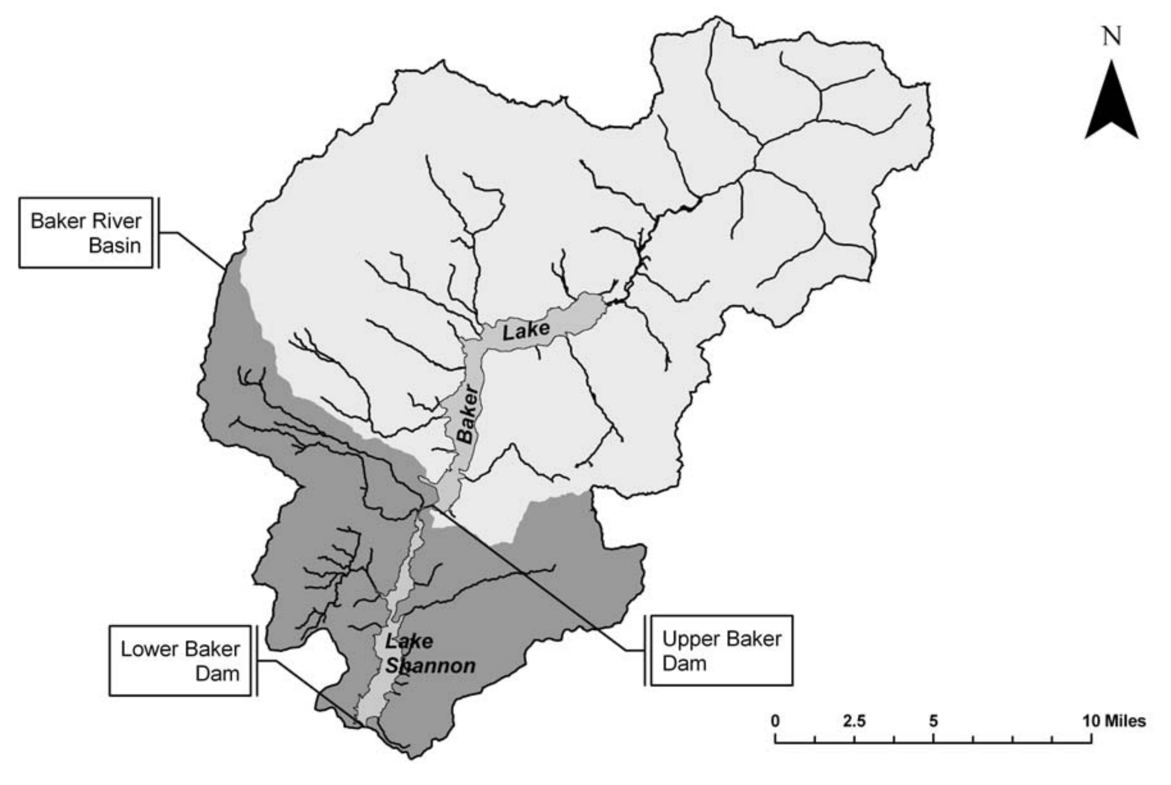

Figure 2-1. Baker River Watershed and Location of Upper Baker and Lower Baker Developments

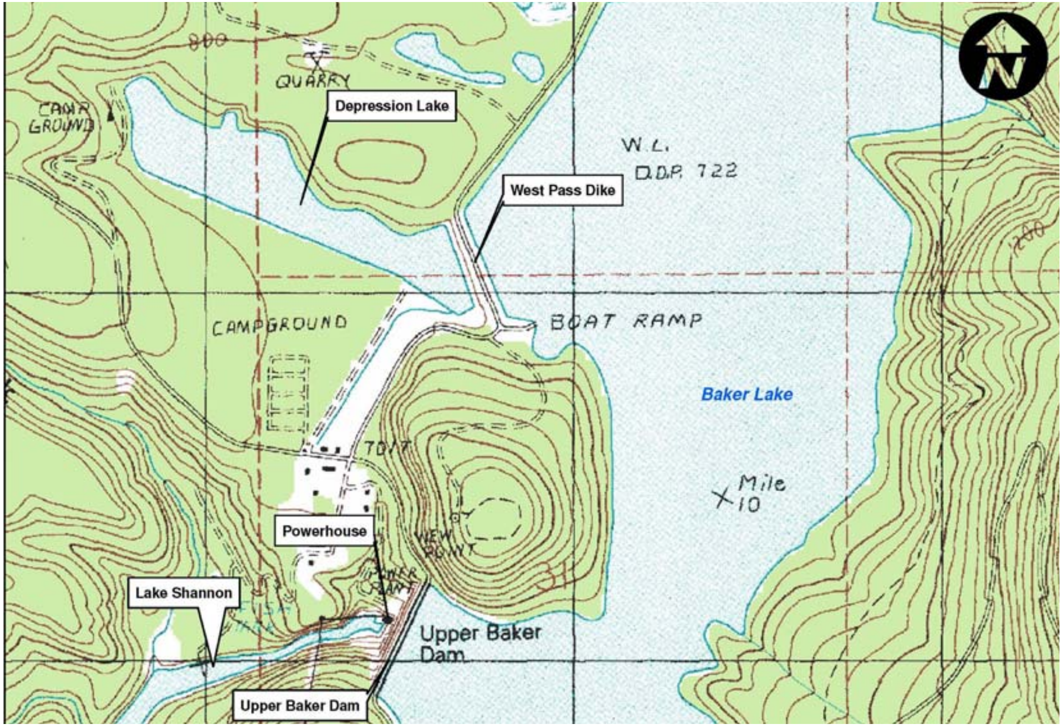

Figure 2-2. Location of Facilities at Upper Baker Development

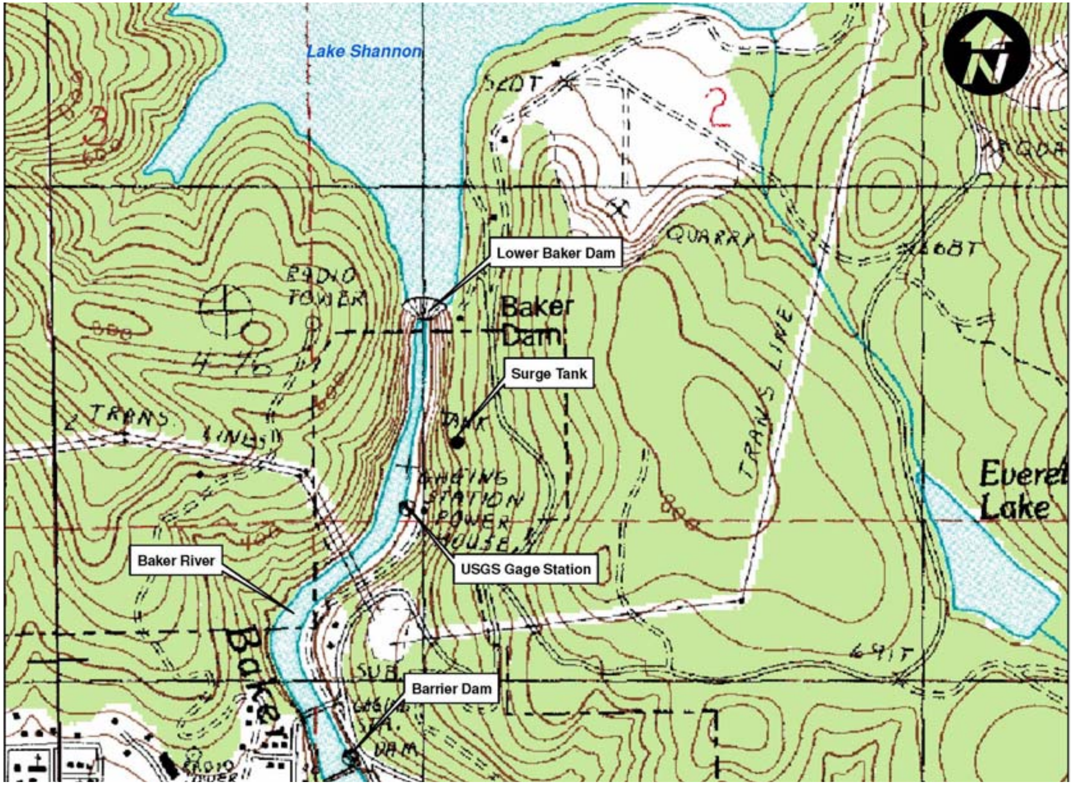

Figure 2-3. Location of Facilities at Lower Baker Development

Upper Baker Dam is a 312-foot-high, 1,200-foot-long concrete gravity dam with an ogee-type spillway. The spillway is controlled by three identical 25-foot-wide, 30-foot-high radial gates that can be operated locally or remotely. The spillway crest elevation is 697.77 feet (NAVD88). The crest elevation of the dam is 735.77 feet (NAVD88). Upper Baker Dam incorporates three concrete non-overflow sections totaling approximately 1,000 feet in length and a 12-foot-wide roadway along the top of the dam. The roadway is used to service the intake gates and spillway gates and also provides access to a system of logging roads in the upper watershed

Upper Baker Dam impounds the 9-mile long Baker Lake. At the normal full-pool elevation of 727.77 feet (NAVD88), Baker Lake has a surface area of 4,980 acres and a total volume of 274,202 acre-feet. The normal full-pool elevation is 8 feet below the crest of the dam and 10 feet below the top of West Pass Dike.

A reinforced concrete and steel powerhouse is located at the downstream toe of the dam at approximately the centerline of the dam. The powerhouse contains two turbine driven generators with a combined authorized installed capacity of 90.7 MW. Water from Baker Lake is conveyed to the turbines by means of two 13.5-foot-diameter steel lined penstocks. A 16-foot-wide, 20-foot-high fixed-wheel vertical gate is mounted at the upstream end of each intake opening. The vertical gates are operated by individual fixed hoists mounted above the dam crest and can be operated either locally or remotely.

West Pass Dike, located approximately 1,500 feet north of Upper Baker Dam on the western bank of Baker Lake, is an earth-and-rock-fill embankment with a compacted impervious core that was constructed at the same time as Upper Baker Dam to close off a low saddle area in the topography. West Pass Dike is 115 feet high and 1,200 feet long. The crest elevation of the dike is 737.77 feet (NAVD88), 2 feet higher than the crest elevation of the dam. The top elevation of the compacted impervious core is 733.77 feet (NAVD88). The upstream face of the dike has a horizontal-to-vertical slope of 2.5:1 and is protected with a mixture of compacted rock and riprap. The downstream face of the dike is constructed at a 1.3:1 slope (H:V). Appendix A shows a typical cross section of West Pass Dike.

Depression Lake, a 0.7-mile-long pond in a natural depressional area immediately downstream (west) of West Pass Dike, is partially formed by a 3,000-foot-long, 22-foot-high earth-fill dike. Depression Lake receives subsurface flow from Baker Lake through the underlying fractured volcanic bedrock material. A 54,000-gallon-per-minute water recovery system pumps water from Depression Lake back into Baker Lake.

Downstream-migrating fish are collected using a barrier net guidance system and a surface collector attraction barge. Fish are captured and sampled in a fish trap/sampling facility, transferred to a tank trailer, and trucked to the mouth of the Baker River where they are released. Upstream-migrating fish are trapped and trucked to Baker Lake from Baker River downstream of Lower Baker Dam.

Lower Baker Development

The Lower Baker Development consists of a concrete arch dam (Lower Baker Dam), a reinforced concrete powerhouse structure, a concrete surge tank and facilities for collecting and transporting migratory fish. These facilities are shown on Figure 2-2.

Lower Baker Dam is a 285-foot-high, 550-foot-long concrete arch dam consisting of a non-overflow section at each abutment and a central gated spillway section. The spillway is controlled by 23 vertical slide spill gates, each approximately 14 feet high and 9.5 feet wide, which are normally supported on the fixed concrete spillway crest. All of the vertical slide gates must be lifted from above. Ten of the gates are manually operated from a traveling-type hoist cart that must be moved across the top of the dam, positioned, and secured above the gate to be lifted. The remaining 13 gates have electrically powered drives; five of them can be operated remotely, and the other eight must be operated from controls at each gate. The spillway crest elevation is 428.55 feet (NAVD88). The crest elevation of the top deck of the dam at the gated spillway section is 450.64 feet (NAVD88).

Lower Baker Dam impounds the 7-mile long Lake Shannon. At the normal full-pool elevation of 442.35 feet (NAVD88), Lake Shannon has a surface area of 2,278 acres and a total volume of 146,279 acre-feet. This elevation is 2.2 feet below the top of the parapet wall on the east abutment and 2.8 feet below the top of the parapet wall on the west abutment.

A reinforced concrete powerhouse on the east bank contains a single turbine-driven generator with an installed capacity of 77.0 MW. Water from Lake Shannon is conveyed through a gated concrete intake structure into a 22-foot-diameter concrete-lined penstock that transitions to a 16-foot-diameter steel-lined penstock. The concrete intake is equipped with a trash rack. The intake narrows to two headgate-controlled openings that are each 20 feet high and 12 feet wide.

Downstream-migrating fish are collected using a barrier net guidance system and a surface collector attraction barge. Fish are captured and sampled in a fish trap/sampling facility, transferred to a tank trailer, and trucked to the mouth of the Baker River where they are released. Upstream-migrating fish are collected in a fish trapping facility at RM 0.6 on the Baker River. A 12-foot high barrier dam prevents upstream-migrating fish from reaching Lower Baker Dam and guides them into the fish trapping facility. The collected fish are transferred into a truck and transported to Baker Lake or to the spawning beaches at the Upper Baker Development.

Normal Condition and Flood Operations

The Baker River Project is operated to provide for hydroelectric power generation, flood control, recreation and fisheries. PSE initially developed the Baker River Project for the primary purpose of hydroelectric production, with a minimal role in flood regulation. With congressional authorization for additional flood control storage at Upper Baker Dam in May 1977, the project has an added federal mandate. Reservoir levels upstream of the two dams fluctuate seasonally to meet the project’s objectives:

- During the November through March flood season, Upper Baker Dam is operated at the direction of the Seattle District United States Army Corps of Engineers (USACE) to allocate flood control volume according to the *Baker River Project Water Control Manual* (USACE 2000). There is no requirement under the current license for flood control storage at Lower Baker.
- Outside the flood control season, the project is operated to meet power, recreational, and fisheries demands. The goal for both reservoirs during this period is to remain as near as possible to the normal full-pool elevation, though in reality both facilities are operated such that the reservoir pool elevation is several feet lower than the normal full-pool level.

Article 32 of the original 1956 FERC license for the project required that Baker Lake be operated “to provide each year 16,000 acre-feet of space for flood regulation between November 1 and March 1 as replacement for the valley storage eliminated by the development” (USACE 2000). In May 1977, 58,000 acre-feet of additional flood control storage was authorized by Congress. Figure 2-4 is the rule curve for Upper Baker Dam, which reflects the provision of the total 74,000 acre-feet of flood control volume. As seen in this figure, the minimum flood control pool elevation of 711.57 feet (NAVD88) must be available by November 15 and must be maintained until March 1.

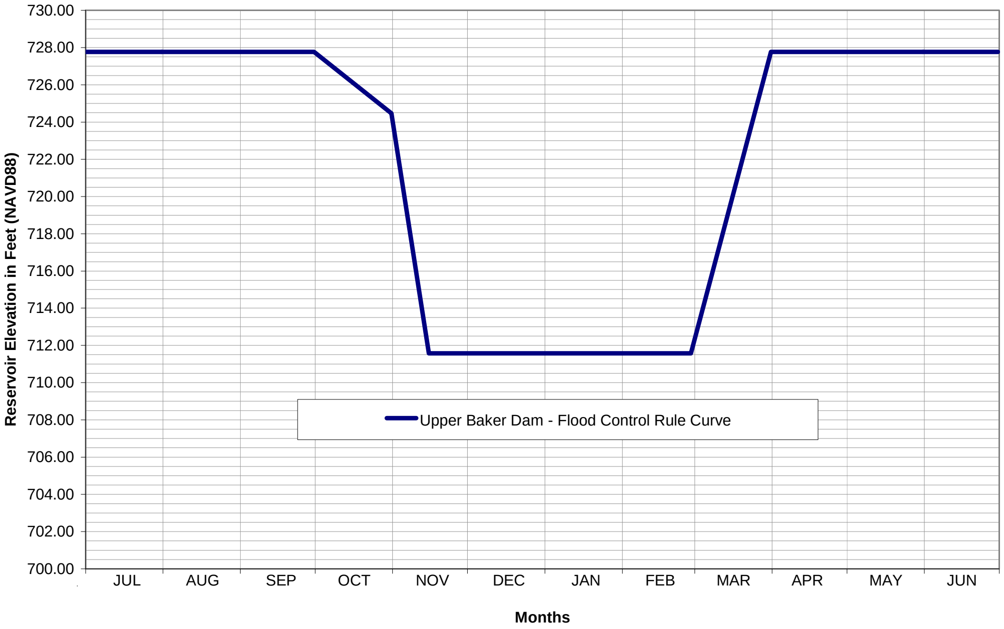

Figure 2-4. Flood Control Rule Curve for Upper Baker Dam (USACE 2000)

To reduce flood damage in the Skagit River valley during the flood control season, the Seattle District USACE assumes operation of the Baker River Project when the unregulated flow rate in the main stem Skagit River is forecast to exceed 90,000 cfs. The operation of Upper Baker Dam is as follows:

- When the minimum flood control pool is reached on a rising flood, PSE must coordinate with the National Weather Service Reservoir Control Center (NWS-RCC) to determine whether to begin passing flow to maintain the pool elevation or to begin active flood control storage. In either event, the minimum discharge from Upper Baker must maintain 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.
- Releases are maintained 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.

SITE VISIT

A site visit to the Upper and Lower Baker Developments was conducted on November 23, 2004 to obtain information not available in published reports, to observe the facilities first-hand, to interview the facility operators, and to conduct reconnaissance level observations of the ground conditions in the upper watershed. Table 2-1 lists the attendees at the site visit. Tetra Tech had prior project experience at the Baker River Project and had previously toured the facilities. Therefore the primary objective of this site visit was to interview the dam operators regarding the normal operation of the spillway gates, the testing schedule of the gates, and the operation of the spillway gates in the event of an OFCN. The site visit was documented in a technical memorandum from Tetra Tech to PSE (Tetra Tech 2005b).

Table 2-1. Site Visit Attendees

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

A supplemental site visit was conducted as part of the second BOC meeting on September 8, 2005. Members of the BOC and staff from the Portland District FERC attended this site visit, the objective of which was to aerially observe land cover conditions, soil, and glacial distribution to assist in developing the distributed hydrologic model, specifically regarding the coverage of exposed rock and glaciers.

WATERSHED DESCRIPTION

The Baker River Hydroelectric Project is located on the Baker River, in the west slope of the northern Cascades in Washington State at approximately Latitude 48º 45’ and Longitude 121º 40’. The Baker River drains approximately a 300-square-mile mountainous watershed and is a tributary watershed to the 3,140-square-mile Skagit River basin. The overall drainage area above Upper Baker Dam is 214.8 square miles, and Lower Baker Dam has a local tributary drainage area of 83.9 square miles. Therefore, the total tributary area to the Lower Baker Dam is 298.7 square miles. Figure 2-1 shows the two major tributary areas.

Topography

Topography in the Baker River watershed is mountainous, with extreme gradients and an elevation difference of nearly 10,500 feet. The elevation of the low point in the watershed is approximately 170 feet. The most prominent topographical features in the watershed 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 feet) and Bacon Peak (Elev. 7,066 feet). The basin is generally steep, with slopes of 20 to 40 percent over much of its area. Steeper slopes (60 to 80 percent) are prevalent in the upper portion of the watershed on the flanks of Mt. Shuksan, Mt. Blum, and Mt. Challenger (see Figure 2-5). Tributary stream systems to Baker Lake have formed broad alluvial valleys as seen in Figure 2-5. Baker River originates from the glaciers of Mt. Challenger in the northeast corner of the basin and descends nearly 5,000 feet to the valley floor in less than 4 miles. Table 2-2 summarizes the percent of the Baker Lake and Lake Shannon tributary areas within each of 10 elevation bands.

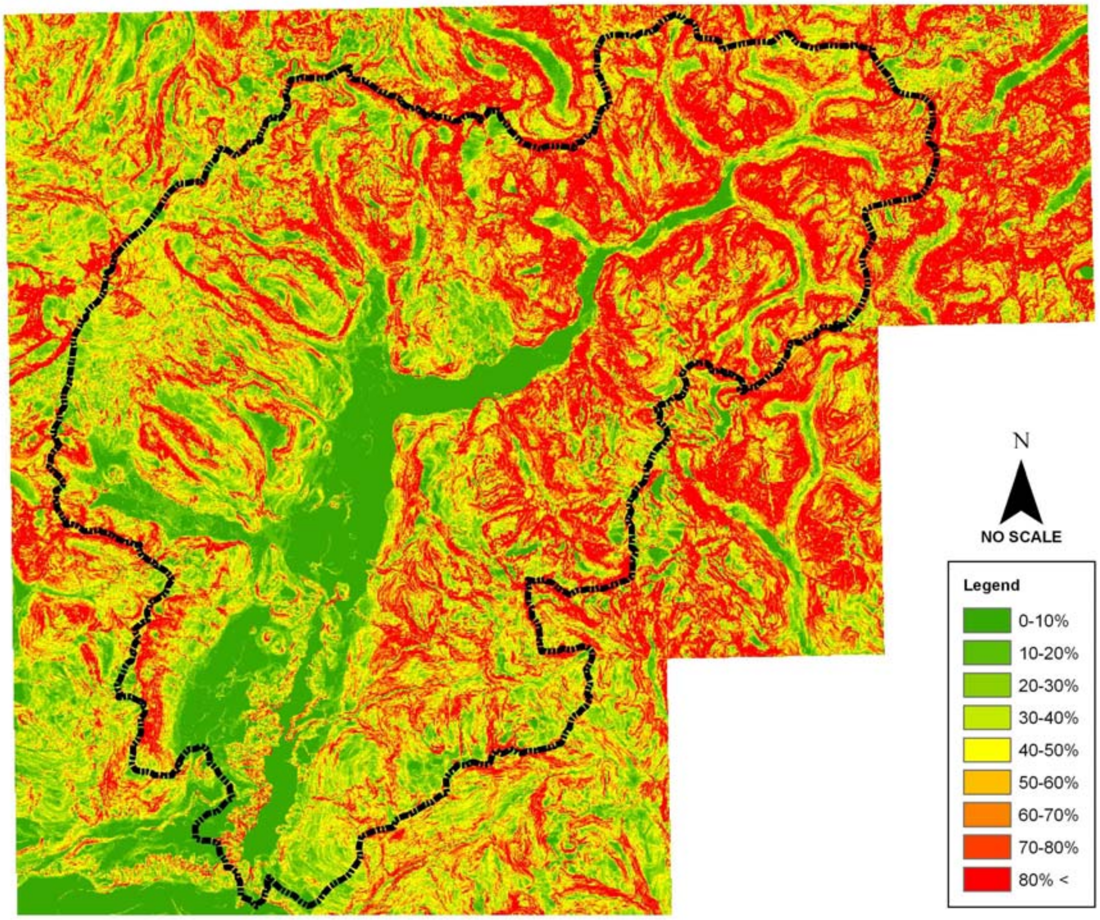

Figure 2-5. Slopes in Baker River Watershed (Source: U.S. Geological Survey 10 meter DEM)

Table 2-2. Summary of Elevations in Baker River Watershed

Elevation Band (ft NAVD88)	Percent of Baker Lake Subbasin		Percent of Lake Shannon Subbasin	
	Incremental	Cumulative	Incremental	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		

Geology and Soils

Geology and soil conditions in the Baker River watershed are highly variable due to the influence of Mount Baker, the historical volcanic activity in the watershed, and the residual effects of glacial retreat.

The lower portion of the watershed is a broad valley of glacial outwash through which the Baker River has carved a deep canyon that is now occupied by Lake Shannon. During the retreat of the continental ice sheet 10,000 to 13,000 years ago, ice filled the Skagit Valley and blocked the mouth of the Baker River, flooding the Baker River valley and depositing a thick layer of clay, sand and gravel. As the ice withdrew, sands and gravels were deposited on top of the glacial deposits. When the ice had completely retreated, the Baker River rapidly down-cut through the glacial deposits to bedrock controls, creating a narrow, deep gorge (USFS 2002).

In the middle portion of the watershed, a cinder cone that formed in Schreibers Meadow nearly 9,800 years ago produced widespread lava flows within the Sulphur Creek drainage that reached the Baker River. Later, huge landslides off Mt. Baker filled the valley floors on the east flank of the mountain, from Swift Creek downstream to the Sulphur Creek lava flows (USFS 2002).

The upper portion of the Baker River, upstream of the present location of Upper Baker Dam, is a very narrow, steep-sided rock canyon with a valley floor of glacial outwash and recent fluvial deposits of sand and gravel (USFS 2002).

Soils in the low-lying elevations of the watershed range from deep well-drained soils with gravelly loam or loamy sand textures to poorly drained sandy clay loams and silty clays. Soils in the mid-elevations of the watershed are typically shallower and of finer texture, such as sandy loams, silty loams and loamy sands. The highest elevations of the watershed are typified by bedrock outcroppings devoid of soil or with a very shallow soil layer.

The underlying bedrock in the watershed consists of a complex mixture of nonmarine sedimentary, igneous (volcanic and magmatic) and metamorphic rocks. Much of the underlying bedrock is highly fractured and weathered and in some instances is extremely conducive to laterally conveying shallow subsurface flows that originate as precipitation in the higher elevations and discharge as springs or reappear as surface flows at the lower elevations. This is especially relevant in the vicinity of the geologically recent lava flows in the Sulphur Creek drainage. As described in Chapter 3, this ability for the underlying bedrock material to laterally convey large quantities of subsurface flows necessitated the need to explicitly model the interflow component of the runoff hydrograph.

Land Use and Land Cover

Land ownership and management in the Baker River watershed is 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 in the basin is predominantly forested. According to the 1992 National Land Cover Dataset (USGS LCI 1992), over 70 percent of the basin consists of evergreen forest cover. The forest cover is predominantly below elevations of 5,500 feet. Perennial snowfields and glaciers occupy nearly 5 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 make up 80 percent of the Baker River watershed.

Hydrometeorological Gaging Stations

Stream Flow and Reservoir Stations

Stream flow and reservoir elevation data were available for this study from PSE records and from the U.S. Geologic Survey (USGS). PSE maintains hourly operation data for each dam, including forebay elevation, turbine discharge, and total spillway discharge. This data was made available by PSE for several of the largest flood events that have occurred in the watershed. The USGS currently maintains and has historically maintained stream flow and reservoir gaging stations in the Baker River watershed and throughout the greater Skagit River basin.

The USGS currently maintains reservoir gages in the forebays of the Upper Baker and Lower Baker dams. Additionally, there are seven abandoned USGS stream gaging stations in the watershed and one currently operating station (see Figure 2-6)—Baker River at Concrete, WA (12193500)—which is just downstream of Lower Baker Dam. Stage readings at this gage are backwater-influenced during high stages in the Skagit River. Therefore, data from this gage was used with caution and was typically supplemented with hourly records of spill and penstock flow from Lower Baker Dam supplied by PSE. Table 2-3 summarizes the period of record for the active and abandoned USGS gaging stations in the Baker River watershed.

Table 2-3. USGS Recording Stations in the Baker River Watershed

Station ID	Station Name	Drainage Area (square miles)	Period of Record
12190700	Morovitz Creek Near Concrete, WA	2.6	11/1/65—12/19/72
12190710	Swift Creek Near Concrete, WA	36.4	8/1/82—9/30/90
12190718	Park Creek at Upper Bridge Near Concrete, WA	10.5	6/1/82—10/29/80
12191500	Baker River Below Anderson Creek Near Concrete, WA	211.0	1910—1924, 1929—1931, 1956—1959
12191800	Sulphur Creek Near Concrete, WA	8.4	3/1/63—9/30/82
12192600	Bear Creek Below Tributaries Near Concrete, WA	14.4	4/1/82—9/30/86
12192700	Thunder Creek Near Concrete, WA[a]	22.4	8/1/82—9/30/94
12193500	Baker River at Concrete, WA	297.0	10/1/10—2/28/15, 9/1/43 - present
12191600	Baker Lake	n/a	7/1/59—present
12193000	Lake Shannon	n/a	11/1/25 - present

[a] Gage converted from a recording station to an annual peak station in October 1973

Snowpack Stations

Historical snowpack data is available primarily from snow course sites monitored by PSE and from Natural Resources Conservation Service (NRCS) SNOTEL sites:

- There are nine snow course sites in the Baker River watershed where end-of-month readings of snowpack depth are taken from December through May. PSE converts the observed snowpack depth to snow water equivalent based on regression analysis of historical data (the snow water equivalent, abbreviated SWE, is the depth of water that a snowpack would yield if fully melted).
- NRCS SNOTEL sites are equipped with sensors that record data at regular, frequent time intervals (daily, six-hour or one-hour). At the SNOTEL stations, hourly records are generally

available as far back as 1993, and daily records are generally available as far back as 1982. Standard data sets include total precipitation, snowpack depth, available snow water equivalent, and air temperature. At enhanced SNOTEL sites, solar radiation and wind speed are also recorded. At the time of this study, there were no NRCS SNOTEL sites located in the Baker River watershed, however, as seen in Figure 2-7, there are nine in the Skagit River basin, four of them close to the Baker River watershed. Of those nearest the Baker River watershed, 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 2-4 and the locations of the stations are shown on Figures 2-6 and 2-7. The period of record indicated for the SNOTEL stations is the record available for daily and hourly data.

Table 2-4. Snowpack Stations within and Adjacent to Baker River Watershed

Station ID	Station Name	Station Elevation (feet)	Station Mean Annual Precipitation[a] (inches)	Period of Record
PSE Snow Course Stations				
	Rocky Creek	2,100	147	1959-present
	South Fork Thunder	2,200	124	1959-present
	Schreibers Meadow	3,400	153	1959-present
	Marten Lake	3,600	146	1959-present
	Dock Butte	3,800	155	1959-present
	Watson Lake	4,500	136	1959-present
	Easy Pass	5,200	133	1959-present
	Jasper Pass	5,400	116	1959-present
	Mt Blum	5,800	156	1965-present
NRCS SNOTEL Stations				
21A32S	Elbow Lake	3,200	129	8/95 - Present
21A01S	Beaver Pass	3,620	101	10/01 - Present
20A41S	Swamp Creek	4,000	48	10/99 - Present
21A31S	Wells Creek	4,200	89	8/95 - Present
20A07S	Thunder Basin	4,200	79	10/88 - Present
20A09S	Rainy Pass	4,780	72	10/82 - Present
21A36S	MF Nooksack	4,890	119	10/02 - Present
20A05S	Harts Pass	6,500	56	10/82 - Present

a. Mean annual precipitation at stations determined from mapping provided by Oregon Climate Service (OCS 2005)

Precipitation Stations

The following resources were used for obtaining precipitation data: Puget Sound Energy; National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS); Natural Resources Conservation Service.

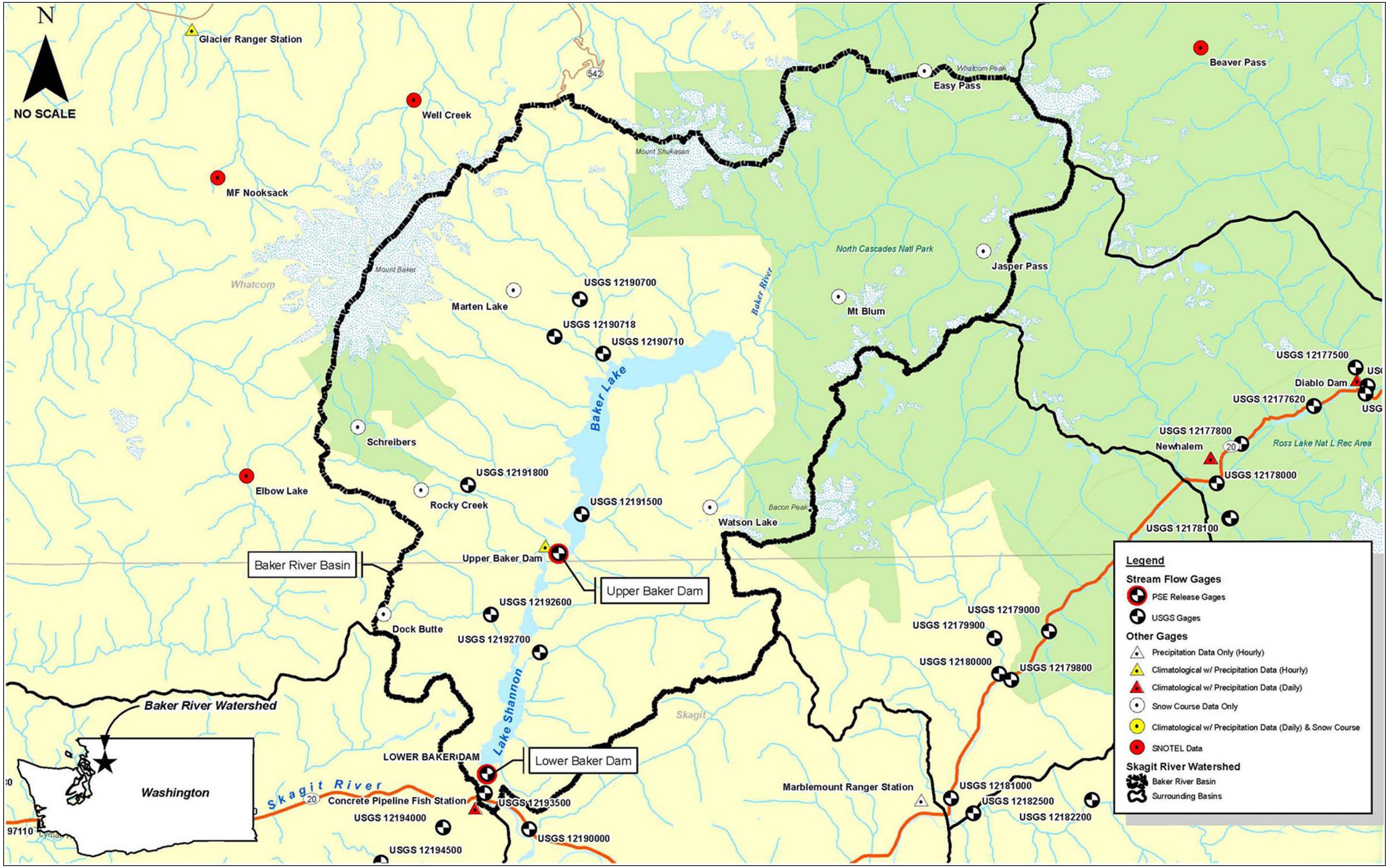

Figure 2-6. Gaging Stations Inside the Baker River Watershed

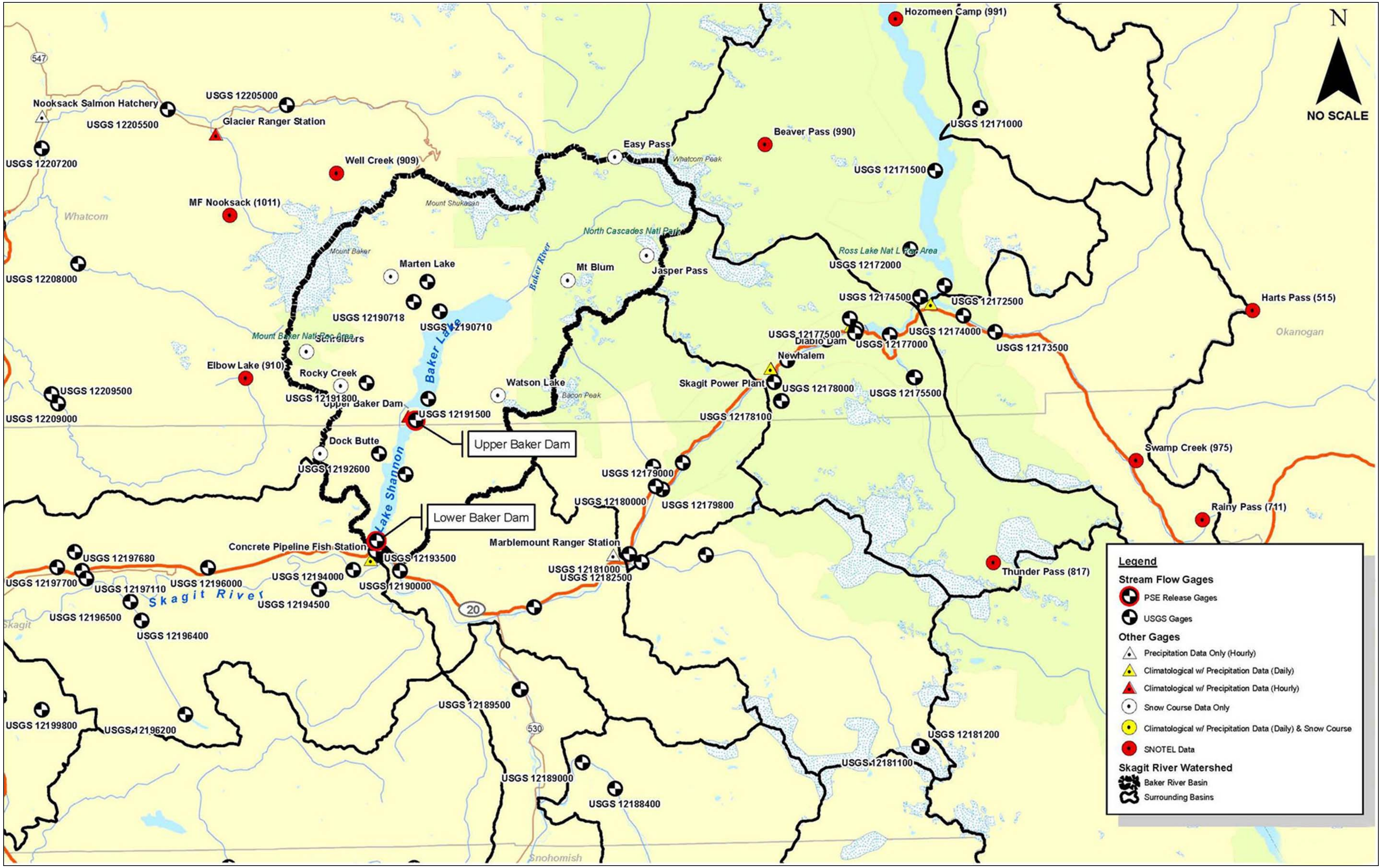

Figure 2-7. Gaging Stations in the Vicinity of the Baker River Watershed

The only active, long-term hourly precipitation recording station in the Baker River basin is the NOAA station at Upper Baker Dam (Station 458715). The location of this station is shown in Figure 2-6. This automated gaging station is equipped with a Fisher-Porter tipping bucket that provides rainfall totals at 15-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 from which daily readings are taken at 7 AM local time.

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

The three nearest long-term hourly precipitation stations outside the Baker River basin are the NOAA/NWS stations at Nooksack Salmon Hatchery, Glacier Ranger Station, and Marblemount Ranger Station (Figure 2-7).

Hourly and accumulated daily precipitation records (total precipitation including snowfall) are available from NRCS SNOTEL stations. 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.

Air Temperature Stations

The following data sources were referenced for air temperature data: upper-air data published by NOAA (collected by radiosonde instrumentation mounted on weather balloons); twice-daily air temperature data from NOAA stations in the watershed; hourly air temperature data from NOAA stations outside the watershed.

Upper-air data were obtained from the Quillayute Station on the west coast of the Olympic Peninsula. Upper-air data is collected by radiosonde instruments mounted on weather balloons, which measure the vertical distribution of atmospheric conditions over a single location. Data is typically recorded at pre-determined pressure levels in the atmosphere and includes temperature, dew point, wind speed and wind direction. The Quillayute Station radiosonde data were primarily used to estimate the atmospheric lapse rates for the historical precipitation events used to calibrate the hydrologic model.

Air temperature data within the Baker River watershed is limited to reports of daily maximums and minimums at the Upper Baker Dam (458715) and Concrete PPL (451679) precipitation stations. Hourly air temperature data is available at nearby stations outside of the Baker River watershed from NOAA/NWS and from the NRCS. For this study, data were used from the NOAA/NWS Stampede Pass Station and from the NRCS MF Nooksack, Elbow Lake and Wells Creek stations. The twice daily data available from within the watershed and the hourly data available from outside the watershed were used together to develop serially complete hourly temperature profiles representative of the conditions at the Upper Baker Dam station for use in the hydrologic model calibration.

Climate and Hydrology

The Baker River watershed lies within a convergence zone between warmer 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 in the Baker River watershed and 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 tap tropical moisture or energy from low pressure centers located over tropical waters. November and December are the wettest months of the storm season, when 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, affecting 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 Northwest from May through August. The Pacific high pressure builds offshore and feeds dry and stable air into the region. Beginning in September, the high pressure weakens and the polar front drops south. The region sees a doubling of the monthly precipitation in September.

The physical attributes of the Baker River watershed result in significant spatial variation in precipitation patterns, caused by the orographic effect of extreme elevations and the basin’s variable topography. Mean annual precipitation measured at the precipitation station near Lower Baker Dam (Elev. 195 feet) is 68.21 inches. Further up in the watershed, the mean annual precipitation at the precipitation station near Upper Baker Dam (Elev. 690 feet) is 99.63 inches. Table 2-5 illustrates the seasonal fluctuation in monthly precipitation at these two NOAA/NWS stations in the Upper Baker River watershed. Figure 2-8 illustrates the spatial distribution of mean annual precipitation in the watershed based on mapping developed in 2005 by the Oregon Climate Service (OCS 2005).

Table 2-5. Monthly Average Total Precipitation in Upper Baker Watershed (inches)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upper Baker Dam (458715)	15.01	10.13	9.65	6.36	4.74	3.55	2.42	2.10	4.49	9.97	15.72	15.49
Concrete PPL FS (451679)	9.57	6.94	6.82	4.55	3.29	2.76	1.51	1.71	3.47	6.81	10.16	10.63

The nine snow course stations in the watershed are monitored monthly, with the first data generally collected at the end of December once a sufficient snowpack has developed. The mean value of the end-of-December snowpack depth ranges between 18 inches at the South Fork Thunder Creek station (Elevation 2,200 feet) and 121 inches at the Jasper Pass station (Elevation 5,400 feet). Steady accumulation of the snowpack begins in late December/early January and continues through the spring. On average, the snowpack depth peaks by February or March at the two lowest-elevation snow course stations and peaks by March or April at the remaining seven snow course stations. Snowfall can be extreme in the higher elevations, as evidenced by the world record for annual snowfall of 1,140 inches set on Mount Baker during the 1998-1999 season.

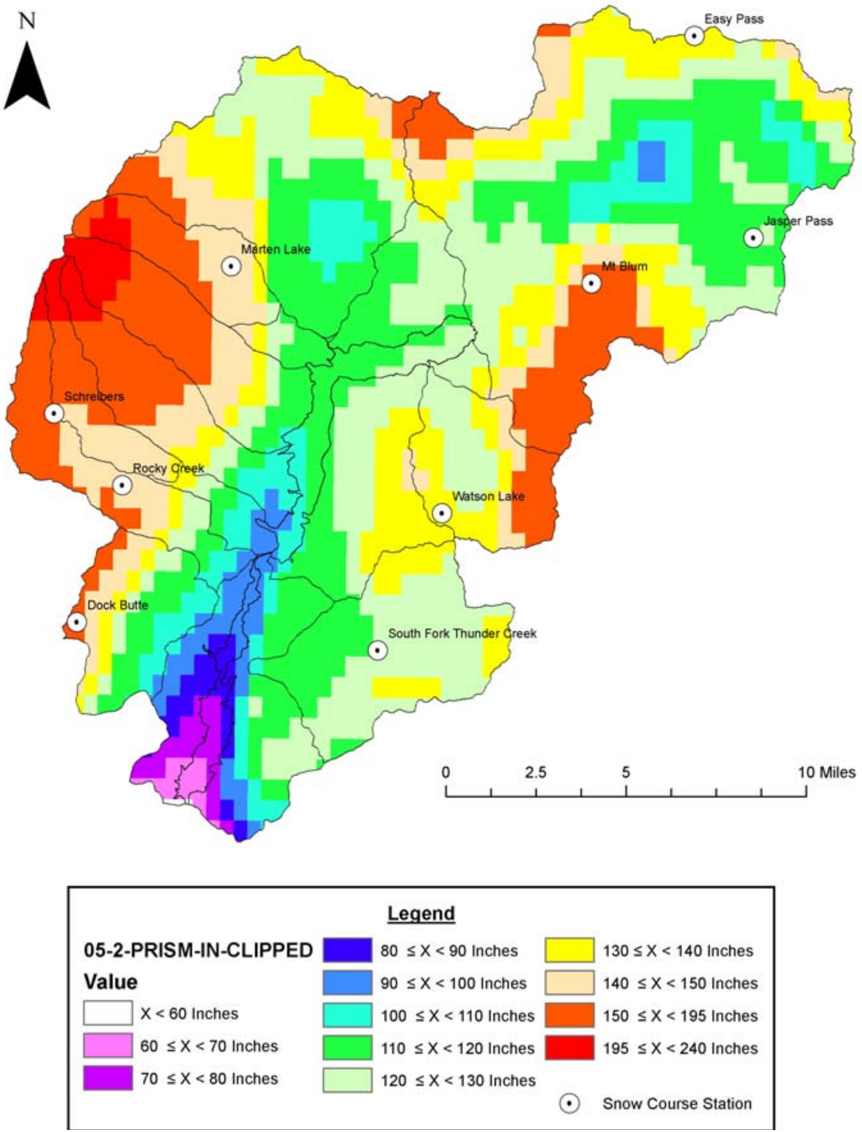

Figure 2-8. Spatial Distribution of Mean Annual Precipitation in Baker River Watershed

3. HYDROLOGIC MODEL AND WATERSHED SUBDIVISION

A hydrologic model of the Baker River basin was developed for use in simulating inflow hydrographs of runoff entering Baker Lake and Lake Shannon in response to extreme precipitation events, including the PMP. This chapter describes the selection of hydrologic modeling software for the Baker River project, the delineation of the watershed into subbasins and hydrologic runoff units, and the modeling approach used for transformation of precipitation into runoff, simulation of interflow, snowmelt and hydrologic routing. More detailed descriptions are provided in *Technical Memorandum No. 7; Model Calibration and Verification* (Tetra Tech, 2006c).

MODEL SELECTION AND METHODOLOGY

The original project work plan identified the USACE HEC-1 model (USACE-HEC 1998a) as the hydrologic model for the Baker River project (Tetra Tech 2005c). In response to a recommendation by the Board of Consultants, the work plan was modified to use the Stochastic Event Flood Model (SEFM) (MGS 2004) in conjunction with the HEC-1 model. The SEFM model functions with the HEC-1 model and provides two capabilities that are absent from HEC-1: the ability to simulate snowpack melt and accumulation using the U.S. Bureau of Reclamation Snow Compaction Procedure (USBR 1966); and the ability to simulate the interflow component of the runoff hydrograph.

For the Baker River project, the SEFM model was initially used in a “deterministic” mode with all parameters fixed. As described in Chapter 8, the stochastic input generation capabilities of the model were used in the sensitivity analysis and provided the basis for determining the final PMF.

The SEFM model simulates snow accumulation and snowmelt and determines excess precipitation (including drainage from the snowpack) after accounting for losses due to infiltration. Infiltrated water is modeled as interflow using a linear reservoir routing procedure. The model’s output includes the time series of precipitation excess, the unit hydrograph ordinates, and the interflow hydrograph. SEFM formats this output into a HEC-1 input file. The HEC-1 model converts the precipitation excess to a surface runoff hydrograph and combines it with the base flow and the interflow hydrograph to produce the total surface runoff hydrograph. Hydrologic routing is also performed by the HEC-1 model.

In addition to the HEC-1 and SEFM hydrologic models, two other modeling programs were used in the study. The Storm Precipitation Analysis System (SPAS) (Tomlinson et al. 2004) was used for distributing point rainfall measurements to a regularly spaced gridded field for each of the events used in the hydrologic model calibration. The Hydrocomp Forecast and Analysis Modeling (HFAM) software was used to provide supplementary information regarding the snowpack conditions for the calibration flood events, which were all early season events.

Figure 3-1 illustrates the relationships among the models used to develop runoff hydrographs for the Baker River watershed and some of the hydrometeorological elements that supported the modeling effort. Gridded mean annual precipitation mapping published by the Oregon Climate Service (OCS 2005), using the Parameter-elevations Regressions on Independent Slopes Model (PRISM), was used as a base map in the SPAS model to distribute point rainfall data. Hourly NEXRAD maps were used to provide additional information on the temporal distribution of the calibration events. Data collected from the nine snow course stations in the watershed and from the SNOTEL stations immediately adjacent to the watershed provided the data to develop air temperature time series for each calibration storm and to determine antecedent snowpack conditions.

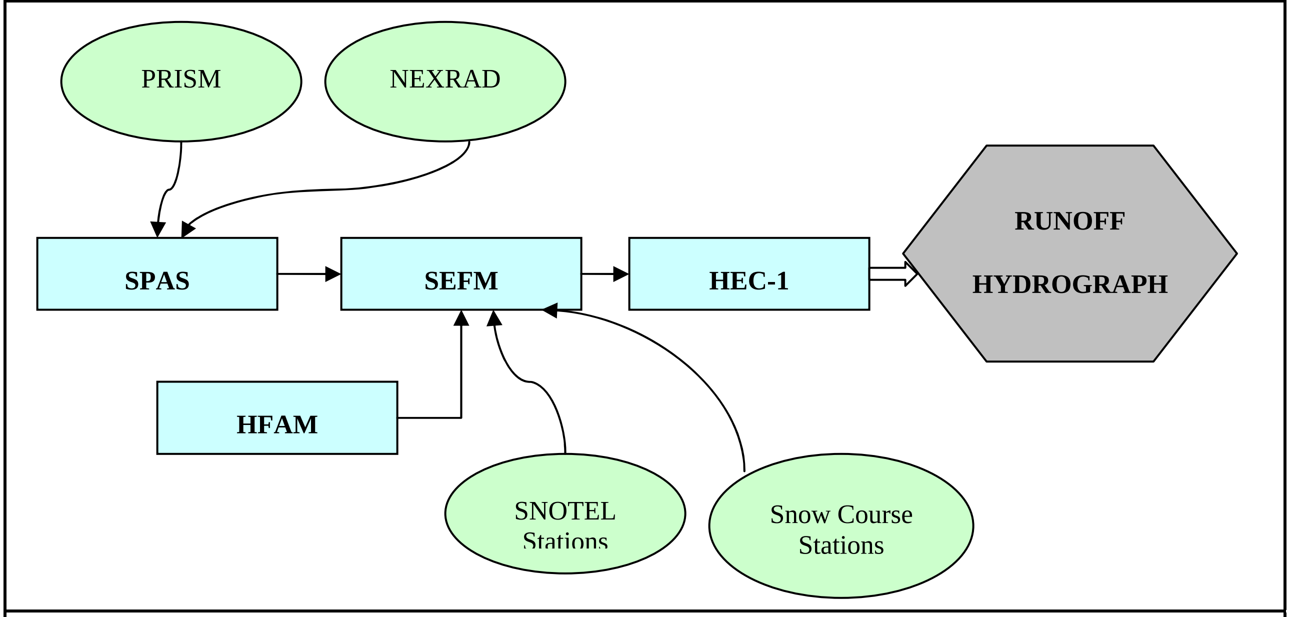

Figure 3-1. Flow Diagram of Models Used in Baker River Project

WATERSHED AND SUBBASIN DELINEATION

Delineation of the 298.7-square-mile Baker River watershed upstream of Lower Baker Dam and delineation of the subbasins was based on topography derived from USGS 10-Meter Digital Elevation Models (DEMs) (USGS 2005). The watershed was subdivided into two tributary areas:

- Upper Baker—the 214.9-square-mile area upstream of Upper Baker Dam
- Lower Baker—83.8-square-mile area locally tributary to Lower Baker and.

Contours at 10-foot increments were developed using ArcGIS 9.0. A hill shade model was developed to aid in the manual delineation of subbasins. The subbasins for two of the tributaries (Sulphur Creek and Park Creek) were further divided to allow for the modeling of portions of these tributaries that were gaged by the USGS at locations upstream of the creek mouth. The Swift Creek and Thunder Creek subbasins were delineated to include the respective USGS gaging stations at the downstream end. The subbasin delineations are shown in Figure 3-2 and summarized in Table 3-1.

HYDROLOGIC RUNOFF UNITS

To account for the spatial variability of soil characteristics, precipitation, and snowpack conditions, a distributed approach was used in the hydrologic model. Therefore, the Baker River watershed was divided for modeling purposes not only into subbasins but also into the following zones:

- **Mean Annual Precipitation Zones**—The watershed was subdivided into eight zones of mean annual precipitation. Several mapping products to identify these zones were evaluated by comparing mean annual precipitation predicted by each product against long-term stream flow records for the watershed. The analysis showed that the 2005 PRISM mapping product (OCS 2005) was the most consistent with the stream flow records, although the PRISM-predicted rainfall was slightly higher than stream flow records for the tributaries in the southeast part of the watershed and slightly lower in the northwest part (Tetra Tech 2005d). The OCS (2005) mapping was adjusted to account for this. Figure 3-3 shows the mean annual precipitation zones based on the revised OCS 2005 mapping.

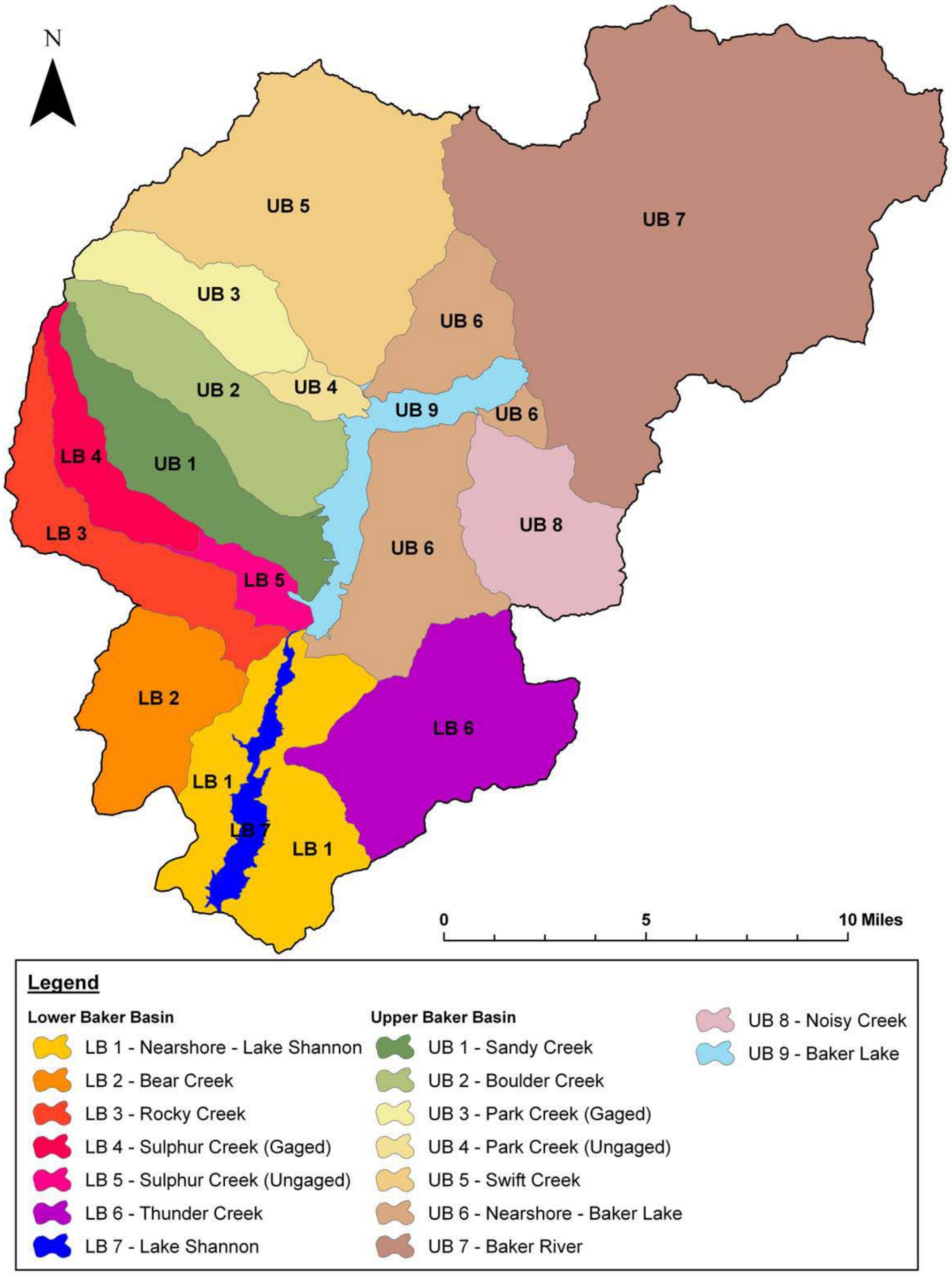

Figure 3-2. Watershed and Subbasin Delineations

Table 3-1. Baker River Subbasin Summary

		Area				Area	
Subbasin	**Subbasin Name**	**Square Miles**	**Acres**	**Subbasin**	**Subbasin Name**	**Square Miles**	**Acres**
LB 1	Nearshore/Lake Shannon	21.2	13,560	**UB 1**	Sandy Creek	13.5	8,626
LB 2	Bear Creek	13.3	8,525	**UB 2**	Boulder Creek	15.4	9,854
LB 3	Rocky Creek	13.0	8,335	**UB 3**	Park Creek - Gaged	9.6	6,146
LB 4	Sulphur Creek - Gaged	6.9	4,410	**UB 4**	Park Creek - Ungaged	2.5	1,592
LB 5	Sulphur Creek - Ungaged	3.2	2,052	**UB 5**	Swift Creek	36.5	23,377
LB 6	Thunder Creek	22.8	14,604	**UB 6**	Nearshore/Baker Lake	26.6	16,993
LB 7	Lake Shannon	3.4	2,193	**UB 7**	Baker River	89.0	56,964
				UB 8	Noisy Creek	14.1	9,005
				UB 9	Baker Lake	7.7	4,916

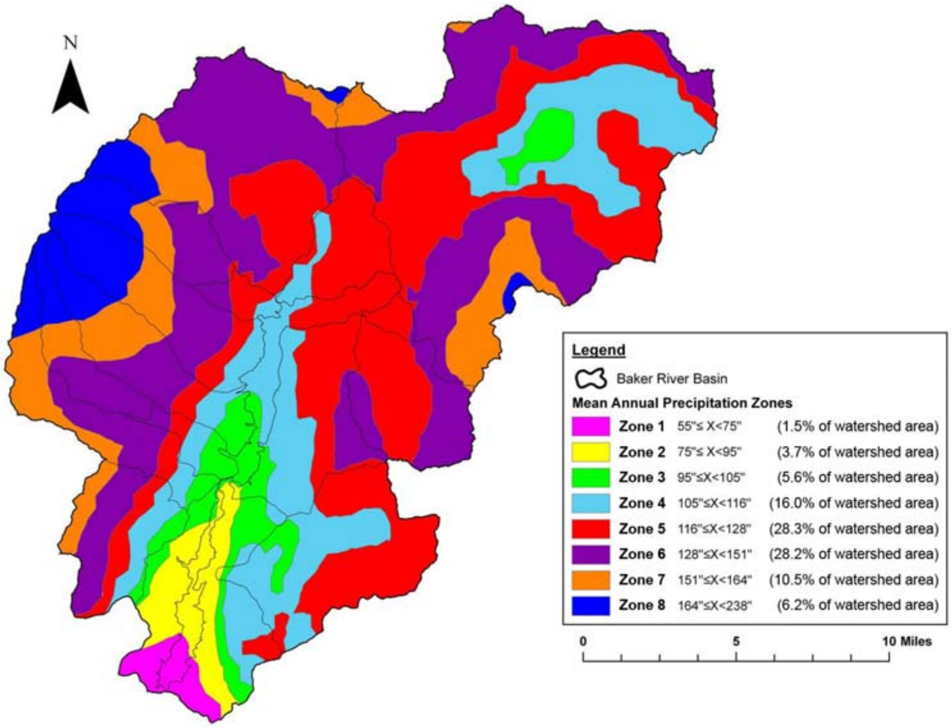

Figure 3-3. Modeled Mean Annual Precipitation Zones

- **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. 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 elevation zones are shown in Figure 3-4.
- **Soil Zones**—The history of glaciation and volcanic activity in area has led to a tremendous degree of spatial variability in the texture and depth of the surface soil and the physical properties of the underlying bedrock material. This necessitated the need to subdivide the watershed into soil zones, differentiated by soil and bedrock material. The watershed was originally delineated into 10 soil zones (Tetra Tech 2006c), which were subsequently modified to address comments from the BOC (Mason et al. 2005). The soil zones are shown in Figure 3-5 and described in Table 3-2.

ArcGIS was then used to create 253 hydrologic runoff units (HRUs) from the intersections of the soil, elevation and mean annual precipitation zones. Each HRU represents a unique combination of soil type, elevation and mean annual precipitation. The subbasin delineations were then intersected with the HRU delineations, and subbasin-specific HRU area components were tabulated.

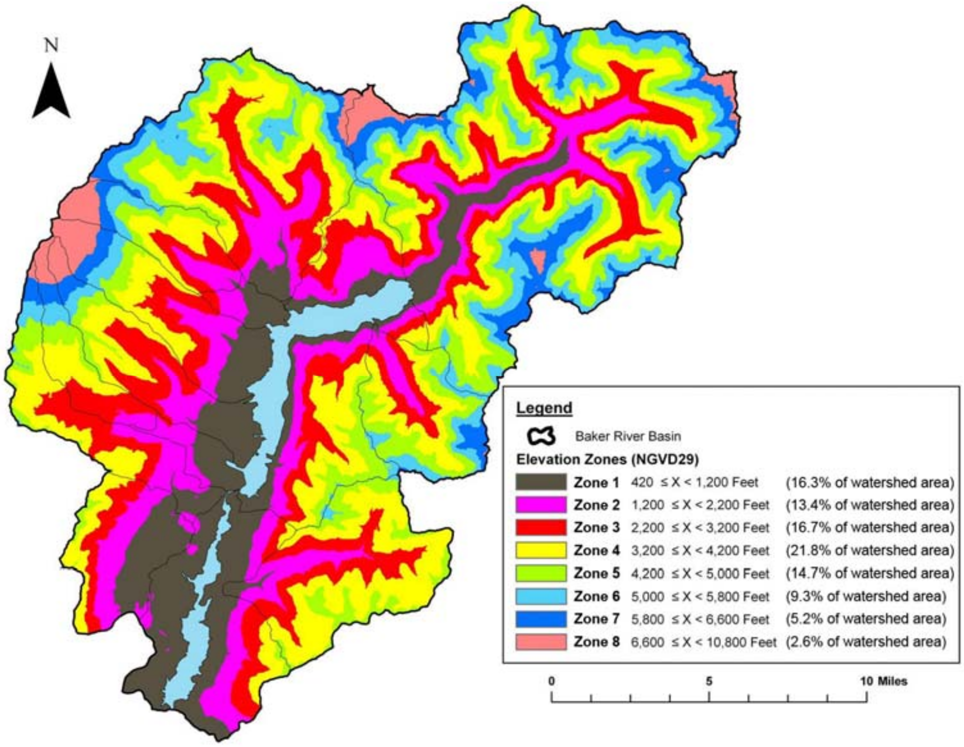

Figure 3-4. Modeled Elevation Zones

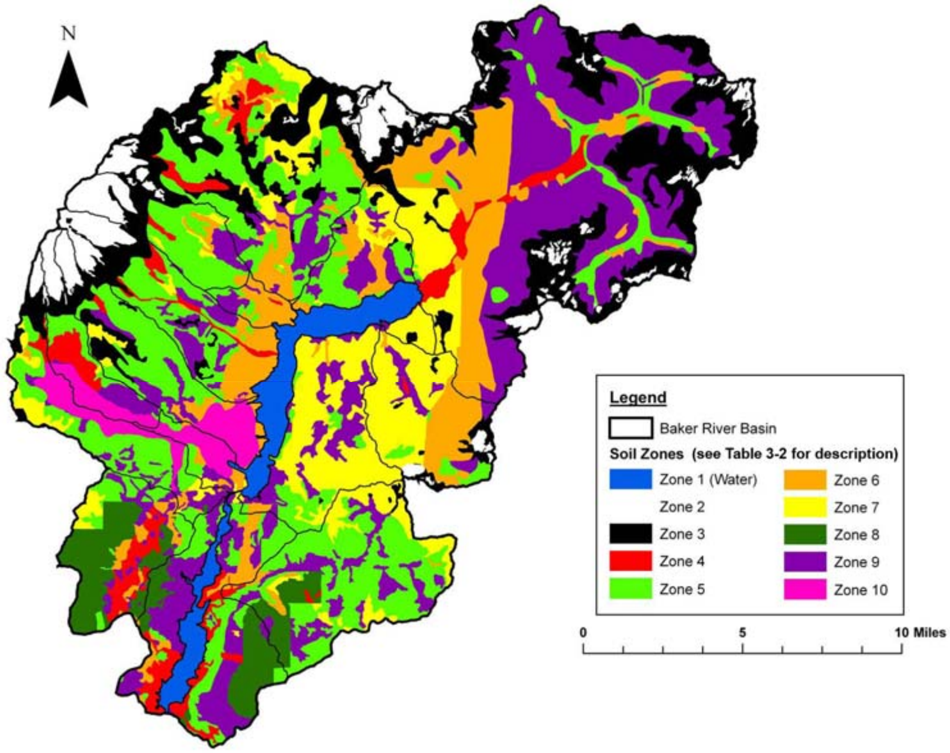

Figure 3-5. Modeled Soil Zones

Table 3-2. Description of Soil Zones

Soil Zone	SCS Hydrologic Group	Surface Layer	Median Surface Layer Depth	Bedrock	Portion of Total Watershed Area
1	—	Open water	—	—	3.7%
2	—	Glacier	—	—	5.0%
3	—	Very shallow soil over bedrock outcropping	6”	Moderate to highly fractured	14.5%
4	A	Very gravelly loams, loamy sands, and glacially deposited sands and gravels.	48”	Minimally fractured	4.1%
5	B	Gravelly silt loams and finer sandy loams, silty loams, loamy sands and loams	18”	Moderate to highly fractured	21.1%
6	B	Same as Zone 5	28”	Minimally fractured	11.2%
7	B	Same as Zone 5	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 and organic material	38”	Minimally fractured	21.4%
10	—	Deep sandy loams	28”	Recent basalt/andesite lava flows in Sulphur Creek basin	2.8%

RAINFALL RUNOFF AND INTERFLOW

Surface runoff hydrographs representing excess precipitation were developed for each subbasin using a unit hydrograph method with a 30-minute duration. The effective excess rainfall for each unit duration—after accounting for drainage from the snowpack, surface infiltration, and loss to deep groundwater—was determined with the SEFM software. The HEC-1 model was used to transform the effective rainfall time series to surface runoff hydrographs using a synthetic unit hydrograph analogous to the Snyder unit hydrograph. Unique unit hydrographs were developed for each of the delineated subbasins, including the subbasins that represented the reservoir surfaces.

Precipitation that infiltrates into the soil can flow through subsurface layers, including fractured bedrock layers, and emerge downslope in a stream channel; this subsurface flow is referred to as interflow. The interflow component of the runoff hydrograph was computed in SEFM using a two-stage linear reservoir routing procedure. The two reservoirs (storage zones) are characterized by separate storage constants, which are used to define the interflow lag time.

SNOWMELT

Snowmelt was computed in the SEFM using a form of the Bureau of Reclamation’s Snow Compaction methodology (USBR 1966). This methodology uses empirical energy budget snowmelt equations similar to those included in HEC-1. However, the improvement over the methodology included in HEC-1 is the incorporation of a water budget algorithm that tracks the changing conditions in snow water equivalent and snowpack density throughout the duration of the simulation. This allows for the explicit modeling of snowpack “ripening” when snowpack conditions are such that the snowpack is not yet fully capable of yielding melt water.

Significant drainage from a snowpack has been found to take place when the snowpack reaches 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. For densities less than the yield density, free water is retained in the snowpack. Once the snowpack density reaches the threshold density, the model allows the pack to melt, thereby releasing free water. The magnitude of released water is computed using the empirical energy budget snowmelt equations.

CHANNEL ROUTING

Each subbasin was delineated with its outlet at the reservoir. The Park Creek and Sulphur Creek subbasins were further delineated at the USGS gaging station locations. In these subbasins, channel routing was only necessary for the channels downstream of the gaging stations. These channel lengths are relatively short—9,900 feet for Park Creek and 18,450 feet for Sulphur Creek—so channel routing was not critical. The kinematic wave technique was used for hydrologic routing, and all channel parameters that were required for the routing model were obtained from USGS field notes for the two gaging stations.

4. HYDROLOGIC MODEL CALIBRATION AND VERIFICATION

This chapter summarizes the calibration of the Baker River watershed hydrologic model. A more detailed description is provided in *Technical Memorandum No. 7; Model Calibration and Verification* (Tetra Tech, 2006c).

MODEL CALIBRATION METHODOLOGY

General Approach

The hydrologic model was calibrated and verified by comparing hydrographs produced by the model to inflow hydrographs reconstructed from observed historical data for Baker Lake (Upper Baker Dam) and Lake Shannon (Lower Baker Dam) and inflow hydrographs from the Swift Creek and Park Creek USGS gaging stations. Separate inflow hydrographs were developed for the Upper Baker and Lower Baker tributary areas. Hourly reservoir elevation and discharge data were used to construct reservoir inflow hydrographs for several storm events selected for the calibration.

Model calibration was conducted using the Generalized Likelihood Uncertainty Estimation (GLUE) procedure (Beven and Binley, 1992). This procedure is based on the premise that "there is no reason to expect that any one set of parameter values will represent a true parameter set … it is only possible to make an assessment of the likelihood or probability of a particular parameter set being an acceptable simulator of the system." The uncertainty associated with replicating observed data results from the compounding of error that is inherent in the model and in the measurements upon which the calibration is based. The GLUE procedure allows for the recognition of multiple parameter sets that reasonably replicate the observed conditions, and assigns a likelihood to each parameter set based on an objective measure of the "goodness-of-fit" between the simulated results and the observed conditions (how well the simulated hydrograph matches the observed hydrograph).

The procedure is based on performing a large number of model runs with sets of parameter values chosen randomly from a specified parameter range. The stochastic input generation component of SEFM lends itself to generating the large number of input parameter sets. For the Baker River watershed hydrologic model, multi-thousand input parameter sets were randomly developed in SEFM based on a realistic but wide range of values for each input parameter. The hydrologic model was then executed for each set. The results of each model run were evaluated using a quantitative measure of the goodness-of-fit between the observed and simulated runoff hydrographs. Parameter sets whose goodness-of-fit failed to achieve a pre-defined threshold value were eliminated, enabling the sampling range for each parameter to be reduced to a narrower range. This process was repeated until the evaluation of the goodness-of-fit could not justify further narrowing of the sampling ranges. The final step of the calibration process was to generate multi-thousand input parameter sets based on sampling from the final narrowed sampling ranges, using a likelihood measure to identify "behavioral" parameter sets, and then ranking the behavioral parameter sets based on the likelihood measures. Behavioral sets are those determined to be most representative of historically recorded conditions.

Model calibration and verification proceeded in five phases:

- **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

Objective Functions

"Objective functions" provide the quantitative measurement of goodness-of-fit. Two objective functions were selected for use in the model calibration (both are calculated by comparing simulated flow to observed historical flow at each time increment of the simulation):

- A modified form of the objective function included in the HEC-1 package (USACE-HEC 1998a); this objective function uses an equation weighted to place greater emphasis on matching peak flows and lesser emphases on lower flows. For this objective function, smaller values represent a better fit, with 0.0 representing a perfect fit.
- The Nash-Sutcliffe Efficiency (NSE) objective function (Lamb 1999); this 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 the observed and simulated conditions increases, with 1.0 representing a perfect fit.

Both objective functions were computed for each observed hydrograph for each flood event used in the calibration. For flood events for which observed hydrographs were available at multiple locations in the watershed, a method of weighting was used to compute the objective function for the flood event. The objective function for the flood event was computed as a weighted sum of the objective functions computed for the individual observed hydrographs, with the individual hydrograph weighting based on the tributary drainage area as a portion of the entire watershed. For example, a flood event that used observed inflow hydrographs into Upper Baker and Lower Baker reservoirs used weighting factors of 0.70 and 0.30 for the Upper Baker and Lower Baker inflow hydrographs, respectively.

Scatter Plot Analysis

The behavior of the hydrologic model in response to each input parameter was evaluated with the use of scatter plots. Scatter plots were created from the output of the multi-thousand simulations by plotting the value of the parameter on the X-axis and the value of the objective function on the Y-axis. Figure 4-1 shows an example scatter plot of NSE objective function versus upper zone interflow storage constant for the November 1989 Park Creek Subbasin runoff hydrograph. The general trend of the scatter plot indicates that lower values for the upper zone interflow storage constant produce better fits to the observed hydrograph, as evidenced by the resulting higher values of the NSE objective function.

Scatter plots were used in the GLUE procedure to evaluate sensitivity of the objective functions (and hence the hydrologic model) to the range of values for each model input parameter and to indicate which input parameters were most dominant in influencing model output. The scatter plots also allowed the range of values for each input parameter to be successively narrowed in order to find the values of each parameter that result in the best simulation, as measured by objective functions. This was generally achieved by defining threshold values for the objective functions and then narrowing the sampling range for the parameter being evaluated to only those values that meet or exceed the threshold. For example, in the scatter plot in Figure 4-1, if the NSE objective function threshold were set at 0.75, then the values of upper zone interflow storage constant for further analysis would be limited to those in the narrowed sampling range shown on the figure, where the NSE values are all 0.75 or greater.

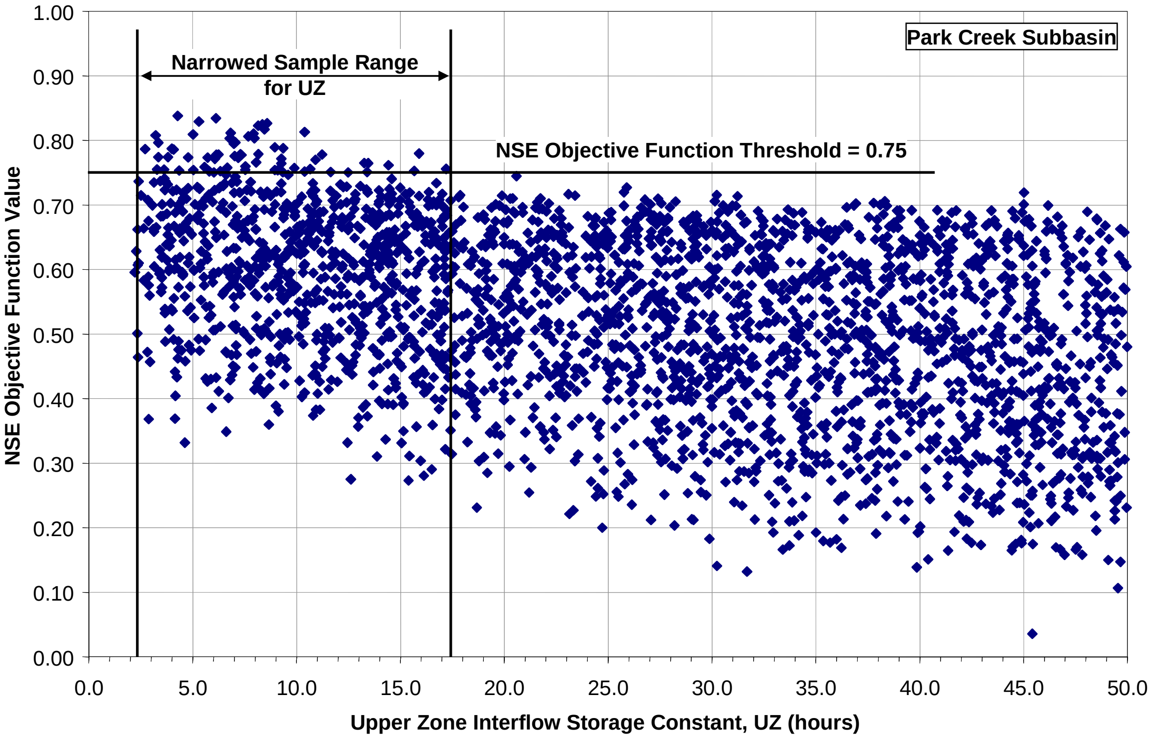

Figure 4-1. Example Scatter Plot Showing Analysis

Likelihood Measures

A likelihood measure was used to identify the behavioral parameter sets that are most likely to produce model results that are most representative of the observed conditions. Behavioral parameter sets are those that result in simulated hydrographs that are acceptably close to the observed hydrographs. The objective functions were used to set the value of the likelihood measure for each parameter set using the following equation:

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

where,

L_k = the likelihood measure for flood event k, which has observed hydrographs at multiple sites

HEC_{group} = the value of the modified HEC objective function for the flood event

M = a user specified parameter, which for this study was assumed to be 1.0 (if M=0, then all behavioral parameter sets have equal likelihood; as the value of M is increased, the single best parameter set has an increasingly greater likelihood relative to all other parameter sets)

The value of the likelihood function for a given parameter set for the group of flood events was computed using Equation (2).

$$Lps = \sum_{k=1}^{n} L_k W_k \tag{2}$$

where,

L_{ps} = the likelihood measure for a given parameter 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. All flood events were given equal weight.

STORM EVENTS USED FOR CALIBRATION AND VERIFICATION

Hourly precipitation data in the Baker River watershed was obtained from the National Climate Data Center (NCDC). Synthesized daily inflows into Baker Lake and Lake Shannon were obtained from PSE. Using the precipitation data and inflow information, a ranking methodology was used to rank storm events since 1949 for use as a calibration/verification event. The list was reviewed to ensure that events with the highest precipitation intensities and events that had potential snowmelt contribution to runoff were included at the top of the list.

Identification, Ranking and Initial Selection of Candidate Storm Events

An initial candidate list of runoff events was created by identifying events that produced either a mean daily inflow or a mean three-day inflow that equaled or exceeded the value associated with the 5-year return period. This was done for both the Baker Lake inflows and the Lake Shannon inflows. This resulted in a list of 47 events (see Appendix B).

Nine numerical parameters were then determined for each of the 47 candidate events (e.g., maximum daily and maximum three-day inflow to Baker Lake and to Lake Shannon; inflow return period; recorded precipitation). For each parameter, the highest value among the 47 candidate events was assigned a rating of 1, and lower values were assigned fractional ratings according to the ratio of the lower value to the highest value. Totaling the rating for all nine parameters yielded an overall score for each candidate event, and the events were ranked based on these overall scores (see Appendix B).

The top 15 events were then considered in more detail. Additional consideration was given to the data that would be available for use in the calibration of the runoff model (e.g., air temperature data, snow data, stream flow data). Based on this review, five events were initially identified for potential use in calibrating the hydrologic model (see Table 4-1), with the intention that the inflow hydrographs for both Upper and Lower Baker tributary areas would be used for each event. In addition, the Swift Creek and Park Creek hydrographs derived from the USGS stream gage data were used in the calibration to the November 1989 event. A detailed description of the process used to identify these events is provided in the technical memorandum *Baker River Project Part 12 PMP/PMF Study - Calibration/Verification Events* (Tetra Tech 2005a)

Final Reduction of Storm Events for Calibration

Of the five initially identified events, the November 90 (2) event was eliminated from further consideration due primarily to the lack of sufficient data to define the atmospheric lapse rate. This was important information for this storm because a large portion of the watershed was likely experiencing sub-freezing temperatures throughout this event, which would affect the balance between snow accumulation and snowmelt. Initial model runs for this storm failed to produce a hydrograph that properly matched the observed hydrograph.

Table 4-1. Events Used for Model Calibration/Verification

				Inflow Hydrograph Volume (acre-feet)			
Ranking	**Event**[a]	**Start Date—End Date**[b]	**Event Length (hours)**	**Upper Baker**	**Lower Baker**	**TOTAL**	**Ratio of UB/LB**
1	November 1990 (1)	11/8/90—11/14/90	144	152,567	46,167	198,734	3.3
2	November 1990 (2)	11/21/90—11/26/90	120	98,399	39,918	138,317	2.5
3	October 2003	10/14/03—10/19/03	120	103,501	17,480	120,981	5.9
4	November 1989	11/8/89—11/12/89	96	102,676	34,300	136,976	3.0
5	November 1995 (2)	11/26/95—12/1/95	120	100,954	38,140	139,094	2.6

a. The number 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.

Of the remaining four storm events, the events chosen to be used for model calibration were the November 89, November 95 (2) and October 03 events; the event used for model verification was the November 90 (1) event.

Because a single low-elevation gage is the only source of hourly precipitation data within the Baker River Watershed, determination of the spatial distribution of the precipitation for the calibration storm events, especially in the higher elevations of the watershed, was challenging. The need for high-elevation precipitation information was especially critical for the October 2003 event given the high ratio of Upper Baker runoff volume relative to Lower Baker runoff volume for that storm, as shown in Table 4-1. Spatial precipitation mapping of these historical events proved challenging, and was especially so for the November 95 (2) and October 03 events. Preliminary runs of the hydrologic model for these two events resulted in volumetric error for the Upper Baker inflow hydrograph of more than 20 percent. For this reason, the Upper Baker inflow hydrograph for these two events was eliminated from use in the calibration process.

The Swift Creek and Park Creek hydrographs that were available for the November 89 event were used as supplemental hydrographs for the hydrologic model calibration. They were both used during the hydrograph volume calibration step (Phase I) to provide additional insight while calibrating the interflow parameters and during the hydrograph shape calibration step (Phase II) to validate decisions regarding the period of rise parameter.

Table 4-2 summarizes the final storm events used for calibration and verification and the specific hydrographs used for each event.

Table 4-2. Hydrographs Used for Model Calibration/Verification

			Hydrographs Used for Comparison			
Event	**Used for Calibration**	**Used for Verification**	**Swift Creek Tributary**	**Park Creek Tributary**	**Baker Lake Inflow**	**Lake Shannon Inflow**
November 89	X		X	X	X	X
November 90 (1)	X	X			X	X
November 95 (2)	X					X
October 03	X					X

Reconstructed Inflow Hydrographs for Model Calibration

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), hydrographs were developed using hourly operations data provided by 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. Inflow rate was calculated at 1-hour intervals from the outflow hydrograph and the change in reservoir elevation, assuming conservation of mass. The reconstructed inflow 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 was done in a way to ensure that the change in volume due to the smoothing was less than 5 percent of the inflow volume associated with the 5-hour moving average hydrograph.

Hydrographs for Park Creek and Swift Creek for the November 89 event were developed from archived USGS records of hourly stage data and the appropriate USGS published rating curves for the gages on these two creeks.

METEOROLOGICAL INPUT

The collection and analysis of meteorological data described in this section were performed for all five of the initially identified calibration storm events.

Precipitation

For the historical storm events evaluated, recorded hourly precipitation was available only for a single station in the watershed (Upper Baker Dam Station No. 458715); recorded daily precipitation was available for an additional station (Concrete PPL Fish Station No. 451679). Additionally, for the 1995 and 2003 storms, pseudo precipitation stations were created within the watershed using NEXRAD data (Applied Weather Associates 2006) and hourly rainfall values at these stations were computed. High spatial resolution hourly rainfall fields were developed using the precipitation data in and adjacent to the Baker River watershed through the use of the SPAS and Geographical Information System (GIS) software.

Air Temperature

The SEFM model assumes that liquid precipitation falls as snow in a given elevation zone if the air temperature is less than the freezing temperature plus 2 degrees Fahrenheit. Available air temperature data for the watershed is limited to daily reports of maximum and minimum temperatures at the Upper Baker Dam precipitation station. For modeling purposes, time series of hourly temperatures at the Upper Baker Dam Station were developed from the daily records and were supplemented with a known hourly temperature time series at a nearby reference station. From the time series developed at the Upper Baker Dam station, air temperature time series for each of the watershed’s eight elevation zones were adjusted using lapse rates calculated from the upper-air radiosonde data. Knowing the percentage of watershed area in each elevation zone, this allowed estimates of the area subject to snowmelt at each one-hour increment for the duration of the storm event. Figures showing the air temperature time series and the computed freezing level time series for each calibration storm event are provided in Appendix B.

Antecedent Snowpack

Output from the calibrated HFAM model for the Baker River watershed included daily values of snowpack density and snow water equivalent at seven of the nine snow course sites in the watershed. Snow water equivalent and snowpack density were exported from HFAM for the first day of each storm event. Using these values from each of the seven snow course sites, relationships were developed between snow water equivalent, elevation and mean annual precipitation for each storm event used in the calibration. These relationships allowed determination of snow water equivalent for each hydrologic runoff unit. Appendix B includes a table showing the estimated snow water equivalent by elevation zone and precipitation zone for each calibration storm event.

DEVELOPMENT OF INITIAL HYDROLOGIC PARAMETER SAMPLING RANGES

Estimates of soil, unit hydrograph and interflow parameters are required to describe the hydrologic response of the watershed to each calibration event. This section provides a summary of the development of the initial values of parameters that were considered fixed in the calibration procedure and the initial sampling range for parameters that were used to calibrate the model with the GLUE procedure. The initial sampling range for each calibration parameter represents a wide yet physically reasonable range of values for the Baker River watershed based on the literature. Sampling ranges were developed as described below for all five of the initially identified calibration storm events. The November 90 (2) event was removed from further evaluation only after the completion of this initial analysis.

Surface infiltration is computed in SEFM using the Holtan Loss Equation, which computes surface infiltration (f) at each time interval of the simulation as a function of the available soil moisture storage capacity at the start of the time interval, the maximum soil moisture storage capacity (S_{max}), the maximum surface infiltration rates (f_{max}), and the minimum or constant infiltration rate (f_c).

Excess precipitation is converted to runoff in SEFM using a form of the Snyder synthetic unit hydrograph methodology. The parameters that describe the unit hydrograph are the period of rise of the unit hydrograph (P_r) and a peaking factor (C_p).

Soil Moisture Parameters

A soil moisture budget algorithm, using a monthly time step, was used in SEFM to determine the water storage deficit of each soil zone at the onset of each calibration event. This deficit was in turn was used to determine the initial infiltration rate at the beginning of the each event. The following input parameters were used in defining the soil moisture deficit antecedent to each calibration event and all of them were considered fixed parameters in the calibration process:

- **Antecedent Precipitation** during the days prior to the storm event. Antecedent precipitation is defined as the cumulative precipitation that fell from October 1 until the day before the calibration event. Antecedent precipitation in the Baker River watershed was based on cumulative precipitation data from the Upper Baker Dam precipitation station.
- **Potential evapotranspiration**, as determined on an individual water year basis, using a grass-related, temperature-based method (Hargreaves et al. 1982, 1985). This method was used to compute monthly evapotranspiration using recorded temperatures at Upper Baker Dam for the water year associated with each historical calibration event. Values were adjusted to each elevation zone based on an assumed lapse rate of 4ºF per 1,000 feet.
- **Change in snow water equivalent**, based on end of month snow water equivalent, estimated as described in the above description of antecedent snowpack. The monthly change in snow water equivalent in the months leading up to the calibration event was input into the soil moisture budget algorithm.

Soil Parameters and Forest Cover

The initial sampling range for each soil parameter in the Holtan Loss Equation was estimated based on a review of the available soil literature and data for the Baker River watershed. A fourth parameter, the deep percolation parameter (f_d), is not a part of the Holtan Loss Equation, but is used in SEFM to account for infiltrated water that is permanently lost to deep aquifers. The forest cover parameter is used in the snowmelt equation of SEFM.

- The **maximum soil moisture deficit (S_{max})** for a given soil is a function of soil depth and the available water capacity of the soil. To establish the initial sampling range for this parameter, the soil depth was assumed to be the median value of the surface layer of all soil units making up each soil zone (see Table 3-2), and the available water capacity of the soil was assumed to range between 0.03 and 0.4 inches of water per inch of soil (NRCS 1994a, NRCS 1994b, USFS 1970).
- The **minimum infiltration rate (f_c)** was assumed to be a function of the SCS hydrologic soil class, and the initial sampling range was based on values published in Maidment (1993). For glacial areas (Soil Zone 2), the minimum infiltration rate was fixed at an artificially high value in order to model all excess precipitation as interflow or losses to deep groundwater.
- The **maximum surface infiltration rate (f_{max})** was based on permeability rates obtained from USFS (1970), the NRCS SSURGO database (NRCS 1994a), and the NRCS STATSGO database (NRCS 1994b). A representative fixed value of the permeability rate was chosen for each soil zone based on the predominant soil texture.
- The **deep percolation parameter (f_d)** allocates runoff between groundwater and interflow and is based on bedrock material and texture. Bedrock that is porous or highly fractured is expected to allow for higher rates of deep percolation. The initial sampling range for the deep percolation parameter was highest for the Sulphur/Rocky Creek and glacial soil zones, slightly lower for soil zones with moderate to high degrees of fracturing (Soil Zones 3, 5, 7 and 8), and lowest for soil zones with minimally fractured bedrock (Soil Zones 4, 6 and 9).
- **Forest cover** was developed from the 1992 National Land Cover Dataset. The percent of forest cover per elevation zone was determined using GIS. These percentages are used in the SEFM snowmelt equation in setting the convection melt coefficient and were assumed to be fixed for all simulations. Only the land use classification for deciduous, evergreen, and mixed forest were used in computing the percent of forest cover per elevation zone.

Unit Hydrograph and Interflow Parameters

Because there are no previously developed unit hydrographs for the Baker River watershed or any of its tributaries, a synthetic unit hydrograph technique was used in SEFM to develop surface runoff hydrographs. The shape of the unit hydrograph is determined internally in the SEFM model based on a gamma distribution and on the values of the period of rise and the peaking factor of the unit hydrograph.

The period of rise for a given subbasin is a factor of the lag time, which is defined as the elapsed time from the centroid of the precipitation event that produces runoff to the occurrence of the peak discharge at the subbasin outlet. As a starting point, the lag time equation presented in USBR (1989) was used to compute the period of rise parameter for each subbasin. This equation calculates lag time based on the basin size and the length, slope and channel roughness of the principal water courses. A range of values for the channel roughness coefficient were input into the USBR (1989) equation to develop the initial sampling range of the period of rise parameter.

The initial sampling range of the peaking factor was based on guidance presented in MGS (2004).

A very wide initial sampling range was assumed for both the upper and lower zone storage constants to account for the potentially long time delays in the interflow hydrograph attributed to the presence of glaciers, fractured bedrock, and deep volcanic geologic material. Throughout the model calibration, the upper zone storage constant was computed as a function of the period of rise, and the lower zone storage constant was computed as a function of the upper zone storage constant. This ensured that the lag times for the interflow component were longer than that for the surface runoff component

Summary

Based on the analyses described above, the initial sampling ranges of key hydrologic parameters were established as summarized in Tables 4-3 and 4-4.

CALIBRATION AND VERIFICATION RESULTS

Phase I Calibration—Hydrograph Volume

The first phase of the calibration process focused on narrowing the initial sampling range for the upper and lower interflow zone storage constants, which have an indirect effect on runoff volume, and on determining reasonable fixed values for the parameters that most directly affect runoff volume—the rate of deep percolation and the maximum soil moisture storage capacity.

Table 4-3. Initial Sampling Range for Subbasin Calibration Parameters

Subbasin	Period of Rise, P_r (minutes)	Peaking Factor, C_p	Interflow Storage Constants (hours)	
			Upper Zone (UZ)	**Lower Zone (LZ)**
Sandy Creek (UB1)	140—300	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Boulder Creek (UB2)	120—260	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Park Creek-Gaged (UB3)	110—240	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Park Creek-Ungaged (UB4)	100—210	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Swift Creek (UB5)	160—350	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Nearshore Baker Lake (UB6)	110—230	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Baker River (UB7)	180—410	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Noisy Creek (UB8)	120—250	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Baker Lake (UB9)	*Open Water*	*Open Water*	*Open Water*	*Open Water*
Nearshore Lake Shannon (LB1)	100 - 200	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Bear Creek (LB2)	100—210	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Rocky Creek (LB3)	180—400	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Sulphur Creek-Gaged (LB4)	130—280	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Sulphur Creek-Ungaged (LB5)	90—190	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Thunder Creek (LB6)	150—320	450—550	$P_r/60 + 1$ to 50	UZ + 1 to 200
Lake Shannon (LB7)	*Open Water*	*Open Water*	*Open Water*	*Open Water*

Table 4-4. Initial Sampling Range for Soil Calibration Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (inches)	Deep Percolation Rate, f_d (inches/hour)	Minimum Surface Infiltration Rate, f_c (inches/hour)	Maximum Surface Infiltration Rate, f_{max} (inches/hour)
1	*Open Water*	*Open Water*	*Open Water*	*Open Water*
2	0	0.10—0.50	f_d + 10	10.0
3	0.4—11.1	0.00—0.30	f_d + (0.00 to 0.30)	4.0
4	0.2—12.0	0.00—0.10	f_d + (0.00 to 0.40)	6.0
5	0.4—11.1	0.00—0.30	f_d + (0.00 to 0.30)	4.0
6	0.6—16.5	0.00—0.10	f_d + (0.00 to 0.30)	4.0
7	0.6—24.8	0.00—0.30	f_d + (0.00 to 0.30)	4.0
8	0.4—12.6	0.00—0.30	f_d + (0.00 to 0.15)	4.0
9	0.2—18.0	0.00—0.10	f_d + (0.00 to 0.15)	2.0
10	0.6—24.8	0.10—0.50	f_d + (0.00 to 0.30)	4.0

Interflow Storage Constants—Initial Narrowing

Scatter plots for the November 89 storm event for the two gaged tributaries, Swift Creek and Park Creek, were developed to show objective function (goodness-of-fit) versus each interflow storage constant for 3,000 model simulations. These plots clearly showed that lower values of the storage constants resulted in simulations with better goodness-of-fit. The plots also showed that the storage constants giving the best fit for the Park Creek subbasin hydrograph were lower than those giving the best fit for the Swift Creek subbasin hydrograph. Based on this observation, the rest of the subbasins in the watershed were grouped based on their geologic and hydrologic similarity as being more like the Park Creek or Swift Creek, as follows:

- Group I—Nearshore Lake Shannon, Bear Creek, Rocky Creek, Sulphur Creek (gaged and ungaged), Sandy Creek, Boulder Creek, Park Creek (gaged and ungaged)
- Group II—Thunder Creek, Swift Creek, Nearshore Baker Lake, Baker River, Noisy Creek.

Based on the evaluation of the scatter plots, the range of interflow storage constants was narrowed as follows:

- For Group I (values achieving an NSE objective function threshold of 0.75):
  - Upper zone storage constant = Period of rise + 1 to 20 hours
  - Lower zone storage constant = Upper zone constant + 1 to 10 hours
- For Group II (values achieving an NSE objective function threshold of 0.70):
  - Upper zone storage constant = Period of rise + 1 to 25 hours
  - Lower zone storage constant = Upper zone constant + 1 to 20 hours

Maximum Soil Moisture Storage Capacity

Another 3,000 simulations of the hydrologic model were executed, using the reduced range of interflow storage constant values. Parameter sets were identified that resulted in a total runoff volume for each storm event within 10 percent of the observed volume for the Lower Baker inflow hydrograph, the Upper Baker inflow hydrograph and the total of the two hydrographs. Eighteen parameter sets were identified that achieved this threshold for all three calibration storm events (November 89, November 95 (2), and October 03). A fixed value for maximum soil moisture capacity was calculated for each soil zone as the average value for these 18 parameter sets. Table 4-5 shows the results.

Table 4-5. Calibrated Values of Maximum Soil Moisture Storage

Soil Zone	Maximum Soil Moisture Storage (inches)	Soil Zone	Maximum Soil Moisture Storage (inches)
1	*Open Water*	6	7.84
2	0	7	10.10
3	5.58	8	5.89
4	5.02	9	6.49
5	3.80	10	10.59

Interflow Storage Constants—Further Narrowing

Another 3,000 simulations of the hydrologic model were executed, using the reduced range of interflow storage constant values and the fixed values for the maximum soil moisture storage capacity (Table 4-5). Scatter plots were generated and reviewed. The plots indicated the need for a third subbasin grouping for the interflow storage parameter, as well as the opportunity to further narrow the sampling range for the interflow storage constants of the previously defined subbasin groupings. Additionally, the initial sampling range for the deep percolation parameter was narrowed for Soil Zones 4 and 8. The final grouping for the interflow parameters was as follows:

- Group I (Rocky Creek, Sulphur Creek (gaged and ungaged), Sandy Creek, Boulder Creek, Park Creek (gaged and ungaged)):
  - Upper zone storage constant = Period of rise + 1 to 18 hours
  - Lower zone storage constant = Upper zone constant + 1 to 15 hours
- Group II (Thunder Creek, Swift Creek, Nearshore Baker Lake, Baker River, Noisy Creek):
  - Upper zone storage constant = Period of rise + 1 to 15 hours
  - Lower zone storage constant = Upper zone constant + 1 to 15 hours
- Group III (Nearshore Lake Shannon, Bear Creek):
  - Upper zone storage constant = Period of rise + 1 to 7 hours
  - Lower zone storage constant = Upper zone constant + 1 to 5 hours

Rate of Deep Percolation

Another 3,000 simulations of the hydrologic model were executed, using the further reduced range of interflow storage constant values, the fixed values for soil moisture storage capacity (Table 4-5), and the narrowed sampling range for Soil Zones 4 and 8. Parameter sets were identified that resulted in a total runoff volume for each storm event within 10 percent of the observed volume for the Lower Baker inflow hydrograph, the Upper Baker inflow hydrograph and the total of the two hydrographs. Two parameter sets were identified that achieved this threshold for all three calibration storm events (November 89, November 95 (2), and October 03). A fixed value for deep percolation rate in each soil zone was calculated as the average value for these two parameter sets. Table 4-6 shows the results.

Table 4-6. Calibrated Values of Deep Percolation Rate

Soil Zone	Deep Percolation Rate (inches/hour)	Soil Zone	Deep Percolation Rate (inches/hour)
1	*Open Water*	6	0.071
2	0.209	7	0.197
3	0.044	8	0.115
4	0.058	9	0.067
5	0.115	10	0.374

Unit Hydrograph Peaking Factor

Throughout this first phase, review of the scatter plots indicated that 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 (500).

Phase II Calibration—Hydrograph Shape

Another 3,000 simulations of the hydrologic model were executed, using the reduced sampling ranges and fixed parameter values determined in Phase I. For Phase II, the scatter plots were based on the HEC objective function rather than the NSE objective function. The HEC objective function places heavier emphasis on matching peak flows and less emphasis on matching lower flows; therefore, using this objective function for this phase of the calibration provides a better measure of how well the simulation matches the timing of peak flows on the hydrographs. The following threshold values for the HEC objective function were established for use in further narrowing the parameter sampling ranges:

- HEC objective function threshold for the November 89 storm event: 0.10
- HEC objective function threshold for the November 95 (2) storm event: 0.02
- HEC objective function threshold for the October 03 storm event: 0.05

The use of these thresholds with the new scatter plots allowed for the following refinements to the model:

- Further narrowing of the sampling range for the upper and lower interflow storage constants; the narrowing involved reducing the upper limits of the range for the Group II subbasins
- Narrowing of the sampling range for the minimum infiltration rate for Soils Zones 5, 6, 7, 8, and 9; the scatter plots for the other soil zones showed no trend that would justify narrowing the sampling range
- Narrowing of the sampling range for period of rise for all subbasins, particularly reducing the upper bound of the sampling range for each subbasin; this refinement was based on review of the individual scatter plots for the Swift Creek and Park Creek hydrographs for the November 89 storm event, as well as the Upper and Lower Baker hydrographs for all three calibration storm events.

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. Tables 4-7 and 4-8 summarize the revised sampling ranges at the end of Phase II.

Table 4-7. Sampling Range of Subbasin Calibration Parameters—Results of Phase II

Subbasin	Period of Rise, P_r (minutes)	Interflow Storage Constants (hours) Upper Zone (UZ)	Interflow Storage Constants (hours) Lower Zone (LZ)
Group I			
Sandy Creek (UB1)	150—300	P_r/60 + 1 to 18	UZ + 1 to 15
Boulder Creek (UB2)	120—240		
Park Creek-Gaged (UB3)	120—210		
Park Creek-Ungaged (UB4)	120—210		
Rocky Creek (LB3)	210—390		
Sulphur Creek-Gaged (LB4)	150—270		
Sulphur Creek-Ungaged (LB5)	90—180		
Group II			
Swift Creek (UB5)	180—330	P_r/60 + 1 to 10	UZ + 1 to 10
Nearshore Baker Lake (UB6)	120—210		
Baker River (UB7)	210—390		
Noisy Creek (UB8)	120—210		
Thunder Creek (LB6)	180—300		
Group III			
Nearshore Lake Shannon (LB1)	120—210	P_r/60 + 1 to 7	UZ + 1 to 5
Bear Creek (LB2)	120—210		

Table 4-8. Sampling Range of Soil Zone Calibration Parameters—Results of Phase II

Soil Zone	Maximum Soil Moisture Storage, S_{max} (inches)	Deep Percolation Rate, f_d (inches/hour)	Minimum Surface Infiltration Rate, f_c (inches/hour)	Maximum Surface Infiltration Rate, f_{max} (inches/hour)
1	*Open Water*	*Open Water*	*Open Water*	*Open Water*
2	0	0.209	f_d + 10	10.0
3	5.58	0.044	f_d + (0.000—0.300)	4.0
4	5.02	0.058	f_d + (0.000—0.400)	6.0
5	3.80	0.115	f_d + (0.075—0.300)	4.0
6	7.84	0.071	f_d + (0.050—0.290)	4.0
7	10.10	0.197	f_d + (0.050—0.250)	4.0
8	5.89	0.115	f_d + (0.010—0.150)	4.0
9	6.49	0.067	f_d + (0.000—0.130)	2.0
10	10.59	0.374	f_d + (0.000—0.300)	4.0

Phase III Calibration—Preliminary Calibrated Parameter Set

Using the parameter sampling ranges defined in Phase II, the model was run with 8,000 randomly generated parameter sets to select an initial calibration parameter set. Behavioral parameter sets were identified for each of the three storm events, using the NSE objective function. For storm events that used both the Upper and Lower Basin inflow hydrographs, an area-weighted NSE objective function was computed. An objective function threshold value of 0.850 was used to define behavioral parameter sets. Of the 8,000 simulations, 4,631, 6,494 and 3,236 parameter sets met this threshold value for the November 89, November 95 (2), and October 03 events, respectively. Table 4-9 summarizes the range of values for the NSE objective measure for each of the three events.

Table 4-9. Summary of NSE Objective Function Values – Phase III

Objective Function	**NOV 89 Event**	**NOV 95(2) Event**	**OCT 03 Event**
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

Of the parameter sets identified as behavioral parameter sets for each of the individual storms, 1,113 sets were identified as behavioral for all three storm events. The likelihood measure was computed for each calibrated storm event and for the group of storm events, using Equations (1) and (2), respectively. All storms were equally weighted in computing the likelihood value for the group of events.

The parameter sets were ranked in descending order using the value of the likelihood measure for the group of events, and the top 10 parameter sets identified. Appendix C summarizes key information about each of these parameter sets, including the runoff volume and goodness-of-fit measures. The mean value from this list of top 10 behavioral parameter sets was computed for each parameter, and the results were identified as the preliminary calibrated parameter set, which is summarized in Tables 4-10 and 4-11.

Phase IV Calibration—Verification of Preliminary Calibrated Parameter Set

The preliminary calibrated parameter set was verified with the hydrologic model using the Upper Baker and Lower Baker inflow hydrographs for the November 90 (1) storm event. Figures 4-2 and 4-3 show a comparison between the simulated and observed hydrographs for this verification event. A review of the model results and the plot of the Lower Baker observed and simulated inflow hydrographs provided the following results and conclusions:

- The predicted volume was within 5 percent of the observed volume.
- The rising limb of the hydrograph was well replicated, indicating that the response of the watershed to precipitation was accurately modeled and that the antecedent soil conditions were well estimated.
- The predicted primary peak of the observed hydrograph was within 12 percent of the observed, indicating that the unit hydrographs used in the model accurately predicted the runoff response.
- The overall reproduction of the inflow hydrograph was aided by the likelihood that the data from the sole hourly precipitation gage in the watershed was representative of the precipitation conditions (timing and intensity) in a majority of the Lower Baker tributary area.

Table 4-10. Preliminary Calibrated Subbasin Parameters

Subbasin	Period of Rise, P_r (minutes)	Peaking Factor	Interflow Storage Constants (hours) Upper Zone (UZ)	Interflow Storage Constants (hours) Lower Zone (LZ)
Sandy Creek (UB1)	240	500	6.4	11.1
Boulder Creek (UB2)	180	500	5.6	10.3
Park Creek-Gaged (UB3)	150	500	5.2	9.9
Park Creek-Ungaged (UB4)	180	500	5.6	10.3
Swift Creek (UB5)	240	500	8.8	12.6
Nearshore Baker Lake (UB6)	180	500	7.7	11.5
Baker River (UB7)	330	500	10.1	13.9
Noisy Creek (UB8)	180	500	7.7	11.5
Baker Lake (UB9)	*Open Water*	*Open Water*	*Open Water*	*Open Water*
Nearshore Lake Shannon (LB1)	180	500	5.1	7.4
Bear Creek (LB2)	150	500	4.6	7.0
Rocky Creek (LB3)	300	500	7.4	12.1
Sulphur Creek-Gaged (LB4)	210	500	6.0	10.7
Sulphur Creek-Ungaged (LB5)	120	500	4.6	9.3
Thunder Creek (LB6)	210	500	8.5	12.3
Lake Shannon (LB7)	*Open Water*	*Open Water*	*Open Water*	*Open Water*

Table 4-11. Preliminary Calibrated Soil Zone Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (inches)	Deep Percolation Rate, f_d (inches/hour)	Minimum Surface Infiltration Rate, f_c (inches/hour)	Maximum Surface Infiltration Rate, f_{max} (inches/hour)
1	*Open Water*	*Open Water*	*Open Water*	*Open Water*
2	0	0.209	10.209	10.0
3	5.58	0.044	0.247	4.0
4	5.02	0.058	0.312	6.0
5	3.80	0.115	0.352	4.0
6	7.84	0.071	0.299	4.0
7	10.10	0.197	0.373	4.0
8	5.89	0.115	0.212	4.0
9	6.49	0.067	0.110	2.0
10	10.59	0.374	0.484	4.0

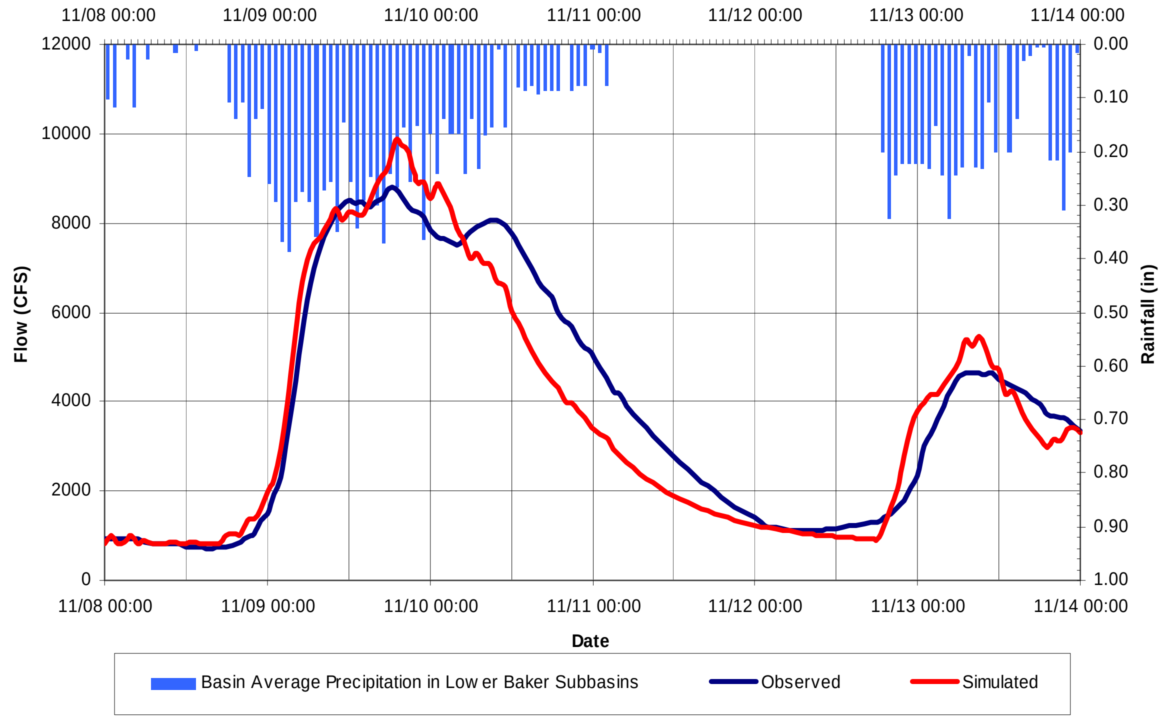

Figure 4-2. Verification of Preliminary Calibrated Parameter Set Against November 90 (1) Storm Event; Lower Baker Inflow

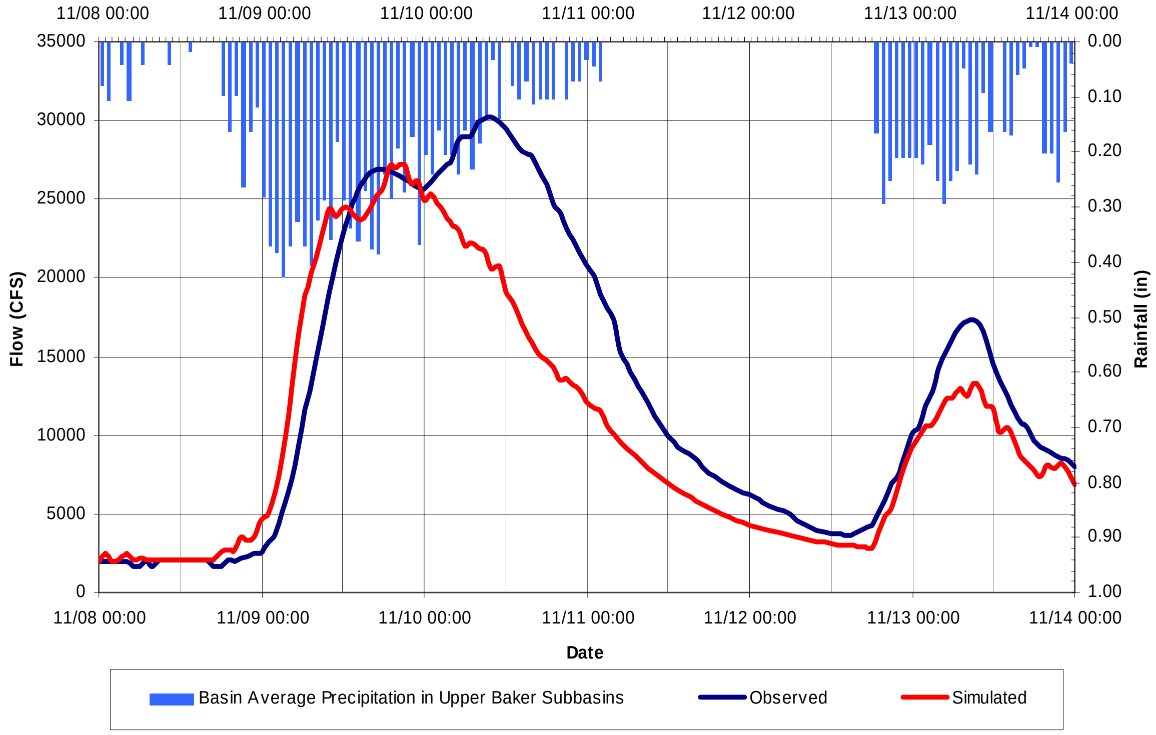

Figure 4-3. Verification of Preliminary Calibrated Parameter Set Against November 90 (1) Storm Event; Upper Baker Inflow

A review of the model results and the plot of the Upper Baker observed and simulated inflow hydrographs provided the following results and conclusions:

- The runoff volume for the simulated hydrograph was 18 percent lower than that of the observed hydrograph; this is partly attributable to the challenge of accurately mapping the precipitation input in the upper high elevations of the watershed.
- The first peak of the simulated hydrograph is within 10 percent of observed, indicating that the unit hydrographs used in the model accurately predicted the surface runoff response.
- The rising limb of the hydrograph was well replicated, indicating that the initial response of the watershed to the precipitation is being accurately modeled and that the antecedent soil conditions were well estimated.
- The hydrologic model was not able to produce the larger second peak that occurred at about noon on November 10, a peak that was more predominant in the Upper Baker inflow hydrograph than in the Lower Baker inflow hydrograph. The fact that the model was not able to replicate this peak is attributed to the lack of historical precipitation data in the upper portions of the watershed. The regularly spaced gridded precipitation fields developed by the SPAS software replicated the temporal and spatial patterns of historical precipitation at the lower elevations, as evidenced by Figure 4-2. However, the lack of data in the higher elevations and in the upper watershed created deficiencies in the gridded mapping that missed the precipitation input that generated this second peak. As will be discussed in the “Final Discussion” section of this chapter, this was not a problem unique to this storm event.

Phase V Calibration—Final Calibrated Parameter Set

The November 90 (1) verification event was incorporated into the process of determining a final calibrated parameter set. This addressed the fact that, while three storm events were used in the earlier phases of the calibration, only one included the use of the Upper Baker inflow hydrograph.

The hydrologic model was run for the November 90 (1) event, using the 8,000 parameter sets generated in Phase III, and behavioral sets for this storm event were identified as those that achieved an NSE threshold value of 0.75 (none of the sets for this storm event achieved the 0.85 threshold value used in Phase III). Of the 8,000 simulations, 676 sets were identified as behavioral for the November 90 (1) event. Table 4-12 summarizes the range of values for the NSE objective measure for this storm event (the range of values for the original three calibration storm events is also included).

Table 4-12. Summary of NSE Objective Function Values – Phase V

Objective Function	**NOV 90(1) Event**	**NOV 89 Event**	**NOV 95(2) Event**	**OCT 03 Event**
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	676	4,631	6,494	3,236

Of the parameter sets identified as behavioral for any one storm, 233 sets were identified as behavioral for all four storm events. The likelihood measure was computed for each calibrated storm event and for the group of storm events, using Equations (1) and (2), respectively. All storms were equally weighted in computing the likelihood value for the group of events. The parameter sets were ranked in descending order using the value of the likelihood measure for the group of events, and the top 10 parameter sets were identified. Appendix C summarizes key information about each of these parameter sets, including the runoff volume and goodness-of-fit measures. The mean value from this list of top 10 behavioral parameter sets was computed for each parameter, and the results were identified as the final calibrated parameter set, which is summarized in Tables 4-13 and 4-14.

A sensitivity analysis was conducted on the final calibrated parameter set by manually adjusting parameters across all soil zones and subbasins. 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 minimum infiltration rate. For each sensitivity model run, the group likelihood measure was calculated to determine if an improvement had been made over the final calibrated parameter set. The following parameter adjustments were included in this sensitivity analysis:

- Deep percolation rate—Reducing this parameter by up to 10 percent improved the simulation of runoff volume; a reduction of more than 10 percent caused the volume for the November 89 Upper Baker inflow hydrograph to become excessively high.
- Minimum infiltration rate—Reducing this parameter up to 5 percent improved the likelihood measure; larger reductions negatively affected the likelihood measure.

Table 4-13. Final Calibrated Subbasin Parameters

Subbasin	**Period of Rise, P_r (minutes)**	**Peaking Factor**	**Interflow Storage Constants (hours)**	
			Upper Zone (UZ)	**Lower Zone (LZ)**
Sandy Creek (UB1)	240	474	7.1	12.0
Boulder Creek (UB2)	180	474	6.1	10.9
Park Creek-Gaged (UB3)	180	474	5.9	10.8
Park Creek-Ungaged (UB4)	180	474	6.0	10.9
Swift Creek (UB5)	270	474	8.5	13.5
Nearshore Baker Lake (UB6)	180	474	6.6	11.6
Baker River (UB7)	360	474	9.6	14.6
Noisy Creek (UB8)	180	474	6.6	11.6
Baker Lake (UB9)	*Open Water*	*Open Water*	*Open Water*	*Open Water*
Nearshore Lake Shannon (LB1)	180	474	5.0	7.8
Bear Creek (LB2)	180	474	5.1	7.9
Rocky Creek (LB3)	300	474	7.8	12.6
Sulphur Creek-Gaged (LB4)	210	474	6.6	11.4
Sulphur Creek-Ungaged (LB5)	150	474	5.5	10.3
Thunder Creek (LB6)	240	474	7.9	12.9
Lake Shannon (LB7)	*Open Water*	*Open Water*	*Open Water*	*Open Water*

Table 4-14. Final Calibrated Soil Zone Parameters

Soil Zone	Maximum Soil Moisture Storage, S_{max} (inches)	Deep Percolation Rate, f_d (inches/hour)	Minimum Surface Infiltration Rate, f_c (inches/hour)	Maximum Surface Infiltration Rate, f_{max} (inches/hour)
1	*Open Water*	*Open Water*	*Open Water*	*Open Water*
2	0.00	0.188	10.000	10.0
3	5.58	0.039	0.255	4.0
4	5.02	0.052	0.284	6.0
5	3.80	0.103	0.353	4.0
6	7.84	0.064	0.282	4.0
7	10.10	0.177	0.354	4.0
8	5.89	0.104	0.170	4.0
9	6.49	0.061	0.138	2.0
10	10.59	0.336	0.458	4.0

- Upper and lower zone interflow storage constants—No changes in these parameters improved the likelihood measure.
- Unit hydrograph peaking factor—Reducing this parameter resulted in slight improvements to the likelihood measure.
- Unit hydrograph period of rise—No changes in this parameter improved the likelihood measure.

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 was decreased by 10 percent for all soil zones.
- Rate of minimum infiltration was decreased by 5 percent for all soil zones.
- Unit hydrograph peaking factor was reduced from 500 to 474.

Figures 4-4 and 4-5 show the calibrated surface runoff unit hydrographs for each subbasin. The final calibrated parameter set was used to predict the runoff hydrographs for all of the storm events considered in the calibration procedure. The final figures comparing the simulated versus the observed hydrographs for the calibration are provided in Appendix D; Figure 4-6 is a sample comparison graph showing the observed and simulated results for Lower Baker for the November 90 (1) storm event. Table 4-15 summarizes a comparison of the simulated and observed runoff hydrographs using the final calibrated parameter set.

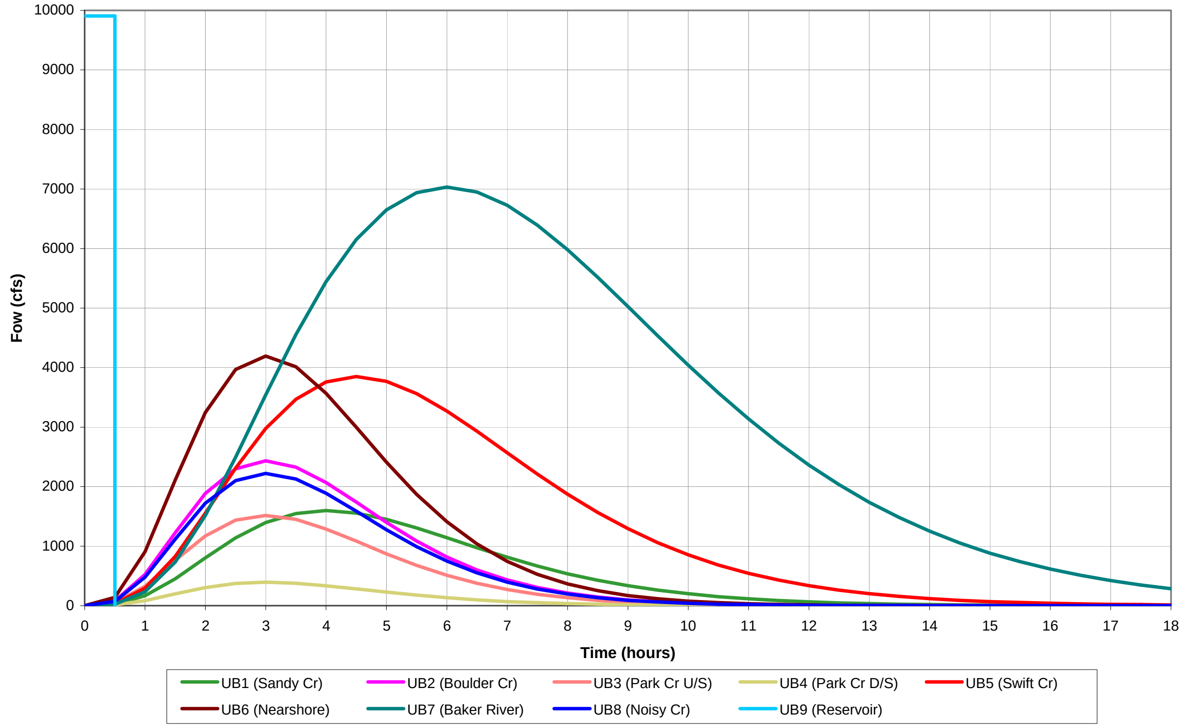

Figure 4-4. Calibrated Surface Runoff Unit Hydrographs—Upper Baker Subbasins

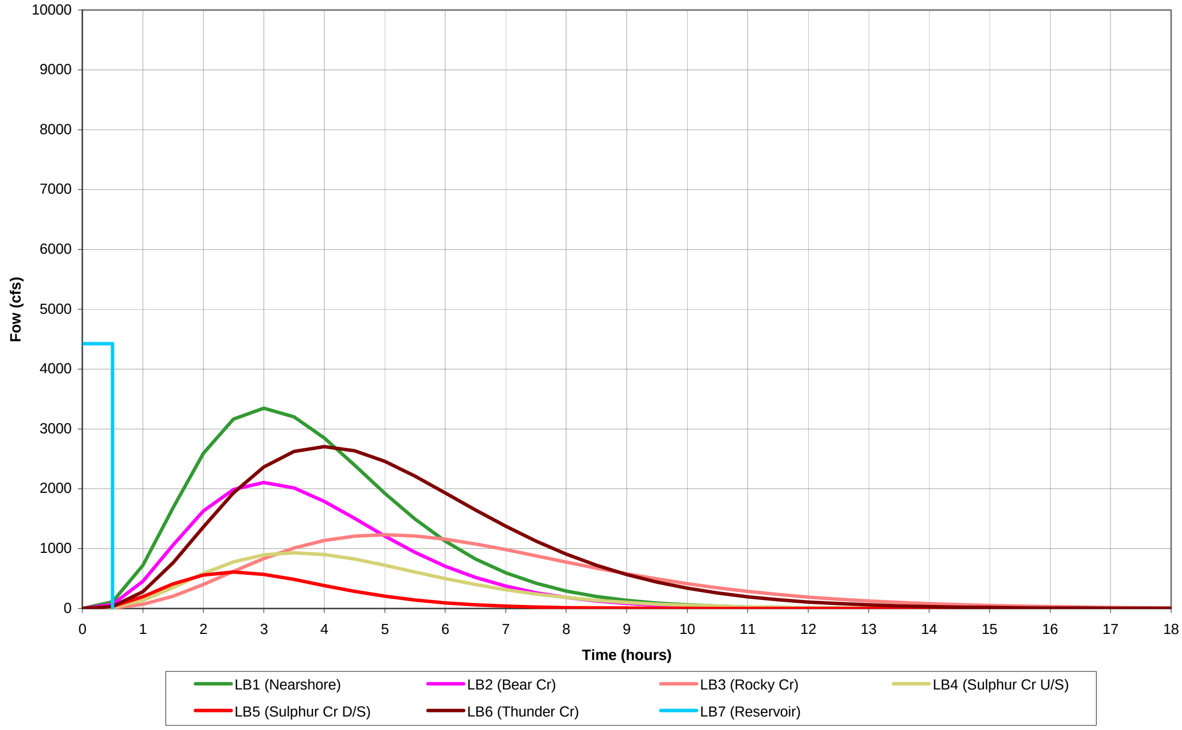

Figure 4-5. Calibrated Surface Runoff Unit Hydrographs—Lower Baker Subbasins

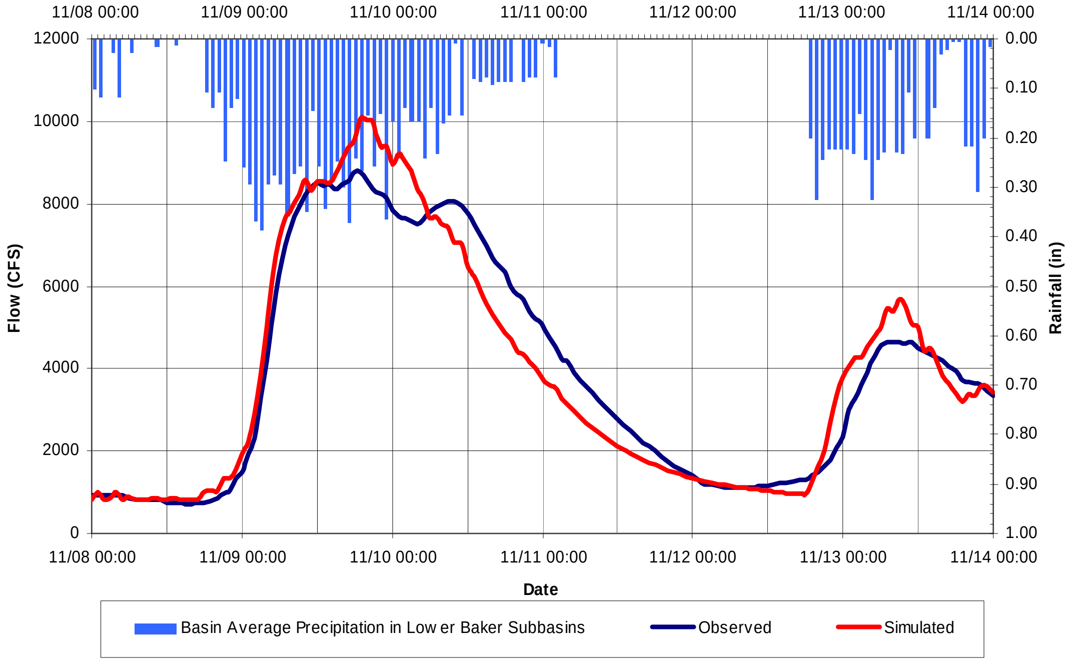

Figure 4-6. Final Calibrated Lower Baker Inflow Hydrograph for November 90 (1) Storm Event

Table 4-15. Summary of Model Results for Final Calibrated Parameter Set

	November 90 (1)		November 89		November 95 (2)	October 03
Objective Measure	**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

FINAL DISCUSSION

The SEFM and the HEC-1 model were used together to successfully develop a calibrated watershed model for the Baker River watershed. The model was calibrated using four of the largest storm events to have occurred in the Baker River Watershed. 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 were used as part of the calibration process for unit hydrograph and interflow timing.

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 there are inherent uncertainties associated with the recorded data upon which the calibration is based. Uncertainties are associated with snowpack data, precipitation gage data and stream flow measurements, and, in the case of the Baker River watershed, with reconstruction of the inflow hydrographs and with the estimation of the air temperature time series.

Objective measures can provide a quantifiable measure of the success of a calibrated model. 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 0.800 to 0.850 have been used to calibrate continuous simulation HSPF models (Chew et al. 1991; Price 1994; and Duncker et al. 1995). As seen in Table 4-15, calibration to the Lower Baker tributary area hydrograph resulted in NSE values that ranged between 0.839 and 0.937 and calibration to the Upper Baker tributary hydrograph resulted in NSE values between 0.773 and 0.876.

Successful aspects of the Baker River watershed model calibration included matching the timing of the hydrograph peaks, reproducing the recession limbs, and reasonably reproducing the runoff volume. The use of the GLUE calibration procedure was a significant contributor to these successes, in that it allowed for a thorough investigation of the parameter space for each calibration parameter.

The simulated hydrographs resulted in runoff volumes that were within 15 percent of the observed runoff hydrographs, which is 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 controlling runoff volume in the model. For the 10 soil zones, the calibrated value of the deep percolation rate ranged between 0.039 inches per hour and 0.336 inches per hour.

The highest rate of deep percolation was for the soil zone in 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 inches per hour, 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 challenges encountered in developing historically accurate spatial and temporal precipitation input for each calibration storm event. The complicating influence of terrain on precipitation patterns in the watershed, combined with the fact that only a single hourly precipitation gage is available within the watershed, contributed to these challenges. The recorded hourly precipitation data at the only gage in the watershed, which is located at Upper Baker Dam (Elevation 690 feet), is more representative of the precipitation patterns in the lower watershed than in the upper watershed. This is on account of the fact that the gage is a relatively low elevation precipitation gage that is not affected by orographic influences.

Several techniques were used in conjunction with the SPAS software to attempt to resolve the difficulties in developing accurate precipitation mapping. These included using a variety of climatological base mappings, incorporating NEXRAD data, and developing pseudo-stations in the upper watershed to resolve the temporal characteristics of the storm events.

Despite these challenges, the results summarized in this chapter and the graphics included in Appendix D indicate 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 will provide a sound basis for analyzing the PMP and PMF for the Baker River watershed.

5. RESERVOIR ROUTING MODEL

MODEL SELECTION AND METHODOLOGY

The HEC-5 reservoir simulation program (USACE-HEC 1998b) was selected as the software tool for routing inflow hydrographs through the Baker River Project. It was necessary to use a program such as HEC-5 because the spillways at both dams are gate-controlled and special reservoir operating rules are implemented at Upper Baker Dam during flood events. Under these operating rules, outflows from Upper Baker Dam are determined based on hydrologic conditions at downstream control points in the Skagit River. The HEC-5 computer program was formulated to perform sequential reservoir operation for a dendritic (branching) reservoir system configuration, using single or multiple downstream reservoir control points.

MODEL APPLICATION

The Seattle District Corps of Engineers developed a HEC-5 model of the Skagit River basin for its Skagit River Flood Control Feasibility Study. This HEC-5 model includes the Upper and Lower Baker Dams as well as Seattle City Light's Ross Dam in the upper Skagit River watershed. During flood events, the Seattle District Corps of Engineers' Reservoir Control Center (RCC) regulates operation of both Upper Baker Dam and the Ross Dam to coordinate their regulated discharges and optimize their combined flood control storage, using a common control point location on the main stem Skagit River at Concrete.

For the Baker River Project PMF study, the Skagit River HEC-5 model was revised in two ways. The first revision was to update the discharge rating curve for Lower Baker Dam based on more current topographic information provided by PSE (PSE 2005). The specifics of the revision to the Lower Baker Dam discharge rating curve is described in the following section. The second revision was to modify the boundary conditions in the HEC-5 model to include a coincident occurrence of a 500-year return period flood in the main stem Skagit River during the Baker River PMF simulations. The Seattle District provided the necessary inflow design hydrographs for this condition.

DISCHARGE RATING CURVES

According to the plant manual for Upper Baker Dam, the Upper Baker Dam spillway discharge rating curve is based essentially on results of model tests. Therefore, the spillway discharge rating curve was used as published. However, since the published rating curve only extended to an elevation 2 feet below the top of the dam, it was necessary to extend the spillway discharge rating curve to include weir flow over the top of the dam and over West Pass Dike. Figure 5-1 shows the total discharge rating curve for the Upper Baker Development, including West Pass Dike, used in the analysis.

For the Lower Baker Dam, an independent analysis was performed to verify the published rating curve and to incorporate new topographic survey data (PSE 2005) for features that impact the published rating curve. For example, a vertical-faced rock outcrop just upstream of the west abutment has the potential to cause local contraction of approach flows and to therefore reduce the effective weir length of the west non-overflow section. Immediately upstream of the east abutment, the headgate building has the potential to have a similar effect on the approach flows to the east non-overflow section. Parapet walls of various heights exist along the length of the dam and were assumed to remain undamaged and in-place for all simulated flood events. The Lower Baker Development discharge rating curve is therefore based on a series of controlling elevations, as summarized in Table 5-1. As seen in this table, as the reservoir elevation increases, different types of flow conditions exist across the dam:

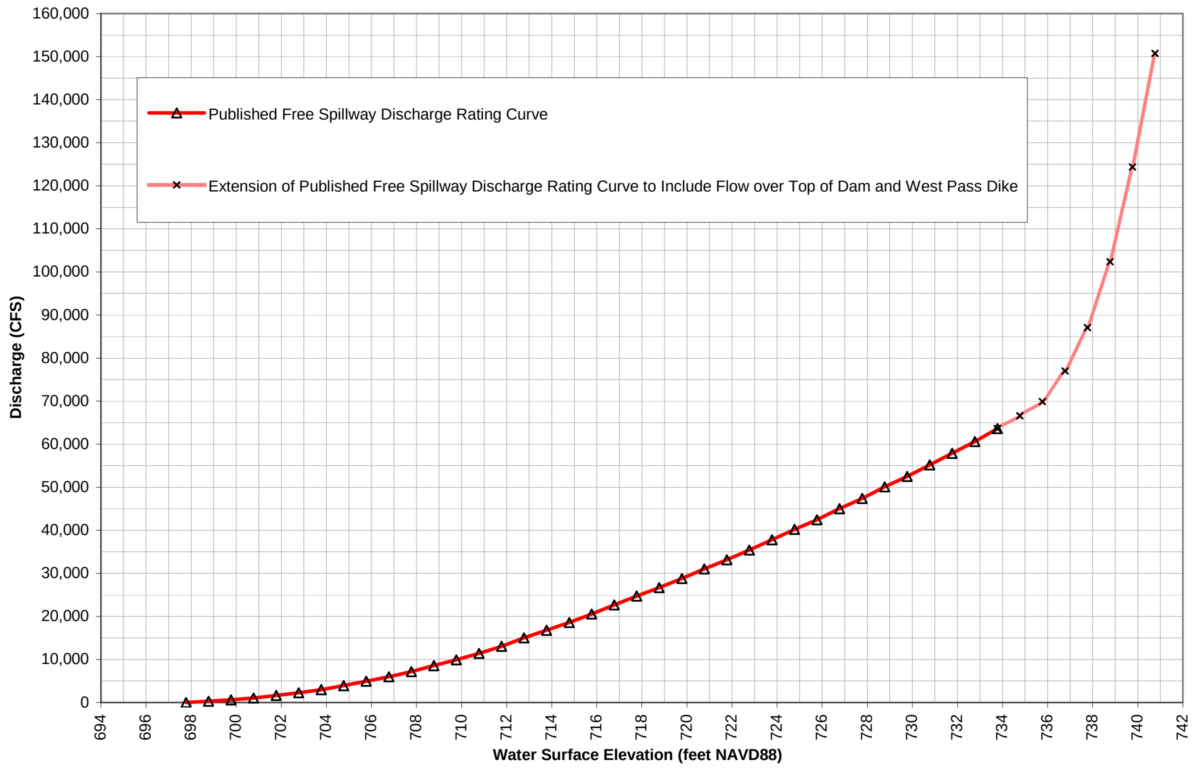

Figure 5-1. Upper Baker Development Discharge Rating Curve, Including West Pass Dike

- Free, unobstructed discharge exists through all of the gate openings until the reservoir water surface elevation reaches 439.08 feet (NAVD88), at which point the fixed vertical slide gates (1 and 2) begin acting under submerged conditions. For the free discharge condition, reduction in conveyance through the spillway bays caused from pier and abutment constriction was accounted for.

- Starting at a water surface elevation of 439.08 feet (NAVD88), the flow through Spillway Bays 1 and 2 behaves as orifice flow because the gates cannot be removed. The transition to orifice flow occurs at the other gates at slightly higher water surface elevations as summarized in Table 5-1.

- Once the water surface elevation reaches 449.26 feet (NAVD88), free discharge no longer exists for any of the spillway bays and flow through all of the spillway bays behaves as orifice flow. This transition to orifice flow is seen in the rating curve as a short period of non-increasing flow for increasing water surface elevation.

- At an elevation of 444.57 feet (NAVD88), flows begin overtopping the east non-overflow section of the dam. At lower elevations, flow conditions over this section were assumed to be those of a submerged weir caused by the interaction of the upstream and downstream parapet walls. Once the downstream parapet wall was sufficiently submerged, the flow conditions over the east non-overflow section were assumed to transition to a free discharge weir condition. Adjustments to the rating curve were also made to account for the effect of the headgate building on the approach flow to the east non-overflow section.

- Weir flow over the west non-overflow section of the dam begins at Elevation 445.14 feet (NAVD88). Similar to the approach used for the east non-overflow section, the flow characteristics over the west non-overflow section were assumed to transition to a free discharge weir condition once the downstream parapet wall was sufficiently submerged.

- 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 feet (NAVD88).

The resulting discharge rating curve used for routing flows through the Lower Baker Development is shown in Figure 5-2. For comparative purposes, this figure also includes the currently published rating curve for the Lower Baker Development.

Table 5-1. Controlling Elevations for the Lower Baker Development Discharge Rating Curve

Flow Condition					**Controlling**
Gated Free Spill	**Orifice**	**Submerged Weir**	**Free Flow Weir**	**Controlling Structure**	**Elevation (feet NAVD 88)**
X				Spillway crest	428.62
X	X			Bottom of unremovable gates when fully open (Gates 1 & 2)	439.08
X	X			Bottom of unremovable gates when fully open (Gate 23)	440.62
X	X			Bottom of unremovable gates when fully open (Gates 3—10)	444.12
X	X	X		Top of parapet wall at east non-overflow	444.57
X	X	X	X	Top of wall above head gates near east abutment	444.59
X	X	X	X	Top of parapet wall at west non-overflow section	445.14
X	X	X	X	Transition from submerged weir condition to free flow weir condition at west non-overflow section	447.73
X	X		X	Bottom of gate opening for removable gates (Gates 11—22)	449.26
	X		X	Top deck of dam	450.64
	X		X	Top of wall above Gates 3—23	453.52
	X		X	Top of unremovable gates (Gates 1 & 2)	453.58
	X		X	Top of unremovable gate (Gate 23)	455.12
	X		X	Top of wall at west non-overflow section above Gates 1 & 2	456.91
	X		X	Top of unremovable gates (Gates 3—10)	458.32

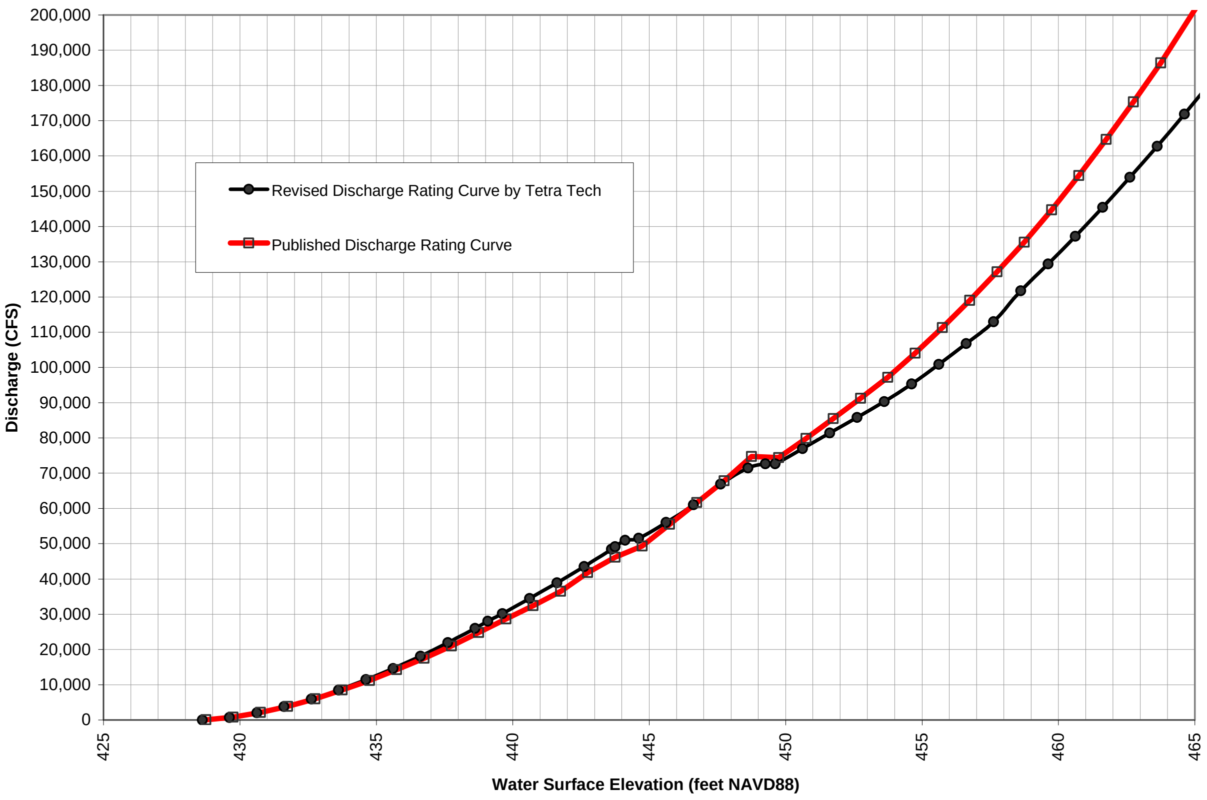

Figure 5-2. Lower Baker Development Discharge Rating Curve

6. PROBABLE MAXIMUM PRECIPITATION

This chapter summarizes the development of a probable maximum precipitation (PMP) estimate for the Baker River watershed for input into the calibrated watershed model, including the development of spatial and temporal distributions of PMP.

The PMP estimate for the Baker River watershed was determined using the National Weather Service's *Hydrometeorological Report No. 57* (HMR 57), which defines probable maximum precipitation for the Pacific Northwest states (NWS 1994). HMR 57 recommends that both general and local storm values of PMP be calculated for drainages smaller than 500 square miles, such as the Baker River watershed. The larger of the two estimates is taken to represent the basin PMP.

Details regarding development of the PMP are presented in *Baker River Project Part 12 PMP/PMF Study; Technical Memorandum No. 6—Determination of Probable Maximum Precipitation Using HMR 57 (*Tetra Tech 2006a).

GENERAL STORM PMP

Generalized PMP studies such as HMR 57 rely on index maps that show the geographic variation of PMP over a study region. Typically, index maps are based a 10-square-mile storm that lasts for 24 hours because the most reliable data are available for storms of this size and duration. The generalized PMP studies extend the information from the index maps to storms of other durations and areas using depth-duration and depth-area relations. This is the approach applied to the Baker River PMF study.

General storm PMP estimates were developed for three storm-centering scenarios: centering over the entire 298.7-square-mile Baker River watershed; centering over the 214.8-square-mile Upper Baker tributary area; and centering over the 83.9-square-mile Lower Baker tributary area. The procedure started with estimating all-season index PMP values for the total watershed, the Upper Baker tributary area and the Lower Baker tributary area. These index PMP values were estimated by overlaying each drainage area over the index map from HMR 57. The resulting index PMP depth values were 20.3 inches for the total watershed, 20.7 inches for the Upper Baker tributary area, and 19.4 inches for the Lower Baker tributary area. Because the HMR 57 index map is based on a specific duration and area size, these index values were adjusted as follows to account for seasonal variation, different durations, and the larger basin areas:

- Seasonal Adjustment—Seasonal index maps in HMR 57 were used to estimate seasonal average reduction factors for each month or sequence of months (October, November—February, March, April and May, June, July and August, and September). The seasonal reduction factors were then applied to the all-season index PMP estimate to obtain the seasonal index PMP estimates.
- Depth-Duration Adjustment—HMR 57 presents depth-duration ratios based on climatic subregions of the Pacific Northwest. The Baker River watershed lies within Climatic Subregion 4 (West of the Cascades—Orographic), and the ratios for that subregion were applied to the seasonally adjusted PMP values. Additional ratios for durations not included in HMR 57 were obtained from WDOE (1989).
- Areal Reduction—Areal reduction factors are a function of the size of the drainage area, the duration of the storm event, and whether the drainage area is located within an orographic or a non-orographic subregion. The Baker River watershed lies within an orographic subregion. The appropriate areal reduction factors were applied to the duration-adjusted index PMP values for each duration (1-, 2-, 3-, 6-, 9-, 12-, 24-, 36-, 48-, 60- and 72-hour).

The results and intermediate calculations in support of the general storm PMP estimation are summarized in Appendix E. Figures 6-1, 6-2 and 6-3 present the PMP depth-duration curves for the general storms centered over the total basin, over Upper Baker and over Lower Baker, respectively.

LOCAL STORM PMP

In HMR 57 the term "local storm" is defined as 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). Since the Baker River Basin is fairly large, it is unlikely that any local storm will be the controlling event for the Baker River PMF study. It is more likely that one of the seasonal general storms will be the controlling event. However, to be complete, local storm PMP values and the associated areal reduction factors were determined for the three storm-centering scenarios, as follows:

- Index PMP—HMR 57 gives the basin average, 1-hour duration, 1-square-mile local storm index PMP value as 5.0 inches.
- Adjustment for Duration— Adjustments to the index value for durations less than 1-hour and up to 6 hours, expressed as a percentage of the 1-hour index value, were obtained from HMR 57.
- Adjustment for Basin Area—Areal reduction factors for the total basin, Upper Baker and Lower Baker were obtained from the depth-area relation in HMR 57, and were applied to the duration-adjusted index values.

The results and intermediate calculations in support of the local storm PMP estimation are summarized in Appendix E. Figure 6-4 represents local storm depth-duration curves for each storm-centering scenario.

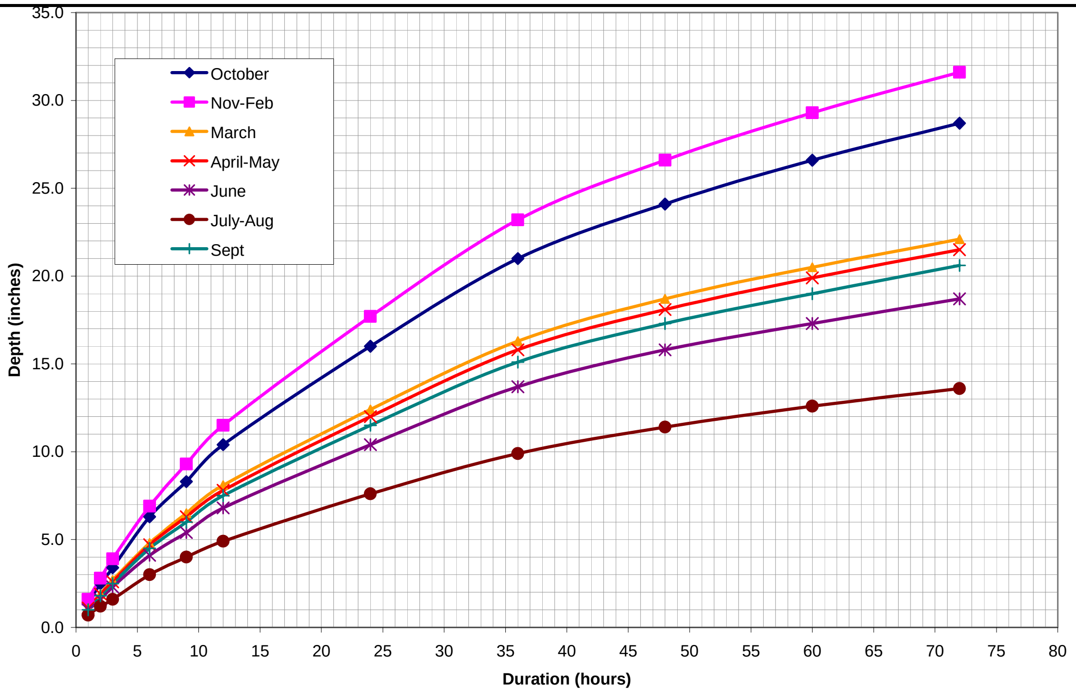

Figure 6-1. General Storm PMP Depth-Duration Curves for Total Basin

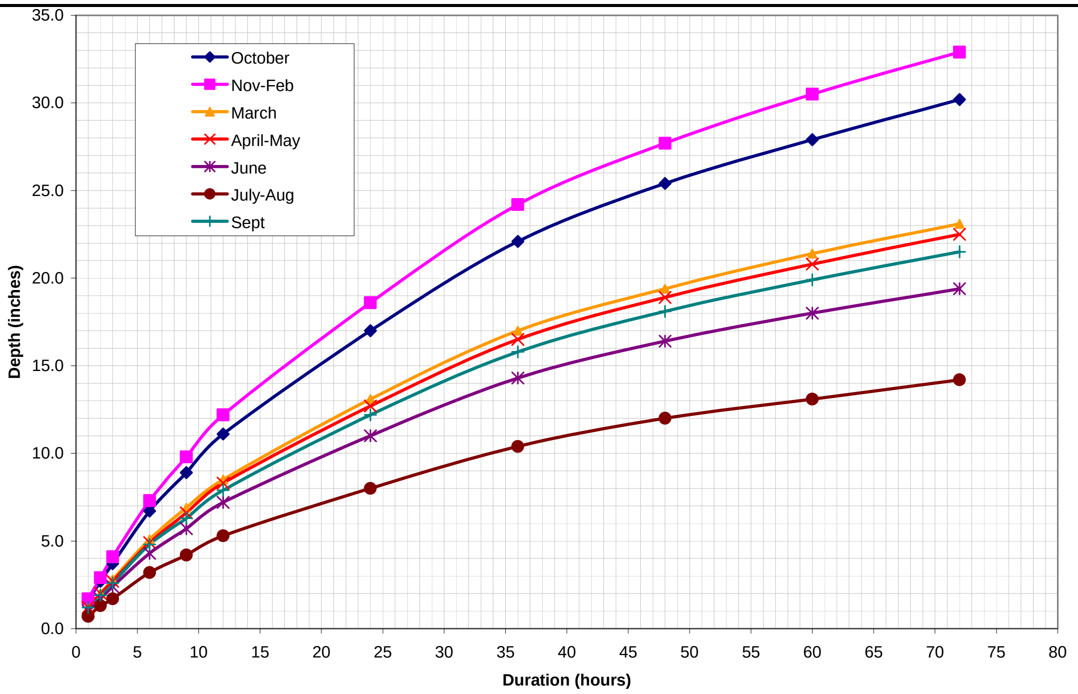

Figure 6-2. General Storm PMP Depth-Duration Curves for Upper Baker Tributary Area

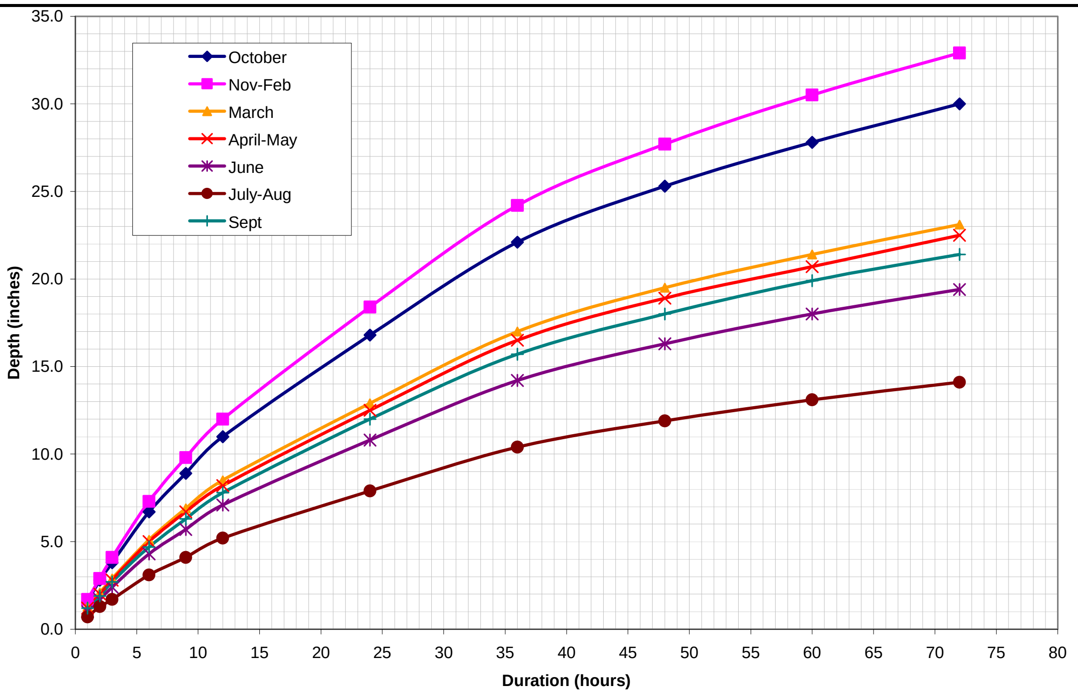

Figure 6-3. General Storm PMP Depth-Duration Curves for Lower Baker Tributary Area

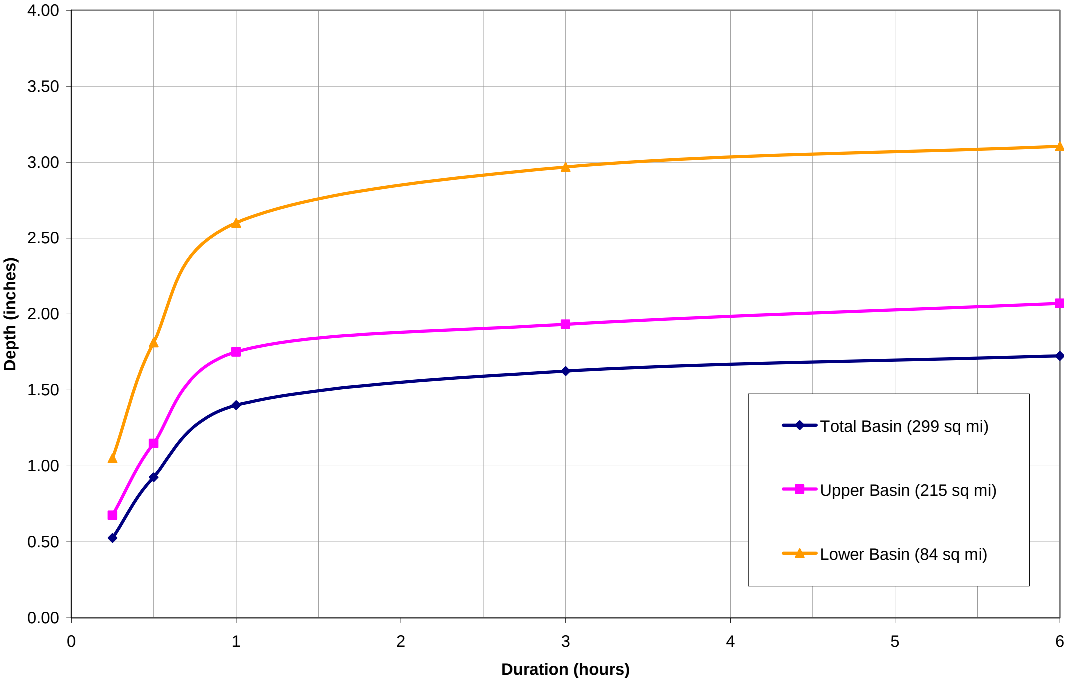

Figure 6-4. Local Storm PMP Depth-Duration Curves

SPATIAL DISTRIBUTION OF PMP

General Storm

The Baker River watershed is subdivided into 16 subbasins in the hydrologic model, and it was necessary to compute average seasonal PMP volumes for each subbasin. Spatial distribution of PMP was determined using 100-year precipitation frequency maps from a study conducted for the Washington State Department of Transportation (Schaefer et al. 2006). Figure 6-5 shows the distribution of the 100-year precipitation in the Baker River watershed. The procedure for developing spatial distribution of the general storm PMP using the 100-year frequency climatological base map was as follows:

- Determine the basin average general storm PMP value for each season and storm-centering scenario for the entire Baker River watershed.
- Using the gridded data set for the 100-year, 24-hour precipitation (Schaefer et al. 2006), determine the basin average 100-year, 24-hour precipitation depth for the Baker River watershed. This was computed to be 9.87 inches.
- For each season and storm centering scenario, compute the ratio of the watershed-average general storm PMP depth to the watershed-average 100-year 24-hour precipitation depth. This ratio ranged from 1.42 for the summer months to 3.29 for the November-February winter season
- Multiply the value of each grid in the 100-year 24-hour data set by the computed ratio to develop a gridded data set for the specific PMP event.
- For each tributary subbasin in the watershed model, compute the subbasin average PMP using the PMP gridded data set.

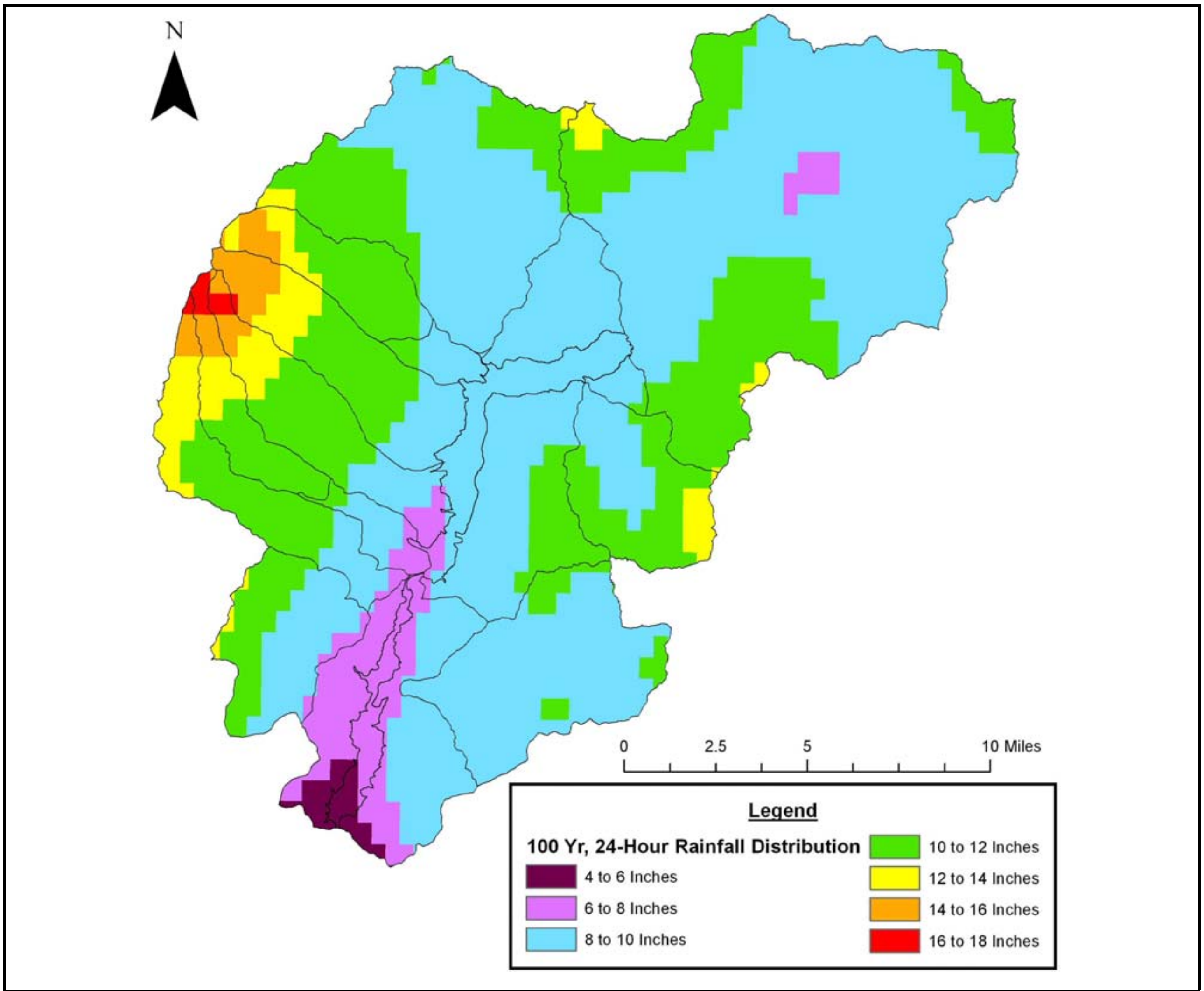

Figure 6-5. 100-Year 24-Hour Precipitation Distribution for Baker River Watershed

Local Storm

Spatial distribution of the local storm PMP was developed for this project using the method presented in HMR 57. This method uses an idealized elliptical storm pattern to estimate the spatial distribution. The pattern is modified by reduction factors that account for reductions due to area and storm duration.

TEMPORAL DISTRIBUTION OF PMP

General Storm

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 located between hour 36 and hour 48 of the 72-hour duration general storm. FERC (2001) further recommends that reference be made to the appropriate HMR or any pertinent site-specific studies. HMR 57 provides guidelines to use in constructing temporal distribution patterns for PMP. However, the guidelines are quite general, and it is left to the analyst to determine "which sequence will provide the temporal distribution most critical to the specific drainage of interest."

Instead of using the temporal patterns presented in FERC (2001), temporal distributions of the subbasin-average PMP volumes were developed using the frequency-based methodology presented in WDOE (1989). This methodology was designed to allow for the development of temporal patterns for synthetic design storm events based on a probabilistic analysis of extreme storm events that have occurred in Washington State. The details of how the methodology was applied to this analysis are documented in Tetra Tech (2006a). Three temporal patterns were considered, the primary difference between them being the time of occurrence within the 72-hour general storm of the high-intensity 1-hour segment. The time of occurrence of this high-intensity segment is one of many temporal characteristics considered in WDOE (1989) and is associated with an exceedance probability. The three temporal patterns are characterized as follows:

- High-intensity segment occurs at hour 33 of elapsed time. This is associated with the 50-percent exceedance probability (EP).
- High-intensity segment occurs at hour 46 of elapsed time. This is associated with the 20-percent exceedance probability.
- High-intensity segment occurs at hour 58 of elapsed time. This is associated with the 5-percent exceedance probability.

Figures 6-6 through 6-8 present the incremental precipitation distributions for the three temporal patterns.

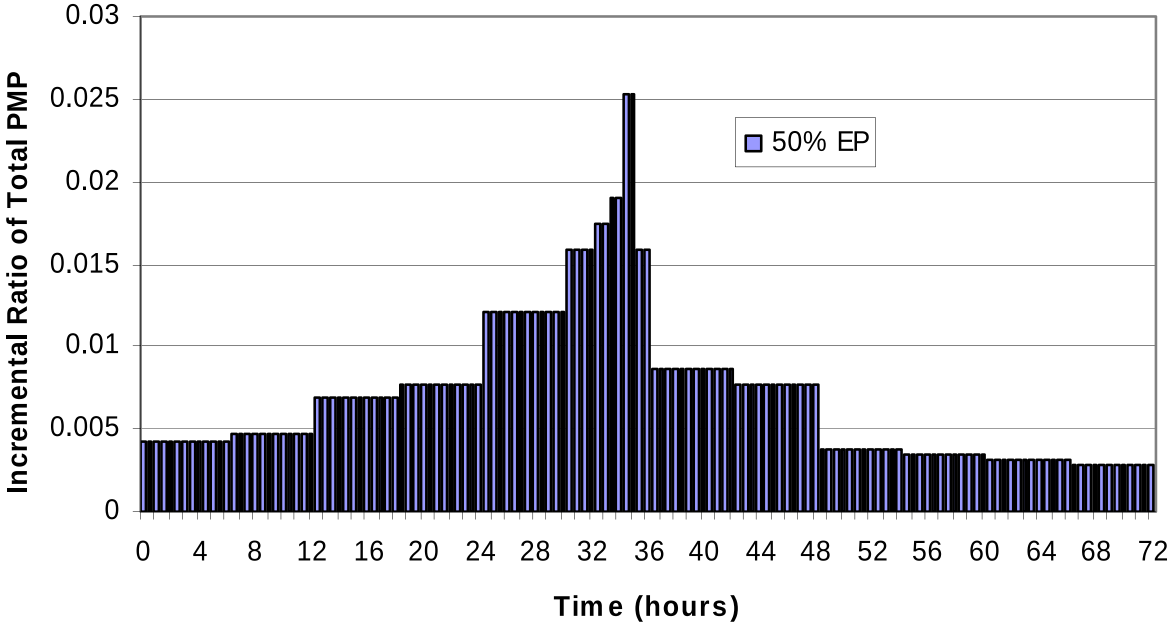

Figure 6-6. 50-Percent Exceedance Probability Temporal Pattern

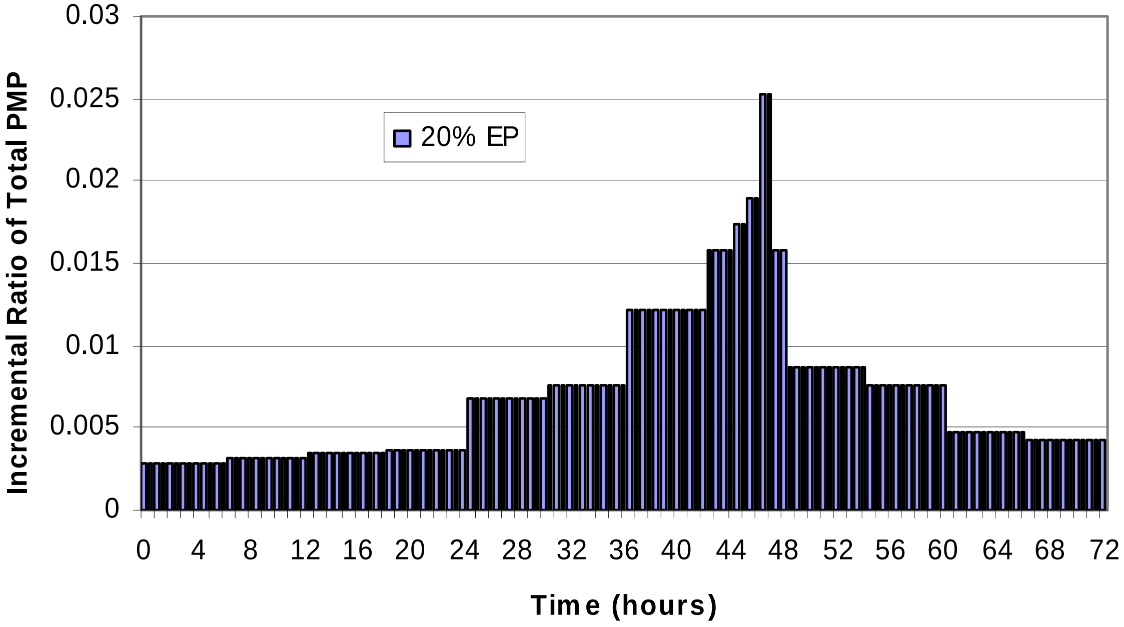

Figure 6-7. 20-Percent Exceedance Probability Temporal Pattern

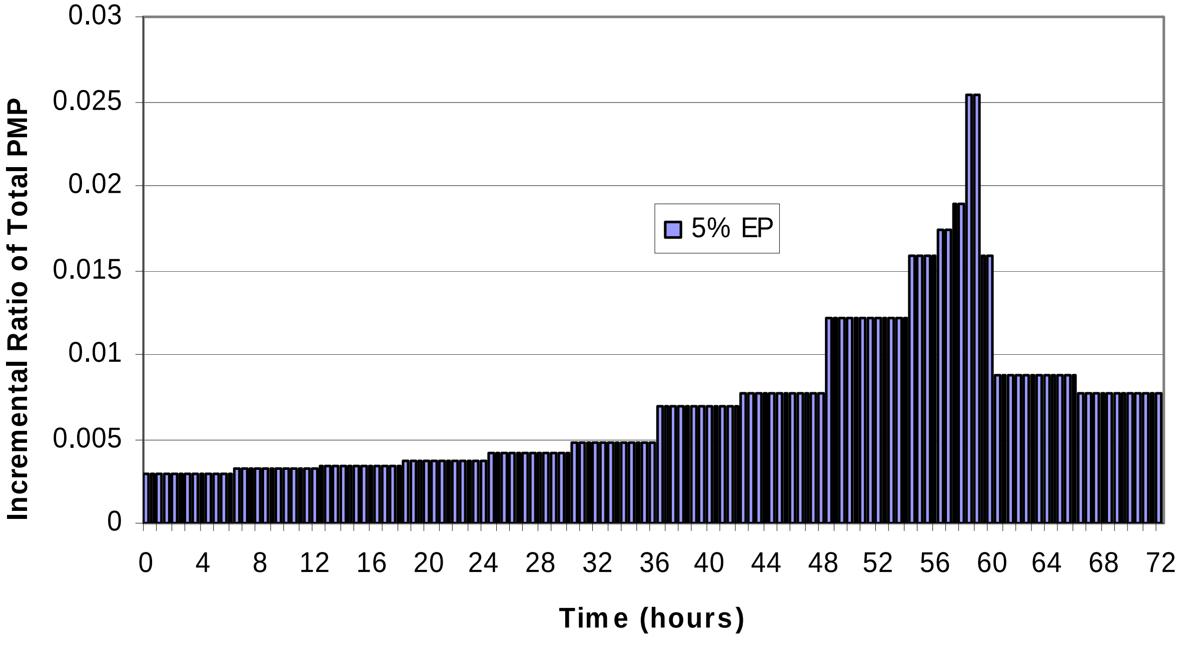

Figure 6-8. 5-Percent Exceedance Probability Temporal Pattern

Local Storm

Local storms in the Pacific Northwest generally draw on a limited amount of moisture that 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 (WDOE 1989). Therefore, the temporal distribution of the local storm was developed with the highest intensity 15-minute segment occurring within the first hour. As per NWS (1994), the subsequent 1-hour segments were arranged in a descending order.

CANDIDATE STORMS FOR PMF ANALYSIS

For drainage areas less than 500 square miles in size, HMR 57 recommends that the larger of the general storm PMP and local storm PMP values 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 for this study; however, the detailed hydrologic model evaluation was conducted only for the general storm.

General storms are defined in HMR 57 as major events that produce precipitation over areas in excess of 500 square miles and over durations much longer than 6 hours. In the Pacific Northwest, and within the Baker River watershed, general storms can occur at any time of year, but are least dominant during the summer. Based on an independent review of 47 long-duration storms in the Baker River watershed since 1949, 83 percent of these events occurred during the months of October through March, and 79 percent occurred during the months of October through February (Tetra Tech 2005a). A Washington Department of Ecology analysis of the seasonality of occurrence for extreme storms (WDOE 1989) concluded that in the Western Washington lowlands and mountain areas, the long duration, 24-hour events occur in the late fall and winter months, specifically from October through March.

Local storms are defined in HMR 57 as having durations up to 6 hours, covering areas up to 500 square miles, and often occurring independently of any strong wide-area weather feature. In Washington State, local storms are usually a warm weather season feature and are most often observed east of the Cascades (NWS 1994).

For the Baker River project, the methodology for determining PMP estimates for the general storm category was followed, and PMP estimates were made for all 12 months of the year. Using the calibrated hydrologic model, inflow hydrographs were developed for each month for the Upper Baker tributary area and the local tributary area to Lower Baker Dam. However, only the inflow hydrographs for October through February were routed through the facility using the reservoir routing model. As explained in Chapter 8, it was evident from review of the inflow hydrographs that the most conservative estimate of PMF for the Baker River project would be a product of an October through February general storm.

The HMR 57 methodology for estimating PMP for local storms was also followed. However, the evaluation of the local storm as a PMF candidate was not conducted using the hydrologic and reservoir routing models but was instead conducted on a purely volumetric basis, with the conservative assumptions that all precipitation would be converted to runoff, that all runoff would instantaneously enter the reservoirs, and that there would be no releases from the dams during the storm event. For the Upper Baker tributary drainage, the 6-hour duration local storm volume was determined to be 2.07 inches (see Appendix E). The instantaneous runoff volume was computed to be 23,700 acre-feet. Assuming a full pool reservoir elevation of 727.77 feet (NAVD88), input of this runoff volume would cause Baker Lake to rise to elevation 732.43 feet (NAVD88), nearly 3.3 feet below the top of the dam.

As discussed in Chapter 8, the general storm category was capable of producing more severe conditions than the local storm condition. Therefore, the local storm was not considered any further in the analysis, and the remainder of this report refers only to the general storm category.

7. COINCIDENT AND ANTECEDENT CONDITIONS FOR INITIAL ANALYSIS

Antecedent and coincident hydrologic and meteorological conditions were developed for input into the watershed model, as summarized in this chapter. These conditions were used for the initial analysis of the PMF, and were subsequently modified as appropriate based on further analysis for the final PMF. Detailed descriptions of the development of antecedent (prior to the modeled event) and coincident (during the modeled event) conditions are presented in Baker River Project Technical Memorandums No. 10 and No. 11 (Tetra Tech 2006b; Tetra Tech 2007)

DATA SOURCES

The sources of information for developing the coincident and antecedent conditions for the initial PMF analysis were as follows:

- Reservoir Elevation—Reservoir elevation data was obtained from USGS end-of day reservoir elevation records for Baker Lake (USGS Station 12191600) and Lake Shannon (USGS Station 12193000). Periodic gaps in the USGS data were filled using data from PSE internal records.
- Base flow—Estimates of average monthly base flow into Baker Lake and Lake Shannon were developed using USGS stream flow records for the Baker River (USGS Station 12193500).
- Snowpack Density and Water Content—PSE provided snowpack density and water content information from the end-of-month snow surveys conducted at the nine snow course stations in the Baker River watershed.
- Antecedent Precipitation—Cumulative antecedent precipitation for the Baker River watershed was estimated using NOAA/NWS Upper Baker Dam precipitation station (Station 458715) data.
- Air Temperature—Development of antecedent and coincident air temperature time series for the PMF was based on the methodologies outlined in HMR 57 (NWS 1994).
- Wind Speed—Development of antecedent and coincident wind speed time series for the PMF was based on the methodologies outlined in HMR 57 (NWS 1994).

In general, these same sources of data were also used in developing the model input for the sensitivity analysis described in Chapter 8. However, to determine antecedent precipitation, a more rigorous procedure was used to estimate end-of-month precipitation, based on supplemental data from five additional long-term NOAA/NWS stations in the Skagit River basin and two additional long-term NOAA/NWS stations outside of the Skagit River basin.

RESERVOIR ELEVATION

Upper Baker reservoir provides up to 74,000 acre-feet of flood control and operates according to the flood control rule curve shown in Figure 7-1 (USACE 2000). An analysis of reservoir operation records for five extreme storms found that the Upper Baker reservoir has historically been drawn back down to the rule curve elevation within an average of eight days of cresting (Tetra Tech 2006b). This likely is a conservative estimate of how long it would take to draw the reservoir down to the minimum flood control elevation following an extreme storm in preparation for a second extreme storm. For the five events that were considered in detail, releases from Upper Baker Dam were delayed until flows in the main stem of the Skagit River were below the damage level. If a second precipitation event were predicted, such as a PMP level event, the USACE may request that PSE increase reservoir releases to evacuate the flood pool.

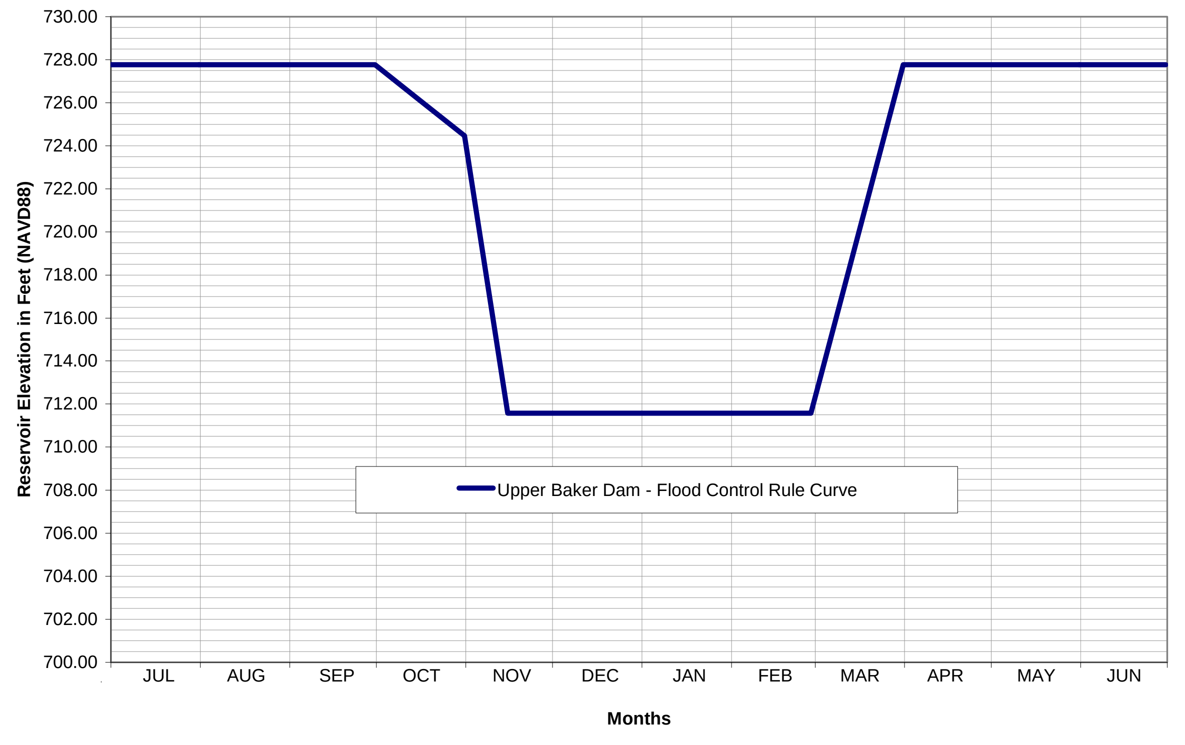

Figure 7-1. Flood Control Rule Curve for Upper Baker Dam

Therefore, it was assumed for the initial PMF analysis that the antecedent reservoir elevation at Upper Baker Dam (the elevation at the onset of the PMP event) would be equal to the minimum flood control pool elevation consistent with the flood control rule curve. 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).

BASE FLOW

Average monthly flow, as recorded at the Baker River at Concrete Gage (USGS 12193500), was used as the base flow coincident with the occurrence of the PMP. Monthly base flow estimates for Upper and Lower Baker are described in Tetra Tech (2006c) and summarized in Table 7-1.

Table 7-1. Seasonal Base Flow Rate (cubic feet/second) Coincident with PMP

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Total Basin	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

SNOWPACK DENSITY

It was assumed that mean end-of-month values for snowpack density would be representative of reasonable antecedent conditions in the watershed. The mean end-of-month snowpack densities for each snow course station in the Baker River watershed are summarized in Table 7-2. 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 months when the computed density was greater than the model's threshold (yield) density of 0.40 inches per inch. For those months, the antecedent density was set to 0.40 inches per inch. Also, the end-of-month values for October and November were assumed to be equal to the computed end-of-month value for December, due to the lack of early season snowpack data. The resulting values of the antecedent snowpack density for each month in the PMF analysis are summarized at the bottom of Table 7-2.

Table 7-2. Mean Value of End-of-Month Snowpack Density (inches/inch)

	Snowpack Density (inches/inch)							
Snow Course Station and Elevation (in feet)	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**
Rocky Creek 2,100	—	—	0.35	0.39	0.41	0.44	0.48	0.55
SF Thunder 2,200	—	—	0.34	0.39	0.38	0.39	0.50	n/a
Schreibers Meadow 3,400	—	—	0.37	0.39	0.42	0.44	0.49	0.54
Marten Lake 3,600	—	—	0.35	0.39	0.41	0.43	0.48	0.56
Dock Butte 3,800	—	—	0.36	0.40	0.42	0.43	0.48	0.54
Watson Lake 4,500	—	—	0.35	0.39	0.41	0.42	0.47	0.54
Easy Pass 5,200	—	—	0.36	0.38	0.42	0.43	0.47	0.55
Jasper Pass 5,400	—	—	0.34	0.39	0.41	0.42	0.47	0.55
Mt Blum 5,800	—	—	0.35	0.38	0.41	0.42	0.47	0.55
Value Used for PMF	**0.35**	**0.35**	**0.35**	**0.39**	**0.40**	**0.40**	**0.40**	**0.40**

For October through January, the snowpack density values used are less than the model's threshold density of 0.40 in/in, so the snowpack will not yield snowmelt until it has risen to the threshold density. For the remaining months, the antecedent snowpack density is equal to the threshold density, thereby allowing for immediate snowmelt from the pack at the onset of the PMP event.

SNOWPACK WATER CONTENT

The water content of the snowpack antecedent to the PMP event was determined using an iterative execution of the hydrologic model to determine the most conservative conditions for each season. The objective was to determine the antecedent conditions that would result in the highest volume of snowmelt for the 72-hour duration general storm. It was anticipated that there would be a point in this iterative method at which a snowpack associated with a higher non-exceedance probability (i.e. a deeper pack with higher snow water equivalent) would actually result in less runoff volume from the basin due to the snowpack's ability to store precipitation during the process of snowpack ripening. As such, a deeper pack (such as the 99-percent non-exceedance snowpack) may produce less runoff volume than a shallower snowpack (such as the 50-percent non-exceedance snowpack).

The hydrologic model was run first assuming basin-wide antecedent snowpack conditions associated with the 50-percent non-exceedance probability (based on a frequency analysis of the snow course records), and the resulting runoff volume was recorded. The process was repeated for the 80-percent non-exceedance probability, and on up to the 99-percent non-exceedance probability for each month. 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-percent exceedance probability) was used. The recorded runoff volumes were reviewed to determine at which point in the process the runoff volume 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 the initial PMF analysis.

Table 7-3 summarizes the results of this iterative analysis. The results show that for months that had snowpacks with densities below the yield point, shallower snowpack conditions yielded the highest runoff volume. Deeper packs simply allowed for precipitation to be used initially to ripen the pack, thus reducing the overall snowmelt volume. October was a unique situation in which full melt-out of the snowpack occurred regardless of the depth. Therefore, the 99-percent non-exceedance snowpack produced the highest magnitude of snowmelt volume for October.

Table 7-3. Non-Exceedance Probability of Antecedent Snowpack Yielding the Largest Snowmelt Volume

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

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 watershed soils for the late fall and winter months. Antecedent soil moisture conditions were computed using a soil moisture budgeting algorithm in the hydrologic model. Input to the algorithm included average values of the cumulative end-of-month precipitation for each of the eight zones of mean annual precipitation, as determined from an analysis of the historical precipitation record at the Upper Baker Dam precipitation station. Table 7-4 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 mean annual precipitation zones in the hydrologic model using a ratio of the mean annual precipitation for each zone to the mean annual precipitation at the Upper Baker precipitation gage.

Table 7-4. 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 Water Year 1966 through Water Year 2004.

AIR TEMPERATURE

Air temperatures coincident with the PMP were determined using the methodology outlined in HMR 57 (NWS 1994). Table 7-5 summarizes the un-ordered 1,000-mb air temperature values developed by this method for the six-hour increments of the 72-hour PMP. These temperatures were re-ordered to conform to each PMP temporal distribution, with the highest 6-hour air temperature corresponding to the highest 6-hour period of rainfall and the lowest 6-hour air temperature corresponding to the lowest 6-hour period of rainfall. Finally, the temperatures were adjusted to account for elevation differences among the eight elevation zones. Figure 15.32 in NWS (1994) was used to adjust the air temperature time series. The lapse rates ranged between 2.45ºF and 3.10ºF per 1,000 feet for elevations less than 4,000 feet and between 2.52ºF and 3.18ºF for elevations between 4,000 feet and 8,000 feet.

Table 7-5. 1000-mb Air Temperatures for 6-Hour Time Increments Coincident with the PMP

	Ranked Air Temperatures for Each 6-Hour Time Increment (ºF)											
Month	**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
MA	54.2	53.4	52.8	52.4	51.7	51.3	51.1	50.7	50.3	50.1	49.8	49.6
APR	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
JUN	61.5	60.7	60.1	59.6	58.9	58.6	58.3	57.8	57.4	57.3	56.8	56.5
JUL	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
SEP	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

WIND SPEED

Wind speeds coincident with the PMP were determined using the methodology outlined in HMR 57. Table 7-6 summarizes the un-ordered wind speed values developed by this method for the six-hour increments of the 72-hour PMP. These wind speeds were re-ordered to conform to the temporal distribution of the PMP, with the highest 6-hour wind speed corresponding to the highest 6-hour period of rainfall and the lowest 6-hour wind speed corresponding to the lowest 6-hour period of rainfall.

Table 7-6. Anemometer-Level Wind Speeds for 6-Hour Time Periods Coincident with the PMP

	Ranked Wind Speeds for Each 6-Hour Time Increment (mph)											
Month	**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
SEP	32	29	26	24	23	21	20	19	18	18	17	17

8. PROBABLE MAXIMUM FLOOD HYDROGRAPHS

Probable maximum flood (PMF) hydrographs were developed for the Upper Baker and Lower Baker reservoirs using the PMP storm events and antecedent conditions described in previous chapters of this report. The calibrated hydrologic model (with adjusted unit hydrographs as described in this chapter) and the reservoir routing model were used to develop the PMF hydrographs. The analysis was conducted in three steps, using FERC engineering guidelines (FERC 1993; FERC 2001) and methodologies outlined in HMR 57:

- The first step developed an initial estimate of the PMF using a deterministic approach, which attempts to represent the most severe combination of meteorological and hydrologic conditions considered reasonably possible for the drainage basin (FERC 1993). The calibrated hydrologic model and the reservoir routing model were executed for numerous combinations of coincident and antecedent conditions, and the model results were reviewed to identify the most conservative results.
- A global sensitivity analysis (GSA) was performed to identify the dominant input parameters in the model and to evaluate the level of conservatism inherent in the initial estimate of PMF. The GSA indicated that the initial estimate of the PMF was characterized by compounding conservatism, resulting in an overly conservative estimate of the PMF. Therefore, alternative magnitudes for specific input parameters were developed to minimize this conservatism, consistent with FERC engineering guidance and historical data.
- The final step was to run the hydrologic model and reservoir routing model using the final set of input parameters. The final estimate of the PMF was then compared against the results of the GSA to quantify the overall conservativeness of the final PMF results.

Detailed discussion of the analysis and results is presented in *Baker River Project Part 12 PMP/PMF Study, Technical Memorandum No. 11—PMF Results and Global Sensitivity Analysis* (Tetra Tech 2007).

UNIT HYDROGRAPH ADJUSTMENT FOR PMP MODELING

The unit hydrograph method for transformation of excess precipitation is based on the assumption that subbasin response is linearly related to the effective precipitation input. In reality, a subbasin responds much more quickly (i.e., the period of rise becomes shorter) as precipitation intensity increases. This is due to higher channel velocities and hence shorter travel times. Since precipitation intensity and the resulting runoff flow rates associated with a PMP event generally are much greater than the historical data used to calibrate a hydrologic model, calibrated unit hydrographs are typically adjusted to account for this change before using the model to simulate the PMP event. The adjustment is accomplished by reducing the input value for period of rise, often by applying a percentage reduction based on engineering judgment. USACE (1991) guidance recommends a reduction of 25 to 50 percent.

For this project, an estimate of the reduction of the period of rise was determined using a modified version of the hydrologic model developed for the Baker River watershed. The HEC-1 unit hydrograph model was converted to a HEC-1 kinematic wave model, which is based on physical attributes of the watershed and produces a non-linear response to precipitation excess. The kinematic wave HEC-1 model of the Baker River watershed was calibrated against the historical November 90 (1) storm event. The calibrated kinematic wave model was then used to compare the response of the watershed to hypothetical PMP level rainfall intensities versus typical historical rainfall intensities.

As expected, the higher PMP level rainfall intensities resulted in subbasin response time that was between 6 and 39 percent shorter than that associated with the historical rainfall intensities. Based on these results, a 7-percent reduction factor on period of rise was established for subbasins with well-developed floodplains and large overbank areas (Subbasins 5, 6, 7 and 8), and a 22-percent reduction factor was established for all other subbasins. Table 8-1 compares the calibrated and PMP-adjusted period of rise values for each Baker River subbasin.

Table 8-1. Reduced Period of Rise Used for the PMP Storm

Sub-Basin	Period of Rise (minutes)	
	Calibrated	**Reduced for PMP**
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	*Open Water*	*Open Water*
LOWER BAKER SUBBASINS		
10	180	150
11	180	150
12	300	240
13	210	180
14	150	120
15	240	210
16	*Open Water*	*Open Water*

INITIAL PMF ANALYSIS

For each month, the calibrated hydrologic model was used to produce candidate PMF hydrographs to both the Upper Baker reservoir and the Lower Baker reservoir for nine modeling scenarios. The nine scenarios represent combinations of the three PMP general storm-centering scenarios and the three temporal distributions of PMP. Each model scenario for each month was identified by the naming convention, XXX_Y_ZZ, where:

- XXX = the month (OCT, NOV, DEC, etc.)
- Y = the general storm centering scenario (E=Entire watershed, U=Upper Baker, and L=Lower Baker)
- ZZZ = exceedance probability associated with the timing of the high-intensity segment (05 = 5-percent exceedance probability, 20 = 20-percent exceedance probability, and 50 = 50-percent exceedance probability)

Thus, for example, Model Scenario NOV_U_50 is the November PMP event with storm-centering over the Upper Baker tributary area and a temporal distribution based on the 50-percent exceedance probability for the location of the high intensity segment.

For this initial analysis of the PMF, all of the other hydrometeorological inputs were assumed fixed at the values presented in Chapter 7. The results were reviewed to determine the combination of centering scenario and temporal distribution that resulted in the most conservative result for each month and for each reservoir; higher peak flow rates and higher inflow volumes represent more conservative results.

Initial PMF Inflow Hydrographs

Figures 8-1 and 8-2 show sample inflow hydrographs developed in the initial PMF analysis. Figure 8-1 shows the effect on the Upper Baker inflow hydrograph from changing the storm-centering scenario for a constant PMP temporal distribution and month. Figure 8-2 shows the effect on the Upper Baker inflow hydrograph from changing the PMP temporal distribution for a constant storm-centering scenario and month.

Tables 8-2 and 8-3 summarize the combination of centering scenario and temporal distribution that resulted in the most conservative result for each month for the Upper Baker and Lower Baker tributary areas, respectively. The tables identify the maximum peak inflow rate, the maximum inflow volume, and the critical modeling scenario. These initial results indicate that the largest peak inflows and inflow volumes for the Upper Baker tributary area are associated with the upper centering model scenario, while the largest peak inflows and inflow volumes for the Lower Baker tributary area are associated with the lower centering model scenario.

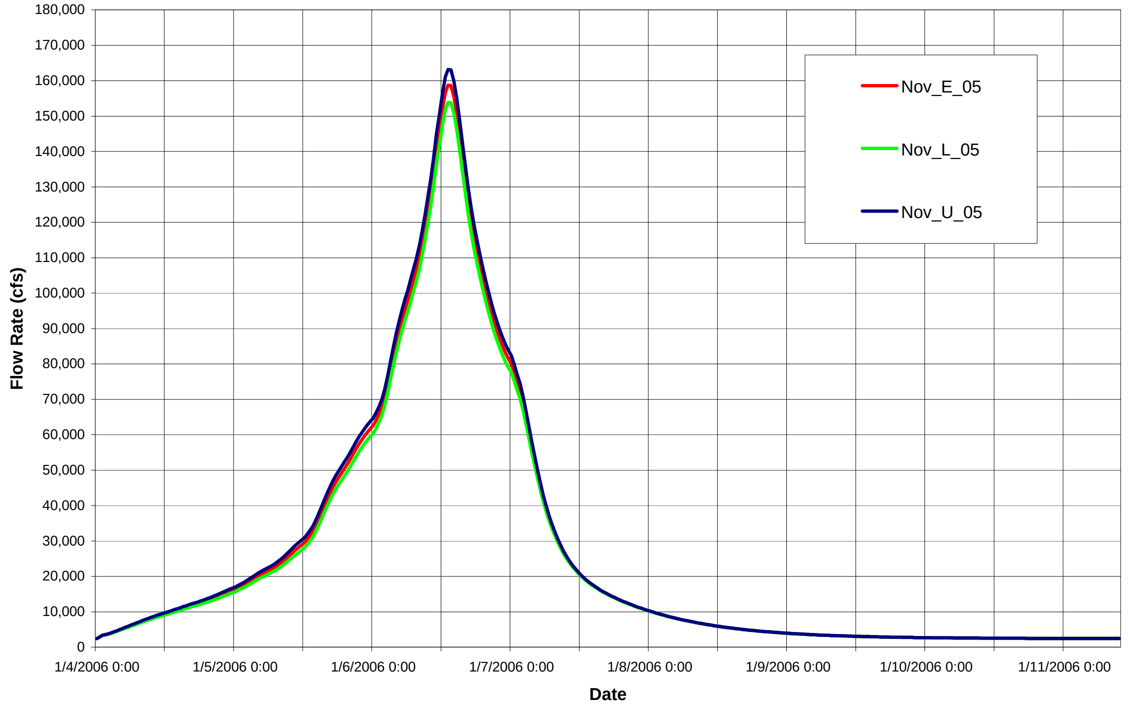

Figure 8-1. Effect of Storm-Centering Scenario on Upper Baker Inflow Hydrograph for November

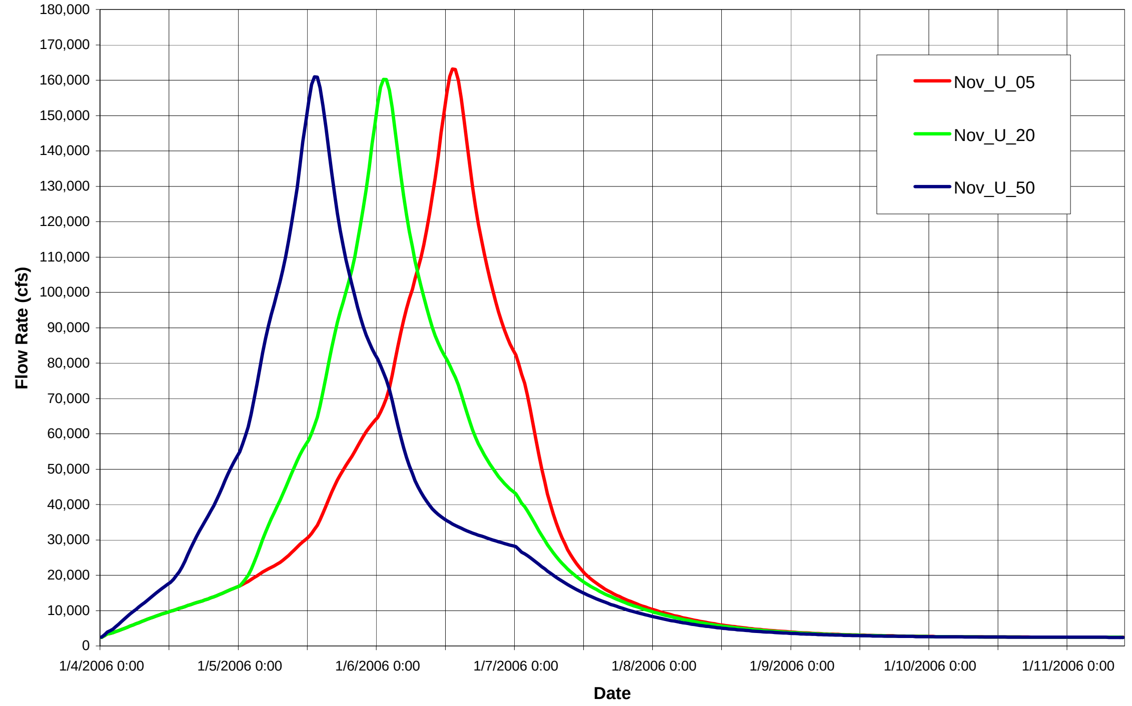

Figure 8-2. Effect of Storm Temporal Distribution on Upper Baker Inflow Hydrograph for November

Table 8-2. Summary of Maximum Peak Inflow Rate and Inflow Volume by Month for Local Inflow Hydrographs to Upper Baker Reservoir

	Peak Inflow		**Inflow Volume**	
Month	**Maximum Peak Inflow Rate (cfs)**	**Controlling Model Scenario**	**Maximum Inflow Volume (acre-feet)**	**Controlling Model Scenario**
October	139,300	OCT_U_05	345,900	OCT_U_20
November	**163,200**	**NOV_U_05**	**392,000**	**NOV_U_50**
December	155,600	DEC_U_05	368,500	DEC_U_50
January	152,400	JAN_U_50	356,700	JAN_U_50
February	150,800	FEB_U_05	342,700	FEB_U_20
March	105,000	MAR_U_50	247,500	MAR_U_50
April	103,500	APR_U_05	242,600	APR_U_50
May	109,300	MAY_U_05	273,700	MAY_U_50
June	73,800	JUN_U_05	183,700	JUN_U_20
July	46,900	JUL_U_05	123,200	JUL_U_20
August	45,700	AUG_U_05	110,000	AUG_U_05
September	78,500	SEP_U_05	157,700	SEP_U_05

Table 8-3. Summary of Maximum Peak Inflow Rate and Inflow Volume by Month for Local Inflow Hydrographs to Lower Baker Reservoir

Month	Peak Inflow		Inflow Volume	
	Maximum Peak Inflow Rate (cfs)	**Controlling Model Scenario**	**Maximum Inflow Volume (acre-feet)**	**Controlling Model Scenario**
October	54,800	OCT_L_05	118,800	OCT_L_20
November	**67,200**	**NOV_L_05**	**146,900**	**NOV_L_50**
December	65,400	DEC_L_05	139,700	DEC_L_50
January	65,900	JAN_L_05	140,900	JAN_L_50
February	65,700	FEB_L_05	136,900	FEB_L_05
March	44,900	MAR_L_05	94,000	MAR_L_20
April	42,700	APR_L_05	88,600	APR_L_20
May	43,900	MAY_L_05	95,400	MAY_L_20
June	31,100	JUN_L_05	66,700	JUN_L_20
July	19,800	JUL_L_05	43,200	JUL_L_05
August	19,100	AUG_L_05	37,200	AUG_L_05
September	34,100	SEP_L_05	59,900	SEP_L_05

The 5-percent exceedance probability temporal distribution typically generates the highest peak inflows, but the temporal distribution associated with the maximum inflow volume varies from month to month. Therefore, it was concluded that inflow volume is not sensitive to the storm 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 initial results presented in Tables 8-2 and 8-3, November is the month with the highest peak inflows and volumes for both the Upper Baker tributary area and the Lower Baker tributary area, and is therefore, the leading candidate for producing the critical PMF hydrograph.

Initial PMF Outflow Hydrographs

The initial PMF inflow hydrographs were routed through the reservoirs using the USACE HEC-5 model (USACE-HEC 1998b) to determine the corresponding peak reservoir elevations, depths of overtopping, and peak outflow rates. Overtopping of Upper Baker Dam occurs when reservoir elevations exceed 735.77 feet (NAVD88), which represents the roadway on the top of the dam. When reservoir elevations at Upper Baker Dam exceed 737.77 feet (NAVD88), West Pass Dike begins to overtop. Overtopping of Lower Baker Dam occurs when reservoir elevations exceed 444.57 feet (NAVD88), which represents the top of the parapet wall at the east non-overflow section of the dam.

The November PMF inflow hydrographs were considered first because they are characterized by the highest peak inflow rates and the largest inflow volumes of all months considered. Table 8-4 summarizes the outflow hydrograph results for the nine combinations of temporal distribution and general storm centering for the month of November.

Table 8-4. Reservoir Routing Summary for November Inflow Hydrographs

	Model Scenario	Peak Inflow (cfs)	Peak Outflow (cfs)	Max. Pool Elev. (feet NAVD88)	Overtopping (feet)
UPPER CENTERING					
Upper Baker Development	NOV_U_05	163,200	126,100	739.84	**4.07**
	NOV_U_20	160,300	109,300	739.08	**3.31**
	NOV_U_50	160,900	107,100	738.99	**3.22**
Lower Baker Development	NOV_U_05	156,100	136,700	460.56	**15.99**
	NOV_U_20	136,200	120,800	458.49	**13.92**
	NOV_U_50	133,600	118,900	458.24	**13.67**
ENTIRE WATERSHED CENTERING					
Upper Baker Development	NOV_E_05	158,700	119,200	739.54	**3.77**
	NOV_E_20	155,800	102,200	738.76	**2.99**
	NOV_E_50	156,500	100,400	738.64	**2.87**
Lower Baker Development	NOV_E_05	150,900	133,700	460.18	**15.61**
	NOV_E_20	130,600	118,300	458.16	**13.59**
	NOV_E_50	128,400	116,300	457.89	**13.32**
LOWER CENTERING					
Upper Baker Development	NOV_L_05	153,800	111,800	739.20	**3.43**
	NOV_L_20	150,900	95,900	738.34	**2.57**
	NOV_L_50	151,600	94,000	738.23	**2.46**
Lower Baker Development	NOV_L_05	145,500	130,900	459.81	**15.24**
	NOV_L_20	126,200	115,800	457.83	**13.26**
	NOV_L_50	123,800	113,800	457.55	**12.98**

The inflow hydrographs for October and December were then routed to verify that the November inflow hydrographs represented the critical conditions. Tables 8-5 and 8-6 summarize the results. In these tables, the peak outflow associated with the Upper Baker Development includes flow over the spillway, over the top of the dam and over the crest of West Pass Dike. The peak outflow associated with the Lower Baker Development includes flow over the spillway and over the top of the dam.

Tables 8-4 through 8-6 show that the critical condition for both Upper Baker and Lower Baker is the November event with the upper centering scenario and the 5-percent exceedance probability temporal distribution. The inflow and outflow hydrographs and reservoir elevations for this event are shown in Figures 8-3 and 8-4 for the Upper Baker and Lower Baker Developments, respectively.

Summary

The initial results of the PMF study are derived from conservative but physically reasonable estimates for the magnitude of each input parameter. Table 8-7 summarizes the antecedent and coincident conditions that represent the critical condition, based on the initial PMF results. Table 8-8 summarizes the resulting overtopping depths. This table compares the maximum PMF pool elevation of 739.84 feet (NAVD88) and 460.56 feet (NAVD88) for the Upper Baker and Lower Baker Developments, respectively, against the elevations of various features of the two developments.

Combining multiple parameters that are based on conservative assumptions may lead to unlikely and highly conservative PMF results due to the compounding of conservatisms. The Global Sensitivity Analysis was used to evaluate model sensitivity to changes in input magnitude and to provide the information needed to make objective decisions about the conservatism of the initial estimate of the PMF.

Table 8-5. Reservoir Routing Summary for October Inflow Hydrographs

	Model Scenario	**Peak Inflow (cfs)**	**Peak Outflow (cfs)**	**Max. Pool Elev. (feet NAVD88)**	**Overtopping (feet)**
UPPER CENTERING					
Upper Baker Development	OCT_U_05	139,300	103,600	738.83	**3.06**
	OCT_U_20	138,700	100,200	738.63	**2.86**
	OCT_U_50	138,100	101,800	738.74	**2.97**
Lower Baker Development	OCT_U_05	125,900	112,700	457.41	**12.84**
	OCT_U_20	122,200	109,000	456.92	**12.35**
	OCT_U_50	124,300	111,600	457.26	**12.69**
ENTIRE WATERSHED CENTERING					
Upper Baker Development	OCT_E_05	134,400	97,300	738.44	**2.67**
	OCT_E_20	133,800	94,000	738.23	**2.46**
	OCT_E_50	133,200	96,000	738.36	**2.59**
Lower Baker Development	OCT_E_05	120,900	109,500	456.99	**12.42**
	OCT_E_20	117,300	105,900	456.47	**11.90**
	OCT_E_50	119,700	108,700	456.88	**12.31**
LOWER CENTERING					
Upper Baker Development	OCT_L_05	131,200	93,300	738.18	**2.41**
	OCT_L_20	130,500	90,000	737.97	**2.20**
	OCT_L_50	130,000	92,000	738.10	**2.33**
Lower Baker Development	OCT_L_05	120,100	109,600	457.00	**12.43**
	OCT_L_20	118,500	106,000	456.49	**11.92**
	OCT_L_50	119,700	108,900	456.90	**12.33**

Table 8-6. Reservoir Routing Summary for December Inflow Hydrographs

	Model Scenario	**Peak Inflow (cfs)**	**Peak Outflow (cfs)**	**Max. Pool Elev. (feet NAVD88)**	**Overtopping (feet)**
UPPER CENTERING					
Upper Baker Development	DEC_U_05	155,600	114,400	739.32	**3.55**
	DEC_U_20	153,500	99,300	738.57	**2.80**
	DEC_U_50	153,600	98,300	738.51	**2.74**
Lower Baker Development	DEC_U_05	142,100	125,100	459.06	**14.49**
	DEC_U_20	124,400	111,300	457.22	**12.65**
	DEC_U_50	123,300	110,300	457.09	**12.52**
ENTIRE WATERSHED CENTERING					
Upper Baker Development	DEC_E_05	151,200	107,500	739.01	**3.24**
	DEC_E_20	149,200	93,400	738.19	**2.42**
	DEC_E_50	149,300	92,500	738.13	**2.36**
Lower Baker Development	DEC_E_05	136,700	122,300	458.70	**14.13**
	DEC_E_20	120,000	108,700	456.88	**12.31**
	DEC_E_50	118,800	107,700	456.74	**12.17**
LOWER CENTERING					
Upper Baker Development	DEC_L_05	146,600	100,100	738.62	**2.85**
	DEC_L_20	144,500	86,700	737.74	**1.97**
	DEC_L_50	144,700	86,100	737.68	**1.91**
Lower Baker Development	DEC_L_05	131,400	119,900	458.38	**13.81**
	DEC_L_20	121,500	106,500	456.57	**12.00**
	DEC_L_50	121,000	105,700	456.44	**11.87**

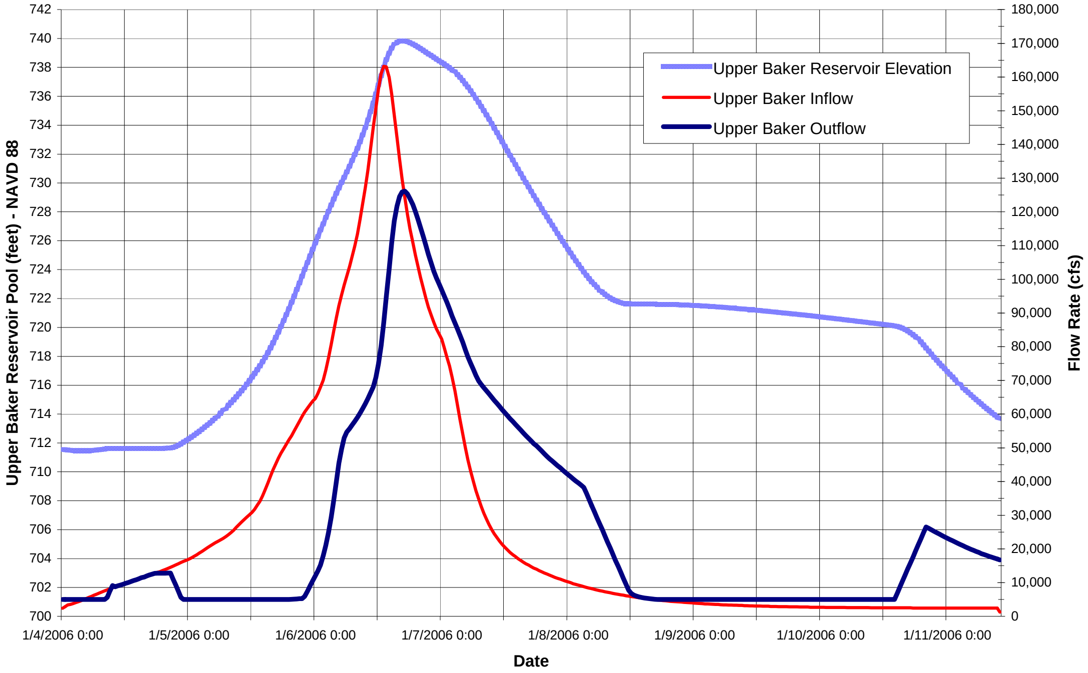

Figure 8-3. Upper Baker Development Initial PMF Hydrographs (NOV_U_05)

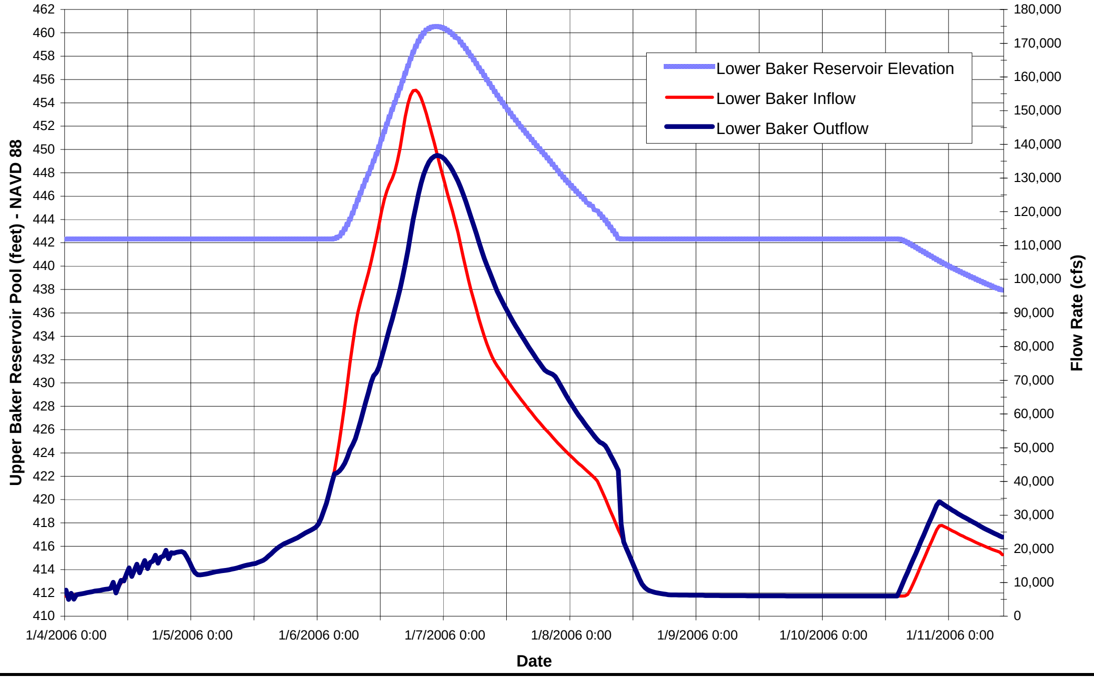

Figure 8-4. Lower Baker Development Initial PMF Hydrographs (NOV_U_05)

Table 8-7. 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 Schreibers Meadow snow course station
Antecedent Snowpack Density	0.352[b]
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. Average value determined from historical record

Table 8-8. Overtopping Depths for Initial PMF Results

	Critical PMF Reservoir Elevation (feet NAVD88)	Elevation of Feature (feet NAVD88)	Overtopping Depth at Feature (feet)
UPPER BAKER DEVELOPMENT			
Top of Dam	739.84	735.77	**4.07**
Top of West Pass Dike		737.77	**2.07**
LOWER BAKER DEVELOPMENT			
Top of Wall—East Abutment of Dam	460.56	444.57	**15.99**
Top of Wall—West Abutment of Dam		445.14	**15.42**
Top Deck of Dam		450.64	**9.92**
Top of Parapet Wall on Dam		453.52	**7.04**

GLOBAL SENSITIVITY ANALYSIS

The initial PMF results 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 represent 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 (FERC 1993). However, the conservatism inherent in each of these inputs is compounding, which can lead to a set of modeling conditions for the PMF that is so conservative as to be beyond reasonably possible.

A global sensitivity analysis (Saltelli et al. 2000) was performed in part to address the potential for excessive conservatism resulting from multiple conservative inputs. The GSA was also performed to evaluate the sensitivity of the hydrologic and reservoir routing models to changes in magnitude in the input parameters. A GSA approach (as opposed to a one-at-a-time sensitivity analysis) apportions the uncertainty in the output variables to the uncertainty in the input parameters. Probability distributions for each input parameter, generated from historical data, provide the input to the GSA. The GSA evaluates each parameter's influence on the model output while preserving dependencies among parameters, such as the correlation between antecedent snowpack magnitudes antecedent precipitation. The objectives of the GSA were as follows:

- Rank the parameters to which flood response and reservoir response are most sensitive.
- Develop a probabilistic characterization of the range of PMP-produced floods.
- Provide guidance in the selection of antecedent and coincident conditions that represent a conservative yet reasonable parameter set for the final PMF.

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 were generated using a "Monte Carlo" sampling procedure that selects a value for each parameter from user-defined probability distributions. Dependencies among the parameters are maintained by defining the order in which parameters are sampled and which parameters can be sampled independently of all others. The 10,000 input parameter sets were then run through the SEFM, HEC-1 and HEC-5 models, and final output was organized in an Excel spreadsheet. For each of the 10,000 model runs, the spreadsheet listed the sampled value for each input parameter, the peak flow rate of the inflow hydrographs, the peak flow rate of the outflow hydrographs, and the maximum reservoir elevations. Scatter plots were generated from the output of the GSA to evaluate the model sensitivity to changes in input magnitude for each of the hydrometeorological input parameters listed above. Because the GSA employs a probabilistic sampling methodology, its output was used to develop a probabilistic characterization of the range of flood magnitudes possible for the various combinations of model input.

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 ultimately chosen by visually verifying that the distribution adequately described the data.

The GSA uses 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, snowpacks with high snow water equivalent occur during wet years (higher antecedent precipitation), and snowpacks with low snow water equivalent occur during dry years (lower antecedent precipitation). Historical precipitation and snow water equivalent data were therefore 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.

Appendix F provides a detailed discussion of the analyses performed to determine appropriate input parameters and parameter distributions for the GSA. Table 8-9 summarizes the parameter dependencies that were maintained in the GSA and the probability distribution or sampling methodology employed in the Monte Carlo Sampling procedure for each of the inputs.

Table 8-9. Input Parameter Dependencies and Distributions for Global Sensitivity Analysis

Input Parameter	**Dependencies**	**Sampling Methodology**
Seasonality of Occurrence	Independent	Based on twice-monthly probability histograms for seasonality of extreme storms published in WDOE (1989), Schaefer et al. (2002), and Schaefer et al. (2006). Minor smoothing of the cumulative probability distribution was conducted.
Centering of Storm	Independent	Assumed an equal likelihood of occurrence for each of the three defined storm-centering scenarios
Storm Temporal Pattern	Independent	Sampled from a discreet population of seven temporal patterns. The probability of occurrence for each pattern was based on a normal distribution and recommendations by Schaefer (2006).
Antecedent Precipitation	Seasonality of Occurrence	Used the three-parameter gamma distribution. Data from nine precipitation stations in the region, including the data at Upper Baker Dam and Lower Baker Dam, were used to develop regional estimates of the distribution parameters.
Antecedent Snow Water Equivalent	Seasonality of Occurrence & Antecedent Precipitation	Computed from correlation between historical antecedent precipitation at a key station in the watershed and historical snow water equivalent at a key station in the watershed. Snow water equivalent data was fit to the log-normal distribution.
Antecedent Snowpack Density	Seasonality of Occurrence	Snowpack density data was fit to a beta distribution.
Antecedent Reservoir Elevation Lower Baker	Seasonality of Occurrence	Used a resampling methodology from 27 years of reservoir elevation data (1980 to 2006)
Antecedent Reservoir Elevation Upper Baker	Seasonality of Occurrence	Used a resampling methodology from 27 years of reservoir elevation data (1980 to 2006)

Flood Response and Reservoir Response Sensitivity

Scatter-plots of the GSA output for the 10,000 input sets were used to evaluate the sensitivity of flood response and reservoir response to changes in the magnitude of each model input parameter. Input parameters were plotted as independent variable on the x-axis and output parameters were plotted as dependent variables on the y-axis. Appendix G provides a detailed discussion of the GSA findings for flood response and reservoir response sensitivity, including scatter plots for each input parameter.

For 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 in Figure 8-5. For input parameters sampled from a limited number of discrete conditions, such as the temporal pattern parameter, the scatter-plots are represented as columns of points, as in Figure 8-6. For these discrete-condition plots, sample statistics were computed for each column of points to indicate the central tendency and the variability of the points in each column. The 25th-percentile value, median value and 75th-percentile value for each column are indicted on the scatter-plots as horizontal dashes.

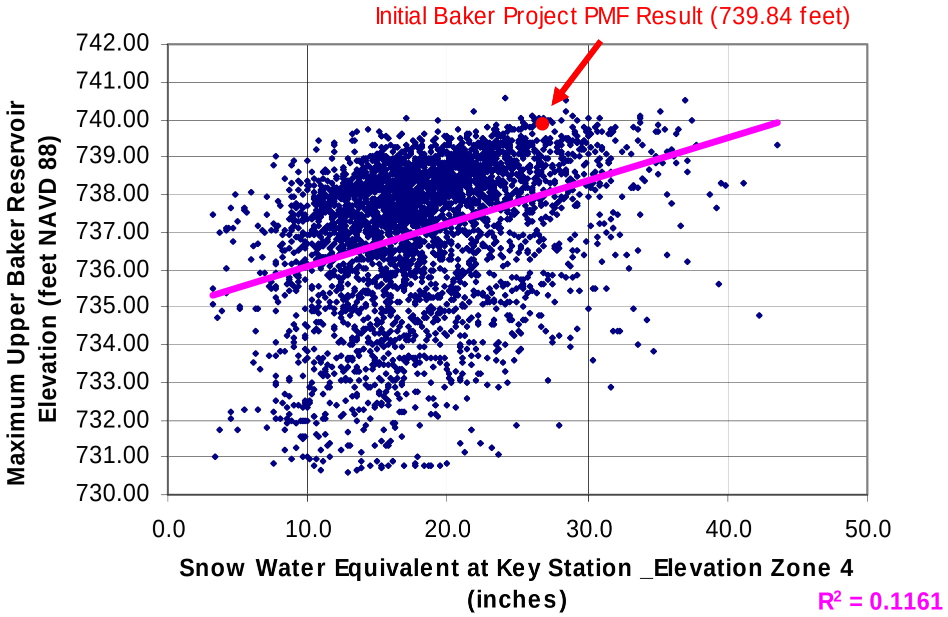

Figure 8-5. Example Scatter-plot –Snow Water Equivalent Parameter

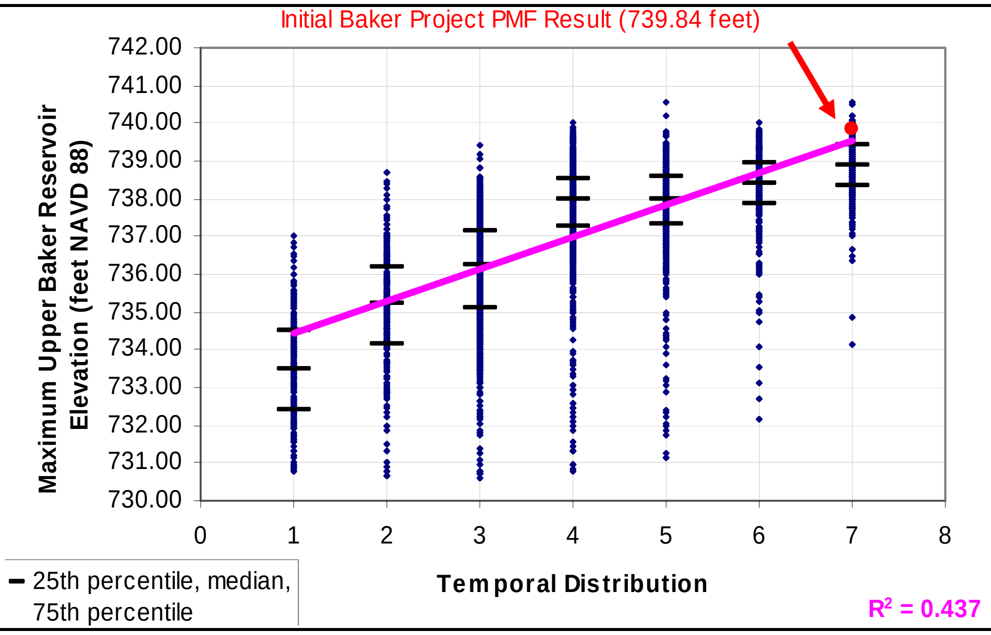

Figure 8-6. Example Scatter-plot –Temporal Pattern Parameter

Standard linear correlation was used to fit trend lines to the data in each scatter-plot. A flatter trend line indicates less sensitivity and a steeper trend line indicates more sensitivity. The degree of scatter about the trend line represents variability in 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 establish qualitative evaluation of the model sensitivity to each input parameter. Input parameters with high R^2 values were identified as highly sensitive relative to the other input parameters. Table 8-10 summarizes the sensitivity of flood response (peak flow) and reservoir response (peak reservoir elevation) to the input parameters evaluated in this analysis. Appendix G provides additional detail on these findings. Also shown in Table 8-10 is a qualitative assessment of the relative uncertainty in parameter estimation, based on the length of the period of record for the data, the source of the data, and the resolution of the data.

Table 8-10. Flood and Reservoir Response Sensitivity to Input Parameters, and Input Parameter Uncertainty

Input Parameter	Flood Response Sensitivity	Reservoir Response Sensitivity	Parameter Uncertainty
Seasonality of Occurrence	Moderate	Moderate	Low
Centering of Storm	Low	Low	Moderate
Storm Temporal Pattern	Moderate	**High**	Low
Antecedent Precipitation	Moderate	Moderate	Low
Antecedent Snow Water Equivalent	**High**	**High**	Moderate
Antecedent Snowpack Density	Low	Low	High
Antecedent Reservoir Elevation Lower Baker	n/a	Low	Moderate
Antecedent Reservoir Elevation Upper Baker	n/a	Moderate	Moderate

The analysis found that the model response is 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 showed that the model was not sensitive to antecedent snowpack density. This is important because antecedent snowpack density had a higher magnitude of uncertainty than the other input parameters. Since the model response was not sensitive to antecedent snowpack density, the uncertainty in this parameter did not contribute to a high degree of uncertainty in the model results.

Probabilistic Characterization of Results

The GSA results were also used to develop a probabilistic characterization of the range of inflow and outflow flood magnitudes possible with a 100-percent PMP event. This probabilistic characterization was 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.

Upper Baker Results

Figures 8-7 through 8-9 present the frequency histograms for the Upper Baker GSA results. The initial PMF results, indicated on the graphs by red arrows, are at the upper end of the histograms, but do not exceed the highest of the 10,000 simulations. Other observations include the following:

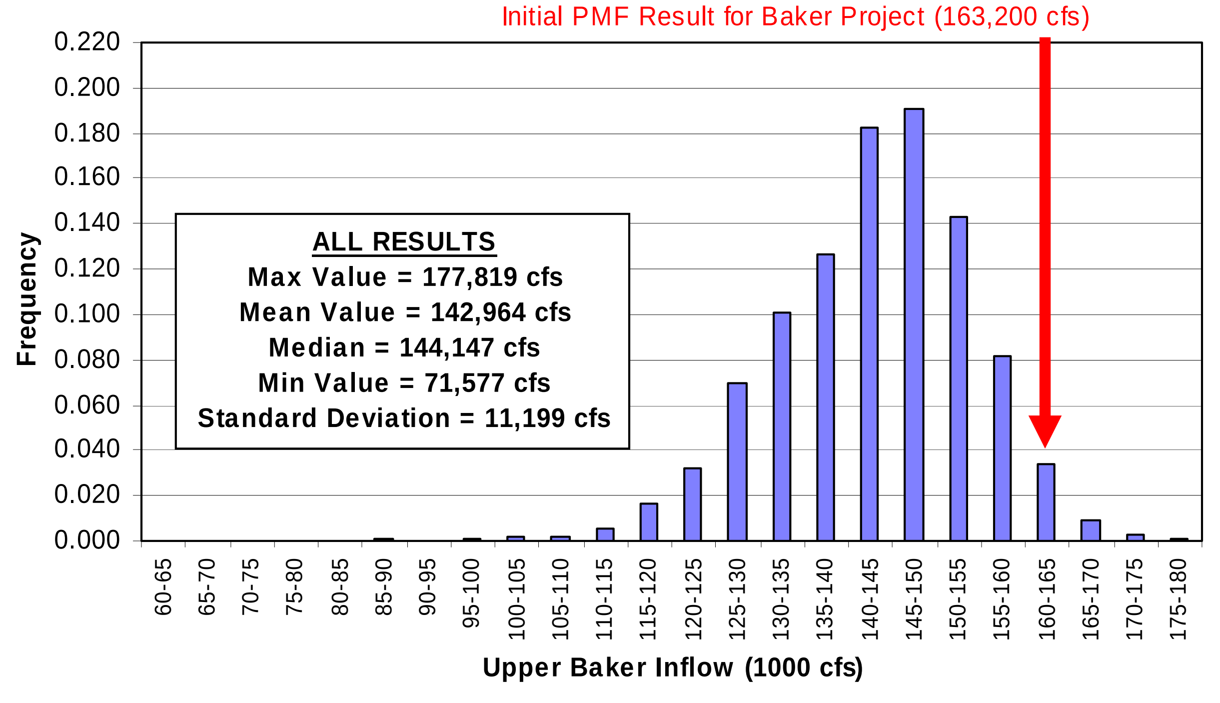

Figure 8-7. Frequency Histogram of Upper Baker Peak Inflows Produced by PMP

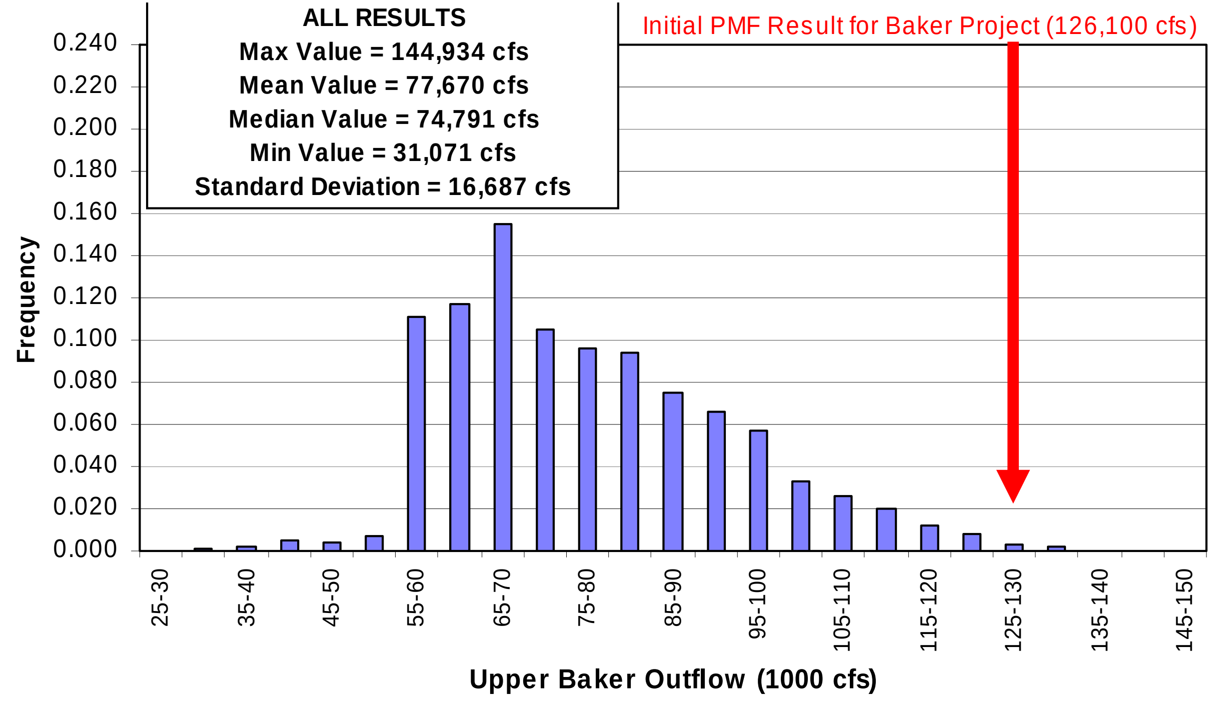

Figure 8-8. Frequency Histogram of Upper Baker Peak Outflows Produced by PMP

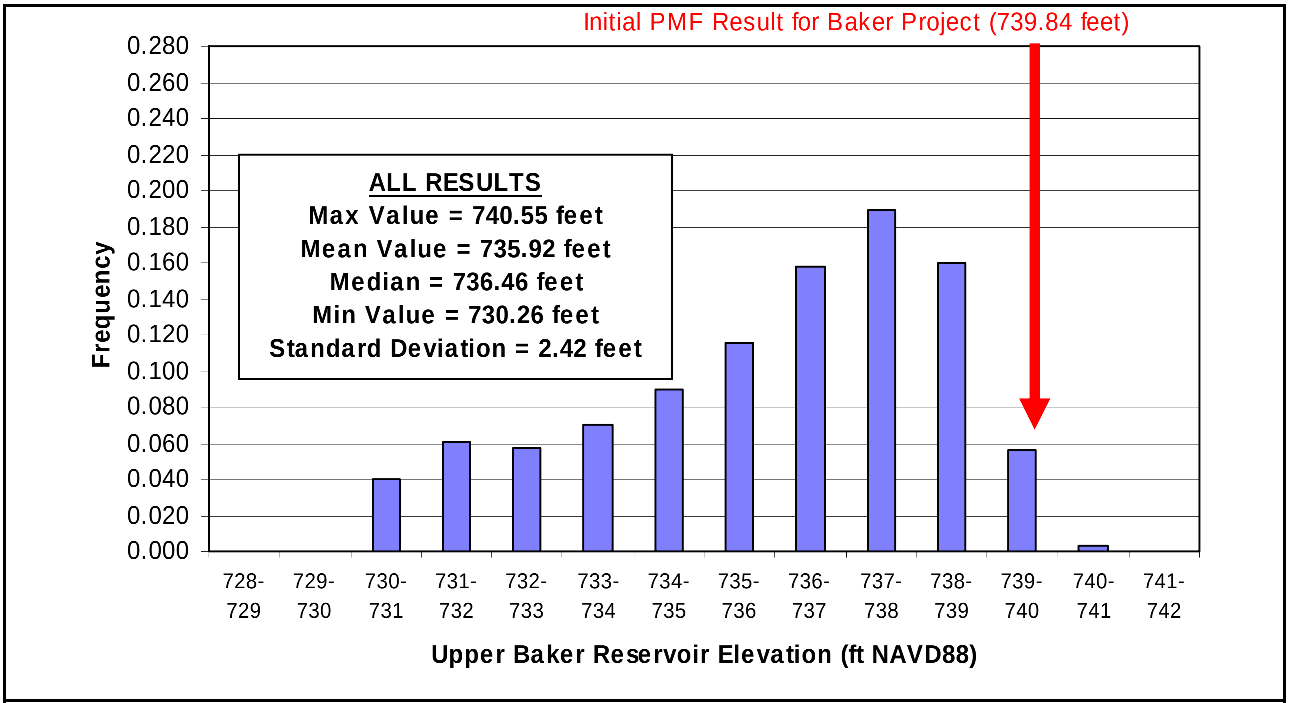

Figure 8-9. Frequency Histogram of Upper Baker Peak Reservoir Elevations Produced by PMP

- 187 of the 10,000 simulations resulted in an Upper Baker peak inflow greater than the initial PMF result. This means that the initial PMF inflow result is greater than the result for 98.1 percent of the 10,000 GSA simulations. Of these 187 simulations, 66 percent were November simulations and 34 percent were October simulations.
- 50 of the 10,000 simulations resulted in an Upper Baker maximum reservoir elevation greater than the initial PMF result. This means that the initial PMF reservoir elevation result is greater than 99.5 percent of the 10,000 GSA simulations. Of these 50 simulations, 60 percent were November simulations and 40 percent were October simulations.

Lower Baker Results

Figures 8-10 through 8-12 present the frequency histograms for the Lower Baker results. For all three output parameters (peak inflow, peak outflow and peak reservoir elevation), the initial PMF results (indicated by the red arrows) are greater than the results for all 10,000 model simulations. The following factors contribute to this result:

- The GSA simulations reflect the historical distribution of Upper Baker end-of-month reservoir elevations, with 85 percent of the 10,000 simulations (and 92 percent of the November simulations) using antecedent Upper Baker reservoir elevations lower than the 711.57-foot value that was assumed for the initial PMF simulation. The use of so many GSA simulations with antecedent reservoir elevations less than 711.57 feet resulted in reduced magnitudes of outflow volume and peak outflow from Upper Baker into Lower Baker.

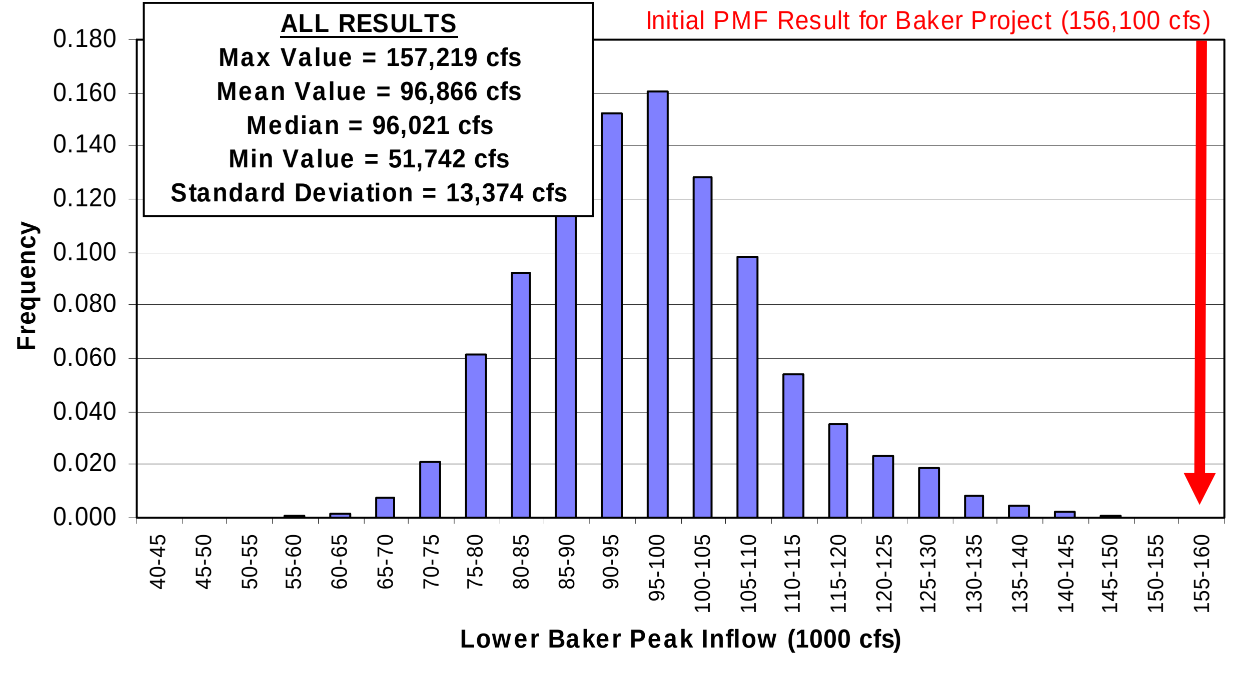

Figure 8-10. Frequency Histogram of Lower Baker Peak Inflows Produced by PMP

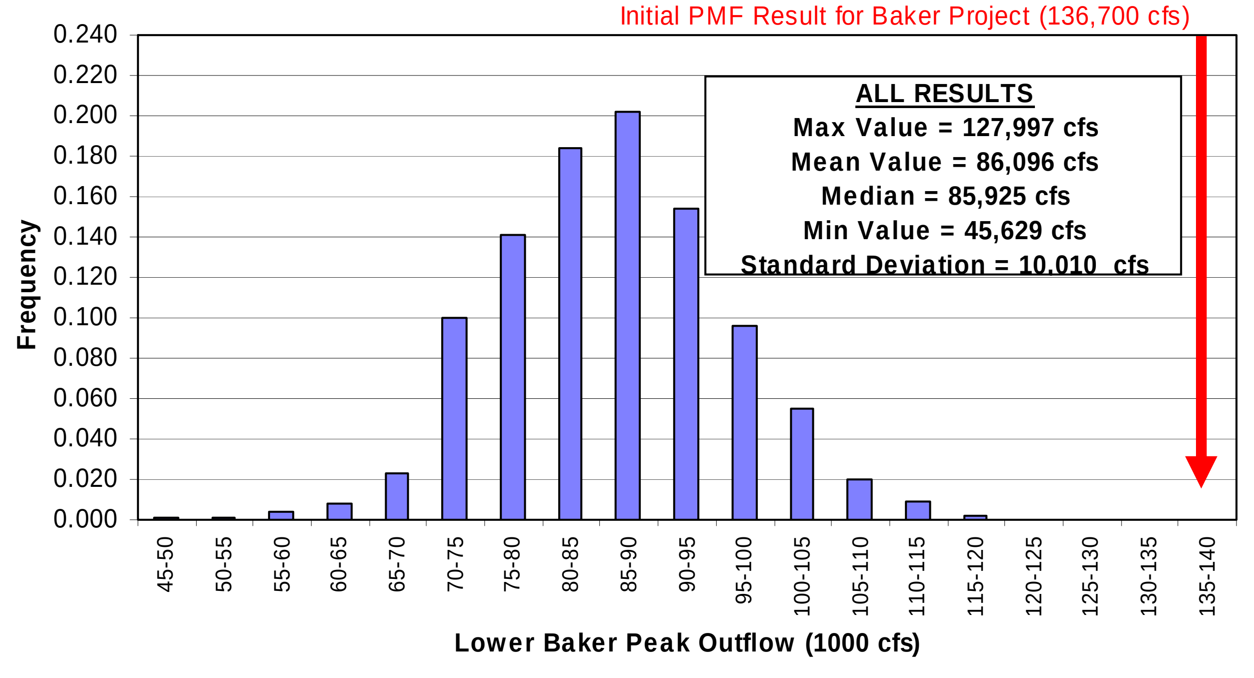

Figure 8-11. Frequency Histogram of Lower Baker Peak Outflows Produced by PMP

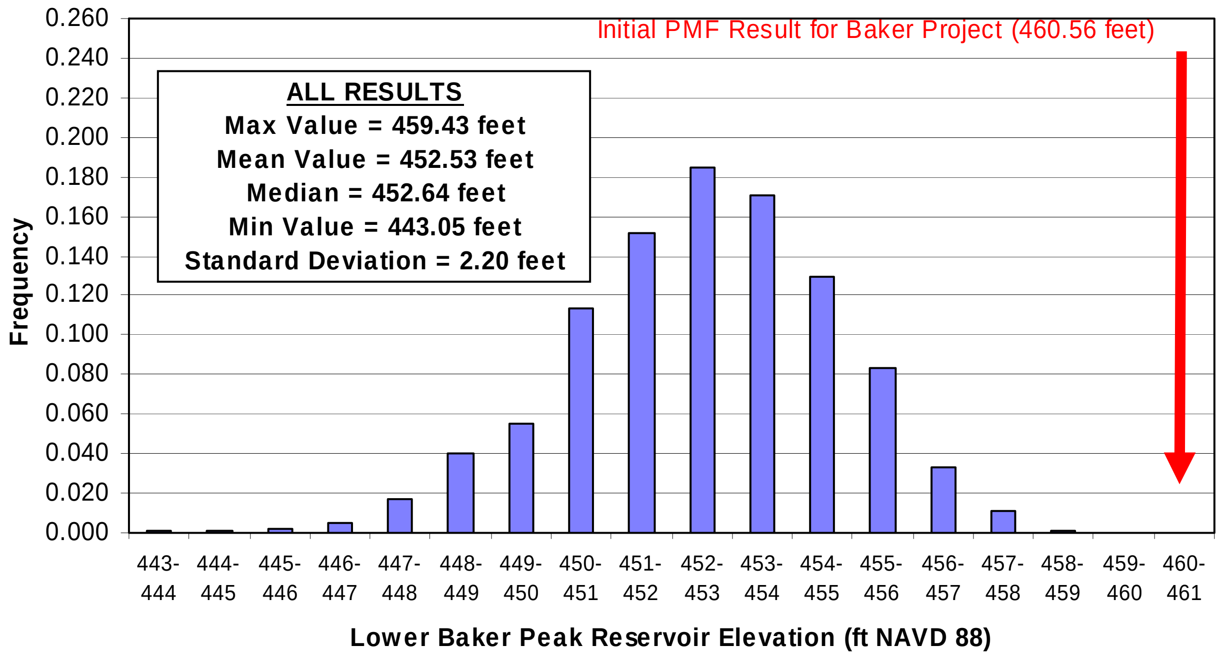

Figure 8-12. Frequency Histogram of Lower Baker Peak Reservoir Elevations Produced by PMP

- All of the GSA simulations used 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.
- 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 is affected more because it has more low elevation coverage.

Conclusions

The frequency histograms for Upper Baker indicate that the initial PMF results are in the top 1 to 2 percent of the 10,000 GSA model simulations, establishing them as clearly conservative. The fact that the initial PMF results for Lower Baker exceed the entire range of GSA results indicates a high degree of conservatism. Overall, the GSA results indicate that the conservatism in the individual parameter estimates in the initial PMF modeling is compounding in such a way as to result in a conservative estimate of the PMF. It is therefore recommended that the basis for selecting the magnitude of some input parameters be revisited, using the results of the GSA as a guide. This revisitation of the input parameters is presented in the following sections.

FINAL PMF ANALYSIS

Revised Input Assumptions

As summarized in Table 8-10, seasonality of occurrence, temporal pattern and antecedent snow water equivalent are the three parameters that have the most influence on the model results. Therefore, the values of these three input parameters were considered first for potential modification in developing a final PMF. FERC engineering guidance (FERC 2001) was considered during the process of reviewing these parameters for potential modification. The following sections describe the recommendations for all the input parameters for the final PMF. Further details are provided in Appendix G.

Season of Occurrence

The analysis conducted for the initial PMF determined that November is the critical month, and the GSA substantiated this determination (see Appendix G). The November GSA simulations produced the highest peak inflow rates and maximum reservoir elevations for both Upper Baker and Lower Baker. Therefore, it is recommended that November remain as the basis for the final PMF analysis.

Storm Centering

The GSA substantiated the initial PMF analysis finding that the upper storm-centering scenario produces the highest peak inflows and peak reservoir elevations for both Upper Baker and Lower Baker. 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 Baker centering is the only logical choice for Upper Baker Dam. Therefore, it is recommended that the Upper Baker centering scenario remain as the basis for the final PMF analysis for both Upper Baker and Lower Baker Dams.

Storm Temporal Pattern

The initial PMF results were based on a “back-loaded” storm event with the peak 1-hour intensity at Hour 58 of the 72-hour storm event. The non-exceedance probability associated with this time of peak-intensity occurrence is 5 percent (WDOE 1989), meaning that 95 percent of extreme storms 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. 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 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, with peak 1-hour intensity at Hour 33 (50-percent exceedance probability)
- Temporal Pattern 5 with 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.

Antecedent Precipitation

Under FERC guidance, 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 soil conditions during the winter season. Therefore the assumption made for the initial PMF of average antecedent precipitation is recommended for the final PMF.

Antecedent Snow Water Equivalent

The initial PMF results were based on an iterative procedure that sought to identify snow water equivalent conditions for each month that maximized snowmelt runoff volume. The initial PMF analysis for the month of November determined that this corresponded with a snowpack with a 90-percent non-exceedance probability, although the 80-percent non-exceedance probability snowpack produced similar results. This iterative procedure is consistent with the intent of the FERC (2001) guidance because 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, but the FERC guidance does not account for snowpack ripening. For the Baker project, the effect of snowpack ripening is accounted for.

To develop snow water equivalent inputs for the final PMF, single runs of the hydrologic model for November, using the Upper Baker storm centering and Temporal Pattern 5, were again conducted with varying magnitudes of snow water equivalent. Table 8-11 summarizes the results. As in the initial PMF analysis, the critical snowpack was between a 80 percent and 90 percent non-exceedance probability. However, the 50-percent non-exceedance probability snowpack also yields a high volume of runoff, and it was melted out in its entirety for the lowest four elevation zones (less than 3,700 feet), while portions of the 80-percent non-exceedance snowpack remained as low as 2,700 feet at the end of the simulation. Moreover, the 50-percent non-exceedance snowpack has a significantly increased likelihood of occurrence. Therefore, it is recommended that the conservatism of the initial PMF results be reduced using the 50-percent non-exceedance snowpack for the final PMF.

Table 8-11. Iterative Snow Water Equivalent Model Runs for Final PMF Analysis

Snowpack Non-Exceedance Probability	Starting Snow Water Equivalent (acre-feet)	Ending Snow Water Equivalent (acre-feet)	Change in Snow Water Equivalent (acre-feet)
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

The 50-percent non-exceedance snowpack was selected to represent antecedent conditions for the final PMF, with the goal of minimizing the compounding conservatism from the initial PMF analysis. This antecedent snowpack condition is reasonably likely, but it maintains a high degree of conservatism.

Antecedent Snowpack Density

FERC guidance does not include discussion of antecedent snowpack density. The initial PMF results used an average value for snowpack density based on historical snow course station data. Given the FERC guidance that antecedent conditions should represent reasonable meteorological conditions, the average snowpack density condition is a justifiable assumption. Therefore the assumption made for the initial PMF of a 35-percent average snowpack density is recommended for the final PMF.

Antecedent Reservoir Elevation

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 required to draw the Upper Baker reservoir down to the flood control pool elevation following extreme precipitation events (Tetra Tech 2006c).

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 used 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.

Recommended Input Values for Final PMF

Table 8-12 summarizes the 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-percent non-exceedance probability to the 50-percent non-exceedance probability.

Table 8-12. Summary of Hydrometeorological Inputs for Final PMF

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 Schreibers Meadow snow course station)
Antecedent Snowpack Density	0.352[b]
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. Average value determined from historical record

Results

Overview

Table 8-13 compares the results of the final recommended PMF model to the results of the initial PMF model. Table 8-14 summarizes the key inputs and outputs for the final PMF flood model simulation. The values presented in Table 8-14 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. The summary of key hydrologic inputs presented in Table 8-14 is for the 72-hour duration precipitation time period. However, due to the lag time associated with the surface runoff hydrographs and the interflow hydrograph, the summary of key hydrologic outputs in Table 8-14 is for the 10-day time period starting when the precipitation event started. Figures 8-13 and 8-14 show the final PMF inflow and outflow hydrographs for Upper Baker and Lower Baker, respectively.

Table 8-13. Comparison of Initial and Final PMF Model Results

	Model Scenario	**Peak Inflow (cfs)**	**Peak Outflow (cfs)**	**Max. Pool Elev. (feet NAVD88)**	**Dam Overtopping Depth (feet)**
Upper Baker Development	NOV_U_05, INITIAL PMF INPUTS	163,200	126,100 *a*	739.84	**4.07**
	NOV_U_20, FINAL PMF INPUTS	157,800	111,500 *a*	739.19	**3.42**
Lower Baker Development	NOV_U_05, INITIAL PMF INPUTS	156,100	136,700	460.56	**15.99**
	NOV_U_20, FINAL PMF INPUTS	136,800	120,300	458.43	**13.86**

a. Peak outflow at the Upper Baker Development includes overtopping of West Pass Dike, which has a top crest elevation of 737.77 feet (NAVD88)

Table 8-14. 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		
Surface Runoff	19.49	14.59
Interflow Runoff	12.00	9.60
Total Runoff (inches)	**31.49**	**24.19**

Note: Results for Final PMF Model (NOV_U_20 with 50-percent non-exceedance probability snow water equivalent conditions) for 72-hour duration.

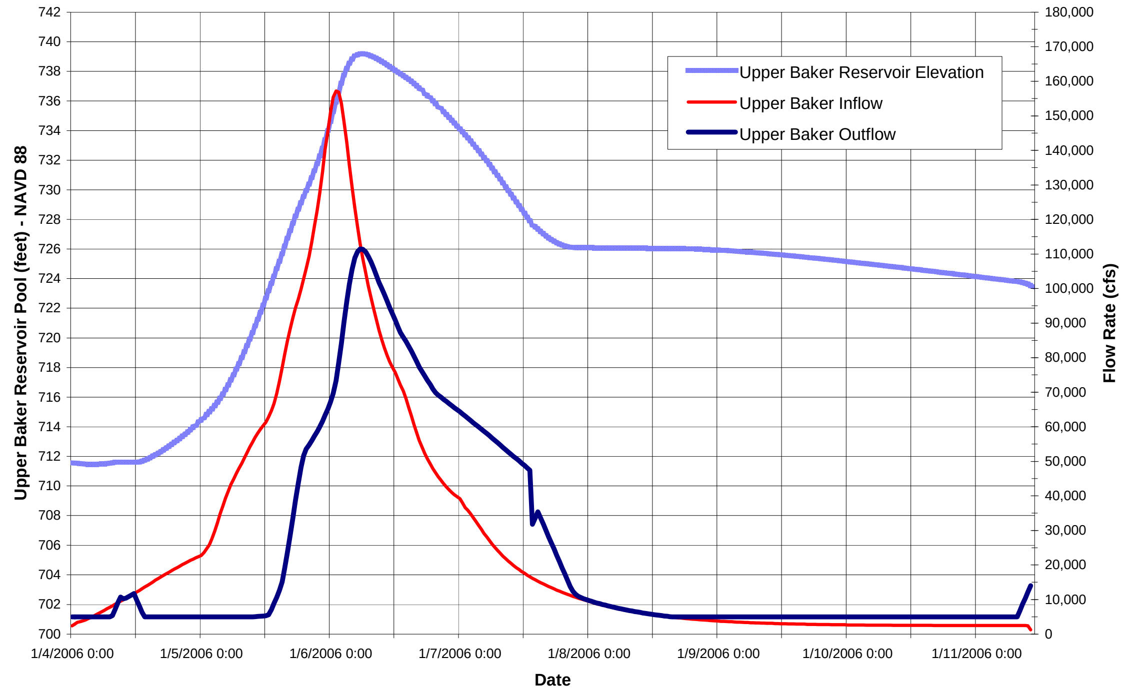

Figure 8-13. Final Upper Baker Development PMF Inflow and Outflow Hydrographs

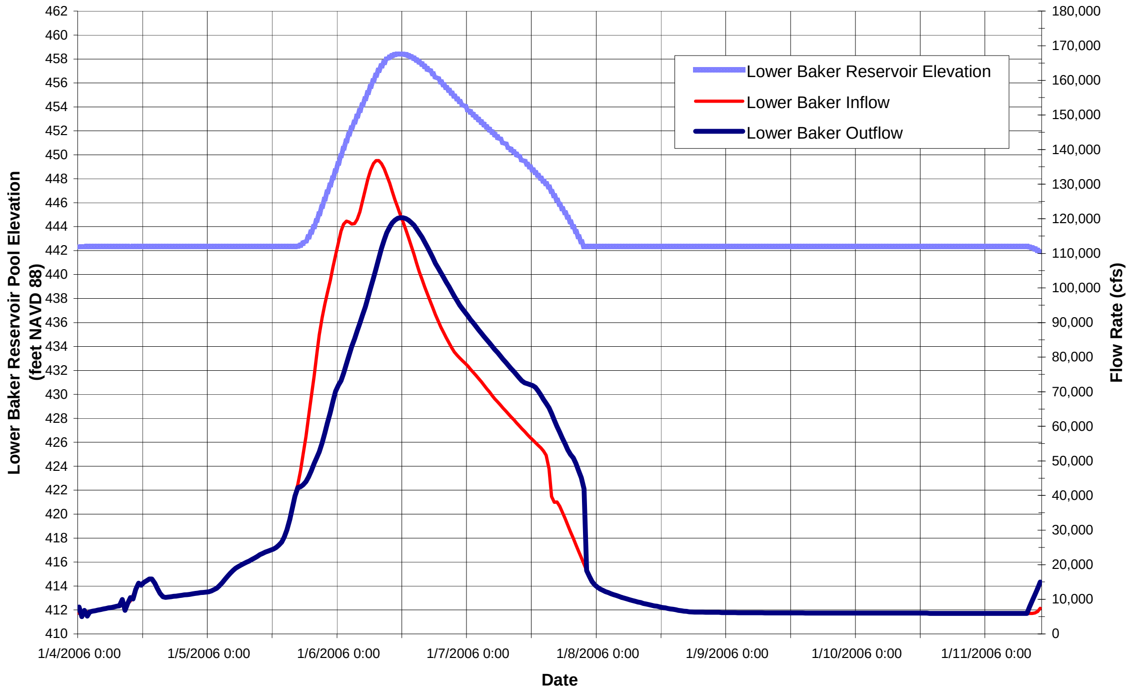

Figure 8-14. Final Lower Baker Development PMF Inflow and Outflow Hydrographs

Snowmelt in the Final PMF

A review of the model output for the final PMF simulation found that most of the precipitation fell as liquid precipitation throughout the 72-hour duration of the precipitation event. However, during the first 24 hours of the event, precipitation fell as snow in the highest elevation zone (Elevation Zone 8) because air temperatures in this elevation zone were less than 34ºF. As presented in Table 8-14, 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 in the mid-elevations between 3,200 feet and 5,000 feet, where the antecedent snowpack was melted out in its entirety. Table 8-15 summarizes, by elevation zone, the snowmelt that occurred during the 72-hour precipitation event.

Table 8-15. Summary of Snowmelt by Elevation Zone, Expressed in Inches

Elevation Zone	Area (square miles)	Antecedent Snow Water Equivalent (inches)	Ending Snow Water Equivalent (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

As seen in this Table 8-15, there was no antecedent snowpack in the lowest two elevation zones and therefore no snowmelt contribution. The procedure used to allocate snow water equivalent was based on using physical data supplemented by HFAM hydrologic model output for nine snow course stations in the watershed. For the 50-percent non-exceedance conditions for the end-of-November period, snow water equivalent in these two lower elevation zones was zero. Figure 8-15 illustrates the spatial allocation of the 50-percent non-exceedance antecedent snow water equivalent for the end-of-November PMF conditions.

Comparison to GSA Results

Figures 8-16 through 8-19 show frequency histograms and non-exceedance curves of the Upper Baker GSA results, with the initial and final PMF results indicated by arrows. Figures 8-20 through 8-23 present the same information for Lower Baker. 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.

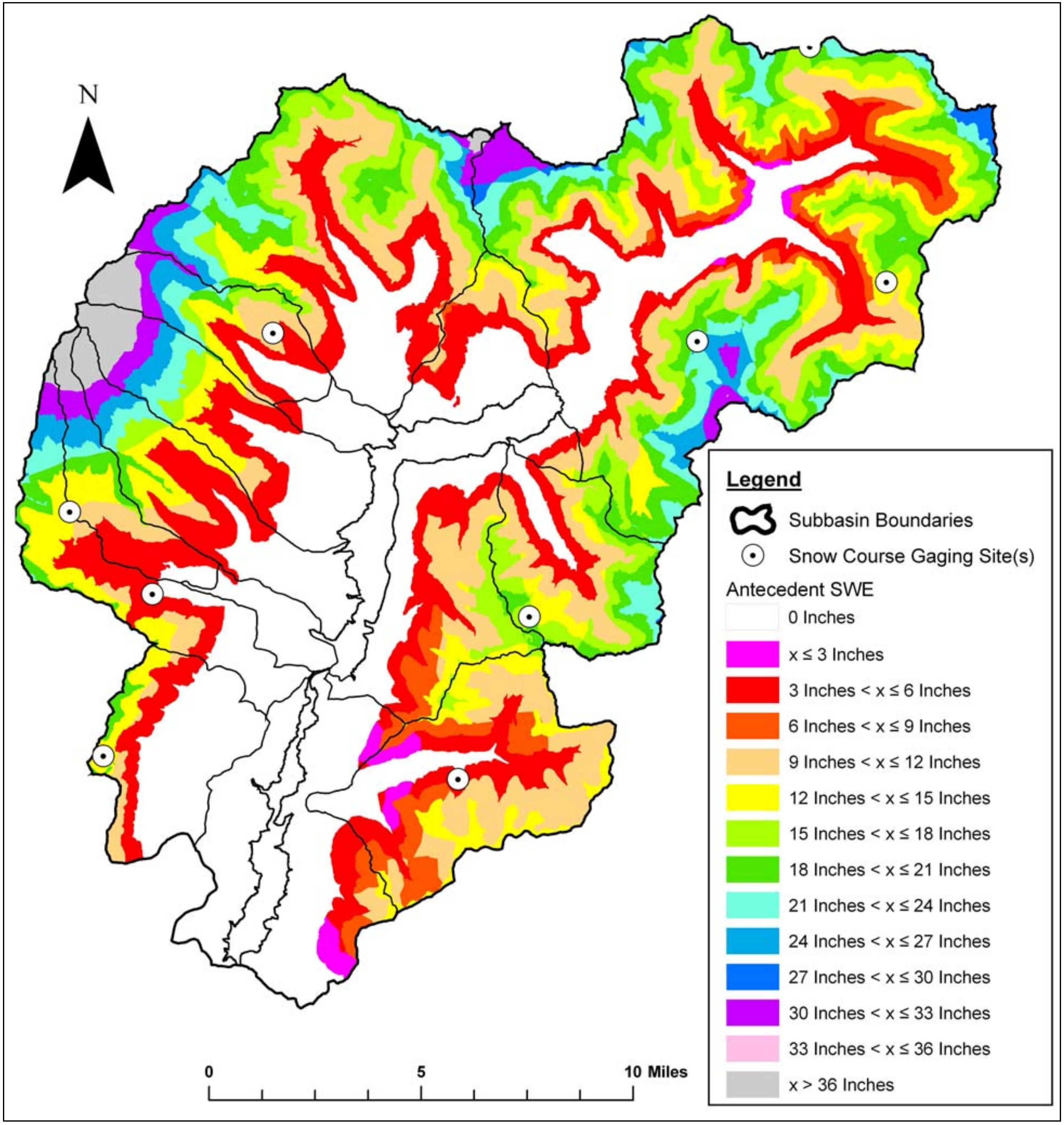

Figure 8-15. Spatial Distribution of Antecedent Snowpack for Final PMF Determination

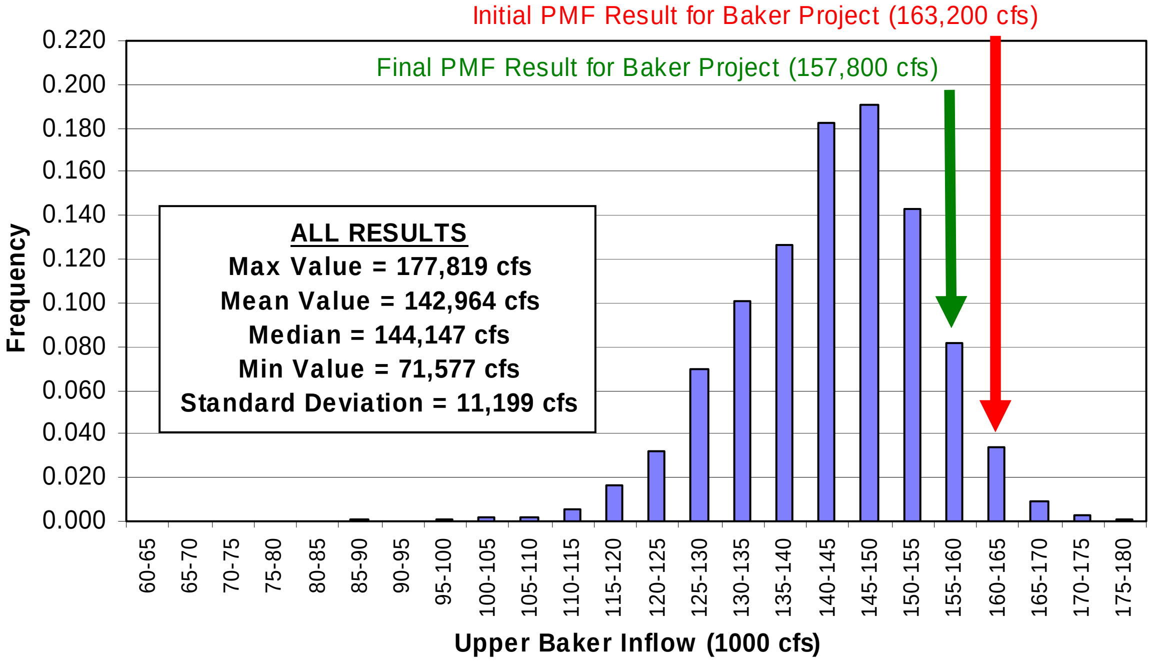

Figure 8-16. Frequency Histogram of Upper Baker Peak Inflow Rates Produced by PMP

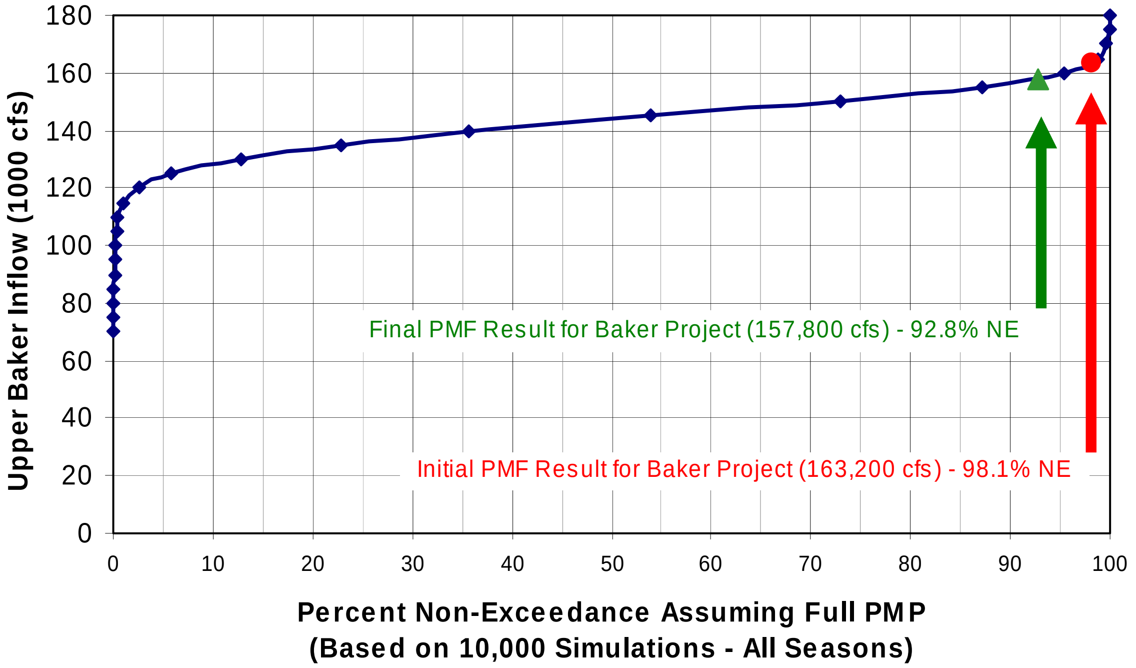

Figure 8-17. Percent Non-Exceedance for Upper Baker Peak Inflow Rates

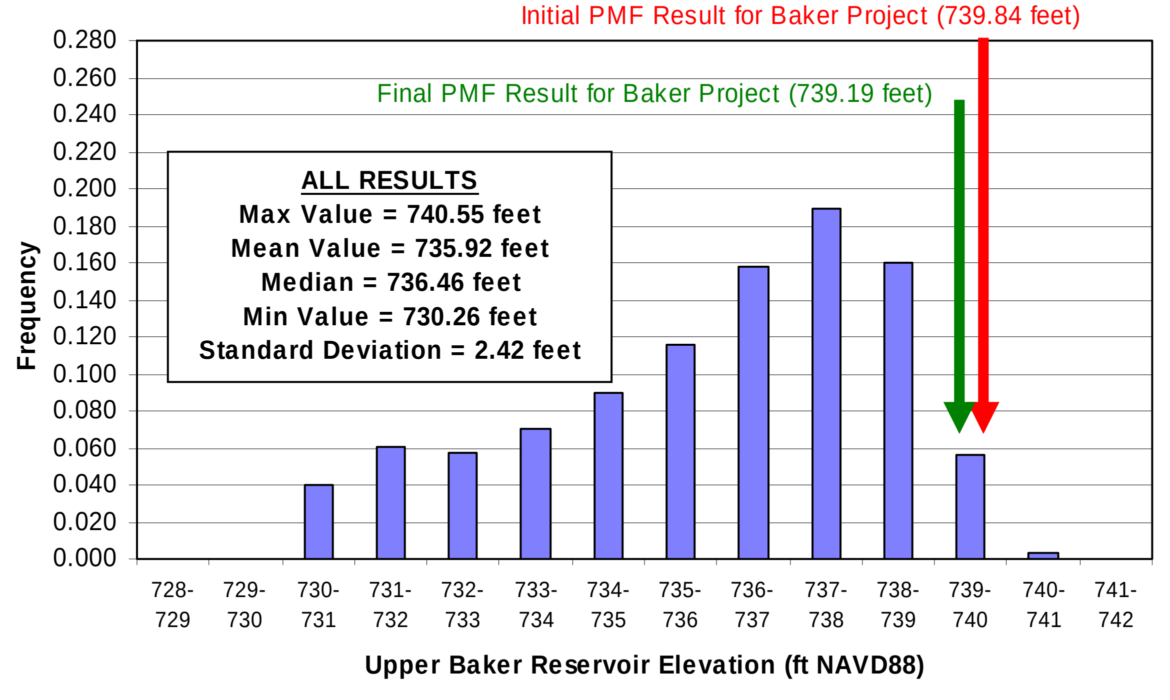

Figure 8-18. Frequency Histogram of Upper Baker Peak Reservoir Elevations Produced by PMP

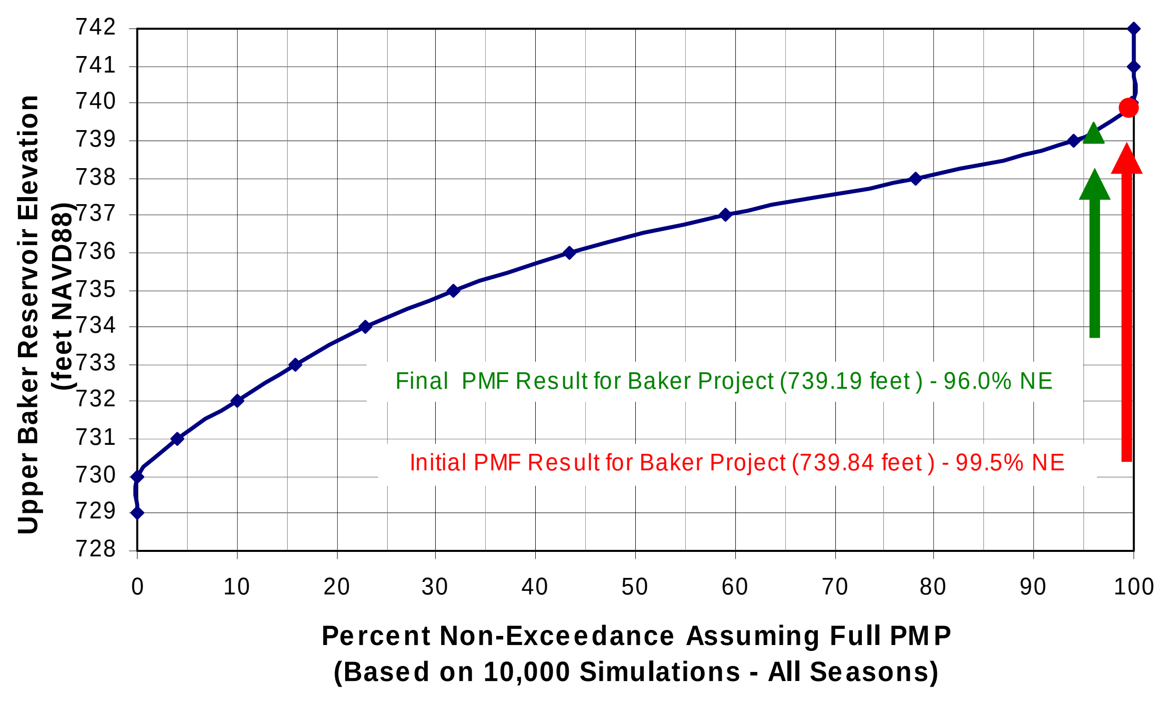

Figure 8-19. Percent Non-Exceedance for Upper Baker Peak Reservoir Elevations

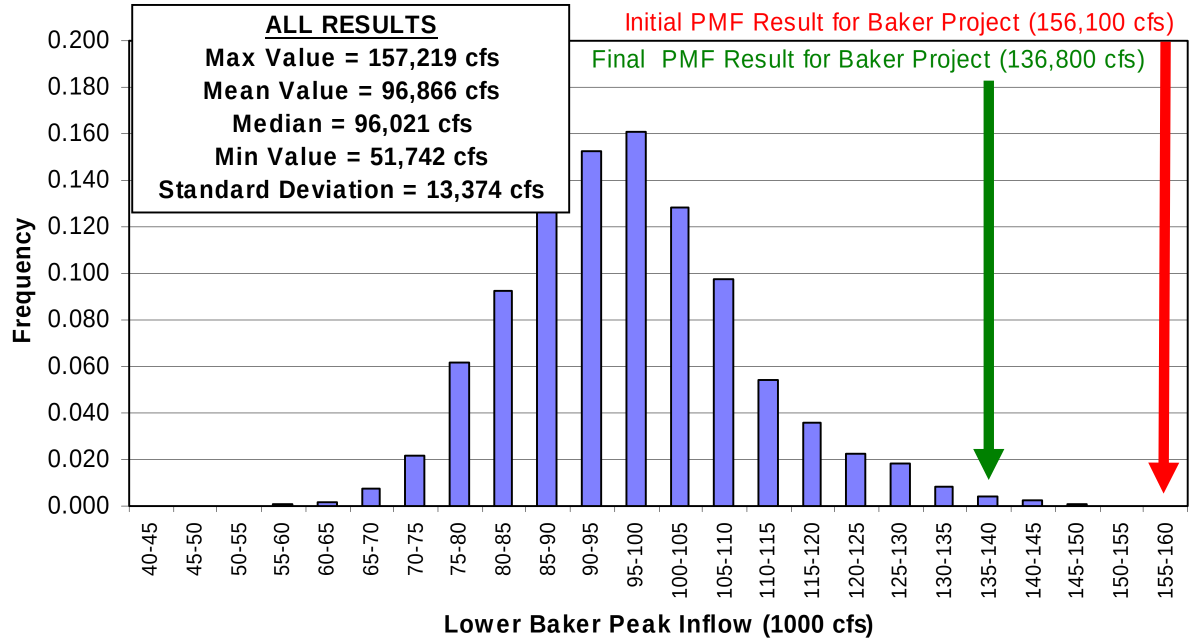

Figure 8-20. Frequency Histogram of Lower Baker Peak Inflow Rates Produced by PMP

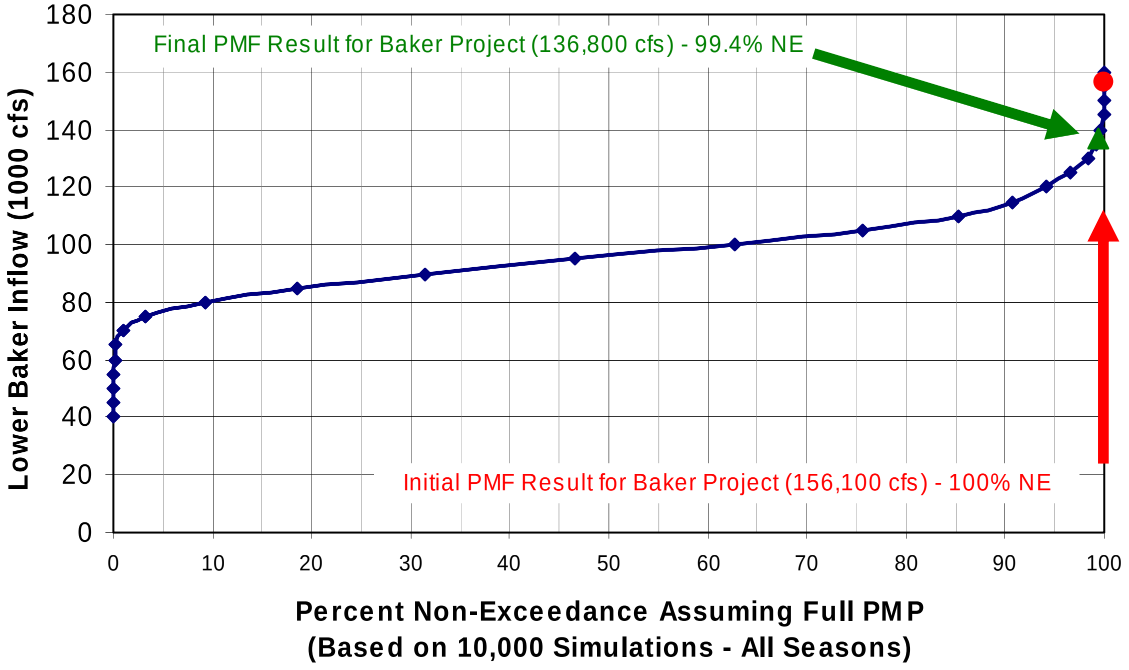

Figure 8-21. Percent Non-Exceedance for Lower Baker Peak Inflow Rates

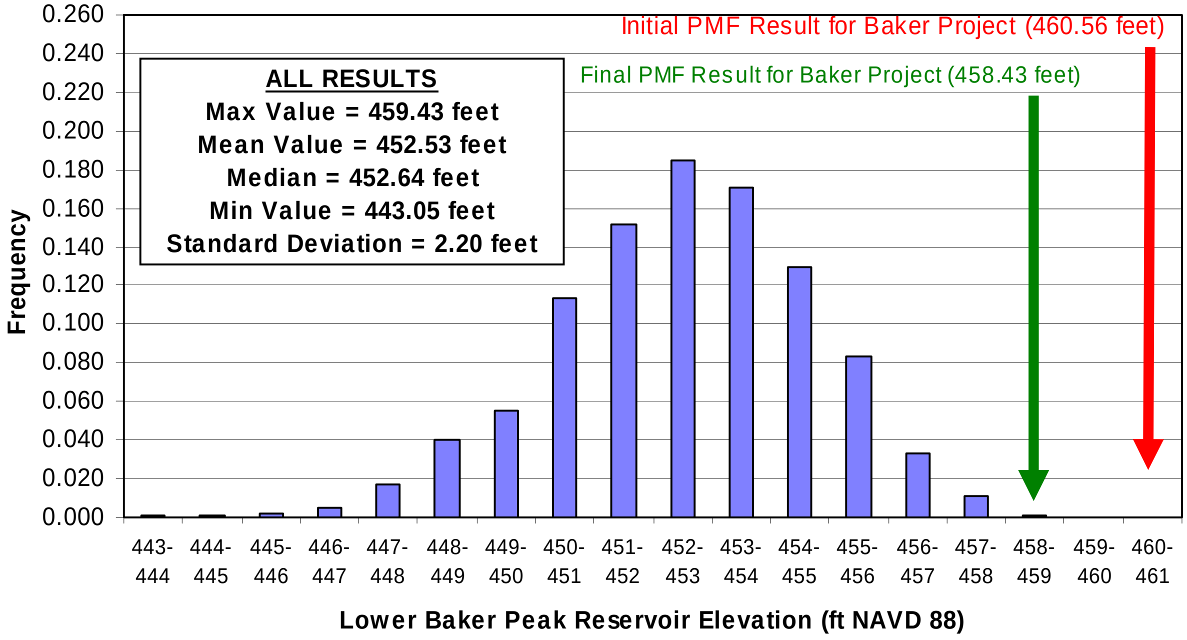

Figure 8-22. Frequency Histogram of Lower Baker Peak Reservoir Elevations Produced by PMP

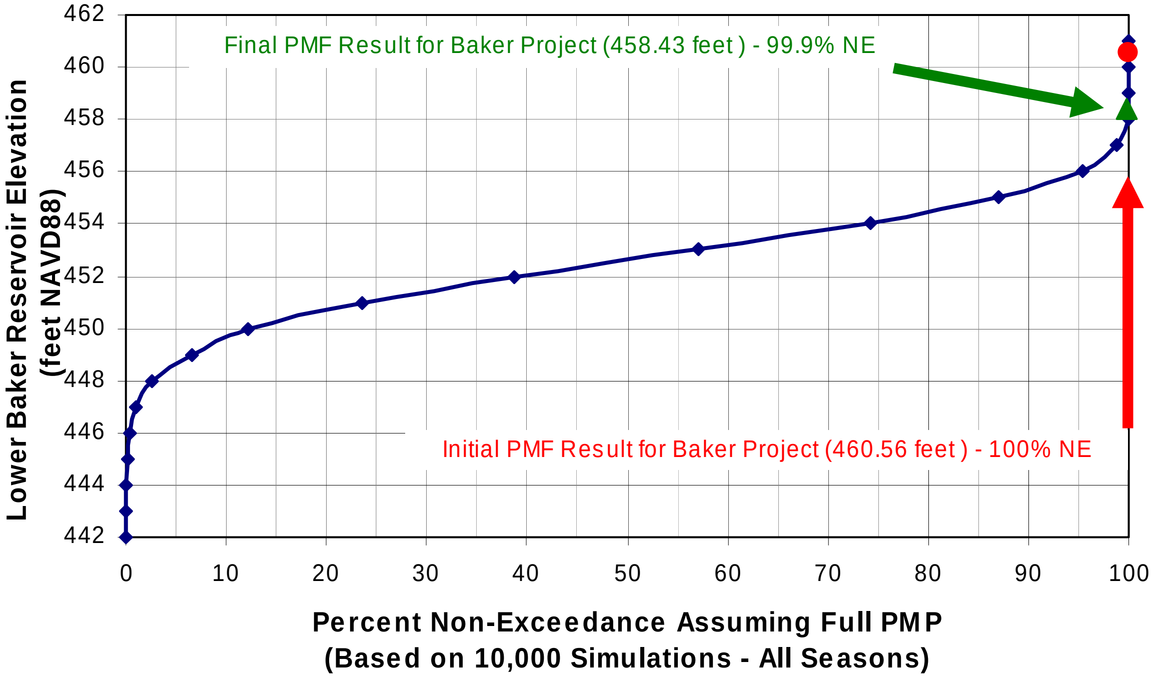

Figure 8-23. Percent Non-Exceedance for Lower Baker Peak Reservoir Elevations

Conclusions

The adopted final PMF represents a conservative yet physically realistic estimation of the PMF, based on a thorough investigation of the range of hydrometeorological input values for the Baker River watershed. The following are the key indicators of the appropriateness of the final PMF:

- The magnitudes of the input parameters that were used to generate the final PMF results are consistent with FERC guidance and with methods presented in HMR 57.
- Within the context of the 10,000 PMF simulations generated by the GSA, the final PMF results for Upper Baker are approximately equivalent to the 93-percent non-exceedance value and the 96-percent non-exceedance value for peak inflow rate and peak reservoir elevation, respectively (see Figures 8-17 and 8-19).
- Within the context of the 10,000 PMF simulations generated by the GSA, the final PMF results for Lower Baker are slightly more conservative, with values of 99-percent and 99.9-percent non-exceedance for the peak inflow rate and the peak reservoir elevation, respectively (see Figures 8-21 and 8-23).

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Puget Sound Energy

Baker River Project Part 12
Probable Maximum Flood Study

APPENDIX A.
FACILITY SCHEMATICS

December 2007

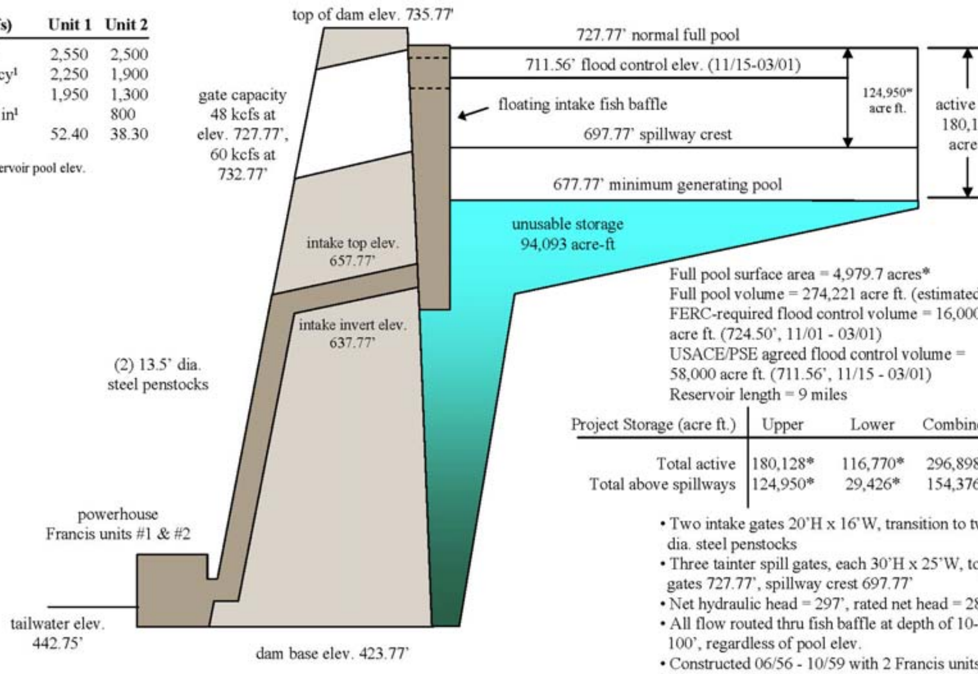
APPENDIX A.
FACILITY SCHEMATICS

Upper Baker Dam

Section View - Not to Scale

Turbine Operation (cfs)	Unit 1	Unit 2
normal max[1]	2,550	2,500
peak efficiency[1]	2,250	1,900
normal min[1]	1,950	1,300
emergency min[1]		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.***

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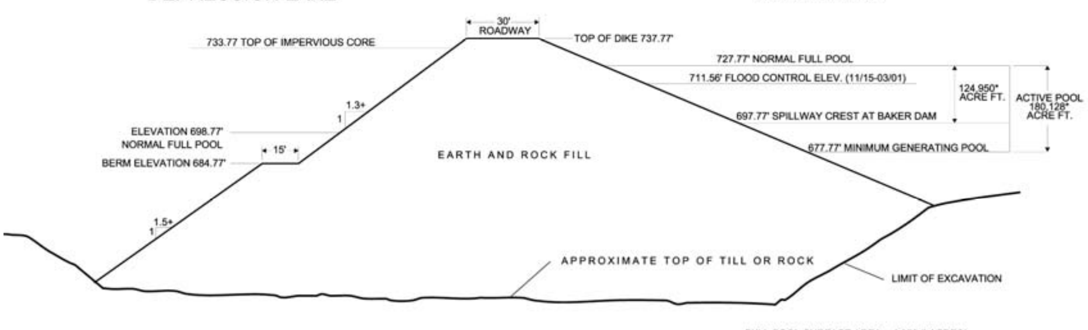
WEST PASS DIKE



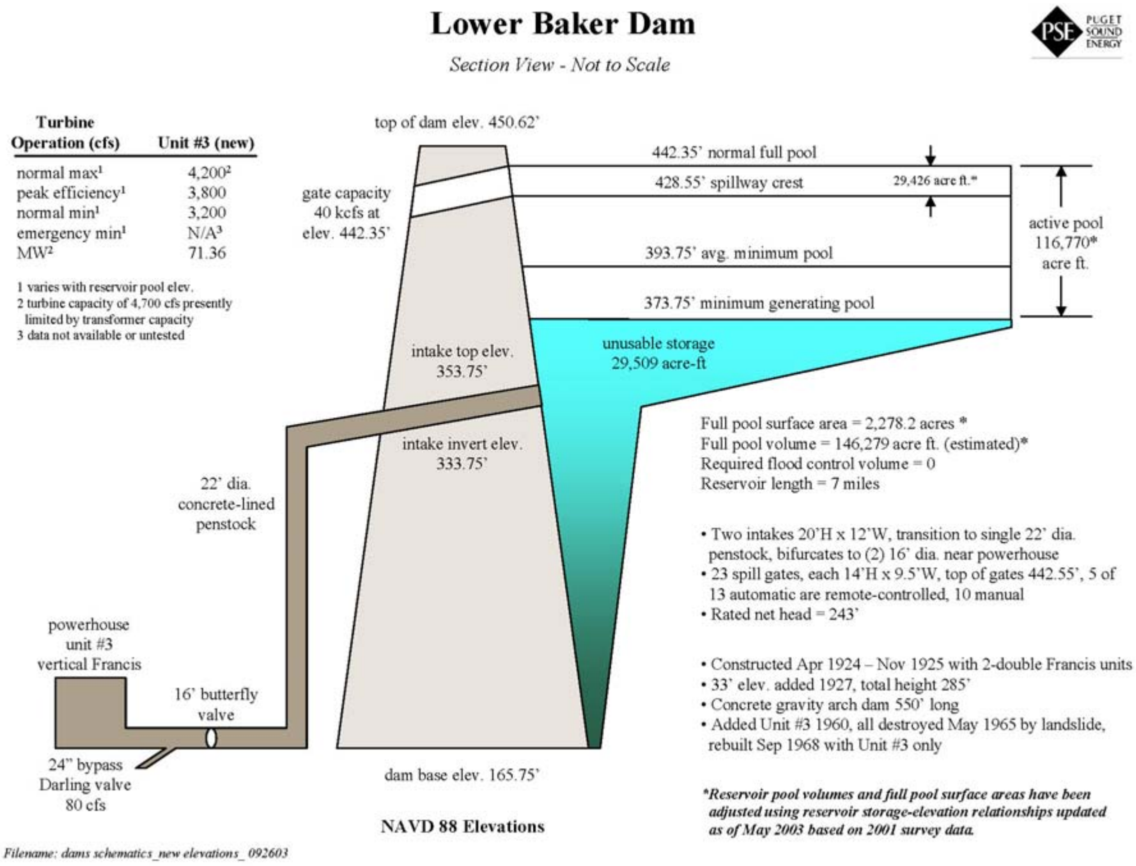
FULL POOL SURFACE AREA = 4,979.7 ACRES*
FULL POOL VOLUME = 274,221 ACRE FT. (ESTIMATED)*
FERC - REQUIRED FLOOD CONTROL VOLUME = 16,000 ACRE FT. (724.50', 11/01 - 03/01)
USACE/PSE AGREED FLOOD CONTROL VOLUME = 58,000 ACRE FT. (711.56', 11/15 - 03/01)
RESERVOUR LENGTH 9 MILES (BAKER LAKE)

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



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

Puget Sound Energy

Baker River Project Part 12

Probable Maximum Flood Study

APPENDIX B.
MODEL CALIBRATION CANDIDATE STORM EVENT DATA

December 2007

APPENDIX B.
MODEL CALIBRATION CANDIDATE STORM EVENT DATA

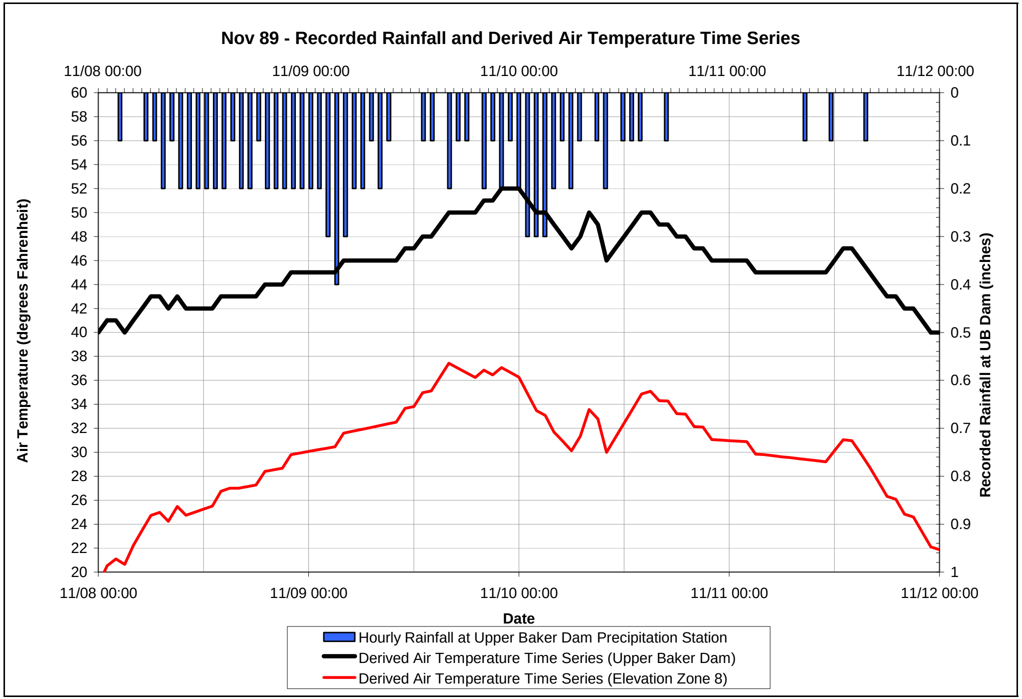


Figure B-1. Derived Air Temperature and Recorded Rainfall at Upper Baker Dam—NOV 89

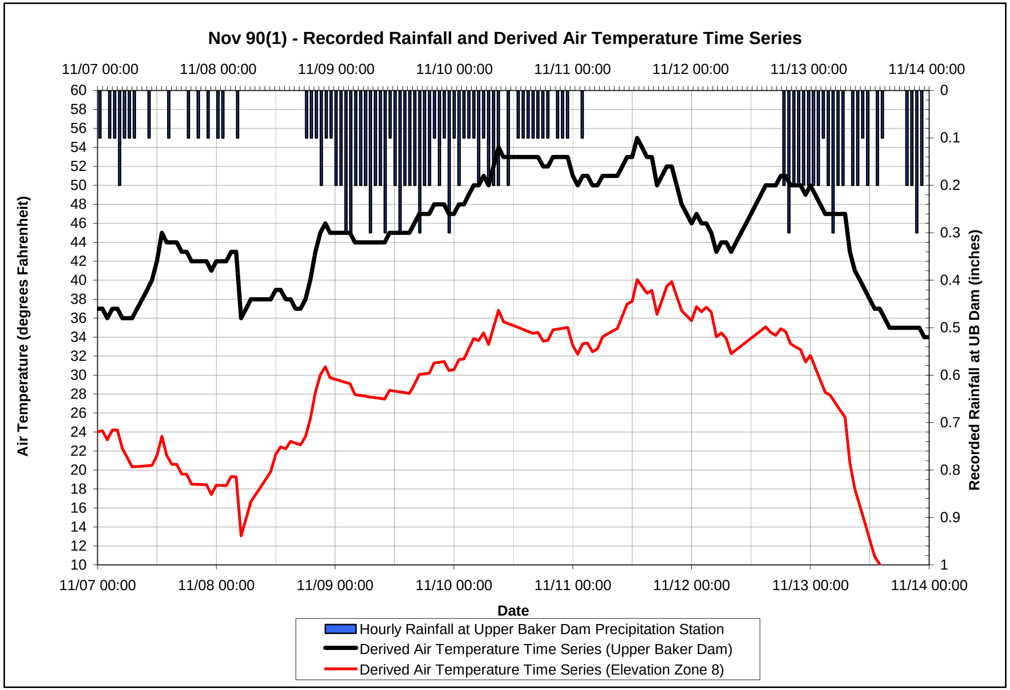


Figure B-2. Derived Air Temperature and Recorded Rainfall at Upper Baker Dam—NOV 90 (1)

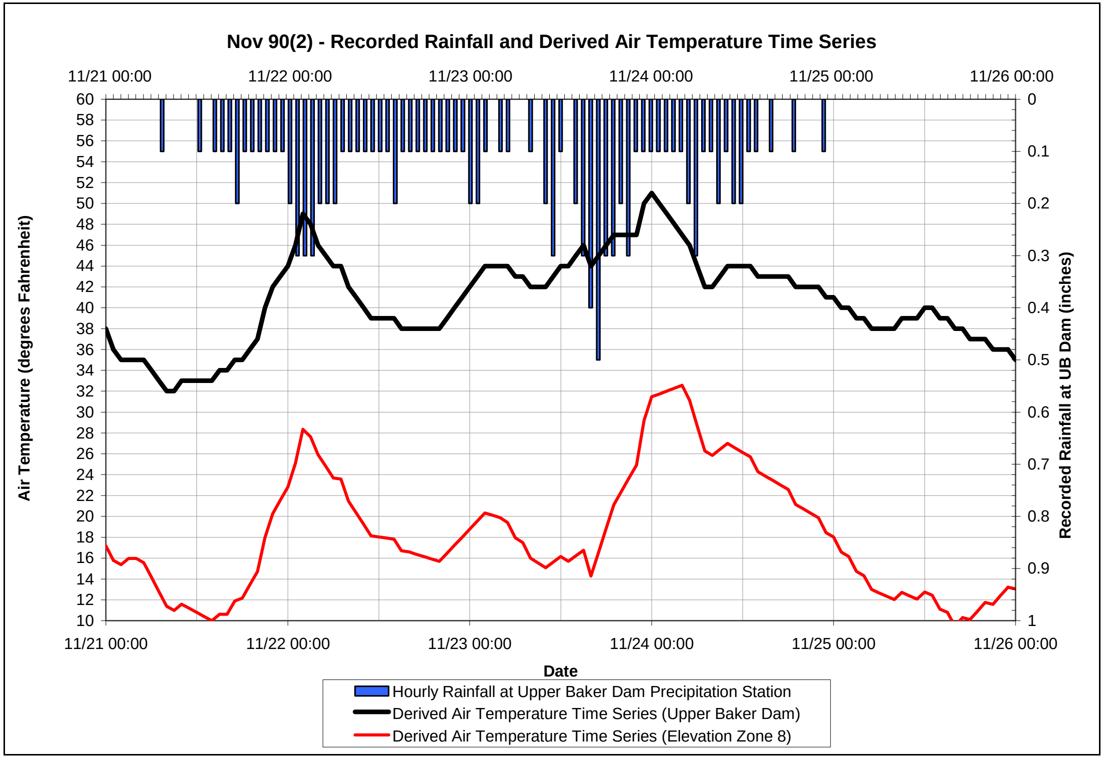


Figure B-3. Derived Air Temperature and Recorded Rainfall at Upper Baker Dam—NOV 90 (2)

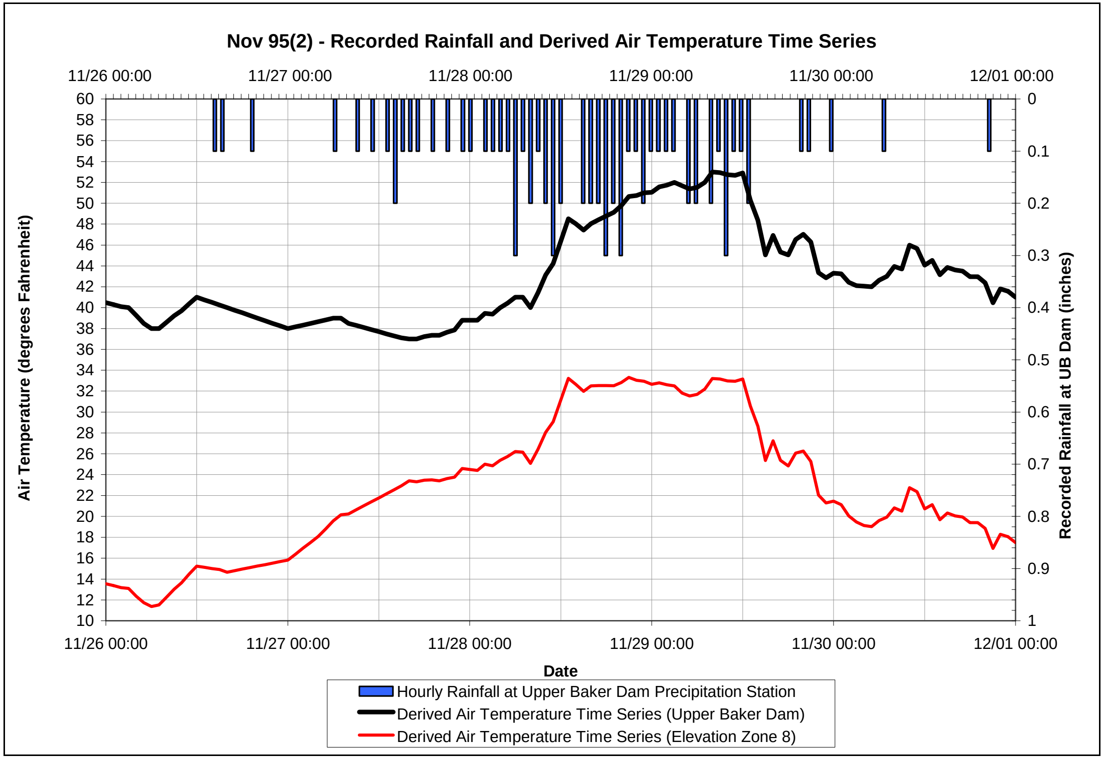


Figure B-4. Derived Air Temperature and Recorded Rainfall at Upper Baker Dam—NOV 95 (2)

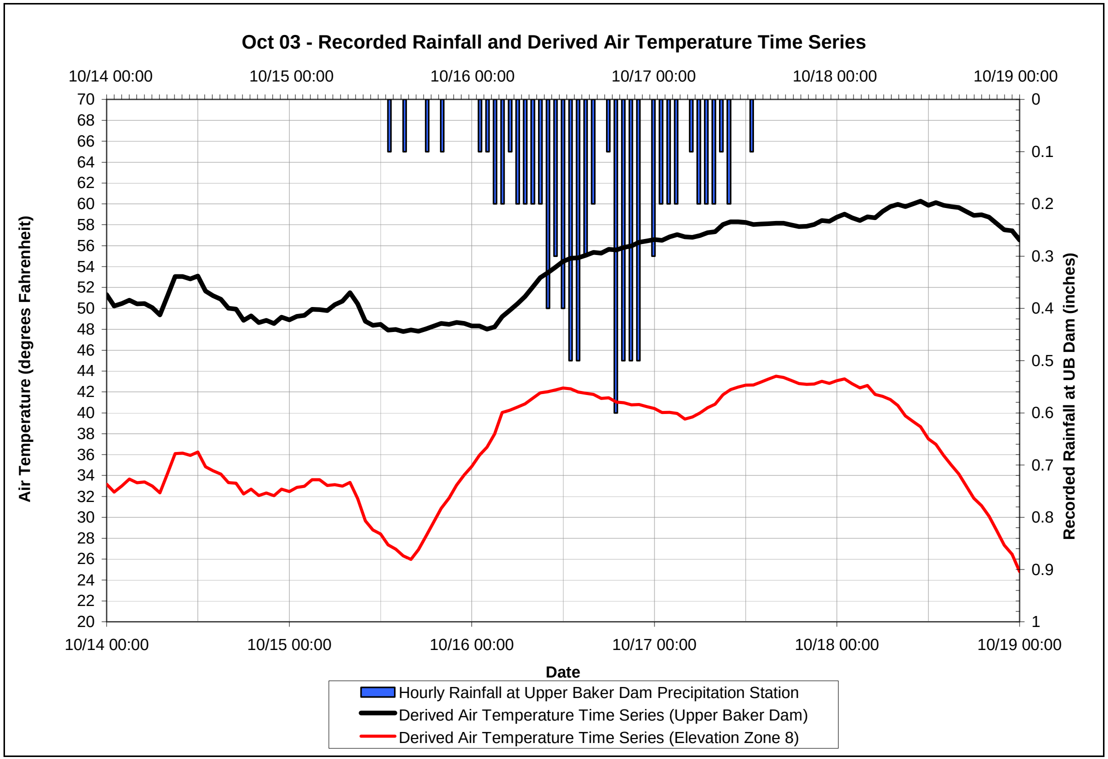


Figure B-5. Derived Air Temperature and Recorded Rainfall at Upper Baker Dam—OCT 03

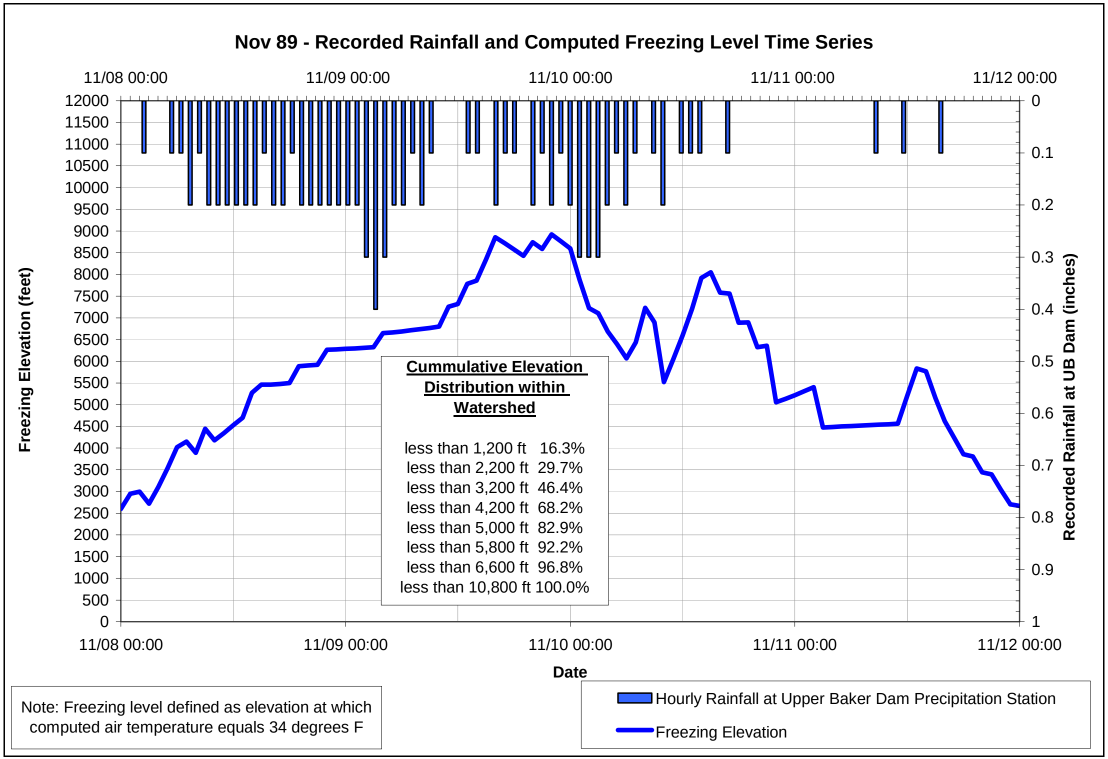


Figure B-6. Estimated Freezing Level and Recorded Rainfall at Upper Baker Dam—NOV 89

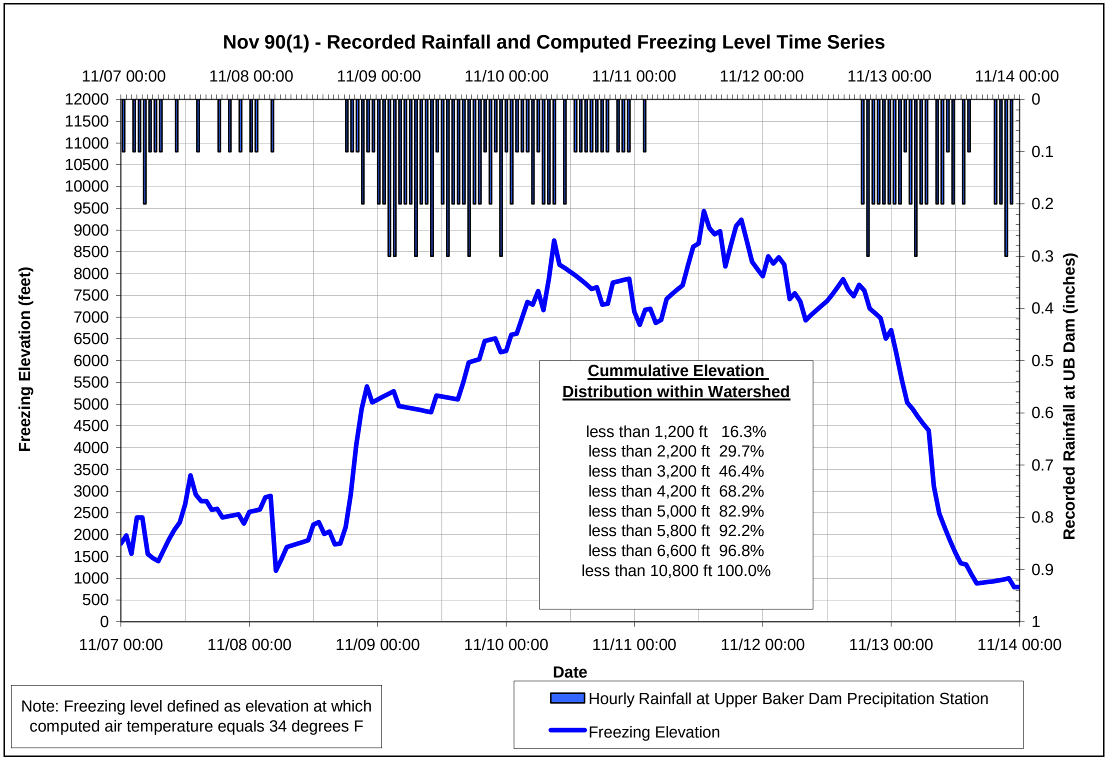


Figure B-7. Estimated Freezing Level and Recorded Rainfall at Upper Baker Dam—NOV 90 (1)

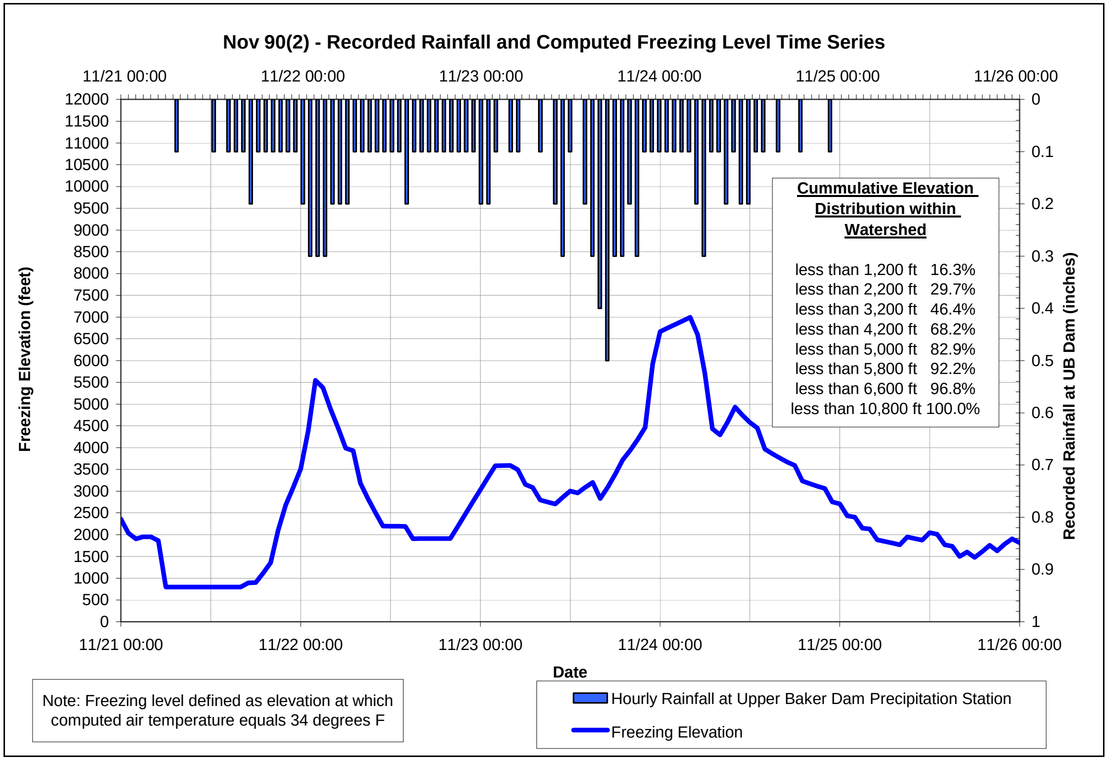


Figure B-8. Estimated Freezing Level and Recorded Rainfall at Upper Baker Dam—NOV 90 (2)

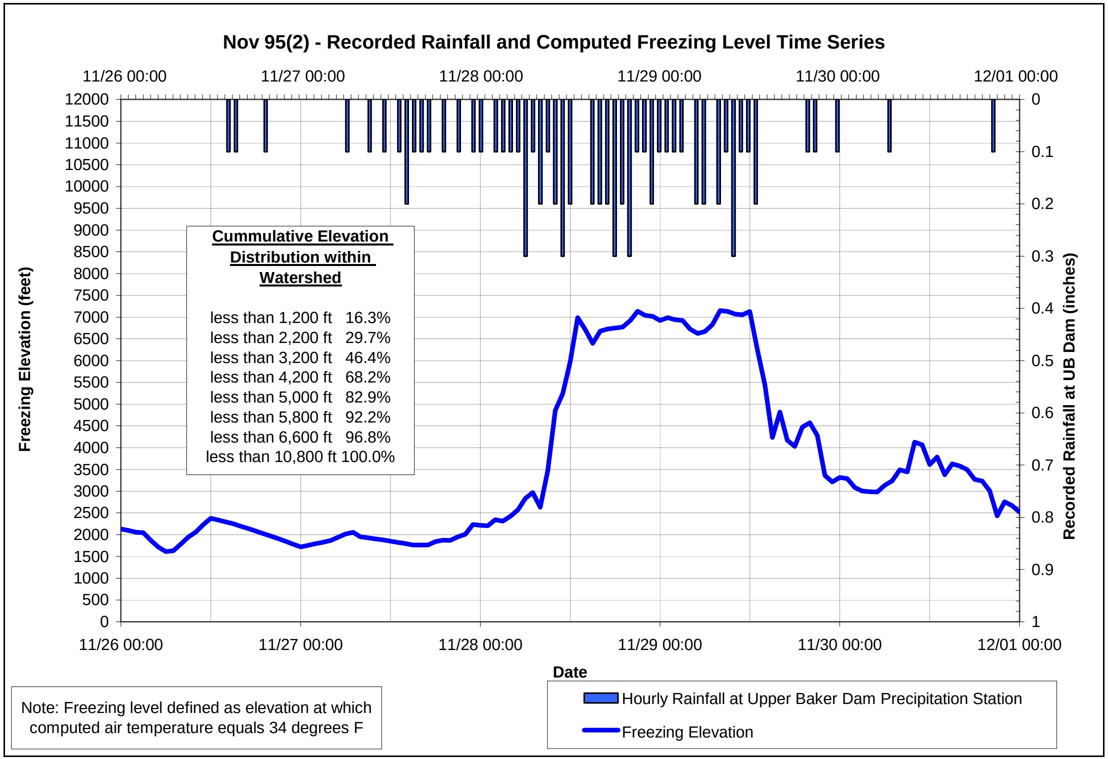


Figure B-9. Estimated Freezing Level and Recorded Rainfall at Upper Baker Dam—NOV 95 (2)

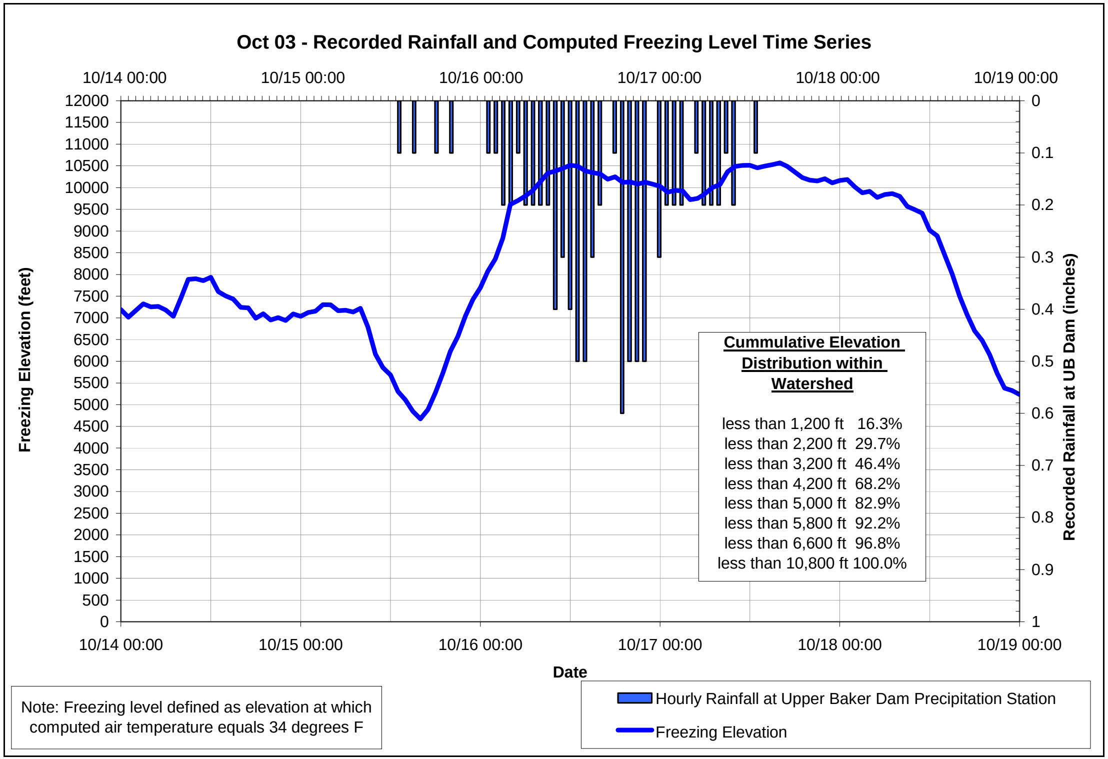


Figure B-10. Estimated Freezing Level and Recorded Rainfall at Upper Baker Dam—OCT 03

Table B-1. 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

Table B-2.
Relative Ranking of Significant Runoff Events in Baker River Basin (1949 – Present)

				UPPER BAKER SYNTHESIZED 1-DAY INFLOWS				UPPER BAKER SYNTHESIZED 3-DAY INFLOWS				LOWER BAKER SYNTHESIZED 1-DAY AND 3-DAY INFLOWS		PRECIPITATION									MAIN STEM SKAGIT UNREGULATED MEAN DAILY FLOWS (from CONDR-2T.XLS)		ANTECEDENT PRECIPITATION
														UPPER BAKER DAM			BAKER LODGE			UPPER BAKER RIVER					
Rank	Total Score	3-day event	Storm Event ID	Mean 1-day Inflow UB Dam 1975-2002 (from R2) (cfs)	Mean 1-day Inflow UB Dam 1948-2003 (from PSE) (cfs)	Adopted Mean 1-day Inflow UB Dam (cfs)	Approx. Return Period (yrs)	Mean 3-day Inflow UB Dam 1975-2002 (from R2) (cfs)	Mean 3-day Inflow UB Dam 1948-2003 (from PSE) (cfs)	Adopted Mean 3-day Inflow UB Dam (cfs)	Approx. Return Period (yrs)	Mean 1-day Inflow LB Dam 1948-2002 (from PSE) (cfs)	Mean 3-day Inflow LB Dam 1948-2002 (from PSE) (cfs)	1-HR (inches)	6-HR (inches)	24-HR (inches)	1-HR (inches)	6-HR (inches)	24-HR (inches)	1-HR (inches)	6-HR (inches)	24-HR (inches)	WY25 - WY03 Main Stem Skagit River Unreg 1-day Flow (cfs)	WY25 - WY03 Main Stem Skagit River Unreg 1-day Flow (return period)	7-Day Antecedent Precip. (inches)
1	7.7	11/9-11/11	NOV 90 (1)	27,106	27,185	27,106	37	19,341	19,436	19,341	59	38,522	26,799	0.3	1.5	5.1							179,826	22	2.9
2	6.3	11/23-11/25	NOV 90 (2)	23,012	19,581	23,012	16	16,196	14,546	16,196	21	29,408	22,328	0.5	2.0	4.7							159,207	15	3.5
3	6.3	10/16-10-18	OCT 03 (1)		28,124	28,124	42		17,093	17,093	25			0.6	2.4	6.8							-	-	3.8
4	5.5	11/9-11/11	NOV 89	18,918	18,972	18,918	9	14,742	14,957	14,742	15	27,218	22,010	0.4	1.6	4.9							119,787	7	7.3
5	5.3	11/28-11/30	NOV 95 (2)	22,579	23,022	22,579	16	14,332	14,239	14,332	11	29,916	19,309	0.3	1.4	3.8							166,014	17	3.2
6	4.9	1/3-1/5	JAN 84	23,775	23,961	23,775	19	13,287	13,367	13,287	8	29,981	17,231	0.3	1.0	3.0							94,587	4	-
7	4.8	11/7-11/9	NOV 95 (1)	22,169	22,385	22,169	14	10,772	10,672	10,772	4	28,313	13,875	0.3	1.4	5.0							122,266	7	1.1
8	4.8	3/18-3/20	MAR 97	17,056	15,433	17,056	8	10,363	10,631	10,363	5	20,677	14,763	0.4	2.1	5.2							87,919	3	1.7
9	4.7	10/16-10/18	OCT 75	15,236	19,858	15,236	6	10,729	11,046	10,729	4	23,921	13,363	0.5	1.9	4.4	incomplete (10/14-10/16 only)						55,422	2	2.0
10	4.6	7/12-7/14	JUL 83	17,072	13,536	17,072	10	14,637	11,854	14,637	19	15,300	13,321	0.4	1.5	3.2							79,967	3	0.5
11	4.4	1/14-1/16	JAN 74		17,247	17,247	5		13,765	13,765	9	20,967	16,928	0.4	1.4	2.9	incomplete (1/12-1/14 only)						104,658	5	-
12	4.4	2/24-2/26	FEB 86	14,588	14,946	14,588	4	11,679	12,095	11,679	5	19,765	15,286	0.4	1.5	5.2							82,416	3	1.4
13	4.4	12/17-12/19	DEC 79	13,574	15,594	13,574	3	12,802	12,830	12,802	7	20,837	18,550	0.4	1.6	3.4	0.4	1.6	5.0				126,402	8	11.0
14	4.3	11/11-11/13	NOV 99	17,872	17,910	17,872	6	13,069	13,118	13,069	8	21,162	15,421	0.4	1.2	2.8							117,183	6	3.0
15	4.0	7/12 - 7/14	JUL 72		15,614	15,614	4		11,064	11,064	4	18,288	14,983	0.3	1.3	4.2	hourly data not available						79,890	3	1.3
	4.0	12/25-12/27	DEC 80	23,140	23,236	23,140	17	15,750	15,804	15,750	18	32,708	20,758	hourly data not available			hourly data not available								
	3.8	2/26-2/28	FEB 80	14,871	15,153	14,871	4	10,406	10,585	10,406	4	19,395	13,675	0.3	1.2	3.7	0.3	1.6	5.2						
	3.7	12/16 - 12/18	DEC 66		12,417	12,417	2		9,980	9,980	3	15,139	12,128	0.4	1.5	3.7	hourly data not available								
	3.7	10/14 - 10/16	OCT 88	11,756	11,759	11,756	2	9,909	9,917	9,909	3	14,676	12,113	0.4	1.5	3.4									
	3.6	11/23 - 11/25	NOV 86	8,988	9,552	8,988	1.3	7,466	7,022	7,466	1.5	14,722	12,198	0.4	1.8	4.0									
	3.6	6/1 - 6/3	JUN 68		14,507	14,507	3		9,965	9,965	3	19,089	12,900	0.3	1.1	3.2	0.3	1.4	4.2						
	3.5	2/9-2/11	FEB 51		19,912	19,912	9		14,740	14,740	14	28,606	21,176	hourly data not available			hourly data not available								
	3.3	12/2/12/4	DEC 75	18,152	18,198	18,152	6	15,459	14,999	15,459	16	25,668	21,694	hourly data not available			hourly data not available								
	3.3	10/26-10/28	OCT 85	14,054	14,052	14,054	3	8,335	8,335	8,335	1.8	17,125	10,707	0.3	1.3	2.3									
	3.0	7/8 - 7/10	JULY 97	12,130	12,321	12,130	2	9,560	9,707	9,560	3	15,243	12,178	0.2	0.9	2.5									
	2.6	12-3-12/5	DEC 89	18,258	18,419	18,258	7	11,372	11,446	11,372	4	24,004	14,605	hourly data not available											
	2.6	11/25 - 11/27	NOV 49		17,049	17,049	5		11,550	11,550	5	23,382	15,840				incomplete (avail 11/26 on)								
	2.5	12/12-12/14	DEC 98	18,608	19,037	18,608	7	10,138	10,458	10,138	3	24,176	13,705	hourly data not available											
	2.5	11/3 - 11/5	NOV 55		15,498	15,498	4		11,752	11,752	5	21,780	16,750				hourly data not available								
	2.5	1/14-1/16	JAN 61		18,020	18,020	6		10,047	10,047	3	25,109	13,945				incomplete (portions of days)			0.53	2.60	8.00			
	2.4	6/19 - 6/21	JUN 67		7,704	7,704	1.1		7,501	7,501	1.6	12,825	12,056	0.2	0.8	1.3	hourly data not available								
	2.3	10/21 - 10/23	OCT 63		17,005	17,005	5		10,631	10,631	4	18,706	13,311				hourly data not available			0.45	2.09	4.13			
	2.3	10/19-10/21	OCT 03 (2)		23,026	23,026	16		15,553	15,553	17			hourly data not available											
	2.1	11/14 - 11/16	NOV 01	13,830	13,951	13,830	3	10,802	10,832	10,802	4	17,398	13,213	hourly data not available											
	2.1	1/18-1/20	JAN 86	14,397	14,674	14,397	3	10,140	10,278	10,140	3	18,822	12,901	hourly data not available											
	2.0	11/15 - 11/17	NOV 83	13,915	13,926	13,915	3	9,461	9,436	9,461	3	18,067	12,603	hourly data not available											
	2.0	4/29 - 5/1	APR 59		12,402	12,402	2		10,168	10,168	3	16,597	13,617				incomplete data set								
	2.0	11/19 - 11/21	NOV 62		14,228	14,228	3		9,156	9,156	2	18,241	11,786				hourly data not available			incomplete data set					
	2.0	1/7-1/9	JAN 02	21,582	22,073	21,582	13	14,097	14,293	14,097	11			hourly data not available											
	2.0	10/24 - 10/26	OCT 55		14,740	14,740	4		8,175	8,175	1.8	19,012	10,624				hourly data not available								
	1.9	10/3-10/5	OCT 90	15,349	15,381	15,349	4	7,837	7,851	7,837	2	18,635	9,856	hourly data not available											
	1.8	12/3 - 12/5	DEC 82	13,461	13,556	13,461	3	7,598	7,628	7,598	1.6	17,626	9,701	hourly data not available			hourly data not available								
	1.7	12/1 - 12/3	DEC 58		9,710	9,710	1.5		8,973	8,973	2	13,328	12,124				hourly data not available								
	1.7	11/22 - 11/24	NOV 59		10,401	10,401	1.6		8,475	8,475	1.9	13,087	12,119				hourly data not available								
	1.6	6/18 - 6/20	JUN 74		7,922	7,922	1.2		7,813	7,813	1.7	13,464	13,099	0.0	0.0	0.0	0.0	0.0	0.0						
	1.5	7/14 - 7/16	JUL 64		8,427	8,427	1.2		7,145	7,145	1.4	13,648	11,920				hourly data not available			0.14	0.60	1.18			
	1.2	12/11 - 12/13	DEC 04		17,899	17,899	5		8,425	8,425	1.9			hourly data not available											

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APPENDIX C.
BEHAVIORAL PARAMETER SET RESULTS FOR CALIBRATION PHASE III AND PHASE V

December 2007

Table C-1. Model Results for Top Ten Behavioral Parameter Sets from Phase III Calibration

		November 89 Event							November 95 (2) Event					October 03 Event				
Sim No.	**Average Likelihood**	**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 C-2. Model Results for Top 25 Behavioral Parameter Sets and Final Calibrated Parameter Set

		November 89 Event							November 90 (1) Event							November 95 (2) Event					October 03 Event				
Sim No.	Average Likelihood	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

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APPENDIX D.
RUNOFF HYDROGRAPHS FROM MODEL CALIBRATION

December 2007

APPENDIX D.
RUNOFF HYDROGRAPHS FROM MODEL CALIBRATION

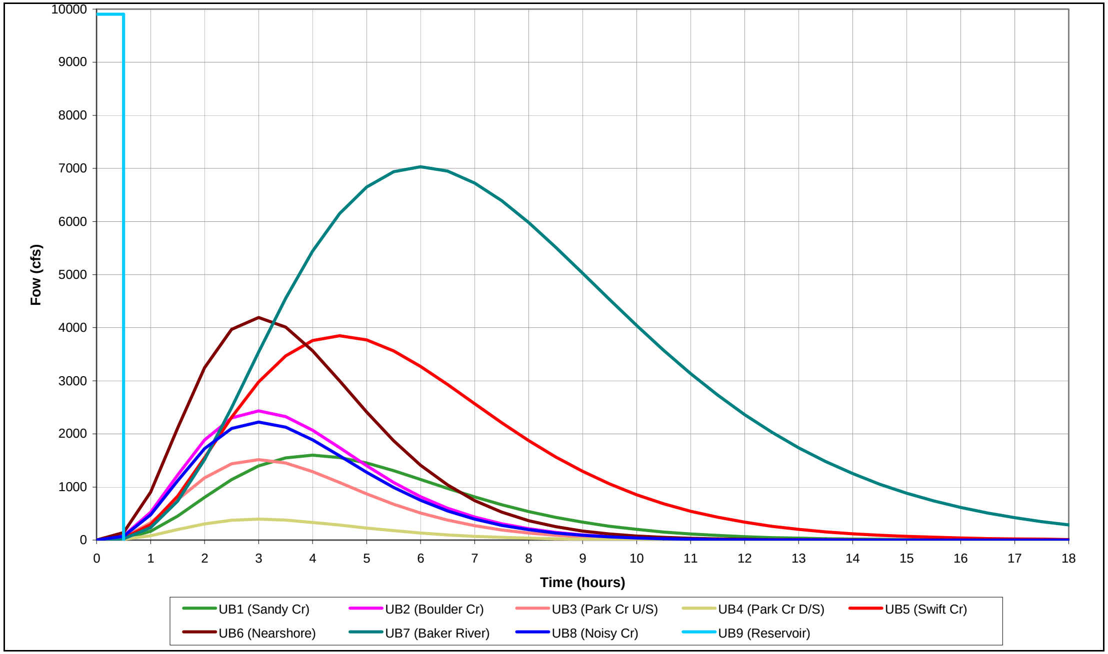


Figure D-1. Calibrated Surface Runoff Unit Hydrographs—Upper Baker Subbasins

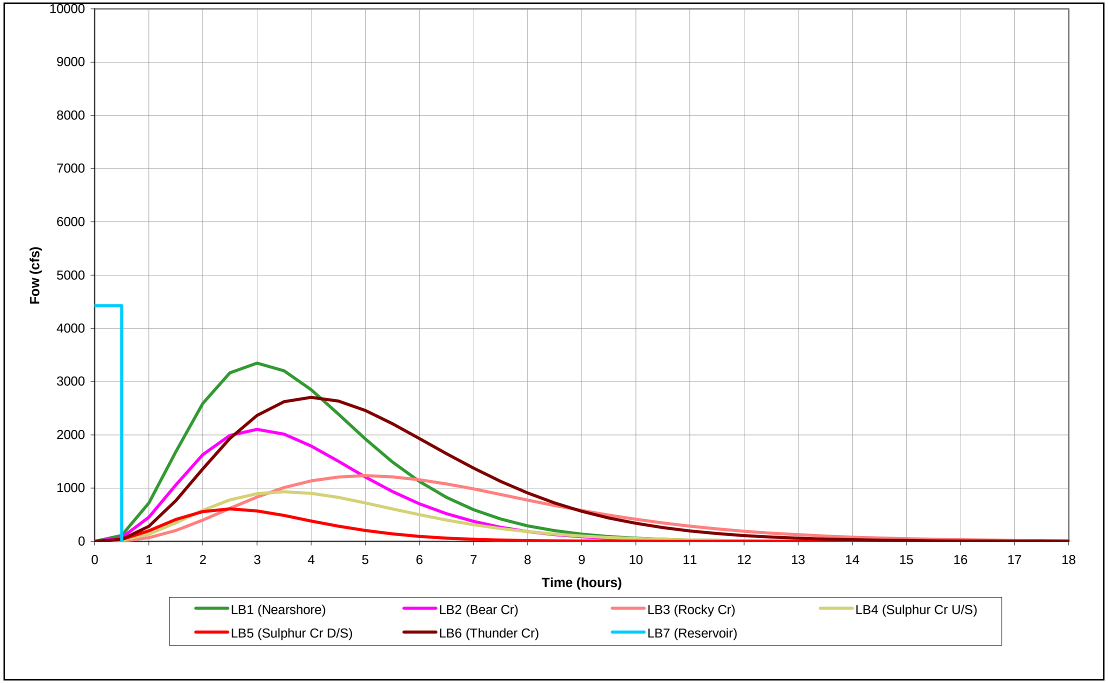


Figure D-2. Calibrated Surface Runoff Unit Hydrographs—Lower Baker Subbasins

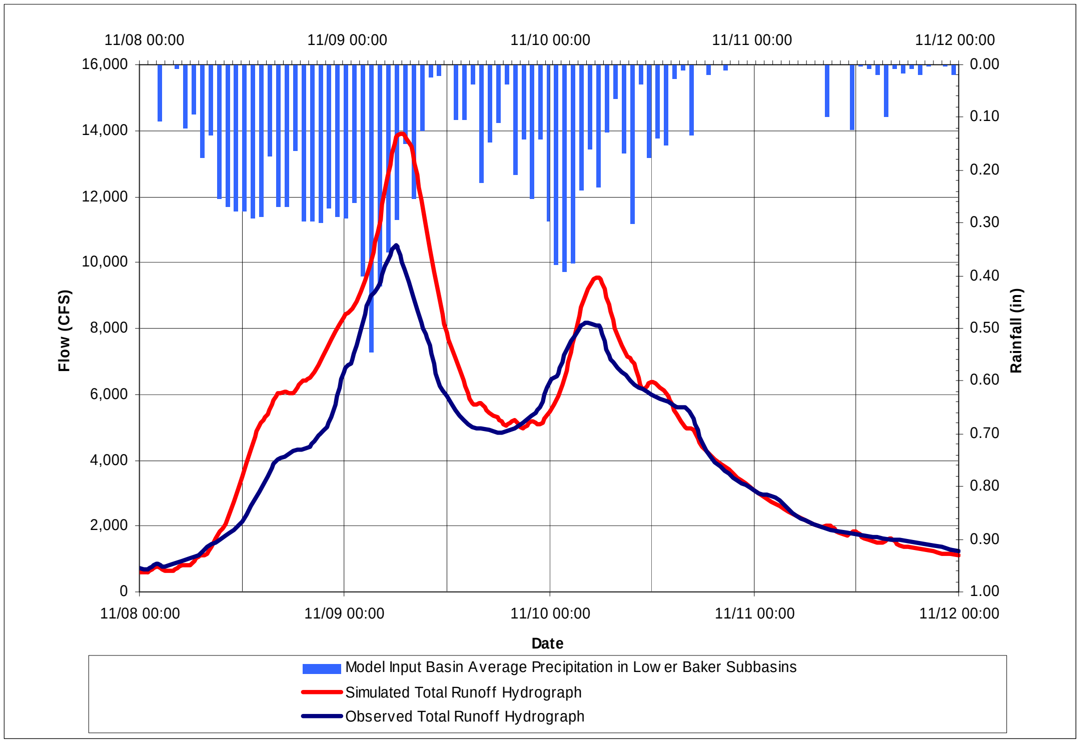


Figure D-3. Final Calibrated Lower Baker Inflow Hydrograph for NOV 89 Event

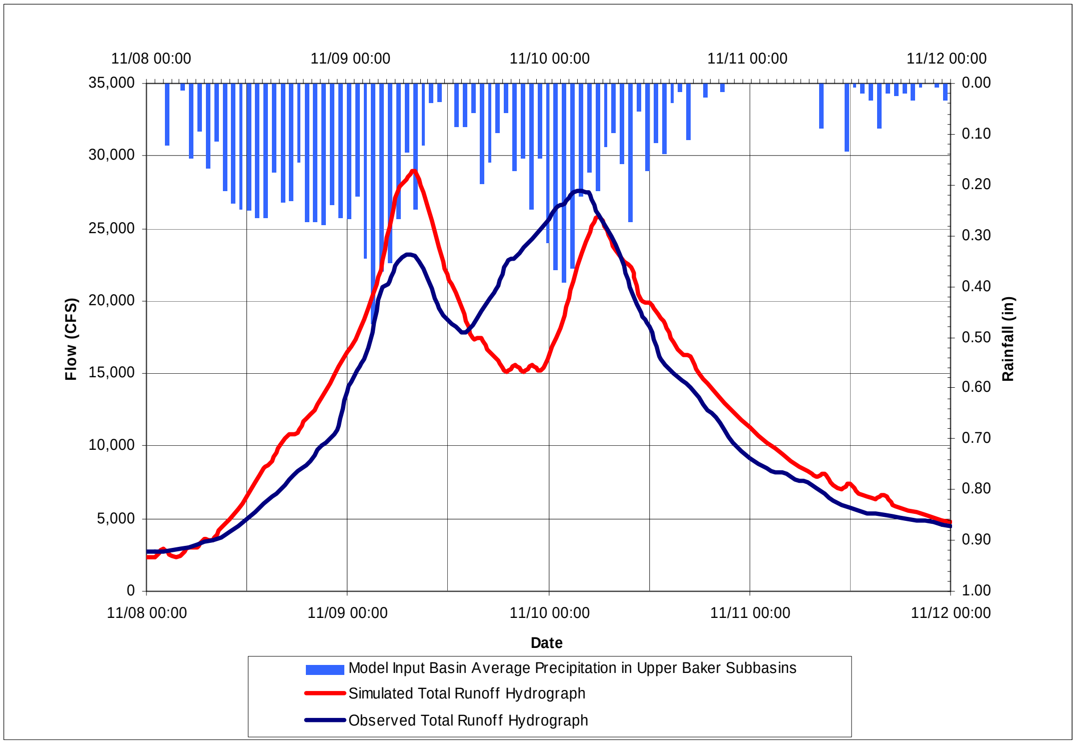


Figure D-4. Final Calibrated Upper Baker Inflow Hydrograph for NOV 89 Event

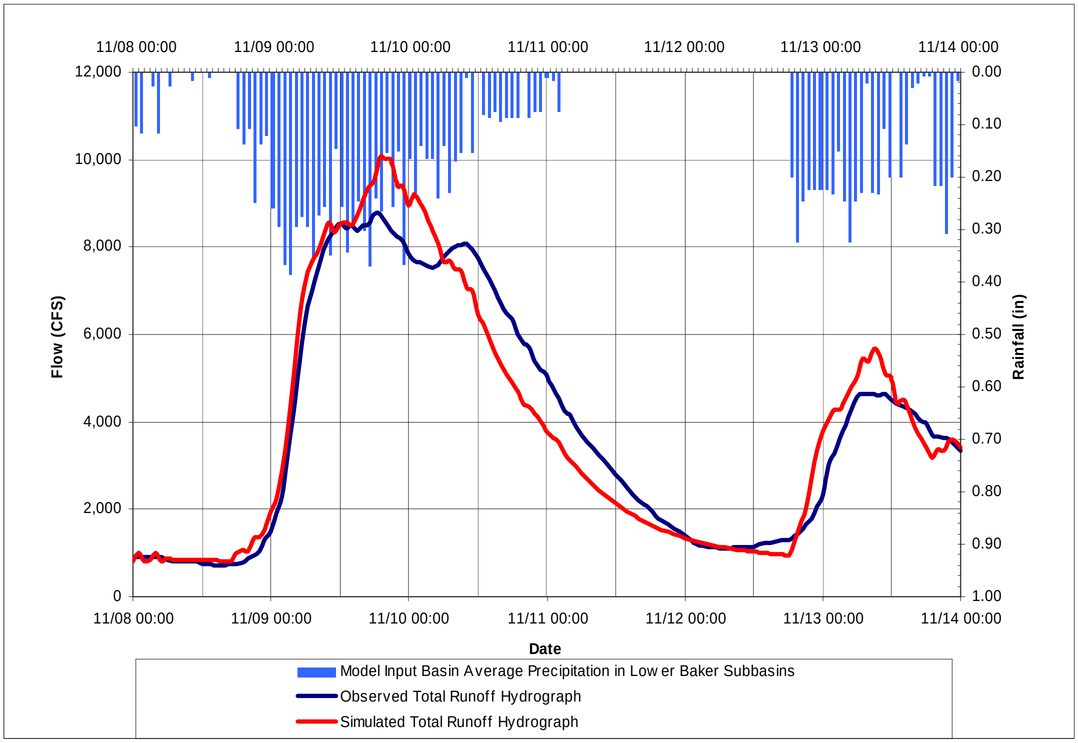


Figure D-5. Final Calibrated Lower Baker Inflow Hydrograph for NOV 90 (1) Event

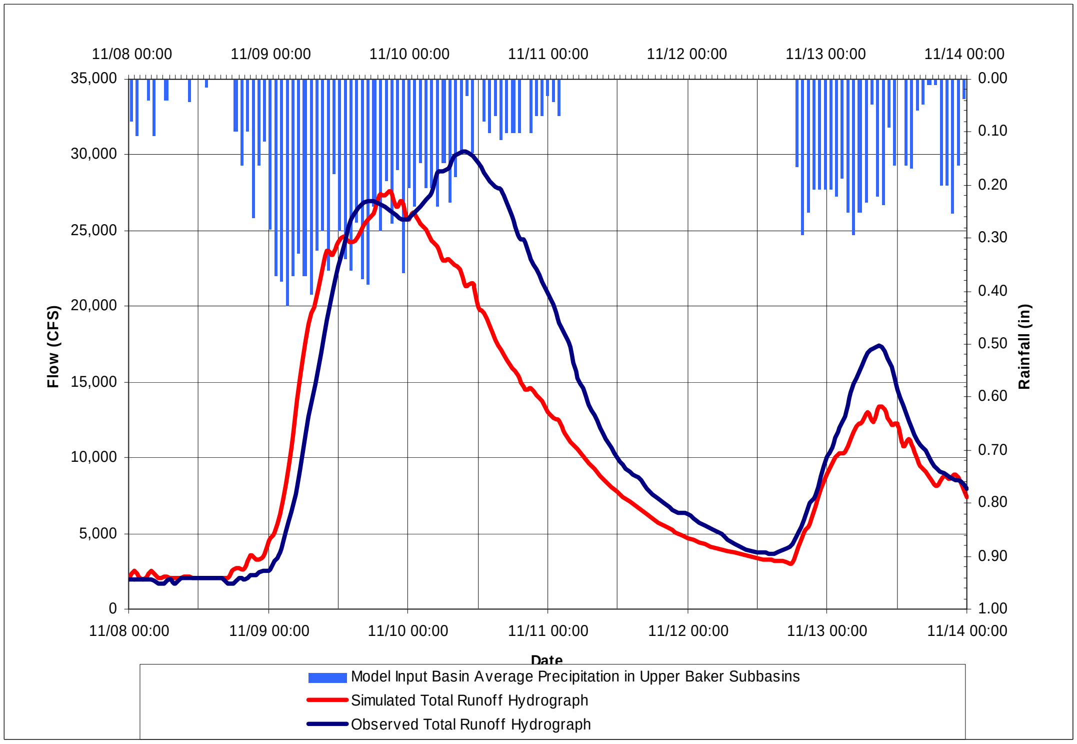


Figure D-6. Final Calibrated Upper Baker Inflow Hydrograph for NOV 90 (1) Event

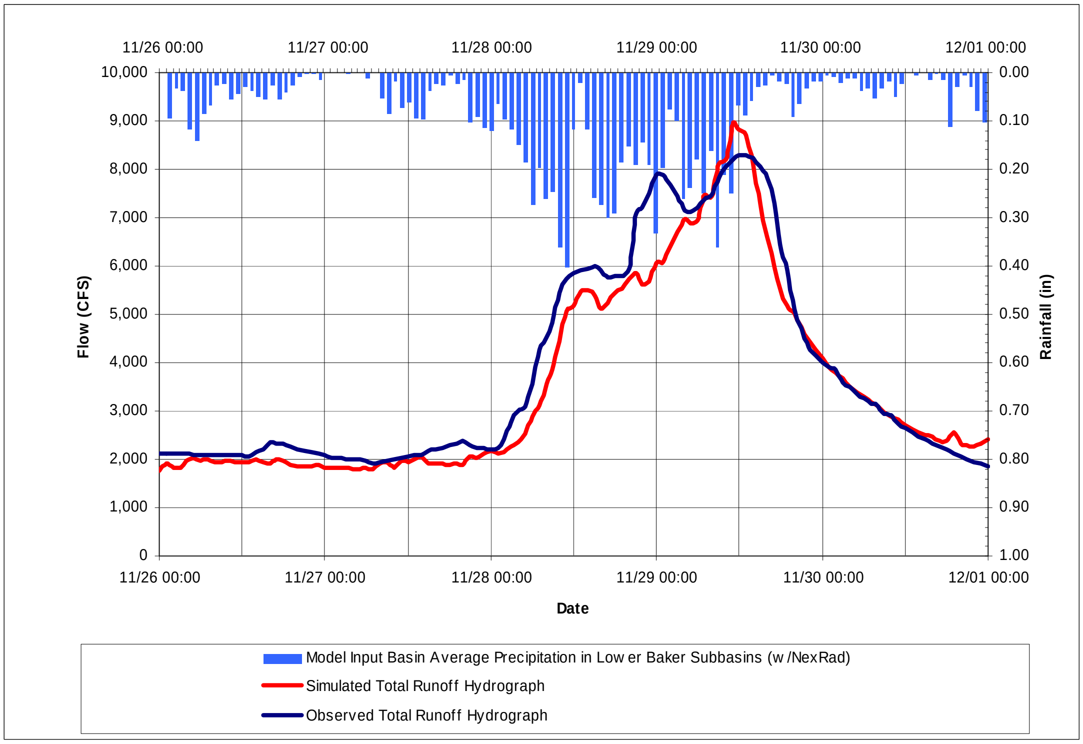


Figure D-7. Final Calibrated Lower Baker Inflow Hydrograph for NOV 95 (2) Event

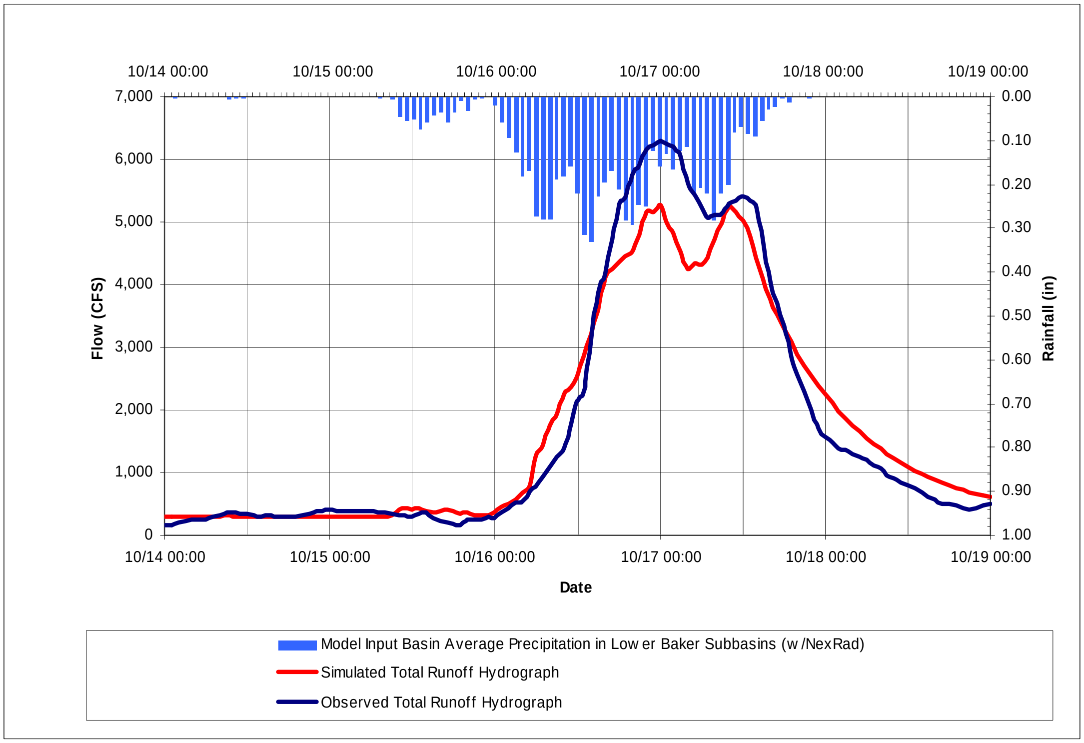


Figure D-8. Final Calibrated Lower Baker Inflow Hydrograph for OCT 03 Event

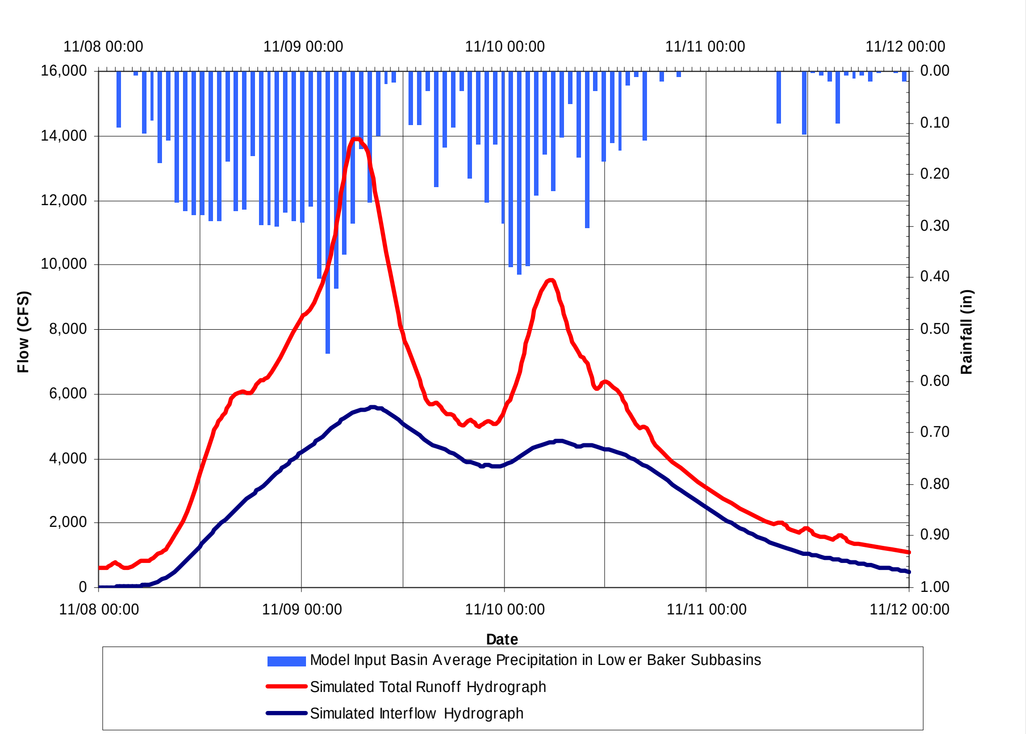


Figure D-9. Interflow Hydrograph for Calibrated Lower Baker Inflow Hydrograph—NOV 89 Event

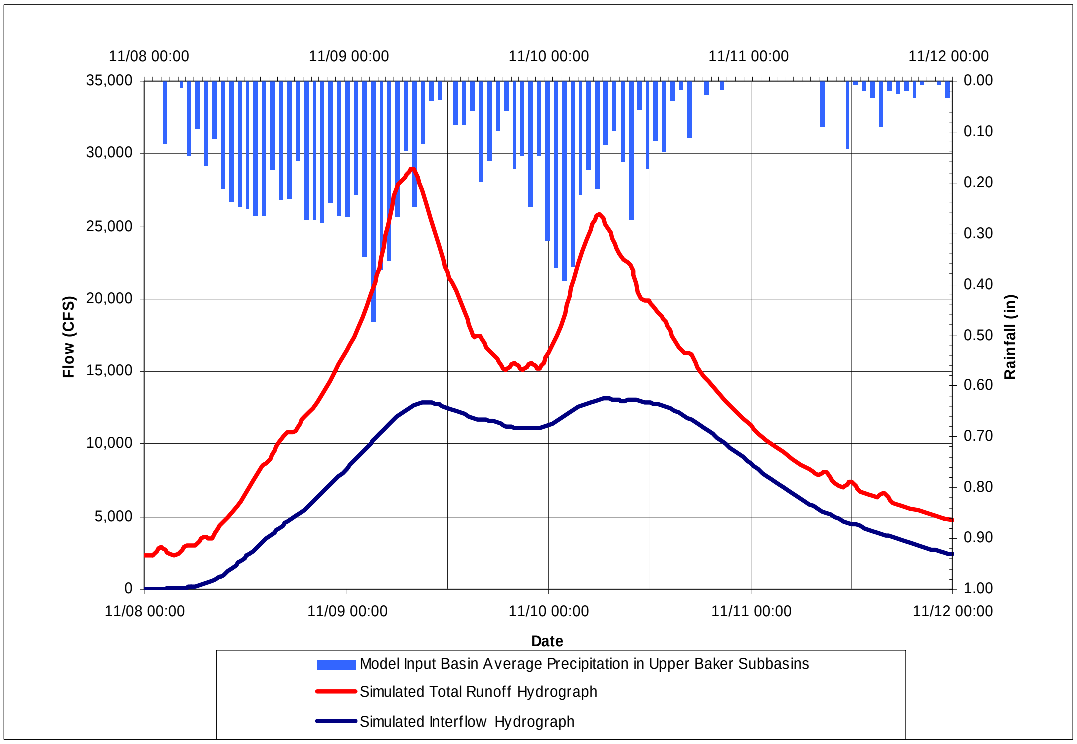


Figure D-10. Interflow Hydrograph for Calibrated Upper Baker Inflow Hydrograph—NOV 89 Event

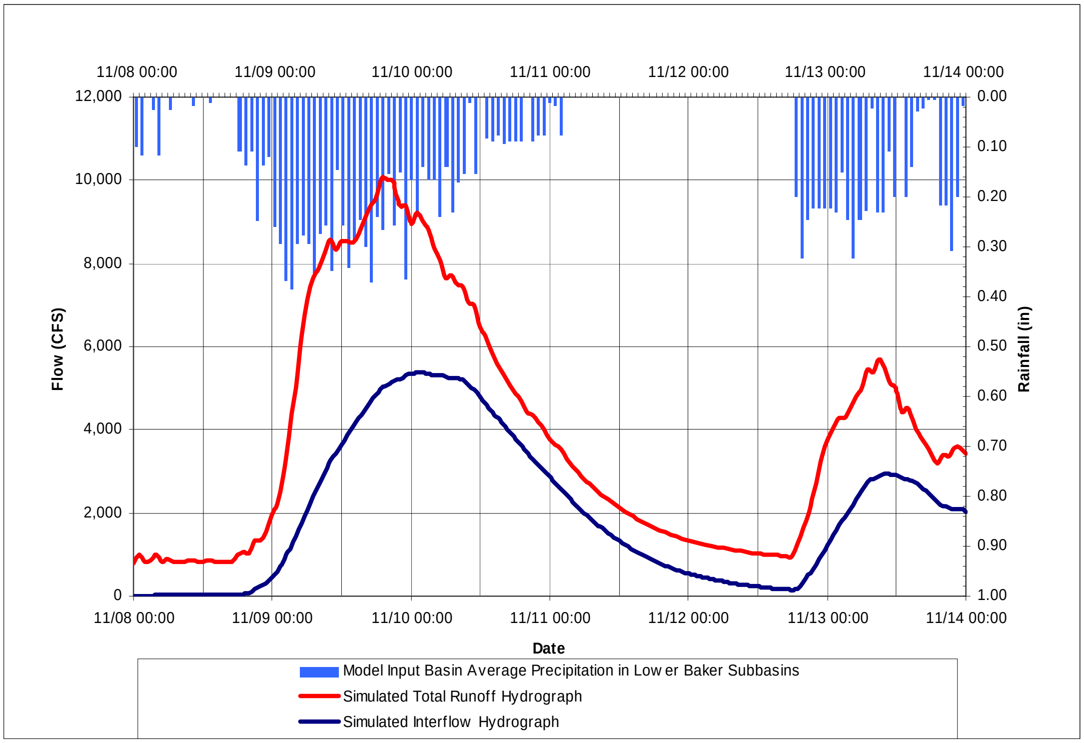


Figure D-11. Interflow Hydrograph for Calibrated Lower Baker Inflow Hydrograph—NOV 90 (1) Event

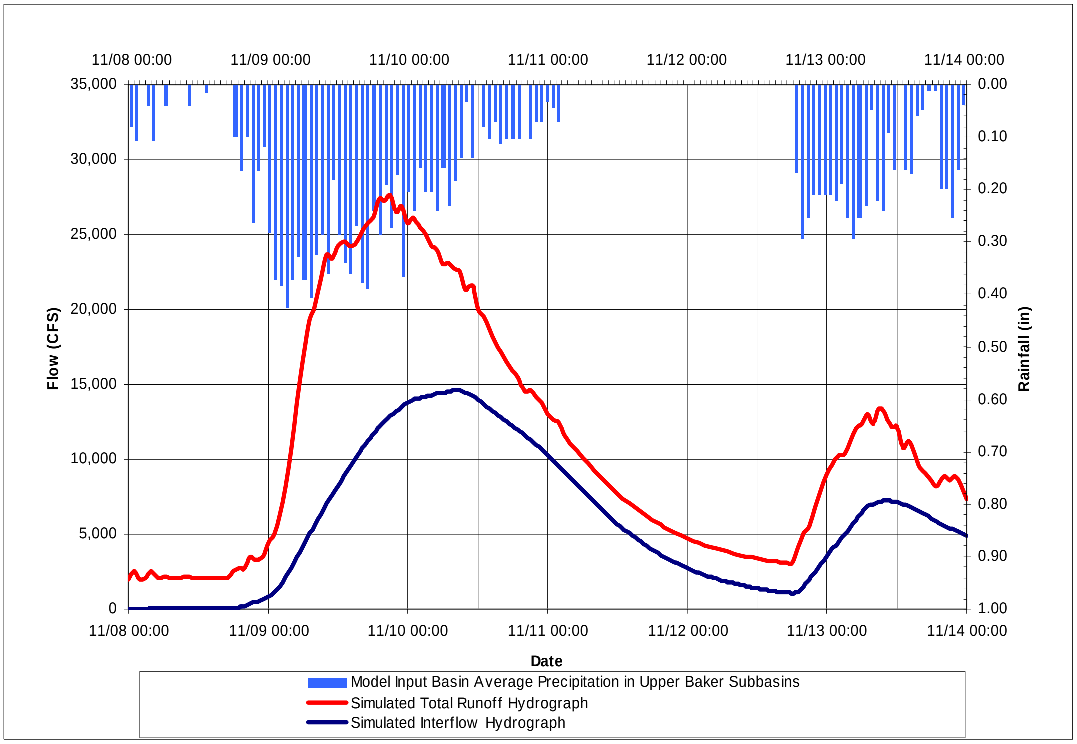


Figure D-12. Interflow Hydrograph for Calibrated Upper Baker Inflow Hydrograph—NOV 90 (1) Event

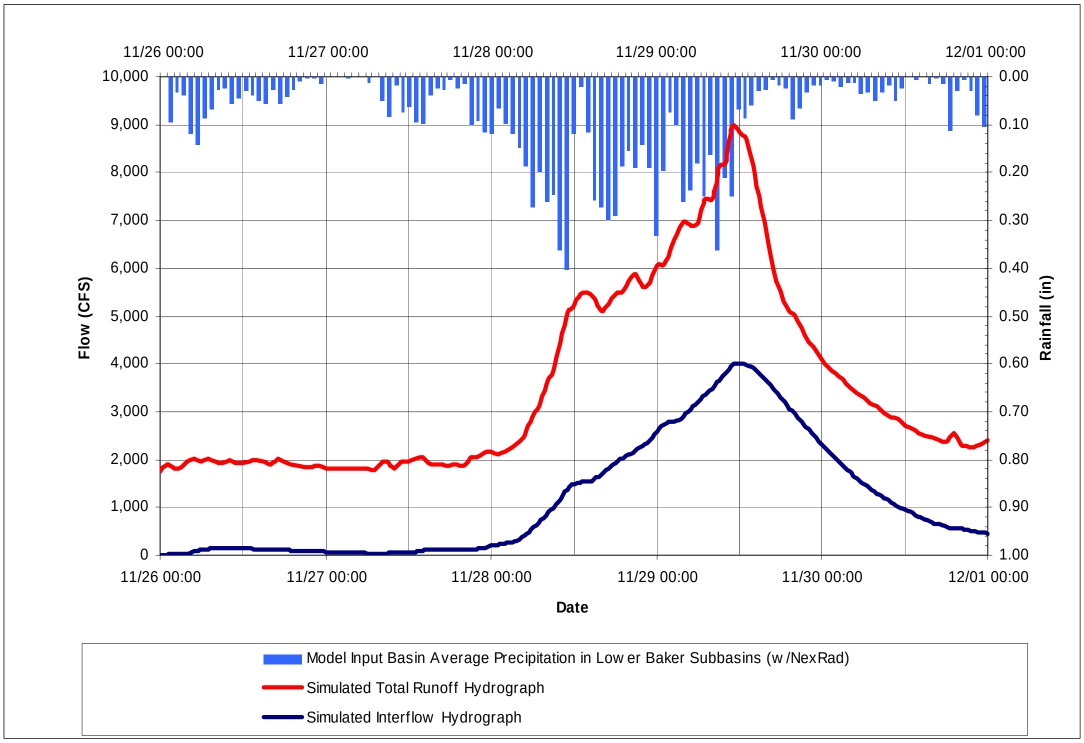


Figure D-13. Interflow Hydrograph for Calibrated Lower Baker Inflow Hydrograph—NOV 95 (2) Event

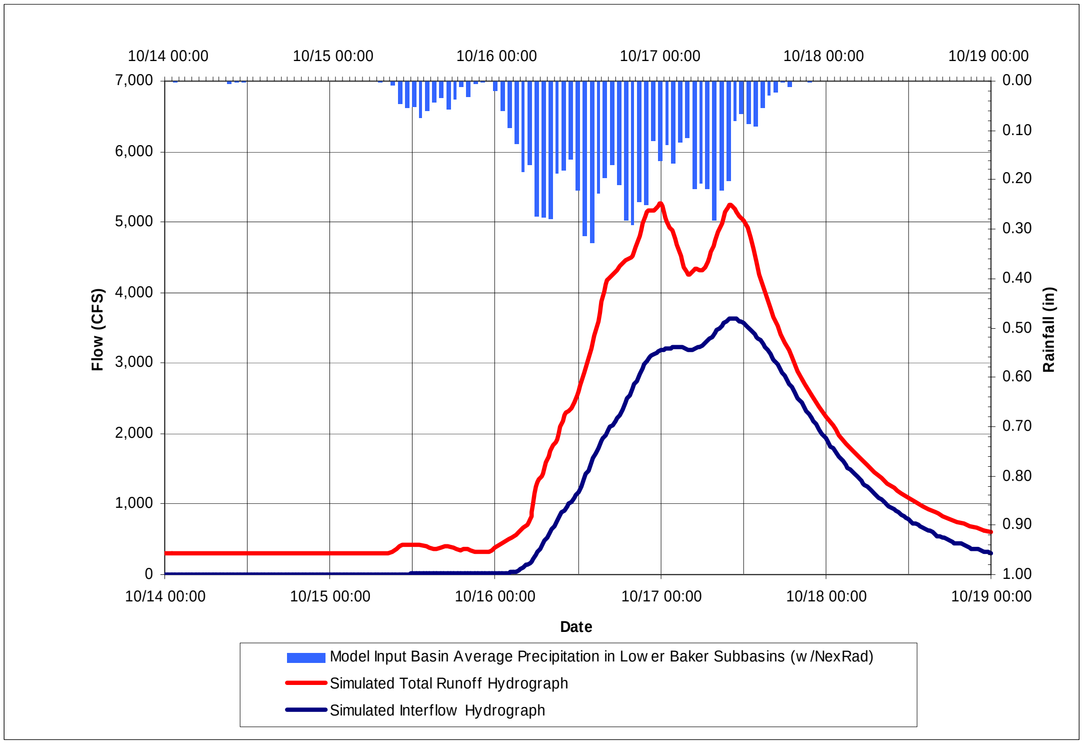


Figure D-14. Interflow Hydrograph for Calibrated Upper Baker Inflow Hydrograph—OCT 03 Event

Table D-1. 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 D-2. 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

Puget Sound Energy

Baker River Project Part 12

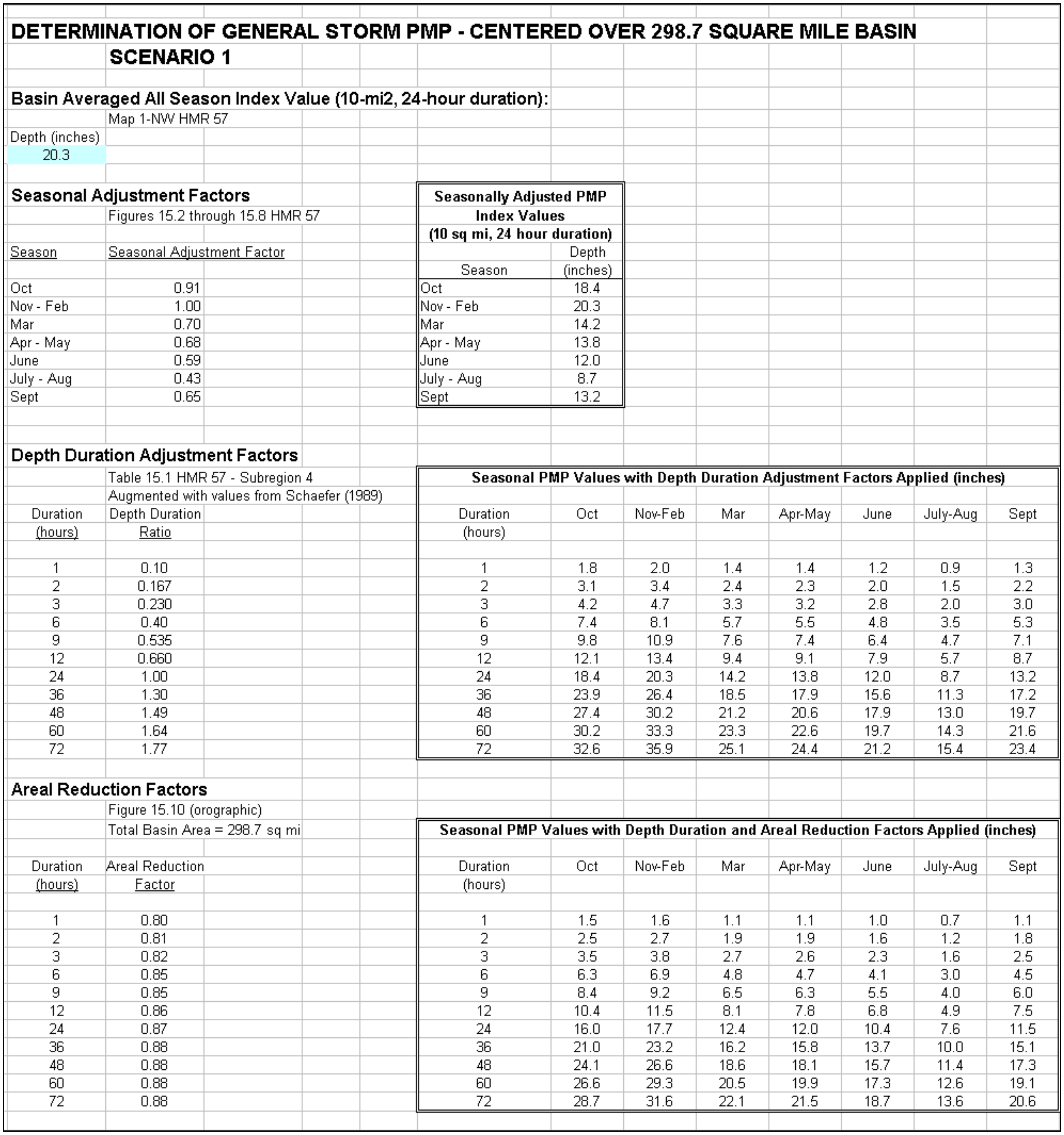
Probable Maximum Flood Study

APPENDIX E.
PROBABLE MAXIMUM PRECIPITATION CALCULATIONS

December 2007

APPENDIX E.
PROBABLE MAXIMUM PRECIPITATION CALCULATIONS

Table E-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)

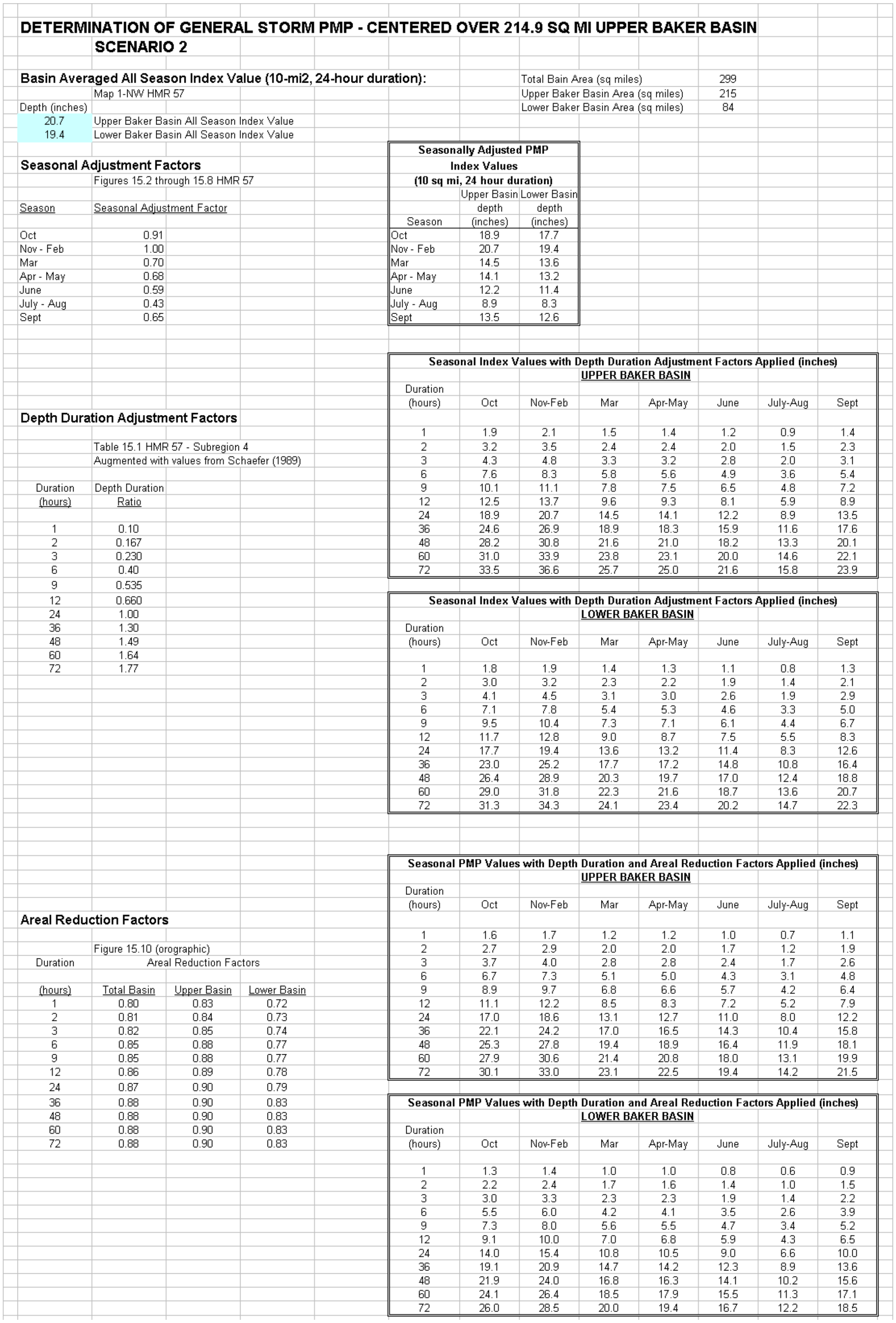
Total Basin Area = 298.7 sq mi

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 E-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

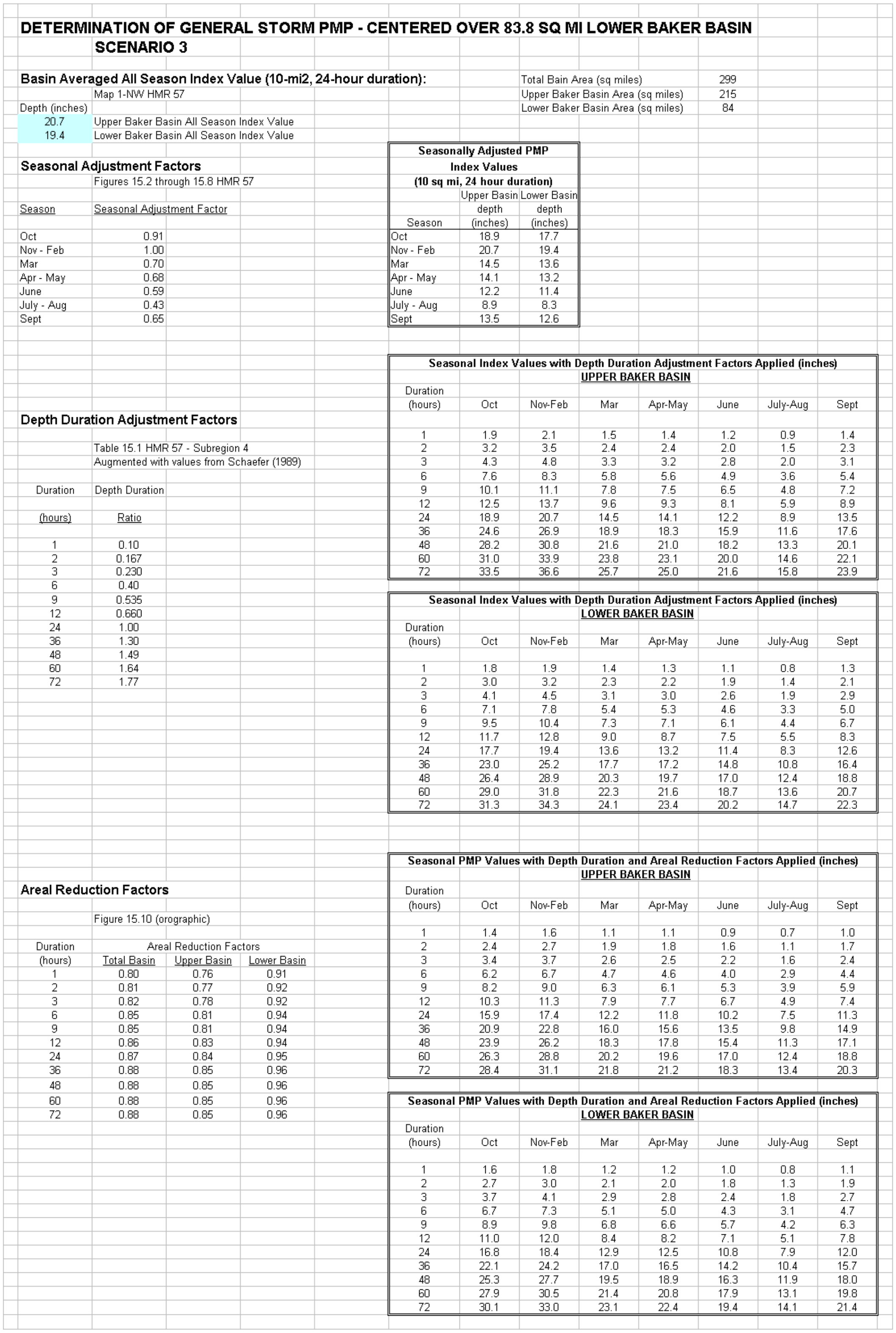
Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)
UPPER BAKER BASIN

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 E-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 (hours)	Areal Reduction Factors 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

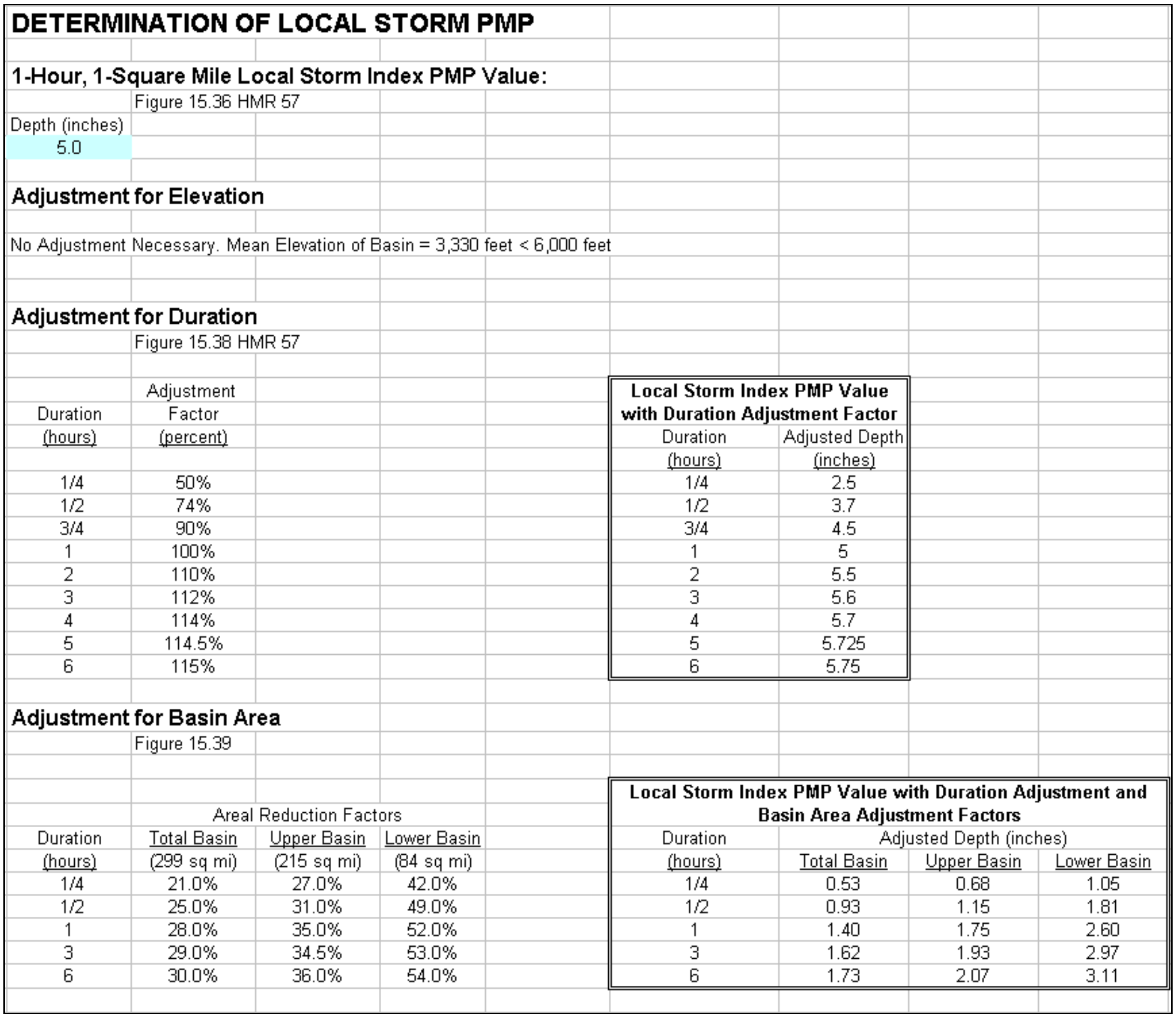
Seasonal PMP Values with Depth Duration and Areal Reduction Factors Applied (inches)
UPPER BAKER BASIN

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

Table E-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

Puget Sound Energy

Baker River Project Part 12
Probable Maximum Flood Study

APPENDIX F.
DEVELOPMENT OF GSA INPUT PARAMETERS

December 2007

APPENDIX F.
DEVELOPMENT OF GSA INPUT PARAMETERS

For the GSA, it was necessary to 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 Stochastic Event Flood Model (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 F-1 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.

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 F-2 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.

SEASONALITY OF OCCURRENCE

The seasonal relationship of probable maximum precipitation (PMP) in the Baker River watershed was determined according to methodologies in HMR 57 (NWS 1994) and was documented in Tetra Tech (2006a). Figure F-1 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.

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 F-3 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 F-2 is the probability histogram for seasonality and Figure F-3 is the cumulative probability distribution for seasonality.

Table F-1. 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 Hydrometeorological Report No. 57 (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 (SWE)	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 Hydrocomp Forecast and Analysis Modeling (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 best 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 best reflects the current flood control operation at Upper Baker Dam.

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 F-3. 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.

Table F-2. 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

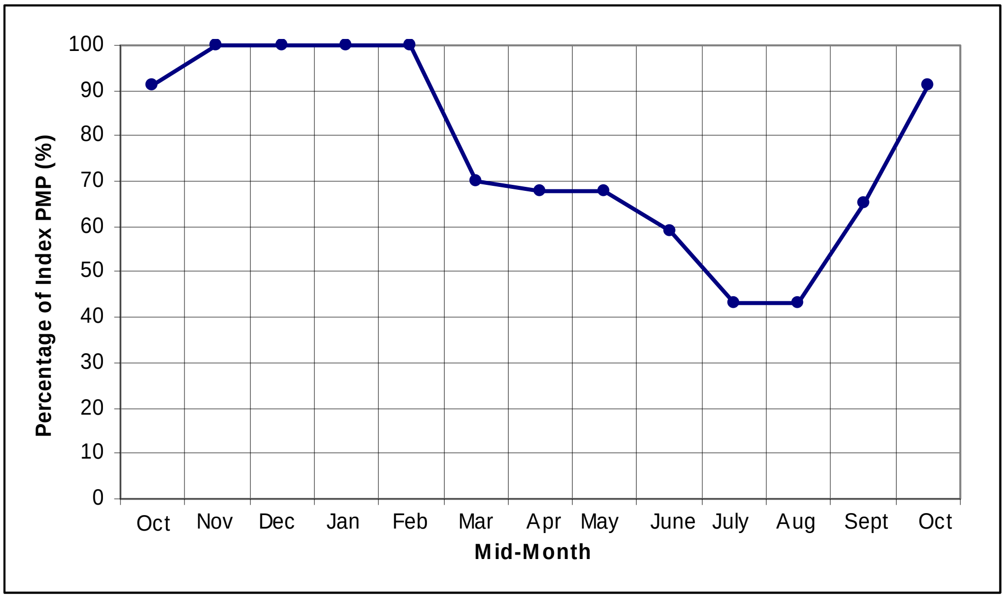


Figure F-1. Seasonality of PMP

Table F-3. Twice Monthly Probabilities for Seasonal Occurrence of Extreme Storms

	Monthly Period									
	Oct 16—Nov 15		Nov 16—Dec 15		Dec 16—Jan 15		Jan 16—Feb 15		Feb 16—Mar 15	
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	

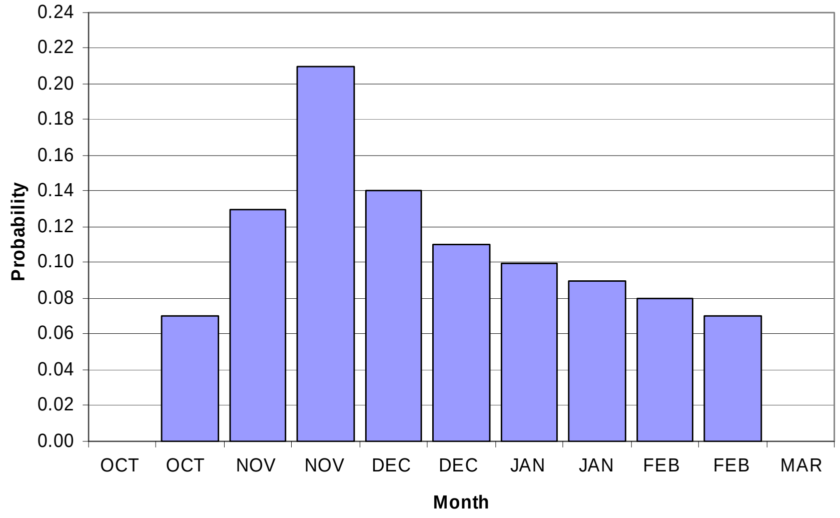


Figure F-2. Probability Histogram for Seasonality of Extreme Storms

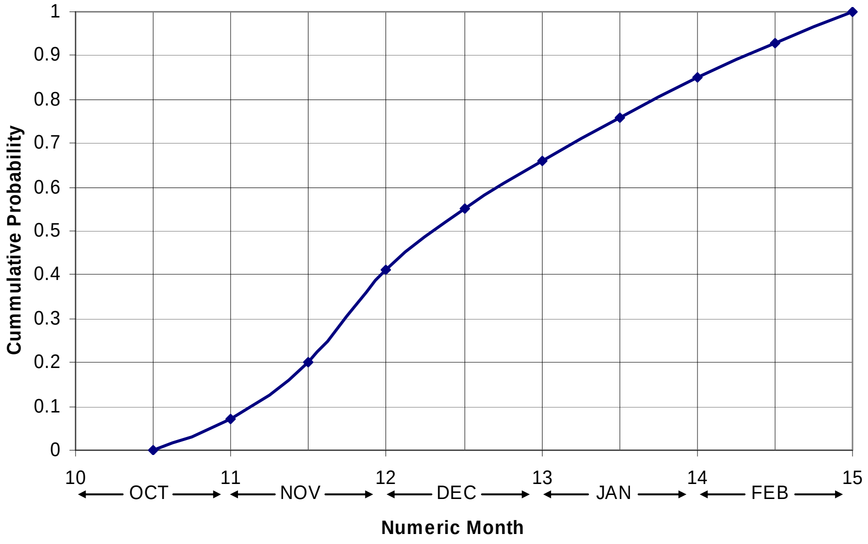


Figure F-3. Cumulative Probability for Seasonality of Extreme Storms

STORM CENTERING

Three storm centering scenarios have been investigated for the general storm PMP in the Baker River watershed (Tetra Tech 2006a):

- Upper Centering—General storm is centered over the 214.8 mi^2 Upper Baker tributary area
- Entire Centering—General storm is centered over the entire 298.7 mi^2 watershed
- 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 F-4. The storm centering scenario input parameter was sampled independently of all other hydrometeorological input parameters.

Table F-4. Probabilities for Storm Centering Scenario

Upper Centering	Entire Watershed Centering	Lower Centering
0.33	0.33	0.33

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 probable maximum flood (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 F-5, 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 F-5. Figure F-4 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 (2006b) 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 F-5. 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

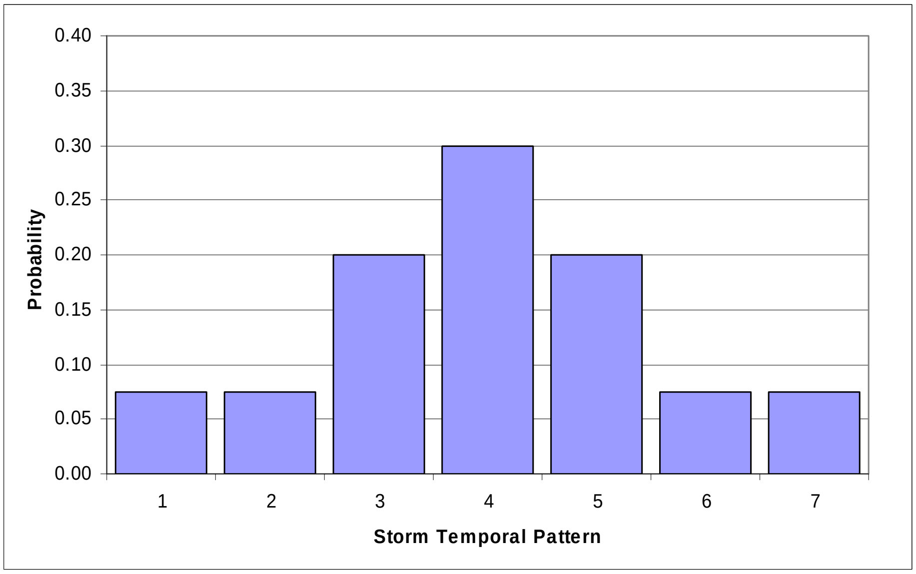


Figure F-4. Probability Histogram for Storm Temporal Patterns

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 F-6 for the station period of record (1965 to 2005). Figure F-5 shows the end-of-November antecedent precipitation data fit to the Gamma distribution, and Table F-7 summarizes the values of mean annual precipitation for specific non-exceedance probabilities.

Table F-6. 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

Table F-7. 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

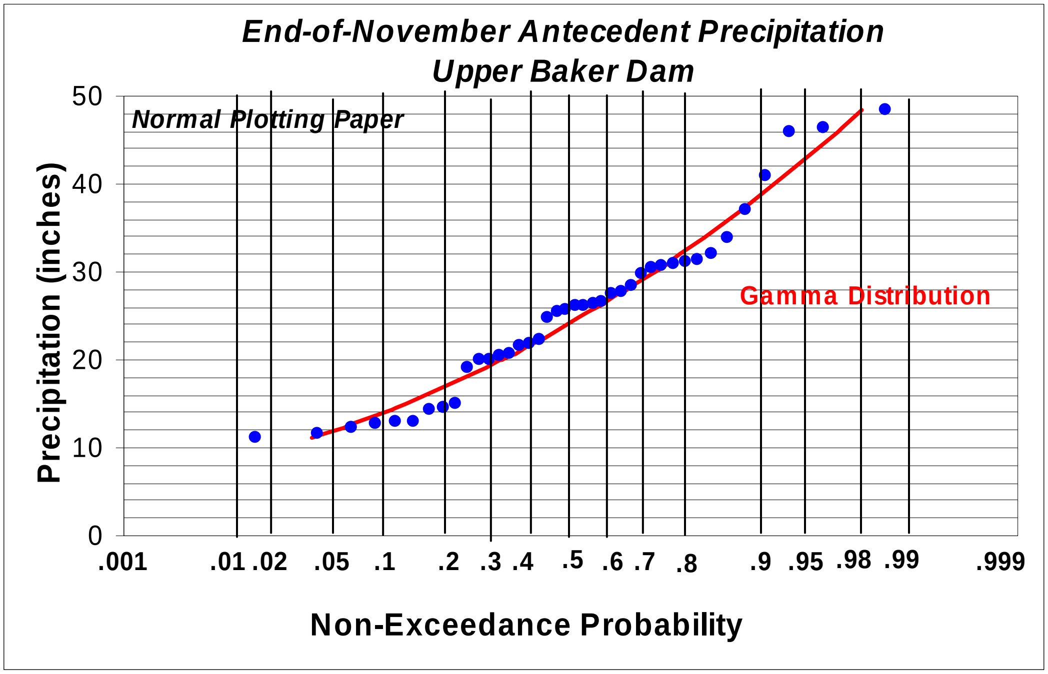


Figure F-5. Gamma Distribution Fitted to End-of-November Antecedent Precipitation for Upper Baker Precipitation Station (Key Precipitation Station)

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 F-8). 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 F-6 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 F-7 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 F-8. Again, the Mount Baker Lodge station was not included in the analysis due to insufficient data.

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 F-6 for developing estimates for the coefficient of variation and using the seasonal relationship exemplified in Figure F-7 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 WDOE (1993) and Schaefer et al. (1999).

Table F-8. 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)

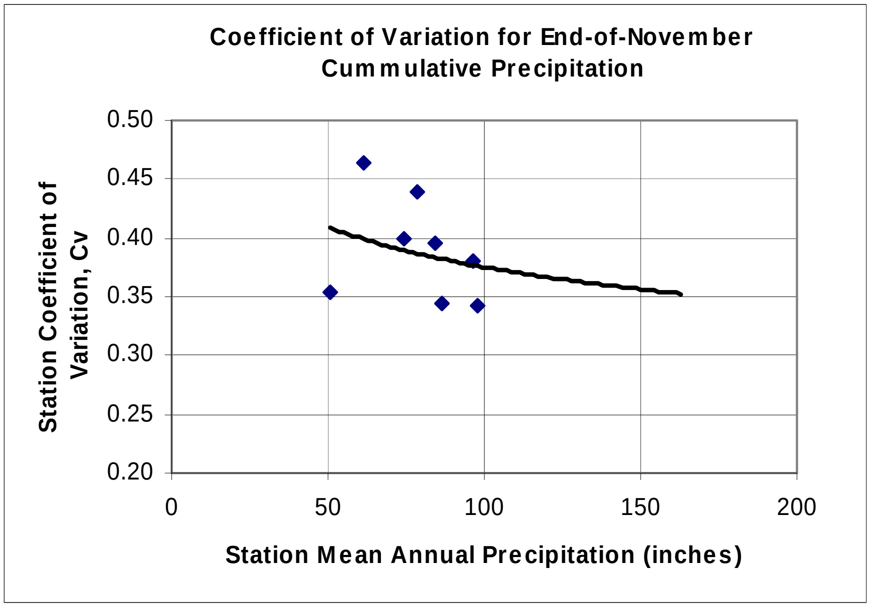


Figure F-6. Relationship of Coefficient of Variation to Station Mean Annual Precipitation for End-of-November

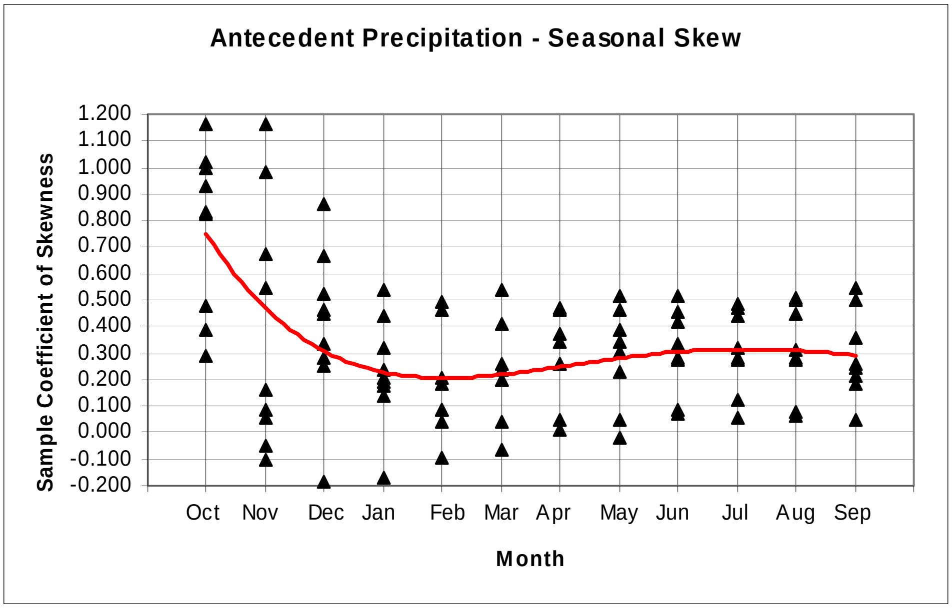


Figure F-7. Seasonal Relationship of Coefficient of Skewness

WDOE (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 F-9 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.

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 F-6 and Figure F-5).
- 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 F-9).

Table F-9. 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

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 F-8 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 F-8, 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.

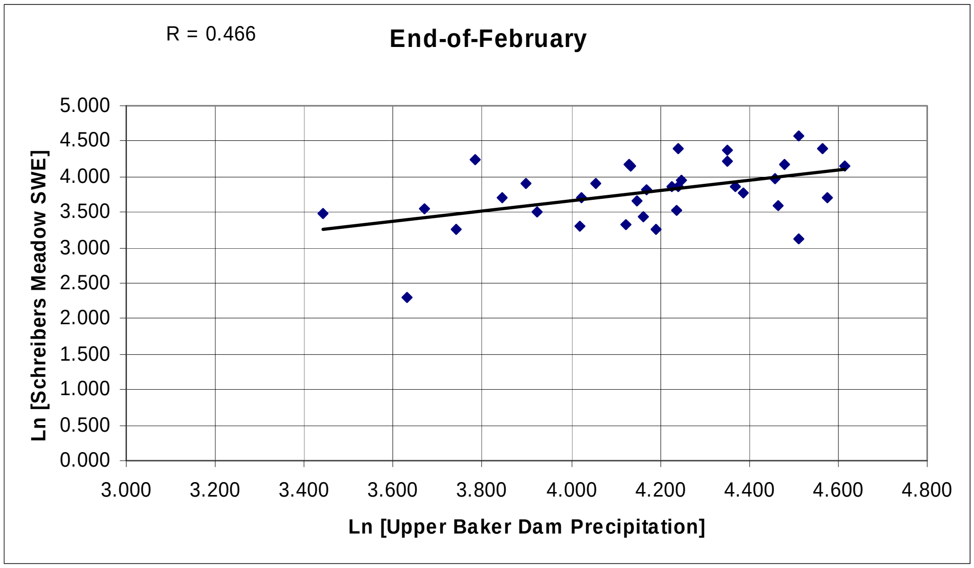


Figure F-8. Logarithmic Correlation Between Antecedent Precipitation and Snow Water Equivalent

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 F-9 illustrates the Log-Normal distribution for the end-of-November data for the key snow course station and Table F-10 summarizes snow water equivalent values for specific non-exceedance probabilities.

Table F-10. 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

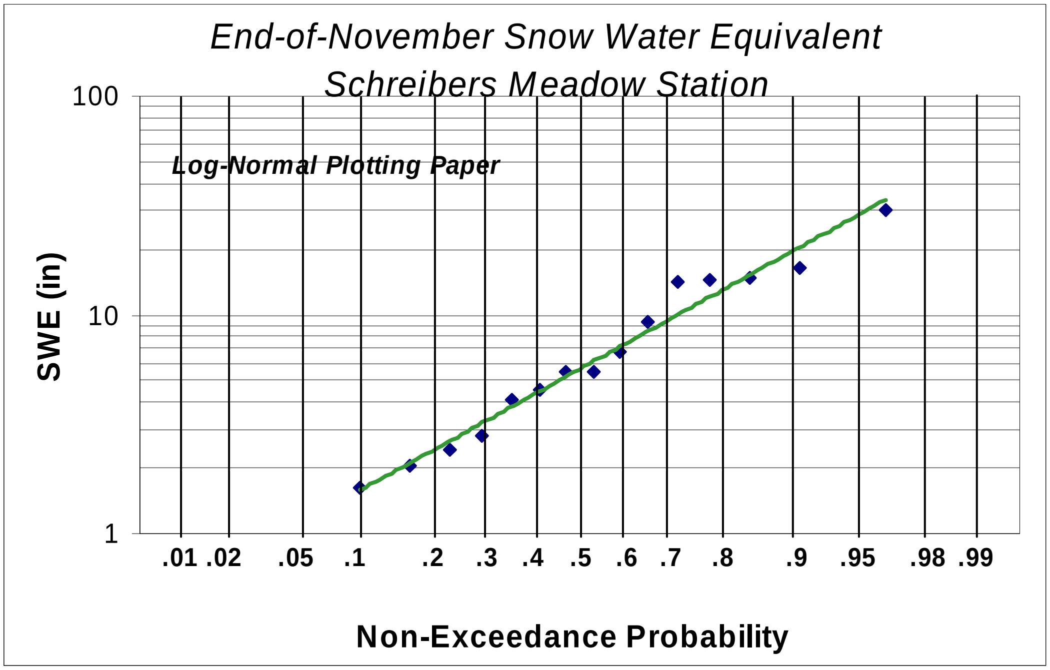


Figure F-9. Log-Normal Distribution Fitted to End-of-November Snow Water Equivalent Data for Schreibers Meadow Station (Key Snow Course Station)

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 F-10 shows an example of such a plot, illustrating the variation in the frequency of snow-free ground for the end-of-October period.

For the GSA, the model proceeded through the following steps to spatially allocate antecedent snow water equivalent for each model simulation (MGS 2004):

- A value of antecedent precipitation at the key precipitation station was selected using Monte Carlo sampling.
- 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 F-8).

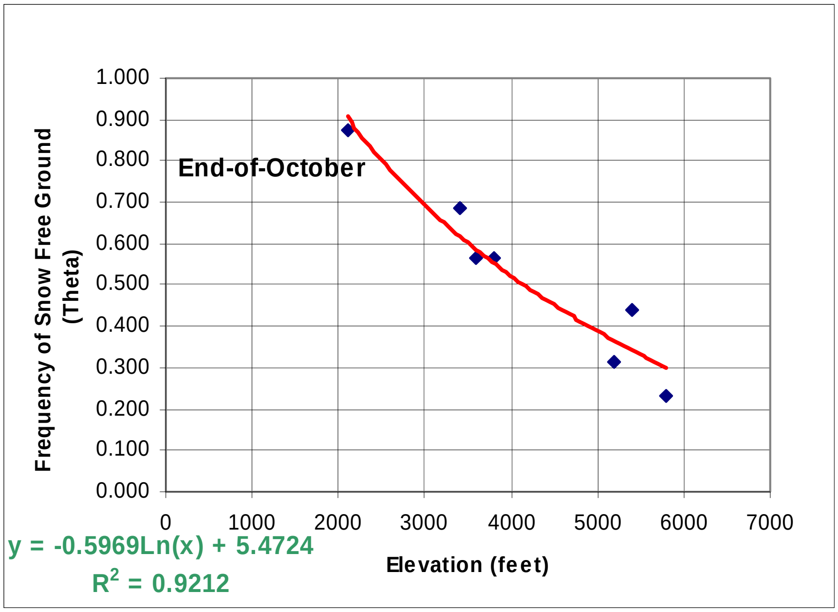


Figure F-10. Regression Relationship for Frequency of Snow-Free Ground Term (Theta)

- 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 F-9).
- 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 F-10).
- 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).

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 F-11. 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.

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 F-12. The cyclic melt and accumulation of the snowpack during the early winter season is a factor in the poor correlation.

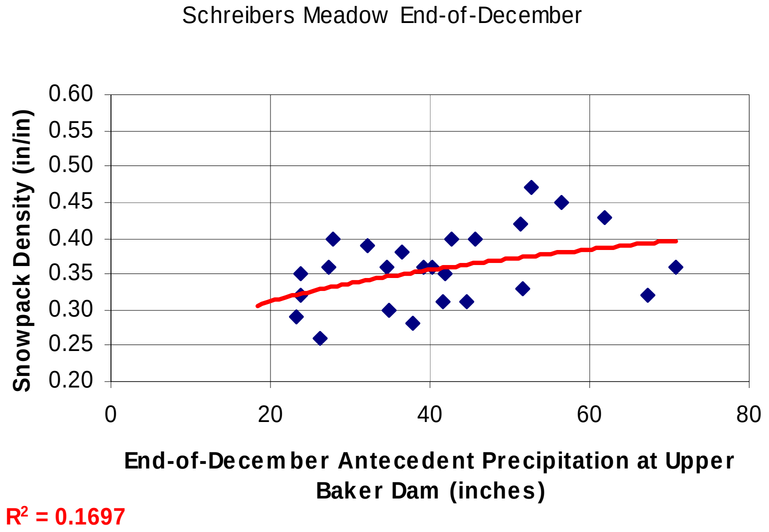


Figure F-11. Correlation of End-of-Month Antecedent Precipitation with End-of-Month Snowpack Density

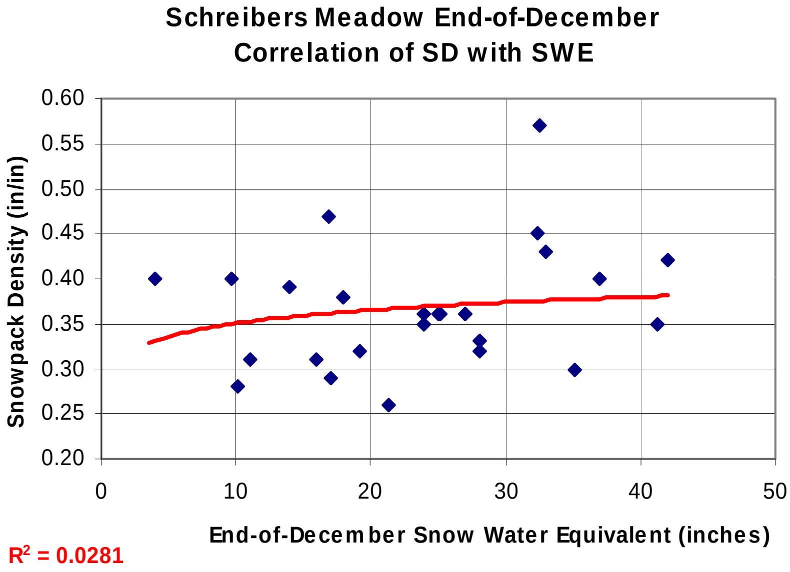


Figure F-12. Correlation of End-of-Month Snow Water Equivalent with End-of-Month Snowpack Density

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 F-13 compares the frequency histogram for the end-of-November data to the data using the four-parameter Beta distribution. Figure F-14 illustrates how the historical data fits the Beta distribution, and Table F-11 summarizes snowpack density values for specific non-exceedance probabilities.

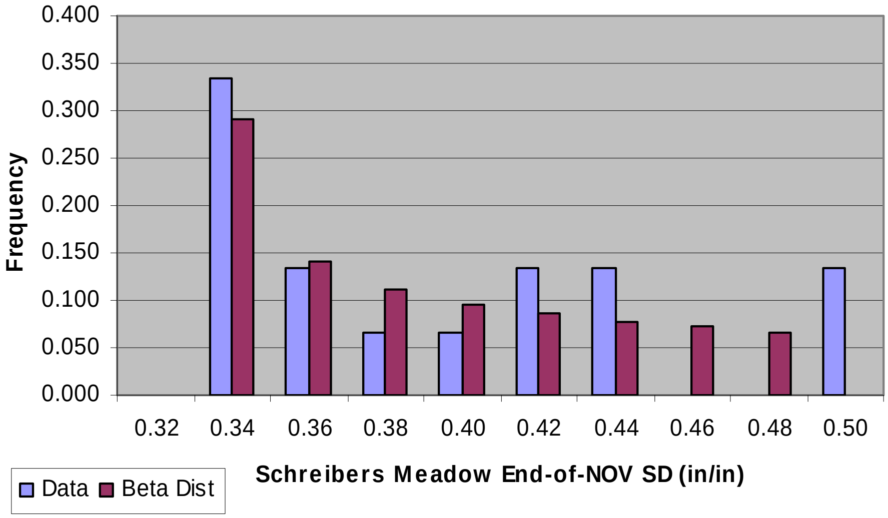


Figure F-13. Frequency Histogram for End-of-November Antecedent Snowpack Density at Schreibers Meadow Snow Course Station

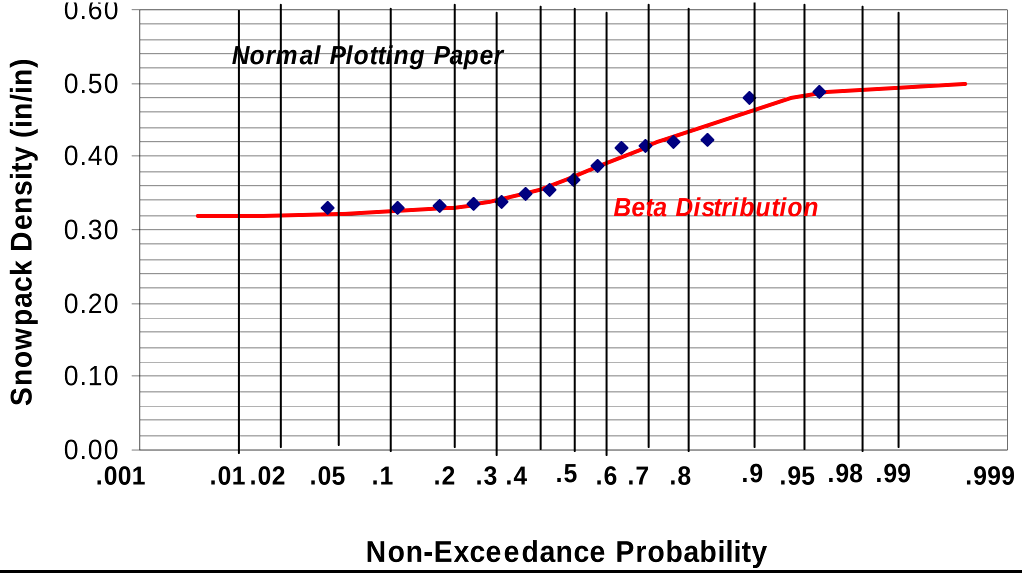


Figure F-14. Probability Plot for End-of-November Antecedent Snowpack Density at Schreibers Meadow Snow Course Station

Table F-11. 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

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 F-14). 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 2006b).

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 Puget Sound Energy (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.

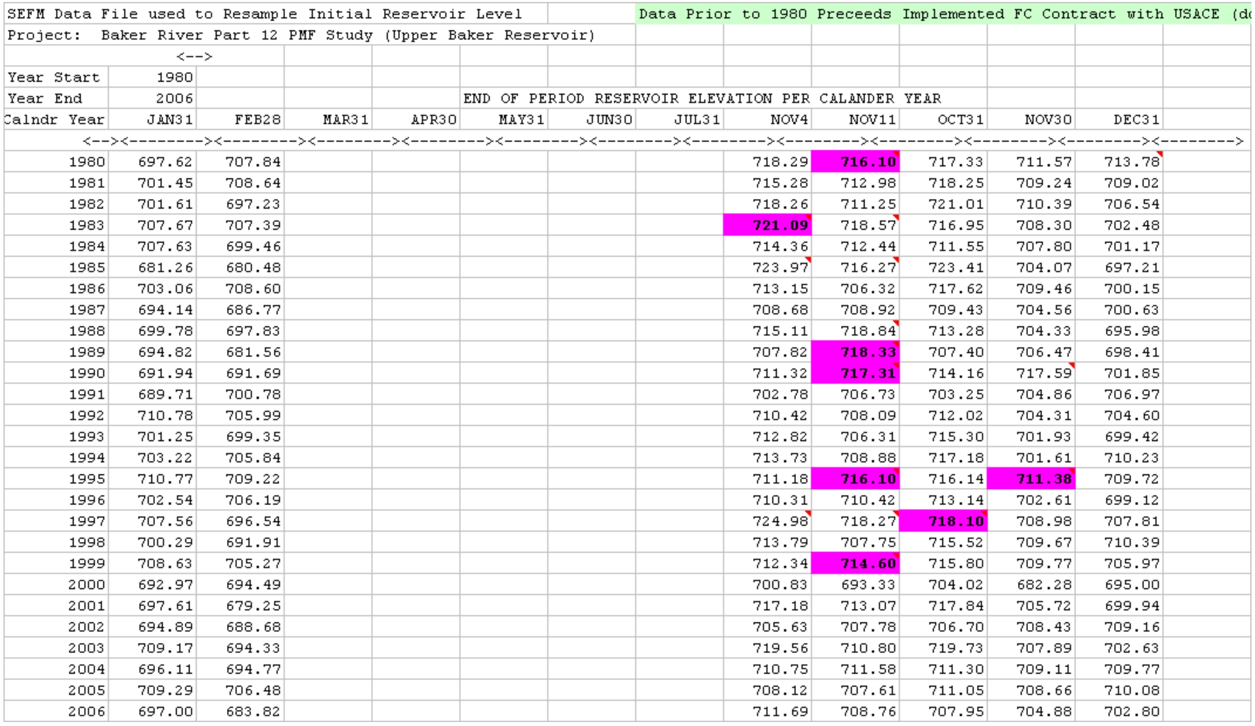
Input to the resampling methodology required that end-of-month reservoir elevation data be compiled for both Upper Baker Dam and Lower Baker Dam. The data from 1980 to the present was used because this period reflects the current flood control operation conditions at Upper Baker Dam. From October 1st through March 31st, PSE operates Upper Baker Dam as a flood control facility in accordance with the flood control rule curve. 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 F-12 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 but uses either Nov 4th or November 11th reservoir elevation data.

Table F-12. 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 F-15 and F-16 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 F-15 are those that were changed according to the procedure described in the previous paragraph.



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)
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 F-15. 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)
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 F-16. End-of-Period Reservoir Elevation Data—Lower Baker Reservoir

Figures F-17 through F-24 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.

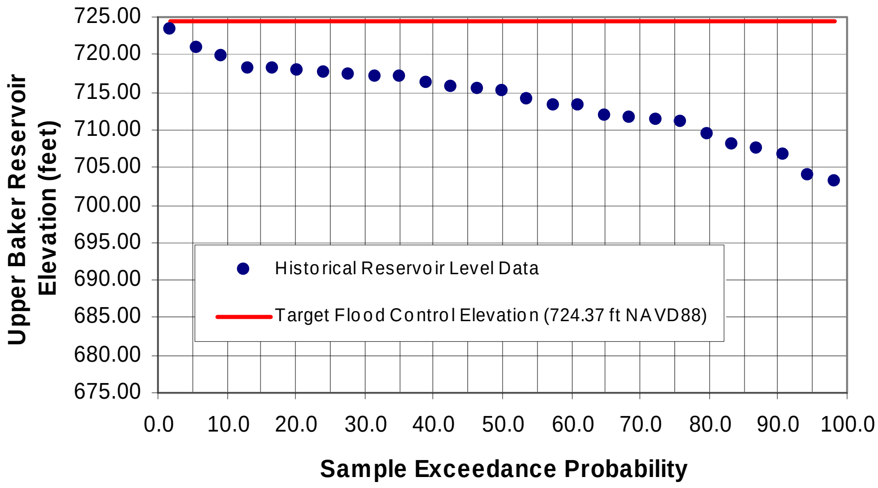


Figure F-17. Probability Plot of End-of-October Reservoir Elevation Data for Upper Baker Dam

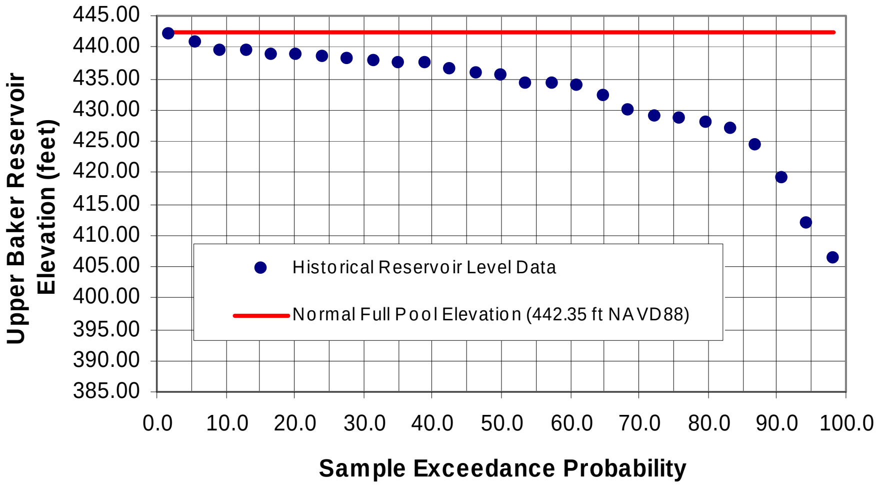


Figure F-18. Probability Plot of End-of-October Reservoir Elevation Data for Lower Baker Dam

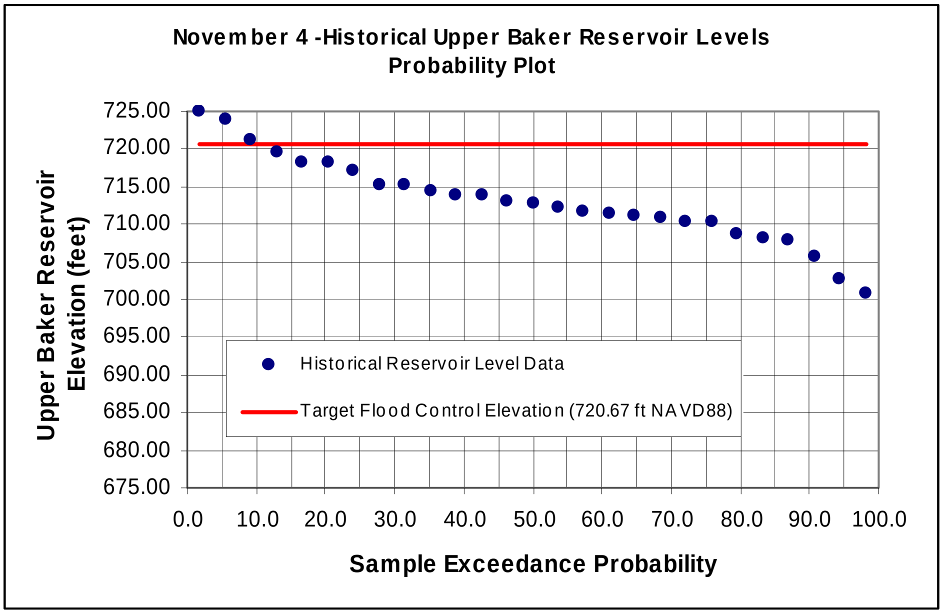


Figure F-19. Probability Plot of November 4th Reservoir Elevation Data for Upper Baker Dam

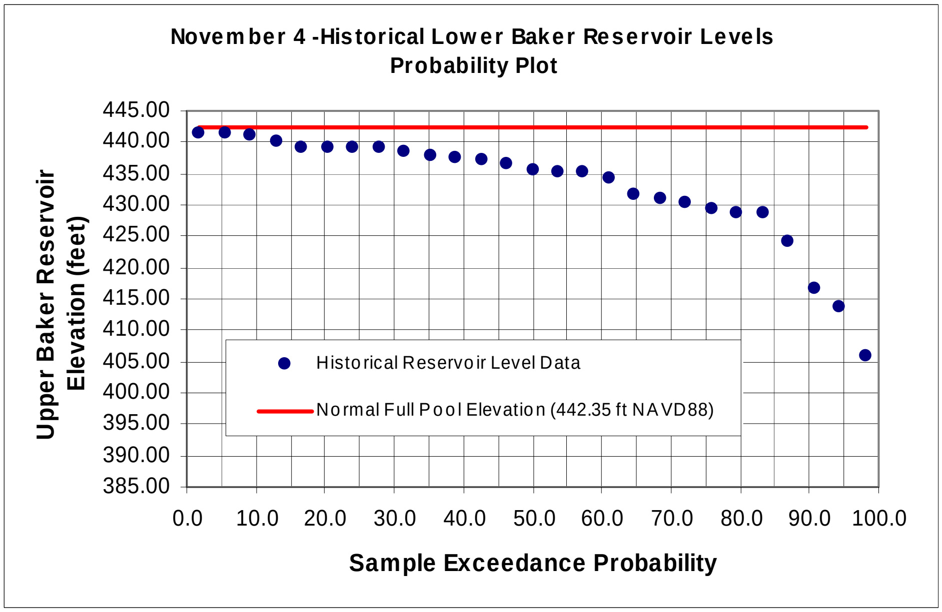


Figure F-20. Probability Plot of November 4th Reservoir Elevation Data for Lower Baker Dam

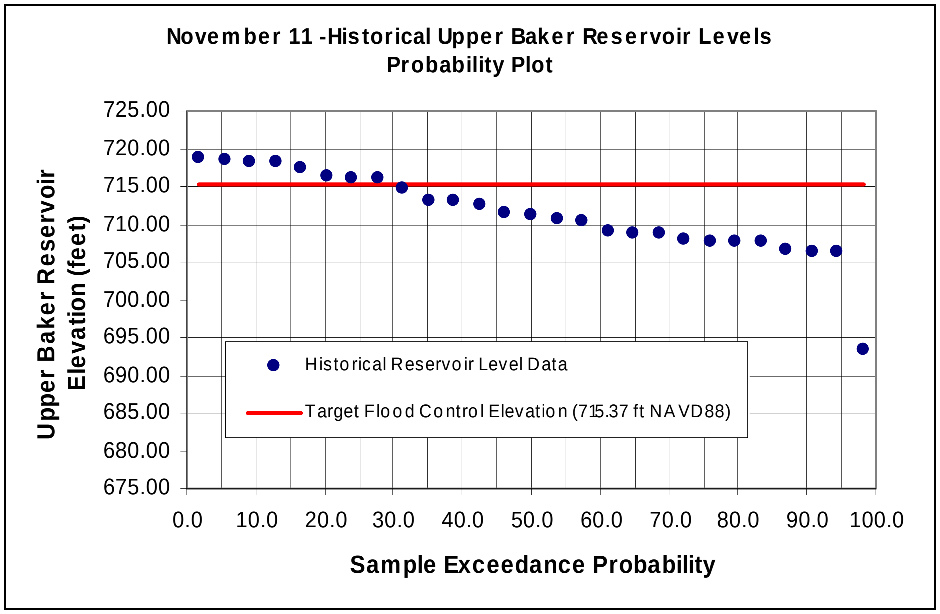


Figure F-21. Probability Plot of November 11th Reservoir Elevation Data for Upper Baker Dam

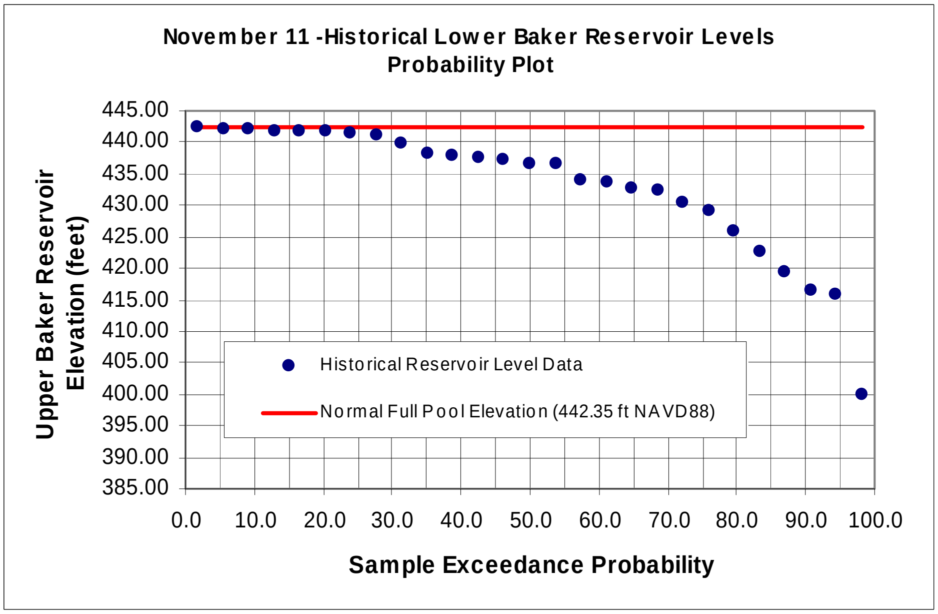


Figure F-22. Probability Plot of November 11th Reservoir Elevation Data for Lower Baker Dam

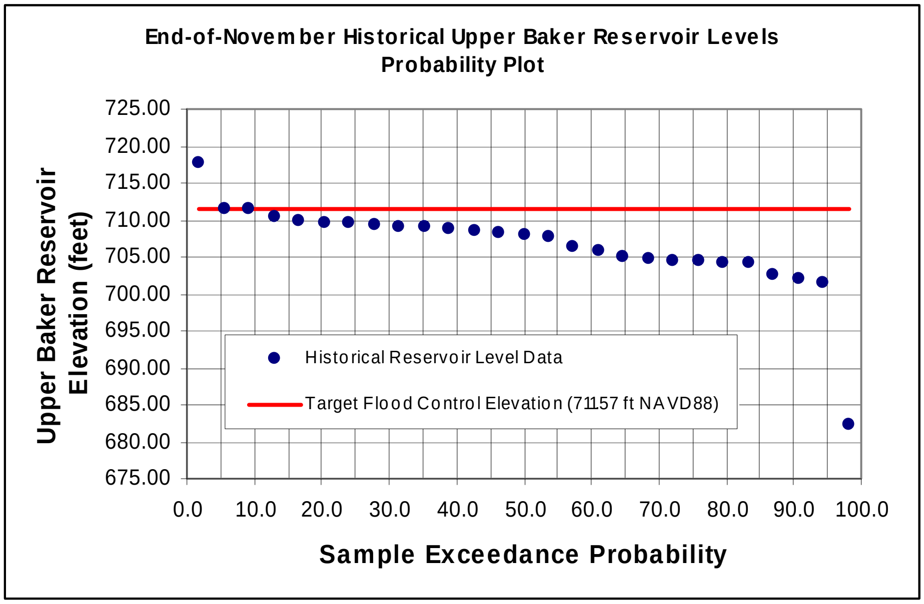


Figure F-23. Probability Plot of End-of-November Reservoir Elevation Data for Upper Baker Dam

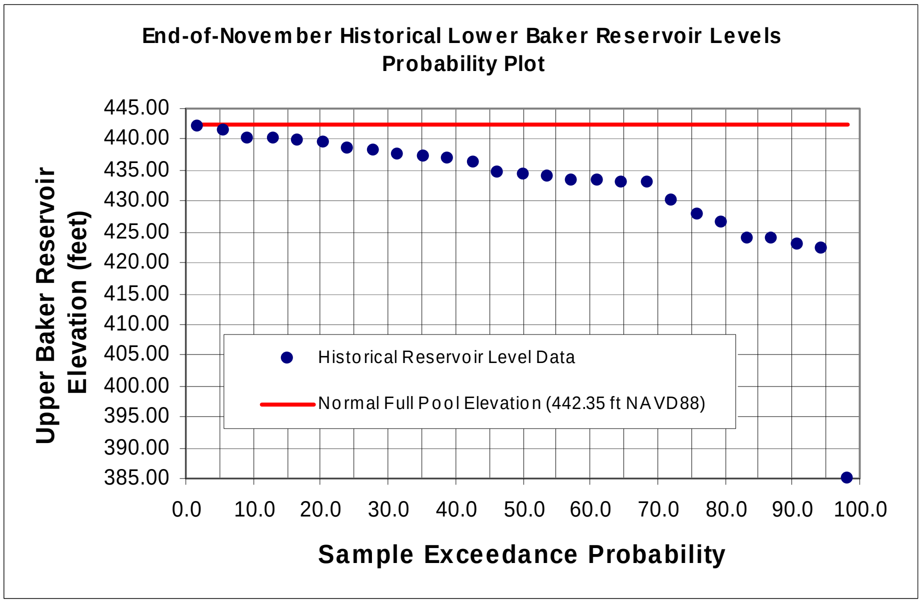


Figure F-24. Probability Plot of End-of-November Reservoir Elevation Data for Lower Baker Dam

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Puget Sound Energy

Baker River Project Part 12
Probable Maximum Flood Study

APPENDIX G.
GSA SENSITIVITY RESULTS

December 2007

APPENDIX G.
GSA SENSITIVITY RESULTS

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 G-1 and G-2 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 G-1. 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 G-2. 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.

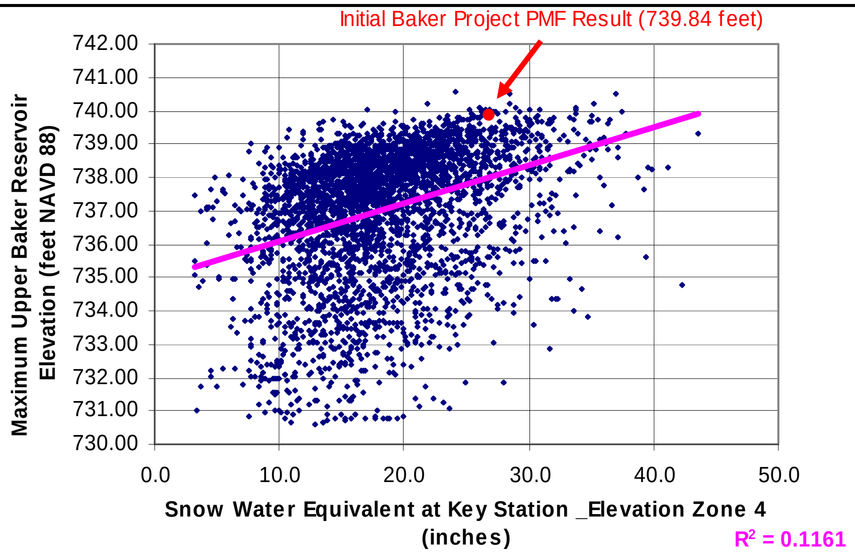

Figure G-1. Example Scatter-plot –Snow Water Equivalent Parameter

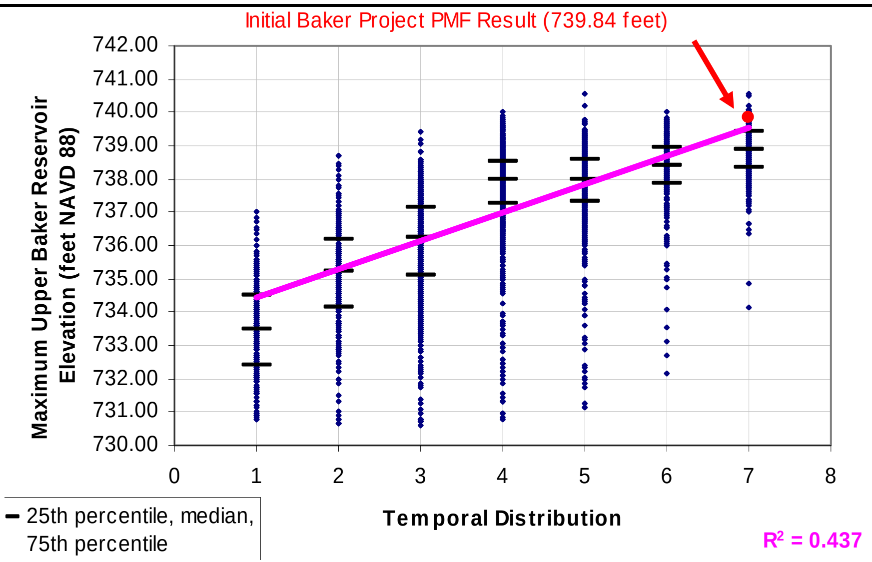

Figure G-2. Example Scatter-plot –Temporal Pattern Parameter

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 in terms of model sensitivity using a subjective evaluation of the scatter-plots. Since the R^2 value is a quantitative measure of output variability 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 sensitivity to seasonality of occurrence 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 probable maximum flood (PMF) analysis had identified the month of November as the critical month for PMF.

Table G-1 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 Stochastic Event Flood Model (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 G-1. 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 G-1, are discussed first.

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 G-3 through G-6 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 G-3 and G-4 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 G-3 and G-4 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 G-4) than for the Upper Baker inflow results (Figure G-3). 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 G-5 and G-6 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.

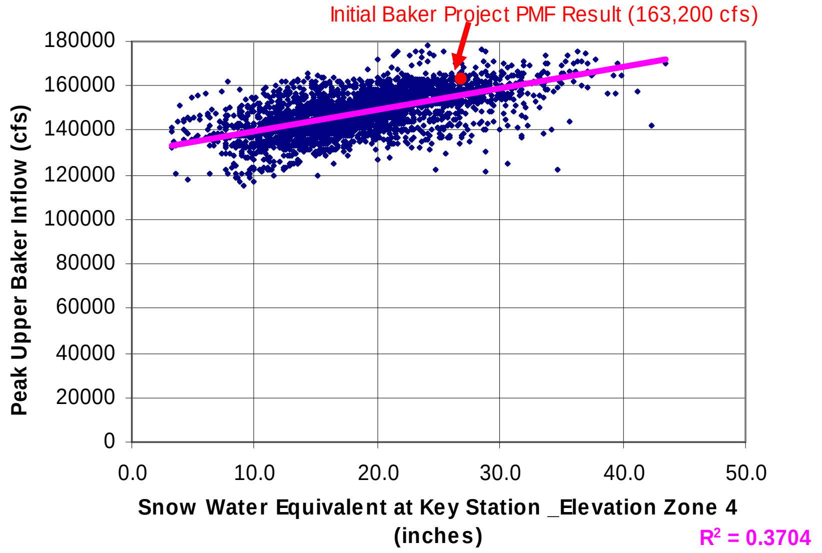

Figure G-3. Sensitivity of Upper Baker Peak Inflow to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

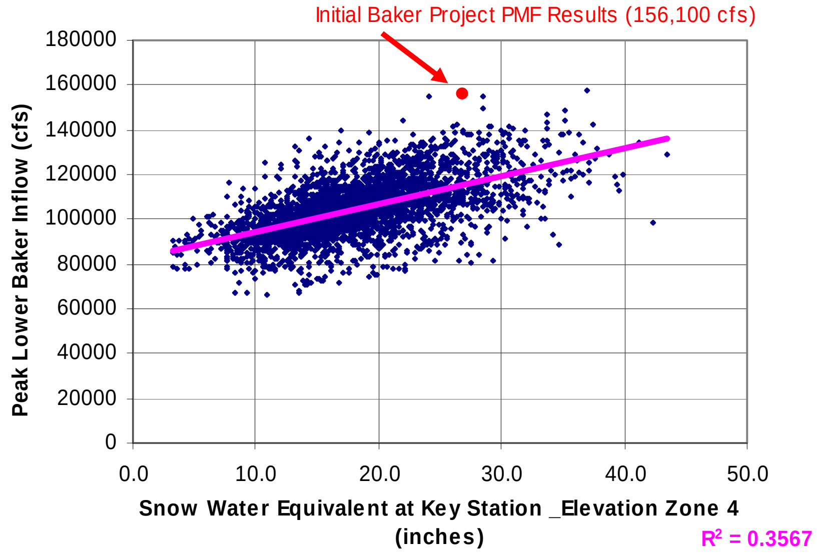

Figure G-4. Sensitivity of Lower Baker Peak Inflow to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

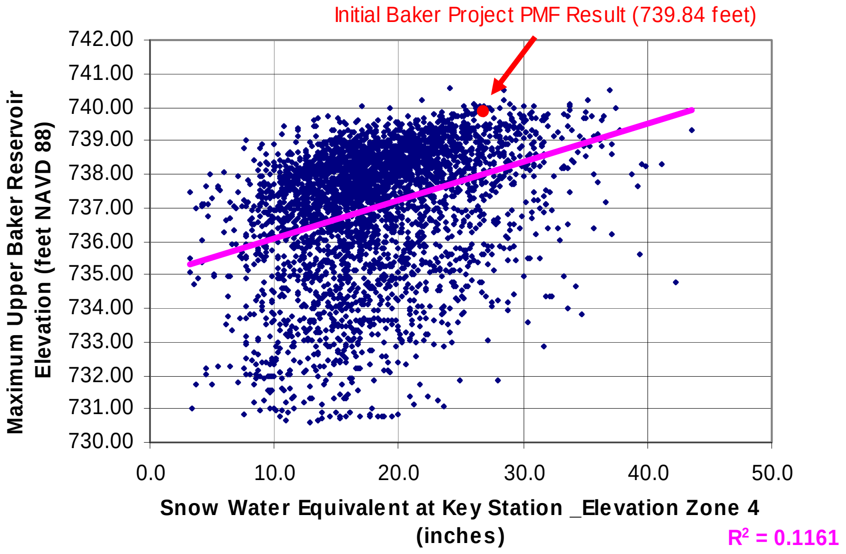

Figure G-5. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

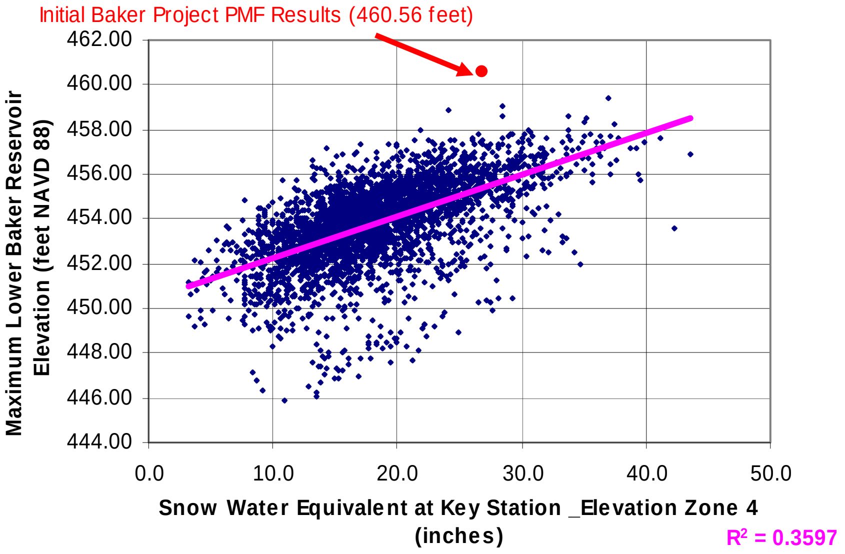

Figure G-6. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Snow Water Equivalent for END-OF-NOVEMBER Results Only

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 G-7 and G-8 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.

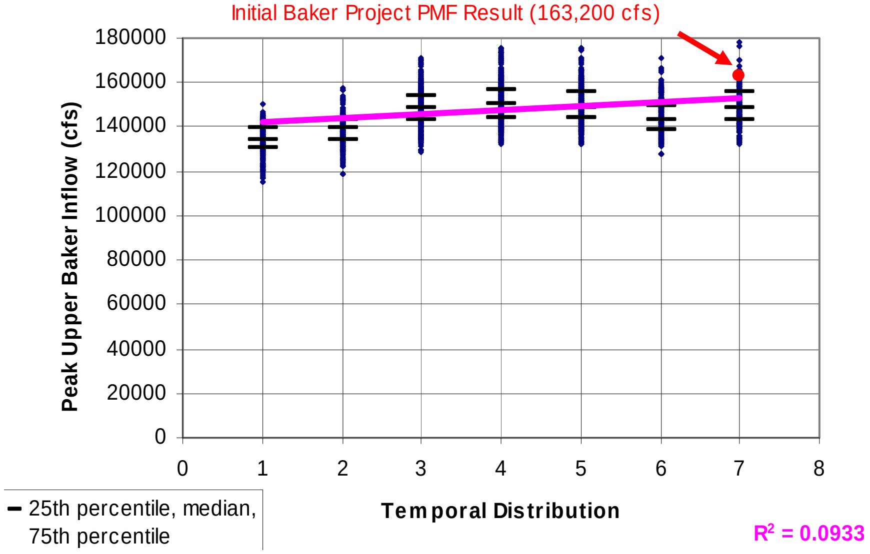

Figure G-7. Sensitivity of Upper Baker Peak Inflow to PMP Temporal Pattern for END-OF-NOVEMBER Results Only

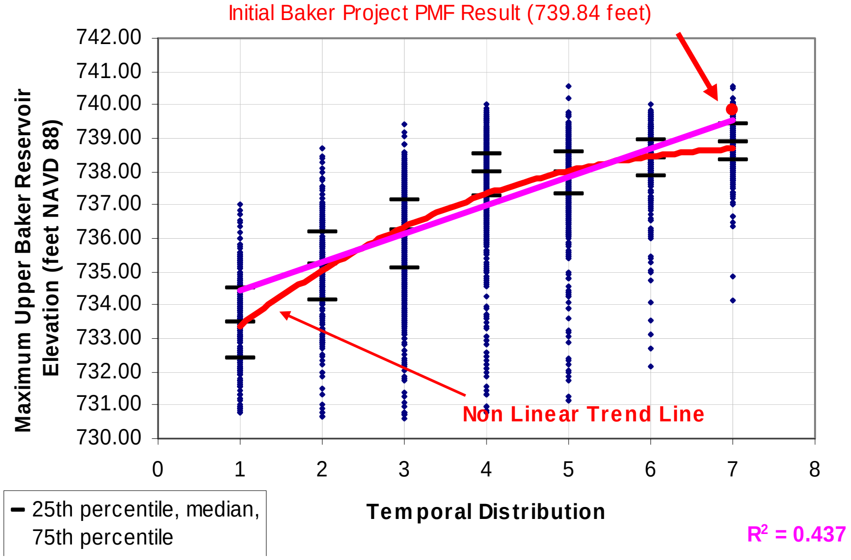

Figure G-8. Sensitivity of Upper Baker Peak Reservoir Elevation to PMP Temporal Pattern for END-OF-NOVEMBER Results Only

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 G-7), 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 G-8). 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 G-8, 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.

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 G-9 and G-10. Figure G-9 shows the sensitivity of the flood response (in this case, peak Upper Baker inflow) and Figure G-10 shows the sensitivity of the reservoir response (in this case, peak Upper Baker reservoir elevation).

As seen in Figure G-9, 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 G-9 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 probable maximum precipitation (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.

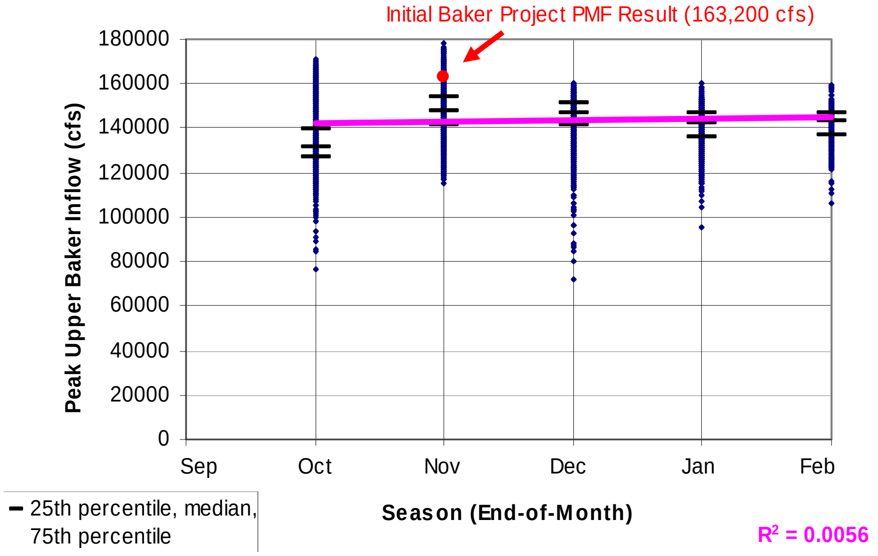

Figure G-9. Sensitivity of Upper Baker Peak Inflow to Seasonality of Occurrence

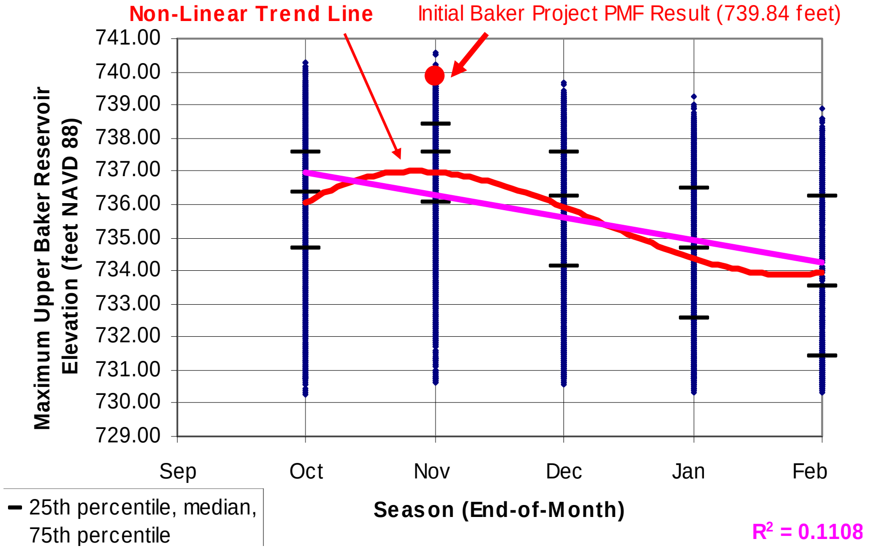

Figure G-10. Sensitivity of Upper Baker Peak Reservoir Elevation to Seasonality of Occurrence

As seen in Figure G-10, 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 G-10 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 G-10, 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.

ANTECEDENT PRECIPITATION

Flood response and reservoir response were both determined to have a moderate sensitivity to antecedent precipitation. Figures G-11 through G-14 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 G-11 through G-14 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.

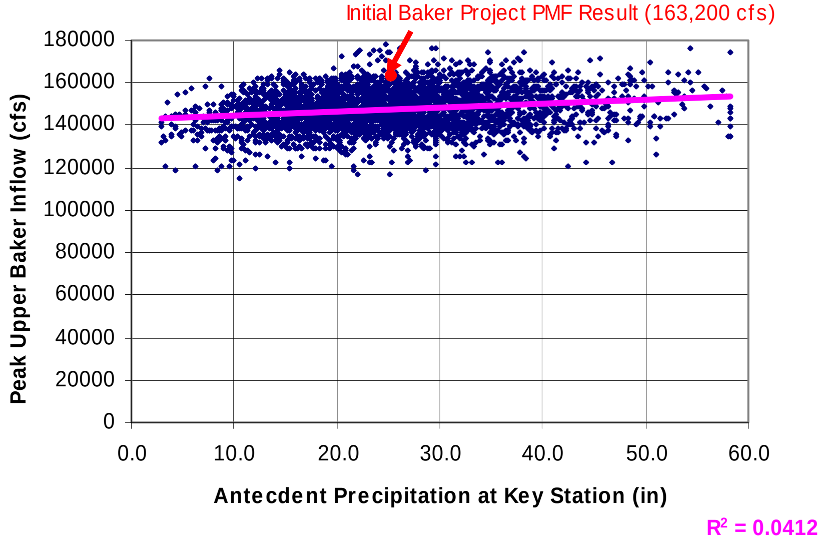

Figure G-11. Sensitivity of Upper Baker Peak Inflow to Antecedent Precipitation for END-OF-NOVEMBER Results Only

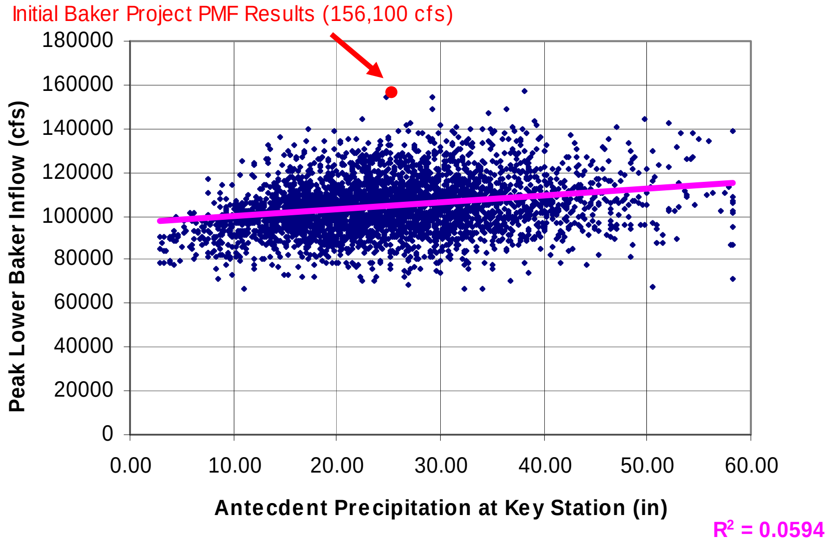

Figure G-12. Sensitivity of Lower Baker Peak Inflow to Antecedent Precipitation for END-OF-NOVEMBER Results Only

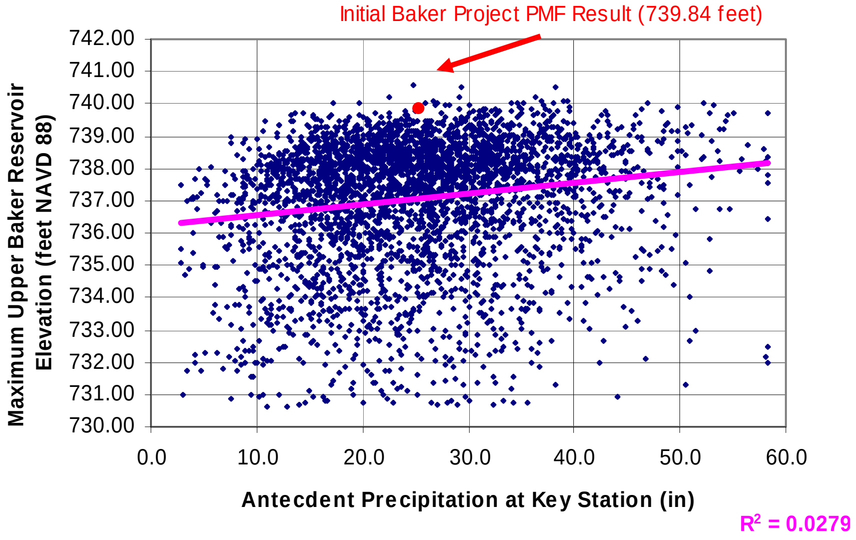

Figure G-13. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Precipitation for END-OF-NOVEMBER Results Only

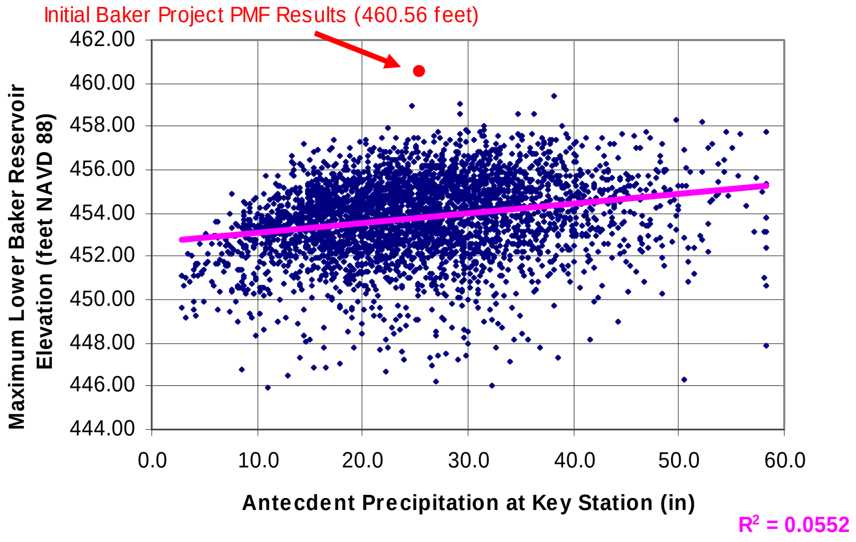

Figure G-14. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Precipitation for END-OF-NOVEMBER Results Only

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 G-15 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.

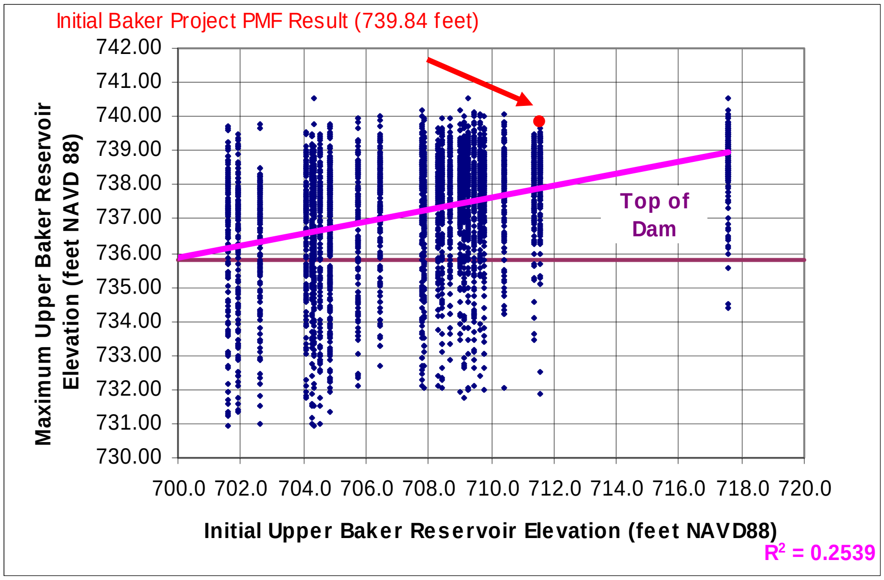

Figure G-15. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Reservoir Elevation for END-OF-NOVEMBER Results Only

Figure G-16 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.

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 G-17 through G-19 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 G-17 and G-18) 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 G-19) 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.

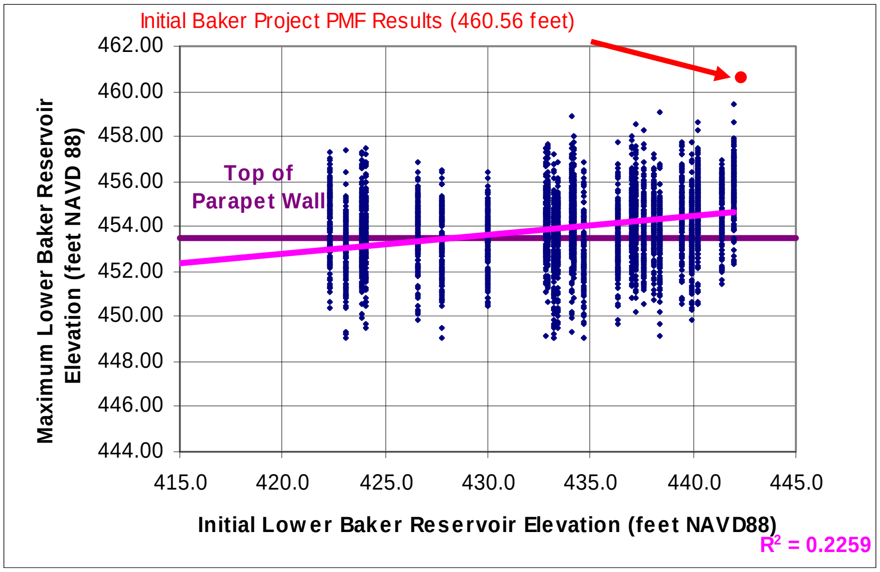

Figure G-16. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Reservoir Elevation for END-OF-NOVEMBER Results Only

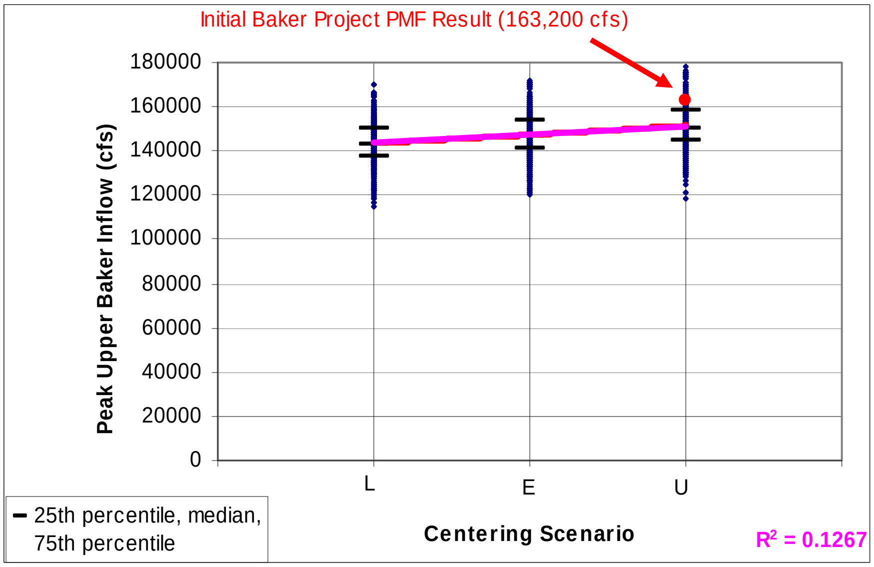

Figure G-17. Sensitivity of Upper Baker Peak Inflow to General Storm Centering Scenario for END-OF-NOVEMBER Results Only

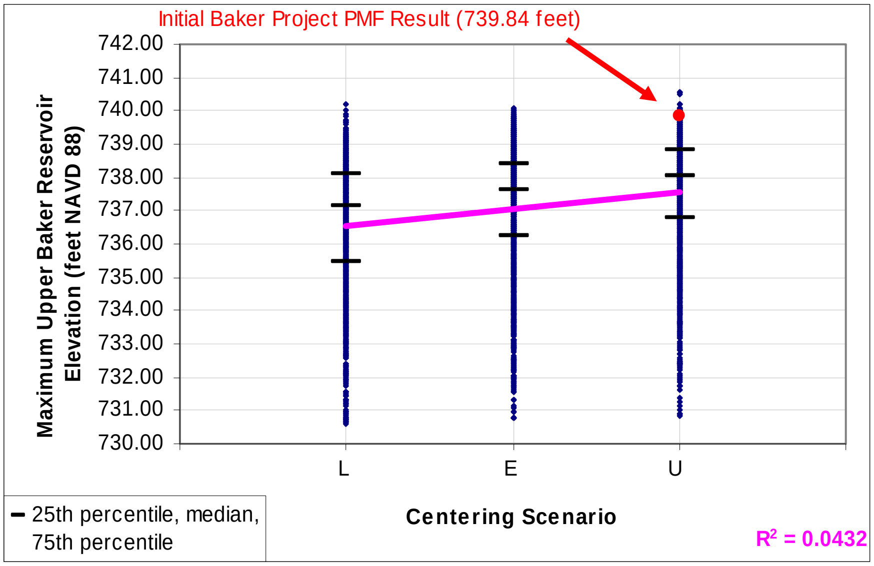

Figure G-18. Sensitivity of Upper Baker Peak Reservoir Elevation to General Storm Centering Scenario for END-OF-NOVEMBER Results Only

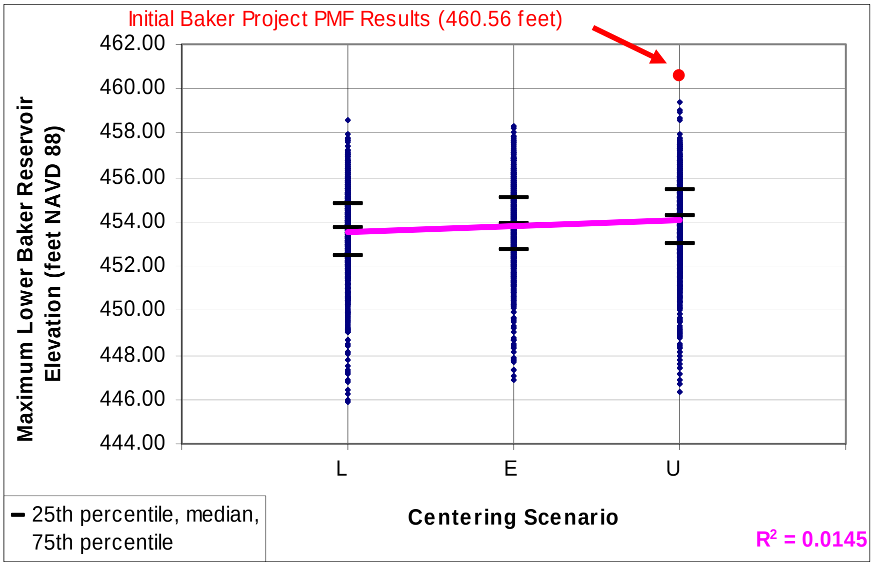

Figure G-19. Sensitivity of Lower Baker Peak Reservoir Elevation to General Storm Centering Scenario for END-OF-NOVEMBER Results Only

ANTECEDENT SNOWPACK DENSITY

Flood response and reservoir response were determined to have a very low degree of sensitivity to antecedent snowpack density. Figures G-20 through G-22 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.

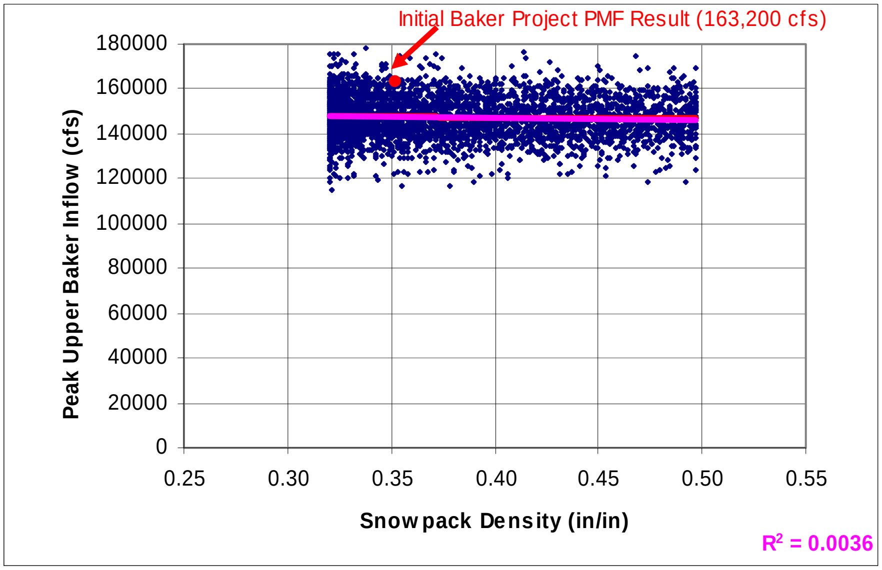

Figure G-20. Sensitivity of Upper Baker Peak Inflow to Antecedent Snowpack Density for END-OF-NOVEMBER Results Only

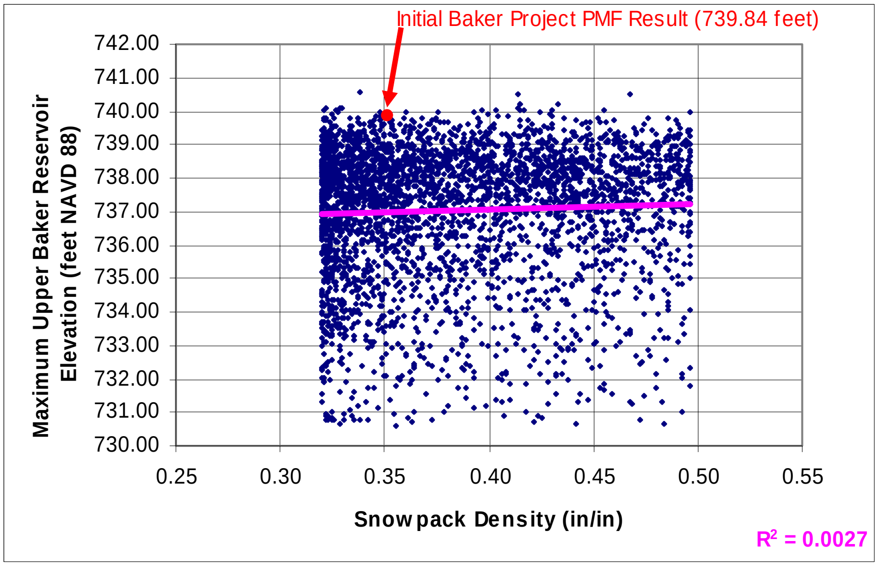

Figure G-21. Sensitivity of Upper Baker Peak Reservoir Elevation to Antecedent Snowpack Density for END-OF-NOVEMBER Results Only

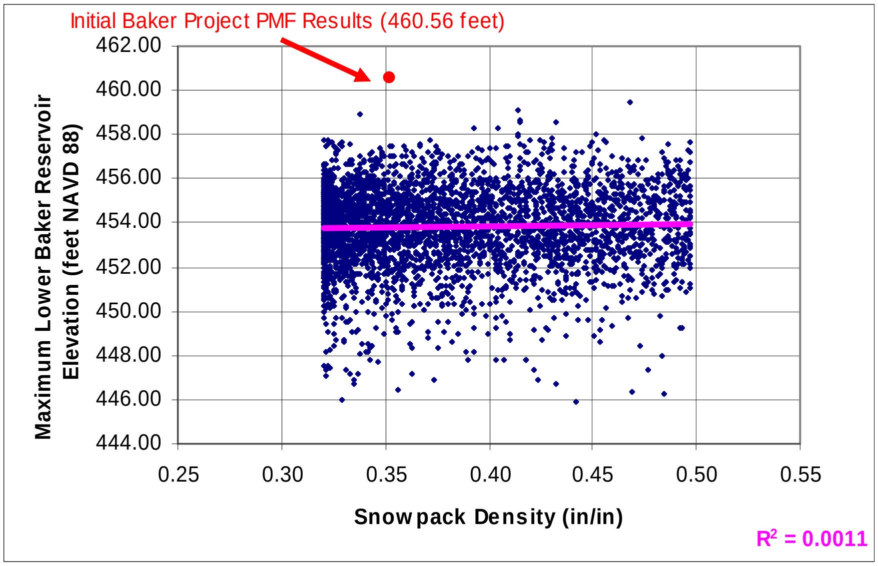

Figure G-22. Sensitivity of Lower Baker Peak Reservoir Elevation to Antecedent Snowpack Density for END-OF-NOVEMBER Results Only

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.

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 G-2 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 G-2. 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