Calibration of the Inflow to Hungry Horse and Libby Reservoirs

Eric Anderson, January 2009

Introduction

In the fall of 2007 the Northwest River Forecast Center (NWRFC) requested assistance for a recalibration of the inflows to Hungry Horse and Libby reservoirs in northwest Montana. The RFC had been having some problems with operational forecasts for these reservoirs. The NWRFC provided most of the data, performed consistency analyses on the precipitation and temperature data, and generated monthly means for the precipitation and temperature stations. Data were provided for the period from water year (WY) 1949 though WY 2003. Eric Anderson completed the historical data analysis (i.e. generated the Mean Areal Precipitation (MAP) and Temperature (MAT) time series) and calibrated the models. This report documents this recalibration effort. To go along with the report a CD is available that contains all the data (both station data and areal time series), the input to the various NWSRFS programs (including model parameters), and spreadsheets that were used to assist in the analysis. Appendix A lists the contents of the CD. The CD was primarily prepared for use along with the report for calibration training. Excel spreadsheets that were used as part of the historical data analysis or calibration evaluation are referenced in the text.

Hungry Horse dam lies east of Kalispell, Montana and just south of Glacier National Park. Construction of the dam began in 1948 and was completed in 1952. Storage began in September 1951. The inflow to the dam drains an area of 1654 sq. miles of the South Fork of the Flathead River (NWS id HHWM8). The watershed is over 80% forested (primarily lodgepole pine, Douglas fir, and ponderosa pine) with alpine conditions above the tree line. The elevation ranges from about 3200 feet to 9255 feet at Swan Peak. About 75% of the drainage area falls within the Bob Marshall Wilderness Area complex. The only road access is along the shores of the reservoir. Almost all the precipitation and temperature stations lie outside the watershed. There were no high elevation data prior to the installation of the Snotel network starting in the late 1970's. Daily inflow data are available for the entire WY 1949-2003 period. These values are derived from pool elevation and outflow observations since the construction of the dam. There is also a USGS streamflow gage upstream of the reservoir with records from WY 1965-1982 and WY 1985-2003 (South Fork Flathead above Twin Creek near Hungry Horse, Montana – TNCM8 – 1160 sq. miles). Winter records are not available at this site starting with WY 1985. The mean annual runoff is about 29.5 inches (less than 26 inches above TNCM8 and over 38 inches for the local below that gage) with nearly 49 inches of mean annual precipitation.

Libby Dam lies just east of Libby, Montana. Construction of the dam began in 1967 and was completed in 1973. Storage began in March 1972. The inflow to the dam drains an area of 8985 sq. miles of the Kootenai River (LYDM8); the majority of which is in Canada. The basin lies just west of the continental divide and mostly south of Banff

National Park. Much of the watershed is heavily forested with an elevation range of about 2100 to 11250 feet at Mount Joffre. The surface area of Lake Koocanusa is about 73 sq. miles and there are diversions for irrigation of about 13,000 acres in the US and Canada. Again there were no high elevation data prior to the installation of the Snotel network in the US and a few similar stations in Canada beginning in the late 1970's. Daily inflow data are available for the entire WY 1949-2003 period. These values are derived from pool elevation and outflow observations since the construction of the dam. There are 3 primary river gages upstream from the dam in Canada. These are the Kootenay (notice different spelling in Canada) River at Fort Steele, BC (FSTQ2 – 4400 sq. miles), the Elk River at Fernie, BC (ERFQ2 – 1200 sq. miles), and the Bull River near Wardner, BC (BULQ2 – 590 sq. miles). The mean annual runoff for the entire basin is about 17 inches (nearly 20 inches for the 69% of the drainage above the Canadian streamgages and just over 11 inches for the local area below those gages) with a little over 35 inches of mean annual precipitation.

The initial recalibration for Hungry Horse Dam raised several significant issues. The calibration was based on the period WY 1979-2003 which was after Snotel data were available. Using the model parameters based on that period resulted in a significant negative bias for the period prior to WY 1979. This raised questions regarding what period should be used for the computation of station means of precipitation and temperature, the period that should be used to calibrate the models, and what time series should be used when making extended streamflow prediction (ESP) runs. After analyzing a variety of data and after much discussion among those involved, the NWRFC revised their policies on the periods to use for computing station means and calibrating the models. This resulted in revising the historical data analysis and adjusting the calibration for HHWM8 and redoing the data analysis for Libby. Thus, before presenting the results of the historical data analysis and recalibration for Hungry Horse and Libby reservoirs, the issues that arose and analysis and decisions that followed needs to be first described.

Issues Regarding Period of Record and Data to Use for Historical Data Analysis, Model Calibration, and ESP

Background

The initial recalibration for HHWM8 used the WY 1979-2003 period to determine the model parameters. This was the period for which Snotel data were available. The RFC performed the consistency analysis over the entire Clark Fork and Flathead basins. For these basins 18 of the 34 Snotel sites had precipitation data available starting in WY 1979. Precipitation records for 9 other Snotel sites began in WY 1980. The last Snotel site used began collecting precipitation data in WY 1990. Of the 31 Snotel sites for which temperature data were used, the first data were available in WY 1982 and all sites were collecting temperature data by WY 1992. Prior to WY 1979 there were no high elevation precipitation or temperature data made available for this study by the RFC. The Snotel sites range in elevation from 4300 to 8250 feet. Prior to WY 1979 the highest data available was at an elevation of 5506 feet. The station mean monthly values for precipitation for the initial recalibration of HHWM8 were based on the period WY 1971-2000 to coincide with the PRISM analysis and monthly mean max/min temperatures were based on the entire period of record, i.e. WY 1949-2003. For stations with temperature data for only a portion of the entire period of record, the NWRFC used the procedure outlined in Section 6-4 of the Calibration Manual (*Anderson 2002*) to estimate the mean monthly max and min values.

After calibrating the models on the WY 1979-2003 period, a simulation was run for the earlier years. The period prior to WY 1979 produced a large negative bias compared to the period used for calibration. This can be seen in Figure 1 (the analyses included in this section can be found in the Excel spreadsheet 'Accum_RO_compare.xls'). That figure shows the accumulated difference between simulated and observed flows. Values are shown based on the HHWM8 initial recalibration (Eric's calibration), the previous RFC calibration that used data through WY 1993, and a run with a precipitation adjustment (PXADJ in the SNOW-17 operation) of 1.078 applied to the WY 1949-1978 period. It can be seen that there is an abrupt change in the simulation results from Eric's calibration at around WY 1978. The deviation of simulated and observed flows is nearly a straight line before and after that date. This raised questions regarding why this was occurring.

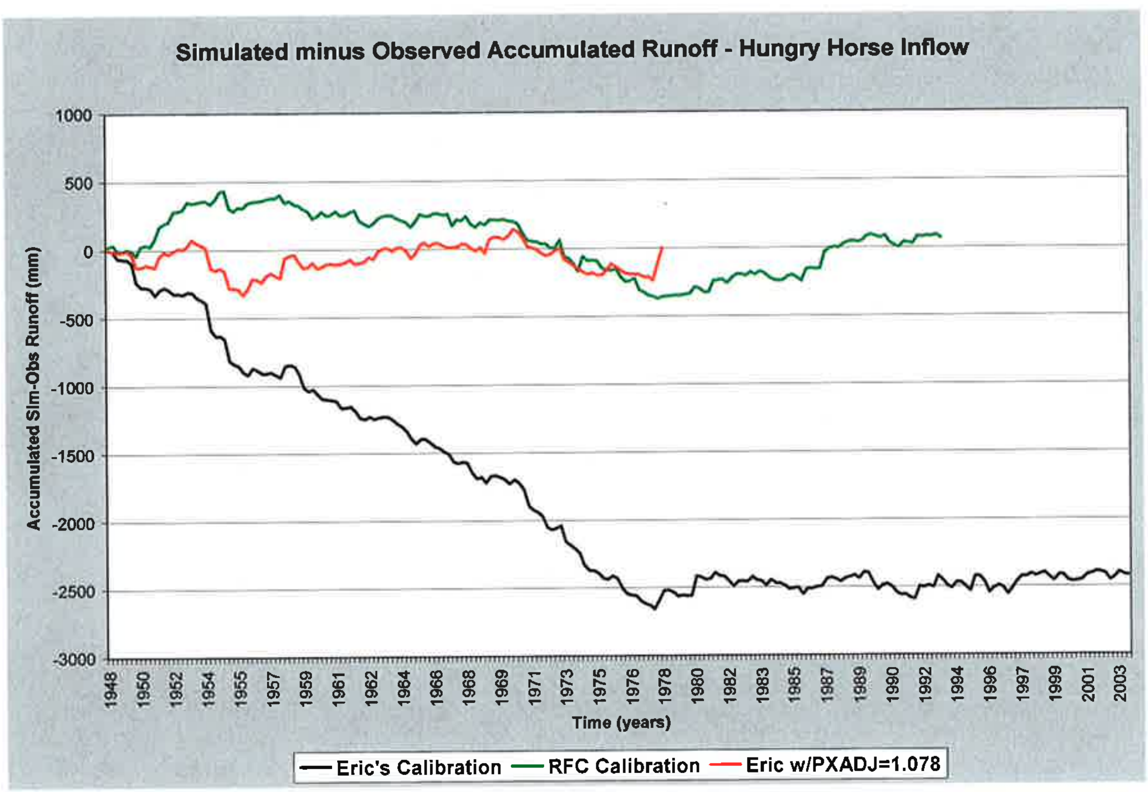

Figure 1. Simulated minus observed accumulated runoff for HHWM8.

Possible Reasons for Runoff Increase Prior to WY 1979

One of the first questions was "Is there a problem with the runoff data for HHWM8?". To answer that question streamflow data from a number of gages in the region with data for the entire WY 1949-2003 period were analyzed. Some of these are shown in Figure 2 (besides HHWM8, gages included WGCM8 – Middle Fork of the Flathead near West Glacier, SWRM8 – Swan River near Bigfork, FCFM8 – North Fork of the Flathead near Columbia Falls, and LYDM8). The RFC looked at additional gages. Of the flow records shown in Figure 2 some are derived from pool elevation and outflow measurements (HHWM8 and LYDM8) and some from streamgages (WGCM8, SWRM8, and FCFM8). Figure 2 shows the accumulated deviation from the average observed runoff at each station. For most sites the runoff was generally above the average until about WY 1976. After that date the runoff was typically below average. SWRM8 had above average runoff until the early 1980's and then generally below average values afterward. Based on this analysis, the gages examined by the RFC, and RFC discussions with the USGS concerning any abrupt changes in streamgaging methods, it was concluded that there was no problem with the runoff data. Thus, a real change in runoff from generally above average to below average over the WY 1949-2003 period occurred in the mid 1970's in this region.

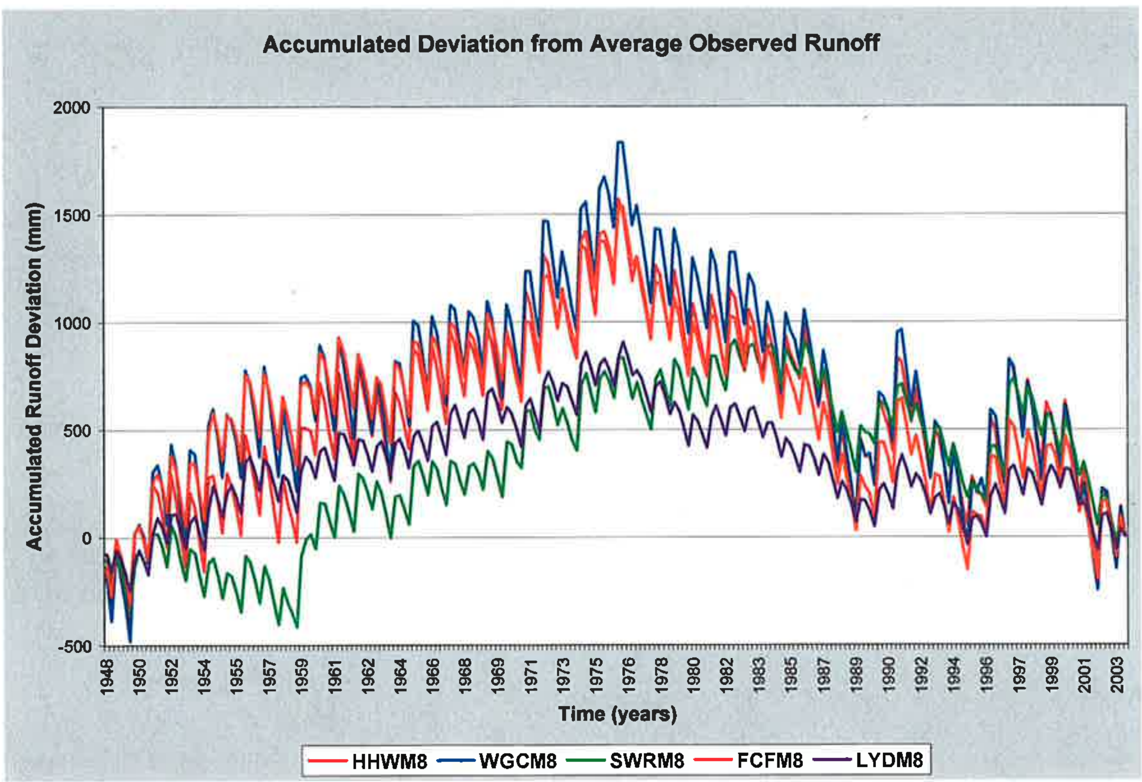

Figure 2. Accumulated deviation from average runoff for selected stations.

Table 1 shows how the amount of runoff varies from WY 1949-1978 to WY 1979-2003 for HHWM8 and several nearby stations. From Table 1 it can be seen that the ratio of runoff for the early years as compared to the later years is about 1.12. Table 2 shows the how the amount of precipitation in the MAP time series generated for HHWM8 varies from the early period to the later years. This shows that the MAP ratio for the early years as compared to the later years is only about 1.01. It is clear that only one percent more precipitation in the early years can't produce 12% more runoff unless the other components of the water balance changed abruptly and significantly. Thus the next thing to look at was the components of the water balance and factors that could affect those components.

Watershed	Hungry Horse HHWM8	MF Flathead WGCM8	NF Flathead FCFM8	Swan – Bigfoot SWRM8
Annual RO 49-78	31.59	37.21	28.34	25.03
Annual RO 79-03	28.08	33.09	24.96	22.79
Ratio	1.12	1.12	1.14	1.10

Table 1. Comparison of runoff (inches) for different periods.

Area	Below 6500 feet	Above 6500 feet	Total Basin
Avg. Annual 49-78	43.60	46.40	44.44
Avg. Annual 79-03	42.90	46.50	43.98
Ratio	1.02	1.00	1.01

Table 2. MAP time series (inches) comparison for different periods for HHWM8.

The increased runoff in the early years could be caused by less evaporation in those years. Abrupt changes in evaporation would occur if there were large scale changes in the forest cover caused by a forest fire. No such event occurred over the size area that experienced the above average runoff, plus a forest fire would cause evaporation rates to decrease resulting in more runoff for a given amount of precipitation after the fire. Pan evaporation data should be an indicator of trends in evaporation over time; however, there are not many pan sites with continuous long term measurements. The only station with data in this region for the entire WY 1949-2003 period was Moscow, Idaho. Figure 3 shows the variation in May-September evaporation at that station. It can be seen that pan evaporation was below the period average through 1965 and then above the average after that date. The ratio of WY 1949-1978 pan evaporation to that for WY 1979-2003 for Moscow is 0.936. Using that value as PEADJ in the SAC-SMA operations reduced the bias for the WY 1949-1978 period from -10.5% to -7.6% or about 25%. Thus lower evaporation rates in the early years could explain part of the reason why the models using WY 1979-2003 parameter values, including ET-demand rates, under compute runoff for the WY 1949-1978 period.

The MAT time series give some insight as to how temperature has changed over time. Figure 4 shows the cumulative variation in MAT values from the average for the WY 1949-2003 period (values shown for the upper and lower zones with a dividing elevation of 6500 feet). The variation is not only shown for annual temperatures, but also how the snowmelt season averages (April-June) varied over time. Figure 4 shows that the temperatures were below the period average until about 1985 (most significantly below for the first 6 years) and then above the average since then (melt season temperatures were much above the average in the late 1980's). One caution is that the upper zone MAT values are based on lapse rates that were determined using data for the later years after Snotel temperature measurements were available. Lapse rates could have been different in the early years, but there is no data to determine if this was the case. Cooler temperatures in the early years would cause the snow to melt later than normal.

Generally when the snow melts later there is a decrease in the volume of snowmelt runoff due to the evaporation rates being greater when the melt occurs. This is opposite to what would be needed to explain the greater runoff efficiency in the early years; however, due to the lower evaporation rates in the early years it is not clear if the cooler than average temperatures would have had much effect on runoff volume.

Figure 3. Variation in May-September pan evaporation for Moscow, Idaho.

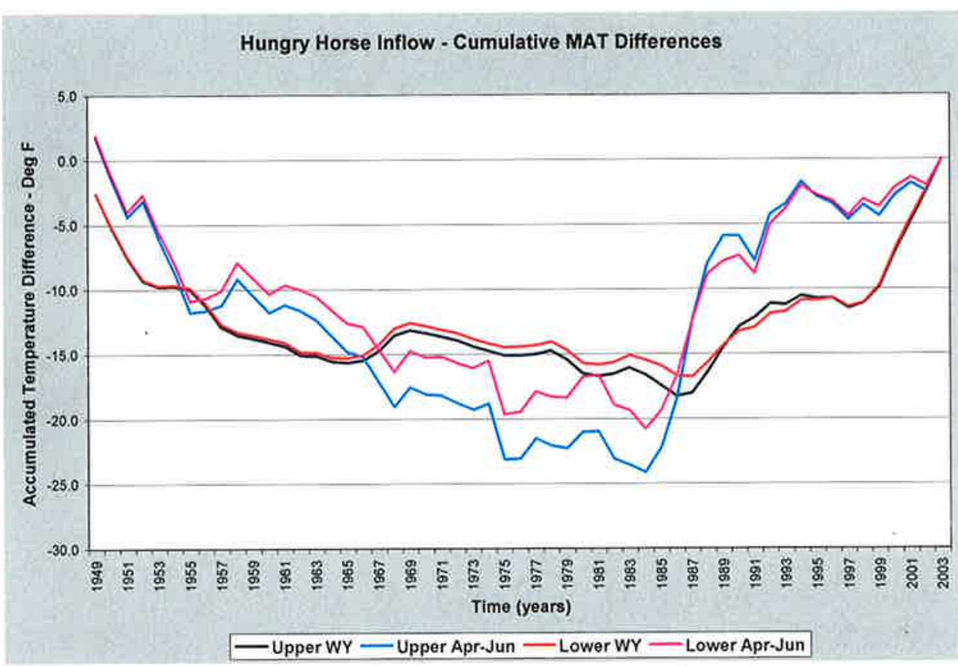

Figure 4. Cumulative variation in MAT values from the average.

Based on all this information it is likely that the change in runoff that occurred in the mid 1970's is real, lower evaporation rates in the early years could have accounted for some of the increased runoff during the period prior to WY 1979 (possibly about 25% of the increase), and there was more precipitation over the region than indicated by the precipitation gages available in the early years. If all the increase in runoff was due to greater precipitation than indicated by the MAP time series it would require that the MAP values for the WY 1949-1978 period be about 8% greater than those used for the initial recalibration. Even taking lower evaporation rates in the early years into account would require that the MAP values would need to be in the order of 5-6% greater than originally estimated prior to WY 1979. The only way to generate greater MAP values in the early years would be if the ratio of high elevation to low elevation precipitation was significantly greater than what it was in the later years. This would infer that the orographic effects in the typical storms in the early years were greater than those in later years due to a shift in the prevailing storm characteristics. In the MAP computations all the high elevation Snotel sites are estimated from low elevation stations in the early years based on the ratio of Snotel gage catch to a low elevation base station during the later years when Snotel data were available (Hungry Horse Dam was used as the base station in PXPP – West Glacier was also used without any significant change in results). Since there were no high elevation precipitation data prior to WY 1979 available anywhere in this region, it is impossible to verify this conclusion using precipitation measurements. Possibly someone with a climatological/meteorological background and the necessary meteorological data could determine if there was a shift in the prevailing storm characteristics in this region in the mid 1970's. From the limited range of elevations of the stations available prior to WY 1979 there is some indication that this may be the case, but without higher elevation data it is impossible to say definitely. Figure 5 shows the ratio of annual precipitation amounts for WY 1949-1978 compared to WY 1979-2003 for stations in the vicinity of Hungry Horse Dam with data that spans both periods. This figure shows that the trend is for the ratio to increase up to the elevation of the highest gage that existed for the entire period of record. The mean elevation for the HHWM8 drainage is about 5800 feet.

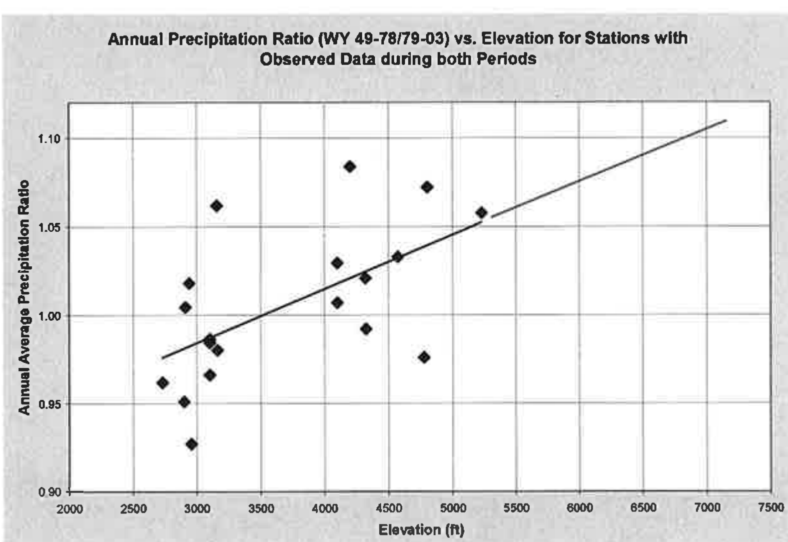

Figure 5. WY 49-78/79-03 precipitation ratio versus elevation.

Based on all the information that was available for this project, the conclusion is that the orographic component of the typical storm in this region prior to WY 1979 was greater than after that date. Thus using the relationships between the high elevation Snotel stations and the lower elevation climatic stations determined using data after WY 1978 would underestimate the MAP values for both elevation zones, especially for the upper zone, prior to that date. This underestimation of the higher elevation precipitation along with lower evaporation rates in the early years is the reason that the model parameters determined based on the WY 1979-2003 period were not able to simulate the proper amount of runoff for the WY 1949-1978 period.

Recommendations

Based on this analysis of why more runoff was generated prior to WY 1979 than during the later years and the conclusion that this was primarily the result of a greater orographic effect during the typical storms prior to WY 1979, along with lower evaporation rates in the early years, the following recommendations are offered.

Period to Use for Model Calibration – The calibration should be based on the later years after the Snotel data are available. During that period the station network best represents the precipitation and temperatures that have occurred over the full elevation range of western mountain watersheds. Thus the time series produced from the historical data analysis should be the best that can be generated and have the least amount of bias and noise therefore allowing for the best chance of determining model parameter values that can be used to forecast the future.

In general one wants to calibrate hydrologic models on a period that has similar conditions to those that currently exist and are expected to exist in the near future. For all watersheds, including those in non-mountainous regions, changes in land use (e.g. rural to suburban), changes in vegetation (e.g. forest to open or changes in type of vegetation), and changes in agricultural practices (e.g. change to amount of irrigation, change in crops, addition of farm ponds) will affect the amount and timing of runoff and affect the period to use for calibration. Climatic changes can also affect the period used for calibration in all watersheds if they aren't reflected in the input data (e.g. if evaporation rates increase over time and mean values are used by the models, then only the more recent years should be used for calibration). This analysis shows that in mountainous areas it appears that the amount of orographic precipitation can vary over time. If the network consists of only low elevation stations, this variation can't be detected resulting in a possible bias and certainly more noise in the model input. It is also possible that temperature lapse rates could change over time. Therefore if at all possible the models should be calibrated using a period when data are available from the fullest possible range of elevations.

For Hungry Horse and Libby reservoirs a reasonable calibration period seems to be WY 1979-2003. Sufficient Snotel precipitation data are available for this entire period. Even though adequate high elevation temperature data weren't available until the mid 1980's, lapse rates were probably stable enough that the calibration can begin as soon as the high elevation precipitation data are available.

<u>Period to Use for Historical Data Analysis</u> – While time series can be generated for the entire period of record, it seems like the computation of station mean monthly values of precipitation and max/min temperature should be based on the more recent period. As seen it appears that the orographic component of the precipitation field can vary over time and it is also possible for temperature lapse rates to vary from one portion of the period of record to another, thus it is more likely that the more recent period reflects the current and near future meteorological conditions.

When doing a precipitation analysis in the western mountains, the PRISM estimates of precipitation are helpful in coming up with realistic areal mean values. The PRISM estimates are based on the 30 year period used to compute station normals. Currently this is the WY 1971-2000 period. Unless there is some overriding reason, this is a reasonable period to use for computing monthly means as it simplifies comparisons between PXPP precipitation estimates and those available from PRISM.

It should be noted that the period used to compute the monthly means may not have much affect on the resulting time series even though one period has more precipitation or warmer temperatures than another. This is because the MAP program uses ratios between stations and the MAT program uses differences to estimate missing values. Thus as long as the basic relationship between stations remain about the same, the resulting time series will be essentially the same even though the means are greater or smaller in one period than another. Also even if the relationship between stations differ, as is likely with precipitation in this case, the time series will be essentially the same no matter which period is used to compute the monthly means when the data used to define the relationship is only available for a portion of the period of record. In this case the ratio of monthly mean precipitation and the differences between temperature stations would be basically the same if WY 1979-2003 or WY 1949-2003 were used to compute the means because data are only available in the later years to define the relationships. Thus the resulting time series should be essentially the same.

My recommendation would be to use the period that PRISM estimates are available to determine the mean monthly precipitation and temperature values for use in computing the MAP and MAT time series. This simplifies the comparison between means computed from the station data and the PRISM estimates. The NWRFC decided to use the WY 1971-2003 period.

<u>Time Series to Use for ESP Analyses</u> – For use when making probabilistic extended predictions the goal is to use time series that are essentially equally likely to occur in the near future and model parameters that reflect current

conditions. If the model is calibrated on more recent data, the model parameters should reflect the current state of the basin and if mean monthly evaporation estimates are used, those values should reasonably reflect the average evaporation rates that should occur in the near future. Whether the MAP and MAT time series generated for the entire period of record can be used directly for ESP runs requires more thought and analysis.

In the case of Hungry Horse and Libby the question becomes should the time series generated using monthly means that define the relationships between stations based on data in the recent years when high elevation values were available be used directly or should they be adjusted in some fashion. In the case of MAP values it has been shown that an adjustment of somewhere in the range of 1.05-1.08 is needed in order to simulate the correct volume prior to WY 1979. Thus should the MAP time series be adjusted prior to use for ESP? My argument is that they should not be adjusted. It seems like for the past 25 years or so the relationship between high and low elevation stations has been fairly stable and different than what it likely was prior to that time. The MAP values generated using station means computed from recent data reflect this high/low relationship even though they under simulate runoff volume prior to WY 1979. If the earlier MAP time series values are adjusted, they would no longer reflect the current high/low relationship, but instead would reflect the increased orographic effects that apparently existed in the typical storm prior to the late 1970's.

As far as MAT time series the issue is different. While there isn't data available to determine whether the lapse rates prior to when Snotel data were available differ from those since that time, it is clear that at least for lower elevation stations the temperatures were typically cooler in the past than in recent years. Assuming that the average lapse rates haven't changed significantly, it probably can't be said that the MAT time series from the early years are equally likely to occur in the near future as those from the later years. Thus, it would probably be best to adjust the MAT time series for the early years prior to using them for ESP. This could be done by increasing the values for the early years by a constant amount or even better by rerunning MAT for the early years using synthetic station means based on the recent period and station means computed based on the early years (the difference between high and low elevation stations would still have to be based on recent years when data were available for both).

Thus, my recommendation regarding ESP analyses would be to base the calibration on the most recent years, use the MAP time series computed based on station relationships in the later years (i.e. don't apply any adjustments), and adjust the MAT time series upward for the early years to reflect the warmer temperatures that have prevailed in recent years.

Historical Data Analysis for Hungry Horse and Libby Reservoir Inflows

Introduction

The area above Hungry Horse dam was divided into 2 elevation zones with a dividing elevation of 6500 feet. The area above Libby dam was divided into 3 elevation zones with dividing elevations of 5000 and 8000 feet. The dividing elevations had been previously selected by the NWRFC. In the final calibration the area above Hungry Horse dam was treated as a headwater. Initially it was separated into 2 areas; a headwater above the Twin Creek gage and a local below that location. Based on the results from the initial recalibration and the needs of the NWRFC, the final calibration treated the entire drainage as a headwater. The area above Libby dam was broken down into 2 drainages due to the size of the area and the significant distance from north to south. A headwater consisting of the combined drainages of the 3 Canadian streamgages (Kooteney at Fort Steele, Elk at Fernie, and Bull River near Wardner) was created. MAP and MAT time series were generated for that headwater and also for the local area below those gages and Libby dam.

Available Data

As mentioned previously the NWRFC provided most of the data used for this project. The period of record provided was WY 1949-2003. The data used were as follows:

> Precipitation – Data were provided for the entire Flathead/Clark Fork basin of which the Hungry Horse drainage is a part and the Kootenai basin including the portion downstream from Libby reservoir. For the U.S., hourly and daily data from NCDC and daily values from the NRCS Snotel network were included. For Canada, daily data were provided for a number of climatic stations and high elevation daily values for a few Snotel like sites in the later years. Only very limited hourly data were available for 4 stations for some recent years. Figure 6 shows the precipitation station network in the vicinity of the Hungry Horse drainage and Figure 7 shows the network above Libby reservoir. It can be seen that for Hungry Horse there are no stations within the boundaries of the watershed except for 3 stations immediately adjacent to the divide near the dam. This is because of the remote nature of the watershed and the fact that much of the drainage is within Wilderness Areas. For Libby the station network is quite sparse especially for much of the northern basin (i.e. the area above the 3 Canadian streamgages).
>
> The NWRFC provided the observation times (including changes over time) for all stations. The RFC also performed the consistency analysis of the data using the PXPP program and generated the mean monthly station values. Originally the station averages for the Flathead/Clark Fork were for the WY 1949-2003 period. After dealing with the issue of increased runoff in the early years, the decision was made to base the monthly averages on the WY 1971-2003 period.

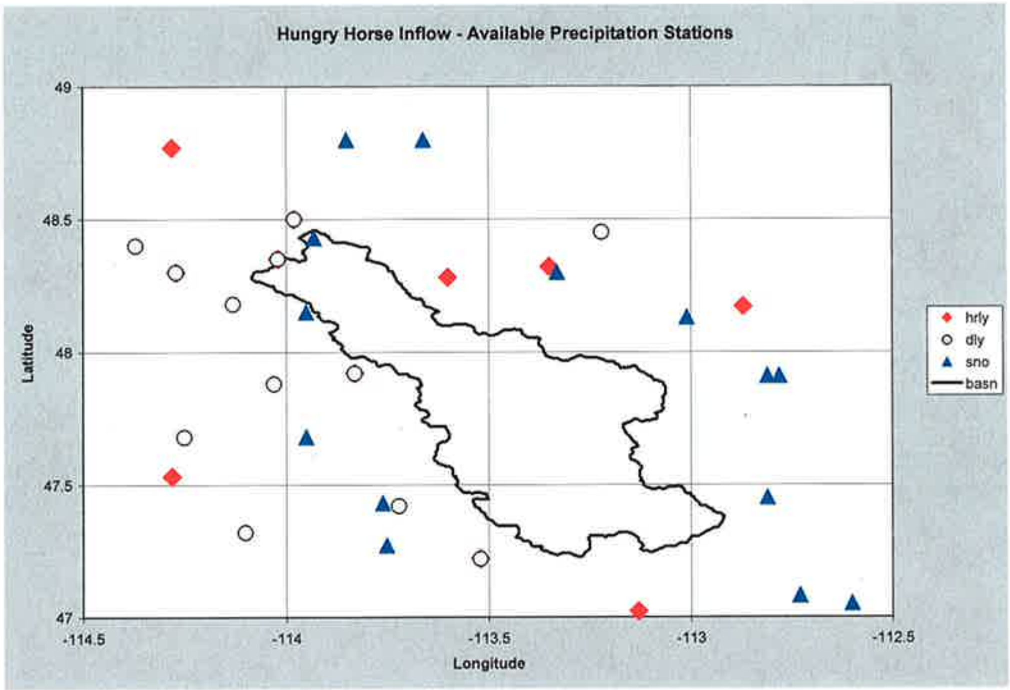

Figure 6. Hungry Horse precipitation stations.

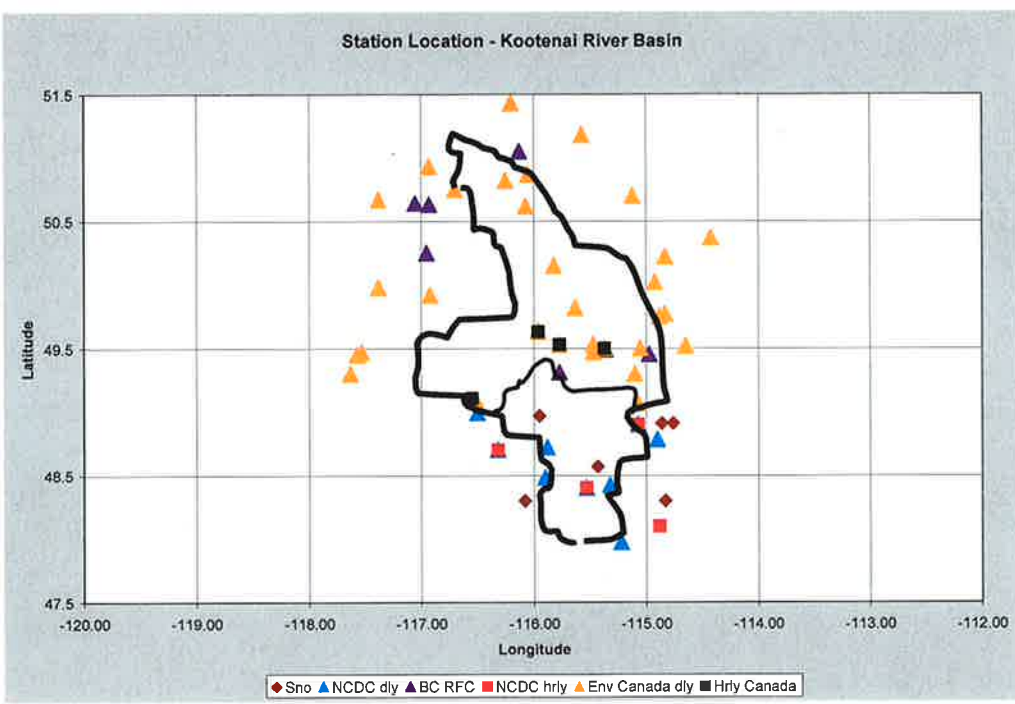

Figure 7. Libby reservoir precipitation stations.

<u>Temperature</u> – Again data were provided for the entire Flathead/Clark Fork and Kootenai basins. Max and min daily temperatures were available for most of the daily stations shown in Figs 6 and 7. The NWRFC again provided the observation time meta data and performed the consistency analysis. Station

means were computed by the RFC based on data for the WY 1971-2003 period. For stations with significant missing data for a portion of that period, the procedure outlined in Section 6.4 of the Calibration Manual was used. That procedure involves computing the monthly max and min temperature difference between the stations with missing data and a base station with nearly complete data for the time when both stations have valid data. These differences are then applied to the base station means to estimate the means for the stations with partial data for the period being analyzed.

Streamflow – Mean daily inflow values were provided for both reservoirs. Once the reservoirs were in operation, the values were computed based on outflow and change in pool elevation. This results in quite a bit of noise in the data at low flows. In order avoid problems with computations by the STAT-QME and WATERBAL operations, negative flows were removed from the record. This was done by changing the negative values to a value similar to the average of surrounding positive values. Also for Hungry Horse a few of the extreme fluctuations in the record were smoothed out, but this effort took too much time and was abandoned. The datacard file for the reservoir inflow time series retains the original values in addition to the edited changes.

Daily data for other streamgages in the region were available via the NOAA Hydrologic Data System (NHDS) web site for the USGS stations and from the NWRFC for the Canadian stations. Peak flow data were also used for the TNCM8 station upstream of Hungry Horse reservoir.

Evaporation - Monthly summaries of pan evaporation from class A pan stations in the region and values computed from meteorological variables were used to estimate PE. The summaries for stations with evaporation pans were obtained using the Dlytran program via the NHDS web site and the meteorological estimates were obtained from NOAA Technical Report NWS 34 (*Dept. of Commerce, 1982*).

Snow Water Equivalent - Daily snow water equivalent values for Snotel stations were obtained by downloading water year summaries from the NRCS web site and converting these to datacard format using a FORTRAN program. Snow water equivalent data could only be obtained for three stations via the NHDS web site without problems, thus the alternative route was used for most of the snow data (correspondence indicates that this problem has been since corrected). A FORTRAN program was also written to convert snow pillow data obtained via the British Columbia (BC) RFC web site to datacard format.

Areal Extent of Snow Cover - Seann Reed of OHD added the capability to the Calibration Assistance Program (CAP) to generate areal extent of snow cover values derived from NOHRSC satellite analyses as part of the DMIP2 project. Values of cloud cover and the areal snow cover over the cloud free area are computed for a given drainage area for days when the NOHRSC did a snow cover analysis. Values can be obtained for individual elevation zones. The NWRFC used CAP to produce values for the total Hungry Horse inflow drainage area, the area above the Twin Creek USGS gage, and the total Libby basin. NOHRSC area cover data are available beginning with water year 1990. Besides the cloud cover and areal snow cover values, images were also supplied (the .gif images are not included on the CD). CAP included entries for windows that didn't completely cover the area being analyzed. These were removed.

A program was written (copy on the CD) as part of the DMIP2 project to convert the areal snow and cloud cover to a daily time series of areal extent of snow cover in datacard format (data type AESC). The program only produces areal extent values on days when the cloud cover is less than a specified amount. For Hungry Horse and Libby time series values were only generated when the cloud cover is less than or equal to 10%. Since there is significant cloud cover in this region during much of the winter and spring, most days when NOHRSC did a snow cover analysis didn't result in a time series value. On days with some clouds, but less than 10%, the assumption was made that the fraction of areal snow cover under the clouds is the same as for the cloud free portion of an elevation zone.

GIS Information - The NWRFC used CAP to generate mean monthly, seasonal, and annual precipitation estimates based on PRISM, mean PE based on the NOAA Technical Report NWS 33 (*Dept. of Commerce, 1982*) analysis, mean PE adjustments derived from greenness fraction, mean elevation and forest cover, and a forest type breakdown for each elevation zone for the area above the TNCM8 gage and the local area between that gage and the Hungry Horse dam. Area-elevation and mean annual precipitation-elevation relationships were also supplied for both areas. For the Canadian portion of the Libby drainage forest cover and PE values weren't available. Basic information for the basins are contained in the Excel spreadsheets 'HHWM8 basic info.xls', 'TNCM8 basic info.xls', and 'CAP Info Libby.xls'.

After the original recalibration for Hungry Horse new PRISM estimates became available. The new estimates were provided at a finer grid scale than the original values and included the Canadian portion of the Libby drainage. The new PRISM estimates were used in the final recalibrations for both Hungry Horse and Libby.

Precipitation Analysis

The precipitation analysis consists of 2 main parts. The first is to determine the appropriate average areal precipitation for each watershed and second to determine the station weights to be used to generate the desired areal values. All of the data and figures used for the precipitation analyses are contained in the Excel spreadsheets labeled 'Pcpn_ET_analysis_flatclark.71-03.xls' and 'Pcpn_ET_analysis_libby.xls'.

Estimating Average Areal Precipitation – The 2 primary sources of information for estimating the average areal precipitation are PRISM and water balance computations. The PRISM data consists of gridded estimates of precipitation on a monthly basis for the period WY 1971-2000. These data can be used to compute annual and seasonal estimates of average precipitation for each elevation zone. Before using the PRISM data it is a good idea to verify the values against station data and water balance computations.

The PXPP program generates consistent estimates of monthly average precipitation for each station being used. Station estimates from PXPP can be compared to the PRISM values for the grid square that includes each station. In steep terrain the elevation of a station may not be close to the mean elevation of the grid, thus causing some scatter. This is less of a problem with the new PRISM analysis which uses a finer grid. Figures 8-11 show comparisons of PXPP and PRISM estimates for each station for the winter and summer seasons for the Flathead/Clark Fork and Kootenai basins. October to April is used as the winter season and May to September for summer. In these figures the PXPP values are for the WY 1971-2000 period (i.e. same as for PRISM). The average ratios for the Flathead/Clark Fork basin for the winter and summer, respectively are 1.02 and 1.01. The average ratios for the Kootenai are also 1.02 and 1.01. These figures indicate that, at least over a large region such as these river basins, PRISM provides a reasonable estimate of the average amount of precipitation on a seasonal basis.

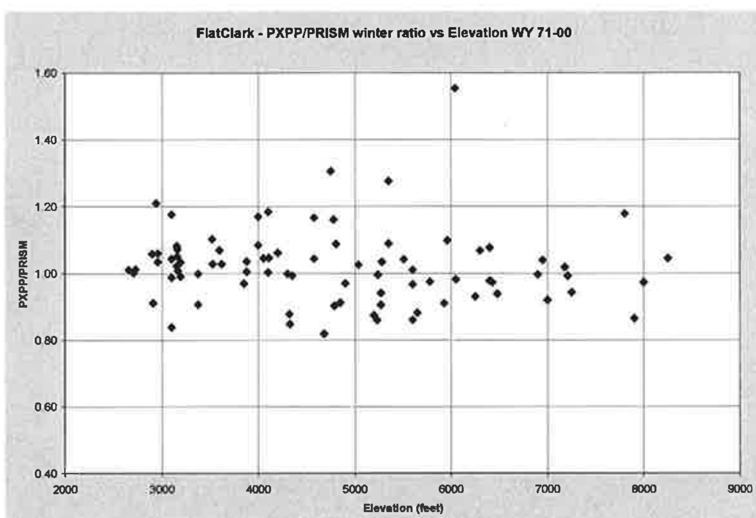

Figure 8. Winter PXPP/PRISM ratio for Flathead/Clark Fork stations.

Another way to verify the PRISM estimates is to plot the PXPP/PRISM seasonal ratio for each station on map to see if there is a pattern. A pattern indicates that the PRISM areal averages for certain watersheds may need to be adjusted. This was done for both basins. For the Flathead/Clark Fork and the Kootenai basins there is no real pattern to the ratios. This suggests that the PRISM values could be used directly to estimate the average seasonal precipitation for the WY 1971-2000 period at least for larger watersheds comparable in size to the area covered by multiple precipitation stations.

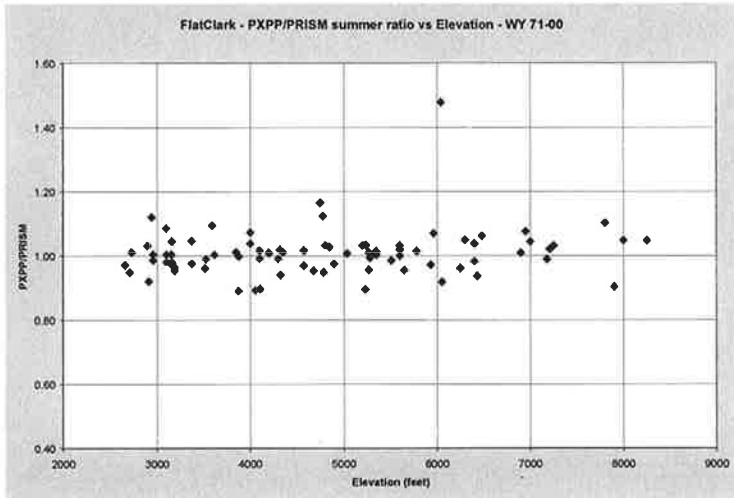

Figure 9. Summer PXPP/PRISM ratio for Flathead/Clark Fork stations.

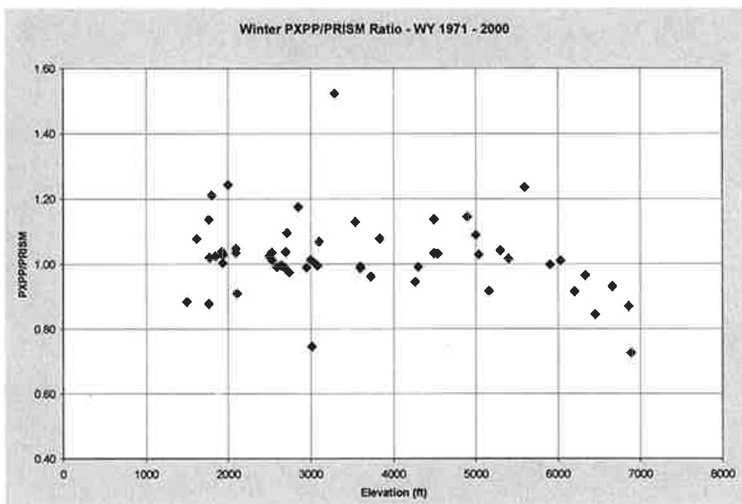

Figure 10. Winter PXPP/PRISM ratio for Kootenai stations.

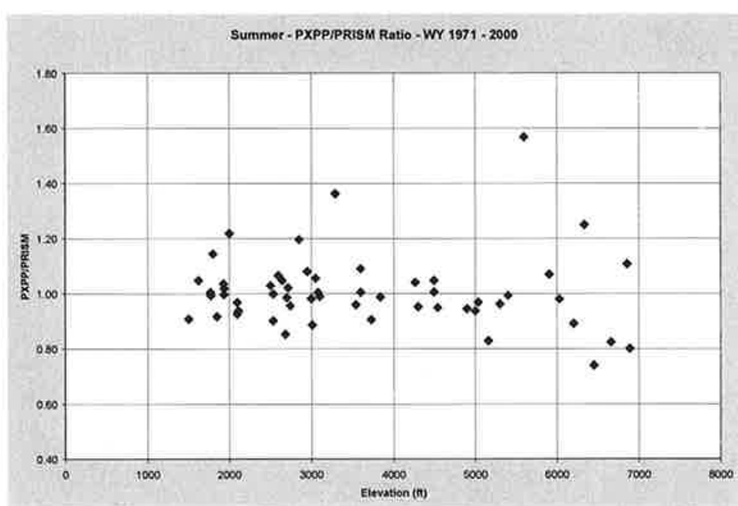

Figure 11. Summer PXPP/PRISM ratio for Kootenai stations.

A water balance analysis can show at a smaller scale whether adjustments need to be applied to the PRISM areal annual averages and also can be used to determine the magnitude of the adjustment. Water balance computations were done for a number of watersheds within the Flathead/Clark Fork and Kootenai basins. These are shown in Table 3. The actual observed runoff for WY 1971-2000 is subtracted from the PRISM estimate of average annual precipitation. A few streamgage sites didn't have complete data for the entire WY 1971-2000 period. In those cases the average runoff was computed using the ratio of runoff between the site and a nearby location for the period when data were available times the 30 year average for the nearby station. The computed actual ET, determined by subtracting runoff from precipitation, should be fairly similar over the region though decrease somewhat with elevation. Figure 12 shows a plot of actual ET versus elevation for the watersheds in Table 3. In Fig. 12 the watersheds in and near the Kootenai basin are separated from those in the Flathead/Clark Fork basin.

Watershed	NWS id	Mean Elev (ft)	PRISM annual (in)	PRISM source	Runoff annual (in)	Actual ET (in)	Pcpn Adj (in)	Adj Pcpn (in)	Adj Act ET (in)
Hungry Horse Dam	HHWM8	5818	49.11	new	29.51	19.6	-1	48.11	18.60
SF Flathead - Twin Ck	TNCM8	6139	48.98	old	25.70	23.28	-4	44.98	19.28
Hungry Horse Local	HHWM8L	5086	49.42	old & new	38.46	10.96	6.2	55.62	17.16
NF Flathead Columbia F	FCFM8	5009	43.43	new	26.16	17.27	2	45.43	19.27
MF Flathead W. Glacier	WGCM8	5363	49.68	new	33.78	15.9	2	51.68	17.90
Swan R Bigfork	SWRM8	5037	44.43	old	24.06	20.37	0	44.43	20.37
Bigfoot R Bonner	BONM8	5409	29.09	old	9.25	19.84	0	29.09	19.84
Rock Ck Clinton	RCCM8	6429	26.26	old	8.44	17.82	0	26.26	17.82
Stillwater R Whitefish	STWM8	4496	26.75	old	8.1	18.65	0	26.75	18.65
Fisher R Libby	FISM8	4121	27.76	old	8	19.76	0	27.76	19.76
Yaak R Troy	TRYM8	4619	37.44	new	15.21	22.23	-2	35.44	20.23
Libby Dam	LYDM8	5401	35.58	new	17.08	18.5	0.025	35.61	18.53
Libby Local	LYDM8L	4392	31.54	new	11.12	20.42	0	31.54	20.42
Kootenay Ft Steele	FSTQ2	5783	37.46	new	19.06	18.4	-1	36.46	17.40
Bull R Wardner	BULQ2	5909	39.38	new	26.22	13.16	5.5	44.88	18.66
Elk R Fernie, BC	ERFQ2	6142	36.21	new	19.25	16.96	1	37.21	17.96

Table 3. Water balance for the Flathead/Clark Fork and Kootenai basins.

In a few cases the computed actual ET using PRISM data appeared to deviate more than expected from the average relationship. In these cases an adjustment was applied to the PRISM precipitation estimate. The water balance computations indicate that in general the PRISM values are a reasonable estimate of the average annual precipitation for this region though some adjustments need to be made for some smaller drainage areas. The annual average actual ET in this region varies from just over 20 inches at around 4000 feet to around 17-18 inches at 7000 feet.

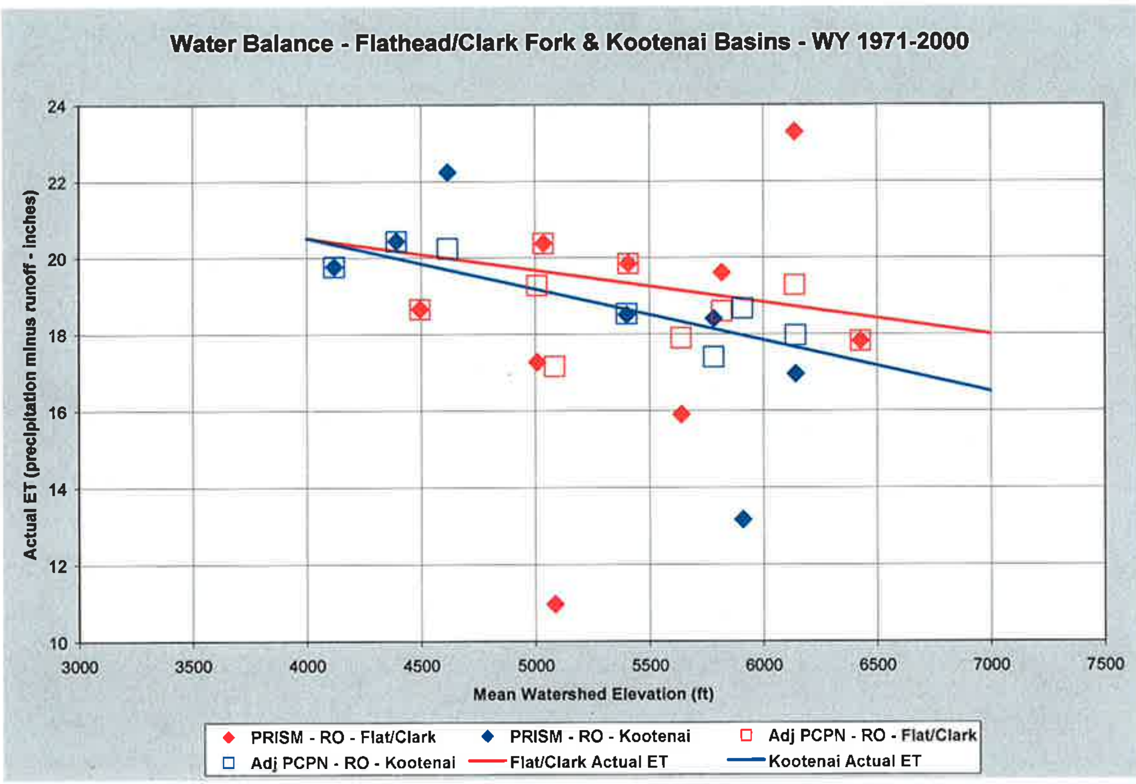

Figure 12. Actual ET computed from water balance computations.

Based on the water balance computations the adjusted annual average precipitation for the entire area above Hungry Horse dam is very close to the PRISM estimate even though it appears that the PRISM value is too high for the area above Twin Creek and too low for the local. The same is true for the area above Libby dam. While adjustments were needed for the area above the Canadian gages, the net effect is that the water balance estimate for the combined area above these 3 gages is essentially the same as the PRISM estimate. No adjustment was needed for the Libby local. Since the RFC selected WY 1971-2003 as the period for computing monthly mean values, the adjusted areal annual estimates from the water balance computations were modified based on the average ratio of station precipitation for WY 1971-2003 to that for WY 1971-2000. The ratios for the Flathead/Clark Fork are 0.99 for winter and 0.98 for summer. For the Kootenai the values also are 0.99 and 0.98.

The last step in estimating the average areal precipitation for MAP computations is to break the annual estimates for the entire drainage down into seasonal values for each elevation zone. Besides PRISM data, plots of seasonal average precipitation generated by PXPP versus elevation were also considered. Figures 13 and 14 show these precipitation versus elevation plots for the Flathead/Clark Fork and Kootenai basins. Based on the precipitation versus elevation plots, for Hungry Horse the winter precipitation was decreased by about 5% and the summer increased by 5% for both elevation zones over that indicated by the PRISM data. For Libby winter precipitation was increased by 7% and summer decreased by 6%. For winter, the 5000-8000 foot zone for the local area was decreased while all other zones were increased. For summer, more of the decrease was applied to the higher elevations with even an increase for the local area lower zone.

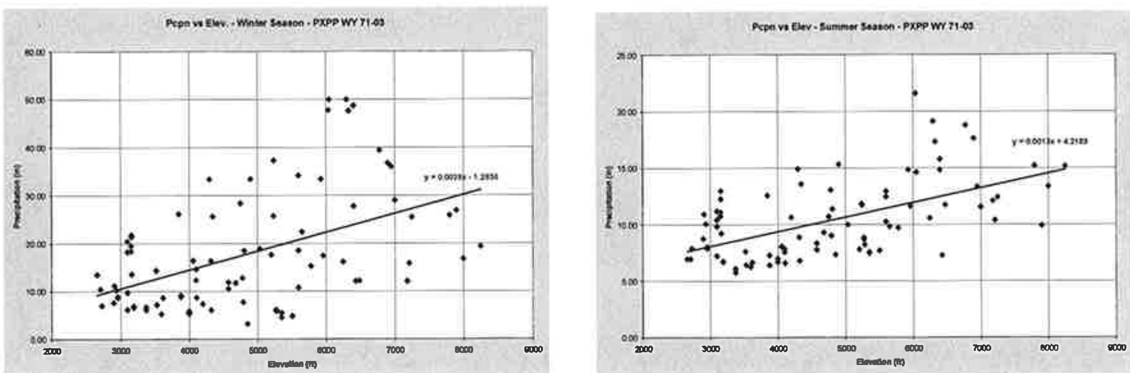

Figure 13. Precipitation versus elevation for winter and summer for the Flathead/ Clark Fork basin.

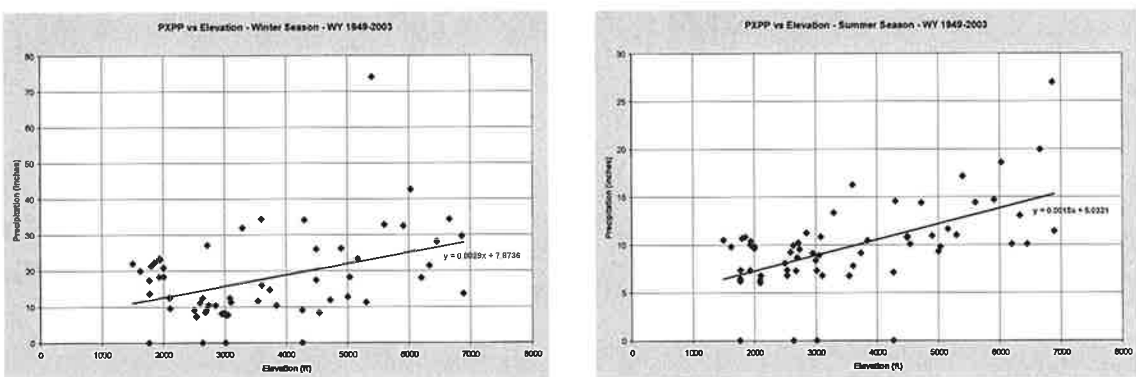

Figure 14. Precipitation versus elevation for winter and summer for the Kootenai basin.

Determination of Station Weights – The mountainous area procedure described in Section 6-3 of the Calibration Manual was used to determine the station weights to be used for generating the MAP time series for the elevation zones for each area. This procedure basically consists of assigning relative weights to the stations and then adjusting those relative weights such that the resulting time series contains the desired or 'target' amount of precipitation. The adjustment is the ratio of the target seasonal precipitation for the zone to the sum of the relative weights for each station times the average seasonal value for the station.

In this region most of the winter precipitation is in the form of snow. While it is well known that precipitation gages are generally deficient in snow catch, a water balance estimate ends up including this gage catch deficiency in the computed amount. If we use the water balance precipitation estimate as the target for MAP computations it infers that the SCF parameter (snow correction factor) in the SNOW-17 operation should be 1.0. It would also result in any rain occurring in the winter being treated just as snow even though the catch deficiency for rain is typically much less than for snow. This would tend to overestimate the amount of precipitation during winter rain events and underestimate the amount for snow events. In order to use the SCF parameter as intended, an assumed realistic SCF value was applied to the estimated winter precipitation for each zone to get a target value for MAP computations. An SCF of 1.1 was used for the lower elevation zones, 1.2 for the upper zones, and 1.15 for the middle zone for Libby.

When assigning relative weights one consideration is which stations are available operationally. A bias can be injected when different networks are used for calibration and operations unless one is very careful. Even if the recommendations are followed, different reporting characteristics between the climatological and real-time networks can result in a bias. The ideal situation is to use the exact same data for both calibration and operations though in many cases this is impossible due to significant differences in the networks.

The NWRFC indicated that all of the stations in the immediate vicinity of the Hungry Horse drainage were available operationally except for West Glacier, Kalispell Glacier AP, and Lindbergh Lake. Only one daily value is available for the Pike Creek Snotel site. For stations with both hourly and daily historical records, the operational observation comes from the hourly gage (Hungry Horse Dam, Seeley Lake RS, and Swan Lake). Thus, since almost all the stations that potentially could be assigned weight are available operationally, it was decided to only weight the stations that submit real time reports when computing the MAP time series. For Seeley Lake and Swan Lake the hourly gages were weighted since not only do they provide the operational report, but they had comparable or better historical records than the daily gage [hourly record longer for Swan Lake – period of record the same for Seeley Lake with the amount of missing data nearly the same (daily gage slightly more complete)]. For Hungry Horse Dam the daily gage was weighted for the historical analysis since it has a much longer period of record than the hourly gage. Thus, the operational MAP weights should be slightly different for the lower elevation zone that uses this station since the mean seasonal values for the hourly and daily gages are not exactly the same. The only stations assigned weight for the upper elevation zones for Hungry Horse are Snotel sites. The lower elevation zones use a combination of NCDC stations and lower elevation Snotel sites.

For Libby there is some uncertainty as to the real-time status of some of the gages, plus some of the key Canadian stations may not be available operationally. Thus for that reason and the sparsest of the network on the Canadian side of the boarder, the relative weights were assigned independent of whether the data would be available operationally. The use of all available precipitation data should reduce the amount of noise in the precipitation input and give a better chance of determining proper values for the model parameters. The station weights used operationally for Libby will need to be computed carefully so that there is not a bias between the calibration and operational MAP values. The relative weights and the resulting actual weights for both Hungry Horse and Libby can be found in Excel spreadsheets that contain the precipitation analysis. For Hungry Horse both the computed historical station weights using the Hungry Horse dam daily gage and operational weights using the Hungry Horse Dam hourly gage are included.

Temperature Analysis

The temperature analysis primarily consists of determining the average relationship between max and min temperature and elevation on a monthly basis. Once this is done synthetic stations are established at the mean elevation of each elevation zone and mean monthly max and min temperatures are assigned to the synthetic stations based on the temperature-elevation relationships. The synthetic stations are then given a weight of 1.0 and the MAT time series are generated. All of the data and figures used for the temperature analysis are contained in the Excel spreadsheets 'Temp_Elev_flatclark.xls' and 'Temp_Elev_Libby.xls'.

Temperature vs. Elevation for Hungry Horse – Mean max and min temperatures determined by the NWRFC were plotted against the elevation of the stations for each month. Initially the monthly means were for the WY 1949-2003 period. The final temperature-elevation relationships were based on the WY 1971-2003 period. All of the stations within the Flathead/Clark Fork basin were included on the plots, however, the stations in the immediate vicinity of the Hungry Horse drainage were uniquely identified from the others in the basin. The temperature-elevation relationships are based on the Hungry Horse stations only. Figure 15 shows the plot for May using WY 1971-2003 data.

The initial relationships were drawn manually. After doing this for all months, the lapse rates were computed and plotted to make sure that the seasonal variation in lapse rates made sense and avoided abrupt changes from month to month. Figure 16 shows the seasonal lapse rates for Hungry Horse for the WY 1971-2003 period. In some cases minor revisions were made to the temperature-elevation plots for some months.

Since temperature-elevation relationships had originally been generated for the WY 1949-2003 period a comparison was made between the mean monthly max and min temperatures computed for the mean elevation of each elevation zone

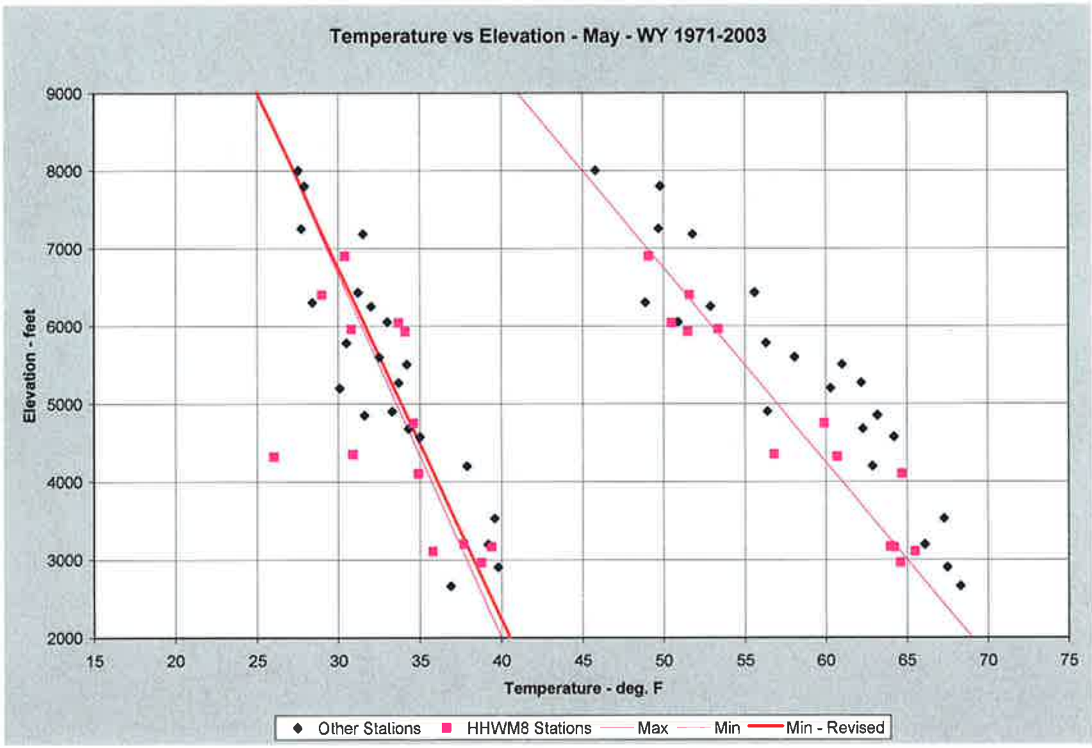

Figure 15. Temperature-elevation plot for May for Hungry Horse - WY 1971-2003 data.

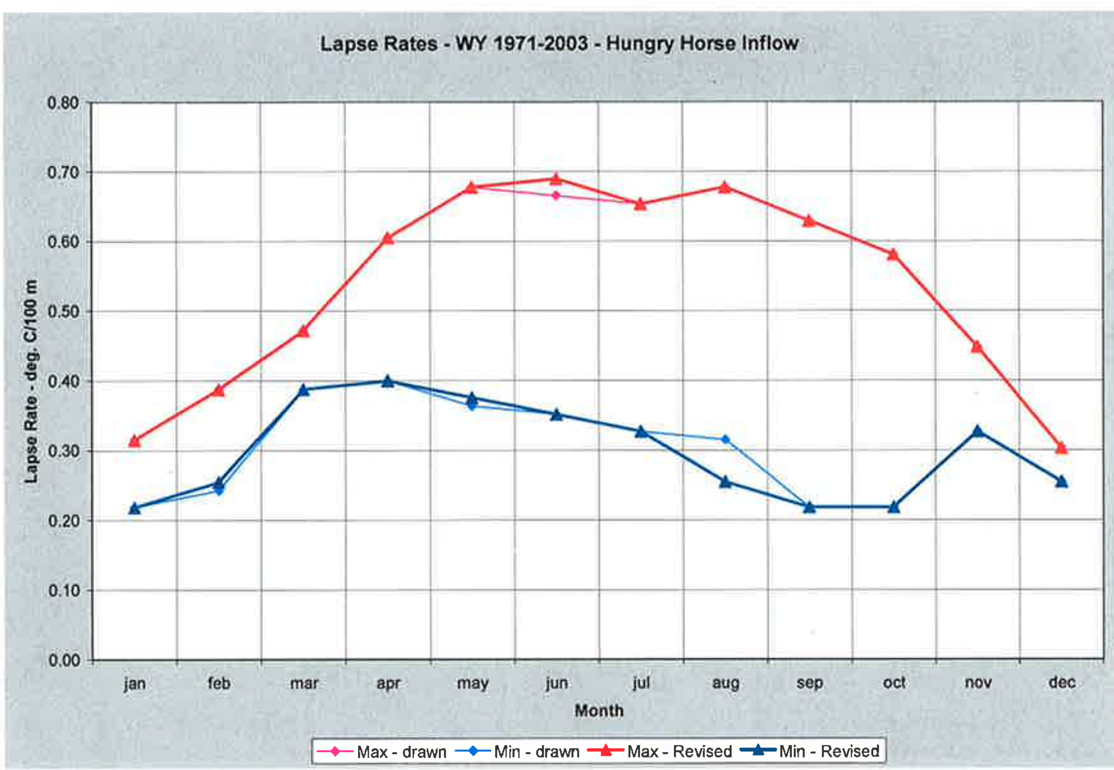

Figure 16. Seasonal variation in lapse rates for Hungry Horse – WY 1971-2003.

(upper zone mean is 7060 feet and the lower zone mean is 5292 feet) for each data period. The comparison of the relationships for these 2 periods helped verify the lapse rates. Normally such information wouldn't be available to use as part of a historical data analysis. Figure 17 shows the max temperature difference between WY 1971-2003 and WY 1949-2003 for the upper and lower elevation zones for Hungry Horse. Similar plots were generated for the stations that had complete data for the entire WY 1949-2003 period. The max temperature plot is shown in Figure 18. It was expected that the general shape of the seasonal variation in temperature differences should be similar for the elevation zones as for the stations. In order for this to be the case, some further revisions were made to the temperature-elevation relationships. Once the temperature-elevation relationships were finalized for each month, mean monthly max and min values were extracted at the mean elevation of each elevation zone and MAT time series were produced.

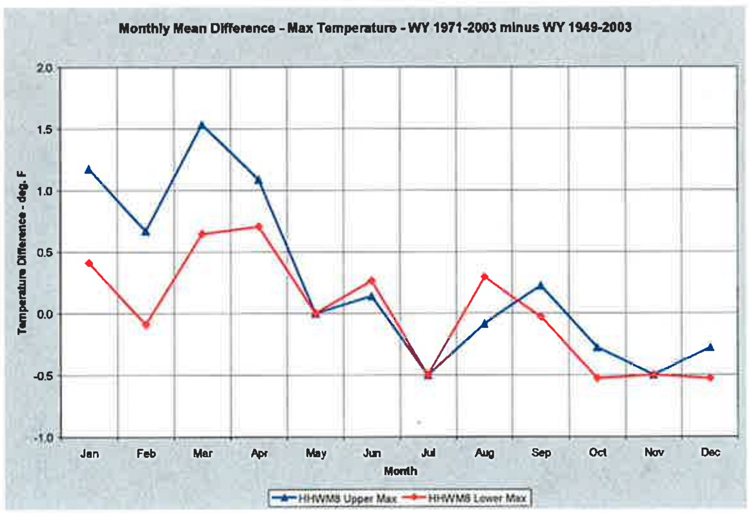

Figure 17. Seasonal difference in mean max temperature for each elevation zone from WY 1971-2003 to WY 1949-2003 for Hungry Horse.

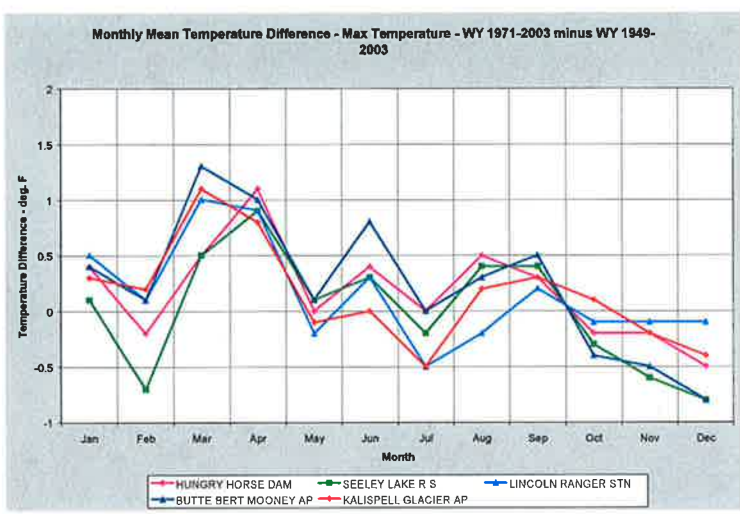

Figure 18. Seasonal difference in mean max temperature for selected stations from WY 1971-2003 to WY 1949-2003 in the Flathead/Clark Fork basin.

Temperature vs Elevation for Libby – The same steps were followed for Libby as for Hungry Horse. The only difference was that due to the large distance from the northern most part of the basin to the dam separate temperature-elevation relationships were determined for the northern basin (area above the 3 Canadian streamgages) and the local area between those gages and the dam. Stations in each portion of the basin were uniquely identified on the monthly plots. Figures 19 and 20 show the temperature-elevation relationship for February and May for Libby. In the winter months the temperatures in the south tended to be warmer than those in the north at all elevations. In the spring and summer it was mainly the lapse rates that appeared to vary with steeper max temperature lapse rates in the south and steeper min temperature lapse rates in the north. This resulted in warmer max temperatures and cooler min temperatures at higher elevations in the north as compared to the south during that time of the year.

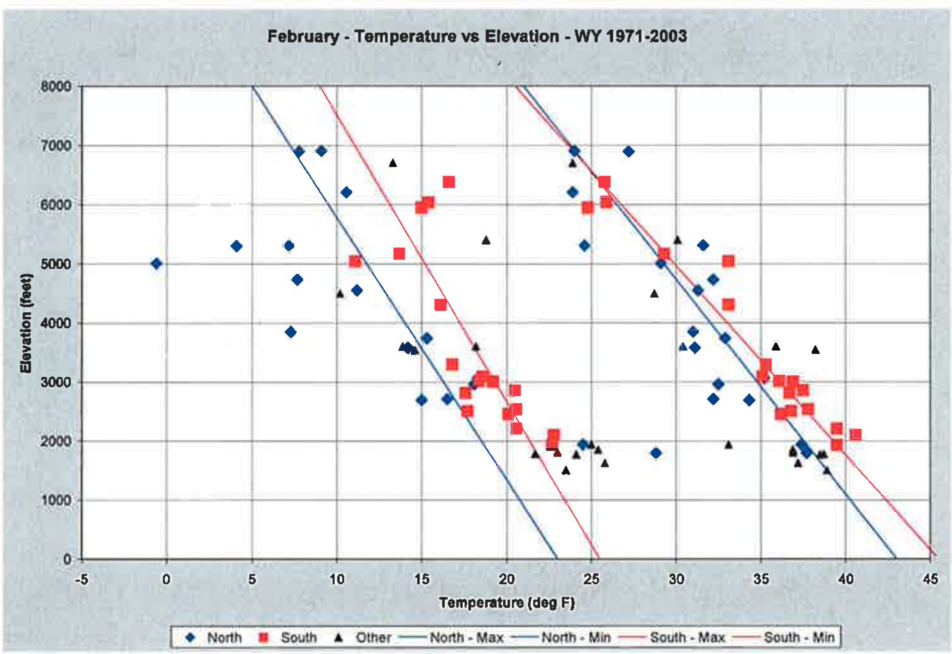

Figure 19. Temperature vs. elevation for February for Libby – WY 1971-2003.

Figure 20 shows the seasonal variation in lapse rates for Libby for the WY 1971-2003 period. It can be seen that the max temperature lapse rate is steeper in the south and the min temperature lapse rate is steeper in the north. Figure 21 shows the seasonal difference between the mean max temperature for each elevation zone from WY 1971-2003 to WY 1949-2003. Figure 22 shows the same thing for stations that had data for essentially the entire WY 1949-2003 period. As with Hungry Horse, the seasonal lapse rate and temperature difference plots were used to make revisions to the temperature-elevation relationships. Five MAT time series were generated for Libby; lower, middle, and upper elevation zones for the north and lower and middle zones for the south (the area above 8000 feet in the south is negligible).

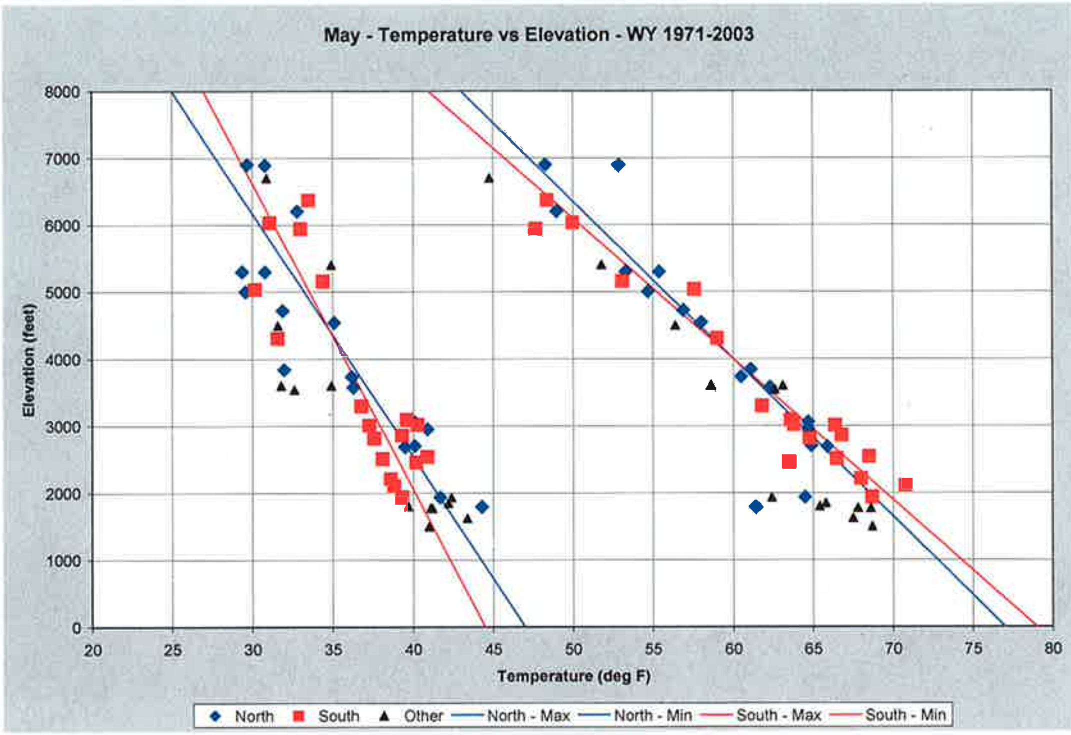

Figure 19. Temperature vs. elevation for May for Libby – WY 1971-2003.

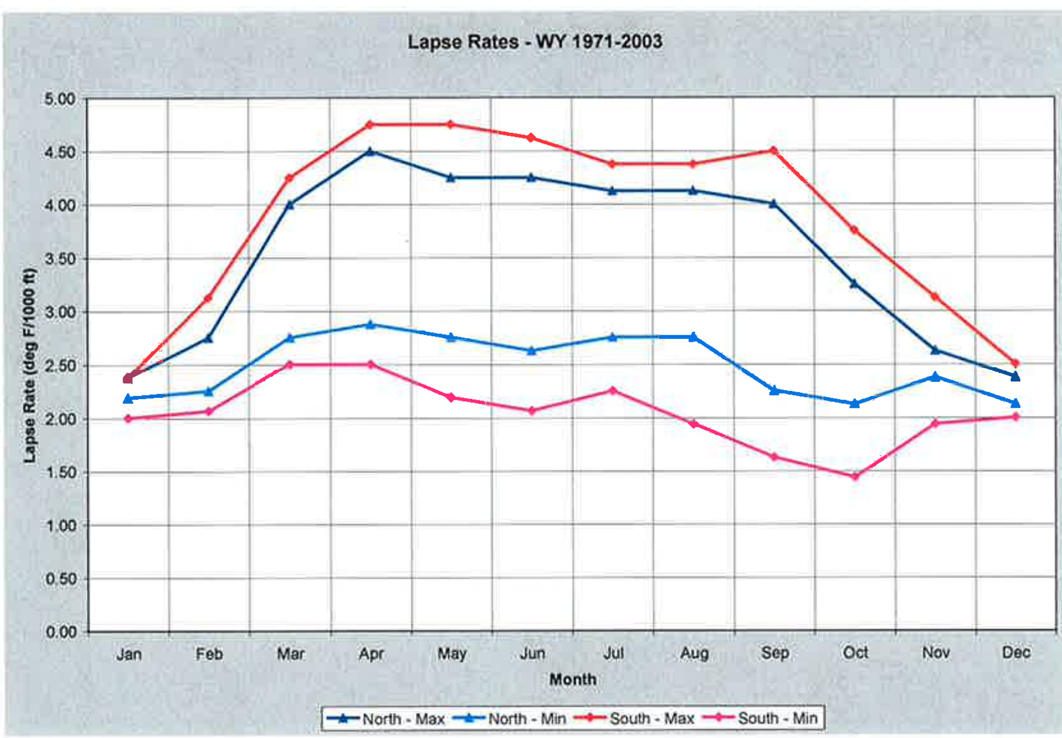

Figure 20. Seasonal variation in lapse rates for Libby for WY 1971-2003.

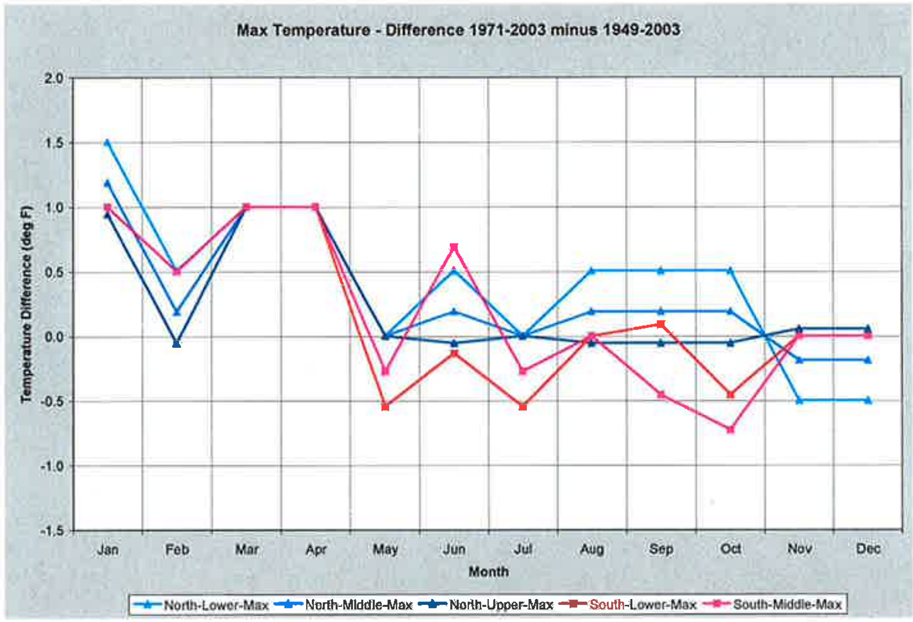

Figure 21. Seasonal difference in max temperatures for each elevation zone from WY 1971-2003 to WY 1949-2003 for Libby.

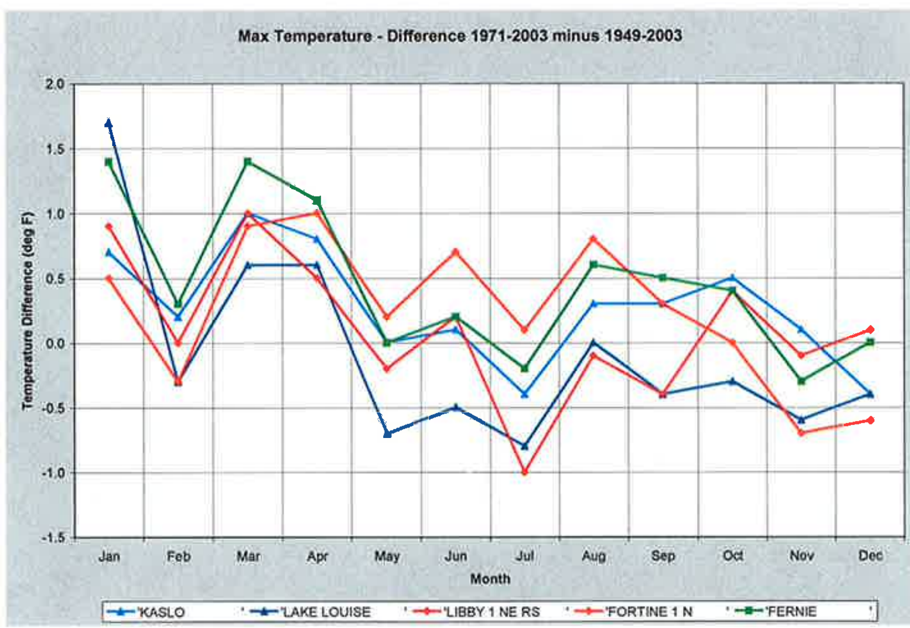

Figure 21. Seasonal difference in max temperatures for selected stations from WY 1971-2003 to WY 1949-2003 for the Kootenai basin.

Evaporation Analysis

For these basins mean monthly ET-demand values were to be used by the Sacramento model. ET-demand is defined as the maximum evaporation rate given the type and activity level of the vegetation in the area. ET-demand is computed by multiplying Potential Evaporation (PE – which is the evaporation rate from actively growing grass when the moisture supply is unlimited) by a seasonal PE adjustment factor which accounts for the type and activity level of the vegetation. To get realistic ET-demand values for Hungry Horse and Libby an annual PE versus elevation relationship was first derived. Then the annual PE was broken down into monthly values and finally a seasonal PE adjustment curve was established. The data and figures for the Evaporation analyses are in the Excel spreadsheets labeled 'Pcpn_ET_analysis_flatclark.71-03.xls' and 'Pcpn_ET_analysis_libby.xls'.

Annual PE versus Elevation – Though TR#33 shows how lake evaporation (essentially the same as PE) varies throughout the U.S., it doesn't contain enough precision to adequately define the variation of PE with elevation for a given region. Regional pan evaporation versus elevation relationships were derived to construct the TR#33 maps, but except for the 2 regions shown in the report these plots have been lost over the years. For the Flathead/Clark Fork basin data from 5 evaporation pan stations (Hungry Horse Dam, Moscow Idaho, Babb 6 NE Montana, Canyon Ferry Dam Montana, and Western Agriculture Research Station Montana) and values computed from meteorological data for Missoula WB Airport Montana (from TR#34) were used to construct an annual PE versus elevation relationship. Annual PE values for the pan stations were estimated using the pan coefficients from TR#33 and by determining from the TR#33 maps that roughly 83% of the annual evaporation occurs from May to October in this region. In addition to the pan estimates, a relationship derived in a similar manner from a previous calibration study for the Upper Missouri basin was used to help construct the annual PE versus elevation relationship for the Flathead/Clark Fork basin. These relationships are shown in Figure 22.

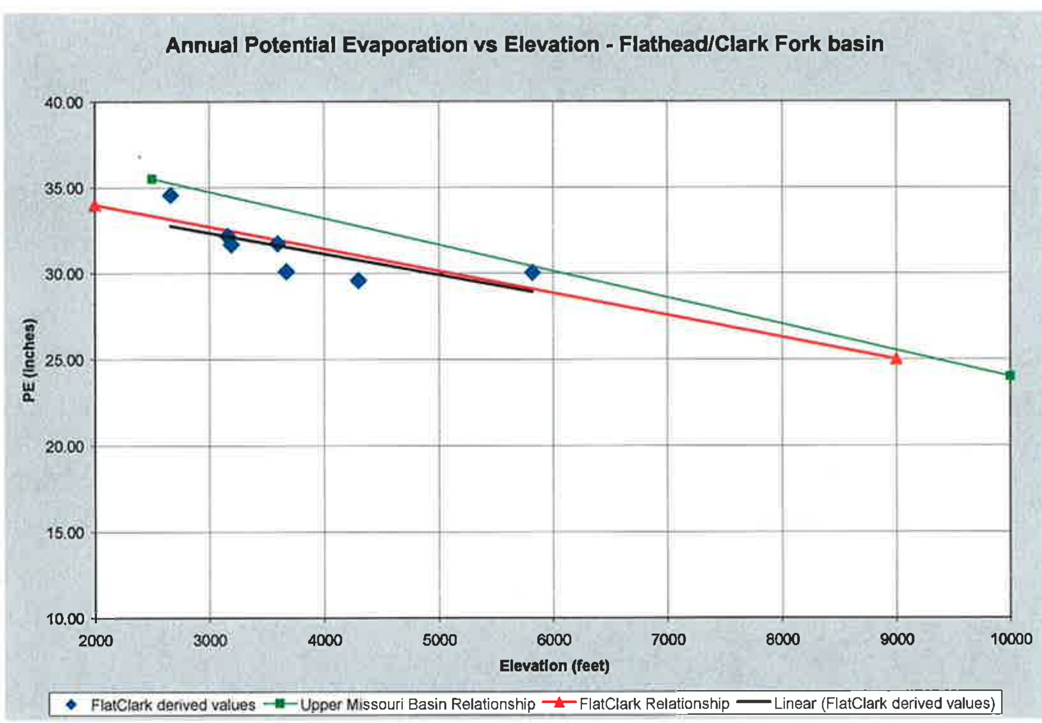

Figure 22. Annual PE versus elevation for the Flathead/Clark Fork basin.

For the Kootenai basin no pan evaporation or meteorological estimates could be found. The annual PE versus elevation relationship for the Kootenai was constructed by using the PE-elevation relationships for the Flathead and Upper Missouri basins and the actual ET versus elevation relationships derived from water balance computations (see Fig. 12) for the Flathead and Kootenai basins. This annual PE-elevation relationship is shown in Figure 23.

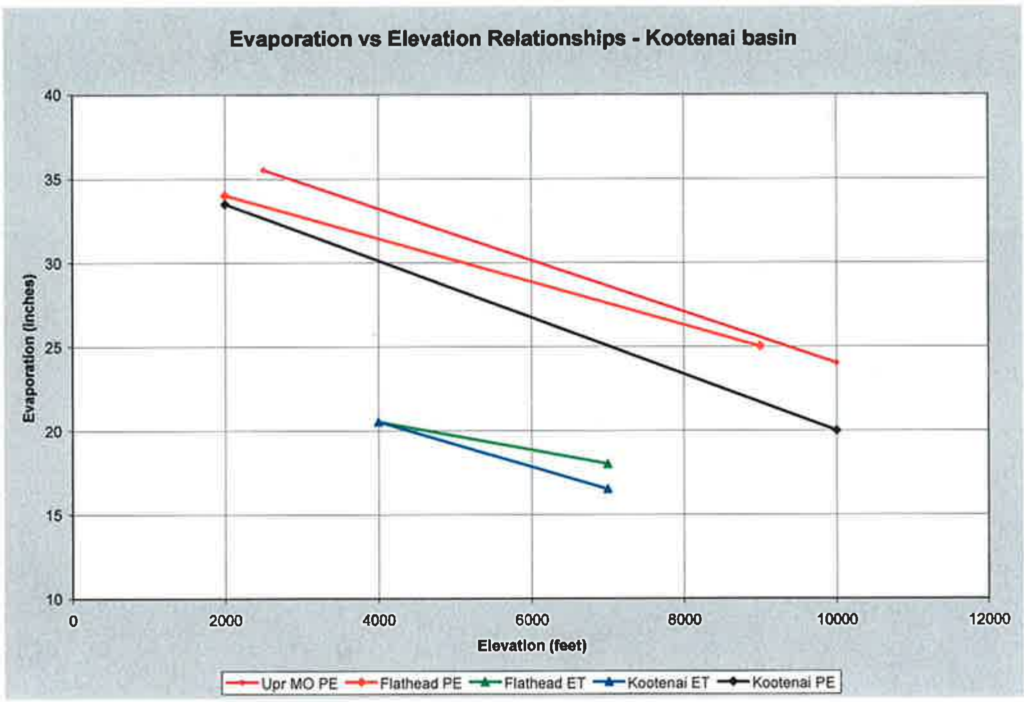

Figure 23. Annual PE versus elevation for the Kootenai basin.

<u>Elevation Zone Seasonal PE</u> – For each elevation zone the annual PE is determined from the annual PE versus elevation relationship for the basin using the mean elevation of the zone. For Hungry Horse the annual PE values for each zone were broke down into monthly values using the monthly PE distribution estimated for the Hungry Horse dam pan station. Figure 24 shows the monthly PE estimates for each zone (when these were determined the analysis was being done for the TNCM8 headwater and the HHWM8 local area). The monthly PE computed by CAP from a digitized version of the TR#33 annual lake evaporation map is also shown. For a lack of any other information the same monthly PE distribution was used for the Kootenai basin. Figure 25 shows the resulting monthly PE estimates for each elevation zone for the Kootenai. CAP values aren't included because TR#33 doesn't include Canada.

<u>Seasonal PE Adjustment Curves</u> – The seasonal PE adjustment curves for each basin were initially subjectively assigned based on available knowledge of the vegetation and past studies. These values were then modified during the calibration process (discussed in the model calibration portion of this report). ET-

demand is then computed for each zone by taking the mean PE for the month multiplied by the PE adjustment for that month. Changes to ET-demand were always made during the calibration by modifying the seasonal PE adjustment curve and then computing new ET-demand values. This is the only way to insure that the seasonal PE adjustment curves remain realistic. Figure 26 shows the final seasonal PE adjustment curves for Hungry Horse (both upper zones have the same values as do both lower zones) and Figure 27 shows the curves for Libby (both lower zones have the same values). Values for the entire drainage computed by CAP based on a relationship between the seasonal adjustments and greenness data using only 4 watersheds in the south and northeast U.S. are also shown on Fig. 26. The resulting final ET-demand curves are shown in Figures 28 and 29.

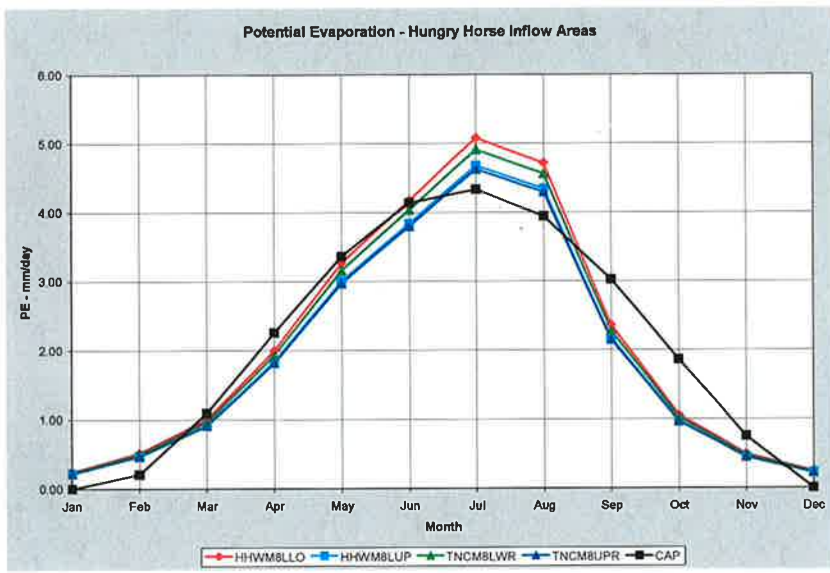

Figure 24. Monthly PE for each elevation zone above Hungry Horse dam.

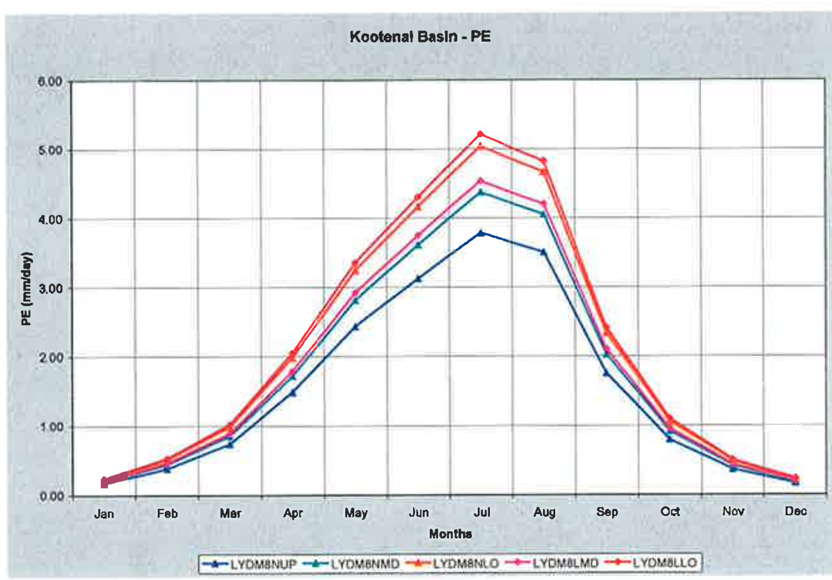

Figure 25. Monthly PE for each elevation zone above Libby dam.

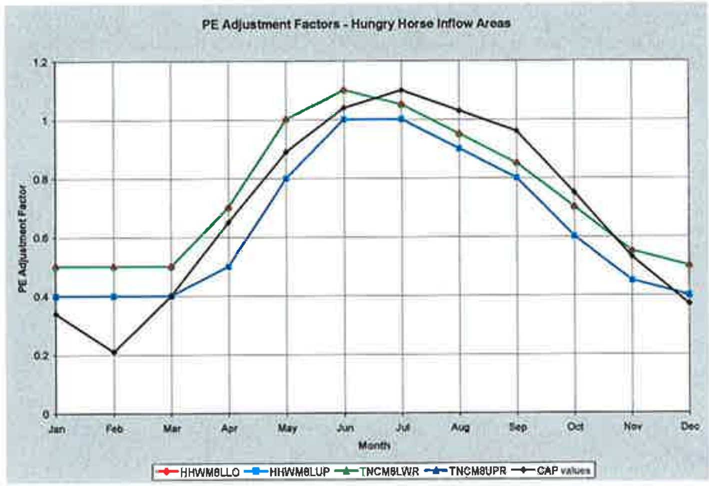

Figure 26. Final seasonal PE adjustment values for Hungry Horse.

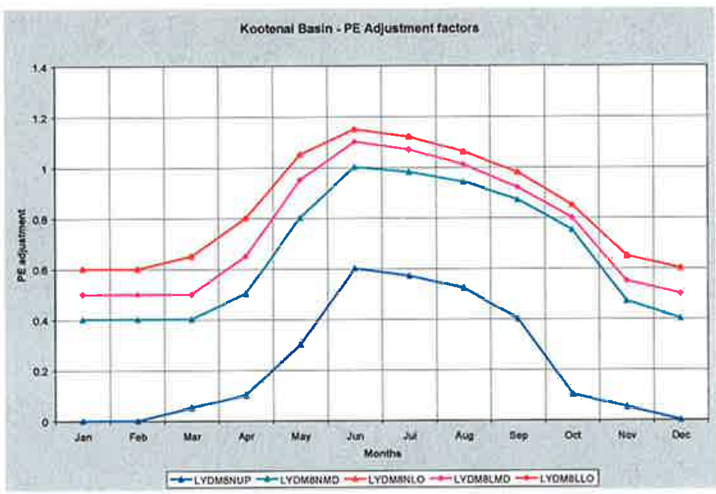

Figure 27. Final seasonal PE adjustment values for Libby.

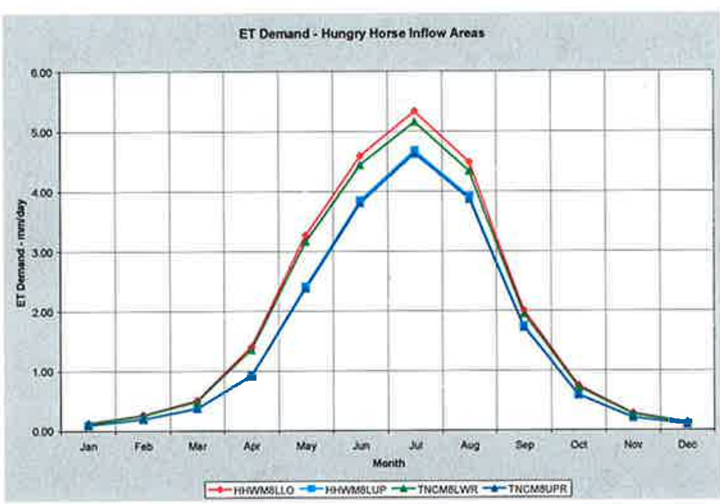

Figure 28. Final ET demand curves for Hungry Horse.

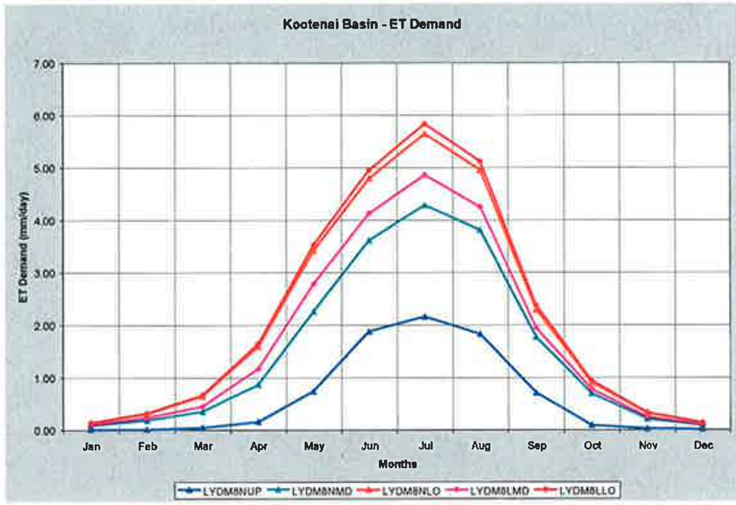

Figure 29. Final ET-demand curves for Libby.

Model Calibration

General Strategy

After generating MAP and MAT time series and determining initial ET-demand values for each elevation zone, the SNOW-17 and SAC-SMA models were calibrated for the Hungry Horse and Libby drainages. The basic strategy that was followed for both basins was generally the same. The calibration utilized the new Java based Interactive Calibration Program (ICP) developed for the Weather Service by Riverside Technology Inc. Except for a few minor bugs, this new version of ICP proved very successful for calibrating the models. The number of mouse clicks needed to perform certain functions has been significantly reduced from the old ICP and the displays are much more stable, especially in regard to using the PLOT-TS operation for displaying results.

The strategy that was used for Hungry Horse and Libby is the same as would be used for any other snowmelt runoff dominated basin in the Intermountain West. Watersheds in this region are characterized by the vast majority of the runoff coming from snowmelt, very few significant rain events with those that do take place occurring typically in the late fall/early winter or possibly near the end of the melt season, spotty convective storms during the summer, significant amounts of baseflow, and interflow dominating snowmelt runoff peaks and storm events. The sequence of steps in such basins for determining model parameter values is generally the same though at any point if there are clearly parameters that are in error, this needs to be dealt with immediately. Large errors in the value of a parameter can distort the simulation such that it is difficult to properly make decisions regarding the other parameters. Also after a group of parameters is initially adjusted it is likely that the calibrator will need to return to those parameters periodically, after making changes to other parameters, in order to verify that the prior values are still valid or whether they need some further modifications.

The general philosophy that was followed in these basins in regard to variations in parameter values from one elevation zone to another is that unless the effect of each zone can be clearly identified, the parameter is assigned the same value in all zones. Differences in parameter values between elevation zones can sometimes be identified based on physiographic information such as forest cover or soils data or based on climatic information such as typical amount of snow and average temperature. In other cases parameter differences between elevation zones can be determined based on the timing of the response of each zone or the amount of snow that accumulates.

Most of the parameter adjustments were based on an examination of the WY-PLOT or PLOT-TS displays. In some cases output from the STAT-QME operation was used, especially the seasonal runoff bias and flow interval bias values. The WY 1979-2003 period was used to determine the parameter values as this was the period when high elevation precipitation were available. WY 1990-2003 was first used during the initial recalibration for Hungry Horse that involved modeling TNCM8 and the HHWM8 local and then WY 1979-1989 was used to verify the results. The final recalibrations used the entire WY 1979-2003 period.

Regional Runoff Comparison – The first step was to compare streamflow data from various gages in the region to determine how the response varied. This provides an insight into how parameter values might vary from one watershed to another. The MCP control decks for these runs are labeled 'qmeplot.curr' for both the Flathead and the Kootenai. All the streamflow data are scaled to a common area before being displayed using the WY-PLOT operation. WY-PLOT displays are not included in this report. If one wants to see the regional runoff comparisons, the qmeplot.curr control decks need to be run using ICP.

The Flathead runoff comparison indicated that the response from TNCM8 and HHWM8 were similar except that TNCM8 had lower flows in the winter and sometimes in the fall. The response for HHWM8 was very similar to the North Fork (FCFM8) and the Middle Fork (WGCM8) of the Flathead. The main difference was that recession after the snowmelt season was quicker and the amount of baseflow during this period lower for HHWM8; indicating differences in the magnitude and withdrawal rate of supplemental baseflow and possibly percolation. Since TNCM8 had lower winter flows than HHWM8 and HHWM8 had similar flows as FCFM8 and WGCM8 during this time of year, it would seem to indicate that either the HHWM8 local produced a very large amount of primary baseflow or there was a problem with the winter flow measurements at TNCM8. Since WY 1982 winter flows have not been measured at the Twin Creek gage. SWRM8 has a more damped response (more baseflow – less storm runoff) than the other streams in this region. The other streamgages included, FISM8, TRYM8, STWM8, and RCCM8, have similar shaped responses to the upper Flathead watersheds but less overall runoff; both in terms of baseflow and snowmelt runoff.

The Kootenai runoff comparison indicated that the amount of inflow to Libby (LYDM8) is less than the upper Flathead watersheds (South, Middle, and North forks), the snowmelt response is later for Libby, and the recession after the melt season is similar to that for the North and Middle forks of the Flathead; slower and more baseflow than HHWM8. There are also less small winter runoff events than for the Flathead watersheds. The amount of runoff from the 3 Canadian streamgages (FSTQ2, ERFQ2, and BULQ2) is definitely greater than from the local area between those gages and the reservoir. The response of the local area is also more damped than for the northern part of the basin (baseflow greater, especially primary baseflow, and snowmelt runoff less). Snowmelt runoff from FSTQ2 is later and less in terms of volume than for ERFQ2 and BULQ2.

Overall the runoff comparisons indicate that there should be many similarities in parameter values for the watersheds in this region though there also should be some differences, especially in some of the parameters that control baseflow and percolation. The timing of snowmelt runoff appears to vary mainly with elevation and latitude, i.e. it varies primarily with the average temperatures of an area.

Assign Initial Parameter Values – Not a lot of time was spent deriving initial parameter values. Initial SNOW-17 parameters for Hungry Horse were based on the general guidelines in Section 7-4 of the Calibration Manual and on a previous calibration for the Upper Columbia Snow Laboratory at the south end of Glacier National Park. Initial snow model parameters for Libby were based on the initial recalibration for Hungry Horse. The RSNWELEV operation was used to determine how much of the precipitation was in the form of snow and how much was rain. An adiabatic lapse rate of 0.55 °C/100m and a rain-snow threshold temperature of 1 °C were used in all cases and not changed during the calibration. For Hungry Horse the MAT time series for the upper elevation zone was used to compute the rain-snow line. For the northern part of the Libby drainage the middle elevation zone MAT was used for rain-snow computations while the lower zone MAT was used for the local area above the dam. When Libby was modeled as just a headwater, the MAT for the middle elevation zone was used with the RSNWELEV operation. There are clearly times when there is too much rain or too much snow during an event; however, overall there doesn't appear to be a tendency for one or the other to dominate. No changes were made to any MAT values to adjust the form of precipitation.

Initial SAC-SMA parameters for Hungry Horse were based on the Upper Columbia Snow Laboratory calibration. Libby used the parameters from the initial Hungry Horse recalibration. Effective forest cover estimates were based on forest cover values computed by CAP and on photos of portions of the basins found on the Internet. No forest cover data were available from CAP for the portion of the Kootenai basin in Canada. Initial unit hydrographs were subjectively assigned, though the use of a synthetic unit hydrograph probably would be preferred if the necessary data were available. Based on other calibrations in the western mountains it was assumed that there would likely be very little, if any, surface runoff. The likelihood that most storm runoff was interflow, plus the lack of instantaneous streamflow data, made it very unlikely that a unit hydrograph could be derived from streamflow data. Given the mountainous terrain; it was assumed that the unit hydrographs would peak quite rapidly.

Adjust SNOW-17 Parameters Based on Snow Data – Reasonable values for some of the major snow model parameters can be determined using the observed areal snow cover values from NOHRSC satellite observations along with observed water equivalent values from snow pillow sites. The observed areal cover values allow for an independent determination of these snow model parameters rather than totally having to rely on streamflow simulations. The parameters that can be determined using the observed snow data are the areal depletion curve, SI, to some degree the melt factors (MFMAX and MFMIN), and roughly SCF. The areal cover data are especially valuable in getting an independent estimate of the areal depletion curve and SI. The idea is to modify these parameters in an attempt to reasonably simulate the observed areal cover values for each elevation zone. The areal depletion curve is adjusted based on the shape of the snow cover depletion from year to year. SI can be determined by examining when the observed areal cover clearly drops below 100%, especially by looking at large snow years. The melt factors can be modified based on how fast the snow appears to melt with the main emphasis in western basins on MFMAX. SCF can roughly be determined by judging whether there is sufficient or too much snow to deplete by the time the observed areal cover goes to zero. The point water equivalent values are used to roughly check the timing of the peak accumulation and its magnitude and the timing of when the snow disappears from each zone. Snow water equivalent measurement sites within a given elevation zone should go bare before the snow disappears from the zone as a whole. It may be that the snow model parameter values determined during this step will have to be modified somewhat when later examining the streamflow simulations due to how areal cover is used by the model and problems observing snow cover from satellites, especially in heavily forested areas. However, if the final simulation of areal cover is quite different from the observed values, it is likely that the calibrator is curve fitting and not modeling the area in a physically realistic manner. The observed areal cover data are extremely valuable for verifying that the snow model is reasonably representing what is occurring in nature.

For Hungry Horse observed areal cover values were available for the 2 elevation zones for both the entire drainage and the area above the Twin Creek gage. This allowed for computing separate values for the elevation zones within the local area. For Libby observed areal cover values were only available for the entire drainage. This made it more likely that further adjustments to SI, MFMAX, SCF, and possibly the depletion curve would be needed for the lower and middle zones when modeling the drainage as a combination of a headwater and local area (all of the upper zone is within the northern headwater).

Adjust Baseflow Parameters – The SAC-SMA baseflow parameters are the next major group to be adjusted. The main parameters affecting the amount and timing of baseflow are LZPK, LZSK, LZFPM, and LZFSM. These parameters also control the percolation rate under wet conditions when most of the snowmelt runoff occurs thus it is important to get a reasonable baseflow simulation before proceeding with the parameters that control the more immediate runoff from snowmelt or rain events.

In this region the primary withdrawal rate, LZPK, is typically determined based on baseflow recession during the late fall and winter during years with little or no storm runoff during these periods. LZFPM is adjusted so that the amount of baseflow is reasonable during periods when primary baseflow predominates, typically late fall and winter. The supplemental withdrawal rate is best seen during the recession period after the snowmelt season and after some larger rain-on-snow events that occur during the late fall or winter. LZFSM is adjusted so that the amount of supplemental baseflow is reasonable during the snowmelt season. This can be judged by examining the more steady flow during this period as opposed to the more immediate response from significant snowmelt or rain-on-snow events. If there is too little supplemental baseflow, the simulated flow will consistently drop below the observed several days after a rise and if there is too much supplemental baseflow, the result will be a more damped simulated response than what is observed.

In addition to these SAC-SMA parameters, the daily ground melt parameter, DAYGM, in the snow model can affect the baseflow recession in the winter. If the recession appears flatter in the winter than when snow is not present, it may be because there is a small amount of melt occurring at the snow-soil interface that is recharging the baseflow storages.

Check Snowmelt Runoff, Event Response, and Soil Moisture Deficits – The sequence of these is based on which one the calibrator feels is the most likely source of error. This is a subjective judgment. For Hungry Horse and Libby it varied from one area to another.

> Snowmelt Runoff Timing and Volume – Once baseflow is being reasonably simulated, the snow model parameters affecting the timing and volume of primarily spring runoff can be reexamined. In Intermountain West basins this primarily involves verifying the values of MFMAX as to the timing of snowmelt and SCF as to the volume of melt runoff. There may also be a need to make adjustments to SI (primarily based on large snow years) and sometimes to the shape of the depletion curve though the areal cover data should have been adequate to determine that curve. MFMIN can also be checked if there are periods of mid-winter melt. The UADJ parameter that controls melt during rain-on-snow events could be checked at this point though it many cases it is not that sensitive and unless significantly in error can wait to be checked in the last step. The

minor snow model parameters could also be checked though if the initial parameter guidelines are followed, changes to these parameters are seldom warranted.

Adjust Parameters Controlling Immediate Event Response – The parameters that control the response to significant melt periods and rain-on-snow events are UZK, UZFWM and ADIMP and to some degree REXP, ZPERC. If baseflow volume is basically okay but the quicker response runoff volume is too large or too small, it may be best to first look at either SCF which controls the amount of snow or the SAC-SMA tension water storages and evaporation rates since it is likely there is a problem with the precipitation or evaporation terms in the water balance.

Surface runoff seldom seems to occur in the Intermountain West, thus typically UZFWM is set large enough so that it is never exceeded, however, it is probably best not to set it way higher than any UZFWC that ever occurs. Most of the storm runoff in this region is interflow. UZK is the main parameter controlling the timing of interflow. Peak flows during the melt season are mainly examined when adjusting UZK. It should be noted that the lumped application of a temperature index snow model will result in an overall under simulation of peak flows. This is partly due to modeling the non-linear rainfall-runoff process in a lumped manner. However, it is primarily due to the melt rate being greater than normal during many of the events causing peaks from snowmelt. The melt factors are determined to give the best overall results and thus are more likely to under simulate events with the greatest amounts of melt.

In some Intermountain West basins there is some quick response runoff when the soil is wet. If so, the ADIMP parameter can be used to produce such runoff. Typically some instantaneous flow data are required to determine if the diurnal variation in snowmelt runoff can be adequately simulated using just interflow or whether some variable impervious runoff is needed. Such data were not available for Hungry Horse or Libby though instantaneous flow data for the Upper Columbia Snow Laboratory indicated that the small amount of diurnal flow variation could be modeled adequately with just interflow.

Sometimes peak flow data can be used to judge if variable impervious runoff or even surface runoff is needed. One problem with the PEAKFLOW operation is that the ability to simulate peak volumes is not considered. In cases like with a lumped application in a predominate snowmelt basin where mean daily flows are generally under simulated for peak events, the peak flows should also be under computed. One way to remove the simulation of mean daily flows from the picture and only examine how the models are simulating the instantaneous peaks relative to the daily flows is to use an ADJUST-Q operation prior to the

PEAKFLOW operation. After running ADJUST-Q the adjusted and observed daily volumes will be essentially the same. One can then compare the adjusted instantaneous peaks with the observed peaks using the PEAKFLOW operation. For Hungry Horse and Libby the only peak flow data available were for TNCM8. The PEAKFLOW operation indicated that adjusted and observed peaks were similar at this location without using any variable impervious runoff.

If baseflow is reasonable, then the wet end of the percolation curve shouldn't need any adjustment. Events that occur when soil conditions are drier are the ones to look at in determining whether REXP and ZPERC need any adjustment. This involves looking at events where there is a significant lower zone tension water deficit and little water in lower zone free water storages. In these basins this is most likely in the late fall or at the beginning of the melt season in the lower elevation zones.

Adjust Tension Water Capacities and ET-demand– Upper zone tension water deficits can exist in this region after most of the snow has melted and before there is sufficient rain or snowmelt to fill any deficit that remains after the summer period when evaporation rates are high. Sometimes in the lower elevation zone an upper zone tension deficit can persist all the way to the start of the next spring melt season if there is little rain or melt during the fall and winter. UZTWM is primarily adjusted based on the response of intermediate size summer and early fall events when a significant upper zone tension deficit exists prior to the event. UZTWM will also affect the amount of actual ET. The greater the value of UZTWM, the more ET since the UZTWC/UZTWM ratio remains larger.

The lower zone tension deficit typically builds up over the summer and is either filled by fall rain or melt or the deficit can persist through the winter and is filled early in the melt season. Larger deficits are most common in the lower elevation zone in these basins. Whether runoff is over or under simulated at the time when the lower zone deficit is filling is used to determine whether any adjustment to the value of LZTWM is needed. As with UZTWM, LZTWM affects the computed amount of actual ET.

ET-demand is most likely to need adjustment during the times of the year when evaporation rates are the greatest and the soil is reasonably wet. Adjustments are based on the seasonal runoff bias pattern after attempts have been exhausted to remove any non-random pattern using other model parameters that have an effect on the seasonal bias. This means refining the major snow model parameters, baseflow parameters, and tension water capacities before modifying the seasonal ET-demand curve. As stated previously, changes to the ET-demand curve should be made by adjusting the seasonal PE adjustment curve first and then recomputing the monthly

ET-demand values. This prevents an unrealistic seasonal PE adjustment pattern.

While working with the tension water capacities the values of PFREE and PCTIM can also be checked. The value of PFREE is based on the amount of baseflow recharge during periods when the upper zone tension water is full and a lower zone tension deficit exists. The value of PCTIM is based on runoff from small summer events when an upper zone tension water deficit exists.

Final Parameter Checks – The final step was to go through all the parameters and verify that no further adjustment was warranted. This primarily involves those parameters that were not adjusted previously or were judged to have only a minor effect on the results. For these basins this included UADJ in SNOW-17, RIVA, REXP, and ZPERC in SAC-SMA, and the unit hydrographs. Final adjustments to these parameters were based on how plus and minus variations in their values affected the statistical comparison of simulated and observed daily flows. Final slight modifications to the ET-demand curves were also made at this point to improve the seasonal bias pattern.

For Libby a CHANLOSS operation was added to the local area simulation at the end to remove a small overall bias. It was judged that this bias was the result of evaporation from Lake Koocanusa (surface area of about 73 sq. mi.) and from the approximately 13,000 acres of irrigated land reported by the USGS.

Final Parameter Values

Table 4 shows the final parameter values for the SNOW-17 operation for both basins. For most of the minor snow model parameters the same value was used for all zones. These values were NMF=0.15, TIPM=0.05, MBASE=0.0, and PLWHC=0.05. Figure 30 shows the areal depletion curves for each elevation zone. Table 5 shows the final SAC-SMA parameter values. The value of ADIMP, PCTIM, and RIVA was 0.0 for all elevation zones as was RSERV=0.3. The final ET-demand curves are shown in Figs. 28 and 29. The unit hydrographs for HHWM8, the northern LYDM8 area (LYDM8N), and the LYDM8 local (LYDM8L) all peaked in 12 hours and had a 36 hour base (i.e. 5 6-hour ordinates). The LYDM8N watershed was lagged by 6 hours and a 6-hour attenuation (K) was applied before being added to the local to simulate the total LYDM8 inflow.

	HHWM8UPR	HHWM8LWR	LYDM8NUP	LYDM8NMD	LYDM8NLO	LYDM8LMD	LYDM8LLO
SCF	1.3	1.1	1.10	1.09	1.05	1.13	1.09
MFMAX	0.9	0.6	1.1	0.8	0.65	0.8	0.55
MFMIN	0.1	0.1	0.1	0.1	0.1	0.1	0.1
UADJ	0.08	0.04	0.07	0.05	0.03	0.05	0.03
SI	800.	500.	1500.	400.	300.	400.	300.
DAYGM	0.1	0.3	0.0	0.1	0.2	0.1	0.2

Table 4. Final SNOW-17 model parameter values for Hungry Horse and Libby.

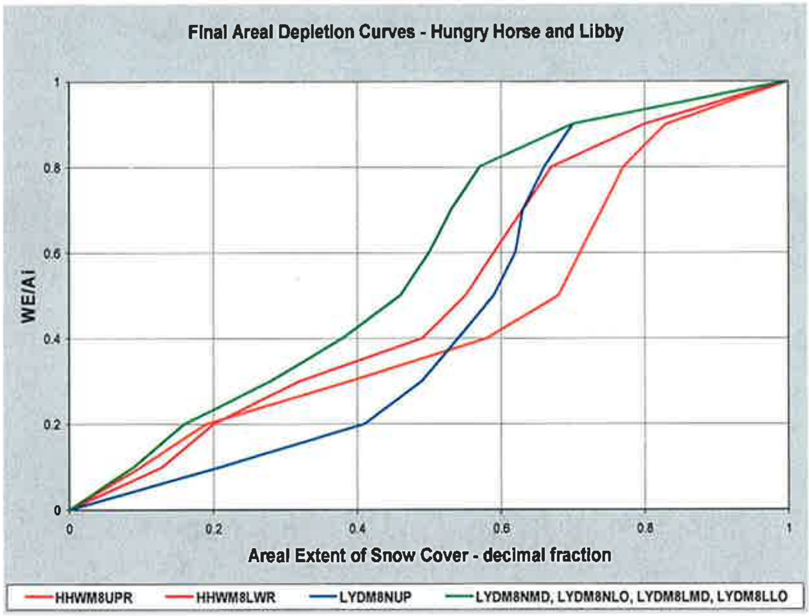

Figure 30. Final areal depletion curves for Hungry Horse and Libby.

	HHWM8UPR	HHWM8LWR	LYDM8NUP	LYDM8NMD	LYDM8NLO	LYDM8LMD	LYDM8LLO
UZTWM	40.	40.	40.	40.	40.	40.	40.
UZFWM	120.	120.	80.	80.	40.	80.	40.
UZK	0.3	0.3	0.2	0.2	0.2	0.2	0.2
EFC	0.70	0.77	0.0	0.7	0.7	0.7	0.7
ZPERC	400.	400.	100.	100.	100.	100.	100.
REXP	3.5	3.5	3.0	3.0	3.0	3.0	3.0
LZTWM	100.	100.	60.	60.	60.	80.	80.
LZFSM	160.	180.	225.	225.	225.	80.	80.
LZFPM	300.	335.	240.	240.	240.	600.	600.
LZSK	0.055	0.055	0.025	0.025	0.025	0.06	0.06
LZPK	.0015	.0015	.0015	.0015	.0015	.0015	.0015
PFREE	0.1	0.1	0.3	0.3	0.3	0.6	0.6

Table 5. Final SAC-SMA parameter values for Hungry Horse and Libby.

For the SNOW-17 model SCF values are fairly similar to the values that were anticipated (see Determination of Station Weights section under Precipitation Analysis). The maximum melt factors (MFMAX) varied with elevation with the highest rates in the upper elevation zones which have the least forest cover and the lowest rates in the lower zones where a dense forest cover exists. The value of MFMIN had little effect on the results and was assigned the same value for all elevation zones. SI of course varies since the amount of maximum snow accumulation increases with elevation. For the area above 8000 feet for Libby bare ground appears to show up as soon as melt begins which is typical for zones that above the tree line. All of the other zones retain 100% cover for some period after melt begins during large snow years. The depletion curves all zones had the same general shape. This shape is typical for most mountainous watersheds. The curves for both zones below 8000 feet for Libby were the same. The same curves were used for the northern and local portions of the Libby drainage since observed areal cover data were only available for the total drainage area and no clear change to the curves determined from those data was discernable. Daily ground melt is greater in the lower elevation densely forested zones and non existent above tree line. UADJ was subjectively made to vary with elevation as it seemed logical that the average wind during rain-on-snow events would increase with elevation. The ratio between zones was preserved when adjusting this parameter.

For the SAC-SMA model the primary baseflow recession (LZPK) was the same for both basins. The supplemental withdrawal rate (LZSK) varied as expected from the regional streamflow comparison. The supplemental recession for HHWM8 is more rapid than that for the northern portion of the LYDM8 basin where most of the runoff is generated. For the Libby local the more damped response that was noted in the regional streamflow plots is reflected in the LZFPM/LZFSM ratio being much greater than for the other watersheds. The UZTWM value appeared to be essentially the same for both drainages. The LZTWM value seemed to diminish as one went further north. There was more baseflow recharge when a lower zone tension deficit existed in the Libby area than for Hungry Horse as reflected in the PFREE values. UZFWM was set high enough so that no surface runoff was generated for almost all events. For the Libby upper elevation zone surface runoff is produced a few times during the period of record. However, since this zone covers less than 7% of the northern drainage it can't be determined whether surface runoff is really needed. Though the calibration was based on WY 1979-2003 the Hungry Horse calibration was run for the period prior to that date to see if surface runoff likely occurred during the June 1964 flood. The simulation shows a small amount of surface runoff for the upper elevation zone on the 8th. The USGS flood report (*Bonner and Stermitz, 1967*) estimates that the total precipitation over the HHWM8 watershed was in the order of 5-6 inches based on all available precipitation reports, including a bucket survey, though few, if any, of the measurements were within the watershed. The MAP time series for HHWM8 for June 7-8, 1964 contain a total of nearly 5.5 inches. The simulated peak is about 14% greater than the observed and the simulated storm runoff for the June 7-12 period is around 30% high. The elimination of the small amount of surface runoff from the upper zone makes very little difference to the simulation during this period. Thus, as for Libby, it can't be really determined for Hungry Horse if a small amount of surface runoff does occur when there are large amounts of rain and melt when the ground is saturated.

Calibration Results

This section summarizes the calibration results for Hungry Horse and Libby. To get a more complete view of the simulation it is necessary to run the ICP program using the appropriate control decks and time series and examine the WY-PLOT and PLOT-TS displays. The WY-PLOT displays show the simulated and observed mean daily flows and various SNOW-17 and SAC-SMA variables. The PLOT-TS displays are primarily used to display simulated and observed snow areal cover and water equivalent along with some flow time series. The MCP control deck for Hungry Horse is labeled 'hhwm8.eric' and the control decks for Libby are labeled 'lydm8.eric' for the simulation of the combined northern area plus the local and 'lydm8.lump' for the simulation that treats the entire drainage as a headwater. The parameters for the Libby simulation that treats the entire drainage as a headwater are a weighted average of the parameters determined when the area was calibrated using a headwater plus local. The results for the Libby headwater plus local calibration are based totally on simulated flows. The headwater values are not adjusted before being routed downstream. The ADJUST-Q operation was used to compute adjusted instantaneous flows for the northern area and the Libby inflow. These adjusted flows were only used for display purposes. Calibration results are included in the Excel spreadsheet labeled 'Calibration_Results.xls'.

Table 6 shows several statistics that summarize the results of the calibration for the WY 1979-2003 period for both basins. The parameters were adjusted so that the overall bias would be near zero for the calibration period. The overall calibration results are quite good considering the available data. The results for Libby were a little better than those for Hungry Horse. The results when treating the total Libby drainage as a headwater are only very slightly worse than modeling the drainage as a headwater plus local. Table 7 shows most of the same statistics when the parameters based on WY 1979-2003 are run for the WY 1949-1978 period. As expected from the earlier analysis in this report there is a significant negative bias when simulating the flows during this period using the calibration based on the later years. Because of this bias, the other statistics all become worse.

Statistic\Watershed	HHWM8	LYDM8 north	LYDM8 hw+local	LYDM8 lump
Bias (percent)	0.3	0.06	0.11	0.22
Daily RMS (cmsd)	42.7	85.8	99.7	100.9
Percent Daily RMS	44.3	35.4	32.6	33
Monthly Volume RMS (mm)	15.5	8.2	6.7	6.7
Percent Monthly Volume RMS	26.2	20.6	19.3	19.3
Correlation Coefficient	.948	0.957	0.956	0.955
Best Fit Line - intercept (cmsd)	1.3	6	7.3	5.5
Best Fit Line - slope	.983	0.975	0.975	0.980

Table 6. Summary statistics for the water year 1979-2003 period.

Statistic\Watershed	HHWM8	LYDM8 hw+local	LYDM8 lump
Bias (percent)	-10.2	-14.8	-14.7
Daily RMS (cmsd)	57	146.7	148.9
Percent Daily RMS	52.3	42.6	43.2
Monthly Volume RMS (mm)	23.9	13.2	13.3
Percent Monthly Volume RMS	35.8	33.7	34
Correlation Coefficient	0.939	0.950	0.949

Table 7. Summary statistics for the water year 1949-1978 period.

The differences in the volume simulations between the two periods can clearly be seen in Figure 31. That figure shows the accumulated difference between the simulated and observed runoff on a quarterly basis for the entire period of record. For Hungry Horse there is a large, fairly consistent, under simulation of runoff through WY 1977. After that there is an abrupt change such that simulated and observed runoff are basically the same for the rest of the period. The change is not quite as abrupt for Libby, but clearly the ability to simulate runoff volume changes significantly at about the same time as for Hungry Horse. As was concluded previously, there is just not enough precipitation in the

MAP time series in the early years to simulate the above normal runoff that occurred during that period. Appendix B describes a test of using the stations with the greatest WY 1948-1978 to WY 1979-2003 ratio as shown in Fig. 5 to compute the MAP time series to show the effect on the accumulated differences for Hungry Horse.

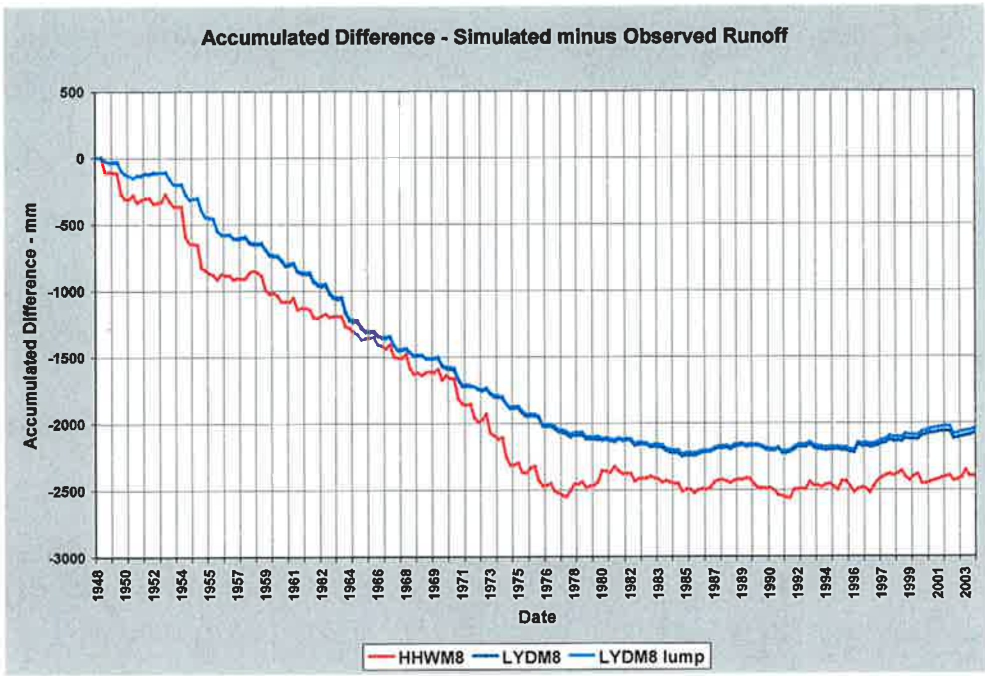

Figure 31. Accumulated deviation of simulated minus observed runoff for the water year 1949-2003 period for Hungry Horse and Libby inflows.

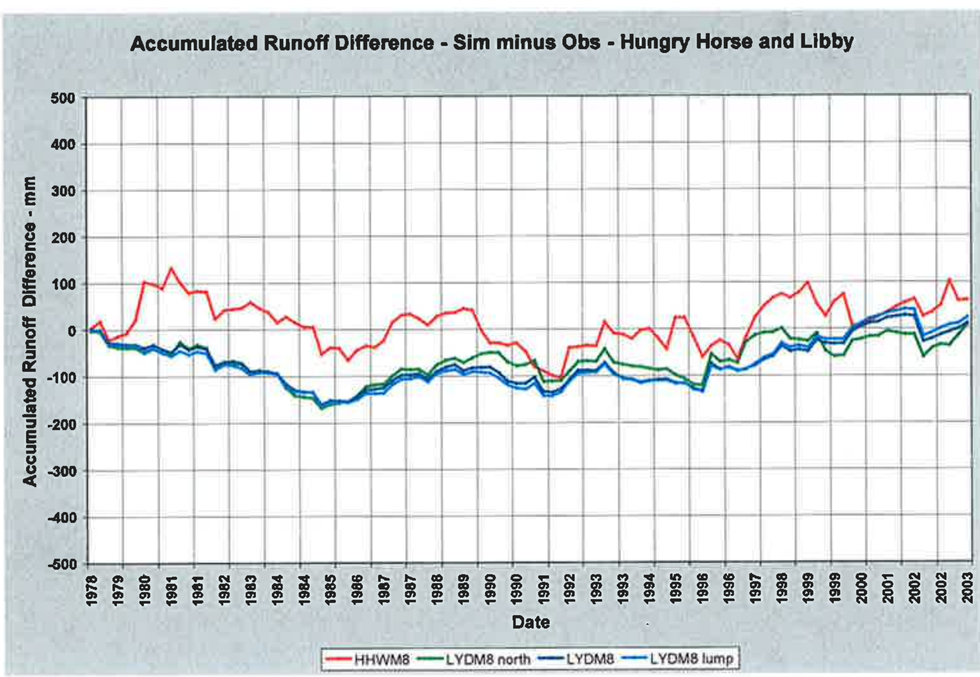

Figure 32. Accumulated deviation of simulated and observed runoff for WY 1979-2003.

Figure 32 shows the accumulated deviation between simulated and observed runoff in more detail for the calibration period. While there are year to year variations, the ability to simulate the proper volume is quite consistent during this period.

Figure 33 shows the seasonal bias pattern for the Hungry Horse calibration. All months are within 10 percent. The largest bias occurs in October, November, February, March, and August. The late fall and winter bias is mainly due to a problem in getting the correct separation between rain and snow and thus producing errors in small runoff events. Figure 34 shows the flow interval bias pattern for Hungry Horse. Very low flows tend to be over simulated while high flows are under simulated. The low flow over simulation is primarily due to the noise in the inflow data especially at low flows. Since the inflows are computed from pool elevation and outflow data, at low flows the results are quite erratic. Every time there is a dip in the computed 'observed' inflow under low flow conditions, the simulated flow, which is very steady, is generally greater than the observed, thus producing the over simulation below 25 cmsd. At high flows, as discuss earlier, there is a tendency for temperature index snow models to under compute melt. This, along with the lumped application of the models, creates a negative bias at high flows during the snowmelt runoff season. Snowmelt runoff dominates in this region.

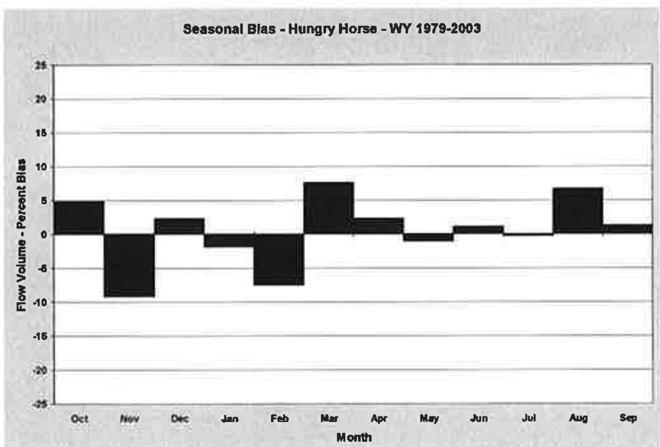

Figure 33. Seasonal bias for Hungry Horse inflows for WY 1979-2003.

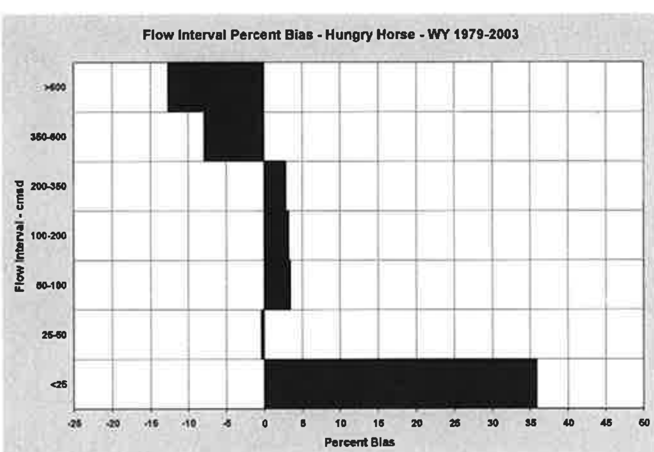

Figure 34. Flow interval bias for Hungry Horse inflows for WY 1979-2003.

Figure 35 shows the seasonal bias pattern for the Libby north headwater. This is a combination of the 3 Canadian streamflow gages (Kootenay at Ft. Steele, Elk River at Fernie, and Bull River near Wardner). The bias is below 5 percent for all months with a fairly random pattern. Figure 36 shows the flow interval bias pattern for this combined headwater location. There is an under simulation of the highest flows as is expected when using a lumped, temperature index snow model. This is offset by a slight over simulation of all other flow levels. The large over simulation of the lowest flows doesn't occur primarily because the observed flows at the 3 gages are calculated directly from stage data, thus the observed low flows don't exhibit the noise that exists in the computed reservoir inflows.

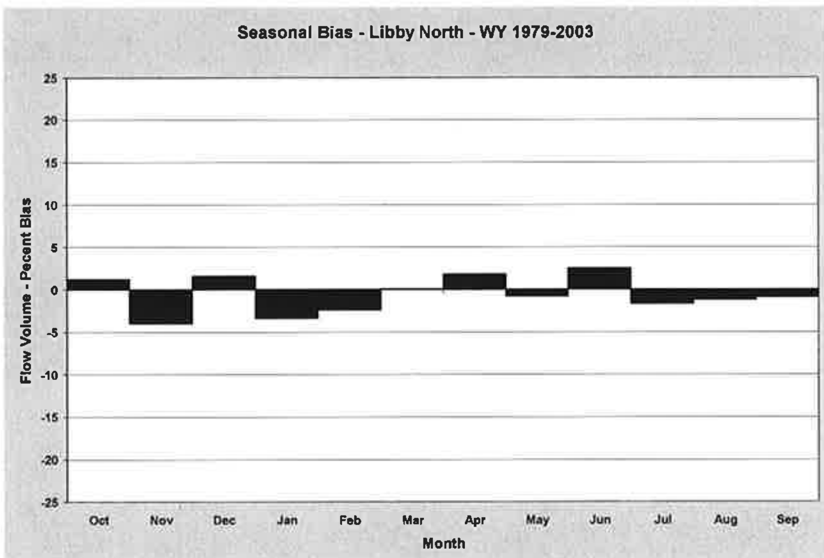

Figure 35. Season bias for Libby north (combination of FSTQ2, ERFQ2, and BULQ2) for water years 1979-2003.

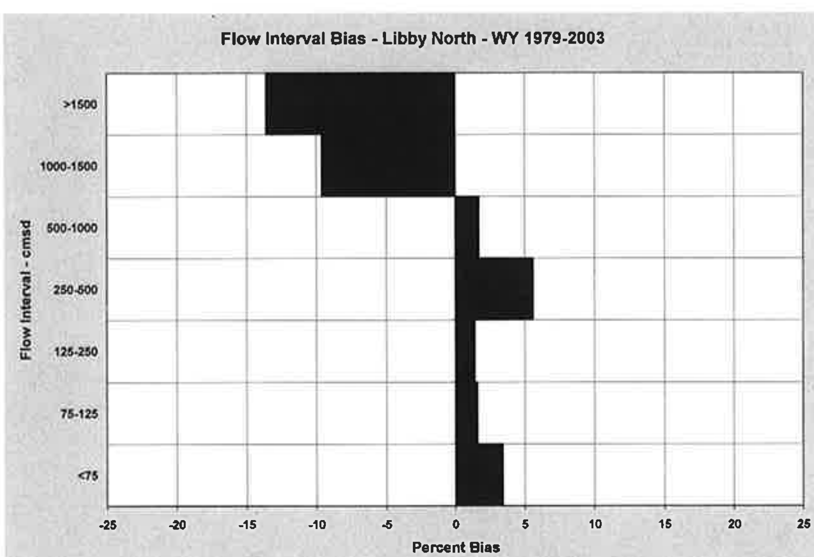

Figure 36. Flow interval bias for Libby north for WY 1979-2003.

Figure 37 shows the seasonal bias pattern for the inflow to Libby reservoir for both the calibration that uses the headwater consisting of the 3 Canadian gages plus the local below those locations and the simulation that treats the entire drainage as a headwater. As with the simulation of the combined 3 northern gages, the bias is within 5 percent for all months. Figure 38 shows the flow interval bias pattern for both simulations for the calibration period. As with Hungry Horse the very lowest flows are significantly over simulated primarily due to the noise in the computed reservoir inflows. The highest flows are somewhat under simulated, just like at the other sites. The seasonal bias patterns are essentially the same for both Libby inflow simulations, while treating the drainage as a headwater plus local produces a slightly better flow interval bias pattern.

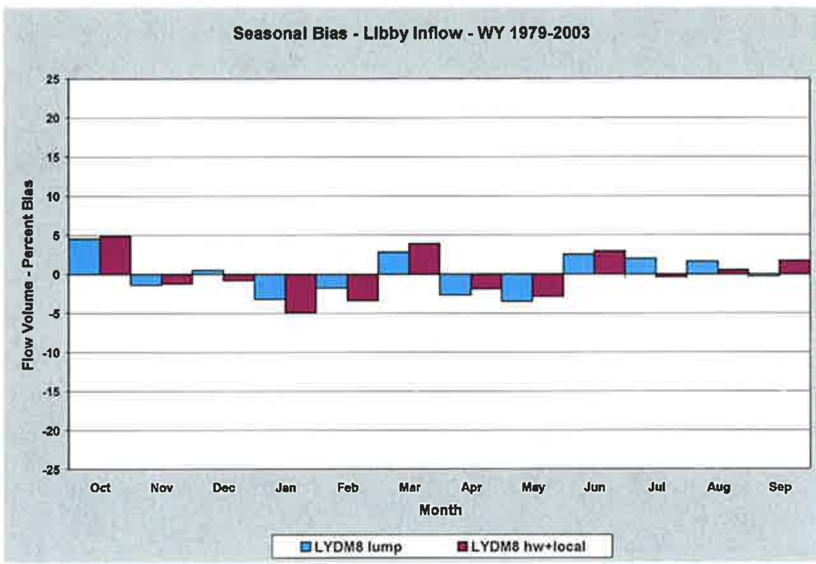

Figure 37. Season bias for Libby inflow simulations (both as a headwater + local and as a lumped headwater) for water years 1979-2003.

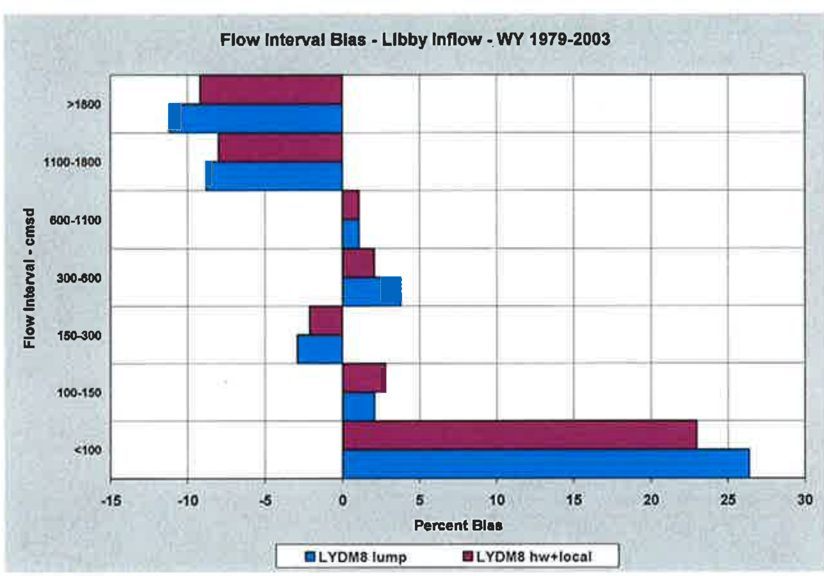

Figure 38. Flow interval bias for the Libby inflow simulations for WY 1979-2003.

As can be seen from the summary statistics and the various figures, the overall simulation of Hungry Horse and Libby reservoir inflows is reasonably good for the WY 1979-2003 period. There are definitely cases where the form of precipitation is not totally correct. In some cases there is too much rain and in others too much snow. This occurs during both the late fall and winter accumulation period and spring snowmelt. This problem can be seen by examining the WY-PLOT displays using ICP. Although errors in the form of precipitation produce some of the variability between simulated and observed daily flows, it appears that the effect is random in that over the long term there doesn't look like there is a tendency to generate either too much rain or too much snow. The timing of the simulated spring runoff overall agrees quite well with observed as does the amplitude of the snowmelt runoff; other than a tendency for the snowmelt peaks to be low as discussed previously. There are some years when the snow melts a little too early and some years where the timing of melt tends to be later than observed. There are clearly random volume errors from one year to the next in the amount of snowmelt runoff. Hopefully the use of water equivalent observations to update the simulated snow cover will reduce this variability during operational use.

A comparison of simulated and observed areal snow cover for each elevation zone reveals the simulated areal cover agrees quite well with observed in most cases. The initial major snow model parameters were first determined based on comparing the simulated snow cover to the satellite observations from NOHRSC. For most of the elevation zones these initial values were basically maintained when checking the snowmelt runoff against observed streamflow. The depletion curves were not altered. The SCF value for all zones was adjusted somewhat as would be expected. The MFMAX values were also modified slightly for some of the zones. For two of the zones the value of SI needed to be reduced in order to improve the streamflow simulation. This was done for the Hungry Horse upper zone (greater than 6500 feet) and the Libby middle zone (5000 – 8000 feet). This resulted in the simulated areal cover staying at 100% longer than the observed during the largest snow years for these 2 zones. For Hungry Horse this can best be seen by examining the PLOT-TS display (using a 365 day duration for the plot) for water years 1991, 1995, 1996, 1997, and 1999. For Libby the main years affected are 1996, 1997, and 1999 (there weren't enough observed values during the other year with the most snow, 1991, to see the effect). It was decided that it was more important to better simulate the spring runoff during large snow years from these zones than to match simulated and observed areal snow cover. The comparison between simulated mean areal water equivalent and point snow pillow observations appears realistic both in terms of the amount of water equivalent and the depletion; including when snow disappears.

Summary

The recalibration of the inflows to Hungry Horse and Libby reservoirs turned out to be a bigger project than initially envisioned. The initial recalibration for Hungry Horse revealed that parameters derived based on the period since high elevation precipitation and temperature data were available produced large under simulations for the years prior to that time. An investigation of the possible reasons for this under simulation prior to the late 1970's indicated that while more runoff was produced in the early years (about 12% more for Hungry Horse) the MAP time series only contained 1% more precipitation. The MAP values for higher elevations for the early years are based on the high/low precipitation ratio that existed after high elevation data were available. Based on the available information the conclusion is that there was a more pronounced orographic effect in the typical winter storm prior to the late 1970's. This couldn't be totally verified since there were no high elevation data anywhere in the region in the early years. There is also some evidence that lower evaporation rates in the early years accounted for some of the problem. It is roughly estimated that an under estimation of precipitation causes about 75% of the under simulation prior to water year 1979 and the use of mean ET-demand based on the later years causes about 25% of the volume error. Based on streamflow data from a number of sites throughout the NWRFC area of responsibility east of the Cascades, it is concluded that this situation existed over at least most of the entire region.

Based on the results of this investigation the NWRFC decided that calibrations should be based on the period after high elevation data are available. For this project water years 1979-2003 were used to determine model parameter values. Previously the RFC had used the entire period of record for calibration dating back to WY 1949. Part of the objective was to have a near zero overall bias for that entire period. The RFC also decided that mean monthly station precipitation and max/min temperatures used in the historical data analysis would be based on a period beginning with the start of the latest 30 year normals. Thus they used the WY 1971-2003 period to compute monthly averages. This also coincides for the most part with the period used to derive the PRISM values (WY 1971-2000). PRISM values play a significant role in determining the appropriate mean areal precipitation for each watershed and elevation zone. Changes in precipitation patterns, evaporation amounts, and temperatures over time also have an impact on which time series should be included when making ESP runs. Recommendations in this regard are included in the report.

After determining the likely causes for the under simulation during the early years and making decisions as to the proper period to use for historical data analysis and model calibration, MAP and MAT time series were generated and the hydrologic models calibrated for Hungry Horse and Libby. The initial recalibration for Hungry Horse used a headwater at the Twin Creek streamgage above the reservoir and the local below that point. Due to some possible problems with some of the Twin Creek data, the fact that a simulation treating the entire drainage above the dam as a headwater produce slightly better results than the headwater plus local simulation, and the preference of the NWRFC, the final calibration for Hungry Horse treats the entire inflow to the reservoir as a headwater. Libby was calibrated by treating the combined area above 3 Canadian streamgages in the northern part of the basin as a headwater and then modeling the local below those gages separately. This was done because of the large size of the drainage and the considerable distance from north to south. Separate temperature-elevation relationships were developed for the northern and southern portions of the Libby drainage. After completing this calibration, a simulation was made treating the entire drainage above Libby dam as a headwater. Parameter values were a weighted average of the values from the headwater plus local calibration. The overall results from this simulation were only very slightly worse than treating the drainage as a headwater plus local. The RFC can decide which configuration they want to implement operationally. The headwater plus local setup does allow for operational comparisons with the Canadian flow data and there are some differences in the response of the local from that of the headwater area. The headwater plus local setup uses 5 elevation zones, whereas treating the entire area as a headwater uses only 3 zones.

The overall simulation for these two basins for the calibration period is quite good. The seasonal bias patterns and the accumulated deviations of simulated and observed flow volumes are minimal and mostly random. There is a tendency to under simulate the highest flows. This is generally the case when using a temperature index snow model, especially in a lumped mode, because actual melt rates during many peak snowmelt periods are greater than the average melt rates used by the model. When the parameter values based on the WY 1979-2003 calibration period are run on the earlier years (WY 1949-1978) there is a significant under simulation. The overall bias for the early years is a negative 10-15%. This likely indicates, at least in part, why the NWRFC had problems when using their previous calibration for these drainages for operational forecasting. The previous calibration was based on WY 1949-1993. The goal at that time was to produce an overall near zero bias for the entire period. Based on this study, such a calibration would likely over simulate runoff volumes when used for the most recent years. Hopefully this new calibration, if implemented properly, will provide for improved forecasts and more realistic ESP probabilistic predictions.

References

Anderson, Eric, "Calibration of Conceptual Hydrologic Models for Use in River Forecasting", August 2002 (available at http://www.nws.noaa.gov/oh/hrl/hsmb/hydrology/calibration/training_Aug2002.html)

Bonner, F.C. and Frank Stermitz, "Floods of June 1964 in Northwestern Montana", USGS Water Supply Paper 1840-B, 1967

Dept. of Commerce, "Evaporation Atlas for the Contiguous 48 United States", NOAA Technical Report NWS 33, June 1982

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Appendix A – Contents of CD

The CD that accompanies this report contains 6 main directories containing the report, analyses, program input, and data used for the calibrations. The contents of each directory are as follows.

- **Report** – contains a copy of this report and appendices.

- **Spreadsheets** – contains Excel spreadsheets used to analyze the historical data and model results.
    - TNCM8 basic info.xls – contains CAP information for the area above the Twin Creek streamgage upstream of Hungry Horse reservoir.
    - HHWM8 basic info.xls – contains CAP information for the local area between Twin Creek and the dam and the total drainage above the reservoir.
    - CAP info libby.xls – contains CAP information for the area above the Libby reservoir
    - Pcpn_ET_analysis_flatclark.71-03.xls – contains the precipitation and evaporation analysis for the Flathead/Clark Fork basin including Hungry Horse dam based on WY 1971-2003 monthly means.
    - Pcpn_ET_analysis_Libby.xls – contains the precipitation and evaporation analysis for the Libby Dam inflow drainage.
    - Temp_Elev_flatclark.xls – contains the temperature versus elevation analysis for the Hungry Horse Dam drainage.
    - Temp_Elev_Libby.xls – contains the temperature versus elevation analysis for the Libby Dam drainage.
    - Accum_RO_compare.xls – contains the information used to analyze the initial recalibration for Hungry Horse in an attempt to understand the reasons for under simulating runoff in the early years.
    - Calibration_Results.xls – contains the analysis of the calibration results for both Hungry Horse and Libby.

- **Program Input** – contains input files for the PXPP, MAP, MAT, and MCP3 programs.
    - **PXPP**
        - flatclark.71-03 – input file for the Flathead/Clark Fork basin used to compute station averages for the WY 1971-2003 period.
        - kootenai.71-03 - input file for the Kootenai basin used to compute station averages for the WY 1971-2003 period.
    - **MAP**
        - flatclark.sta.71-03 – input to check the consistency results for the stations in the Flathead/Clark Fork basin using the monthly means for the WY 1971-2003 period. Stations with 'CLOC' or 'LOC' in the name have monthly means that are locked. These are stations that are used in more than one basin. The means are locked so that the same set of means is used for all basins affected.

- hhwm8.total.71-03 – input to generate time series for the upper and lower elevation zones for the total area above Hungry Horse using the monthly means for the WY 1971-2003 period.
- kootenai.sta.71-03 – input to check the consistency results for the stations in the Kootenai basin using the monthly means for the WY 1971-2003 period.
- lydm8.split.71-03 – input to generate time series the area above Libby Dam. The area is treated as a headwater above the 3 northern Canadian streamgages and the local below those gages and the dam. Lower, middle, and upper elevation zone time series are produced for the northern headwater and lower and middle zone time series for the local.
- hhwm8.total.test – input to generate time series used for the test case described in Appendix B.

- **MAT**
  - flatclark.sta.71-03 – input to check the consistency and monthly means for the stations in the Flathead/Clark Fork basin using the monthly means based on the WY 1971-2003 period.
  - hhwm8.total.71-03 – input to generate time series for the upper and lower elevation zones for the total area above Hungry Horse using the monthly means for the WY 1971-2003 period.
  - kootenai.sta.71-03 – input to check the consistency and monthly means for the stations in the Kootenai basin using the monthly means based on the WY 1971-2003 period.
  - lydm8.split.71-03 – input to generate time series the area above Libby Dam. The area is treated as a headwater above the 3 northern Canadian streamgages and the local below those gages and the dam. Lower, middle, and upper elevation zone time series are produced for the northern headwater and lower and middle zone time series for the local.
- **MCP3**
  - hhwm8
    - qmeplot.curr – control deck for the streamflow comparison for the Flathead/Clark Fork basin.
    - hhwm8.eric – final calibration control deck for the total area above Hungry Horse dam.
    - hhwm8.test – control deck used for the test case described in Appendix B.
  - lydm8
    - qmeplot.curr – control deck for the streamflow comparison for the Kootenai basin.
    - lydm8.eric – final calibration control deck for Libby dam using a headwater and a local area.
    - lydm8.lump – final calibration control deck for Libby dam treating the entire drainage as a headwater.

- **Preprocess Output** – contains output files from generated by the PXPP, MAP, and MAT input files described above under Program Input

- **Station Data** – contains the station data for precipitation and max/min temperature.
  - pcpn
    - flatclark – contains data for the 86 precipitation stations used for the Flathead/Clark Fork basin.
    - kootenai – contains data for the 68 precipitation stations used for the Kootenai basin.
  - tempt
    - flatclark – contains max/min data for the 70 temperature stations used for the Flathead/Clark Fork basin.
    - kootenai – contains max/min data for the 48 temperature stations used for the Kootenai basin.

- **Area Time Series** – contains all the Input time series used in the MCP3 program control decks.
  - hhwm8
    - Observed snow water equivalent (SNWE) time series for 7 Snotel stations (BADM8, EMCM8, KRCM8, MSPM8, MTKM8, NFJM8, NOIM8, PICM8, and WODM8)
    - Observed areal snow cover (AESC) time series for the upper and lower elevation zones for the total area above Hungry Horse
    - Observed mean daily flow (QME) time series for 9 USGS headwater gages (BONM8, FCFM8, FISM8, RCCM8, STWM8, SWRM8,TNCM8, TRYM8, and WGCM8) and the outflow from Hungry Horse dam (CFMM8)
    - Observed daily reservoir inflow time (RQIM) series for Hungry Horse dam (HHWM8)
    - Computed mean areal precipitation (MAP) time series for the Hungry Horse upper and lower elevation zones for both the calibration and the test case described in Appendix B.
    - Computed mean areal temperature (MAT) time series for the Hungry Horse upper and lower elevation zones
  - lydm8
    - Observed snow water equivalent (SNWE) time series for 6 Snotel stations (BANM8, BRMM8, GRCM8, HANM8, HAWM8, and STAM8) and 3 Canadian snow pillow sites (FLKQ2, MORQ2, and MYMQ2)
    - Observed areal snow cover (AESC) time series for the upper, middle, and lower elevation zones for the total area above Libby Dam
    - Observed mean daily flow (QME) time series for 4 Canadian stations (BULQ2, ERFQ2, FSTQ2, and KOXQ2) and the outflow from Libby dam (LYDM8)

- Observed daily reservoir inflow time (RQIM) series for Libby dam (LYDM8I)
- Computed mean areal precipitation (MAP) time series for the upper, middle, and lower elevation zones above the northern Canadian headwater and the middle and lower zones for the local between those gages and the dam
- Computed mean areal temperature (MAT) time series for the upper, middle, and lower elevation zones above the northern Canadian headwater and the middle and lower zones for the local between those gages and the dam

Appendix B – MAP Test Case for Hungry Horse

Introduction

In order to further test the conclusion that there should have been more precipitation in the MAP time series for the period prior to WY 1979, a test was run using the information shown in Fig. 5. That figure indicated that there appears to be a tendency for the ratio of WY 1948-1978 to WY 1979-2003 precipitation to increase with elevation. If this was the case, it would indicate that there was an increased orographic effect in the typical storm prior to WY 1979. Since high elevation precipitation data aren't available for the earlier period to verify this conclusion, it was decided to at least see what the effect would be on the accumulated runoff difference pattern if the stations with the highest early period to late period ratios in Fig. 5 were used to generate the MAP time series. This appendix describes the results of that test.

Computation of Test MAP

MAP time series were generated for the 2 elevation zones for the total area above Hungry Horse dam by weighting only those stations that had the highest ratio of WY 1948-1978 to WY 1979-2003 precipitation. The stations given weight, their early years to later years ratio, and their relative weights were Summit hourly (1.06, 0.2), East Glacier (1.07, 0.2), Rogers Pass 9 NNE (1.08, 0.2), West Glacier daily (1.06, 0.2), Lincoln Ranger Station daily (1.03, 0.1), and Seeley Lake hourly (1.03, 0.1). These weren't all the highest elevation stations used for Fig. 5, but during the early years there weren't any real high elevation sites. Of these 6 stations, the 4 with the greatest early to late period ratio are all to the east of the Hungry Horse watershed along the Continental Divide. The other two are generally south of the watershed but were included so that the stations used surround the watershed to some extent. The Seeley Lake daily gage only had a 1.01 early to late period ratio. The pattern of ratios for the stations included in Fig. 5 may suggest that the increased orographic effect in the early years could be more due to a change in the typical storm track than in storm type.

Season	Winter		Summer	
Elevation Zone	Lower	Upper	Lower	Upper
Test – 49-78 (in)	31.51	34.78	13.81	14.85
Calb – 49-78 (in)	29.47	32.1	13.72	14.59
Test/Calb ratio	1.069	1.083	1.007	1.018

Table B.1. Comparison of test MAP and calibration MAP time series for the WY 1949-1978 period for Hungry Horse.

The actual weights were first computed based on the WY 1971-2003 means and water balance analysis. They were then adjusted so that the resulting time series had the same average seasonal amounts for both zones as the MAP time series used for the calibration for the WY 1979-2003 period. Using these actual weights, test MAP time series were produced for the WY 1949-2003 period (MAP input file is labeled 'hhwm8.total.test' on the CD). Table B.1 shows the difference in these MAP time series compared to those used for calibration for the WY 1949-1978 period. The test MAP time series contain 5-6% more precipitation than those used for the calibration for this period. Most of the increase occurs during the winter (7-8%) as opposed to the summer (only 1-2%).

Streamflow Simulation

These test MAP time series were then used to simulate streamflow for Hungry Horse (MCP3 input deck labeled 'hhwm8.test' on the CD). In order to match the overall bias for the calibration period (WY 1979-2003), the SCF snow model parameter was increased slightly for both zones (1.1 to 1.11 for the lower zone and 1.3 to 1.32 for the upper). After making sure that the overall bias was the same for the calibration period, the test MAP time series were used to simulate the entire WY 1949-2003 period. All other time series and model parameters were the same as for the calibration. Figure B.1 shows the accumulated runoff difference using the test MAP time series versus that produced with the calibration MAP time series. The overall bias for the WY 1949-1978 period is reduced from -10.2% to -1.4%. The calibration summary statistics are definitely worse when using the test MAP time series during WY 1979-2003 and even generally a little worse for the WY 1949-1978 period even though most of the bias is removed. A few of the summary statistics are shown in Table B.2. Besides fewer gages to compute the MAP time series, the test series results have a much more pronounced seasonal bias (see Excel spreadsheet labeled 'Calibration_Results.xls'). This is mainly due to more precipitation being typed as rain than when using the calibration MAP time series. This is partly because of differences in the monthly amounts (most of the winter increase is in October and April when more rain occurs) and probably partly because of differences in the timing of the precipitation.

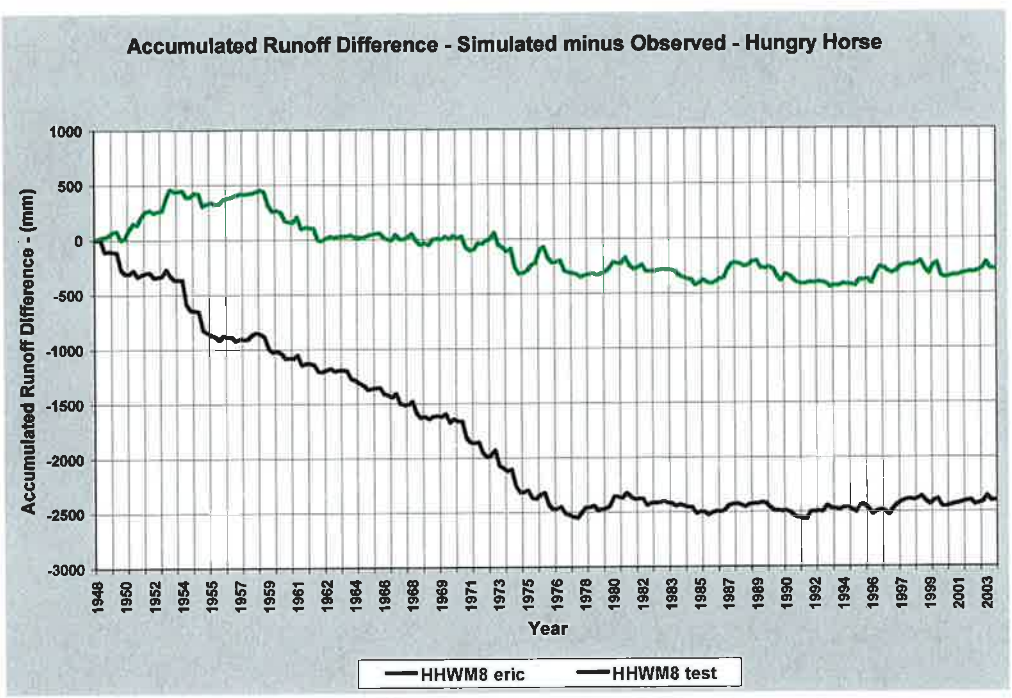

Figure B.1. Accumulated runoff difference using test MAP time series versus using the calibration MAP time series for Hungry Horse for the total period of record.

Period	WY 1979-2003		WY 1949-1978	
Case	Calb MAP	Test MAP	Calb MAP	Test MAP
Overall Bias (%)	0.34	0.32	-10.2	-1.4
Daily RMS (cmsd)	42.7	49.1	57.0	58.8
Monthly Vol RMS (mm)	26.2	30.5	35.8	33.3
Correlation Coefficient	0.948	0.931	0.939	0.928

Table B.2. Some summary statistics comparing the use of the test MAP time series versus the calibration MAP time series for Hungry Horse.

Summary

The analysis of the increase in runoff in the early years as compared to the areal precipitation estimate generated based on precipitation patterns during the later years when high elevation data were available suggested that there was likely a more pronounced orographic effect in the typical storms during the early years. The data for stations that had data for all or most of the WY 1949-2003 period of record suggested that the ratio of early period (WY 1949-1978) to late period (WY 1979-2003) precipitation increases with elevation (see Fig. 5). To see if much of the streamflow simulation negative bias during the early years (produced when using the MAP time series based on later year station relationships) could be removed, MAP time series were generated by weighting only those stations that had the highest early to late period ratio. The streamflow simulations using these test MAP time series did remove most of the early year bias though the overall results were not as good. This seems to indicate that if high elevation data were available for the early years, MAP time series could be generated that would not only produce generally unbiased streamflow simulations for the entire period of record, but would give results for the entire period that were compatible to those produced for the calibration period.