Appendix A

Background

Hydrology

Reports

Skagit River Basin Hydrology Investigation

Table of Contents

List of Figures

List of Tables

Supplement – Skagit River Basin Hydrology from Concrete to Mount Vernon

Appendices

1.0 Introduction

The Skagit River Basin is located in Northwest Washington State. The drainage basin is located within Skagit, Whatcom, and Snohomish Counties. The total drainage area of the basin is approximately 3,100 mi^2. The main tributaries of the Skagit River are the Sauk and Baker Rivers. Five reservoirs are located within the Basin. The Skagit River dams include Ross, Diablo, and Gorge, which are owned and operated by Seattle City Light. The Baker River has two dams (Upper and Lower Baker) that are owned and operated by Puget Sound Energy. The reservoir formed by Lower Baker Dam is often referred to as Lake Shannon. Figure 1 on the following page is an illustration of the basin.

The main goal of this study is to determine regulated and unregulated hypothetical flood hydrographs for the Skagit River near Concrete location (USGS gage #12149000). The USGS near Concrete gage is the focal point for reservoir flood operations and early flood warning for the lower Skagit Basin. Flood flows in the upper basin (the basin above Concrete) are generally contained within the channel. Below Concrete, flood flows leave the channel and overbank storage areas can attenuate the hydrograph. The flood hydrographs were used for input to hydraulic models in order to determine the complex floodplain in the lower basin, and evaluate structural and non-structural flood control alternatives. The hydraulic model used data from this hydrology report to account for runoff from tributaries downstream of Concrete. The flow of the main stem Skagit River with tributary inflow below Concrete was summarized at Sedro-Woolley and Mount Vernon.

1.1 History of Dam Construction in the Skagit Basin

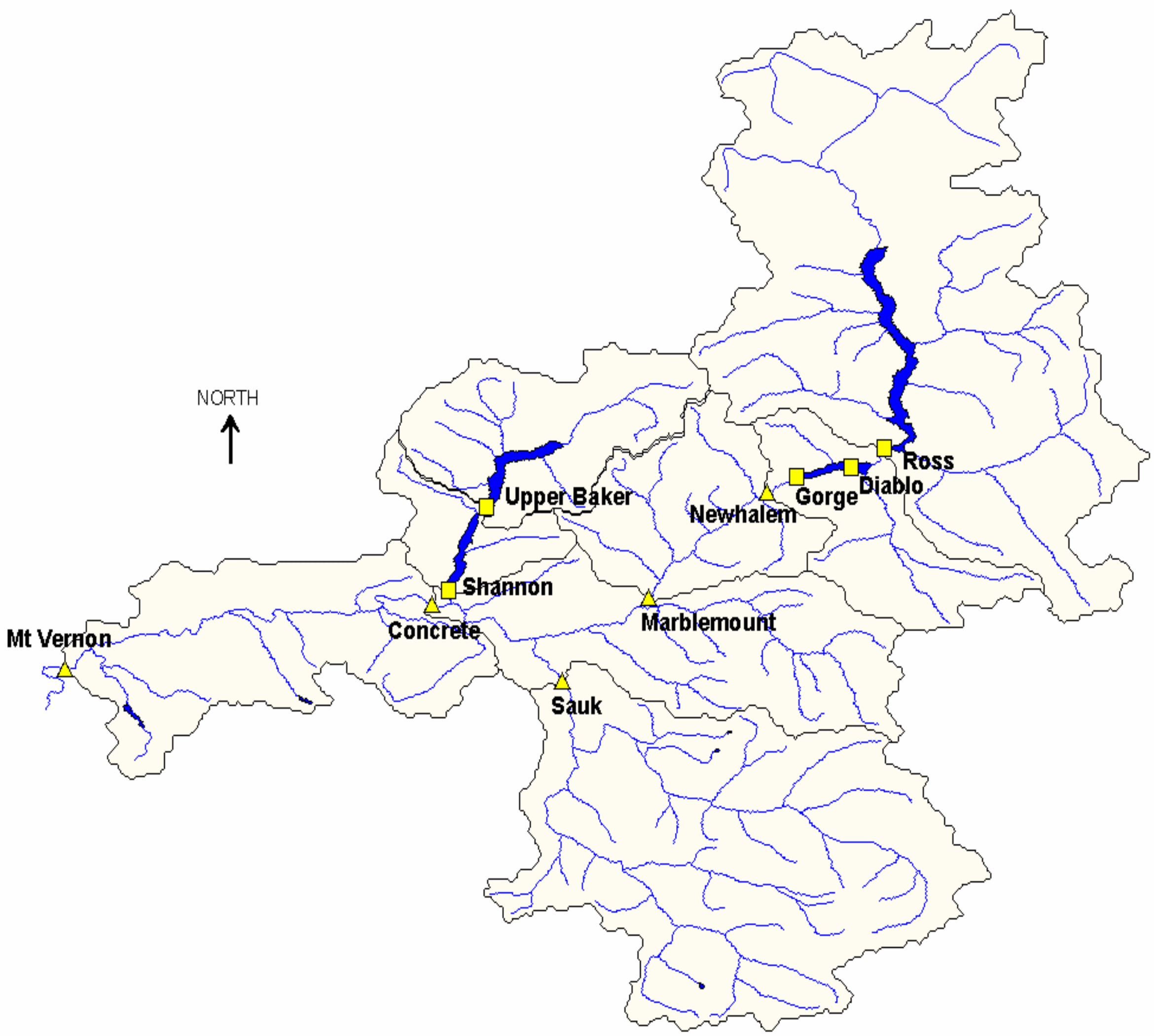
Dam construction in the Skagit basin began in 1924 with the Low Gorge dam. Additional dam construction continued until 1961 with the completion of High Gorge Dam. All dams were designed and built as hydropower generation structures. As the magnitude of Skagit Basin flooding problems became more evident, flood control storage was later required in Ross and Upper Baker Reservoirs. No flood control storage is required in Diablo, Gorge, or Lower Baker Reservoirs. The following Table 1 is a synopsis of dam construction and important flood control storage requirements in the Skagit Basin.

Table 1 - Synopsis Of Dam Construction and Flood Control Events

Year	Significant Construction or Flood Control Event
1924	Low Gorge Dam completed
1925	Lower Baker Dam completed
1929	Diablo Dam completed
1940	Ross Dam 1st step construction completed
1946	Ross Dam 2nd step construction completed
1949	Ross Dam 3rd step construction completed
1950	2nd Gorge Dam completed
1954	120,000 acre-ft of flood storage required in Ross Reservoir by FERC license
1956	16,000 acre-ft flood storage required in Upper Baker Reservoir by FERC license
1959	Upper Baker Dam Completed
1961	High Gorge Dam completed
1977	An additional 58,000 acre-ft flood storage in Upper Baker Reservoir authorized by Congress

Figure 1 - Skagit Basin Map

Squares represent dams; triangles represent significant USGS gaging stations.



2.0 Methods Used in This Study

The basic methods of hydrologic analysis used in this study are outlined below:

1. Create a peak and 1-day flow database for all available locations in the Skagit Basin.
2. Conduct frequency peak, 1-day, 3-day, and 7-day analyses for selected locations. Create frequency curves.
3. Unregulated 1-day flows at Concrete.
4. Use unregulated 1-day to unregulated peak relationship to create an unregulated peak flow frequency curve at Concrete. Create 1-, 3-, 7-, and 15-day unregulated frequency curves at Concrete.
5. Create 10-, 50-, 75-, 100-, 250-, and 500-year unregulated hypothetical flood hydrographs at Concrete.
6. Create a HEC-5 model of the upper basin.
7. Use statistical regression analyses to determine the most probable combination of flows in the upper basin that will create the unregulated hypothetical flood flows at Concrete.
8. Adjust upper basin flows until the unregulated routed hydrographs at Concrete match the unregulated hypothetical flood hydrographs.
9. Analyze the effects of adding reservoirs (Upper Baker and Ross) to the HEC-5 model. Determine the regulated flood hydrographs at Concrete by routing hypothetical flood flows with reservoirs input to the HEC-5 model.
10. Estimate local runoff between gages by subtracting the upstream gaged flows (such as at Concrete) from downstream gaged flows (such as at Mount Vernon).
11. Estimate the shape of the local hydrograph by factoring observed gage flows from a known drainage area to the drainage area of the local vicinity.
12. Estimate local runoff rates by the difference between the backwater-computed discharge at a location and the discharge value needed to reach an observed high-water mark.
13. Estimate local flows using regression relationships from known gage locations.
14. Estimate local flows using the frequency of an event and frequency curves at the site.
15. Frequency computations use the standard log-Pearson Type III procedure.
16. Discharges along the main stem (such as at Sedro-Woolley and Mount Vernon) are computed by adding the appropriate local flow to the discharge routed from Concrete (using the hydraulic model).

Each of the above tasks was performed in detail for this report.

2.1 Skagit Basin Database

The Skagit Basin Database is composed of all available peak and 1-day discharge values. The data was obtained via the internet at the USGS web site. Appendix D contains a summary of available peak and 1-day USGS flow data in the Skagit Basin. All daily flows were entered into a DSS storage format. Unregulated mean daily flows at the Skagit at Newhalem, Skagit at Concrete, and at the Baker River at Concrete gages were also calculated and input to a DSS format.

For the analysis of ungaged runoff from the lower basin below Concrete, additional data was used from gages nearby, but outside of the basin. Three useful gages near the Skagit basin are shown at the bottom of Table 1 in Appendix D. The North Fork Stillaguamish River near Arlington is approximately 15 miles south of the Skagit River. The South Fork Nooksack River near Wickersham is approximately 7 miles north of Skagit River. Samish River near Burlington is just a few miles north of Skagit River.

2.2 Runoff from Large Storms

The runoff downstream from Concrete was examined with observed data from some large historical floods. Peak flow data for four selected flood events are shown in Table 3 of Appendix D for a variety of gage sites below Concrete.

The December 1975 flood provided useful data from numerous gage sites that were discontinued in later years. Mainstem gages were active at Hamilton and Sedro-Woolley, which showed that the quantity of local inflow approximately matched the amount of attenuation that caused the peak flow to diminish due to the effect of storage in the flood plain over long reaches. Daily local runoff from Concrete to Sedro-Woolley and then to Mount Vernon was computed as an aggregate of all the creeks scaled to the drainage area of the two reaches. Hourly discharges were obtained by fitting the daily hydrograph to an hourly hydrograph that was computed from the unsteady-state hydraulic model (UNET). The local flow computation process was repeated using the observed hydrograph from the South Fork Nooksack River in order to develop a procedure for other floods after the gages at all the creeks were discontinued in the late 1970's. The hydrograph of the North Fork Stillaguamish River was also used but dropped in favor of the South Fork Nooksack River gage because the discharge-frequency data for the Nooksack River gage was better developed than for the Stillaguamish River gage.

The December 1980 flood shows how much the peak of the Skagit River can attenuate from Concrete (148,700 cfs) to Mount Vernon (114,000 cfs). The November 1990 flood from Concrete (149,000 cfs) to Mount Vernon (152,000 cfs) shows how much local runoff can add to the peak river flow even including the channel attenuation. The peak flows of November 1990 and December 1980 are the two most extreme events on the regression of "Peak Water Year Flow at Mount Vernon versus Peak Water Year Flow at Concrete" in Appendix B. The peaks for the November 1995 flood are near the expected value on the fitted line for the same regression plot so this flood is more typical for determining runoff characteristics.

2.3 Frequency Analyses, Mixed Populations of Floods

Frequency analyses were conducted at all pertinent locations within the basin (including Upper Baker and Ross Reservoirs). Log Pearson type III analyses were completed in accordance with the Water Resources Council Guidelines. The expected probability adjustment was applied to all analyses.

Floods in the Skagit Basin can be classified as either spring snowmelt, or winter rain-on-snow events. For the majority of time, the unregulated peak flow at Concrete recorded in any water year will occur within the time period Nov-Feb. These winter events have the potential to produce the highest peak flows when significant low elevation snowfall is present, followed by rising freezing levels, rain, and wind. The hydrograph produced by a winter flood event shows relatively quick rising and falling limbs compared to the broader, higher volume spring runoff hydrograph. It is very unusual to observe a regulated spring snowmelt peak flow at Concrete that exceeds 90,000 cfs. Hydropower reservoirs are refilling during the spring runoff, and usually decrease the spring peaks. All observed floods that have caused significant damage have been winter rain on snow floods events. Figure 2 on the following page is a summary hydrograph for unregulated flows at the Concrete gage. The average curve shows the normal flow for a given date, while the maximum curve displays the largest mean daily flow on a specific date for the period of record. Figure 3 on page 7 is a summary hydrograph for regulated and unregulated flows at Concrete. Regulated flows are usually less than unregulated flows for the spring and summer period as the hydropower reservoirs are storing water. During the fall and winter period, regulated flows are generally greater than unregulated flows as stored water is released for hydropower generation.

A two population flood frequency analysis for the Skagit River and its tributaries would be very difficult to perform, would be extremely expensive, and is probably not necessary. The winter type flood events comprise the majority of annual flood flows, and define the upper end (high return interval portion) of the frequency curves. The spring events dominate the low return interval portion of the frequency curve(s). Additionally, the best-fit line of median plotting positions using a mixed population analysis is very good for locations in the Skagit Basin. No high or low outliers or unreasonable skew coefficients were detected using mixed population data. The USACE Hydrologic Engineering Center Training Document #17 (Mixed Population Frequency analysis) gives the following advice on when to use a two-population analysis.

> "The primary motivation behind a combined-population analysis is to provide a better fit between the analytically derived distribution and the plotting positions that can be obtained with a mixed population analysis. The combined 2-population frequency curve approach should be considered when the frequency curves from mixed population analyses exhibit rather sudden breaks in the

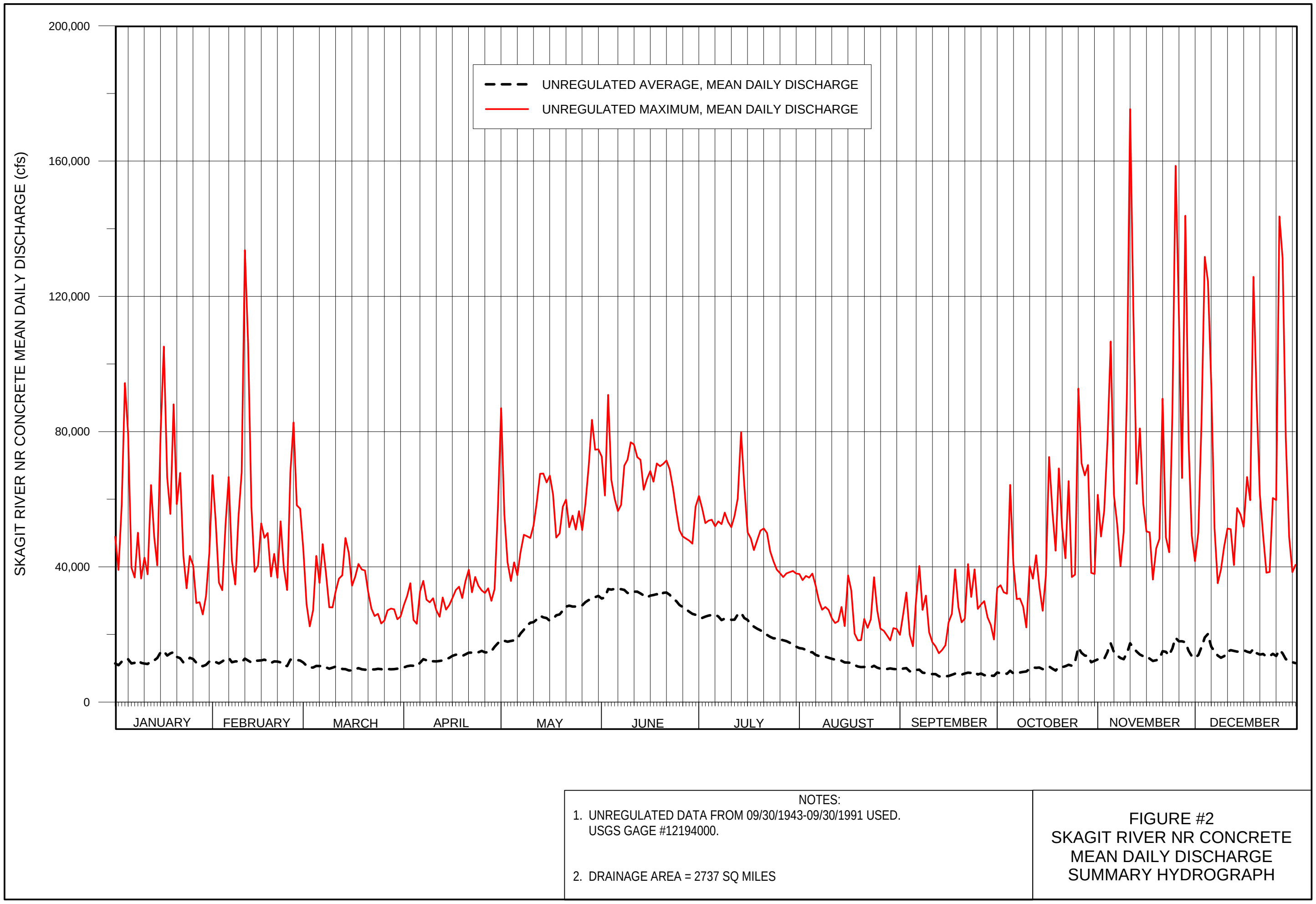
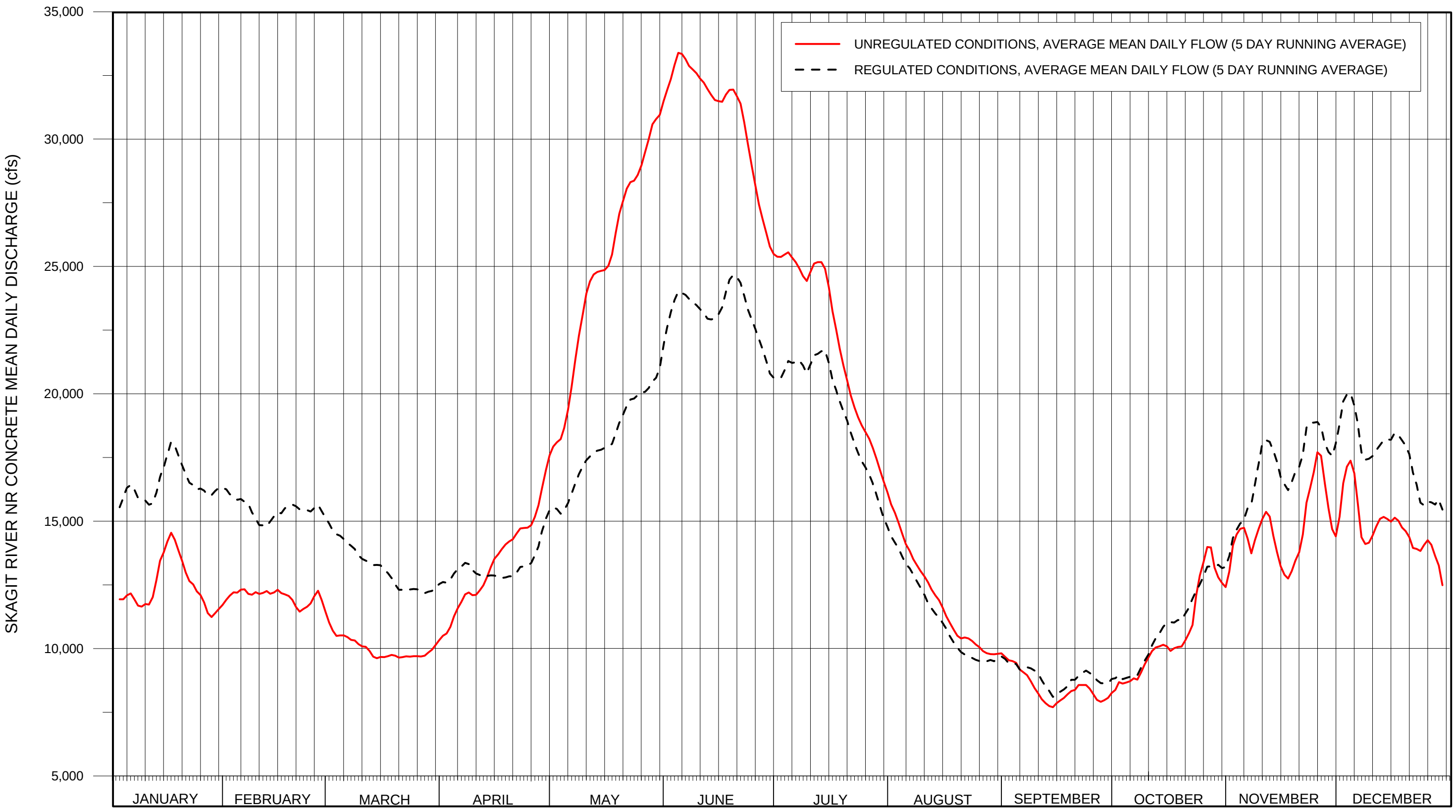


Figure 2 – Skagit River near Concrete Unregulated Mean Daily Discharge Summary Hydrograph



NOTES:
1. REGULATED DATA OBTAINED FROM USGS GAGE #12194000 FOR DATES 01/01/1956--09/30/1996. UNREGULATED DATA FROM 09/01/1943-9/30/1991 USED.
2. DRAINAGE AREA = 2737 SQ MILES

FIGURE #3
SKAGIT RIVER NR CONCRETE
MEAN DAILY DISCHARGE
SUMMARY HYDROGRAPH

Figure 3 – Skagit River near Concrete Regulated Mean Daily Discharge Summary Hydrograph

> curvature of the frequency curve. If historical data is available, and the incorporation of these data in a frequency analysis provides a good fit to the plotted data, then a combined two population frequency analysis may not be warranted."

The mixed population frequency analyses for the Skagit Basin produce reasonable fits to median plotting positions for all locations. Therefore, a two-population analysis was not used in this study. Frequency curves for all pertinent locations in the Skagit Basin are located in Appendix A.

For the local flow study below Concrete, discharge-frequency data was used from small drainage basins that are not included in Appendix A. Numerous small drainage basins in Appendix D have useful streamflow records that were discontinued in the late 1970's. Tabulated data in the following reference was useful to obtain summarized statistics for gaged sites between Concrete and Mount Vernon, Streamflow Statistics and Drainage-Basin Characteristics for the Puget Sound Region, Washington, U.S. Geological Survey Open-File Report 84-144-B, 1985. The USGS publication included frequency statistics of the East Fork Nookachamps Creek. Discharges per unit drainage area for selected frequencies were combined with those from Alder Creek, Day Creek, and Samish River to compute a discharge-frequency curve at the mouth of Nookachamps Creek. A plot of discharge-frequency information for Nookachamps Creek is included at the end of Appendix A. The discharge-frequency information for the Nookachamps Creek was transferred to the drainage area between Concrete and Sedro-Woolley using similar information at Alder Creek, Day Creek, South Fork Nooksack River, and North Fork Stillaguamish River.

2.4 Unregulated Flows/Unregulated Frequency Curve at Concrete

In order to determine the unregulated peak, 1-, 3-, and 7-day frequency curves for the Skagit River at Concrete location, the currently available regulated flows had to be adjusted for the effects of dam regulation. That is, what would the flows look like at Concrete if no dams had been constructed?

The method used to unregulate mean daily flows at Concrete is based on unregulating the daily flows at the Skagit River at Newhalem gage, and at the Baker River at Concrete gage. After the flows were unregulated at Newhalem and on the Baker River, the difference between the unregulated mean daily flows and observed regulated flows at the gages was calculated. This difference (either positive or negative) was then lagged to the Concrete gage location to determine the mean daily unregulated flow at Concrete. Appendix C shows diagrams and calculation methods for unregulating mean daily flows at the 3 gages. The same logic used for unregulating mean daily flows could be used for hourly data as well.

All gaged peak flow data at the USGS Concrete gage has been affected by dam regulation to some degree. To determine unregulated peak flows at Concrete, a regression relationship between unregulated mean daily flows and unregulated peak flows was developed. The unregulated peak flows were calculated for recent flood events by the Seattle District's Hydrology and Hydraulics Section. Figure 4 on the following page is a plot of the regression. The unregulated 1-day flows were calculated using the above-mentioned method.

Figure 5 on page 12 is a plot of the unregulated peak frequency curve for the Skagit River near Concrete. The USGS has published 6 major historical events (ungaged events). Historical events are usually estimated from historical literature in the area, or very old high water marks. The discharge estimates are subject to large errors. The following table summarizes the historical events for the Concrete gage.

Table 2 - Historical Floods for the Skagit River at Concrete

Date of Historical Flood Event	USGS published Discharge at Concrete (cfs)
1815	500,000
1856	350,000
11/19/1897	275,000
11/30/1909	260,000
12/30/1917	220,000
12/13/1921	240,000

The latest 4 flood events (1897, 1909, 1917, 1921) are all documented as flooding events in early photographs and newspaper articles. The magnitude of the events is questionable, but the fact that the flood events occurred is not. The earliest historical flood events (1815, 1856) were also likely large events, but the cause of these floods is in question. Research (by Kunzler etc.) indicates that these early flood events were likely caused by geologic rather than hydrometerologic forces. There is evidence that land or debris slides may have blocked parts of the Skagit and Baker Rivers causing large dams. The failure of these dams may have caused the very high stages associated with the 1815 and 1856 flood events. Melting of ice and snow on volcanically active peaks in the basin may also have been a factor in these early floods. Consequently, the 1815 and 1856 floods were not used in the unregulated frequency curve calculations. Missing years of data in the analysis were not used due to gage failure at either the Newhalem or Baker at Concrete Gages. None of the missing data represented high flood years that would significantly influence the upper part of the frequency curve.

Figure 4 – Peak versus 1-day Unregulated Regression for Skagit River near Concrete

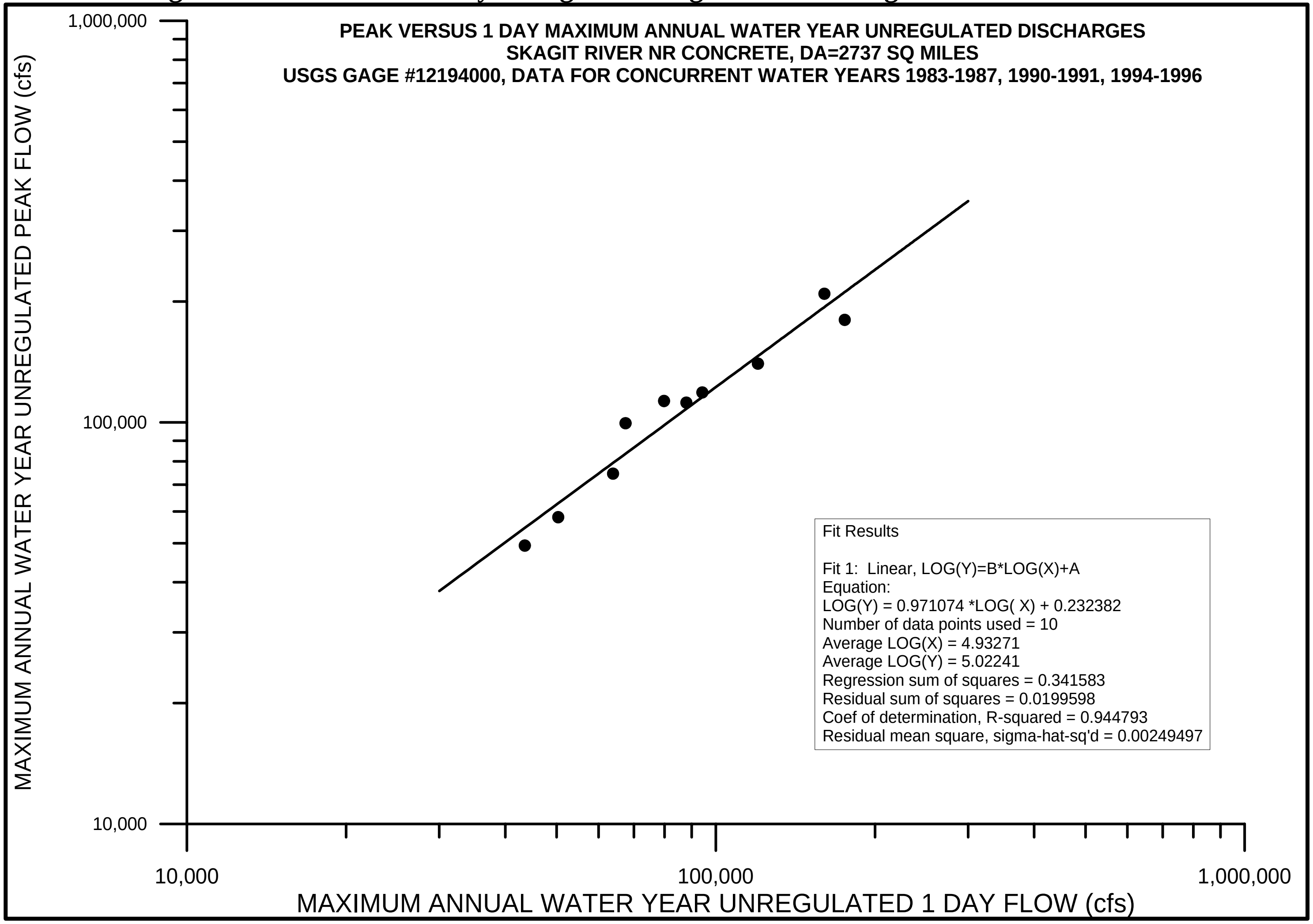
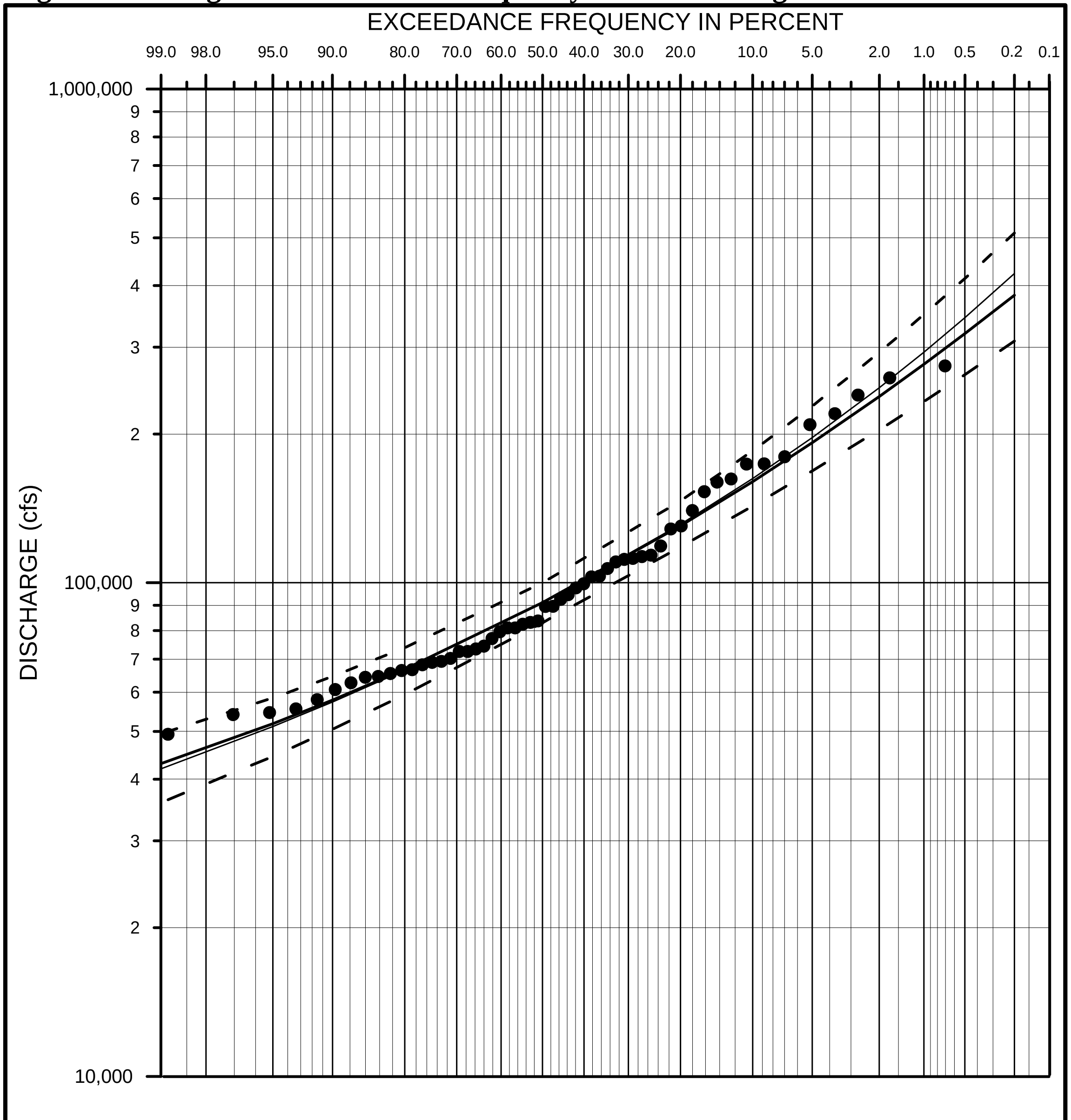


Figure 5 - Unregulated Peak Flow Frequency Curve for Skagit River near Concrete



HEC-FFA COMPUTED CURVE
EXPECTED PROBABILITY ADJUSTMENT
5% CONFIDENCE LIMITS
95% CONFIDENCE LIMITS
MEDIAN PLOTTING POSITIONS

LOG TRANSFORM SYSTEMATIC STATISTICS		NUMBER OF EVENTS	
MEAN=	4.9744	HISTORIC EVENTS=	4
ST. DEV.=	0.1744	HIGH OUTLIERS=	0
COMPUTED SKEW=	0.6973	LOW OUTLIERS=	0
REGIONAL SKEW=	0.0000	ZERO OR MISSING=	0
ADOPTED SKEW=	0.5000	SYSTEMATIC EVENTS=	52
		HISTORIC RECORD=	99 YRS

SKAGIT RIVER NEAR CONCRETE
USGS #12194000
UNREGULATED PEAK FLOWS
DERIVED FROM PEAK VERSUS 1DAY REGRESSION

CORPS OF ENGINEERS, SEATTLE DISTRICT
28 APR 1998
BASIN AREA= 2737 SQ MI
WATER YEARS OF RECORD
HISTORIC EVENTS= 1898, 1909, 1917, 1921
RECORDED EVENTS= 1925, 1944-1991, 1994-1996

CONSTRUCTED BY:	APPROVED BY:
C. FITZGERALD, E.I.T.	

2.5 Hypothetical Unregulated Hydrographs at Concrete

10-, 50-, 75-, 100-, 250-, and 500-year unregulated hypothetical flood hydrographs for the Skagit River at Concrete were developed using statistical frequency peak and volume analyses. The hydrograph shapes were based on the 1990 and 1995 unregulated flood events at Concrete. The peak values were taken from the unregulated frequency curve on page 12. 1-day, 3-day, and 7-day maximum averages were calculated using the HEC-STATS computer program.

The 1-, 3-, and 7-day maximum averages associated with the peak value were developed by regression analyses. All regression analyses used for this study are located in Appendix B. The hydrographs were then "balanced" to the 1-day and 3-day values. That is, the area of the hydrograph defined by the 100-year peak and 1-day value was shaped so that the 24 hourly discharge values summed and averaged were equal to the 100-year 1-day discharge. The same was applied to the flood hydrographs defined by the peak, 1-day and 3-day values.

A similar procedure was used to develop local runoff hydrographs for the drainage areas downstream of Concrete. Regression plots in Appendix B were used to arrive at unique return periods to match with a specific hydrograph at Concrete. Concrete hydrographs for 10-, 50-, 100-, 250-, & 500-year events were combined with local inflow hydrographs scaled to 7-, 25-, 50-, 110-, & 200-year events. The selection of coincident frequencies for the local drainage areas was determined by examining coincident data between Day Creek and Concrete. Similar comparisons were made by examining coincident runoff from the Marblemount local and the Sauk River versus Concrete. The Day Creek procedure was selected because Day Creek is within the local basin. Day Creek was used in the rigorous 1979 study, and because it produces amounts that are similar to what would be expected when comparing coincident Mount Vernon peaks with Concrete peaks.

Hypothetical hydrographs for the local areas were balanced among the volume-durations to have the same frequency throughout the durations. The balancing procedure was verified by examining similar information on the Sauk River, a local inflow point above Concrete. Regression curves between various durations at the Sauk River gage closely match coincident values from the respective volume frequency curves suggesting that observed hydrographs are usually balanced at this location. Hydrographs developed for the mouth of Nookachamps Creek are illustrated at the end of Appendix E.

2.5 Regulated Frequency Curve at Concrete

The regulated peak frequency curve at Concrete reflects the influence of flood storage and hydropower operations at Seattle City Light and Puget Sound Energy Reservoirs. The method to calculate the regulated frequency curve at the Skagit River near Concrete gage could be approached in the following two ways:

1) Use observed regulated flow data at Concrete with recent flood storage requirements in effect to calculate the frequency curve.

2) Create a hydrologic model of the basin. Use regression analyses to estimate the combination of coincident routed hydrographs that will reproduce the unregulated hypothetical flood hydrographs at Concrete. Insert flood control reservoirs into the model to calculate the regulated hydrographs at Concrete.

The first method was used to calculate regulated median plotting positions using data from water years 1956 to 1997. Ross Reservoir was required to provide 120,000 acre-feet of flood storage in 1954. In 1956 Upper Baker provided 16,000 acre-ft of flood storage. The problem with using observed regulated events is that large return interval (extremely large historic events) are not input to this analysis. This technique likely underestimates the high return interval portion of the frequency curve, which is the main area of interest in this study. The observed, regulated frequency curve gives a good estimate of the smaller return interval peak flows.

The second method uses regression analyses to estimate upper basin hydrographs that are coincident with the hypothetical unregulated hydrographs at Concrete (method outlined on page 4). The coincident hydrographs are then adjusted and routed to match the unregulated hypothetical hydrographs at Concrete using a hydrologic model. Flood control reservoirs are then input to the model in order to evaluate the effects of flood control operations. The advantage of this method is that large, historical flood events are taken into account in the analysis. This gives better estimates of large return interval unregulated and regulated flows. A combination of observed regulated peak flow events and hypothetical computer-simulated data (combination of the methods #1 and #2) were used to calculate a regulated peak flow frequency curve at Concrete. The computer-simulated data was used to draw the upper end of the frequency curve, while the observed data was used to define the lower end. A "best fit" line of the observed data was not used because regulated peak flow data does not fit any statistical distribution such as the Log Pearson type III (used to fit unregulated peak flow data).

The current flood storage requirement of 74,000 acre-ft in Upper Baker Reservoir was not implemented until 1977. This study assumed that all regulated peaks from water year 1956 to 1997 essentially show the effects of current flood control requirements. The 1-day, 3-day, and other regulated flow durations at Concrete may have changed due to changing storage requirements, but is unlikely that regulated peak flows from water year 1956 to 1976 would have changed significantly with the present flood storage conditions. Regulations dictate that as the unregulated flow at Concrete is forecasted to reach 90,000 cfs in 8 hours, upper basin reservoirs (Ross and Upper Baker) must limit their discharges to 5,000 cfs. The effects of additional storage at Upper Baker would not have significantly affected regulated peaks. It would have taken some time for the Upper Baker flood storage to be used, and use of gate regulation schedule discharges warranted. The regulated hydrograph at Concrete would have been in recession before any increase in discharge from Upper Baker Reservoir would have occurred. Figure 6 on page 16 is a plot of the regulated and unregulated peak flow frequency curves for the Skagit River near Concrete. Figure 7 on page 17 shows the regulated curve with associated two standard deviation error confidence limits. The regulated frequency curve at Concrete shows discontinuities or slope changes at regulated flows of about 65,000 and 90,000 cfs. These flows correspond to regulation “trigger points”. The 65,000 cfs discontinuity represents the “shutting down” of Ross and Upper Baker Reservoir discharges to minimum flows due to a forecast of 90,000 cfs at Concrete. The flattening of the plotting positions at 90,000 cfs represents regulation attempts to limit river flows to this value. The regulated curve does not merge back into the unregulated frequency curve at high exceedance frequencies. This is due to incidental hydropower operations peak flow reductions (for small return interval floods).

2.6 Confidence Limits For The Regulated Frequency Curve at Concrete

Confidence limits for the Skagit River at Concrete regulated frequency curve were developed using guidelines from the HEC-FDA computer program (flood damage analysis program). The confidence limits were derived using the “ordered statistics” approach outlined in the USACE engineering technical letter 1110-2-537 (Uncertainty, A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis.) The +2 standard error curve approximates the 5% confidence limit curve, while the 95% confidence limit curve is approximated by the -2 standard error curve.

Figure 6 - Unregulated and Regulated Peak Flow Frequency Curves for Skagit River near Concrete

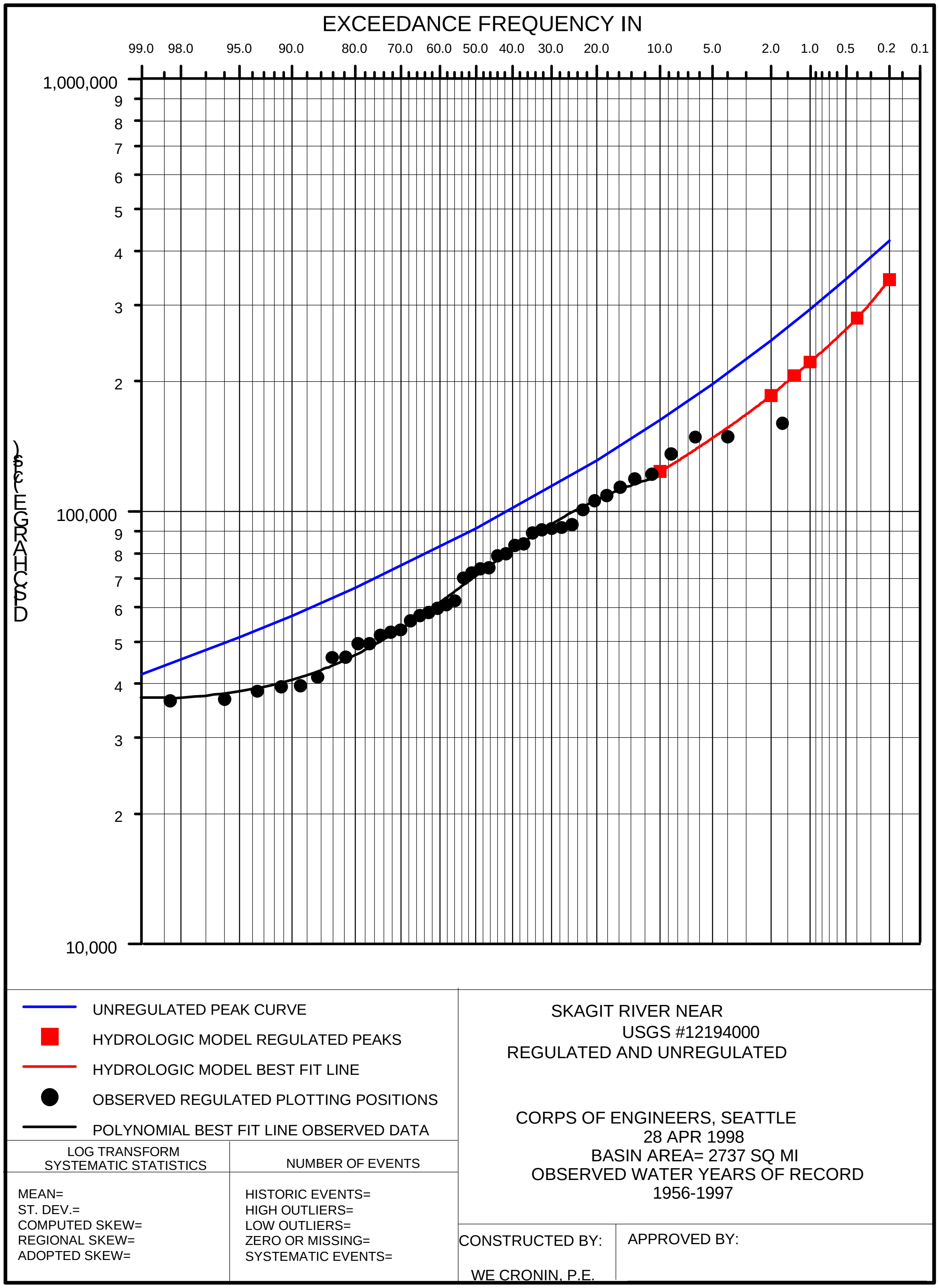
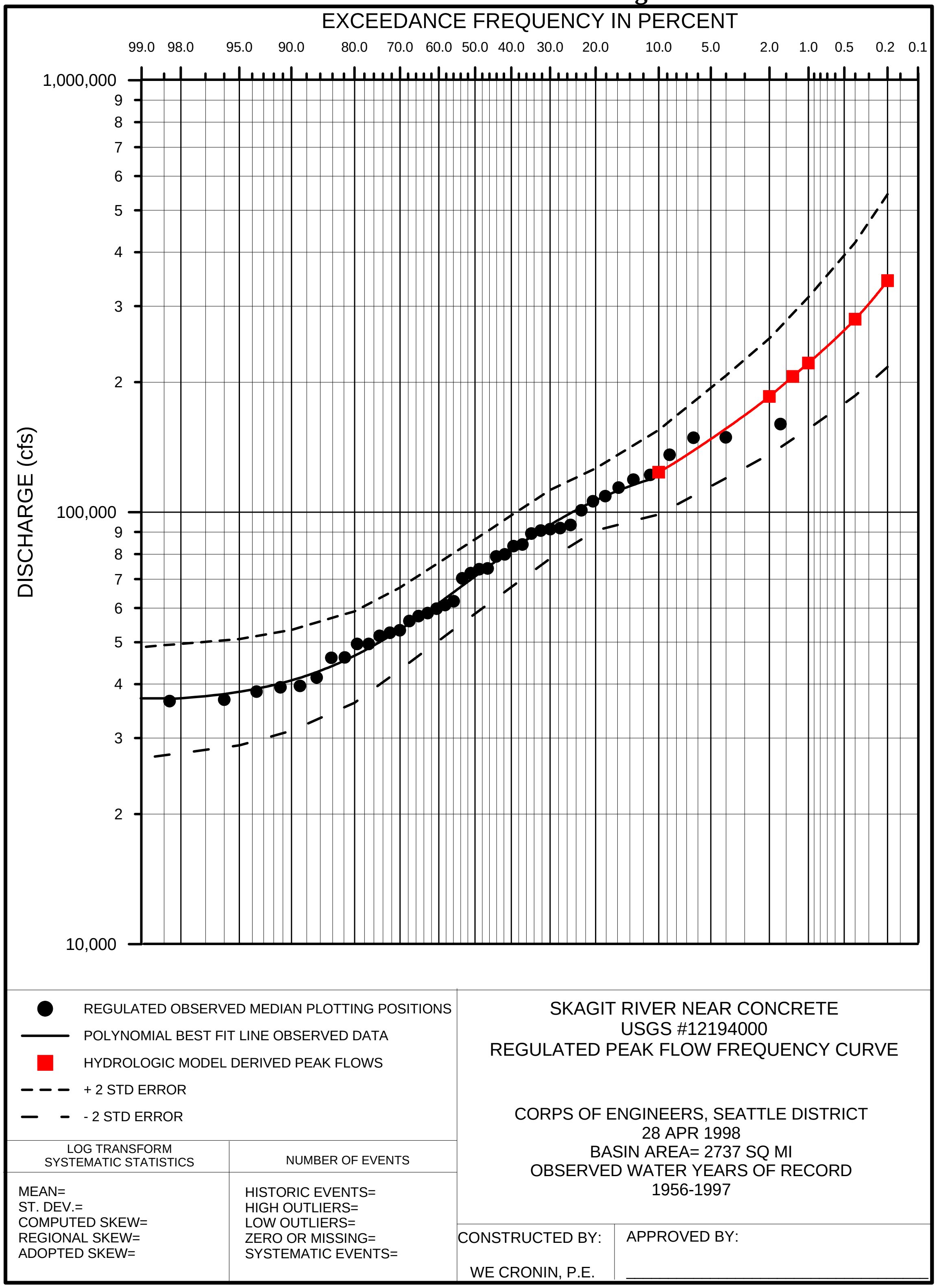


Figure 7 - Regulated Peak Flow Frequency Curve for Skagit River near Concrete with 5 and 95% Confidence Ranges



2.7 HEC-5 Skagit Basin Model to Concrete

A HEC-5 hydrologic model of the Upper Skagit Basin was constructed in order to calculate regulated flood hydrographs at the Concrete location. Figure 8 on page 19A is a HEC-5 schematic representation of the basin. The Table 3 below summarizes inputs to the HEC-5 Skagit Basin model.

Table 3 - HEC-5 Skagit Basin Model Summary

HEC-5 Control Point / Naming Convention	Description
#10	Ross Reservoir inflow hydrograph
#20	Skagit River at Newhalem, USGS gage #12178000
#30	Skagit River at Marblemount, USGS gage #12181000
#40	Confluence of Skagit and Sauk
#50	Upper Baker Reservoir inflow hydrograph.
#60	Baker River at Concrete, USGS gage #12193500
#70	Skagit River at Concrete, USGS gage #12194000
Local #1	Local inflow hydrograph between Ross Dam and Skagit at Newhalem gage. Includes Thunder Creek
Local #2	Local inflow hydrograph between Newhalem and Marblemount USGS Skagit River gages.
Local #3	Local inflow hydrograph between Marblemount and Skagit/Sauk River confluence. Includes the Sauk River flow.
Local #4	Local inflow hydrograph Between the Skagit/Sauk River confluence, and the Skagit at Concrete gage.
Local #5	Local inflow hydrograph between Upper Baker Dam and the Baker River at Concrete gage.

The coincident combination of flows in the upper basin were adjusted and routed until the modeled flows matched the shape and magnitude of the hypothetical unregulated flood hydrographs at Concrete. This was an iterative procedure that included scaling and adjustment of upper basin coincident hydrographs. After the unregulated hydrographs at Concrete were matched, reservoirs were input to the model and reservoir operations were simulated in order to calculate regulated hypothetical flood hydrographs at Concrete. Appendix E contains plots of the regulated and unregulated hypothetical flood hydrographs at Concrete.

Routing of the local and reservoir inflow hydrographs was accomplished using the Muskingum method. Upstream of Concrete, the Skagit River is a confined river with a fairly steep gradient. There are no large overbank storage areas to attenuate flood hydrographs, and flows are essentially translated downstream. The k and x Muskingum parameters used in the routing were equal to the travel time through the reach in hours, and 0.4 respectively. The k value of 0.4 represents minimal attenuation.

The following assumptions were used in the HEC-5 Skagit Basin model:

- Full flood storage is available in both Ross and Upper Baker Reservoirs before flood hydrographs enter the reservoirs. Pool levels are at 1592.1 at Ross and 707.9 ft at Upper Baker Reservoir before the simulation begins.

- No flood storage is available in Lower Baker, Diablo, or Gorge reservoirs. It is assumed that these reservoirs are full, and discharges from Ross and Upper Baker quickly pass through the lower reservoirs (the lower reservoirs have minimal flood storage) to the Skagit River at Newhalem and Baker River at Concrete gages.

- Outflows from Ross and Upper Baker reservoirs are equal to inflows until 8 hours before Concrete is forecasted to reach 90,000 cfs. The outflows are then dropped to 5,000 cfs at each reservoir.

Figure 9 on page 20 is a plot of the hypothetical 100-year flood at Concrete. The regulated curve shows the influence of reservoir flood control operations.

3.0 Example of Limited Flood Protection in the Skagit Basin

To illustrate the limited flood protection available in the Skagit Basin, a HEC-5 simulation was conducted with theoretical unlimited storage in both Ross and Upper Baker Reservoirs. All of the 100-year inflow hypothetical hydrographs were stored with no discharge from the reservoirs. Figure 10 illustrates the results. The hypothetical 100-year regulated peak discharge at Concrete is 222,000 cfs, while the largest possible reduction in the peak at Concrete is 205,000 cfs. The floodplain inundated in the lower basin would be about the same, as levees near Mt. Vernon overtop between 140,000-160,000 cfs. This example shows the limited flood protection potential in the Skagit Basin with the current reservoirs. The reservoirs were built for hydropower generation. They were constructed high in the basin, where gradients are steep and head drop can be utilized to generate power. Only 40 percent of the drainage is controlled by dams, leaving 60% of the drainage area uncontrolled. The Sauk, Cascade and other rivers below the dams alone have the potential to produce uncontrolled, damaging flood flows.

The current flood control reservoirs only provide approximate 20-25 year flood protection for the lower basin population centers. Levees near Mt Vernon will likely overtop when a greater than 30-year regulated flood event occurs.

Figure 8 - Regulated and Unregulated 100-year Hypothetical Hydrographs for Skagit River near Concrete

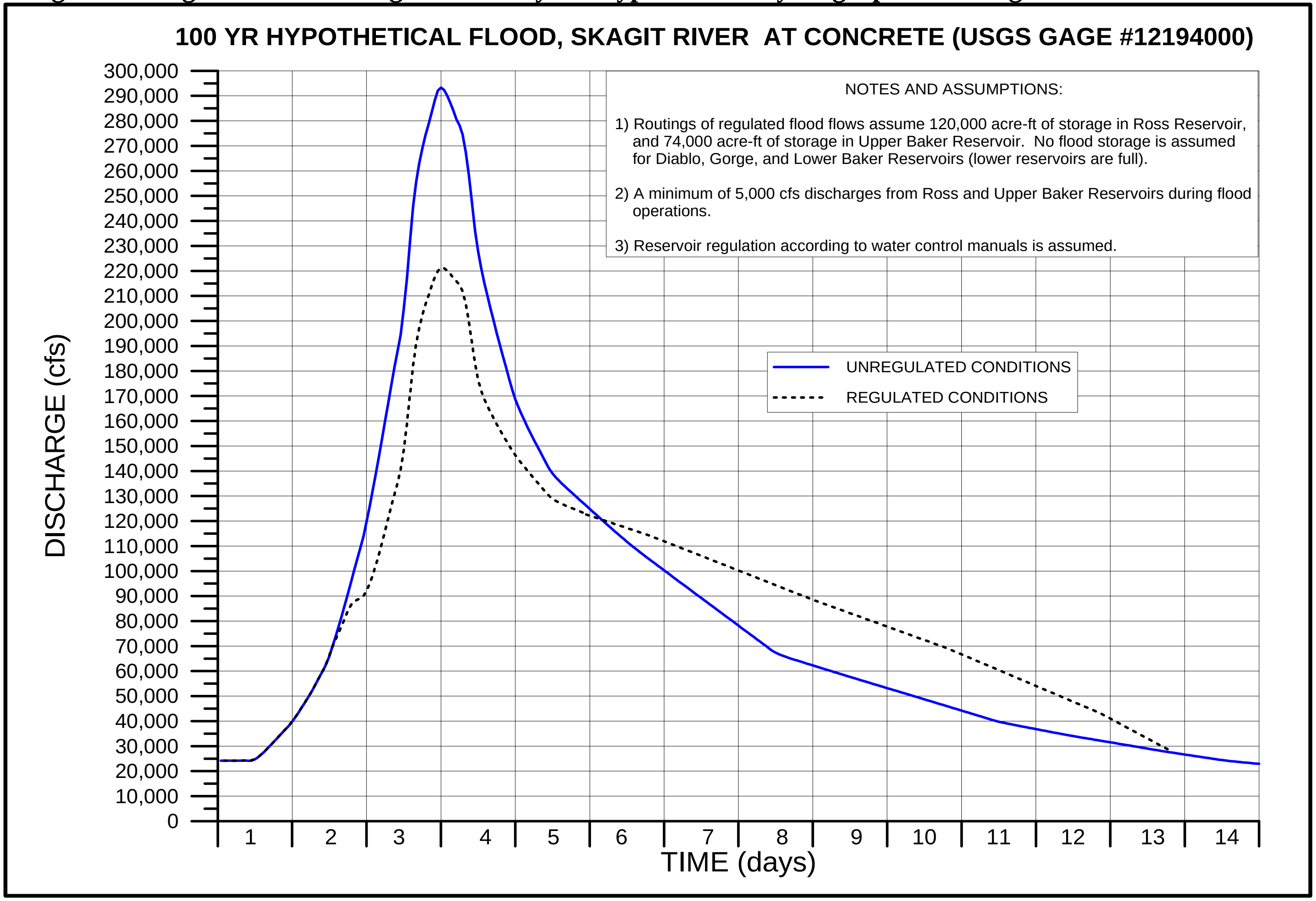
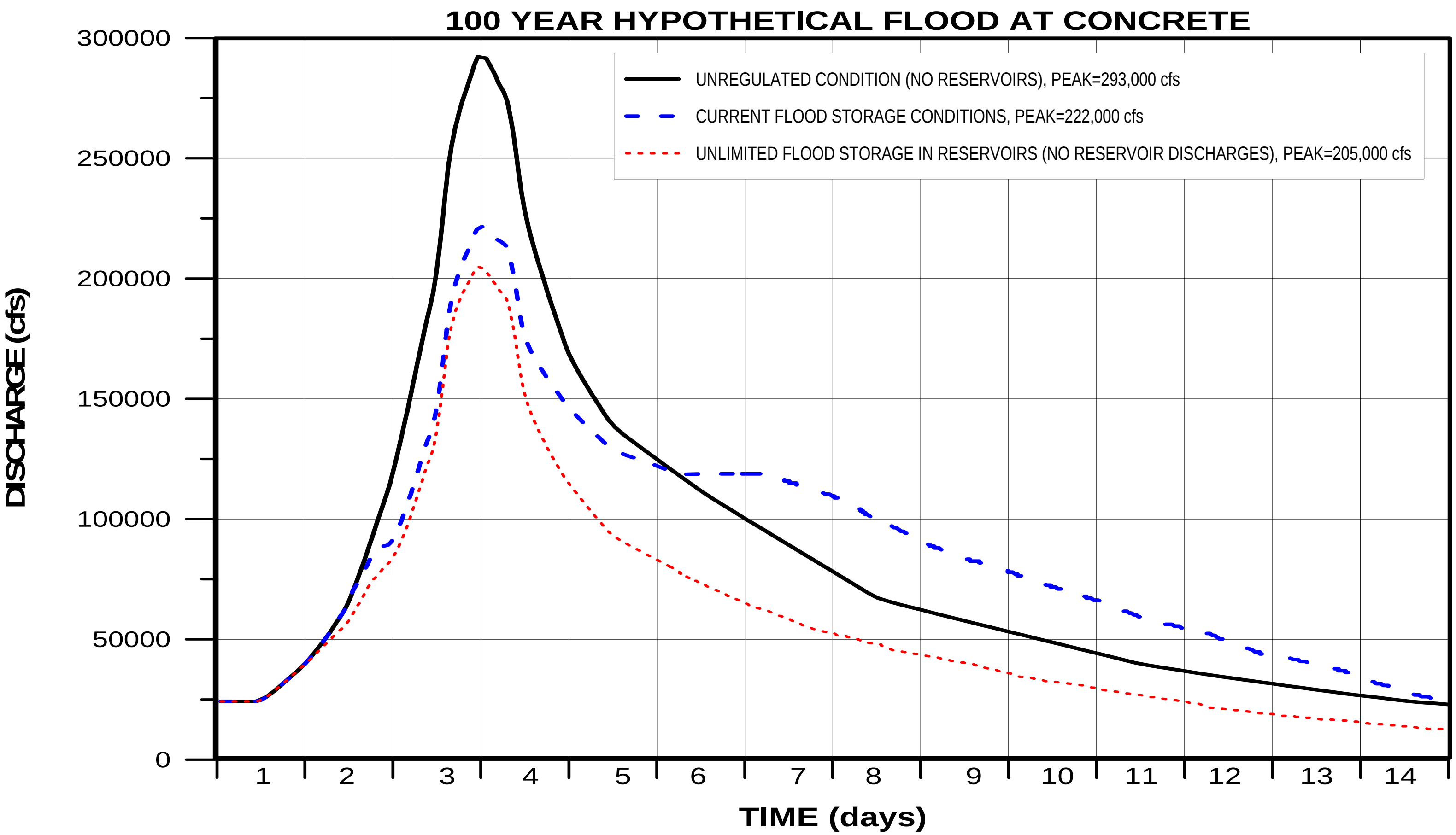


Figure 9 - Regulated and Unregulated 100-year Hypothetical Hydrographs for Skagit River near Concrete with an Additional Maximum Regulation Run



SKAGIT RIVER BASIN HYDROLOGY
FROM CONCRETE TO MOUNT VERNON

1. Previous 1998 Hydrology Investigation

This narrative follows after the report, "1998 Skagit River Basin Hydrology Investigation." The 1998 investigation extended from Ross Reservoir to Newhalem, Marblemount, Sauk River, Baker River (with reservoirs), to Concrete. The focus of the 1998 study was to determine the frequency of discharges along the main stem Skagit River. Storm discharges were converted to natural conditions by removing the effects of the flood-control storage reservoirs. The reservoir effects were then added back in by computing their effects on large storm hydrographs that were input to a basin model. The result of all the computations was a regulated frequency curve for the Skagit River at Concrete that showed peak discharges along a range of probabilities out to a 500-year event. Frequency curves for Concrete and upstream are in Appendix A of the Skagit River Basin Hydrology Investigation Report (**Reference**).

2. 1999 Hydrology Investigation

The 1999 hydrology investigation adds data from the smaller tributaries in the lower basin from Concrete to Mount Vernon including runoff from Nookachamps Creek, which accounts for 91% of the drainage area from Sedro Woolley to Mount Vernon. A tabulation showing the location of stream gages with their period of discharge observations is in Appendix D of the Skagit River Basin Hydrology Investigation Report. The scope of work for this study focuses on discharge magnitudes from the tributaries, which adds to the primary flow along the main stem Skagit River below Concrete. The hydrology investigation does not compute discharges along the main stem Skagit River below Concrete due to unknown routing effects. The river below Concrete spreads out into a wider and shallower flood plain. The Skagit River water surface elevation becomes much more sensitive to channel characteristics with and without levees, changing flood plain widths, bridge crossings, and back-water caused by slower velocities as the gradient reduces near the mouth. A hydraulic model is used to calculate the time-varying discharges and stages along the Skagit River instead of a hydrologic model. The hydraulic model takes regulated discharge conditions at Concrete, adds tributary flow along the lower Skagit River and calculates information that is used to construct discharge frequency curves at Sedro Woolley and Mount Vernon. Other calculations produce water surface profiles for various conditions. The hydraulic model is calibrated by numerous field observations taken during 2 large floods, the December 1975 event and the November 1995 event. This hydrology study continues by determining the local inflow along the main stem during the December 1975 and the November 1995 flood events.

3. Local Inflow Using the Hydraulic Model

Local inflow for the 2 storm events was first calculated during calibration computations of the hydraulic model. The primary input to the hydraulic model was the observed discharge hydrograph at Concrete. A secondary input was a local flow hydrograph that was evenly distributed by the model along all the cross sections. The unknown local flow hydrograph was estimated by scaling down the observed Concrete hydrograph. Computations were made by the model and the calculated water surface was compared to field observations at observed locations. A new estimate of the scaling factor was made according to whether the calculations were high or low compared with the observed high-water marks. This iterative procedure was continued until the magnitude of adjustments became insignificant. The shape of the local inflow hydrograph determined in this manner had the same shape as the Concrete hydrograph. This hydrologic investigation started by checking the shape and volume of the inferred local inflow hydrographs so a reasonable amount of water was routed downstream to not only match observed water surface elevations, but to match volume characteristics observed at the stream gages. Appendix B of the Skagit River Basin Hydrology Investigation Report includes many plots of peak versus 1-day, 3-day, and 7-day discharges at significant gates. The appendix also includes cross comparisons between the same durations at upstream and downstream locations. These relationships were used in this analysis and supplemented where needed at locations downstream of Concrete.

4. December 1975 Flood Event

The December 1975 flood event was a fairly large magnitude flood. The Skagit River flood peak of 122,000 cfs at Concrete was approximately a 10-year event. This flood happened to occur when there was many active stream gages in the basin. Figure 1 shows the relative locations of stream gages between Concrete and Mount Vernon. Table 1 shows the flood peaks recorded at and near the lower Skagit River. Most of the gages also have daily discharges available. However, the gages on Alder Creek, Day Creek, East Fork Nookachamps Creek, and Samish River were crest stage recorders without daily discharges. The South Fork Nooksack River was included because it measures runoff from the drainage area on the north side of the ridge east of Lyman Mountain. The south side of the same ridge includes runoff into the Skagit River and includes the Alder Creek basin.

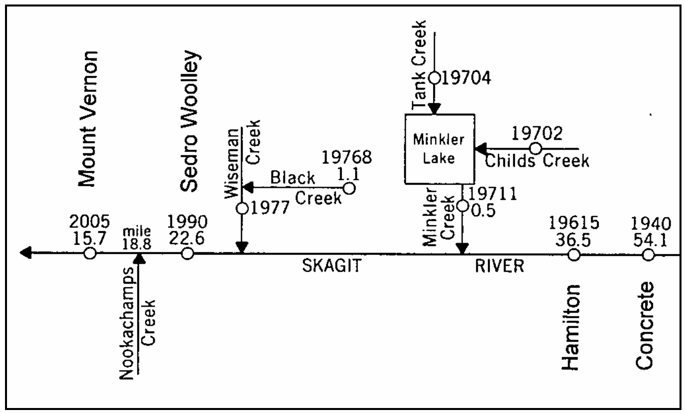


Figure 1. Schematic of stream gage locations from 1976 USGS Water Data Report.

Table 1. December 1975 Flood Observations Below Concrete

River	Location	Area	Date	Peak (cfs)	Peak per Area
Skagit River	Concrete	2,737	12-4-75	122,000	44.6
Alder Creek	Hamilton	10.7	12-3-75	482	45.0
Skagit River	Hamilton	2,870	12-4-75	122,000	42.5
Day Creek	Lyman	6.56	12-3-75	977	148.9
Childs Creek	Lyman	2.4	12-2-75	320	133.3
Minkler Creek	Lyman	5	12-2-75	150	30.0
Wiseman Creek	Lyman	3	12-2-75	462	154.0
Skagit River	Sedro Woolley	3,015	12-4-75	121,000	40.1
Ea.Fk. Nookachamps Cr.	Big Lake	3.56	12-2-75	636	178.6
Skagit River	Mount Vernon	3,093	12-4-75	130,000	42.0
Samish River	Burlington	87.8	12-2-75	6,090	69.4
So.Fk. Nooksack River	Wickersham	103	12-2-75	17,200	167.0

Examination of the peak discharges at the top of the table shows that the runoff between Concrete and Hamilton equaled the amount that was attenuated because the Skagit peak was the same at both locations. Some of the creeks between Hamilton and Sedro Woolley had relatively high peaks on the 2^{nd} and 3^{rd}, the runoff on the 4^{th} must have been much less than the peaks. Runoff between Sedro Woolley and Mount Vernon was greater than the sub areas above Sedro Woolley as shown by the relatively high discharge of East Fork Nookachamps Creek and the increase in the peak discharge on the Skagit River at Mount Vernon. The main stem Skagit River is divided into 2 reaches.

4.1 Concrete to Sedro Woolley

Daily discharges measured by the USGS below Concrete were tabulated for 3 small creeks in table 2. The small creeks had different responses to the December 1975 storm.

Table 2. Daily Discharges for the December 1975 Event

Day	Concrete	Minkler	Childs	Wiseman	So. Fk. Nooksack	Local =0.73*SF Nooksack
30 Nov	18,000	24	40	45	820	596
1 Dec	25,700	130	*200*	143	2,790	2,030
2 Dec	72,800	*150*	197	*306*	9,920	7,210
3 Dec	*108,000*	100	65	187	*10,100*	*7,340*
4 Dec	108,000	70	40	103	6,410	4,660
5 Dec	67,900	40	20	49	2,140	1,560
Area	2,737	5.0	2.4	3.0	103	278

There was a tendency for the maximum daily discharge of the storm runoff to shift to the 2^{nd} and 3^{rd} of December as the size of the drainage area increased. The drainage area for the South Fork Nooksack River was closer to the area of the local runoff basin so it was selected as an indicator for local runoff on the lower Skagit River. The daily discharges on the South Fork Nooksack River were scaled to the local Skagit River drainage area by using a ratio of the unit peak discharge of Alder Creek and the peak discharge of South Fork Nooksack River. The ratio computed to 0.73 and was multiplied times the daily discharges on the South Fork Nooksack River to obtain an estimate of the daily local discharge between Concrete and Sedro Woolley.

Other techniques were used to examine local flows, but not used in the final computation. For instance, daily discharges at Concrete, Hamilton, Sedro Woolley, and Mount Vernon were directly compared. Attempts were made to compute incremental local inflows between the gages by subtracting the downstream gage from the upstream gage. However, the subtraction produced many negative numbers because the process was sensitive to unknown routing effects. Even by assuming different routing parameters, the negative values came closer to positive, but still persisted. It was assumed the measurement of daily values was not accurate enough for this process. The daily discharges computed from South Fork Nooksack were further factored to hourly discharges by using hourly discharges from the hydrograph that was computed from the hydraulic process of fitting high water marks. The resulting hydrograph was reduced to daily values for comparison with the local computation in the above table. Values in the hourly hydrograph were multiplied by the appropriate factor for that day. The hourly values were smoothed as the discharge hydrograph crossed midnight from one day to another that had a different daily conversion factor. The resulting hydrograph is shown in figure 2.

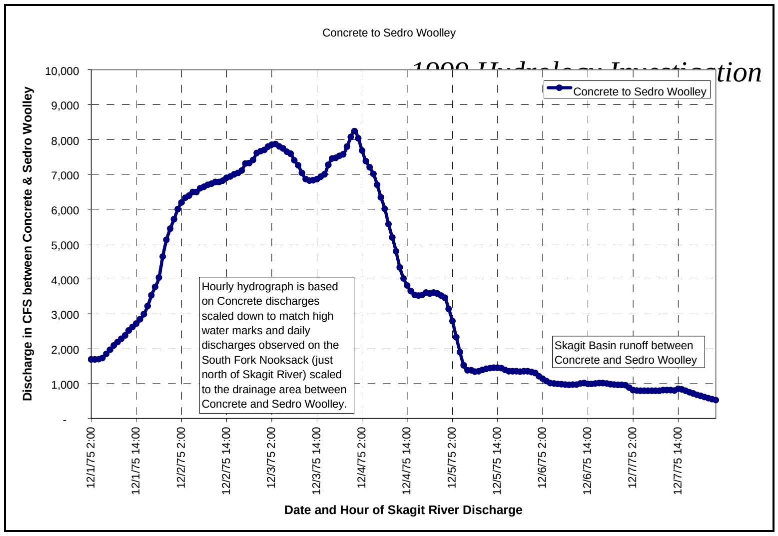


Figure 2. Skagit basin runoff between Concrete and Sedro Woolley for the December 1975 storm.

4.2 Sedro Woolley to Mount Vernon

The Nookachamps Creek hydrograph was computed from the peak on the East Fork (table 1) and a 1-day to peak discharge relationship. Other daily discharges were computed from Minkler, Tank, & Wiseman Creeks factored from 7-day relationships among the creeks. East Fork Nookachamps Creek was then routed to its mouth by adding flow proportional to the observed Samish runoff. Samish River lies adjacent to the Skagit River north of Burlington and should have similar runoff characteristics to the Skagit River reach in the same vicinity. Samish River had an observed peak, but no daily discharges. The small amount of local flow below the Nookachamps to Mount Vernon was added as a percent (8.9%) of Nookachamps occurring 1 day earlier.

5. November 1995 Flood Event

There was not as much discharge data recorded during the November 1995 flood event as there was during the November 1975 event. Table 3 shows peak observations at the available gages.

Table 3. November 1995 Peak Flood Observations Below Concrete

River	Location	Area	Date	Peak (cfs)	Peak per Area
Skagit River	Concrete	2,737	11-29-95	160,000	58.5
Skagit River	Mount Vernon	3,093	11-30-95	141,000	45.6
So.Fk. Nooksack River	Wickersham	103	11-29-95	16,900	164.1

There was no small tributary data such as was available for the 1975 flood, the only data available nearby for a moderate sized drainage area was at the South Fork Nooksack gage near Wickersham. The November 1995 event was analyzed by first estimating runoff from the total drainage area between Concrete and Mount Vernon, then dividing the hydrograph into smaller sub basins.

The comparison of the peak discharge at Mount Vernon and Concrete in table 3 suggests that there is very little inflow between the gages. A comparison of all the peak flows from 1941 to 1996 is available as a plotted chart in the Skagit River Basin Hydrology Investigation Report (Appendix B). There is a wide range of flows expected at Mount Vernon given a particular discharge at Concrete. Two of the most extreme events at these 2 locations occurred in 1980 and 1990. These events are compared with the Nov. 1995 event in table 4. Notice the proportion of the Mount Vernon peak is nearly the same as the average value between the 2 extreme events. This means that the amount of local inflow from tributary runoff between the gages during the 1995 event is not expected as a minimum, it is likely close to some average expected value.

Table 4. Comparison of Large Peak Floods at Concrete & Mount Vernon

River	Location	Nov. 1995	Nov. 1990	Dec. 1980
Skagit River	Concrete	160,000	149,000	148,700
Skagit River	Mount Vernon	141,000	152,000	114,000

Ratio of Mount Vernon to Concrete	88%	102%	77%
Average of 1949 & 1990 ratios		89%	

5.1 Concrete to Mount Vernon

Daily discharges observed by the USGS in the Concrete-to-Mount Vernon vicinity are shown in table 5. Discharges for the South Fork Nooksack gage were scaled to the total local drainage area between Concrete and Mount Vernon by using a drainage area ratio. The resulting discharges were compared with those obtained by the hydraulic method that added local inflow along the same reach by fitting the computed water surface along a profile determined from high water marks observed during the flood. By lagging the discharges computed from the South Fork Nooksack earlier by one-half day, the resulting hydrograph better represents the smaller and faster drainage basins and has nearly the same fit along the water surface profile of high-water marks. The daily values for the total local flow hydrograph is shown in the last column of table 5. Notice the relative magnitude of the values compared to the South Fork Nooksack is much smaller than the relative magnitudes in the November 1975 event. This total flow hydrograph was then further scaled down to the drainage areas of Nookachamps Creek and the area size between Concrete and Sedro Woolley.

Table 5. November 1995 Flood Observations By Date

Date	Skagit at Concrete	Skagit at Mt. Vernon	South Fork Nooksack	Total Local, Conc. To Mt.Vern.
27 Nov	45,600	51,900	1,890	2,315
28 Nov	65,500	59,300	8,000	3,877
29 Nov	131,000	91,600	13,400	1,206
30 Nov	106,000	132,000	4,170	718
1 Dec	78,200	93,600	2,480	538
2-Dec	70,200	78,700	1,860	402
Area	*2,737*	*3,093*	*103*	*356*

6. Hypothetical Floods

6.1 Base Flood for Pattern

Same as used in prior studies

6.2 10-, 50-, 100, 250-, & 500-Year Floods

Based on Concrete. Based on peak, 1-day, 3-day, & 7-day relationships with Concrete peak.

7. Discharge-Frequency Relationships near Main Stem.

7.1 Nookachamps Creek

Based on previous study because there is no new data.

7.2 Samish River

Update of previous curve.

7.3 Tidal Frequency

Based on previous study because there is no new data.

8. Discharge-Frequency Relationships on Main Stem

8.1 Sedro Woolley

Based on Concrete with the addition of local inflows between Concrete and Sedro Woolley.

8.2 Mount Vernon

Based on Sedro Woolley with the addition of local inflows at Nookachamps Creek and between Nookachamps Creek and Mount Vernon.

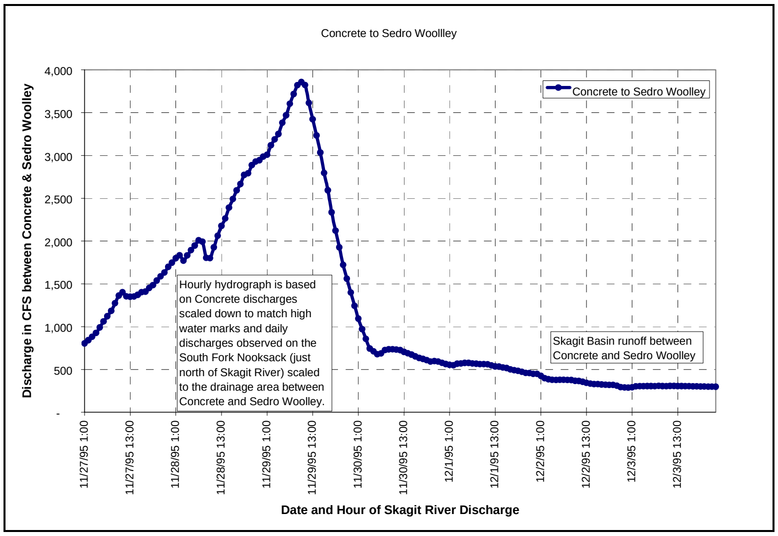


Figure 3. Skagit basin runoff between Concrete and Sedro Woolley for the November 1995 storm.

9. Continuation of Hydrology Investigations

After coordination with hydraulic computations on the Skagit River downstream from Concrete, the hydrology investigation will continue with natural Skagit River discharge-frequency curves determined at Sedro Woolley and Mount Vernon. Phase II hydrology investigation will produce hydraulic and hydrology information for the river with proposed structural modifications for flood control in place. Hydrologic analysis will then conclude with the development of regulated condition discharge-frequency curves at Sedro Woolley and Mount Vernon. These will be used to determine economic benefits and costs of proposed features.

9.1.1 Notes:

Upper local(278A) is based on Alder(q10=54) and S.F.Nooksack(q10=28)

Lower local(78A) is based on E.F.Nookachamps(q10=180) and Samish(q10=60)

The study in the 1970's was based on Alder Creek alone.

The 1998-1999 study has additional information in the way of local flows from Newhalem to Marblemount.

Location	Drainage Area	10-Year cfs per sq.mi.	100-Year cfs per sq.mi.	Ratio of 100 to 10-year
Alder Creek (44-79)	10.7 sq.mi.	54	87	1.61
Marblemount Local	206 sq.mi.	173	398	2.30
Nookachamps nr. Clear Lk.	20.5	179	215	1.20
S.F.Nooksack	103	277	427	1.54
various locations	observed discharges and high water marks indicate that local runoff between Concrete and Mount Vernon is relatively low.			

Local inflow should be based on observations and at locations where there are frequency curves.