Skagit River Basin
Skagit River Flood Risk Management Feasibility Study

FINAL REPORT

HYDROLOGY TECHNICAL DOCUMENTATION

US Army Corps
of Engineers

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HYDROLOGY TECHNICAL DOCUMENTATION
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APPENDICES

Important Note on Elevations and Vertical Datum

Elevations in this document are reported to a variety of vertical datums including NGVD29, NAVD88 and local datums, and are provided for general context or general information purposes only; elevations should be checked before being used for any other purpose.

1.0 Background

1.1 General

Authority for the Skagit River, Washington, flood risk management feasibility study is derived from Section 209 of the Flood Control Act of 1962 (Public Law 87-874). Section 209 authorized a comprehensive study of Puget Sound and Adjacent Waters, including tributaries such as the Skagit River, in the interest of flood risk management, navigation, and other water uses and related land resources. The current feasibility study was initiated in 1997 as an interim study under this statutory authority. Skagit County is the local sponsor of the feasibility study and is providing a combination of cash and in-kind services equaling 50 percent of the total study effort. The purpose of the study is to formulate and recommend a comprehensive flood risk management plan for the Skagit River floodplain that will reduce flood risk in Skagit County with a focus on downstream of Sedro-Woolley.

The authorization for the Skagit River Flood Risk Management Feasibility Study necessitated hydrologic and hydraulic analysis of the Skagit River basin. This allows for a basin-wide, systematic evaluation of the Skagit River. These analyses incorporate historical rainfall-runoff, reservoir operations, and flow along the major river systems to effectively evaluate the hydraulic performance of the flood management systems. The models can be used to assess the performance of the current systems or modified systems under a wide range of hydrologic conditions.

1.2 Purpose of Documentation

The main goal of the hydrologic analysis is to provide the hydrologic inputs necessary to adequately evaluate potential flood risk management measures. The main product components of this effort include:

- Description of the hydrologic analysis methodology
- Development of flows necessary to characterize the 2-, 5-, 10-, 25-, 50-, 75-, 100-, 250-, and 500-year flood events for the Skagit River Basin

1.3 Study Area

The study area encompasses the mainstem Skagit River from Skagit Bay to Ross Dam, the Baker River from the confluence with the Skagit to Upper Baker Dam, the Sauk River from the confluence with the Skagit to the Sauk River at Sauk gage, and the Cascade River from the confluence of the Skagit to the old Cascade River at Marblemount gage. The Skagit River basin has a drainage area of 3,115 square miles.

1.4 Study and Technical Review Chronology

Draft Hydrology Technical Documentation for the Skagit River Flood Risk Management Feasibility Study was produced by the Seattle District USACE in August 2004, with technical review by the Hydrologic Engineering Center. Hydrologic analyses for the study were subsequently revised and updated by the Seattle District primarily to incorporate additional hydrologic data and to account for revisions by the US Geological Survey to published peak discharges for historic floods. However the Hydrology Technical Documentation was not updated at that time. Further revisions to the hydrologic analyses and preparation of a March 2011 update to the Hydrology Technical Documentation were carried out by Northwest Hydraulic Consultants Inc. (NHC) under contract to the local sponsor, Skagit County (contract C20080424, Task Assignment 4, authorized 15 October 2009). Significant revisions or analyses conducted for the March 2011 update by NHC, in close consultation with the Seattle District, included:

- Use of computed probability flood quantiles throughout, consistent with requirements for subsequent risk and uncertainty analysis. (Earlier work incorporated an expected probability adjustment to flood frequency estimates).
- Analysis of the effects of seasonal variation in available flood control storage at Upper Baker and Ross reservoirs.
- Modification to “best” and “worst” case reservoir regulation scenarios to provide more realistic inputs for subsequent risk and uncertainty analyses.
- Reanalysis and downward adjustment of Nookachamps Creek coincident flows, incorporating hydrologic data either not used or not available for earlier work.
- Estimation of coincident flood hydrographs for Samish River, flows from which comingle with right bank Skagit River floodplain flows.

The present report is a further update to the March 2011 Hydrology Technical Documentation. Hydrologic analysis and preparation of the present August 2013 update were carried out by NHC under contract to the Seattle District USACE (contract W912DW-11-D-1006, Task Order No. 3). The principal revisions comprised:

- Updated analysis of the effects of seasonal variation in available flood control storage at Upper Baker and Ross reservoirs, including comprehensive update and revisions to Appendix G.
- Adoption of weighted regulated hydrographs to account for the effects of seasonal variation in flood control storage in place of previous “best” and “worst” case reservoir regulation scenarios.
- Updated routing of regulated and unregulated flows using the most recent (February 2013) HEC-RAS model of the lower Skagit River which includes revisions to the model representation of the BNSF railroad bridge at about

RM 17.6 and other model corrections and refinements. (Revisions to the HEC-RAS model are described in the study Hydraulic Technical Documentation)

The hydrologic analyses conducted by the USACE have relied on discharge data published by the USGS, including the USGS-published estimates of peak discharges for the historic floods of water years 1898, 1910, 1918 and 1922 on the Skagit River near Concrete. Particular attention has focused on the estimated magnitudes of these events since they have a significant influence on estimates of Skagit River flood quantiles. Reviews have been performed by County consultants (NHC 2010, NHC 2007, and PIE 2004), federal agencies (USGS 2010, FEMA 2010, USGS 2006, and FEMA 2006), and City of Burlington (PIE 2010 and PIE 2008). Reassessments of the magnitude of the historic floods were conducted by the USGS following the flood of October 2003 (USGS 2005), and again following the flood of November 2006 (USGS 2007). The USGS 2007 reevaluation resulted in a downward adjustment of about 5% in the estimated magnitude of the historic floods to produce the current published values which provide the basis for the updated hydrologic analyses presented both in the March 2011 report and in this report.

A chronological list of **selected** flood hydrology reports, reviews and reevaluations is provided in Appendix A. Many of the documents referred to in Appendix A can be found at www.skagitriverhistory.com.

2.0 General Basin Characteristics

The Skagit River basin is located in the northwest corner of the State of Washington (see Figure 1). The Skagit River drainage area is 3,115 square miles and the basin extends about 110 miles in the north-south direction and about 90 miles in the east-west direction between the crest of the Cascade Range and Puget Sound. The northern end of the basin extends 28 miles into Canada.

The Skagit River originates in a network of narrow, precipitous mountain canyons in Canada and flows west and south into the United States where it continues l35 miles to Skagit Bay. Skagit River falls rapidly from its source to an elevation of 1600 ft at the United States-Canadian Border. Stream profiles on Figure 2 show that within the first 40-miles south of the International Border, the River falls 1,l00 feet and that the remaining 500 feet fall is distributed along the 95 miles of the lower river.

The Skagit River crosses a broad outwash plain between Sedro-Woolley and the river mouth. Immediately downstream from Mount Vernon, the river divides into two principal distributaries, the North Fork and the South Fork. These two distributaries carry about 60 percent and 40 percent of the normal flows of the Skagit River, respectively. During floods, flows on the two distributaries are approximately equal.

The Skagit Valley, the 100,000-acre valley area downstream from the town of Concrete, contains the largest residential and farming developments in the basin. The 32-mile long valley between Concrete and Sedro-Woolley is made up of mostly cattle and dairy pasture land and wooded areas. West of Sedro-Woolley, the flood plain forms a large alluvial fan with an east-west width of about 11 miles and a north-south width of about l9 miles.

2.1 Topography

A major portion of the Skagit River basin lies on the western slopes of the Cascade Range. Most of the eastern basin is mountainous land above an elevation of 6,000 ft. The two most prominent topographical features in the basin are Mount Baker at an elevation of l0,778 feet on the western boundary of the Baker River basin, and Glacier Peak at an elevation of l0,568 ft in the Sauk River subbasin. In the eastern basin, 22 peaks are above an elevation of 8,000 ft. The upper reaches of nearly all tributaries are situated in precipitous steep-walled mountain valleys.

The Skagit River flows in a l-mile to 3-mile wide valley from Rockport to Sedro-Woolley. In this section, the valley walls are moderately steep timbered hillsides with few developments. Below Sedro-Woolley, the valley falls to nearly sea level and widens to a flat, fertile outwash plain that joins the Samish valley along the northeast side of the valley and extends west through Mount Vernon to La Conner and south to the Stillaguamish River near Stanwood.

2.2 Geology

The eastern mountainous region of the upper Skagit Basin consists of ancient metamorphic rocks, largely phyllites, slates, shales, schists, and gneisses together with intrusive granitic rocks and later andesitic lavas and pyroclastic deposits associated with Mount Baker and Glacier Peak. The valleys are generally steep sided and frequently flat floored. Valley walls are generally mantled with a mixture of rocky colluvium, and to a considerable elevation, by deposits of continental and alpine glaciation. These deposits are a heterogeneous mixture of sand and gravel together with variable quantities of silt and clay depending on the mode of deposition. Some of these deposits are highly susceptible to land sliding when saturated.

The floodplain of the Skagit River below Concrete is composed of sands and gravels that diminish to sands, silts, and some clays further downstream. Below Hamilton, fine-grained floodplain sediments predominate. The Baker River valley in the vicinity of the Baker Lake is geologically quite different from most of the other Skagit tributaries. This is largely due to the influence of Mount Baker, a volcanic cone rising to an elevation of l0,778 feet, that sets astride the western boundary of the Baker River basin.

Present bedrock exposures adjacent to Ross Lake consist of Chilliwack sediments, volcanics and granitics, Skagit gneiss, and Nooksack group phyllite. The continental ice movement and mountain glaciers sculpted the basic geological forms and rock types into the major landforms that are recognizable today. A large mass of metamorphic rock, known as the Skagit gneiss, forms the foundation rock for all three of the Skagit River Project hydroelectric plants. The age of its parent strata is presumed to be Paleozoic. The resistance to erosion provided by the massive gneiss is undoubtedly the reason for the narrow gorge of the Skagit River where the dams are located. Alpine glaciers have contributed to the steepness of the valley sides and to the depth of the valley bottoms. Over ten thousand years ago the upper Skagit Valley and the peaks were severely glaciated, removing not only the soil, but much of the loose rock. Many river channels created during the glacial melt have continued to aggrade, and as a result of that glacial action, the bedrock bottoms of most canyons are covered with glacial alluvium.

2.3 Sediment

Predicted rates of bed accumulation for 100 years in the Skagit River system vary in depth from 4 feet at the mouth of the 2 distributaries, the North and South Forks of the Skagit River, to 2 feet at Mount Vernon. The 2 feet of depth continues upstream to Burlington. The River annually transports about 10,000,000 tons of sediment of mostly glacial origin. Size of bed material, as determined by field observations and samples, varies from 1/4-inch to 3/4-inch gravel and coarse sand at Mount Vernon to medium and fine sand near the River mouths. From Burlington to Concrete, channel sediments are predominantly fine-to-coarse sands, gravels, and cobbles together with small quantities of silt and clay.

2.4 Climate

The major factors influencing the climate of the Skagit River basin are terrain, proximity of the Pacific Ocean, and the position and intensity of the semi-permanent high and low pressure centers over the north Pacific. The basin lies about 100 miles inland from the moisture supply of the Pacific Ocean. Westerly air currents from the ocean prevail in these latitudes bringing the region considerable moisture, cool summers, and comparatively mild winters. Annual precipitation throughout the basin varies markedly due to elevation and topography. Major storm activity occurs during the winter when the basin is subject to rather frequent ocean storms that include heavy frontal rains associated with cyclonic disturbances generated by the semi-permanent Aleutian Low. During the summer months, the weather is relatively warm and dry due to increased influence of the semi-permanent Hawaiian high-pressure system. A summary of precipitation, snowfall, and temperature data for twelve representative stations is provided in Table 1. The locations of climatological stations in or near the basin, station elevations, and periods of record are shown on Figure 3.

2.4.1 Temperature

Normal monthly mean temperature data for eight representative stations are presented in Table 2. The mean annual temperature for stations in or near the basin varies from 47.8 degrees Fahrenheit (^{o}F) at Upper Baker Dam to 51.0^{o}F at Anacortes. Normal monthly temperatures vary in January from 32.9^{o}F at Ross Dam to 40.3^{o}F at Anacortes, and in August from 66.1^{o}F at Ross Dam to 62.7^{o}F at Anacortes. The temperature extremes recorded in the basin are 109^{o}F at Newhalem and -14^{o}F at Darrington Ranger Station.

TABLE 1 - SUMMARY OF CLIMATOLOGICAL DATA (STANDARD UNITS)

	ELEV. (feet)	PERIOD OF RECORD	ANNUAL PRECIP. MEAN (inches)	ANNUAL PRECIP. GREATEST (inches)	ANNUAL PRECIP. LEAST (inches)	SNOW FALL MEAN (inches)	ANNUAL TEMP. MEAN ° F	ANNUAL TEMP. HIGHEST ° F	ANNUAL TEMP. LOWEST ° F
ANACORTES	34	1893-2005	26.20	39.43	15.89	4.5	51.1	95	4
BAKER LAKE	674	1926-1934	102.88	133.39	69.26	58.1	NA	NA	NA
CONCRETE FS	199	1920-2005	68.13	93.12	46.85	24.8	50.9	106	-1
DARRINGTON RS	554	1926-2005	79.64	104.89	51.20	40.3	49.1	105	-14
DIABLO DAM	895	1934-2005	77.07	115.34	45.86	55.0	48.6	106	-10
MARBLEMOUNT RS	352	1941-2005	77.23	101.2	50.36	NA	NA	NA	NA
MT. BAKER LODGE	4,154	‘26-’42 ‘46-60	109.85	142.33	74.13	525.3	40.1	91	-12
NEWHALEM	529	1924-2005	81.41	104.22	47.59	36.6	49.6	109	-6
ROSS DAM	1236	1960-2005	57.31	79.11	38.66	47.5	48.6	101	-10
SEDRO WOOLLEY	64	1896-2005	46.44	69.2	28.18	8.4	50.8	99	-2
SILVERTON	1,479	1942-1987	112.61	151.27	77.03	88.0	46.7	103	0
UPPER BAKER DAM	694	1961-2005	101.83	132.61	68.61	52	47.8	102	-5

Records through 2005. NOT AVAILABLE (NA). RS = Ranger Station FS = Fish Trap

TABLE 2 - NORMAL MONTHLY MEAN TEMPERATURE DATA (°F)

STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Anacortes	40.3	42.4	45.5	49.8	54.9	59.0	62.3	62.7	58.8	51.5	44.7	40.5	51.0
Concrete	37.0	39.8	43.8	49.0	54.7	59.1	63.6	64.2	59.8	51.5	42.4	37.3	50.2
Darrington RS	35.4	38.9	43.8	49.4	55.8	60.3	65.2	65.4	59.8	50.3	41.0	35.6	50.1
Diablo Dam	33.6	36.7	41.5	47.5	54.4	59.7	64.8	65.8	59.8	49.9	39.7	34.3	49.0
Newhalem	34.6	37.2	41.8	47.6	54.1	58.9	63.9	64.6	59.4	49.8	40.2	35.1	48.9
Ross Dam	32.9	35.7	40.6	46.6	53.6	59.3	65.1	66.1	59.7	49.8	39.3	33.8	48.5
Sedro Woolley	39.1	41.8	45.6	49.9	55.1	59.3	62.8	63.5	58.8	51.2	43.9	39.3	50.9
Upper Baker Dam	33.4	36.5	40.8	46.5	52.8	57.6	62.4	63.0	57.9	49.2	39.5	34.2	47.8

Climatological normals based on record period 1971-2000

TABLE 3 - NORMAL MONTHLY MEAN PRECIPITATION DATA (INCHES)

STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Anacortes	3.69	2.49	2.21	1.86	1.63	1.51	1.06	1.04	1.36	2.25	4.14	3.81	27.05
Concrete	9.99	7.56	6.92	4.86	3.71	3.01	1.83	1.69	3.23	6.20	11.37	11.02	71.39
Darrington RS	11.16	9.43	8.39	5.32	3.96	3.00	1.80	1.80	3.51	7.12	13.34	12.15	80.98
Diablo Dam	11.38	8.45	7.12	4.72	3.30	2.49	1.85	1.74	3.23	7.47	14.36	12.76	78.87
Mount Vernon	4.22	2.85	2.81	2.53	2.42	1.95	1.20	1.34	1.70	2.89	4.83	3.96	32.70
Newhalem	11.62	8.75	7.10	4.71	3.53	2.80	2.07	1.82	3.26	7.32	13.46	13.06	79.50
Ross Dam	8.84	6.47	5.14	3.01	2.15	1.65	1.39	1.22	2.19	5.23	10.51	9.64	57.44
Sedro Woolley	5.77	4.11	4.15	3.76	3.03	2.85	1.77	1.62	2.68	3.97	6.88	5.97	46.56
Upper Baker Dam	14.34	11.05	9.75	6.42	5.06	3.69	2.64	2.11	4.27	9.09	16.47	15.70	100.59

Climatological normals based on record period 1971-2000.

2.4.2 Precipitation

Normal monthly mean precipitation data for nine stations are presented in Table 3 preceding this page. Average annual precipitation over the Skagit basin varies by about 150 inches. Mean annual precipitation is 40 inches or less near the mouth of the Skagit River and in the portion of the basin in Canada that lies in topographic rain shadows. Average precipitation of l80 inches or more falls on the higher elevations of the Cascade Range in the southern end of the basin and over the higher slopes of Mount Baker. The annual precipitation over the basin above the town of Mount Vernon averages 92 inches with approximately 75 percent of this amount falling during the 6-month period, October-March. The mean monthly precipitation at stations in or near the basin ranges from 1.04 inches in August at Anacortes to 16.47 inches in November at Upper Baker Dam. The mean annual precipitation at Upper Baker Dam and Diablo Dam is 100.59 inches and 78.87 inches, respectively. The maximum-recorded precipitation for one month was 4l.95 inches at Silverton in January 1953. Storm studies indicate that 5 to 6 inches of rainfall in a 24-hour period have occurred over much of the basin.

The locations of precipitation stations presented in Table 3 together with several other stations in the Skagit basin vicinity are shown on Figure 3. A basin normal annual isohyetal map is shown on Figure 4.

2.4.3 Snowfall

Snowfall in the Skagit River basin is dependent upon elevation and proximity to the moisture supply of the ocean. The mean annual snowfall at stations in the basin varies from 4.5 inches at Anacortes to 525.3 inches at Mount Baker Lodge, with a maximum recorded value of 1,140 inches at Mount Baker Lodge during the July 1998 through June 1999 season. Snow surveys have been made within the Skagit River basin since 1943. Locations of snow courses in the basin are shown on Figure 3.

2.4.4 Wind

Surface wind speeds in the basin are the result of the pressure gradient between high- and low-pressure cells, storm intensity, and topographic effects. Prevailing winds in the lower basin are generally from the southerly quadrant from September through May and from the northerly quadrant from June through August. In the upper valleys above Concrete, the airflow is subject to a topographic funneling effect and is generally up the valley in the winter and down slope in the summer. A diurnal change in direction often occurs in the summer. Occasionally in the winter, cold continental air from eastern Washington or eastern British Columbia will flow through mountain passes creating cold east winds down the valley. In the winter season, storm winds will vary from 20 to 30 miles per hour (mph). During extreme events, winds will exceed 60 mph for short durations with 100 mph gusts occurring over mountain peaks.

2.4.5 Storms

Flood-producing storms occur chiefly during the winter season but are not uncommon in late fall or early spring. The sharp increase in frequency, duration, and severity of storms in late fall is a result of a southward displacement and renewed activity of the semi-permanent Aleutian low-pressure system. Frequently, a series of waves develop along the polar front. As the waves move landward, the unstable, moist air masses are orographically lifted by the mountains. This results in widespread, often heavy, precipitation that increases with elevation. Winter storms in the Pacific Northwest are typically of this basic type, having similar origins, air mass trajectories, and a moisture source in the Pacific Ocean. These storms sometimes follow in quick succession. On mountain slopes, storm precipitation is often heavy and continuous as a result of the combination of frontal and orographic affects. The November 1909, November 9-12, 1990, November 21-25, 1990, November 27-30, 1995 storm, and the October 16-21, 2003 storms are described below.

2.4.5.1. November 1909 Storm

November l909 was a month of above-average precipitation with a period of almost continuous moderate-to-heavy precipitation during the last 2 weeks of the month as a series of low-pressure systems moved across the Pacific Northwest. The fastest moving storm was the last one of the series which caused heavy rain on the 28th and 29th. During the 66-hour period beginning at 6 a.m. on the 27th and ending at midnight on the 29th, total storm precipitation amounts were 9.2 inches at Goat Lake, 8.3 inches at Skagit Powerplant, 5.9 inches at Concrete, and 2.5 inches at Sedro-Woolley. Maximum 24-hour amounts were 5.6, 5.8, 3.8 and l.3 inches, respectively, at these stations. The mean basin and maximum 24-hour precipitation for this storm period were 6.7 inches and 3.6 inches, respectively.

2.4.5.2. November 9-12 and 21-25, 1990 Storms

Precipitation amounts in Western Washington during the month of October were as much as 200 percent of normal. The snowpack was also 200 percent of normal and the snowline was at about 2000 feet mean sea level with an excess of 2 inches of water in the pack above 2,500 feet. The conditions, therefore, were primed to saturation in advance of the actual rainfall for the November 9-12 event. From November 9th through 12th, western Washington was dominated by a warm, moist subtropical air mass whose source region was an area just north of the Hawaiian Islands. During this entire period, the polar jet was vigorous, strong, and extraordinarily persistent. The core of the jet was generally oriented southwest to northeast and aimed at southern British Columbia and northern Washington. Maximum winds in the core of the jet were always in the excess of 100 knots and at times were in the 170-190 knot range.

Heavy and intense rains fell in western Washington during the 3-day period of November 8th through the 10th. Due to the strength and location of the core of the polar jet stream and the resulting wind structure at lower levels, the rains were highly orographic in nature. Heaviest rainfall centered in the Cascade Mountains from the Snoqualmie basin northward into Canada. The rainfall distribution can be seen in Table 4.

TABLE 4 – PRECIPITATION DURING THE NOVEMBER 8-11, 1990 STORM (INCHES)

River	Precipitation Station	November 8	November 9	November 10	November 11	Total
Sauk	Darrington	0.9	4.2	1.2	0.1	5.8
Skagit	Marblemount	0.9	6.1	2.5	0.1	9.6
Skagit	Diablo	4.0	7.3	1.0	0	12.3

Prior to the event, the freezing level was about 4,000 feet in western Washington but quickly jumped to 9,000-10,000 feet with the arrival of the tropical air mass. The freezing level stayed above 9,000 feet until November 13th and then dropped to about 3,000 feet late on November 14th. Warm air and rain falling on the snowpack melted an average of about 2 inches of water from the snowpack in the mountainous regions between 2,500 feet and 5,500 feet. Snowmelt, therefore, contributed significantly to the severity of flooding.

There was still substantial standing water left over from this first event in the basin when the second flood hit from November 21-26. A persistent low pressure system in the Gulf of Alaska generated a series of frontal systems that tracked across the Pacific Northwest from November 21st through the 26th. Normally there is a pool of heavy cold air that follows these frontal systems and forces them over the Cascades and into the Rocky Mountains. In this event, however, these frontal systems lacked sufficient cold air to drive them swiftly through the region. As a result, the systems were slow moving and stalled in the Cascades, allowing the orographic rains to continue much longer than normal. The cumulative rainfall for this event was greater than the first event but the first event had periods of much greater intensity. The rainfall distribution for this event can be seen in Table 5.

TABLE 5 – PRECIPITATION DURING THE NOVEMBER 21-25, 1990 EVENT

River	Precipitation Station	Nov. 21	Nov. 22	Nov. 23	Nov. 24	Nov. 25	Total
Sauk	Darrington	1.4	1.9	3.3	4.1	0.6	11.3
Skagit	Marblemount	1.0	2.5	1.0	2.2	0.3	6.0
Skagit	Diablo	2.8	3.5	5.8	3.2	0.2	15.5

Although the snowpack had built back up after the first event, the freezing level stayed quite low during the week of the event. Hence, although an average of 2 to 3 inches of water melted from the snowpack in the lower parts of the basins, the snowpack above 4,000 feet actually increased during the event. Snowmelt, therefore, did not contribute significantly to the severity of this event.

2.4.5.3. November 27-30, 1995 Storm

November 1995 was the wettest November on record at several locations in the Pacific Northwest. Flooding resulted from a combination of saturated ground, heavy rains, high freezing levels, and melting snow. Heavy rains that began on November 27 resulted from three storms that carried moisture laden, semi-tropical air into the Pacific Northwest. These storms were fed by a very strong polar jet stream that helped produce strong orographic precipitation on south and west facing slopes of the Olympic and Cascade Mountains. The heaviest rainfall from the first storm was in the central and northern Cascades, while the Olympics and southern Cascades felt the brunt of the last two systems. Four-day precipitation totals (November 27-30) at the NWS stations, Skagit River near Marblemount, and Sauk River near Darrington, were 7.5 inches and 5.7 inches, respectively. Inches of snow-water runoff during the November 1995 storm at Stevens Pass in the Skykomish River basin and at Corral Pass in the Green River basin, from snow pillow data, are listed in Table 6.

TABLE 6 - CHANGE IN SNOW-WATER EQUIVALENT FOR THE NOVEMBER 27-30, 1995 STORM

Date of Snow Observation	Stevens Pass Elev. 4070 ft	Corral Pass Elev. 6000 ft
Nov. 28	5.30 in	4.00 in
Nov. 29	4.70 in	4.00 in
Nov. 30	3.40 in	3.50 in
Dec. 1	4.40 in	4.00 in
Dec. 2	5.40 in	4.60 in

2.4.5.4 October 16-21, 2003 Storm

Prior to this event, northwest Washington experienced the driest summer on record and September precipitation about 50% of normal. As a result, soil conditions were relatively dry when the first storm made landfall on October 15th. The storm was made up of two events: the first between October 15th and 18th and the second one between October 19th and 23rd. Both storms were charged with tropical moisture that was transported into the area by the jet stream. These types of event have been typically called “pineapple express” events due to the long southwesterly moisture fetch. Being of tropical origin, the air contained very high concentrations of precipitable water (around 1.5 inches). The combination of high precipitable water and high speed jet stream results in very heavy precipitation on favorable slopes. Freezing levels were also very high, so precipitation during these events fell as rain at all elevations in the basins.

Measurements made at NRCS SNOTEL sites within the Skagit and Nooksack Basins on October 15 showed that 6 of the 9 stations had no snow and the remaining sites had only a few tenths of an inch of snow water equivalent. On October 20, prior to the onset of the heaviest rainfall, the snow water equivalent only increased by a few tenths of an inch. Low snow water equivalent is typical for this time of year. On October 21 after the heaviest precipitation, the snow water equivalent was relatively unchanged, indicating that snowmelt or rain-on-snow did not contribute toward the magnitude of the flood event.

Record 24-hour rainfall totals were recorded at Ross Dam (5.63 inches) and Upper Baker Dam (6.60 inches) on October 16th. Both records are noteworthy because each of these gages has a record length greater than 35 years. Other noteworthy 24-hour rainfall totals include 5.3 inches at Ross Dam on October 20th (second wettest 24-hour period of record), 6.8 inches at Darrington on October 20th (second wettest 24-hour period of record), and 6.82 inches at Diablo Dam (wettest 24-hour period of record in October). This suggests that the heavy rainfall during the first storm event on October 16th was sufficient to prime the basin for the flooding that resulted following the arrival of the second storm event on October 20th. This resulted in large instantaneous peak flows in the upper basin including a 124-year recurrence flow at the Sauk River at Sauk gage (119,000 cfs), a 72-year recurrence flow at the Thunder Creek near Newhalem gage (17,600 cfs), a 70-year recurrence flow for the inflow to Upper Baker Dam (37,000 cfs), and a 50-year recurrence flow for the inflow to Ross Dam (45,000 cfs). The regulated peak flow at Concrete of 166,000 cfs corresponds to roughly a 30-year event. The unregulated event is estimated to be roughly 206,000 cfs, which corresponds to roughly a 25-year event (see Section 6.0, Table 22).

While the maximum 24-hour rainfall totals associated with the 1990 and 1995 events were lower than the maximum 24-hour totals during the 2003 event, the rainfall amounts preceding these events were much greater than the rainfall amounts preceding the 2003 event. For example, the fall months of both 1990 and 1995 were quite wet with November 1990 (31.3 inches) and November 1995 (30.9 inches) being the wettest two months of record at the Upper Baker Dam gauge. Although the intensity of the short-duration rainfall associated with the 1990 and 1995 events was less than similar duration rainfall during the 2003 event, the consistently wet conditions preceding these events resulted in larger overall runoff volumes and hence longer duration peak flows, which results in a higher peak flow at Mt. Vernon relative to the 2003 event. There was also no snowmelt component to the 2003 event due to the lack of preceding precipitation and the earliness of the season, which helped to keep the flood volumes down. The volumes of water seen in the peak 3-day period for the 2003 event were not nearly as unusual as the instantaneous peak flows. These 3-day volumes for the Sauk River at Sauk gage, the inflow to Upper Baker Dam, and the inflow to Ross Dam have recurrences of 10-year, 25-year, and 14-year, respectively.

2.4.6 Channel Characteristics

2.4.6.1 International Border to Gorge Dam

The Skagit River from the United States-Canadian Border to Gorge Dam flows through the three Skagit River Plants (Ross, Diablo and Gorge) in a hydraulically-connected reservoir waterway.

2.4.6.2. Gorge Dam to Newhalem.

The 15,000-feet long reach from Gorge Dam to the Gorge Powerhouse is usually dry during normal hydropower operations. During flooding, however, local runoff generally fills the limited storage space in Gorge Lake prior to the flood peak, causing Gorge to spill into the normally dry channel between the dam and Gorge Powerhouse. When the channel is filled below Gorge, releases from Ross can be routed to Newhalem in a half hour or less provided the spill gates at Diablo and Gorge are opened when the release is made at Ross.

2.4.6.3 Newhalem to Concrete

The 39.6 miles long Skagit River reach from Newhalem to Concrete falls approximately 8 feet per mile. The upper half of the reach contains a steep rugged channel located between narrow rock canyon walls in many places. Most of the channel bed is composed of large irregular-shaped boulders, rocks, and cobbles. The River flows in a series of water drops and deep pools. The lower half of the reach is much more placid with a wider flatter channel with smaller rocks and gravel materials. Hydraulic travel time from Newhalem to Concrete is approximately eight hours at the higher range of flows that occur during flood conditions.

2.4.6.4 Concrete to Mount Vernon

The 38.4 mile long reach from Concrete to Mount Vernon falls approximately 150 feet (an average of about 3.9 feet per mile). River gradients range from 5.3 feet per mile near Concrete to l.5 foot per mile below Sedro-Woolley. Hydraulic velocities vary according to the location along the river, ranging from 5 feet per second to 10 feet per second. This reach is comparatively placid with a wide, gravel-lined channel with mostly small cobbles and gravels, soil embankments, and numerous side channels, oxbows and overbank erosion scars created during large floods of the past. Travel time through this reach varies with the rate of discharge, decreasing from 15-20 hours at low flow to between 10-15 hours at higher discharges. There is a wide range of hydraulic travel times between Concrete and Mount Vernon and the above values are occasionally exceeded.

2.4.6.5 Mount Vernon to Skagit Bay

From Mount Vernon, the Skagit River flows approximately 6 miles to the point at which it splits into the North and South Fork distributaries. The North and South Fork then each flow approximately 8 miles, west and south respectively, to discharge into Skagit Bay. During moderate (10-year return period) flood conditions, tidal influence is felt approximately 7 miles upstream from the bay on the North Fork and 5 miles on the South Fork. The river gradient from Mount Vernon to Skagit Bay is approximately 2 feet per mile. Upstream from the tidally-affected reach, hydraulic velocities range from about 3 feet per second to 9 feet per second, depending on location and discharge. The Skagit River downstream from Mount Vernon is fully confined by levees on both banks. The North and South Forks are similarly confined until they approach Skagit Bay. The channel bed material from Mount Vernon downstream is predominantly sand.

2.4.7 Streamflow Characteristics

The Skagit River basin is subject to rain and snowmelt runoff during the fall and winter, and snowmelt runoff during the spring. Spring snowmelt runoff is caused predominantly by melting of the winter snowpack and is characterized by a relatively slow rise and long duration. Some minor contribution to the rate and peak of the snowmelt is occasionally provided by warm spring rains, but the spring rain-on-snow impact is usually not significant. Highest mean monthly snowmelt discharges are usually reached in June. The resulting runoff occasionally inundates low areas adjacent to the river but rarely reaches the major damage stage. The maximum-recorded spring snowmelt discharge at Mount Vernon was 92,300 cfs in April of 1959.

Power reservoirs are normally refilled during the annual spring snowmelt runoff; and as a result, the spring peak discharges are generally reduced. The Skagit River and all of its major tributaries usually have low flows during August and September after the high-elevation snowpack has melted and the baseflow has partially receded.

With the advent of heavy precipitation in the fall and winter, the Skagit River experiences a significant flow increase. Floods and the highest daily and highest instantaneous peak discharge of the year usually occur during this period. Heavy rainfall and warm winds during typical 1-3 day winter storms causes streamflows to rise rapidly in a matter of hours to flood levels. Streamflows recede rapidly within hours after the storms have moved eastward through the region, although base flows and basin soil moistures usually remain high for several days. Several minor rises usually occur each winter, while major floods are more intermittent. Winter rain-type floods usually occur in November or December but may occur as early as October or as late as February.

The Skagit River, which receives the effect of the initial lifting of Pacific air over the Cascade Range, varies in seasonal streamflow throughout the basin, generally due to the basin's heavy winter precipitation, spring snowmelt runoff, dry summers and topographical and elevation differences. The average annual runoff at the following stations reflects the runoff variation throughout the basin; Skagit River at the Newhalem streamgage, 50.8 inches; Sauk River Near Sauk streamgage, 82.4 inches; Baker River at Concrete streamgage, 121.1 inches; Skagit River near Concrete streamgage, 74.4 inches; and Skagit River near Mount Vernon, 72.7 inches. The 999 square mile watershed above Ross dam, located in the lee of western mountains that shield the basin from winter storms, has an annual runoff of only 45.6 inches. Average annual runoff at Ross and Upper Baker Dams is approximately 32 percent of the average annual runoff at Mount Vernon.

Maximum and minimum extremes in recorded annual runoff at Mount Vernon during the 1941-1999 period are 16,752,595 acre-feet in l991 and 7,608,893 acre-feet in l944 or 101.6 and 46.1 inches, respectively, for the 3,093 square mile basin.

2.4.8 Streamgage Stations

The locations of U.S. Geological Survey streamgaging stations in the Skagit River basin are shown on Figure 1 and a summary of both active and inactive gaging stations, along with their periods of record, is provided in Appendix B. A summary of streamflow data from selected long-term stations is provided in Table 7. Mean monthly streamflows for the Skagit River system are provided in Table 8.

TABLE 7 - SUMMARY OF STREAMFLOW DATA (CFS) 1/

STREAMGAGE	DRAIN. AREA MI^2	PERIOD OF RECORD	YEARS OF RECORD	AVERAGE ANNUAL DISCHARGE	MAXIMUM ANNUAL DISCHARGE	MINIMUM ANNUAL DISCHARGE	MAX. INST.	MIN. INST.
Skagit River at Newhalem	1,175	1909-14, 1921-2005	91	4,395	6,251	2,627	63,500	54
Sauk River near Sauk	714	1912, 1929-2005	78	4,332	6,048	2,662	106,000	572
Baker River below Anderson	210	1911-25, 1929-31, 1956-59	22	2,073	2,600	1,540	36,800	219
Baker River at Concrete	297	1911-15, 1944-2005	67	2,649	3,469	1,865	36,600	30
Skagit River near Concrete	2,737	1925-2005	81	15,010	21,270	9,512	166,000,	2,160
Skagit River near Mt. Vernon	3,093	1941-2005	65	16,560	23,140	10,500	152,000	2,740

1/ Data from USGS Water Resource Data through Water Year 2005. All years listed represent water years.

TABLE 8 - MEAN MONTHLY STREAMFLOWS (CFS)

STREAMGAGE	PERIOD	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Skagit River at Newhalem	1909-14, 1921-2004	3,130	4,014	4,062	4,123	4,082	3,756	4,170	5,890	7,314	6,129	3,646	2,781
Sauk River near Sauk	1912, 1929-2004	2,867	4,479	4,624	4,163	3,789	3,256	3,957	6,468	7,894	5,611	2,791	2,091
Baker River at Concrete	1911-15, 1944-2004	2,490	3,353	2,883	2,737	2,485	2,101	1,974	2,774	3,716	3,274	2,116	1,823
Skagit River near Concrete	1925-2004	11,240	15,550	15,850	14,850	13,790	12,150	13,800	20,230	24,430	19,120	10,830	8,563
Skagit River near Mt. Vernon	1941-2004	12,420	18,100	18,610	17,650	16,720	14,320	15,070	20,360	24,570	20,130	11,730	9,469

Notes: 1/ Data from USGS Water Resource Data through Water Year 2004

2.4.9 Floods

Major floods on the Skagit River are the result of winter storms moving eastward across the basin with heavy precipitation and warm snow-melting temperatures. Several storms may occur in rapid succession, raising antecedent runoff conditions and filling various river storage areas. Frequently, a low-elevation snowpack forms over large parts of the basin. Heavy rainfall and warm snow-melting complete the flood producing sequence. Minor floods usually last about three days, rising to damage proportions in a day or less, reaching a flood crest in the next several hours, and receding rapidly in 24 hours or less. Floods of this variety have flood peaks less than 125,000 cfs below Concrete and are expected approximately every 10 years. Minor floods described above become major floods when the primary flood ingredient, intense storm rainfall, is extended for a longer period of time, or multiple storm systems occur in rapid succession. Several minor rises usually occur every year, but major floods occur with less regularity. However, two major floods have occurred in a single season, while several years have passed without a significant flood event. Winter rain-type floods usually occur in November or December but may occur as early as October or as late as February.

In l923, Mr. J. E. Stewart of the USGS collected data and reported on several very large historical floods in the Skagit River basin. Data collected and conclusions reached, together with information concerning floods of record through l957, are published in USGS Water Supply Paper l527. Mr. Stewart concluded that great floods occurred in l8l5 and l856 prior to the arrival of white settlers, and that the larger flood of l8l5 was probably as large as the greatest flood on the Skagit River within the last several hundred years. The published magnitudes of these floods, which are based on high water marks, have a high degree of uncertainty and have been classified by the USGS as “estimates”. There is also some concern that large woody debris jams that developed over decades, may have affected these high water marks. As a result of this high uncertainty, the floods of 1815 and 1856 are not considered in the analyses presented in this report.

Mr. Stewart also documented and estimated the magnitudes of a number of other large floods which occurred prior to the widespread establishment of stream gages within the basin. The most significant of these events were the large floods which occurred in water years 1898, 1910, 1918, and 1922. Estimates for the magnitudes of these floods were based on a variety of high water information, including both eyewitness reports of flood levels and natural indicators of high water levels, such as mud marks.

The estimated magnitudes of the historical floods of 1898, 1910, 1918 and 1922 have been the subject of considerable review, analysis and discussion, as described in Section 1.4. The analyses present in this report rely on peak discharge data for these floods as currently published by the USGS.

Between l920 and late 1950, prior to completion of present storage facilities at Ross and Upper Baker, incidental flood reduction was provided to varying degrees by storage operations at the initial power reservoirs. Regulation of 74,000 acre-feet and 120,000 acre-feet of flood control storage at Upper Baker and Ross since 1977 and 1953, respectively, have reduced all floods to some degree. Peak discharges for selected flood events, including the currently published peak discharges for the historical floods, are listed in Table 9.

Flood volume, channel storage, and Concrete to Mount Vernon local inflow have a marked effect on the routing and attenuation of flood peaks between Concrete and Mount Vernon. For example, during the two large floods in November 1990, the first flood peak attenuated between Concrete and Mount Vernon while the second flood increased in the same reach.

Skagit River flood peaks usually attenuate between Concrete and Mount Vernon. However, floods with high peaks and large volumes will generally fill the channel storage, and combined with runoff from the 356 square mile local area between Concrete and Mount Vernon, will cause the peak discharge to increase as it moves downstream.

During dry summer weather, soil moistures in the Skagit basin become substantially depleted. With the beginning of fall and winter rainfall, soil moistures are recharged; however, there is often a noticeable loss of runoff volume during the initial floods of the season until the various loss parameters are fully satisfied.

TABLE 9 - SUMMARY OF HISTORICAL FLOODS (CFS)
(Flows from USGS Records Except as Noted)

STATION	**Skagit River near Concrete**		**Skagit River near Mt Vernon**	
PERIOD OF RECORD	**October 1924-Present**		**October 1940-Present**	
	2,737 square miles		3,093 square miles	
	Peak Discharge		**Peak Discharge**	
Date	**cfs**	**cfs / sq. mi.**	**cfs**	**cfs / sq. mi.**
1815	510,000	186.3	--	--
1856	340,000	124.2	--	--
16 Nov 1896	--	--	--	--
18-19 Nov 1897	265,000	96.8	--	--
16 Nov 1906	--	--	180,000	58.2
18 Nov 1908	--	--	--	--
29-30 Nov 1909	245,000	89.5	--	--
21 Nov 1910	--	--	--	--
29-30 Dec 1917	210,000	76.7	--	--
12-13 Dec 1921	228,000	83.3	--	--
27 Feb 1932	147,000	53.7	--	--
13 Nov 1932	116,000	43.4	--	--
22 Dec 1933	101,000	36.9	--	--
25 Jan 1935	131,000	47.9	--	--
27 Nov 1949 1/	154,000	56.3	114,000	36.9
10 Feb 1951 1/	139,000	50.8	144,000	46.6
3 Nov 1955 2/	106,000	38.7	107,000	34.6
23 Nov 1959 2/3/	89,300	32.6	91,600	29.6
20 Nov 1962 2/3/	114,000	41.7	83,200	26.9
13 Jul 1972 2/3/	91,900	33.6	80,600	26.1
4 Dec 1975 2/3/	122,000	44.6	130,000	42.0
27, 28 Dec 1980 2/3/	148,700	54.3	114,000	36.9
9-12 Nov 1990 2/3/	148,800	54.4	142,000	45.9
22-26 Nov 1990 2/3/	146,000	53.3	152,000	49.1
28-30 Nov 1995 2/3/	160,000	58.5	141,000	45.6
17-21 Oct 2003 2/3/	166,000	60.7	129,000	41.7
6-7 Nov 2006 2/3/	145,000	53.0	125,000	40.4

1/ Ross Dam began storing water in March 1940.

2/ Includes effect of 120,000 acre-feet of flood storage established at Ross Dam in 1953

3/ Upper Baker Dam began storing water in July 1959 (74,000 acre-feet of flood storage at Upper Baker began in 1977)

2.4.9.1. Flood Runoff From Uncontrolled Watersheds

Runoff from the uncontrolled watersheds in the Skagit Basin has a major effect on flooding in the lower Skagit Valley. Flood control at Ross and Upper Baker is sufficient to control floods in the lower valley (with the lower valley defined as within the levee system from Burlington to the mouths) with exceedance frequencies of four to five percent (20-25 year event), but flood runoff from the Skagit's uncontrolled watersheds during events greater than approximately 4 percent (25-year event) exceedance frequency at Mount Vernon is sufficient to produce major flooding in the valley regardless of the flood control regulation at Ross and Upper Baker. The floods of November 1990 and November 1995 were 5 to 6 percent (16-20 year event) exceedance frequency events that raised the river to the tops of the main levees.

Flood control storage at Ross and Upper Baker is sufficient to store inflow while releasing only the minimum outflow for up to a two percent exceedance (50-year) event. The contribution from the uncontrolled watersheds for this event (50-year), however, is still large enough to deliver 175,000 cfs to the Mount Vernon area, which exceeds the current levee capacity. This will likely mean that the lower Skagit Valley will have flooded due to levee failures as a result of runoff from the uncontrolled watersheds. The magnitude of the uncontrolled watershed runoff is implied by the following runoff data for the river. Ross and Upper Baker reservoir watersheds are 39 percent of the total Skagit River drainage area at Mount Vernon (the remaining 61 percent of the total area is uncontrolled), and their combined annual runoff is 32 percent of the average annual runoff of the Skagit River at Mount Vernon. Uncontrolled runoff is 68 percent of the average annual runoff at Mount Vernon.

2.4.9.2. November 1949 Flood

The flood of November l949 is a good example of a flood crest flattening while moving downstream. Channel storage had a marked effect on the sharpness of the peak between Concrete and Mount Vernon. The peak discharge of 154,000 cfs at Concrete was reduced to 114,000 cfs at Mount Vernon. An absence of precipitation in the lower basin at the time of this flood partially explains the reduction in crest in the lower reaches of the channel. The Sedro-Woolley precipitation gage indicated that very little rain fell in the lower part of the basin.

2.4.9.3. February 1951 Flood

The February l95l flood had a peak discharge of l39,000 cfs at Concrete, a recorded peak of l50,000 cfs at Sedro Woolley, and a peak of l44,000 cfs at Mount Vernon. Reservoir storage reduced the peak discharge at Concrete about l3,000 cfs. However, due to the long duration of the peak discharge between Concrete and Mount Vernon, channel storage and attenuation had little effect on reducing the peak stage in the lower reaches. The flood remained near its peak for 6 hours at Mount Vernon. The duration of this peak was more significant than its magnitude because it minimized the effectiveness of natural storage in the Nookachamps Creek area, and dikes failed because they lacked sufficient cross-sectional dimensions to withstand a long period of high water.

2.4.9.4. November 1990 Floods

The 1990 floods broke through the Fir Island levee and inundated most of the interior farmland. Both events required extensive flood fighting in the vicinity of Mount Vernon. For example, during the November 1990 flood event, the peak discharge of 149,000 cfs at Concrete increased to 152,000 cfs at Mount Vernon, while the discharge of 160,000 cfs at Concrete during the November 1995 flood was reduced to 141,000 cfs at Mount Vernon. During the 1990 and 1995 floods, the stages at Mount Vernon were nearly equal, 37.34 feet and 37.37 feet, respectively. A major levee failure at Fir Island during the November 1990 flood increased the river slope and velocity below Mount Vernon, causing an artificially low crest stage at the Mount Vernon gage. The month of November 1990 included significant floods on November 9-11 (the first flood) and November 24-25 (the second flood). The first flood was slightly larger in volume than the second flood, but peak discharges were similar during both floods, having approximately a 5 percent exceedance frequency at the Concrete streamgage. Total flood storage used at both projects amounted to approximately 194,000 acre-feet during the first flood and approximately 153,900 acre-feet during the second flood. The above volumes include 112,000 acre-feet stored in Ross and 82,000 acre-feet stored in Upper Baker during the first and 100,000 acre-feet stored in Ross and 53,900 acre-feet stored in Upper Baker during the second flood. Inflow to both projects peaked on November 10, 1990 (first flood) as follows; 46,000 cfs at 2400 hours at Ross, and 33,000 cfs at 1000 hours at Upper Baker. Outflows at both projects were regulated to a minimum of 5,000 cfs through the main part of the flood.

A major levee break occurred during the first flood on the eastside of Fir Island, the major farming region between the North and South Forks of the Skagit River about 3 miles downstream from Mount Vernon. The failure occurred about 12-14 hours before the peak at Mount Vernon, inundating most of Fir Island with major damage consequences. The Fir Island levee failure caused the Skagit River to fall abruptly. Many requests were received by the Seattle District USACE Reservoir Control Center (RCC) from flood engineers at Mount Vernon to hold the stored floodwater and limit the rate of storage discharges to provide time for recession of the river's uncontrolled streamflows. (The RCC is responsible for directing flood control operations at both Upper Baker and Ross Dams). The hydraulic relief provided by the Fir Island levee failure was probably instrumental in preventing failure of other major levees in the vicinity. Emergency repairs to the Fir Island levee were made between the first and second floods, but time was insufficient to fully stabilize the levee and the levee failed again during the second flood. Flood peaks between Concrete and Mount Vernon are normally reduced by attenuation and limited local inflow. This relation was reversed during the second flood due to significant local inflow, saturated soil conditions, and remaining pondage from the first flood.

2.4.9.5. November 1995 Flood

Flows on the Skagit River reached 160,000 cfs at Concrete and 141,000 cfs at Mount Vernon during the November 28-30, 1995 flood. Concrete was above zero damage stage for four days and above major damage (90,000 cfs) for one and a half days. Mount Vernon was above zero damage stage for approximately 4 days and above major damage for approximately 3 days. As a result of the reservoir regulation and sandbagging efforts, levees at Mount Vernon and Fir Island were able to withstand the flood without failing. Runoff stored at Ross and Upper Baker are estimated to have reduced flood levels by about 5 feet and 2 feet at Concrete and Mount Vernon, respectively.

RCC took control of Ross flood control storage at 0555 hour on the 28th when the National Weather Service was forecasting a storm that would produce record-level flooding. Ross filled to an elevation of 1602.38 feet on November 30, using 118,623 acre-feet of the total active flood-control storage of 120,051 acre-feet. Ross inflow peaked at about 46,500 cfs at 1400 hours on November 29th. Outflows from Ross were regulated to no more than 13,500 cfs until after the Skagit River near Concrete had peaked and receded to 90,000 cfs on the afternoon of the 30th. Efforts to increase discharge from Ross and pass inflow were delayed nearly two days by the high inflow and the limitation on discharge of 26,000 cfs-28,000 cfs through the Project.

RCC took control of Upper Baker flood control storage on November 28th at 1135 hours when the reservoir was at elevation 707.9 feet. Upper Baker Dam filled to an elevation of 719.1 feet on November 30, using 63,800 acre-feet of the 74,000 acre-feet of total flood-control storage at Upper Baker. Peak inflow into Upper Baker was 31,000 cfs.

This flood set a new crest-stage record at the Skagit River near Concrete gage despite the regulation at Ross and Upper Baker. The Concrete gage reached a crest of 41.57 feet. The Mount Vernon gage reached a crest of 37.34 feet, approximately equal to the record stage of 37.37 feet during the November 25, 1990 flood.

Reservoir inflow caused Ross Lake to fill to elevation 1602.38 feet, which is within 0.12 feet of the maximum full flood control pool. Upper Baker started to evacuate storage at 1800 hours on November 30, nearly a day after the river crested at Concrete. The flood storage evacuation was delayed until the flood recession at Concrete receded below 90,000 cfs in response to reports from the field flood engineers indicating that levees were still holding but a prolonged duration of high river flow was likely to cause failure. At Mount Vernon, the river was 0.5 feet above major damage stage for an extra half day, but the initial height was reduced due to this special evacuation.

2.4.9.6. October 2003 Floods

The floods of October 2003 started with a smaller peak followed by a larger peak. The first flood peaked at 94,700 cfs at Concrete and 73,500 cfs at Mount Vernon on October 17th and 18th. This exceeded the major damage stage for 6 hours at Concrete but did not get above major damage at Mount Vernon. The second flood was significantly larger and spread more completely across the upper basin and peaked at 166,000 cfs at Concrete and 129,000 cfs at Mount Vernon on October 21st. Concrete was above zero damage stage for 57 hours and above major damage (90,000 cfs) for 33 hours. Mount Vernon was above zero damage stage for 64 hours and above major damage for 47 hours. As a result of the reservoir regulation and sandbagging efforts, levees at Mount Vernon and Fir Island were able to withstand the flood without failing.

This flood set a new crest-stage record at the Skagit River near Concrete gage despite the regulation at Ross and Upper Baker. The Concrete gage reached a crest of 42.21 feet, about 0.6 feet greater than the flood of November 1995. The Mount Vernon gage reached a crest of 36.2 feet, which is a foot lower than the peaks seen for the November 1995 and November 25, 1990 floods.

3.0 Hydrologic Study of the Skagit River Basin

This section summarizes the hydrologic analysis that has been completed for the Skagit Flood Risk Management Feasibility Study. Determining hydrology for the Upper Skagit River basin above Concrete (River Mile 54.1) is necessary to perform the hydraulic analysis of each of the proposed alternatives. The major flood damage centers are located from Sedro-Woolley (River Mile 22.4) downstream to the mouths of the North and South Forks.

3.1 Upper Skagit River Basin Above Concrete, WA to Ross Dam

The Upper Skagit River Basin has 1,214 square miles of drainage area behind dams that currently have reservoir storage space set aside for flood control and 1,523 square miles that is uncontrolled. The Upper Skagit River from Concrete, WA to Ross Dam has many tributaries flowing into it. Most of the large tributaries and drainage areas have a long record of stream gage information (see Appendix B). These gaged areas include the Baker River, Skagit River above Ross Dam, Cascade River, Sauk River, and Thunder Creek. Additionally, there are gages with long periods of record for the Skagit River at Newhalem and the Skagit River at Marblemount that provide information on the local flow in between these two areas.

3.2 Baker River

The Baker River, the second largest tributary in the basin, drains the north central portion of the Skagit Basin. The Baker River rises in rugged mountains in the upper Baker Basin and drains 298 square miles of watershed through a narrow rocky channel that flows about 30 miles to the right bank of the Skagit River at RM 56.5. The basin ranges in elevation from 170 to 10,775 feet with approximately two-thirds of the basin located below an elevation of 4,000 feet.

The Baker River Basin features several significant peaks including Mount Baker (10,775 feet), Mount Shuksan (9,127 feet), Mount Challenger (8,236 feet), Mount Blum (7,680 feet), Whatcom Peak (7,574 feet), and Bacon Peak (7,066 feet). Mount Baker is the second most heavily glaciated volcano in the Cascade Range to Mount Rainier with a volume of snow and ice of 0.43 cubic miles. The basin is mostly forested below 5,500 feet as the main land owners in the basin are the US Forest Service, North Cascades National Park, Washington State Department of Natural Resources, and Puget Sound Energy. Above 5,500 feet, only scrub vegetation exists with little or no vegetation on rock outcrops, glaciers, and permanent snowfields. The watershed is fairly steep with slopes from 20 to 40 percent over most of its area except in the vicinity of the channel and valley floor. Lake Shannon and Baker Lake occupy roughly 16 linear miles of the Baker River Valley. The average annual precipitation over the basin is roughly 130 inches.

The Baker River is regulated by two hydroelectric dams on the Baker River that are owned by Puget Sound Energy (PSE). These dams are named Upper and Lower Baker Dams. Upper Baker Dam is a concrete gravity structure that is 330 feet high and 1,230 feet long. The dam is located at River Mile 9.29 and was completed in 1959. At normal full pool elevation of 727.77 feet NAVD88, the reservoir extends 9 miles upstream and contains a surface area of 4,980 acres. There are 180,128 acre-feet of active storage between the normal full pool and the minimum power pool at an elevation of 677.77 ft NAVD88. A maximum of 4,650 cfs can be run through the turbines and the spillway can release up to 48,000 cfs at normal full pool and 60,000 cfs at the maximum design pool. When PSE first received its FERC license in 1956, a volume of 16,000 acre-feet was required to be set aside for flood control to make up for lost valley storage. In 1977, an additional 58,000 acre-feet of flood control storage was authorized by Section 209 of Public Law 87-874. The flood control operating policy requires that a minimum of 5,000 cfs be released from the project to maintain the necessary flood control space for large flood events.

Lower Baker Dam is a semi-gravity concrete arch structure 285 feet high and 530 feet long. It is located at river mile 1.2 and was completed in 1925. At normal full pool elevation of 442.35 feet NAVD88, the reservoir extends 7 miles upstream and contains a surface area of 2,278 acres. There are 116,770 acre-feet of active storage between the normal full pool and the minimum power pool at elevation 373.75 feet NAVD88. A maximum of 4,100 cfs can be run through the turbines and the spillway can release up to 40,000 cfs at normal full pool. There currently is no authorized flood control storage behind Lower Baker Dam. The current restriction during flood control operations is that Lower Baker Dam cannot draw down the reservoir while Upper Baker is storing water for flood risk management.

FERC issued PSE a new, 50-year operating license for the Baker River Hydroelectric Project in October 2008. The timing of flood control storage required at Upper Baker under the terms of the current license is shown in Table 10.

TABLE 10 - UPPER BAKER FLOOD CONTROL STORAGE REQUIREMENTS

	UPPER BAKER ELEVATION (NAVD 88)	**ACTIVE FLOOD STORAGE**
DATE	**FEET**	**acre-ft**
October 1	727.77	0
October 15	724.53	16,000
November 1	724.53	16,000
November 15	711.70	74,000
March 1	711.70	74,000
April 1	727.77	0

Under the terms of its new license, PSE is required to "develop means and operational methods to operate the Project reservoirs in a manner addressing imminent flood events". These methods may include "additional reservoir drawdown below the maximum established flood pool". Section 4.1.2 of the license Settlement Agreement further states that "PSE and Skagit County shall seek an agreement with the ACOE [i.e. USACE] to amend the ACOE Baker River Project Water Control Manual" to reflect a specified reservoir drawdown protocol when a flood event is imminent. It is anticipated that any operational changes to address "imminent floods" would take place after about 2012; the nature and impact of any such changes is not yet known, and are not considered in the hydrologic analyses in this report.

There are three locations on the Baker River where there is useful flow information for hydrologic analysis. Daily flows into the Upper Baker Dam area have been calculated since October 1926. Prior to Upper Baker Dam being built there was a gage (Baker River below Anderson Creek) at this site. Since construction of the dam, the daily flows can be calculated from the daily reservoir elevation and outflow information. The Baker River at Concrete gage has operated from 10/1/1910-2/28/1915 and 9/1/1943 to present. This has a mixed record of pre-dams and post-dams flows and can be influenced by the backwater of the Skagit River during large flood events so care has to be taken when utilizing this data.

There is also some limited local inflow data into Lower Baker Dam. Table 11 shows the runoff per square mile for Upper and Lower Baker inflows for the most recent major flood events for which there was full hourly data. The earlier October 2003 event was oriented more towards the Upper Basin than would be typical so it was not weighted as strongly when determining the factor to use as a ratio of Lower Baker to Upper Baker inflows. It is for this reason that the local inflow to Lower Baker dam is determined to be roughly 0.76 times the runoff per square mile as the Upper Baker inflow on average.

TABLE 11 – RATIO OF LOWER BAKER INFLOWS TO UPPER BAKER INFLOWS

Flood Event	Upper Baker Peak 24-hour Flow (cfs)	Upper Baker Runoff per Square Mile	Lower Baker Peak 24-hour Flow (cfs)	Lower Baker Runoff per Square Mile	Lower Baker to Upper Baker Runoff Ratio
11/10/1990	28255	131.4	8677	105.8	0.81
11/29/1995	24664	114.7	7315	89.2	0.78
10/17/2003	34540	160.7	5606	68.4	0.43
10/21/2003	28024	130.3	8590	104.8	0.80
12/24/2005	13161	61.2	3044	37.1	0.61
11/06/2006	28594	133.0	9188	112.0	0.84
Average					**0.71**
Average w/o 10/17					**0.77**

3.3 Sauk River

The Sauk River is the largest tributary of the Skagit River and flows into it on the left bank at River Mile 67.2. The Sauk River flows mostly north and is over 50 miles in length. It has a drainage area of 732 miles, which is over 25% of the total drainage area of the Skagit River at Concrete. This represents just over 50% of the uncontrolled drainage area in the basin. It is for this reason that the Sauk River is the largest contributor to the flooding that occurs on the Skagit River. Table 12 shows the Sauk's contribution in the last 3 major flood events on the Skagit River.

TABLE 12 - SAUK RIVER CONTRIBUTION TO SKAGIT RIVER FLOODING

Flood Event	Skagit River at Concrete Regulated Peak Flow (cfs)	Contribution from Sauk River at Sauk Flow (cfs)	Percent Contribution
11/10/1990	149,000	66,900	45%
11/29/1995	160,000	73,597	46%
10/21/2003	166,000	106,000	64%
11/06/2006	145,000	84,900	59%
100-year	214,000	111,000	52%

The elevations in the basin range from 210 feet to 10,541 feet. The Sauk River is designated a Wild and Scenic River. The rivers banks are mostly lined with grass and low brush and the overbank areas are mostly made up of forests. There are two large tributaries that flow into the Sauk from Glacier Peak. The largest is the Suiattle River (346 square mile drainage area), which flows in from the west at River Mile 13.2 and is over 40 miles in length. The White Chuck River (86.2 square mile drainage area) flows in from the west at River Mile 31.9.

There are two locations on the Sauk River that have useful flow information for this analysis. The Sauk River at Sauk gage has operated from 4/1/1911-7/31/1912 and 8/1/1928 to present. This gage is the most useful because it measures most of the drainage area (714 square miles) of the Sauk and has a long period of record. The Sauk River above Whitechuck River near Darrington has operated from 10/1/1917-9/30/1922 and 10/1/1928 to present. This gage provides the earliest hints of when the Sauk River might peak and shows the relative contribution from the upper basin.

3.4 Cascade River and Local Flow from Marblemount to Concrete

The Cascade River flows into the Skagit River at River Mile 78.1, just upstream of the town of Marblemount, and has a drainage area of 185 square miles. The Cascade River runs for 29 river miles north and east from South Cascade Glacier on Sentinel Peak to the Skagit River. The basin ranges in elevation from 185 to 8,300 feet. The Cascade River is classified as a Wild and Scenic River. It is mostly forested and the river opens from a canyon where the floodplain is roughly 400 feet wide at River Mile 3.3 to 2,800 feet at the mouth.

The local flow from Marblemount to Concrete covers the flows that enter the Skagit River from River Mile 78.7 to River Mile 54.1. The major creeks that flow into this area are Corkindale Creek, Rocky Creek, Illabot Creek, Bark Creek, and Jackman Creek. This reach has a local drainage area of 173 square miles.

There is one location on the Cascade River that has useful flow information for this analysis. The Cascade River at Marblemount gage operated from 10/1/1928-10/10/1979, and from 6/1/2006 to present. This gage is the most useful because it measures most of the drainage area (172 square miles) of the Cascade River and has a long period of record.

The local flows from Marblemount to Concrete can be calculated by subtracting gage data from the Skagit River at Marblemount, Sauk River at Sauk, and Baker River at Concrete from the Skagit River at Concrete gage but there are many potential sources of error with this approach. The main problem is that it is difficult to accurately time each flow for every event and the calculation sometimes results in negative flows. This may also be impacted by routing effects in this area as there is some storage available in the floodplain. The number of years that all of the gages are working simultaneously is limited, which limits the dataset that is available for use.

There are 9 years prior to October 1979 where there is enough data for all of the gages to allow for an estimate of local flow from Marblemount to Concrete when the Cascade River at Marblemount gage was active. The post-2006 data for the Cascade River at Marblemount was not available at the time the analysis described here was performed. Table 13 shows the comparison of the runoff per square mile of drainage area for the local flow and the Cascade River during the peak winter flow on the Skagit River at Concrete. This shows that the Cascade River is very similar in runoff per square mile of drainage area to the local flow. Although it appears that the Cascade River has slightly less runoff than the local flow, a look at the whole record shows that the Cascade River has slightly more runoff than the local flow. This discrepancy shows some of the inaccuracy of the local calculation. It is for these reasons that the local flow from Marblemount to Concrete is derived assuming that it has the same runoff per square mile of drainage area as the Cascade River.

TABLE 13 – COMPARISON OF RUNOFF PER SQUARE MILE OF DRAINAGE AREA BETWEEN MARBLEMOUNT TO CONCRETE (MMCC) LOCAL AND CASCADE RIVER

Year	Cascade River 1-day Peak Winter Flow (cfs)	MMCC Local Related 1-day Flow (cfs)	Cascade River Runoff Per Square Mile	MMCC Local Related Runoff Per Square Mile	Cascade to MMCC Local Ratio
1944	3210	5850	19	34	55%
1947	6640	8660	39	50	77%
1948	6280	7120	37	41	88%
1949	2340	2500	14	14	94%
1950	10200	11420	59	66	89%
1951	8870	14220	52	82	62%
1977	5860	4280	34	25	137%
1978	4420	5810	26	34	76%
1979	3700	3030	22	18	122%
Average	**5724**	**6988**	**33**	**40**	**82%**

3.5 Local Flow from Newhalem to Marblemount

There are 8 creeks that flow into the Skagit River between the stream gages at Newhalem and Marblemount. These drainages are Newhalem Creek, Goodell Creek, Thornton Creek, Damnation Creek, Alma Creek, Copper Creek, Bacon Creek, and Diobsud Creek. This local flow enters the Skagit River from River Mile 93.7 to River Mile 78.7 and has a drainage area of 206 square miles. These creeks run through steep, heavily forested basins to enter the Skagit.

This local flow can be determined by subtracting the Skagit River at Newhalem gage from the Skagit River at Marblemount gage. The Skagit River at Newhalem gage has flow data from 12/21/1908 to 5/31/1914 and 10/1/1920 to present. The Skagit River at Marblemount gage has flow data from 9/1/1943 to 7/7/1944, 10/1/1946 to 9/30/1951, and 5/20/1976 to present. The local flow can be determined, therefore, for 34 years of concurrent record.

3.6 Thunder Creek and Local Flow from Ross Dam to Newhalem

Thunder Creek flows into the Skagit River on the left bank at River Mile 102.2, just upstream of Diablo Dam. Thunder Creek runs north for 15 river miles from the glaciers of Mount Torment to the Skagit River and has a drainage area of 108 square miles. The basin ranges in elevation from 1,220 to 8,815 feet. The basin is heavily forested.

There is one location on Thunder Creek that has useful flow information for this analysis. The Thunder Creek near Newhalem gage has been in operation from 10/1/1930 to present. This gage is the most useful because it measures most of the drainage area (105 square miles) of Thunder Creek and has a long period of record.

The local flow from Ross Dam to Newhalem has a drainage area of 176 miles of which Thunder Creek represents 60%. Other creeks in this area include Horsetail Creek, Sourdough Creek, Stetattle Creek, Pyramid Creek, and Gorge Creek. The small sample of available data shown in Table 14 indicates that the local flow has roughly the same runoff per square mile as Thunder Creek, so the Thunder Creek gage is used to estimate this local flow.

TABLE 14 – RATIO OF ROSS DAM TO NEWHALEM LOCAL TO THUNDER CREEK

Flood Event	Thunder Creek Peak 24-hour Flow (cfs)	Thunder Creek Runoff per Square Mile	Ross Dam to Newhalem Local Peak 24-hour Flow (cfs)	Ross Dam to Newhalem Local Runoff per Square Mile	Ross Dam to Newhalem Local to Thunder Creek Runoff Ratio
11/29/1995	7872	75	13090	74	0.99
10/17/2003	6622	63	12901	73	1.16
10/21/2003	12667	121	17682	100	0.83
Average					**1.00**

3.7 Skagit River Above Ross Dam

Ross Dam is located at River Mile 105.2 on the Skagit River. Flows in this upper basin originate from Allison Pass in British Columbia and flow 57.1 river miles down to Ross Dam. The river crosses the U.S./Canada border at River Mile 127.0. The drainage area above Ross Dam is 999 square miles.

Ross Dam is a concrete arch dam that has a maximum height of 540 feet with a base width of 208 feet and a top width of 33 feet. The dam was built in 1949 and first had space available for flood control storage in 1954. At normal full pool elevation of 1,602.5 feet NGVD 47, the reservoir extends 23 miles upstream and contains a surface area of 11,700 acres. There are 1,434,796 acre-feet of active storage between the normal full pool and the lowest sluice outlet at an elevation of 1,265 feet. There are two sluice outlet systems, a high level sluice located near the center of the dam at an elevation of 1,340 feet and a low level sluice along the right abutment of the dam. The discharges of the high and low sluices at the normal full pool are 4,130 cfs and 4,400 cfs, respectively. There are two overflow spillway sections that are symmetrically located on either side of the dam. Each spillway section contains six bays at a spillway crest elevation of 1,582 feet with six radial gates of modified monocoque design. Each spillway gate is 20.5 feet high and 20 feet wide. The spillway capacity at normal full pool is 90,000 cfs and can reach 121,000 cfs at the top of the surcharge storage pool elevation of 1,608 feet. The

Seattle District prepared a plan requiring 200,000 acre-feet of flood control storage that was incorporated on 2/20/1950 with the understanding that further studies were needed to refine this number. Subsequent studies resulted in decreasing the flood control storage to 120,000 acre-feet. Eight hours before the natural flow on the Skagit River at Concrete is predicted to hit 90,000 cfs, outflows from the project can be reduced to 0. The timing of the flood control storage availability can be seen in Table 15.

TABLE 15 - ROSS FLOOD CONTROL STORAGE REQUIREMENTS

	ROSS LAKE ELEVATION	**ACTIVE FLOOD STORAGE**
DATE	**FEET(SCL Datum*)**	**acre-ft**
October 1	1,602.50	0
October 15	1,600.80	20,000
November 1	1,598.84	43,000
November 15	1,597.37	60,000
December 1	1,592.11	120,000
March 15	1,592.11	120,000

*SCL Datum is 1.79 ft above NGVD29

A gage existed at the dam site before the dam was built and daily pool elevations and outflows are available since Ross Dam has been in place. From this data, daily flow records are derived for the inflow to Ross Reservoir from 1/1/1919 to present.

4.0 Skagit River near Concrete Frequency Analysis

The hydrologic analysis hinges on flows developed for the Skagit River near Concrete. This location is the focal point for several reasons. There has been a stream gage (USGS gage #12149000) running continuously at this location since October 1924 and there are 4 additional significant historical peaks that have been determined for this location. The stream gage encompasses 88% of the total drainage area of the Skagit River (2,737 square miles). The stream gage is located upstream of any development that could influence the gage other than the dams upstream. It is also in a fairly confined area so there is less likely to be errors associated with the rating of the gage. This provides a firm foundation to determine the magnitude and recurrence of floods in the Skagit River Basin.

4.1 Developing a Consistent Record

In order to perform a frequency analysis correctly, the watershed conditions need to be consistent during the period of record. This is not the case for the Skagit River near Concrete gage because reservoirs have been added throughout the period of record (see Table 19), which have had varying effects on reducing floods in the upper basin. Developing a frequency curve that only included the current watershed condition with the current flood control storage would restrict us to only using the flow data from 1977 to present.

This period does not include the larger earlier floods that could greatly influence the upper part of the Concrete frequency curve. When developing low recurrence flood events (such as a 1% chance of recurrence (100-year event)), it is important to use as much data as possible including historical data unless there is evidence that this data is not indicative of the extended record.

The USGS has published peak discharges for 6 major historical floods (ungaged events). The peak discharges for these historical floods were determined by Stewart in the 1920's and published in 1961 with Bodhaine in USGS Water Supply Paper 1527. These data were revised downward slightly in Scientific Investigation Report 2007-5159 by Mark Mastin of the USGS in 2007. The data for the latest 4 historical floods (water years 1898, 1910, 1918, and 1922) from this report are used for this analysis. The following table summarizes the historical events for the Concrete gage.

TABLE 16 - HISTORICAL FLOODS FOR THE SKAGIT RIVER AT CONCRETE

Date of Historical Flood Event	USGS published Discharge at Concrete (cfs)
1815	510,000
1856	340,000
11/19/1897	265,000
11/30/1909	245,000
12/30/1917	210,000
12/13/1921	228,000

The latest four historical flood events (in water years 1898, 1910, 1918, 1922) are all documented as flooding events in early photographs and/or newspaper articles. The earliest historical flood events (1815, 1856) were also likely large events, but the magnitude of these floods is difficult to determine. The USGS has recently downgraded these flows to "estimates" due to the fact these estimates are based on single high water marks that were obtained long after these events occurred. There are also concerns that there could have been large debris jams in the past that accumulated over decades that could have created an artificial dam break flood. This would represent a changed watershed condition that would be hard to account for. Consequently, the 1815 and 1856 floods are not used in the unregulated frequency curve calculations.

4.1.1 Methodology Used to Estimate Unregulated Peak Annual Discharge from Regulated Discharges for the Skagit River Near Concrete

Although the period of record of streamflow data at the USGS gage 12194000 Skagit River near Concrete location dates to 1924, data collected at this gage reflect the effects of regulation at upstream reservoirs. For instance, by the late 1920's, construction of Gorge and Diablo dams on the Skagit River and Lower Baker dam on the Baker River had been completed. As such, use of the observed data from the Skagit River near Concrete gage to estimate unregulated discharge at this location involves adjusting these data for the effects of upstream regulation. See Figure 5 for location of dams.

The methodology used to account for the effects of regulation was largely dictated by data availability. For instance, the estimated unregulated discharge record was calculated using a daily time-step since this is the shortest time-step at which streamflow data are available over an appropriately long period of record.

The effects of regulation on the Skagit River discharge at Concrete were determined by calculating the effects of regulation from the five upstream hydroelectric power dams within the basin. The effects of regulation were determined independently for the three dams located on the mainstem Skagit River and for the two dams located within the Baker River sub-basin. The effects of regulation from these two sub-basins were then combined to produce an estimate of the overall impact of regulation on the Skagit River discharge at Concrete at a daily time-step. Adjustment of the regulated Skagit River streamflow record at Concrete using the time-series' of estimated effects of upstream regulation resulted in a synthetic time-series of unregulated Skagit River discharges at

Concrete. The following sections provide further details regarding how the regulated streamflow record at Concrete was adjusted to produce a synthetic record of unregulated discharge. For diagrams of these methods, see Appendix C.

4.1.1.1 Methodology Used to Estimate the Effects of Regulation from the Skagit Project

The Skagit Project consists of three dams owned by Seattle City Light located on the mainstem Skagit River – Ross, Diablo, and Gorge. Ross dam, which is the furthest upstream, impounds the largest reservoir and has the most significant impact to streamflow in the downstream reaches of the Skagit River. The drainage area contributing runoff to Ross reservoir is 999 square miles. Diablo and Gorge dams impound significantly smaller reservoirs and have a relatively smaller impact on streamflow.

The effects of regulation from these three dams were estimated by comparing the record of observed streamflow in the Skagit River downstream of these dams with a synthetic record of unregulated streamflow. Regulated streamflow downstream of these dams is best represented by data from USGS gage 12178000, which is located in the Skagit River at Newhalem and is several miles downstream of Gorge dam. The gage at Newhalem has a contributing drainage area of 1,175 square miles and has a continuous record dating back to 1920. A synthetic record of unregulated streamflow at this gaging location was estimated using a combination of a natural (unregulated) streamflow record for the Skagit River at the present location of Ross dam (999 mi^2 drainage area) and an estimated synthetic record of tributary inflow to the Skagit River between Ross dam and the Newhalem gaging site (tributary area of 176 mi^2). The record of natural streamflow in the Skagit River at the Ross dam site was obtained from Seattle City Light. Runoff from a significant portion of the tributary area between Ross dam and Newhalem is reflected in the streamflow record of Thunder Creek (USGS gage 12175500), which measures discharge from a 105 mi^2 area that is tributary to Diablo reservoir. Runoff from the remaining tributary area between Ross dam and Newhalem (71 mi^2) was estimated using data from the Thunder Creek gage and the estimated relationship between runoff in the Thunder Creek sub-basin relative to the 71 mi^2 area that is currently ungaged.

A review of USGS stream gaging stations was performed to locate suitable gaging records that could be used to estimate runoff from the 71 mi^2 drainage area between Thunder Creek and Newhalem. Long-term streamflow records from Stetattle Creek and Newhalem Creek appear to provide the most appropriate data. A 50-year streamflow record is available from Stetattle Creek (USGS station 12177500), which represents a 22 mi^2 drainage area (tributary to Gorge reservoir) located to the north of the Skagit River near the town of Diablo. The Stetattle Creek drainage is part of the 71 mi^2 tributary area to the Skagit River between Thunder Creek and Newhalem. Discharge in Stetattle Creek is considered representative of local inflows entering the Skagit River between Thunder Creek and Newhalem from similarly oriented tributary sub-basins. Mean annual runoff in the Stetattle Creek drainage is about 114 inches.

A 38-year record is available from Newhalem Creek (USGS 12178100), representing a 27.9 mi^2 drainage located to the south of the Skagit River near the town of Newhalem. Newhalem Creek enters the Skagit River just downstream of the USGS gage Skagit River at Newhalem (USGS 12178000) but should be reasonably representative of local inflows entering the Skagit River between Thunder Creek and Newhalem from similarly oriented tributary sub-basins. Mean annual runoff in the Newhalem Creek drainage is about 86 inches. Combined mean annual runoff from the Stetattle Creek and Newhalem Creek drainages, which is about 100 inches, should be representative of local runoff from the 71 mi^2 area between Thunder Creek and Newhalem (it appears as if the tributary area to the Skagit River between Thunder Creek and Newhalem is evenly split between drainages oriented similar to the Stetattle and Newhalem Creek sub-basins). It should be noted that an estimate of the mean annual runoff from this 71 mi^2 area based on the difference between observed discharge in the Skagit River at Newhalem, Thunder Creek, and Skagit River at Ross dam also yields 100 inches. By comparison, mean annual runoff in the Thunder Creek drainage is about 80 inches, or 20 percent less than runoff generated from the tributary area between Thunder Creek and Newhalem. Based on this comparison, the following relationship provides a reasonable estimate of tributary inflows to the Skagit River from the 71 mi^2 area between Thunder Creek and Newhalem:

Tributary inflows from the 71 mi^2 area = (71 mi^2/105 mi^2) * (100”/80”) * Thunder Creek discharge;

Which yields: Tributary inflows from the 71mi^2 area = 0.85 * Thunder Creek discharge.

The following relationship was therefore used to create the synthetic record of unregulated mean daily discharge in the Skagit River at Newhalem (1,175 mi^2):

Mean daily natural discharge in the Skagit River at the Ross dam site (999 mi^2) + mean daily discharge in Thunder Creek (105 mi^2) + 0.85 * mean daily discharge in Thunder Creek (estimated runoff from 71 mi^2)

It should be noted that the values calculated using the above relationship were adjusted slightly to account for the approximate travel time in the natural (unregulated) Skagit River between Ross dam and Newhalem (estimated travel time of 2.3 hours). The resulting time-series is a synthetic representation of the mean daily unregulated discharge in the Skagit River at Newhalem for the period 1930 through 2007. The record begins in 1930 because this is the first year of operation of the Thunder Creek stream gage. Finally, the estimated effect of Skagit Project regulation on the mainstem Skagit River was calculated by taking the difference between the record of mean daily regulated discharge observed at Newhalem (USGS 12178000) and the synthetic record of mean daily unregulated discharge at this location. The effect of regulation on Skagit River discharge at Concrete was estimated by adjusting the time-series to account for an approximate eight-hour travel time from Newhalem to Concrete.

4.1.1.2 Methodology Used to Estimate the Effects of Regulation from the Baker River Project

The Baker River Project consists of two dams owned by Puget Sound Energy (PSE) located on the Baker River within the Baker River sub-basin. Upper Baker dam, which is the furthest upstream, impounds a larger reservoir and has a relatively greater influence on streamflow in the downstream reaches of the Skagit River relative to Lower Baker dam. The drainage area contributing runoff to Upper Baker reservoir (Baker Lake) is 215 mi^2 and the overall drainage area contributing runoff to Lower Baker reservoir (Lake Shannon) is 297 mi^2 (this figure includes the 215 mi^2 drainage to Upper Baker reservoir).

The effects of regulation from these two dams were estimated by comparing the record of observed streamflow in the Baker River downstream of both dams with a synthetic record of unregulated streamflow. A continuous record of regulated streamflow downstream of these dams is best represented by data from USGS gage 12193500, which is located in the Baker River less than one mile downstream of Lower Baker dam and just upstream of the confluence of the Baker and Skagit Rivers (a continuous record for this gage extends back to 1943). It is noted that data from this gage on occasion are affected by backwater from the Skagit River during high Skagit River flows. While PSE maintains a record of mean daily discharge from Lower Baker dam, these data are unfortunately not available over a continuous and suitably long-term record. Furthermore, a comparison of PSE's discharge data from Lower Baker dam with data from the USGS gage during several recent high flow events suggests that use of the USGS data to estimate the effects of Baker River regulation on Skagit River flows has a relatively small impact on the synthetic time-series of unregulated Skagit River flows. This is discussed in further detail in Section 4.1.1.3.

A synthetic record of unregulated streamflow at the Baker River at Concrete gaging site was estimated using a combination of a natural (unregulated) streamflow record for the Baker River at the present location of Upper Baker dam (215 mi^2) and an estimated synthetic record of tributary inflow to the Baker River between Upper Baker dam and USGS gage 12193500 (tributary area of 82 mi^2). The record of natural streamflow in the Baker River at the Upper Baker dam site was obtained from PSE.

A review of streamflow data from the Baker River near Concrete (USGS 12193500) shows a mean annual runoff of 122 inches from the Baker River basin for the period 1943 – 1999. The record of natural Baker River flows at the Upper Baker dam site for this period suggest a mean annual runoff upstream of Upper Baker dam of about 130 inches. Runoff from the 82 mi^2 area tributary to the Baker River downstream of Upper Baker dam can be estimated using the following relationship:

Runoff from 82 mi^2 area = $[(122''*297\ mi^2)-(130''*215\ mi^2)]/82\ mi^2 = 101\ ''/year$

Based on this relationship, mean daily discharge from the 82 mi^2 tributary area downstream of Upper Baker dam can be estimated from natural discharge in the Baker River at the Upper Baker dam site as follows:

Inflows from 82 mi^2 area = (82 mi^2/215 mi^2) * (101”/130”) * natural discharge in the Baker River at the Upper Baker dam site;

Which yields: Inflows from 82 mi^2 area = 0.30 * natural discharge in the Baker River at the Upper Baker dam site.

The following relationship was therefore used to create the synthetic record of unregulated mean daily discharge in the Baker River at Concrete (297 mi^2):

Mean daily natural discharge in the Baker River at the Upper Baker dam site (215 mi^2) + 0.30 * mean daily natural discharge in the Baker River at the Upper Baker dam site (estimated runoff from 82 mi^2).

It should be noted that the values calculated using the above relationship were adjusted slightly to account for the approximate travel time in the natural (unregulated) Baker River between Upper Baker dam and Concrete (estimated travel time of 1.7 hours). The resulting time-series is a synthetic representation of the mean daily unregulated discharge in the Baker River at Concrete for the period 1926 through 2007. The record begins in 1926 because this is the first year of record of natural streamflow in the Baker River at the Upper Baker dam site. Finally, the estimated effect of regulation from the Baker River Project on the Baker River was calculated by taking the difference between the record of mean daily regulated discharge observed at Concrete (USGS 12193500) and the synthetic record of mean daily unregulated discharge at this location. The effect of regulation on Skagit River discharge at Concrete was estimated by adjusting the time-series to account for an approximate one-half hour travel time between the Baker River gage near Concrete and the Skagit River gage near Concrete.

4.1.1.3 Estimated Unregulated Peak Annual 1-day Discharges in the Skagit River at Concrete

A synthetic record of the mean daily unregulated discharge in the Skagit River at the Concrete gaging site was constructed by adjusting the observed record of mean daily Skagit River discharge (USGS 12194000) using the time-series of estimated mean daily regulation effects for the Baker River and Skagit hydroelectric projects. The resulting time-series has a record from 1925 through 2007. A synthetic record of peak annual mean daily unregulated discharge in the Skagit River at Concrete was constructed by selecting the peak annual discharges from the time-series of mean daily unregulated discharge.

As noted previously, estimates of the effects of regulation from the Baker River Project were made using Baker River discharge data collected at the USGS gage at Concrete. These data are occasionally affected by backwater from the Skagit River during high Skagit River flows. As such, Baker River discharge reported at the USGS gage may be artificially high during these periods. Use of the USGS data to estimate the effects of Baker River regulation in these circumstances may result in an underestimate of the benefits of flood control at the Baker River Project, which would therefore result in an underestimate of the unregulated discharge in the Skagit River at Concrete. The potential effect of this on the synthetic record of unregulated Skagit River peak flows was investigated using the three highest Skagit River flow events at Concrete since 1925 (November 1990, November 1995, and October 2003). These three events were selected because discharge records of the Baker River at Concrete are available from both the USGS and PSE (PSE's record reflects discharge from Lower Baker dam). Note that for these events only, the estimated unregulated discharge in the Skagit River at Concrete was determined using Lower Baker dam discharge data obtained from PSE (Baker River USGS data were not used to estimate unregulated Skagit River discharge for these three events). Use of the USGS data to estimate the peak mean daily unregulated discharge in the Skagit River at Concrete during these events would have resulted in peak discharges that are roughly 2 percent lower in 1990, 3 percent lower in 1995, and 4.5 percent lower in 2003 relative to the values computed using PSE's Lower Baker dam discharge data. However, it should be noted that these three events represent the largest mean daily Skagit River peaks at Concrete since 1921. Most of the annual Skagit River peaks at Concrete are much lower than these three peaks and as a result the backwater impacts to the Baker River gage at Concrete are expected to be relatively lower and in many cases negligible. As such, use of the Baker River USGS data is expected to have a relatively small impact to the estimated annual unregulated Skagit River peaks at Concrete.

4.1.2 Determining the Relationship between Historical 1-day Flows and Historical Peak Flows

The historical data contains only instantaneous peak flows so a relationship between peak and 1-day flows is needed to convert this data to 1-day data. Without a similarly sized unregulated basin to draw from, an estimate needs to be made from the existing data. A comparison was made between unregulated 1-day flows and the regulated 1-day flows to determine which floods were minimally affected by regulation. This filtering of the floods was done to identify those floods where the unregulated and regulated 1-day flows were within 5% of each other (there were 18 winter floods that met this criteria). It was then assumed that the observed peak and 1-day flows for those events were representative of unregulated conditions. In addition, there is enough data for the November 1990, November 1995, October 2003, and November 2006 floods to determine the unregulated hourly data for the entire duration of these storms, so peak and 1-day unregulated flows can be derived for these events. Regression of peak against one-day flow using all of these data results in a peak to 1-day relationship for unregulated flows with a correlation coefficient (R^2) of 0.98.

4.2 Winter Flood Frequency Curve

Floods in the Skagit Basin can be classified as either spring snowmelt, or winter or late fall rainfall or 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 of October through March. These winter (or late fall) floods are driven primarily by heavy rainfall. Snowmelt may or may be a significant contributor to flood magnitude or volume and is not a necessity for a winter flood. However, winter events have the potential to produce the highest peak flows and volumes 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 (major damage level). 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 rainfall or rain-on-snow flood events. 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. It is for these reasons that a winter frequency curve is used to define the flood flow frequency for the Skagit Flood Risk Management Study.

The program HEC-FFA was used to perform the flood frequency analysis. This program computes flood frequencies in accordance with the publication titled "Guidelines for Determining Flood Flow Frequencies, Bulletin 17B of the US Water Resources Council". The flood frequency is determined by fitting a Log-Pearson Type III distribution. A generalized skew of 0 is used for the analysis of the peak events, –0.04 is used for the 1-day, and –0.12 is used for the 3-day analysis. The adopted skew used by the program is close to the actual skew of the data due to the long length of records at this site.

The results of flow frequency analyses presented in this report are for computed frequency estimates. An expected probability adjustment, normally applied in accordance with Corps' guidelines contained in EM1110-2-1415 (Engineering and Design – Hydrologic Frequency Analysis), is not appropriate in this instance since a risk-based approach to analysis and design has been adopted per EM1110-2-1619 (Risk-Based Analysis for Flood Damage Reduction Studies).

Frequency curves for unregulated and regulated flows are provided in Appendix D.

4.3 Hypothetical Unregulated Hydrographs for Skagit River near Concrete

Unregulated hypothetical flood hydrographs for the 2-, 5-, 10-, 25-, 50-, 75-, 100-, 250-, and 500-year events were developed for the Skagit River near Concrete using statistical frequency peak and volume analyses. The hydrograph shapes were roughly based on the October 2003 event. The hydrographs were then balanced to match the necessary 1-day and 3-day volumes. 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 are 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. These hydrographs can be seen in Appendix E.

4.4 Regulated Frequency Curve at Concrete

A consistent frequency curve is now developed for the Skagit River near Concrete gage but does not represent the existing condition. This requires developing a regulated frequency curve at Concrete that reflects the influence of flood storage and hydropower operations at Seattle City Light and Puget Sound Energy Reservoirs. There are several steps necessary to develop the existing condition regulated frequency curve at the Skagit River near Concrete gage. These steps include using the data that we have available that reflect the existing flood control operation and then converting the rest of the data set to reflect what the flows would have been if the existing flood control had been available.

4.4.1 Data Available with Existing Flood Control Operation

The existing flood control operation for the upper basin is that up to 74,000 acre-feet at Upper Baker Dam and up to 120,000 acre-feet at Ross Dam are available for flood control storage. The seasonal variation in flood control storage is shown in Tables 10 and 15 for Upper Baker Dam and Ross Dam, respectively. This storage at Ross Dam has been available since 1954. For Upper Baker Dam, 16,000 acre-feet has been available since 1956 and the additional 58,000 acre-feet has been made available since 1977. Even though the current flood storage requirements were not fully implemented until 1977, a closer examination of the record from 1956-77 shows that there were only two floods in that period that significantly exceeded the 90,000 major damage threshold. This study assumed that all regulated peaks from water year 1956 to present 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. The regulated median plotting positions for the 1956 to present data is used to develop the lower magnitude and more frequent events (i.e. the 2- and 5-year flood events).

4.4.2 Development of Regulated Lower Frequency Events

To develop the lower frequency events, unregulated flows for the 10-, 25-, 50-, 75-, 100-, 250-, and 500-year flood events for the Skagit River near Concrete need to be converted to flows that are regulated with the existing flood control requirements. This requires relating the unregulated Concrete flows to each of the upper basin flows, regulating the flows through Ross and Upper Baker Dams, and routing these flows back down to Concrete.

4.4.2.1 Unregulated Skagit River near Concrete to Upper Basin Flow Regressions

To relate the upper basin flows to the unregulated Skagit River near Concrete flows, regressions are developed that relate the observed upper basin gage's 1-day flow to the corresponding unregulated Skagit River near Concrete peak 1-day winter event for the concurrent period of record. These upper basin flows include Upper Baker and Ross Dam inflows, Newhalem to Marblemount Local, Thunder Creek, and Cascade and Sauk Rivers (see Appendix F). The remaining upper basin flows are derived from these as is detailed in Section 3.

The 1-day time period is the duration which has the greatest influence on flood peaks both upstream and downstream. This is because there is storage in the floodplain that can attenuate peak flows as they move downstream so flooding is more related to the volume of flows moving through the system. Instantaneous peaks are also more difficult to determine for the inflows to Upper Baker and Ross Dams. Peak and 3-day volumes for each of the upper basins are derived from their peak to 1-day and 3-day to 1-day regressions for winter floods. (See Appendix F for all regressions).

4.4.2.2 Development of Hypothetical Hydrographs for Upper Basins

The regressions provide 1-day peak flows for each of the upper basins. Regressions are then developed for each of the upper basins to relate their winter peak 1-day flows to their coincident instantaneous peak and 3-day flows (see Appendix F). The upper basin hypothetical hydrographs are then shaped to match these peak, 1-day, and 3-day flows using the October 2003 upper basin hydrograph shapes as a guide. The timing for when each of the upper basin tributaries peaked is determined by evaluating this relationship for past events. Table 17 shows the timing for each of the tributaries.

TABLE 17 – TRIBUTARY TIME OF PEAK IN HOURS BEFORE SKAGIT RIVER NEAR CONCRETE PEAKS

	Ross Inflow	**Thunder Creek**	**Ross to Newhalem Local**	**Newhalem to Marblemount Local**	**Marblemount to Concrete Local**	**Sauk River at Sauk**	**Upper Baker Inflow**	**Lower Baker Inflow**
11/10/90	4		4	7	10	2	6	22
11/24/90	15			19			21	
11/29/95	3	7	-2	8	23	4	10	7
12/13/98	5	6	8	8	15	11		
11/12/99	-3			2	-2	14		
01/08/02	1	1	-4	2	-1	10		
01/26/03	-5		-5	1	8	6		
10/17/03	4.25	5.5	13.25	17	25.75	3.25	11.25	12.25
10/21/03	4.25	7.25	5.25	10.75	14.25	4	11.25	13.25
12/11/04	1	5	8	8	23	0	7	9
12/24/05	-11	3		6			8	
11/06/06	5		6	10		6	15	15
Average of All Events	2.0	5.0	3.7	8.2	12.9	6.0	11.2	13.1
Average of Large Events *	5.9	6.6	5.3	12.0	18.3	3.9	12.4	13.9
Timing Used	4.0	7.0	5.0	12.0	15.0	4.0	11.0	13.0

* Large events are the WY 1991, 1996, 2004, 2007 events.

To ensure that these upper basin flows are correct, the upper basin flows are routed without flood control regulation through a HEC-RAS unsteady flow model (see the Hydraulic Technical Documentation for more information) down to the Skagit River near Concrete for each of the events. These routed flow volumes are then compared with the corresponding unregulated flows that were derived for Concrete in Section 4.2. The upper basin flows are then scaled as necessary to match the unregulated flows at Concrete as closely as reasonably possible. Particular emphasis was given to matching the one-day unregulated flows at Concrete. Due to the complexity of the system, and the desire to maintain nested upper basin flow hydrographs over the full range of events, an exact match to the Section 4.2 unregulated flows was generally not possible. Differences between routed flows and unregulated flows from frequency analysis ranged from: +0.6% to -5.2% for peak flows; +0.4% to +3.4% for one-day volumes; and -6.2% to +8.6% for three-day volumes. The one-day scaled flows are listed in Table 18 below.

The HEC-RAS hydraulic model extends 0.5 miles upstream of Marblemount on the Skagit River and 0.5 miles on the Baker River above its confluence with the Skagit. For the purpose of flow inputs to the HEC-RAS model, for modeling of unregulated conditions, the Ross Dam Inflow, Thunder Creek, and local inflows above Marblemount are lumped into a single input hydrograph. Similarly, on the Baker River, the Upper Baker Dam and Lower Baker Dam inflows are lumped into a single input hydrograph.

TABLE 18 – SCALED UPPER BASIN 1-DAY COINCIDENT FLOWS (IN CFS) DERIVED FROM REGRESSION WITH UNREGULATED SKAGIT RIVER NEAR CONCRETE 1-DAY COMPUTED PEAK FLOWS

Location	2-year	5-year	10-year	25-year	50-year	75-year	100-year	250-year	500-year
Unregulated Skagit River near Concrete	68000	105000	134000	174000	207000	227000	242000	294000	336000
Ross Dam Inflow	9990	20340	26440	35320	41560	46090	49590	60710	69250
Thunder Creek	2100	4340	5620	7330	8690	9640	10300	12600	14390
Ross Dam to Newhalem Local w/o Thunder Ck	1880	3640	4760	6170	7340	8140	8770	10630	12160
Newhalem to Marblemount Local	10060	14910	20390	26750	31570	35050	37220	45630	51680
Cascade River at Marblemount	4920	7320	9570	11910	14530	15830	16990	20170	23350
Marblemount to Rockport Local	2960	4590	5770	7150	8750	9530	10230	12140	14070
Rockport to Concrete Local	2040	3070	3980	4930	6030	6570	7050	8370	9700
Sauk River at Sauk	22630	36040	49390	59900	71400	79670	85790	102200	115900
Upper Baker Dam Inflow	11620	16160	20410	27240	29790	32320	34390	40550	46420
Lower Baker Dam Inflow	3440	5070	6050	7960	8830	9580	10190	12010	13760

4.4.2.3 Determining Low Frequency Regulated Peak Flows for Skagit River near Concrete

To determine the regulated flows for Skagit River near Concrete, the existing flood control regulation is used to alter the upper basin flows. The inflows to Upper Baker and Ross Dams are routed using the existing flood control authority, to come up with regulated outflows at these two dams. Local flows with routing are added to the outflow from Ross Dam and Upper Baker Dam to determine the corresponding flows for the Skagit River at Marblemount and Baker River at Concrete gages. These flows are the upstream inputs to the upstream hydraulic model (see Hydraulic Technical Documentation). These flows are then routed with the necessary local flows to Skagit River near Concrete to produce the regulated hydrograph for that event. This is run for the 10-, 25-, 50-, 75-, 100-, 250-, and 500-year events. Further details of the analysis, including the technique for accounting for seasonal variation in flood control storage, are provided in Section 4.4.2.4.

4.4.2.4 Detail of Methods to Model Existing Flood Control Regulation

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 currently required in Diablo, Gorge, or Lower Baker Reservoirs. The following table is a synopsis of dam construction and important flood control storage requirements in the Skagit Basin.

TABLE 19 - 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

4.4.2.4.1 Reservoir Flood Operation

Flood control regulation at Ross is coordinated with flood control storage regulation at Puget Sound Energy's (PSE) Upper Baker plant. Ross is located approximately 40 miles and an 8-10 hours hydraulic travel time upstream from Concrete, and Upper Baker is located 9.3 miles and 1-3 hours hydraulic travel time upstream from Concrete. The Seattle District of the Army Corps of Engineers' Reservoir Control Center (RCC) regulates both projects concurrently to coordinate their regulated discharges and optimize their combined flood control storage. There is no authorized flood control storage at Diablo, Gorge, or Lower Baker Dams. During flood control events, the RCC, SCL, and PSE must monitor the operation of Diablo, Gorge, and Lower Baker to assure that (1) regulated discharges from Ross and Upper Baker are routed through the lower dams as expeditiously as possible, (2) adequate gate operation staff are available for necessary gate operations at all plants, and (3) no drafting of the three lower plants (Diablo, Gorge, or Lower Baker) will occur without first coordinating with the RCC. This third provision means that these lower 3 dams cannot release more than the outflows seen at the larger upstream dam plus the instantaneous local inflow coming into the project from local tributaries flowing into the dams between the upper dam and the lower dam.

Some pertinent information regarding the system and the regulation analysis include:

- Travel time between Ross and Concrete is considered to be nine hours
- Travel time between Upper Baker and Concrete is considered to be 1.5 hours
- Maximum outlet capacity at Lower Baker Dam is 41,000 cfs. If inflows exceed this value with a full pool the project would be overtopped.
- The ideal maximum flow at Newhalem, downstream of Gorge Dam, is 30,000 cfs.
- The ideal maximum release from Ross Dam is 25,000 cfs.
- Minimum outflow at Upper Baker is 5000 cfs.
- Minimum outflow at Ross is generally 5000 cfs but can be 0 cfs.

The “ideal” maximum flow at Newhalem and “ideal” maximum release from Ross Dam are flows above which damage may start to be experienced. Attempts are made to not exceed these “ideal” maximum flows, but they are not constraints on project operations.

4.4.2.4.2 Flood Regulation

The Water Control Manual (WCM) for each project has specific guidelines as to how each project is to be regulated during a flood. The WCM states that eight hours before the Northwest River Forecast Center forecasts the natural (unregulated) flow at Concrete to be 90,000 cfs, flow out of both Ross and Upper Baker will be set to their respective minimums. Typically, in an effort to preserve storage at Upper Baker, inflows would be passed until about two hours before the natural flow at Concrete is forecast to reach 90,000 cfs. These minimum outflows will be maintained until such time that the regulated flow at Concrete peaks or higher outflows are required by the Special Gate Regulation Schedule (SGRS). When the regulated flow at Concrete has peaked, Upper Baker can be ramped up to evacuate storage and Ross should be ramped up to pass inflow. This ramp up should not increase the flow at Concrete to a level greater than that at which it has already peaked. Care is needed when evacuating Upper Baker to ensure that the increased outflow from Ross does not push Concrete back above its peak or cause a secondary peak. When the flow at Concrete recedes to 90,000 cfs, evacuation of Ross can commence.

4.4.2.4.3 Flood Regulation Simulations

Reservoir regulation simulations were performed to estimate releases from Ross and Upper Baker for the 5-, 10-, 25-, 50-, 75-, 100-, 250-, and 500-year inflow events. The 2-year event was not regulated since it does not reach the 90,000 cfs flow on the Skagit River near Concrete which triggers flood control regulation. Estimation of the inflow hydrographs for these events is described in Sections 4.4.2.1 and 4.4.2.2 of this document.

Simulations were performed using an Excel spreadsheet constructed to route flows through the Ross and Upper Baker reservoirs at an hourly time step according to the flood control regulations described in the project Water Control Manuals. Each of the eight flood events from the 5-year event to the 500-year event was regulated using the spreadsheet model based on an "average case" or "most likely" regulation scheme as follows:

> Upper Baker outflow is reduced to a minimum of 5,000 cfs about three hours before the estimated natural flow at Concrete reaches 90,000 cfs. At Upper Baker, for large events, or events early in the flood control season, where outflow is dictated by the Spillway Gate Regulation Schedule, the Spillway Gate Regulation Schedule is followed until the flow at Concrete peaks. Inflows are then passed for about three to four hours after the Concrete peak has passed, and then only increased by an amount that does not increase the Concrete flow beyond that which occurred three hours after the Concrete peak. When possible, the 5,000 cfs minimum outflow is held for three to four hours after the Concrete peak. Where possible, consideration is given to keeping outflow to a level that allows Lower Baker to operate within its 41,000 cfs outlet capacity or as close to it as is deemed reasonable. Ross outflow is reduced to a minimum of 5,000 cfs eight hours before the estimated Concrete natural flow reaches 90,000 cfs and not ramped up to pass inflow until three to four hours after Concrete has peaked. In addition, the ideal maximum flow of 30,000 cfs at Newhalem is considered, and a reasonable attempt is made not to exceed this flow, or at least limit the amount/duration by which a flow of 30,000 cfs is exceeded.

Some variation from the "average" regulation scheme would be expected, particularly with regard to evacuation of flood control storage in situations where another significant flood is forecast.

A key consideration in the simulation of flood control regulation is the pool elevation (or, equivalently, amount of storage available) at the start of the simulation. The seasonal variation of flood control storage required at Upper Baker and Ross reservoirs is shown in Tables 10 and 15 respectively. The full amount of flood control storage is not required at Upper Baker until November 15 and at Ross until December 1. Large floods have, however, occurred early in the flood control season before the full amount of flood control storage is required under current operating policies. The most recent early season floods include the October 2003 floods described in Section 2.4.9.6, and the flood of November 6-7, 2006

Analyses were conducted of the impact of seasonal variation in flood control storage on regulated flood flows on the Skagit River near Concrete (USGS gage 12194000). The analyses (described in Appendix G) examined the flood control performance of Upper Baker and Ross reservoirs, with seasonally varying flood control storage, at two-week intervals from the start of the flood control season on October 1 through December 1, when the full amount of flood control storage is available at both Upper Baker and Ross. The impact of the seasonal variation of flood storage on regulated flows for the 5-

through 500-year events was then determined by weighting the regulated flow hydrographs for the Skagit River near Concrete on the basis of the historical frequency of occurrence of annual maximum winter flows within each two-week window through the flood control season. The analysis described in Appendix G concluded that allowance for the seasonal variation of flood control storage through use of weighted event hydrographs would increase regulated peak flow quantiles for the Skagit River near Concrete by about 5% for 50-year events and larger. Smaller events showed a smaller increase.

The weighted regulated event hydrographs for the Skagit River near Concrete were subsequently used as input to the lower basin hydraulic models used to characterize flood risk (see the Hydraulic Technical Documentation for hydraulic model details). The unregulated and weighted regulated hydrographs for the Skagit River near Concrete are provided in Appendix E.

4.4.2.5 Regulated Frequency Curve for Skagit River near Concrete

A combination of observed regulated peak flow events and hypothetical data from the reservoir regulation simulations (combination of the two methods mentioned in Sections 4.4.1 and 4.4.2.4.3) are used to calculate a regulated peak flow frequency curve at Concrete. The simulated data are used to draw the upper end of the frequency curve, while the observed data is used to define the lower end. A “best fit” line of the observed data is not used because regulated peak flow data do not fit any statistical distribution such as the Log Pearson type III (used to fit unregulated peak flow data). Frequency curves are provided in Appendix D.

The regulated frequency curve for peak annual flow at Concrete shows discontinuities or slope changes at regulated flows of about 62,000 and 90,000 cfs. These flows correspond to regulation “trigger points”. The 62,000 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 continued peak flow reductions as project releases follow the gate regulation schedules per the Water Control Manuals.

4.4.3 Confidence Limits for The Regulated Frequency Curve at Concrete

Confidence limits for the Skagit River at Concrete regulated frequency curve were developed using the HEC-FDA computer program (flood damage analysis program). The confidence limits are 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.)

5.0 Lower Skagit River Basin from Concrete, WA to Mouths of the North and South Forks of the Skagit River

The majority of damages in the Skagit River floodplain are found from Sedro-Woolley to the mouths of the North and South Forks of the Skagit River. It is necessary, therefore, to translate the regulated Skagit River near Concrete flows downstream to this reach. This requires routing these flows using a hydraulic model (see Hydraulic Technical Documentation for more information on the model) and adding in the local tributary flows that enter in along this reach.

From Concrete to the mouths of the North and South Forks, the Lower Skagit River Basin has 368 square miles of additional drainage area. This lower basin analysis focuses on producing local flows from Concrete to Sedro-Woolley and for Nookachamps Creek.

The lower basin analysis also includes estimation of flows for the Samish River. While the Samish River is not a tributary to the Skagit per se, during large floods, a portion of the spill from the right bank of the Skagit between Sedro-Woolley and Burlington flows north and co-mingles with flows from the Samish before discharging to Samish Bay. The drainage area of the Samish River at its mouth is about 106 square miles.

The hydrology investigation does not compute discharges along the mainstem 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 floodplain 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 the weighted regulated discharges at Concrete, adds tributary flow along the lower Skagit River and calculates information that is used to construct discharge frequency curves for the damage reaches downstream of Sedro-Woolley.

5.1 Local Flow from Concrete to Sedro-Woolley

There are 13 creeks that flow into the Skagit River between Concrete and Sedro-Woolley. These drainages are Finney Creek, Presentin Creek, Grandy Creek, Mill Creek, Boyd Creek, O'Toole Creek, Alder Creek, Cumberland Creek, Jones Creek, Day Creek, Sorenson Creek, Gilligan Creek, and Hansen Creek. This local flow enters the Skagit River from River Mile 54.1 to River Mile 24.2 and has a drainage area of 278 square miles.

Streamgage information on tributaries in the lower Skagit River basin is limited. The significant tributary gages in the lower Skagit River basin are Alder Creek near Hamilton which existed from 1944-79 and has a drainage area of 10.7 square miles, Day Creek near Lyman which existed from 1944-61 and has a drainage area of 34.2 square miles, Day Creek near Hamilton which existed from 1962-69 and has a drainage area of 32.3 square miles, East Fork Nookachamps Creek near Clear Lake which existed from 1944-1950, 1962-1963 and 2001-present and has a drainage area of 20.5 square miles, Finney Creek near Concrete which existed from 1943-8 and has a drainage area of 51.6 square miles, Hansen Creek near Sedro-Woolley which existed from 1943-5 and has a drainage area of 9.66 square miles, and Samish River near Burlington which existed from 1943-71, and 1997–present, and has a drainage area of 87.8 square miles. The two Day Creek gages can be merged together with a small adjustment for drainage area to make a continuous record from 1944 to 1969.

It would be ideal to perform regressions with the lower basins to the unregulated Skagit River near Concrete flows to be consistent with how the upper basin flows are developed. However the lower basin flows do not correlate well with the unregulated flows calculated at Concrete particularly for the higher flows that are being developed. This occurs for several reasons. From 1955-75, the mainstem Skagit River did not experience very large floods. This leaves the 1949 and 1951 floods as the only large floods that some of these gages represent. As is detailed in Section 2.4.9, the 1949 flood had very little precipitation in the lower basin whereas the 1951 flood had a significant contribution from the lower basin. This variation is not unusual and can be seen in the most recent October 2003 event versus the November 9-12, 1990 event. In 2003, the storm hung up on the mountains and continued to rain long after the lower valley had dried out. The event was also preceded by a very dry summer that helped the ground to absorb more in areas that did not receive as much precipitation. The 1990 event was preceded by a very wet month and had a significant low elevation snowpack that added a lot to the lower basin local flows.

The fact that there is not a consistent pattern between the flows seen in the lower basin to the flows seen in the upper basin is not a problem if there is enough data because an average condition can be derived. The concern with the limited data that is present for the lower basin is that it can be skewed to one or two specific conditions. This is what may occur if regressions are done with the data that has only the 1949 and 1951 peak flows. It is for this reason that a correlation with a longer period of record was looked for. There are two gaged basins that drain a nearby area and have a long period of record. These two gages are the North Fork Stillaguamish River near Arlington that has been recording from 1928 to present and drains an area just over the southern ridge of the Skagit River from the Sauk to Sedro-Woolley and the South Fork Nooksack River near Wickersham that has been recording from 1934 to present and drains an area just over the northern ridge of the Skagit River from roughly River Mile 45 to Sedro-Woolley.

In performing 1-day regressions with the lower Skagit River basin flows to these two basins, it is clear that the North Fork Stillaguamish correlates quite well with these Skagit River tributary flows. The North Fork Stillaguamish River runs parallel to the Skagit

River in a direction from East to West while the South Fork Nooksack River runs in more of a U-shaped pattern from South to North. It is likely that this similarity makes the North Fork Stillaguamish River correlate a lot better with the lower basin (Alder, Day, Finney, EF Nookachamps) flows in the Skagit than the South Fork Nooksack River does. Using the North Fork Stillaguamish River adds five Skagit River flows that are larger than the 1949 and 1951 events at Concrete and another five events that are within 15% of these events. This greatly improves the confidence of the definition of the upper flows in the regression relationship between the Skagit River near Concrete and coincident flows on the North Fork Stillaguamish.

The general approach adopted for estimation of coincident lower basin tributary flows between Concrete and Sedro-Woolley was thus a two-step regression. Firstly, a regression relationship was developed between 1-day unregulated peak flows for the Skagit River near Concrete and 1-day peak flows for coincident floods on the North Fork Stillaguamish River. Secondly, regression relationships were developed between 1-day peak flows for the North Fork Stillaguamish River and 1-day peak flows from coincident floods on the lower basin tributaries. The 1-day unregulated flow quantiles for the Skagit River near Concrete derived from frequency analysis (see Section 4.2) were then used as input to the regression relationships to determine first the coincident 1-day peak flow for the corresponding return period for the North Fork Stillaguamish, which flow was then used to determine the coincident 1-day peak flow for the lower basin tributary. Note that due to timing differences, 1-day peak flows in coincident floods sometimes occur on different observation days. Timing differences between flood events on the Skagit River near Concrete and coincident lower basin floods are discussed in Section 5.4.

Because of the limited data sets of some of the lower basins, it was felt necessary to use multiple winter flood events per year to better define the relationship between the flows seen on the North Fork Stillaguamish River compared to the lower Skagit River basin flow. For the regression that determines the relationship between the North Fork Stillaguamish River and the unregulated Skagit River near Concrete flows, all separable floods greater than 30,000 cfs near Concrete are used for the entire period of concurrent record (1943-2007). For the regressions that determine the relationship between the lower Skagit River tributary flows and North Fork Stillaguamish River flows, all separable floods greater than 5,000 cfs on the North Fork Stillaguamish are used for the entire periods of concurrent record.

It is then necessary to determine which of the lower Skagit River tributary flows best represent the flows seen in the entire reach from Concrete to Sedro-Woolley. On the right bank, the only gages that are present are on Alder and Hansen Creeks. Alder Creek's longer record gives greater confidence in the data set. Most of the tributaries along this right bank are similarly oriented in the North to South direction and all have similar sized drainage areas (less than 20 square miles). The limited data set for Hansen Creek shows a slightly higher runoff per square mile but not significantly or consistently enough to justify using a different runoff per square mile runoff ratio for the rest of the basin. Therefore, the entire right bank runoff (69.8 square miles) is estimated from the regression with Alder Creek.

The left bank is a little more complicated. Day Creek has the best record and also is in the middle of the Concrete to Sedro-Woolley reach. In looking at Finney Creek upstream and the East Fork of the Nookachamps downstream as well as the flows from the right bank, Day Creek has a significantly higher runoff per square mile than its counterparts. This is likely due to an orographic effect from the fact that it is surrounded by the Cultus Mountains on the west and Coal Mountain on the east. Finney Creek at the very upstream part of this lower reach and the East Fork Nookachamps Creek on the very downstream part of this lower reach, however, do have very similar runoff per square mile ratios. Because the majority of the tributaries coming in from the left bank enter in the upper half of this lower reach, Finney Creek is used to determine the runoff from the left bank with the exception of Day Creek (174 square miles). Given the short record available, Finney Creek flows were estimated by regression against Day Creek, which flows were in turn estimated by regression against the North Fork Stillaguamish.

All regression relationships are shown in Appendix F and 1-day flows are listed in Table 20 below.

The HEC-RAS hydraulic model uses a single inflow hydrograph uniformly distributed from Concrete to Sedro-Woolley. The bottom line of Table 20 represents the total inflow to the HEC-RAS hydraulic model for the Concrete to Sedro-Woolley reach.

TABLE 20 – CONCRETE TO SEDRO-WOOLLEY 1-DAY COINCIDENT FLOWS (IN CFS) DERIVED FROM REGRESSION EQUATIONS

Location	2-year	5-year	10-year	25-year	50-year	75-year	100-year	250-year	500-year
Unregulated Skagit River near Concrete	68000	105000	134000	174000	207000	227000	242000	294000	336000
North Fork Stillaguamish River near Arlington	15450	20120	23780	28830	33000	35520	37410	43980	49280
Day Creek	2270	2890	3380	4050	4610	4940	5190	6070	6780
Finney Creek	1880	2320	2670	3150	3540	3780	3960	4590	5090
Alder Creek	210	280	330	410	470	510	540	640	720
Left Bank Flows without Day Creek	6350	7840	9010	10620	11950	12760	13370	15460	17160
Right Bank Flows without Alder Creek	1140	1530	1830	2250	2600	2810	2970	3520	3960
Total Concrete to Sedro-Woolley Local	9950	12530	14580	17390	19630	21110	22040	25710	28620

It is recognized that there is considerable uncertainty in the estimates of coincident lower basin flows due to both the paucity of data and the poor regression relationships. Nor is it clear that the two-step regression relationships described above increase the reliability of estimates compared with a direct regression between flood flows for the Skagit River near Concrete and coincident lower basin flows. However we note that, on average, the lower basin tributary inflows peak roughly 17 hours before the peak flow on the Skagit River near Concrete (see Section 5.4). Peak flows for the Skagit River at Sedro-Woolley are thus insensitive to uncertainty in the lower basin tributary inflows.

5.2 Nookachamps Creek

Nookachamps Creek flows northwest into the Skagit River on the left bank at River Mile 18.8, downstream from Sedro-Woolley. Nookachamps Creek flows mostly northwest from Lake McMurray on the west fork and Cultus Mountain on the east fork. It has a total drainage area of 71.6 square miles.

A gage on the East Fork Nookachamps Creek near Clear Lake was operated by the USGS (USGS gage 12200000) from 1944-1950 and 1962-1963 and by Washington State Department of Ecology (WSDOE gage 03G100) from 2001-present. The drainage area at this gage site is 20.5 square miles. A gage on the west fork, Nookachamps Creek at Baker Heights (USGS gage 12199600), was operated for water years 2007-2008 and has a drainage area of 25.5 square miles. Analysis of flows on Nookachamps Creek is complicated by the different characteristics of the east fork and west fork and by the short record available (2 years only) on the west fork.

The east fork drains Cultus Mountain. Slopes are moderately steep and response to rainfall is rapid. Furthermore, storm rainfall amounts on Cultus Mountain are expected to be significantly higher than over the west fork due to orographic effects. Sub-basin average 100-yr 24-hour rainfall amounts estimated by the Oregon Climate Service are about 7 inches above the east fork gage and about 4.5 inches above the west fork gage.

In contrast to the east fork, the west fork is a low gradient stream, with peak flows significantly attenuated by floodplain storage and by routing through a number of lakes (notably Lake McMurray and Big Lake).

Estimates of coincident 1-day peak flows for the East Fork Nookachamps Creek were first derived by regression against 1-day unregulated annual peak flows for the Skagit River near Concrete. The relationship between peak flows on the Skagit River and coincident flows on the East Fork Nookachamps Creeks is poor. The regression relationship is shown in Appendix F and the estimated 1-day coincident flows for the East Fork Nookachamps Creek at the gage site are listed in Table 21 below. These flows were then adjusted for the total drainage area of Nookchamps Creek of 71.6 square miles as follows.

Comparison of the short period of concurrent daily flow record from the east fork and west fork for high flow events with combined daily peak discharges greater than 400 cfs shows that the 1-day peak discharge for the combined flow (combined drainage area of

46 square miles) is on average about 40% greater than the corresponding 1-day peak discharge from the east fork gage alone (drainage area 20.5 square miles). The coincident 1-day flows for the east fork gage site were thus multiplied by 1.4 to estimate coincident flows for the combined gaged area of the basin. These flows were then multiplied by the ratio of total drainage area to gaged area (71.6/46 = 1.56).

The resulting estimates of coincident 1-day peak flows for Nookachamps Creek are listed in Table 21 below.

5.3 Samish River

The Samish River flows generally southwest onto the Skagit River floodplain just north of Burlington and then flows west and northwest to discharge into Samish Bay near Edison. The drainage area of the Samish River where it crosses Interstate-5 at the edge of the Skagit floodplain is approximately 94 square miles. The drainage area at the mouth at Samish Bay is reported as 106 square miles. The Samish River basin upstream from I-5 is in mixed agricultural and forest land-use with some areas of low density residential development. Downstream from I-5, the basin is almost entirely agricultural.

Streamflow data for Samish River are available from Samish River near Burlington (USGS gage 12201500). Daily data are available from 1943-1971 and 1997-present. Annual instantaneous peak flows are available for water years 1944-1984 and 1997-present. The drainage area at the gage site is 87.8 square miles.

The Samish River has a longer gage record than other lower basin streams and includes data concurrent with the 1949, 1951, 2003 and 2006 Skagit River floods. Consequently, coincident flows for the Samish River were derived directly by regression of unregulated winter 1-day peak flows for the Skagit River near Concrete against coincident 1-day peak flows on the Samish (as with development of upper basin flows), using available data through water year 2007. The resulting flows were then adjusted for a drainage area of 106 square miles. The relationship between peak flows on the Skagit River and coincident flows on the Samish is poor. The regression relationship is shown in Appendix F, and the estimated 1-day coincident flows for the Samish River are listed in Table 21 below.

TABLE 21 – NOOKACHAMPS AND SAMISH RIVER 1-DAY COINCIDENT FLOWS (IN CFS) DERIVED FROM REGRESSION EQUATIONS

Location	2-year	5-year	10-year	25-year	50-year	75-year	100-year	250-year	500-year
Unregulated Skagit River near Concrete	68000	105000	134000	174000	207000	227000	242000	294000	336000
North Fork Stillaguamish River near Arlington	15450	20120	23780	28830	33000	35520	37410	43980	49280
East Fork Nookachamps Creek at gage	400	620	790	1030	1220	1340	1430	1730	1980
Total Nookachamps Creek	880	1350	1730	2240	2670	2930	3120	3790	4330
Samish River	1170	1810	2310	3000	3570	3920	4180	5080	5800

5.4 Development of Hypothetical Hydrographs for Lower Basin

The regressions provided 1-day peak flows for each of the lower basin inputs. Regressions are then developed for each of the lower basins to relate their winter peak 1-day flows to their coincident instantaneous peak and 3-day flows (see Appendix F). The lower basin hypothetical hydrographs are then shaped to match these peak, 1-day, and 3-day flows using the October 2003 North Fork Stillaguamish River hydrograph as a guide. The one exception to this approach was for Nookachamps Creek where, due to lack of data, the 1-day to instantaneous peak and 1-day to 3-day flow relationships for the Samish River were applied. The Samish River (gaged area of 87.8 square miles) has a similar basin area to Nookachamps Creek (total drainage area of 71.6 square miles) and similar land use and physiographic features.

5.5 Timing of Lower Basin Flows

The timing for when local discharges from the Nookachamps Creek and Concrete to Sedro-Woolley combine with discharges on the Skagit River can vary considerably. In the 2003 event, the North Fork Stillaguamish River peaked 6 hours before the Skagit River near Concrete. In 1995, it peaked 19 hours before Skagit River near Concrete. The Upper Basin local flow that has the same relative size of drainage basins and proximity to the mainstem Skagit is the Marblemount to Concrete local. From the Upper Basin analysis, it was determined that this local inflow peaks roughly 15 hours before the Skagit River near Concrete does on average. To be consistent with this upper basin timing and assuming that the lower local inflows would peak slightly earlier as it takes some time for the precipitation to travel from the lower basin to the upper basin, a peak timing of 17 hours before the Skagit River near Concrete peaks is used for the lower basin local inflows.

6.0 Hydrologic Results

There are several general locations where it is important to know what the derived flows are for specific events. These locations are Concrete, Sedro-Woolley, and Mount Vernon. Concrete is important because it represents the upstream location where most of the hydrology was developed. Sedro-Woolley's flows are of note because they represent the flows that enter the lower basin before the Nookachamps basin storage is accounted for. The Mount Vernon flows show how much water can make it through the narrowed levee reach. The flows listed in the tables below are derived from "infinite" levee hydraulic model runs which assume that no water can escape from the river channel due to spill, levee overtopping, or levee failure. This information is only for the purposes of understanding the amount of flow that needs to be accounted for in this lower basin. More detailed information on flows and stages for specific levee failure runs can be found in the Hydraulic Technical Documentation. Note that for consistency, all flows reported in Table 22, including the unregulated flows at Concrete, are from routing of the synthetic hydrographs (see Section 4.4.2) as opposed to results of frequency analyses.

TABLE 22 – PEAK FLOWS (CFS) AT CONCRETE, SEDRO-WOOLLEY, AND MOUNT VERNON

Recurrence	Unregulated Concrete	Regulated Concrete[1]	Unregulated Sedro-Woolley	Regulated Sedro-Woolley[1]	Unregulated Mount Vernon	Regulated Mount Vernon[1]
2-year	77,300	77,300	80,500	80,500	76,400	76,900
5-year	120,500	101,100	125,600	105,200	110,500	92,900
10-year	153,300	127,700	159,400	133,000	142,600	119,000
25-year	201,200	165,300	211,700	169,800	169,900	149,800
50-year	229,300	189,100	235,000	197,400	210,200	167,600
75-year	255,500	211,400	261,200	220,000	220,800	192,300
100-year	272,400	225,900	280,100	235,700	236,400	206,500
250-year	325,400	279,700	320,100	289,400	278,100	244,700
500-year	363,600	324,400	356,900	325,400	320,900	282,600

Notes:

1. Regulated data from weighted regulated hydrographs (see Section 4.4.2.4.3)

In addition, it is useful to see the flows derived from frequency analyses for key sub-basins. These values, provided in Tables 23 to 25, are different than the flows in Table 18 for several reasons. The first is because the flows derived in Table 18 are the coincident flows in these basins when the Skagit River near Concrete peaks, which may not correspond to the same frequency for the sub-basin. For example, if the Skagit River near Concrete is having a 100-year event, the contribution from a specific sub-basin could be a 50-year event or a 200-year event. The second complication in comparing these flows is that the analysis for the Skagit River near Concrete uses the historical flows derived by Stewart (as adjusted by the USGS in 2007), but the other gages do not use this information. This factor does not affect the results of this study as the correlations relied on in Table 18 do account for these historical flows. With these caveats, the table below shows the flows derived from frequency analyses for the most critical sub-basins; Upper Baker Dam inflow, Ross Dam inflow, and Sauk River near Sauk. Also shown for purposes of comparison are the regulated flows for the Skagit River near Concrete and Skagit River near Mount Vernon derived from routing of synthetic hydrographs with "infinite" levees.

TABLE 23 – INSTANTANEOUS PEAK FLOWS (CFS) FOR CRITICAL SUB-BASINS

Recurrence	Regulated Concrete[1]	Regulated Mount Vernon[1]	Upper Baker Dam Inflow[2]	Ross Dam Inflow[2]	Sauk River near Sauk[2]
2-year	77,300	76,900	17,200	20,100	30,500
5-year	101,100	92,900	22,300	28,000	47,900
10-year	127,700	119,000	25,800	33,100	61,300
25-year	165,300	149,800	30,400	39,600	80,200
50-year	189,100	167,600	34,000	44,300	95,900
75-year	211,400	192,300	36,200	47,100	106,000
100-year	225,900	206,500	37,700	49,000	113,000
250-year	279,700	244,700	42,900	55,200	138,000
500-year	324,400	282,600	47,000	59,900	159,000

Notes:
1. Quantiles from routing of synthetic weighted regulated hydrographs.
2. Quantiles are for computed probability using annual (full year) data through water year 2004.

TABLE 24 – 1-DAY PEAK FLOWS (CFS) FOR CRITICAL SUB-BASINS

Recurrence	Regulated Concrete[1]	Regulated Mount Vernon[1]	Upper Baker Dam Inflow[2]	Ross Dam Inflow[2]	Sauk River near Sauk[2]
2-year	68,300	72,200	11,400	9,340	22,300
5-year	88,200	89,300	16,400	16,700	35,000
10-year	113,700	115,700	19,900	22,700	44,100
25-year	143,700	143,700	24,300	31,800	56,200
50-year	172,000	165,800	27,800	39,600	65,700
75-year	191,200	182,300	29,800	44,600	71,300
100-year	206,600	200,100	31,200	48,300	75,400
250-year	254,600	236,700	34,800	61,400	88,700
500-year	297,100	273,700	39,700	72,600	99,200

Notes:
1. Quantiles from routing of synthetic weighted regulated hydrographs.
2. Quantiles are for computed probability using winter data through water year 2004.

TABLE 25 – 3-DAY PEAK FLOWS (CFS) FOR CRITICAL SUB-BASINS

Recurrence	Regulated Concrete[1]	Regulated Mount Vernon[1]	Upper Baker Dam Inflow[2]	Ross Dam Inflow[2]	Sauk River near Sauk[2]
2-year	51,800	58,700	8,360	7,680	16,400
5-year	75,300	81,500	11,600	13,200	25,200
10-year	95,500	102,900	13,700	17,600	31,500
25-year	115,900	125,000	16,400	23,800	40,100
50-year	135,900	145,800	18,400	29,000	46,700
75-year	148,600	158,300	19,500	32,200	50,800
100-year	161,400	171,300	20,300	34,500	53,700
250-year	198,200	206,500	22,900	42,600	63,400
500-year	230,000	238,600	24,800	49,300	71,100

Notes:
1. Quantiles from routing of synthetic weighted regulated hydrographs.
2. Quantiles are for computed probability using winter data through water year 2004.

6.1 Comparison with Previous Study Results

The results of the hydrologic analyses presented in this 2013 report differ from the results presented in the 2004 and 2011 draft Hydrology Technical Documentation. A comparison of estimated peak flows from the 2004 draft Hydrology Technical Documentation, the 2008 draft Flood Insurance Study, the 2011 draft Hydrology Technical Documentation, and the present work is provided in Table 26. As in Tables 22 through 25 above, the flows provided for Sedro-Woolley and Mount Vernon represent the “infinite” levee condition.

The principal factors which contributed to changes in peak discharge from the 2004 draft report to the 2011 draft report were as follows:

1. An approximately 5% reduction, by the USGS, in the estimated magnitude of the historic floods of water years 1898, 1910, 1918 and 1922.
2. Increased record length for the Skagit River near Concrete, reflecting both recent data from water years 2005 through 2007, and incorporation of data for the period 1925 through 1943 which had not previously been available.
3. A change from estimation of flood quantiles with expected probability adjustment in the 2004 report to use of computed probability flood quantiles in the 2011 (and 2013) reports, consistent with requirements for risk-based analysis and design of flood risk management projects.

The above three changes are also reflected in the peak discharge estimates reported in the 2008 draft Flood Insurance Study.

There are several other changes which accounted for differences between the 2011 work and the draft FIS study, and which also contributed to the differences between the 2011 and the 2004 drafts. These included:

4. Adjustment to some upper basin hydrographs to improve the consistency in hydrographs for different return periods and provide improved nesting of those hydrographs.
5. Modification to the spreadsheet program used to route floods through Upper Baker and Ross reservoirs to improve model representation of spillway gate regulation curves.
6. Reanalysis and reduction in Nookachamps Creek coincident flows, incorporating data either not used or not available for the earlier work.
7. Rather extensive changes to and recalibration of the HEC-RAS model representation of the Skagit River from Sedro-Woolley to Mount Vernon. Routing of flows from Sedro-Woolley to Mount Vernon is affected by several factors including floodplain storage in the Nookachamps Creek basin and assumptions regarding debris load on the Burlington Northern Railway bridge in Mount Vernon. The HEC-RAS model, its calibration, and hydraulic model results are described in detail in the Hydraulic Technical Documentation.

The principal factors which contribute to differences in estimated peak discharges between the 2011 draft Hydrology Technical Documentation and the current 2013 report are as follows:

8. Use of weighted regulated hydrographs in the current work to account for seasonal variation in flood control storage at Upper Baker and Ross reservoirs.
9. Corrections and refinements to the HEC-RAS model representation of the Burlington Northern Railway bridge, including changes to debris load assumptions. These changes affect floodplain storage in the Nookachamps Creek basin and were found to have a significant impact on unregulated flows at Mount Vernon for the 25-year event and larger as the bridge goes into pressure flow and forces water into the Nookachamps storage area at a lower discharge than previously estimated.
10. Other refinements to the HEC-RAS model, including corrections and refinements to the model representation of the Division Street bridge in Mount Vernon and the Highway 9 and former Great Northern Railway bridges immediately downstream from Sedro-Woolley.

TABLE 26 – COMPARISON OF PEAK FLOWS (CFS) AT CONCRETE, SEDRO-WOOLLEY, AND MOUNT VERNON GAGES

Recurrence Interval and Data Source	**Unregulated Concrete**	**Regulated Concrete**	**Unregulated Sedro-Woolley**	**Regulated Sedro-Woolley**	**Unregulated Mount Vernon**	**Regulated Mount Vernon**
2-yr 2004 GI	72,900	72,900	78,100	78,100	75,700	75,700
2-yr 2011 GI	77,300	77,300	80,500	80,500	76,500	76,500
2-yr 2013 GI	77,300	77,300	80,500	80,500	76,900	76,900
5-yr 2004 GI	119,400	93,900	124,300	99,400	116,500	97,300
5-yr 2011 GI	120,500	100,700	126,000	105,000	110,700	92,400
5-yr 2013 GI	120,500	100,100	125,600	105,200	110,500	92,900
10-yr 2004 GI	156,000	120,400	160,600	125,100	142,700	117,400
10-yr 2008 FIS	159,000	116,300	156,920	123,610		
10-yr 2011 GI	153,300	125,500	159,800	130,400	142,800	117,700
10-yr 2013 GI	153,300	127,700	159,400	133,000	142,600	119,000
25-yr 2004 GI	205,300	158,000	210,300	163,400	199,400	146,000
25-yr 2011 GI	201,200	159,300	203,700	162,600	192,900	143,400
25-yr 2013 GI	201,200	165,300	211,700	169,800	169,900	149,800
50-yr 2004 GI	248,100	192,100	252,000	198,500	233,700	190,900
50-yr 2008 FIS	241,000	180,260	233,290	183,780		
50-yr 2011 GI	229,300	180,300	234,800	186,100	219,100	167,700
50-yr 2013 GI	229,300	189,100	235,000	197,400	210,200	167,600
75-yr 2004 GI	248,100	192,100	252,000	198,500	233,700	190,900
75-yr 2011 GI	255,500	200,700	259,400	205,800	237,400	196,400
75-yr 2013 GI	255,500	211,400	261,200	220,000	220,800	192,300
100-yr 2004 GI	297,100	235,400	298,600	242,000	273,900	230,100
100-yr 2008 FIS	278,000	209,490	277,220	215,270		
100-yr 2011 GI	272,400	214,200	275,500	220,100	250,300	207,300
100-yr 2013 GI	272,400	225,900	280,100	235,700	236,400	206,500
250-yr 2004 GI	372,200	320,200	368,100	319,800	334,000	289,800
250-yr 2011 GI	325,400	267,400	323,500	271,800	288,000	246,300
250-yr 2013 GI	325,400	279,700	320,100	289,400	278,100	244,700
500-yr 2004 GI	437,000	386,900	429,900	380,800	396,700	346,400
500-yr 2008 FIS	373,000	316,530	371,670	322,900		
500-yr 2011 GI	363,600	313,300	353,100	314,200	317,800	280,100
500-yr 2013 GI	363,600	324,400	356,900	325,400	320,900	282,600

2004 GI:	2004 Draft Hydrology Technical Documentation
2011 GI:	2011 Draft Hydrology Technical Documentation
2013 GI:	2013 Hydrology Technical Documentation
2008 FIS:	2008 Draft Flood Insurance Study

7.0 Limits of Downstream Flood Protection

Levees in the lower valley are the only flood control structures in the basin except for the Ross and Upper Baker flood storage projects. Sixteen diking districts in the lower valley provide primary levee protection, protecting 45,000 acres of land. These levees vary in level of protection with hydraulic capacities ranging from about 80,000 cfs to 150,000 cfs. Individual owners have constructed private levees that protect an additional l,000 acres. Between Concrete and Sedro-Woolley, low levees protect several rural areas. Most of the levees were constructed years ago by farmers and local people attempting to protect their property. Many of these older levees have been raised and strengthened in recent years, but sub-standard foundation materials make them vulnerable to failure during major floods due to seepage and erosion conditions. Table 27 is taken from the Water Control Manuals for both Ross and Upper Baker Dams to show the flow levels that create problems in the lower basin.

TABLE 27 - FLOOD CONDITIONS RELATED TO THE GAGE SKAGIT RIVER NEAR MOUNT VERNON, WASHINGTON

Stage (Ft.)	**Discharge**		**Character of Flooding**
	(cfs)		
25.0	53,200	1.	Beginning of backwater in Nookachamps Creek area with flooding of low-lying farmlands --no damage
28.0	67,850	1.	Zero damage
30.3	82,260	1.	Beginning of flooding in town of Hamilton
		2.	South End of Francis Road is overtopped and closed to traffic which is the road to Sedro-Woolley via Clear Lake. Those living in this lower area on Francis Road no longer have an escape route.
		3.	Beginning of overland flow to levee east of Burlington on Fairhaven Street, on north side of river between Sedro-Woolley and Burlington.
32.7	100,300	1	Major damage discharge in the vicinity of Mount Vernon
33.8	110,000	1.	Levee freeboard as follows: Levee east of Burlington on Fairhaven Street -3 to 4 feet.
		2.	Levee failures may occur when river remains above this stage more than 24 hours, with flood conditions varying as levees fail or are overtopped throughout the valley
		3.	In view of the inadequate cross-section of practically all Skagit River dikes, the following action should be taken by the Corps at this time if a 2-foot rise is indicated in the next 24 hours: **Be prepared to evacuate flood fighting crews from areas below Mount Vernon.**
36.60	141,500	1.	Flooding expected in many districts. Dikes on either right or left bank from Hwy. 99 bridge downstream to Mt. Vernon may be breached
38.1	160,000	1.	Emergency raising of Burlington and Mount Vernon levees necessary to prevent flooding