Skagit River Basin Hydrology Draft Report
Existing Conditions

August 2007

Prepared For:

City of Burlington
City of Mount Vernon

By:

PACIFIC
INTERNATIONAL
ENGINEERING PLLC

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Skagit County, Washington

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1.0 Summary

This report presents an update of Skagit River hydrology conducted by Pacific International Engineering (PI Engineering) under an Agreement for Engineering Services authorized in June 2007 by the City of Burlington. The information and results of the analyses presented herein are intended for use in the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS).

The hydrology presented in this report updates the Skagit River flood hydrology contained in the December 2005 report prepared by PI Engineering for Skagit County, entitled "Hydrology and Hydraulics, Skagit River Flood Basin – Existing Conditions" (PI Engineering 2005). The river's hydrology has been the subject of measurement and study for over 85 years, and predictions of flood behavior have been revisited periodically in the light of a growing body of recorded data. PI Engineering has, over the last 5 years, conducted analyses of the available data, and has been actively in discussion with other consultants and agencies involved.

The purpose of this report is to determine the flood frequency and synthetic flood hydrographs for the highly developed floodplain areas of the Skagit River basin from Sedro-Woolley downstream to the confluences of the North and South Forks of the Skagit River with Puget Sound (Figure 1). This report describes the analyses performed to make those determinations with the highest degree of confidence and presents peak flows and flood hydrographs for the 10-, 50-, 100-, and 500-year events, that meet the requirements for the Skagit River FIS in accordance with the current FEMA guidelines (FEMA 2003).

Hydrologic studies have covered the Skagit River from Concrete downstream to Puget Sound. Above this stretch of river are the Ross, Gorge and Diablo Dams and Seattle City Light hydroelectric plants on the main stem of the Skagit, and Puget Sound Energy's Baker River hydroelectric development, on a tributary of the Skagit with its confluence at Concrete. Since their completion these hydroelectric facilities have provided regulation to the flow in the Skagit in accordance with agreements since 1954 and 1980 respectively. Prior to these dates, the presence of the facilities contributed to some regulation of the flows, the extent of which cannot be determined with exactitude.

Prior to 1925, there are no stream gage records on the Skagit River at Concrete. Earlier records are available for gages at Sedro-Woolley, and on tributary streams including the Sauk River and Baker River, as well as stage readings and anecdotal reports of high water observed during high-flow events. In the three decades before the Concrete gage was installed, and before the construction of the hydroelectric developments, high flows caused flooding on the Skagit, notably in 1897, 1909, 1917 and 1921. James E. Stewart, of the U.S. Geological Survey, set out to collect and analyze observations of these major flood events in order to develop flood frequency curves. (Stewart 1923).

Stewart's early work was not revisited until the 1950s, documented in USGS memoranda, and was finally published as USGS Water Supply Paper 1527 in 1961. The intervening period included a number of unusually dry years, with high-flow conditions (over 120,000 cfs at Concrete) occurring only in water years 1932, 1935, 1950, and 1951. Also during this period, the Puget and Seattle hydroelectric developments were completed, and contributed to varying degrees of regulation of the Skagit River peak flows. In spite of the fact that Stewart, and his successors in the 1950s, had access only to limited amounts of historical data, their studies were a valuable contribution to codifying flood expectations for the Skagit River. Both in 1923 and the 1950s, recent flood experience had lent urgency to the need for such analysis. More recent high-flow events, in water years 1991, 1996, 2004 and 2007, continue to show the need for refinement of hydrologic studies of the Skagit River, particularly as they affect development and investment in the region's urbanizing areas.

It is consistent with FEMA's *Guidelines and Specifications for Flood Hazard Mapping* that estimates of flood discharge frequency be updated as the length of gage records increases. There are now over 80 years of records at the Concrete gage, supplemented by the limited observations and estimates of the "historical" floods.

The "historical" estimates are incomplete and hard to reconcile with the results of analysis using more sophisticated current methods. Repeated efforts to validate the estimates of peak flows at Concrete during the unrecorded "historic" floods in 1897, 1909, 1917 and 1921 made by the USGS based on Stewart's 1923 studies have encountered a number of difficulties in verifying data, and reconciling conflicting observations.

As an alternative approach, estimates of peak flows at Concrete for these events have been derived based on estimates made by USGS personnel for flows at the Sedro-Woolley gage, installed in 1908. Estimates by several researchers were screened to eliminate those that were incompatible with contemporary records relating to flow in the right bank side channel near The Dalles, and observations of high water marks on houses in Hamilton surviving from the era of the historical flood events.

Recent studies by PI Engineering using the Corps of Engineers' (USACE) latest HEC model established a consistent relationship between peak flows at Sedro-Woolley and Concrete for each significant flood event. Applying this relationship to the highest supportable USGS estimates of peak flow at Sedro-Woolley results in a set of peak flow estimates at Concrete that can be defended based on recorded observations. Although these estimates are substantially less than those developed by the USGS in the 1950s based directly on Stewart's work, they are not vulnerable to the challenges that arise from the application of more modern modeling and analysis techniques.

Data for these historic events are combined with data sets developed by the USACE and PI Engineering to compile a record covering 87 years of unregulated peak flows for frequency analysis. The analysis results in a prediction of 227,200 cfs as the unregulated peak flow at the Concrete gage for a 100-year flood. Using similar data sets, values are also derived for unregulated one-day flows at Concrete. Using synthetic hydrographs originally developed by the USACE, and the HEC-RAS and HEC-5 models originally developed by the USACE, runs were conducted routing the floods through the Ross/Diablo/Gorge and Baker Dams storage regulation and downstream Skagit Valley to Puget Sound. This enabled regulated flood peaks and hydrographs reflecting the existing basin conditions, to be developed at the location of the highly developed floodplain areas downstream of Sedro-Woolley.

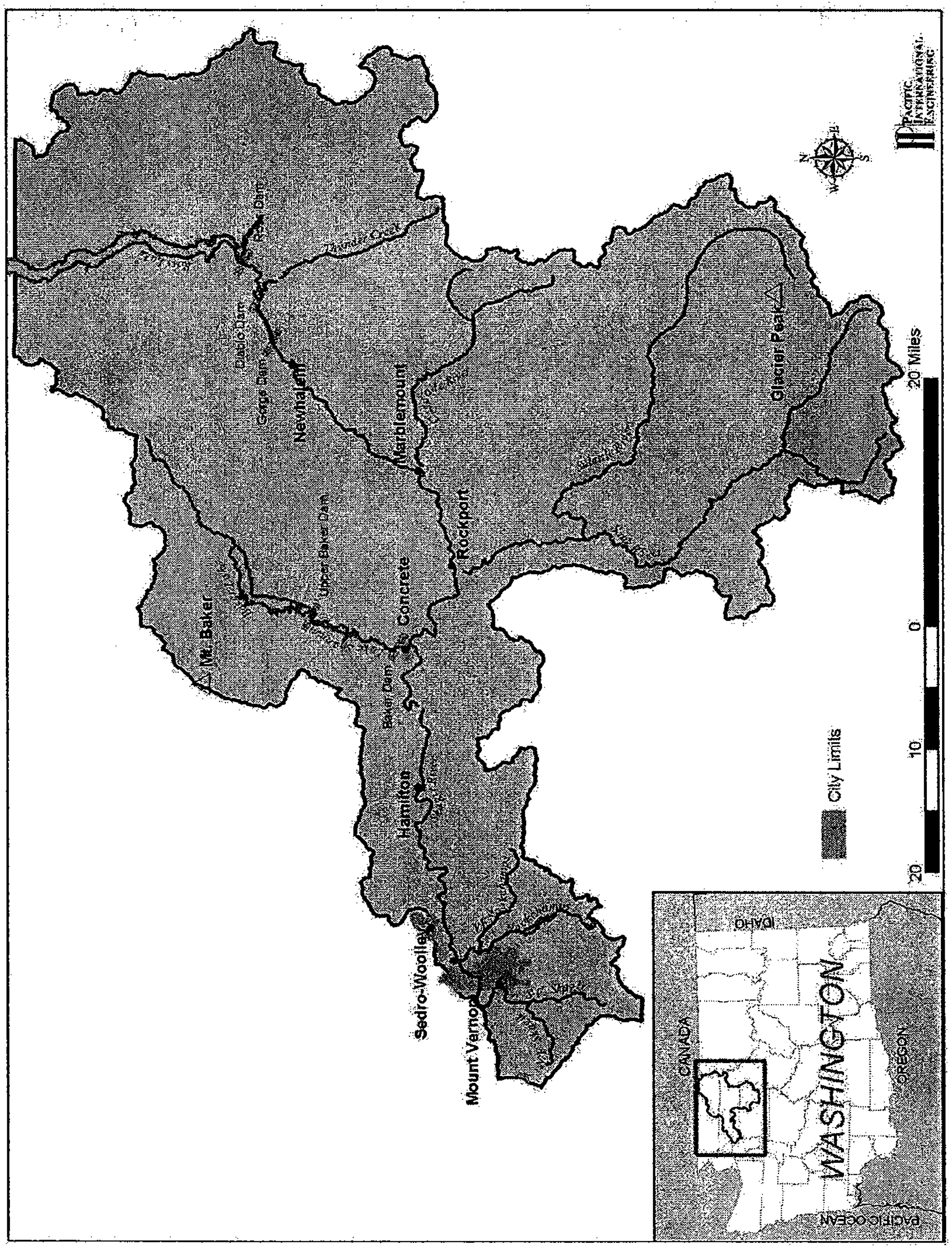

Figure 1. Skagit River Basin

2.0 Skagit River Watershed Characteristics

The Skagit River basin, located in the northwest corner of the State of Washington (Figure 1) is a regulated watershed. It includes three dams located on the mainstem Skagit River (Gorge, Diablo and Ross), and two dams located on the Baker River (Lower Baker and Upper Baker). Gorge Dam was completed as a wooden structure in 1924, and replaced with a concrete dam in 1950. Diablo Dam was completed in 1931, at the time the tallest dam in the world at 389 feet. The first level of Ross Dam (300 feet tall) was completed in 1940, and the second and third levels were both completed in 1949 bringing the dam's total height to 540 feet. Lower Baker Dam was completed in 1925, creating Lake Shannon. Upper Baker Dam was completed in 1959, increasing the size of the naturally occurring Baker Lake. Regulation of the Skagit River using 120,000 acre-feet of flood control storage at Ross Dam began in 1954, and regulation of the Baker River using 74,000 acre-feet of flood control storage at Upper Baker Dam began in 1980.

The Skagit River basin has a total drainage area of 3,115 square miles, originating near the Cascade Mountains in British Columbia, Canada. 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 falls rapidly from its source at elevation 8,000 feet to an elevation of 1,600 feet at the United States-Canadian border. Within the first 40 miles south of the international border, the river falls 1,100 feet, and the remaining 500-foot fall is distributed along the 95 miles of the lower river.

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, respectively, of the normal flows of the Skagit River into Puget Sound.

The Skagit Valley, the 100,000-acre, 32-mile-long valley between Concrete and Sedro-Woolley, contains the largest residential and farming developments in the basin. It is made up of mostly cattle and dairy pastureland and wooded areas. West of Sedro-Woolley, the floodplain forms a large alluvial fan with an east-west width of about 11 miles and a north-south width of about 19 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 portion of the basin is mountainous land above an elevation of 6,000 feet. The two most prominent topographical features in the basin are Mount Baker on the northern side of the basin at an elevation of 10,778 feet, and Glacier Peak in the southern portion of the basin at an elevation of 10,568 feet. In the eastern portion of the basin, 22 peaks are above an elevation of 8,000 feet. 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.

2.2 Geology

The eastern mountainous region of the upper Skagit River 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, such as the recent slide near Newhalem, the slide at the site of the Lower Baker powerhouse, and other locations that contain evidence of large slides.

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 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 10,778 feet, approximately 10 miles west of the northern tip of Baker Lake.

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 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

The Skagit is a "high" sediment system, and 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 Ocean. 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.

2.4.1 Temperature

The mean annual temperature for stations in or near the basin varies from 40.1 degrees Fahrenheit (°F) at Mount Baker Lodge to 50.7°F at Concrete. Normal monthly temperatures vary in January from a low of 26.9°F at Mount Baker Lodge to a high of 39.1°F at Anacortes, and in August from a low of 56.7°F at Mount Baker Lodge to a high of 64.7°F at Diablo Dam. The temperature extremes recorded in the basin are 109°F at Newhalem and -14°F at Darrington Ranger Station. A phenomenon known as the Pineapple Express can cause Pacific Northwest wintertime temperatures to rise to the upper 50s or warmer, such as happened in December 1990 when temperatures in the Seattle area reached 63 degrees. A Pineapple Express occurs when the jet stream dips into the tropics and then carries a large batch of tropical (Hawaiian) moisture northeast into the Pacific Northwest during the winter. This causes wet and warm weather, a common cause of lowland flooding episodes.

2.4.2 Precipitation

The locations of precipitation stations in the Skagit River basin are shown on Figure 2. 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 180 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, as recorded at Ross Dam, Diablo Dam, Newhalem, Upper Baker Dam, Concrete, and Sedro-Woolley, averages 71 inches with approximately 75 percent of this amount falling during the 6-month period of October-March. The mean monthly precipitation at stations in or near the basin ranges from 0.96 of an inch in July at Anacortes to 17 inches in December at Mount Baker Lodge. The mean annual precipitation at Baker Lake and Diablo Dam is 102.88 inches and 77.07 inches, respectively. The maximum recorded precipitation for one month was 41.95 inches at Silverton (south of Darrington) 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. Information on storms and flooding in the basin is discussed in Section 2.7.

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 vicinity of the basin varies from 6.2 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 in the vicinity of the Skagit River basin since 1943. Locations of Snotel snow measuring stations in the vicinity of the basin are shown on Figure 2.

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 winter and down slope in 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

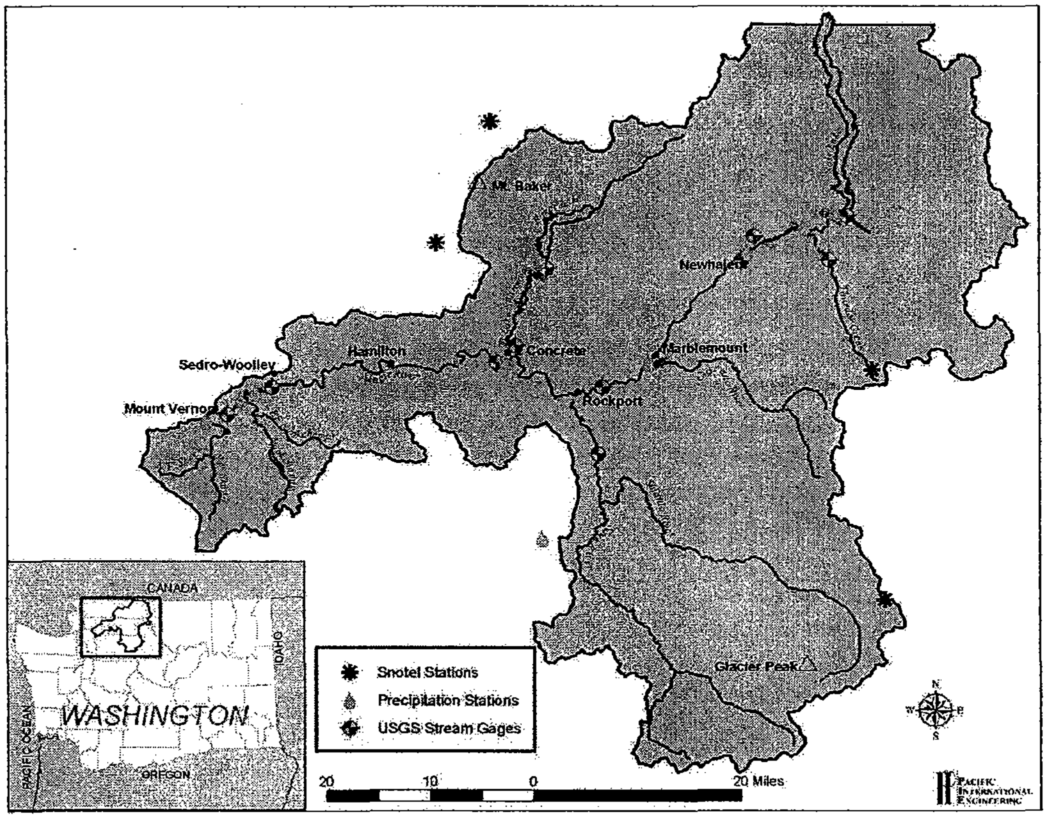

Figure 2. Skagit River Basin Stream Gage and Meteorological Stations Location Map

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. A common producer of high winds in this area is the Pacific Northwest chinook, which results from high and low pressure areas colliding overhead. Two notable chinook wind storms of recent history hit northwest Washington in December 1996 and in December 2003. The 1996 chinook brought winds up to 60 to 70 mph, with gusts to 80 mph. Trees were blown onto power lines causing extensive power outages, and in some cases trees were snapped off at the ground. The 2003 chinook sustained winds of 45 to 50 mph, with gusts to 65 mph.

2.5 Channel Characteristics

2.5.1 International Border to Gorge Dam

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

2.5.2 Gorge Dam to Newhalem

The 15,000-foot-long reach from Gorge Dam to the Gorge Powerhouse is usually dry during normal hydropower operations. During even small flooding events, 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.

2.5.3 Newhalem to Concrete

The 39.6-mile-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, with evidence of past slides, some of which were large enough to block the river channel for a time. 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.

2.5.4 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 1.5 feet 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 between 15 and 20 hours at low flow to between 10 and 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.

2.6 Streamflow Characteristics

The Skagit River basin is subject to rain and snowmelt runoff during the fall, winter, and spring. Spring snowmelt runoff is caused predominantly by melting of the winter snowpack, and is characterized by a relatively slow rise and long duration evidenced by the higher mean high flows for the months of April through June. 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 cubic feet per second (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, even though operation of the upper basin reservoirs increases flows over historic numbers.

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- to 3-day winter storms cause 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.

The Skagit River, which receives the effect of the initial lifting of Pacific Ocean 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 stream gage - 51.1 inches, Sauk River near Sauk stream gage - 83.0 inches, Baker River at Upper Baker - 131.0 inches, Baker River at Concrete stream gage - 121.8 inches, and Skagit River near Mount Vernon - 73.2 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.

Maximum and minimum extremes in recorded annual runoff at Mount Vernon during the 1941-1999 period are 16,752,595 acre-feet (in 1991) and 7,608,893 acre-feet (in 1944) or 101.6 and 46.1 inches, respectively, for the 3,093 square-mile basin. The locations of U.S. Geological Survey stream gauging stations in the Skagit River basin are shown on Figure 2.

2.7 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 stream and 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 major 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 120,000 cfs below Concrete and are expected every 10 years or so. Minor floods become major floods when the 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. For example, 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.

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 (see Section 2.7.4 below), 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 River 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.

The Nookachamps Creek area on the south bank of the Skagit River, between Mount Vernon and Sedro-Woolley, is a major source of valley storage. Storage in this area can reduce major flows by 15,000 cfs to 25,000 cfs downstream from Sedro-Woolley during high-peak/low-volume floods. Larger floods with greater volume will fill the Nookachamps storage prior to the flood crest and offset most of the storage benefit.

2.7.1 Flood Runoff from Uncontrolled Watersheds

Runoff from the uncontrolled watersheds in the Skagit River basin has a major affect on flooding in the lower Skagit Valley. Flood control at Ross and Upper Baker dams is sufficient to control floods in the lower valley (within the levee system from Burlington to the mouths) with exceedance frequencies of approximately three to four percent; but flood runoff from the Skagit's uncontrolled watersheds during events greater than approximately three to four percent 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 dams. The floods of November 1990 and November 1995 (see Sections 2.7.4 and 2.7.5 below) were approximately three to four percent exceedance frequency events that raised the river to the tops of the main levees.

Authorized flood control storage at Ross and Upper Baker dams is sufficient to store inflow while releasing only the minimum outflow for most recent floods. The contribution from the uncontrolled watersheds for a major event, however, is still large enough to exceed the current levee capacity at Mount Vernon. 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 during larger floods. 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.

2.7.2 November 1949 Flood

The flood of November 1949 is a good example of a flood crest flattening while moving downstream. The peak discharge of 154,000 cfs at Concrete was reduced to 114,000 cfs at Mount Vernon. Whereas channel storage had a marked effect on the sharpness of the peak between Concrete and 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.

2.7.3 February 1951 Flood

The February 1951 flood had a peak discharge of 139,000 cfs at Concrete, a peak of 150,000 cfs at Sedro-Woolley, and a peak of 144,000 cfs at Mount Vernon. Reservoir storage reduced the peak discharge at Concrete about 13,000 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.

2.7.4 November 1990 Floods

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 at the Concrete stream gage. The two November 1990 floods broke through the Fir Island levee, and inundated most of the interior farmland in this major farming region between the North and South Forks of the Skagit River, about 3 miles downstream from Mount Vernon. Both events required extensive flood fighting in the vicinity of Mount Vernon.

The major levee failure at Fir Island during the November 1990 floods increased the river slope and velocity below Mount Vernon, causing an artificially low crest stage at the Mount Vernon gage. During the November 1990 flood events, 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.

Total flood storage used at both Ross and Upper Baker 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 reservoir, and

82,000 acre-feet stored in Upper Baker reservoir during the first November 1990 flood; and 100,000 acre-feet stored in Ross, and 53,900 acre-feet stored in Upper Baker during the second November 1990 flood. Inflow to both projects peaked on November 10, 1990 (first flood) as follows: 46,000 cfs at midnight at Ross, and 33,000 cfs at 10 a.m. at Upper Baker. Outflows at both projects were regulated to a minimum of 5,000 cfs through the main part of the flood.

The Fir Island levee failure caused the Skagit River to fall abruptly. 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.

2.7.5 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 reservoirs are estimated to have reduced flood levels by about 5 feet and 2 feet at Concrete and Mount Vernon, respectively.

This flood set a new crest-stage record at the 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 6 p.m. on November 30, nearly a day after the river crested at Concrete.

2.7.6 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. It 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 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 flood.

3.0 Flood Frequency Analysis for Unregulated Flows at Concrete

This section presents the results of a flood frequency analysis for unregulated flows at Concrete. The report is prepared in accordance with FEMA Guidelines and Specifications for Flood Mapping Partners (FEMA 2003) for regulated watersheds, and the guidelines for determining floodflow frequency presented in Bulletin 17B (Interagency Advisory Committee on Water Data 1982) and subsequent modifications. The USGS-developed, FEMA-approved, computer program "PEAKFQ, Annual Flood Frequency Analysis following Bulletin 17B Guidelines" (version 5.0, May 6, 2005) was used for performing this Skagit River flood frequency analysis (USGS 1998). In accordance with the FEMA guidelines (Section c.2.1) (FEMA 2003), the Skagit River flood frequency curves for this analysis were developed for unregulated conditions, and subsequently converted to regulated conditions using the current reservoir operation criteria.

3.1 Unregulated Flow Data in the Skagit River at Concrete

The following unregulated flow data were considered for the Skagit River flood frequency analysis:

Period 1. Unregulated flow data estimated by the Corps for waters years of 1944 through 2004, excluding water years 1992, 1993 and 2003 (58 years of data).

Period 2. Unregulated flow data estimated by PI Engineering for water years of 1925 through 1943, and water years 1992, 1993, 2003, 2005, 2006 and 2007 (25 years of data).

Period 3. Peak flow data for four unrecorded floods: 1897, 1909, 1917 and 1921 (water years 1898, 1910, 1918, and 1922) estimated by PI Engineering using the USGS 1950 proposed revisions with adjustment.

Discussion of the source and any adjustments made to the data are provided in Sections 3.1.1 through 3.1.3 of this report. Figure 2 shows the locations of the USGS stream gages used for this study. Table 1 presents the annual peak and one-day discharge data observed at the USGS gage 12194000 – Skagit River near Concrete - for water years 1925 through 2007. Also included in the table are unregulated flows estimated by the Corps for Period 1 and estimated by PI Engineering for Period 2.

Table 1 **Annual peak and one-day discharge data at the USGS Gage 12194000 - Skagit River near Concrete**

Water Year	USGS Observed Annual Peak Flows (cfs)	Winter Unregulated Annual Peak Flows**	USGS Observed Winter One-Day Flows	Winter Unregulated One-Day Flows**
1925	92,500	92,500	85,400	85,400
1926	51,600	51,600	42,100	42,100
1927	88,900	88,900	56,700	56,700
1928	95,500	95,500	81,200	81,200
1929	74,300	74,300	62,200	62,200
1930	*32,200	43,692	29,200	29,200
1931	*60,600	64,145	48,900	48,900
1932	147,000	147,000	129,000	129,000
1933	116,000	116,000	97,800	97,800
1934	101,000	101,000	85,000	85,000
1935	131,000	131,000	120,000	120,000
1936	*60,000	28,223	14,300	14,300
1937	*68,300	35,698	21,500	21,500
1938	89,600	89,600	63,500	63,500
1939	*79,600	70,686	55,200	55,200
1940	48,200	48,200	38,900	38,900
1941	51,000	51,000	42,200	42,200
1942	76,300	76,300	56,100	56,100
1943	54,000	54,000	45,000	45,000
1944	65,200	67,639	49,000	52,266
1945	70,800	70,077	61,200	54,614
1946	102,000	108,844	87,500	91,954
1947	82,200	81,490	62,000	65,607
1948	95,200	85,040	69,000	69,026
1949	*55,700	45,180	52,100	30,632
1950	154,000	163,325	123,000	144,431
1951	139,000	151,668	128,000	133,202
1952	*43,500	41,628	36,700	27,212
1953	66,000	79,612	60,700	63,798
1954	58,000	61,187	46,900	46,051
1955	*56,300	63,268	51,200	48,055
1956	106,000	124,179	94,100	106,725

Water Year	USGS Observed Annual Peak Flows (cfs)	Winter Unregulated Annual Peak Flows**	USGS Observed Winter One-Day Flows	Winter Unregulated One-Day Flows**
1991	149,000	200,072	135,000	179,826
1992	*53,300	54,343	35,300	39,459
1993	*39,300	40,637	25,300	26,257
1994	36,500	57,927	31,400	42,911
1995	59,800	78,793	51,800	63,009
1996	160,000	185,733	131,000	166,014
1997	*91,400	104,655	63,000	87,919
1998	76,700	75,040	61,400	59,394
1999	61,400	81,043	45,100	65,176
2000	103,000	135,037	86,000	117,183
2001	30,900	42,670	22,800	28,215
2002	94,300	125,293	79,700	107,798
2003	65,500	65,171	43,200	49,889
2004	166,000	185,685	131,000	165,968
2005	99,400	108,346	74,700	91,475
2006	56,300	71,339	47,700	55,830
2007	145,000	167,695	118,000	148,640

* Non-winter event
** See Sections 3.1.1 and 3.1.2 of this report for discussion of the methodology used to determine the unregulated flows.

3.1.1 Period 1 - Unregulated Flow Data Estimated by the Corps

A synthetic record of the mean daily unregulated discharge in the Skagit River at the Concrete gauging site was constructed by the Corps for the period including water years 1944 through 2004 (excluding water years 1992, 1993, and 2003). The Corps constructed this record by adjusting the observed mean daily flows to include estimated effects of the regulation operations occurring at the three Seattle City Light (SCL) dams on the Upper Skagit and two Puget Sound Energy (PSE) dams on the Baker River. The unregulated annual winter peak one-day flows in the Skagit River at Concrete for Period 1 were selected from the mean daily unregulated discharges estimated by the Corps.

The Corps also developed the unregulated annual peak flows for Period 1 based on a regression of the winter peak to one-day flows from water years 1925 through 1953 for the Skagit River near Concrete. The Corps assumed that the regression closely mimicked unregulated basin conditions, as no storage occurred at any of the dams for flood control during this time period. Details of the Corps-developed unregulated annual peak and one-day discharges are documented in the Corps' "Draft Report – Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrology Summary" (Corps 2005).

3.1.2 Period 2 - Unregulated Flow Data Estimated by PI Engineering

The period of record of stream flow data at the USGS gage 12194000 – Skagit River near Concrete – includes the period 1924 to present. Data collected at this gage includes the effects of regulation at upstream reservoirs. Flow data measured by USGS at the Concrete gage during the period between 1924 and 1943 comprised lower annual flood peaks, in general, than the flood peaks measured outside of this period. Prior to 1943, two dams were in operation in the Skagit watershed, Lower Baker Dam and Diablo Dam. (Construction of Ross Dam was completed in 1949, and regulation of Ross Dam for winter flood control storage was initiated in 1954). Prior to 1943, construction and operation of Lower Baker Dam and Diablo Dam had only insignificant incidental regulation effects on the flood flows in the Skagit River for the following reasons:

Diablo Dam – Construction of the dam was completed in 1930, and the power plant began operation in 1936. The dam has never been operated for flood control purposes. During construction, all flows were routed through construction bypass tunnels with no provision for storage during the fall and winter periods. The dam has a relatively small amount of active storage, and during flood events inflow passes directly through the reservoir.

Lower Baker Dam – Construction of Lower Baker Dam was completed in 1925. Operation of Lake Shannon, the reservoir created by Lower Baker Dam, for flood control has never been part of the purpose of the dam. Hydrologically, storms arrive at the Baker system early in the event and the peak flood outflow from the Baker River passes the Concrete gage several hours in advance of the peak flow coming from the Skagit River upstream of the Concrete gage. Historically, the practice by PSE was to operate Lake Shannon at full reservoir during the fall and winter and spill any flood flows as they arrived. PSE has been unable to produce any reservoir operating data that demonstrates that Lower Baker Dam was operated for flood control or had any impact on winter flood peaks. Therefore, this report assumes that the effects of the incidental flood regulation at Lower Baker Dam is insignificant, and it is appropriate to use the full 83 years of USGS records at Concrete in the frequency analysis.

An example of the insignificance of the incidental flood regulation at Lower Baker Dam is the daily storage volume and reservoir elevation data at Lower Baker Dam for the January 1935 flood event (the second largest event during this Period 2). A newspaper article from The Burlington Journal dated February 8, 1935, contains a report indicating that water stored at Lower Baker Dam when the Skagit River near Concrete peaked at 131,000 cfs on January 25, 1935, was calculated at 3,830 acre-feet. For a 3-day period from January 24 to 26, this dam stored a total of 11,800 acre-feet of flood water. This equals 1,930 cfs (or 1.6 percent) and 1,980 cfs (or 2.0 percent) flow reductions to the 1-day peak (120,000 cfs) and 3-day (98,000 cfs) flows, respectively, at the Skagit River near Concrete.

Another example is the February 27, 1932 flood (the largest event during this Period 2), that peaked at Concrete with 147,000 cfs recorded by USGS. The Courier Times newspaper reported on March 3, 1932 that water at the peak of high water flowed nine feet deep over the top of Lower Baker Dam. Also, it reported that early Saturday (February 27, 1932) morning the water flowed over the Diablo spillways, when no more water could be retained behind Diablo Dam. The Skagit River peaked at Concrete late Saturday night. As the newspaper reported, both Lower Baker Dam and Diablo Dam provided storage before the flood but were quickly filled to the top of the dams before the flood peaked. These dams did not have any storage left to reduce the Skagit River flood peak at Concrete during this event.

The winter unregulated one-day flows for water years 1992, 1993, 2003, 2005, 2006 and 2007 were estimated by adjusting the USGS observed one-day flows with the regression of regulated and unregulated flows developed by the Corps for the period of regulated basin conditions from water years 1956 through 2004, excluding 1992, 1993 and 2003. The annual peak discharges for these six years were estimated by using the peak to one-day flow regression developed by the Corps for the water years 1925 through 1953 as discussed in Section 3.1.1 of this report. For those water years when the annual peak flows observed by USGS were non-winter events, USGS-observed one-day flow data were used and the corresponding winter peak flows were estimated by using the same peak to one-day flow regression discussed above.

3.1.3 Period 3 – Peak Flow Data for the Four Unrecorded (Historical) Floods of 1897, 1909, 1917 and 1921.

Background - Four major floods occurred before installation of the USGS gage at Concrete and before construction of any of the five Upper Skagit River dams. These unrecorded floods were estimated by James Stewart in 1923. (Stewart 1923) The accuracy of Stewart's flood peak estimates was questioned by numerous hydrologists, including hydrologists within the USGS (Bodhaine 1954; Riggs & Robinson 1950). Despite the questions raised regarding Stewart's 1923 estimates, USGS published them in 1961 as Water Supply Paper (WSP) 1527.

Now that over 80 years of reliable gage records at Concrete are available, the need for inclusion of the four "historic" events in the data set can be reexamined. Repeated efforts to validate the estimates made for peak flows at Concrete during the unrecorded "historic" floods in 1897, 1909, 1917 and 1921 by the USGS based on Stewart's 1923 studies have encountered a series of setbacks, including:

- Difficulty of confirming the locations and elevations of reported high water in and near Concrete.
- Stewart's data is from the "staff gage at a site 200 feet upstream" of the current gage (Flynn 1954). USGS published these numbers in WSP 1527 as being at the current gage (Table 2). The extrapolation performed by USGS to arrive at the numbers shown in column 2 of Table 2 did not account for a change in water surface elevation between the two gages.

Table 2 Stewart's estimated peak stages and discharges of Skagit River near Concrete for four unrecorded floods (Drainage Area = 2,700 sq. mi.)

Flood	Gage Height at Current Gage* as Published in 1961** (ft)	Staff Gage Height*** Estimated by Stewart in 1923**** (ft)	Discharge Estimated by Stewart in 1923**** (cfs)
1897	51.1	38.4	275,000
1909	49.1	36.4	260,000
1917	45.7	33.0	220,000
1921	47.6	34.9	240,000

* Current gage datum El. 130.00 (NGVD29) at RM 54.15

** These numbers are an extrapolation performed and published by USGS in WSP 1527 (USGS 1961), based on Stewart's 1923 estimated gage heights presented in column 3 of this table

*** Prior to Dec. 10, 1924, a staff gage was located at RM 54.19, 200 feet upstream of the current gage location and at datum 12.7 feet higher than the current gage site (Flynn 1954)

**** These unpublished 1923 estimates by James Stewart were documented in the 1961 U.S. Geological Survey Water Supply Paper (WSP) 1527 (USGS 1961).

- Validation of the stage-discharge curve assumed by Stewart at Concrete. Stewart's use of the slope-area method in The Dalles reach used to support his estimates of peak flows conflicts with results using more sophisticated hydraulic models developed more recently and mandated for use by USACE and FEMA.
- Flow estimates are inconsistent with Stewart's record that flow did not occur in the right bank side channel near The Dalles.
- Conflict in the reconciliation of flows estimated at Concrete with stages observed at the USGS gage at Sedro-Woolley installed in 1908.

- Severity of the 1897 event as estimated by Stewart appears to be inconsistent when comparing Sedro-Woolley and Concrete.
- Difficulty in reconciling HEC-modeled water surface elevations for Stewart's estimated peak flows at Hamilton with reports and observations at the Smith house and the Slipper house.

Subsequent to the USGS findings of the 1950s, new data and methods of analysis have become available. If these can illuminate or validate flow estimates based upon the reports of the "historic" floods, confidence in the flood frequency analyses will be enhanced. Such data and methods include:

- New channel and topographic surveys in the Dalles reach near Concrete and the right bank side channel
- HEC modeling of flows in the Skagit River
- Observations and reports of high water marks in Hamilton

PI Engineering 2004 HEC-RAS Model using Stewart's Original Gage Heights - PI Engineering developed a steady-flow HEC-RAS model for a 7-mile river reach near Concrete. The model overlaps the reach that Stewart analyzed. The model was calibrated to the October 2003 flood HWMs surveyed by USGS in summer 2004, and verified by comparison to the 1990 and 1995 flood stages measured by USGS at the Concrete gage. Peak stages of the two November 1990 floods, the November 1995 flood, and the October 2003 flood generated by the HEC-RAS model calibration and verification runs match well with the USGS observed HWM data for these floods. For a detailed discussion of the HWM data used in the PI Engineering calculations please refer to the Appendix A draft report entitled "Evaluation of Flood Peaks Estimated by USGS" (PI Engineering, 2004).

One conclusion from the model runs was that at flows in excess of approximately 180,000 cfs, a portion of the flow would be diverted into the right bank side channel near the Dalles (see Appendix A, Figure 5). However, Stewart reported that no such flow occurred during the four "historic" events. Any estimate of peak flow for these "historic" events that significantly exceeds 180,000 cfs is therefore unlikely to be supportable.

PI Engineering 2007 Hydraulic Analysis using Smith House Flood Marks - The Smith House is located at 307 Maple Street in the City of Hamilton, or at RM 40.00, approximately 14 miles below the Concrete gage. The Smith House was built in 1908 and therefore experienced three of the four unrecorded floods estimated by Stewart. Only one flood, the November 1995 flood, in the last 99 years, however, has left a water mark above the level of the main floor.

Two separate inspections of the house recently conducted by the City of Burlington (2007) confirm the reported 1995 flood water mark on the exterior wall, verified by interior wall inspection at four locations. The conclusions from the inspections are that water from the 1995 flood just barely covered the main floor and that water from the 2003 event came up into the crawl space just below the level of the sub-floor. There was no evidence of any higher water marks above the observed 1995 flood mark. Supporting evidence that this was representative of high water experienced was obtained in discussion with the owner of the Fred Slipper house in Hamilton (see Declaration of Fred W. Slipper, April 29, 2006. Available at www.skatgitriverhistory.com).

PI Engineering performed an unsteady flow HEC-RAS modeling to estimate the potential 1909, 1917, and 1921 flood stages at the Smith House based on Stewart's estimated peak flows at Concrete. The model was calibrated for the 1995 and 2003 high water marks at the Smith House. The model was further modified to incorporate the 1911 Corps surveyed river channel and banklines in the Hamilton area, reasonably reflecting the conditions of the river existing during the Stewart estimated flood events. Details of the new analysis for the Smith House are presented in Appendix J, "Technical Memorandum, Hydraulic Analysis – Smith House Flood Stages" (PI Engineering, 2007).

The conclusions of the new HEC-RAS hydraulic analysis include the following:

- Stewart estimated peak discharges of 260,000, 220,000, and 240,000 at Concrete for the 1909, 1917 and 1921 floods, respectively, are unreasonably high if the high water marks observed at the Smith House (built in 1908) were not higher than the observed 1995 flood mark at the house.
- Based on the 1911 Corps survey river channel and banklines, the maximum peak flow for the 1909, 1917 and 1921 floods would be about 188,000 cfs without causing any flood mark higher than the observed 1995 flood mark at the Smith House.

These findings are consistent with those relating to the lack of flow in the side channel at Concrete recorded by Stewart during the historic flood events.

Correlation with Sedro-Woolley – The USGS also published estimated peak flows at the site of the USGS gage location at Sedro-Woolley for the four historic flood events. A gage has been in place at Sedro-Woolley since 1908. The flood peaks were estimated by James Stewart at the same time he estimated the flood peaks at Concrete and are published by the USGS in Water Supply Paper 1527 (USGS 1961). Stewart had also made earlier estimates in 1918. Stewart estimated the Sedro-Woolley flood peaks using observed HWMs and the same methodology he applied at Concrete. In subsequent USGS studies, Bodhaine (1954) suggested values for the four floods and other estimates were made by Riggs & Robinson in 1950, and by Hidaka in 1954 for the 1897 and 1909 events. (see Table 3).

Table 3 Stewart and USGS peak discharge estimates for unrecorded floods at Sedro-Woolley

	Stewart		USGS		
Flood	1918	1923	Rigg & Robinson	Hidaka	Bodhaine
1897	171,000	190,000	170,000	145,000	170,000
1909	169,000	220,000	190,000	175,000	200,000
1917	157,000	195,000	160,000	----	195,000
1921	----	210,000	170,000	----	210,000

(Source: Stewart 1918 & 1923 Reports; Proposed Revision of Skagit River Peaks, H.C. Riggs & W.H. Robinson, 11/16/50; Skagit River near Sedro-Woolley, Wash., Proposed revisions of historical flood peaks, F. L. Hidaka, 1/12/54; Skagit River Flood Peaks, Memorandum of Review by G.L. Bodhaine, USGS, 5/13/54). Available at www.skatgitriverhistory.com

Flood peaks for flood events are expected to be approximately the same (within a few percentage points) at Concrete and Sedro-Woolley. The incremental drainage area between Concrete and Sedro-Woolley is 270 square miles, about 10 percent of the total drainage area of 2,737 square miles above the Concrete gage. There are no large floodplain areas that would add storage between Concrete and Sedro-Woolley that could reduce flood peaks significantly more than increases to the flood peak due to the local inflow in the same reach. Comparison of flood peaks for recent recorded floods in 1990, 1995 and 2003, demonstrates that flows at USGS Concrete gage average 1.6% lower than flows at the USGS Sedro-Woolley gage.

Recent studies analyzed by the Corps (2005) and Northwest Hydraulic Consultants (2007) also arrived at similar results. PI Engineering modeled peak flows for each of the 10- to 100-year floods show an increase of 2 percent from Concrete to Sedro-Woolley (PI Engineering, 2005). Therefore, the Sedro-Woolley peak flow values estimated by Stewart and other USGS reviewers for the 1897, 1909, 1917 and 1921 floods represent a close approximation of the coincident flow values at Concrete.

Assuming that the relationship between flows at Sedro-Woolley and Concrete as discussed above is valid, Stewart's flow estimates at Concrete should be approximately 2% lower than his estimates at Sedro-Woolley. In fact, Stewart's estimates at Concrete for the unrecorded floods average 15% higher than his concurrent estimated flood peaks at Sedro-Woolley for the years during which USGS gage records are available at Sedro-Woolley. For the 1897 flood, Stewart's flow estimate is 45% higher at Concrete than at Sedro-Woolley.

Table 4 presents a comparison of the peak flows estimated by Stewart at Sedro-Woolley and Concrete for the historic flood events. The magnitude of the difference between Sedro-Woolley and Concrete for the 1897 flood is not consistent with any of the other flood events. This observation indicates that the HWM for the 1897 event at Concrete may have been inaccurately observed or recorded. HWMs of other three events at Sedro-Woolley are based upon records of the USGS gage installed in 1908.

Table 4 Comparison of Stewart's peak discharge estimates (cfs) for four "historic" floods in the Skagit River at Concrete and Sedro-Woolley

Flood Date	Stewart Estimates @ Sedro- Woolley	Stewart Estimates @ Concrete	% Diff
Nov. 19, 1897	190,000	275,000	-45%
Nov. 30, 1909	220,000	260,000	-18%
Dec. 30, 1917	195,000	220,000	-13%
Dec. 13, 1921	210,000	240,000	-14%

Although reliable stage records at Sedro-Woolley are available for the period starting in 1908, it has always been difficult to establish a rating curve at that location. At this time, it is impossible to develop a rating curve that would reflect the river channel characteristics current at the time of the four historical floods. Part of this difficulty arises from the effect of debris blockage of the SR-9 Bridge and the abandoned railroad bridge at the gage, and a significant factor is the changes in river bank levee and channel geometry that have occurred in the course of nearly a century, particularly immediately downstream of Sedro-Woolley (cutting off the Sterling Bend). These uncertainties preclude an accurate estimate of river flows based upon the stage records.

Selected Peak Flow Values for 1897, 1909, 1917, and 1921 Floods - The maximum flood peak that could have occurred in the Skagit River at Concrete without flow occurring in the Dalles right bank side channel would have been approximately 180,000 cfs. Similarly, the maximum flood peak that could have occurred in Hamilton without causing higher water marks at the Smith House (RM 40.00) would have been 188,000 cfs, as discussed above. This peak flow is substantially less than the USGS published flows at Concrete in WSP 1527. Other reduced revisions proposed by USGS reviewers in the 1950's (Riggs & Robinson 1950; Hidaka 1954; Bodhaine 1954) can be put to the same test.

As shown in Table 3, all of the 1923 Stewart estimates which were published in the 1961 USGS WSP 1527 for the four unrecorded floods are higher than the maximum flows described above. The values suggested by Bodhaine for the 1909, 1917 and 1921 floods are also high. The estimates suggested by Stewart in 1918, Riggs & Robinson, and Hidaka do not exceed the threshold that would cause Dalles side channel flow or higher inundation in Hamilton, and are accordingly not in conflict with other contemporary and recent observations. If the flow estimates exceeding these thresholds are excluded, those remaining fall within the ranges listed in Table 5. Applying the 98 percent reduction factor established as the average shown in HEC model runs to the upper end of the range for each event gives corresponding values for peak flows at Concrete. The listed peak flows at Concrete were used in the flood frequency analysis for Period 3.

Table 5 Peak discharge values (cfs) selected for four "historic" floods

Flood	Supportable USGS Estimates @ Sedro-Woolley	Flows @ Concrete (98% of high end of supportable range)
1897	145,000 - 170,000	166,600
1909	169,000 - 190,000	186,200
1917	157,000 - 160,000	156,800
1921	170,000	166,600

3.2 Flood Frequency Analysis for Unregulated Annual Peak Flows in the Skagit River near Concrete

A flood frequency analysis for unregulated peak flows in the Skagit River near Concrete was performed, using PEAKFQ software (USGS 2005). The result of the PEAKFQ run using 83 water years of data (Table 1) and the four historical events (Table 5) are shown on Figure 3. Output from the PEAKFQ run is presented in Appendix B. The unregulated peak flows at Concrete would have values of 141,700, 200,700, 227,200, and 292,7000 cfs, for the 10-, 50-, 100- , and 500-year floods, respectively.

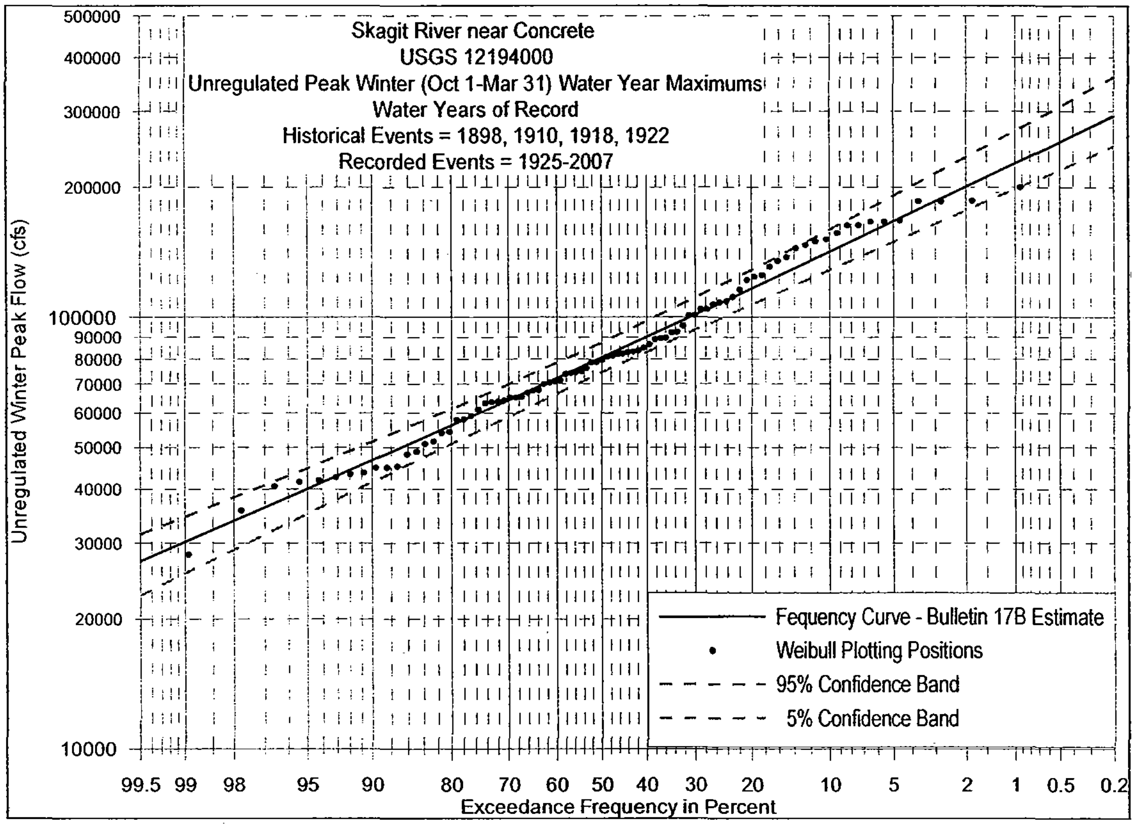

Figure 3. **The unregulated peak flow frequency curve for the Skagit River near Concrete, and the confidence band together with all data used in the frequency analysis at Concrete**

3.3 Flood Frequency Curve for Unregulated One-Day Flows in the Skagit River near Concrete

The one-day flows represent the most critical flood volumes determining the lower Skagit River floodplain flooding conditions after routing through dams and floodplain storages in the Skagit River system. The winter unregulated one-day flow data for water years 1925 through 2007 are provided in Table 1.

The four historical floods estimated by Stewart and other USGS reviewers have only the unregulated peak discharges estimated. To estimate the corresponding unregulated one-day discharges for these four events, a regression of ten recent flood events previously unregulated by the Corps was applied [(see Figure 4 in the Corps' "Skagit River Basin Draft Hydrology Investigation Report (Corps 2001)]. Figure 4 below shows the Corps' unregulated ten floods and the regression curve. Also shown in Figure 4 below, for a comparison, are plots of the Corps' assumed unregulated annual peak and one-day flow data for water years 1925 through 1953. The estimated one-day discharges of the four historical events are listed in Table 6.

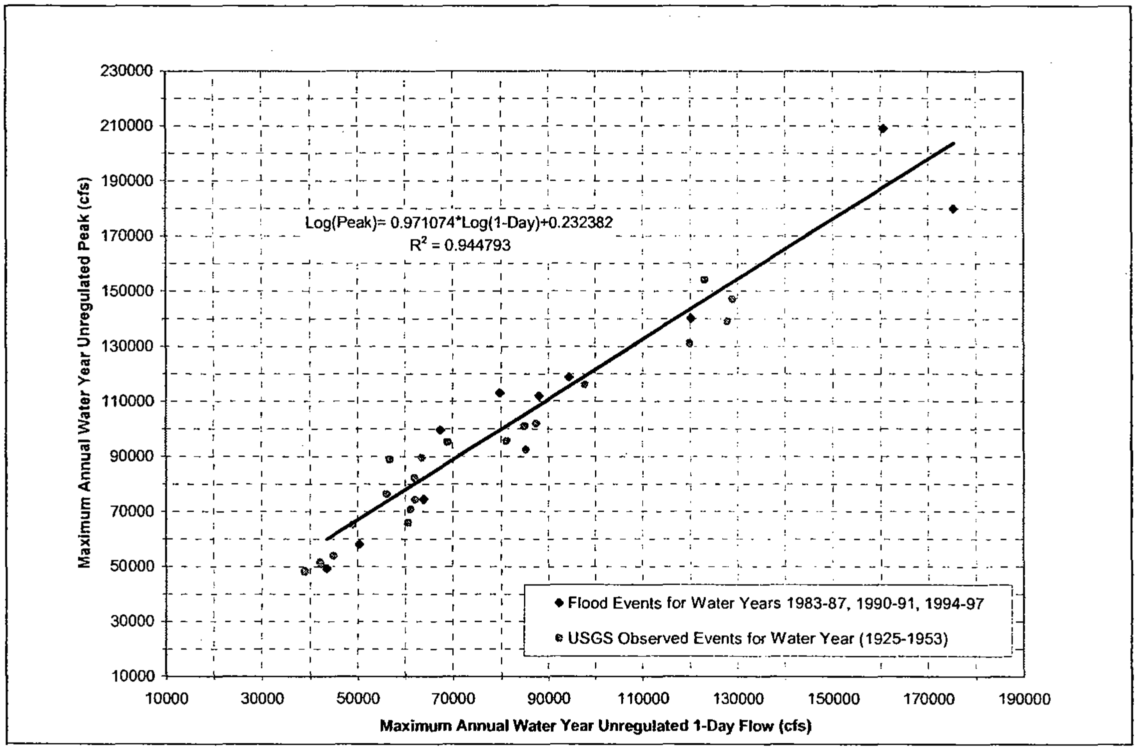

Figure 4. **Regression curve of peak to one-day flow for the ten recent flood events (water years 1983-87, 1990-91, 1994-97) unregulated by the Corps; and plots of annual peak and one-day flow data for water years 1925 through 1953.**

Table 6 Estimated unregulated one-day discharges for four unrecorded floods in the Skagit River near Concrete

Water Year	Date	Peak Discharges (cfs) Estimated at Concrete (Table 6)	One-Day Discharges (cfs) Estimated by Figure 4 Regression
1898	Nov. 19, 1897	166,600	137,400
1910	Nov. 30, 1909	186,200	154,000
1918	Dec. 30, 1917	156,800	129,100
1922	Dec. 13, 1921	166,600	137,400

The one-day flow frequency curve and the confidence band, together with all data used in the frequency analysis, are plotted in Figure 5. The output of the PEAKFQ run for the one-day flood frequency analysis is presented in Appendix C. A generalized skew of 0 and –0.04 was used for the analysis of the peak and one-day flows, respectively, as adopted by the Corps [(Section 4.2 of the Corps Draft Report – Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrology Summary (Corps 2005)].

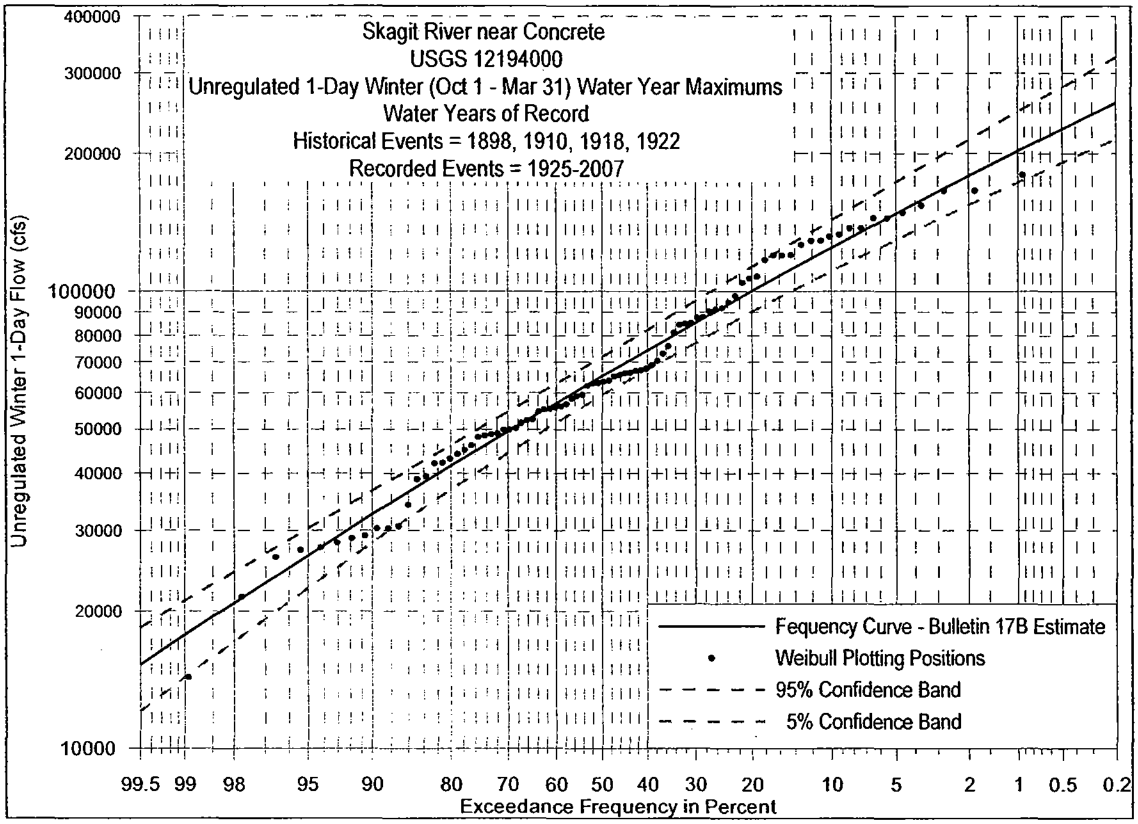

Figure 5. **The unregulated one-day flow frequency curve and the confidence band together with all data used in the frequency analysis at Concrete**

4.0 Synthetic Flood Hydrographs at Concrete

This section presents information on development of the synthetic flood hydrographs for the Skagit River at Concrete. The HEC-5 and HEC-RAS models originally developed by the Corps and subsequently improved by PI Engineering were used to route the coincident synthetic flood hydrographs. The hydrograph routing was performed for the area of the Skagit River above Concrete (see Figure 6), first for unregulated conditions, and then for regulated conditions.

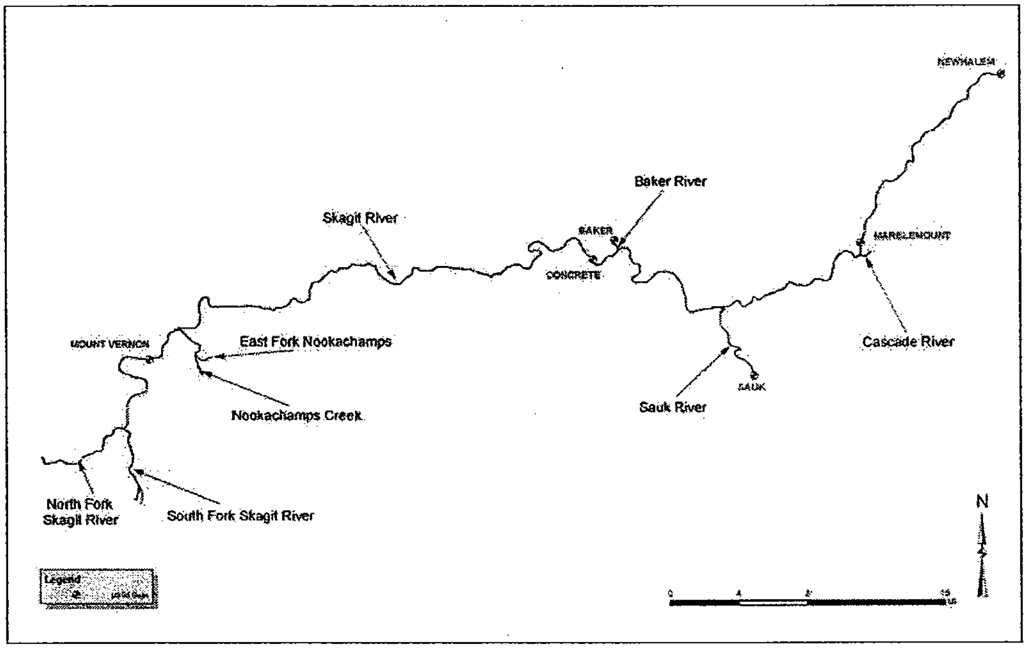

Figure 6. Skagit River HEC-RAS model routing reaches

4.1 Development of Unregulated Synthetic Flood Hydrographs

Based primarily on the unregulated peak one-day flow data and various regressions, the Corps developed coincident flood hydrographs for ten upper Skagit River subbasins above Concrete. A total of nine synthetic flood hydrographs for each subbasin was constructed by the Corps. Details of the Corps-developed synthetic flood hydrographs for these subbasins are presented in the Corps' Draft Report – Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrology Summary (Corps 2005).

PI Engineering applied the improved HEC-5 and HEC-RAS models to route the unregulated flood hydrographs for the FEMA FIS required 10-, 50-, 100-, and 500-year synthetic flood events along the Skagit River from Ross Dam to Concrete including Cascade, Sauk and Baker River tributaries. Details of the HEC-5 (without flood control storage operation) and HEC-RAS models are provided in the Draft Technical Memorandum – Skagit River Basin Historical Flood Modeling –Hydrology (Appendix D) and the Draft Technical

Memorandum – Skagit River Basin Historical Flood Modeling –Hydraulics (Appendix E).

The peak and one-day flows of the synthetic flood hydrographs routed to Concrete were compared with the corresponding unregulated events statistically developed for Concrete. These flows and subbasin hydrographs were then scaled and routed again as necessary until the routed flows matched the unregulated peak and one-day flows that were derived as described in Sections 3.2 and 3.3. The one-day scaled flows are listed in Table 7.

Figures 7 and 8 show the plots of the peak and the one-day flows, respectively, at Concrete for the four HEC-RAS simulated unregulated synthetic flood events, in comparison with the corresponding flood frequency curves developed as described in Sections 3.2 and 3.3. This comparison indicates that the unregulated peak and one-day flows resulting from the HEC-5 and HEC-RAS routing of the constructed synthetic flood hydrographs for each of the 10-, 50-, 100-, and 500-year events match very well with the statistically-derived unregulated peak and one-day flows at Concrete.

Table 7 Unregulated synthetic flood one-day coincident flows (cfs) for upper Skagit River subbasins

	Flood Event			
Location	10-year	50-year	100-year	500-year
Unregulated Skagit River Near Concrete	124,300	178,800	202,400	258,500
Ross Dam Inflow	22,300	34,000	38,600	52,300
Thunder Creek	4,800	8,700	10,000	11,400
Ross Dam to Newhalem Local	3,300	5,900	6,800	7,600
Newhalem to Marblemount Local	18,100	26,100	29,300	38,700
Cascade River at Marblemount	8,500	12,000	13,300	17,600
Marblemount to Sauk Local	5,100	7,200	8,000	10,600
Sauk to Concrete Local	3,500	5,000	5,500	7,300
Sauk River at Sauk	41,400	59,000	65,900	86,600
Upper Baker Dam Inflow	18,000	24,400	26,900	34,600
Lower Baker Dam Inflow	5,200	7,100	7,800	10,000

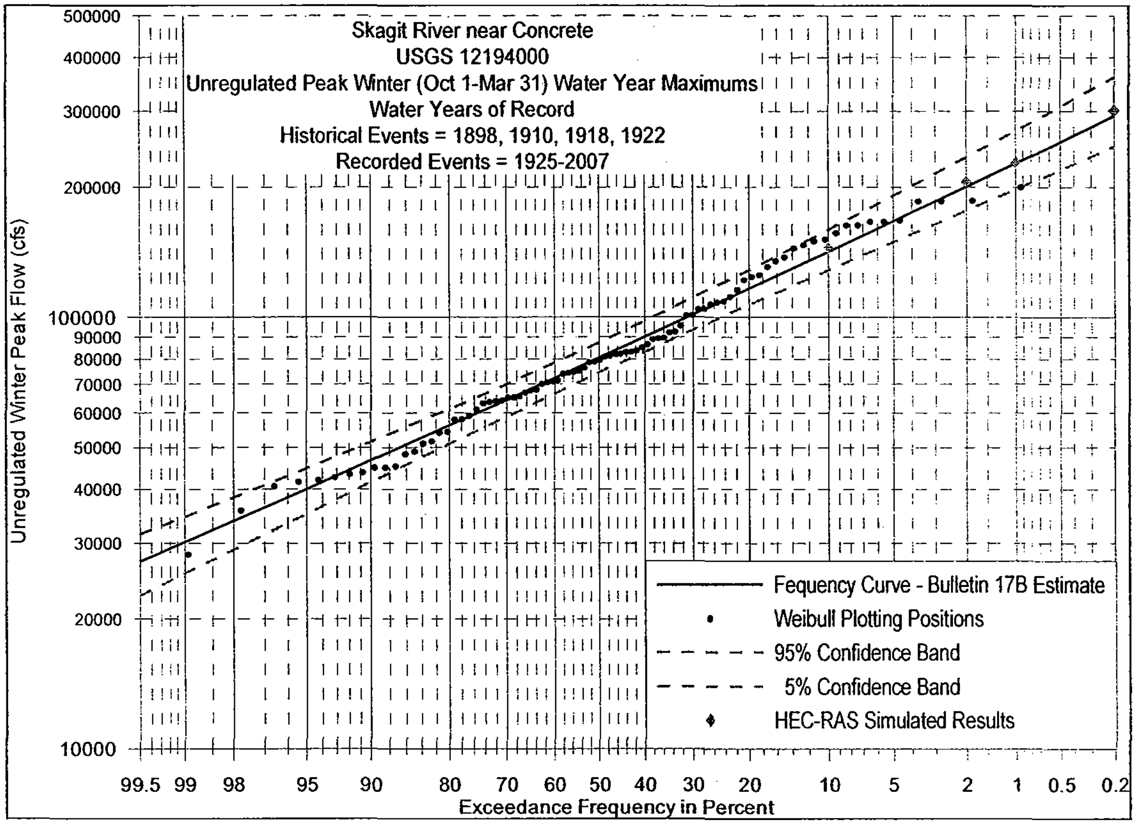

Figure 7. **Flood frequency curve for unregulated peak discharges at Concrete, compared with the HEC-RAS simulated peak flows at Concrete for the 10-, 50-, 100-, and 500-year synthetic events**

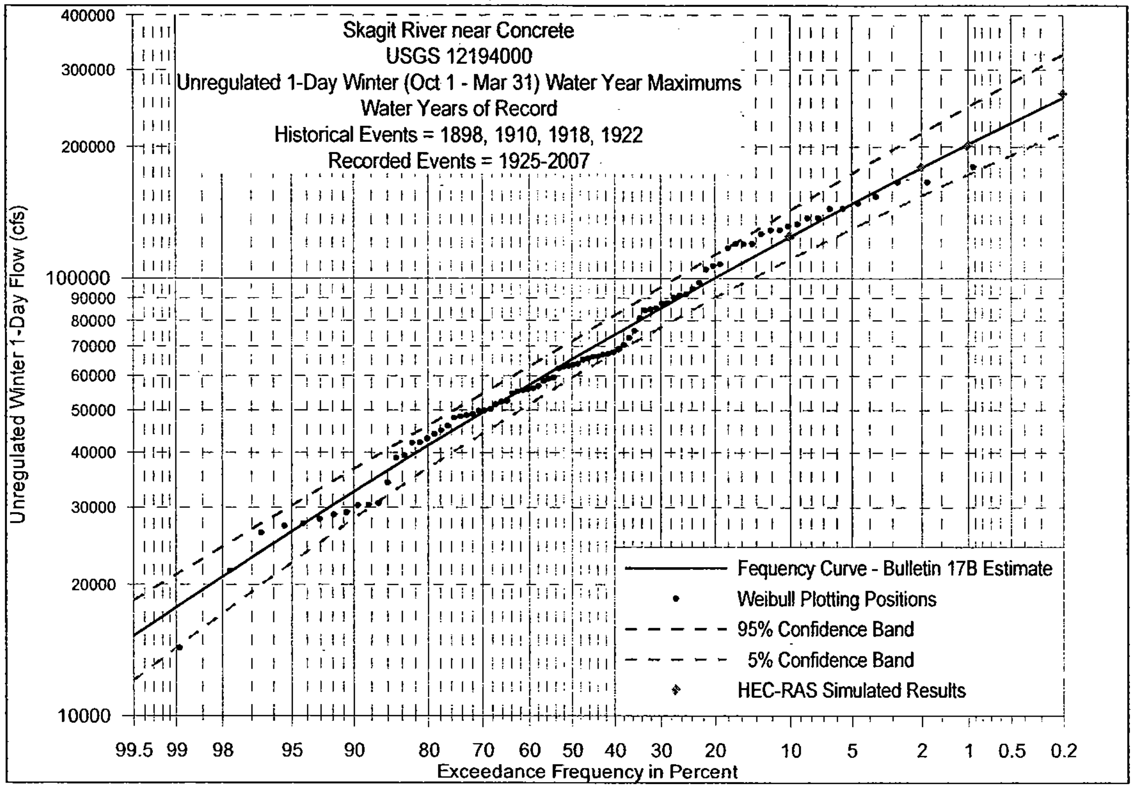

Figure 8. Flood frequency curve for unregulated one-day discharges at Concrete, compared with the HEC-RAS simulated one-day flows at Concrete for the 10-, 50-, 100-, and 500-year synthetic events

4.2 Development of Regulated Synthetic Flood Hydrographs

The coincident unregulated hydrographs of all subbasins above Concrete for each of the 10-, 50-, 100-, and 500-year synthetic flood events derived as discussed above in Section 4.1 were then routed by the HEC-5 model with the existing flood control storage of 120,000 and 74,000 acre-feet provided at Ross Dam and Upper Baker Dam, respectively. The regulated outflow hydrographs at these two dams and local inflow hydrographs representing subsequent flow contribution from subbasins were routed by the HEC-RAS model along the Skagit River and main tributary routing reaches to Concrete. Development and details of the HEC-5 and HEC-RAS routing models are discussed in the Draft Technical Memorandum – Skagit River Basin Historical Flood Modeling –Hydrology (Appendix D) and the Draft Technical Memorandum – Skagit River Basin Historical Flood Modeling –Hydraulics (Appendix E).

Figures 9 and 10 show the plots of the annual peak and one-day flows, respectively, at Concrete for the four routed regulated synthetic flood events, in comparison with the corresponding flood frequency curves based on PEAKFQ modeling of the USGS observed regulated flow data at Concrete for the time period from 1955 through 2006 (water years 1956-2007). Output of the PEAKFQ runs for the observed regulated peak and one-day flows in the Skagit River near Concrete are provided in Appendix F. Appendix G presents the regulated and unregulated hydrographs for the HEC-5 and HEC-RAS routed four synthetic flood events at selected locations in the Upper Skagit River Basin.

The comparison shown in Figures 9 and 10 indicates that the regulated annual peak and one-day flows resulting from the HEC-5 and HEC-RAS routing of the synthetic flood hydrographs for each of the 10-, 50-, 100-, and 500-year events match reasonably well with projection and within the confidence band of the frequency curves based on USGS observed regulated data at Concrete.

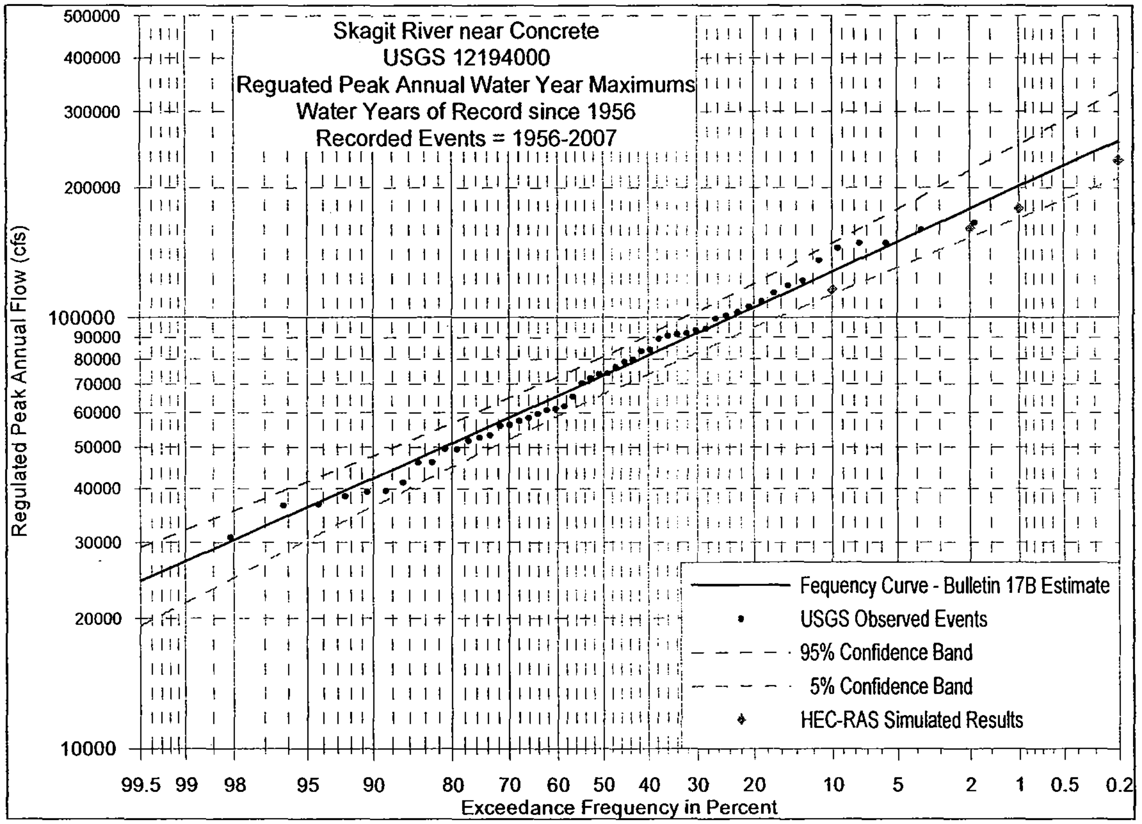

Figure 9. **Flood frequency curve for regulated peak discharges observed by USGS at Concrete, compared with the HEC-RAS simulated regulated peak flows at Concrete for the 10-, 50-, 100-, and 500-year synthetic events**

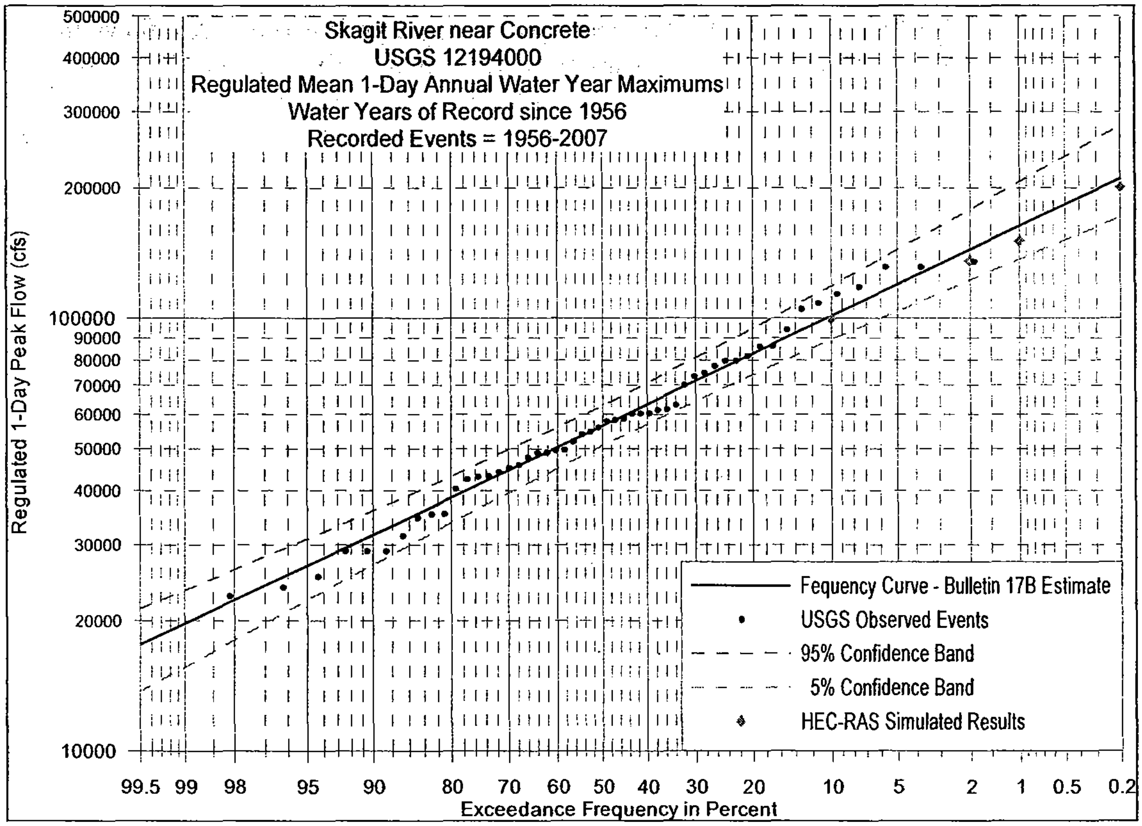

Figure 10. Flood frequency curve for regulated one-day discharges observed by USGS at Concrete, compared with the HEC-RAS simulated regulated one-day flows at Concrete for the 10-, 50-, 100-, and 500-year synthetic events

5.0 Synthetic Flood Hydrographs at Mount Vernon

This section presents information on development of the regulated synthetic flood hydrographs routed by the HEC-RAS model originally developed by the Corps and later improved by PI Engineering along the Skagit River system from Concrete to Mount Vernon. Local coincident inflow hydrographs developed by the Corps were adjusted and used in the flood routing. A flood frequency based on USGS observed regulated events at Mount Vernon was developed and compared with HEC-RAS modeled results.

The majority of flood damages in the Skagit River floodplain occur below Concrete, primarily from Sedro-Woolley to the mouths of the North and South Forks of the Skagit River. It is, therefore, important that the flood modeled results match reasonably well with flood projections based on observed flood records available from USGS at the Mount Vernon gage. The Mount Vernon gage, USGS Station No. 12200500, provides the longest systematic flow record below Concrete (1941 to present).

5.1 Local Inflows Below Concrete

The coincident local inflow hydrographs developed by the Corps for synthetic flood events from Concrete to Sedro-Woolley [see Section 5.1 of the Corps' Draft Report – Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrology Summary (Corps 2005)] were used in development of the synthetic flood hydrographs at Mount Vernon. This data represents flow contribution from the intermediate drainage area of 278 square miles between Concrete and Sedro-Woolley.

The coincident local inflow hydrographs developed by the Corps for the 71.6 square mile Nookachamps Creek [see Section 5.2 of the Corps' Draft Report – Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrology Summary (Corps 2005)] were not used. Instead, the coincident local inflow hydrographs developed by the Corps for the 51.6 square mile Finney Creek [see Section 5.1 of the Corps' Draft Report – Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrology Summary (Corps 2005)] were used with a direct proportional adjustment of the drainage area to represent the flow contribution from Nookachamps Creek. The Corps-developed regression for the Nookachamps Creek drainage area is a weak correlation, while the Corps-developed flow regression for Finney Creek is a better correlation. Finney Creek is located on the left bank of the Skagit River, the same side that Nookachamps Creek is located; and, the size and location of Finney and Nookachamps Creeks are similar enough.

Table 8 lists the one-day coincident flows for the local drainage areas below Concrete, and the unregulated one-day flows at Concrete for the 10-, 50-, 100-, and 500-year synthetic floods analyzed.

Table 8 Unregulated synthetic flood one-day coincident flows (cfs) for lower Skagit River subbasins

Location	Flood Event			
	10-year	50-year	100-year	500-year
Unregulated Skagit River Near Concrete	124,300	178,800	202,400	258,500
Concrete to Sedro-Woolley Local	14,400	17,900	19,400	23,500
Nookachamps Creek	3,500	4,300	4,600	5,600

5.2 Routing of Regulated Flood Hydrographs below Concrete

The regulated flood hydrographs at Concrete for the 10-, 50-, 100-, and 500-year synthetic events, derived as described above in Section 4.2, were routed downstream along the Skagit River to the mouths of the North and South Forks of the Skagit River, using the PI Engineering improved HEC-RAS model. Local inflows as discussed above in Section 5.1 were added to the routing as necessary. It was assumed that there was no levy failure below Concrete, and no levy overtopping below Sedro-Woolley. Details of the HEC-RAS improvements are discussed in the Draft Technical Memorandum – Skagit River Basin Historical Flood Modeling – Hydraulics (Appendix E).

The HEC-RAS routed peak and one-day flows for the 10-, 50-, 100-, and 500-year floods at Sedro-Woolley (RM 22.40) and Mount Vernon (RM 17.05) are listed in Table 9. The regulated peak and one-day values at Concrete (RM 54.15) are also listed in Table 9 for a comparison. The HEC-RAS modeled flood hydrographs for the regulated four synthetic floods at these three locations are presented in Appendix H.

Table 9 Peak and one-day flows (cfs) at Concrete, Sedro-Woolley and Mount Vernon for regulated synthetic floods

	Concrete (RM 54.15)		Sedro-Woolley (RM 22.40)		Mount Vernon (RM 17.05)	
Flood	Peak	One-Day	Peak	One-Day	Peak	One-Day
10-year	116,000	99,400	118,600	108,200	110,400	106,500
50-year	161,000	135,200	162,000	144,000	146,100	137,800
100-year	178,700	150,500	180,900	159,800	162,100	152,400
500-year	231,800	200,300	238,400	211,200	199,600	188,900

Figures 11 and 12 present regressions of the USGS observed peak and one-day flows, respectively, at Concrete and Mount Vernon for the time period from 1955 through 2006 (water years 1956-2007), representing regulated conditions of the Skagit River. The HEC-RAS modeled peak and one-day values for the 10-, 50-, 100-, and 500-year events are also shown in these two figures, indicating a reasonable match of the HEC-RAS modeled results and the USGS observed data. The modeled values appear to be slightly conservative.

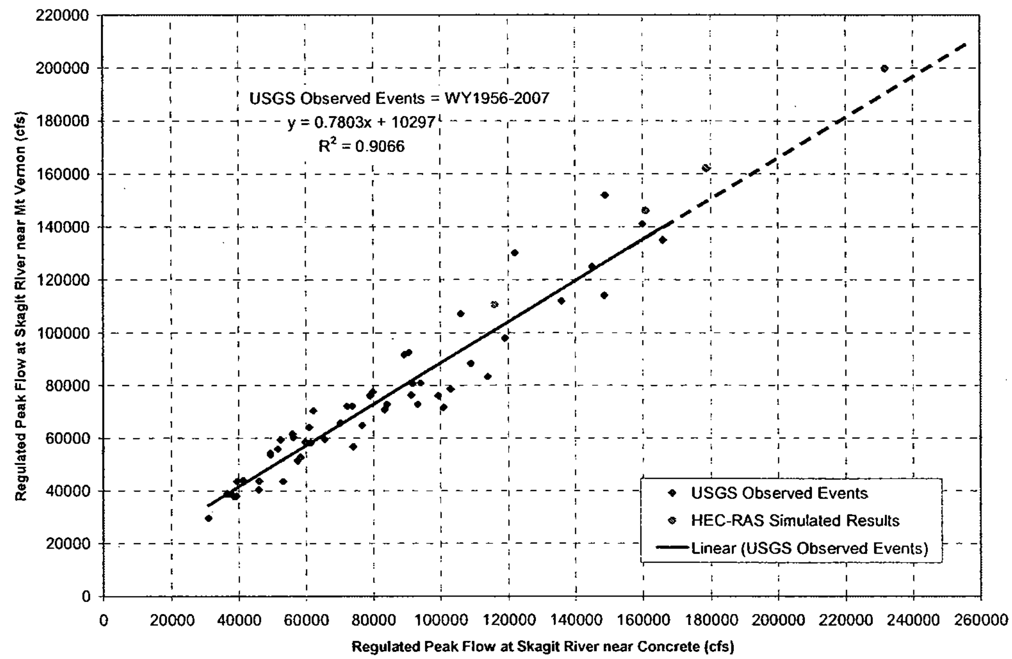

Figure 11. Regression of regulated peak flows observed by USGS at Concrete and Mount Vernon, compared with the HEC-RAS simulated peak values for the 10-, 50-, 100-, and 500-year synthetic events

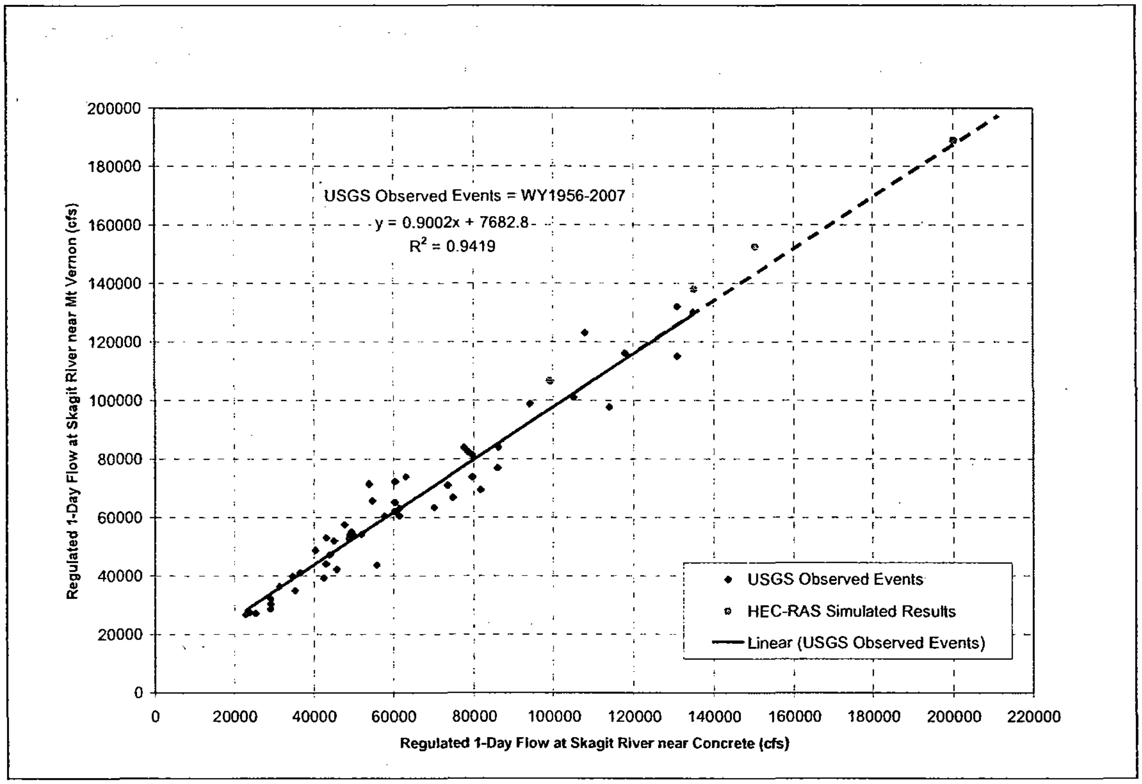

Figure 12. Regression of the regulated one-day flows observed by USGS at Concrete and Mount Vernon, compared with the HEC-RAS simulated one-day values for the 10-, 50-, 100-, and 500-year synthetic events

5.3 Flood Frequency Curves at Mount Vernon

Figures 13 and 14 show the annual peak and one-day flood frequency curves, respectively, at Mount Vernon. These frequency curves were based on the USGS observed flow data at the Mount Vernon gage for the time period from 1955 through 2006 (water years 1956-2007), representing regulated conditions of the Skagit River system. The HEC-RAS modeled peak and one-day flows at Mount Vernon for the 10-, 50-, 100-, and 500-year events were also plotted in Figures 13 and 14 for a comparison with the USGS observed annual flood data and the calculated flood frequency curves. The comparison indicates that the modeled synthetic floods compare well with projection of the frequency curves based on the observed events at Mount Vernon.

The PEAKFQ software was used for the flood frequency analysis. Output of the PEAKFQ runs for the peak and one-day flows at Mount Vernon are provided in Appendix I.

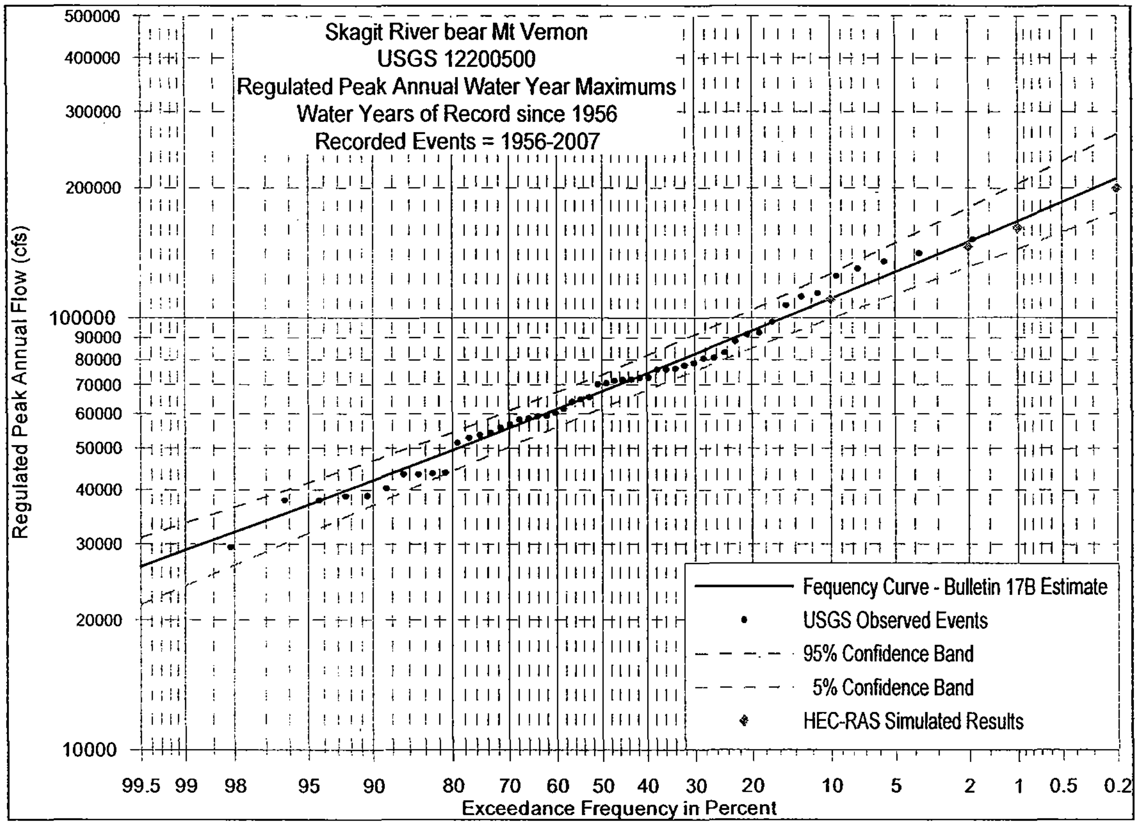

Figure 13. Flood frequency curve for regulated peak discharges observed by USGS at Mount Vernon, compared with the HEC-RAS simulated peak flows at Mount Vernon for the 10-, 50-, 100-, and 500-year synthetic events

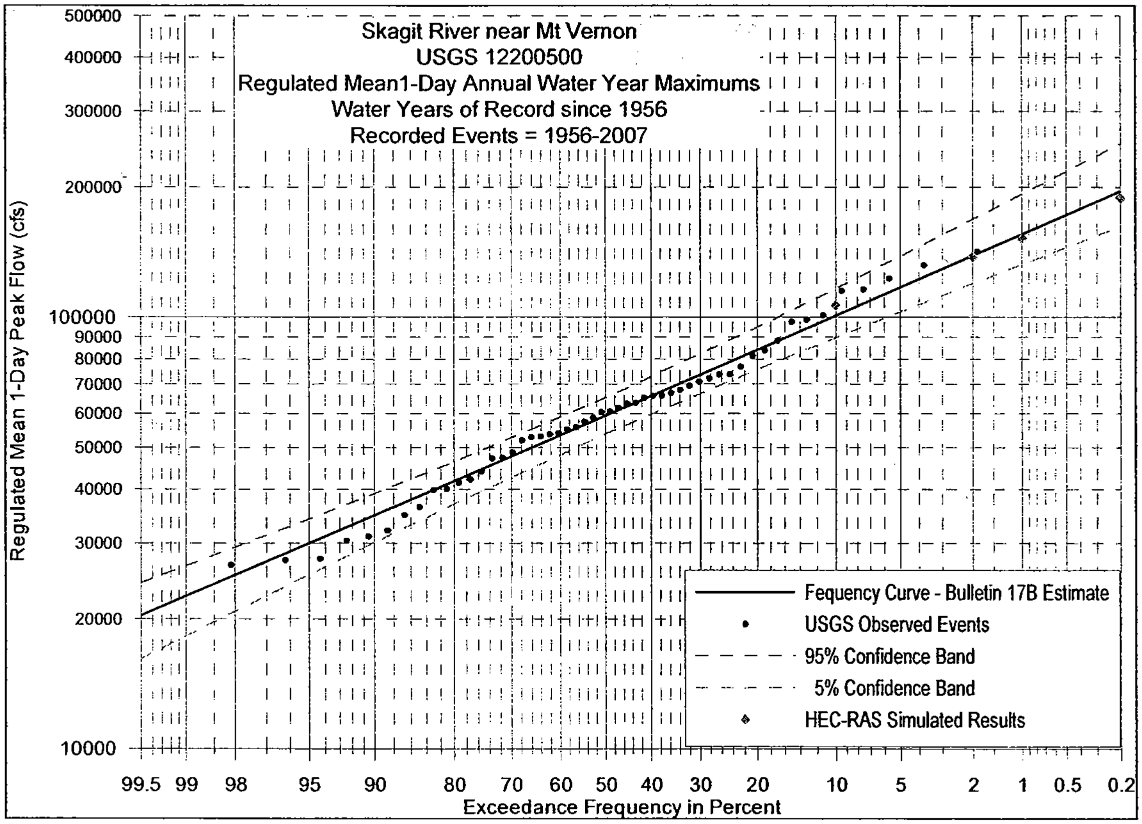

Figure 14. Flood frequency curves for regulated one-day discharges observed by USGS at Mount Vernon, compared with the HEC-RAS simulated one-day flows at Mount Vernon for the 10-, 50-, 100-, and 500-year synthetic events

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