U.S. Army Corps
of Engineers
Seattle District

Skagit River Flood Damage Reduction Feasibility Study

SKAGIT RIVER BASIN

SEDIMENT BUDGET AND FLUVIAL GEOMORPHOLOGY

June 2008

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1.0 INTRODUCTION

This report describes the Skagit River's sediment budget and fluvial geomorphology. These have been important factors in shaping the natural stream system. Other landscape shaping factors, such as geology and climate, are summarized to give a background for the fluvial geomorphology.

The methods and analysis followed in this investigation generally satisfy the criteria for a Stage 1 Sediment Impact Assessment as established in EM 1110-2-4000 *Sedimentation Investigations of Rivers and Reservoirs* (USACE 1995). The purpose of the sediment impact assessment report is to convey to reviewing authorities (1) the amount of effort expended to date in investigating sedimentation problems; (2) the amount and type of field data available for the assessment; (3) the anticipated impact of sedimentation on project performance and maintenance, and (4) the anticipated impact of the project on stream system morphology. A Stage 1 assessment may precede or demonstrate the need for a more detailed Stage 2 Detailed Sedimentation Study.

1.1 General

Authority for the Skagit River, Washington, Flood Damage Reduction 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 control, 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. The purpose of the study is to formulate and recommend a comprehensive flood hazard management plan for the Skagit River floodplain that will reduce flood damages in Skagit County with the focus on the floodplain downstream of Sedro-Woolley. A secondary purpose is to investigate measures to restore ecosystem functions and processes in the project area to benefit fish and wildlife.

In order to identify potential ecosystem restoration actions and to comply with the impact assessment requirements of the National Environmental Policy Act (NEPA) and the Washington State Environmental Policy Act (SEPA) the Skagit River Flood Damage Reduction Feasibility Study must describe the affected environment, including both physical and biological resources. This report addresses those requirements by describing the lower Skagit River's sediment budget and geomorphology. Understanding the sediment budget and fluvial geomorphic processes are important to the formulation of project alternatives and defining potential environmental impacts.

1.2 Purpose of Report

This is the second flood damage reduction study report to address geomorphology and sediment processes in the Skagit River. The Phase I report by Pentec Environmental (2002) described the geomorphology of the river channels downstream of River Mile (RM) 30. The main purpose of this report is to describe the basin-wide sediment budget and the geomorphology of the river and delta channels, and the nearshore areas. This will provide a baseline to evaluate potential sediment budget and geomorphic impacts of alternative flood damage reduction and environmental restoration measures. The main components of this effort include:

- Annual basin sediment yield estimate
- River and delta channel geomorphology
- Nearshore geomorphology

1.3 Study Area

The study area for sediment budget estimates takes in the uncontrolled portions of the Skagit River basin, downstream of Gorge and Lower Baker dams (see Figure 1). The geomorphic analysis is focused on the mainstem Skagit River, the North and South Fork channels, and the Puget Sound nearshore.

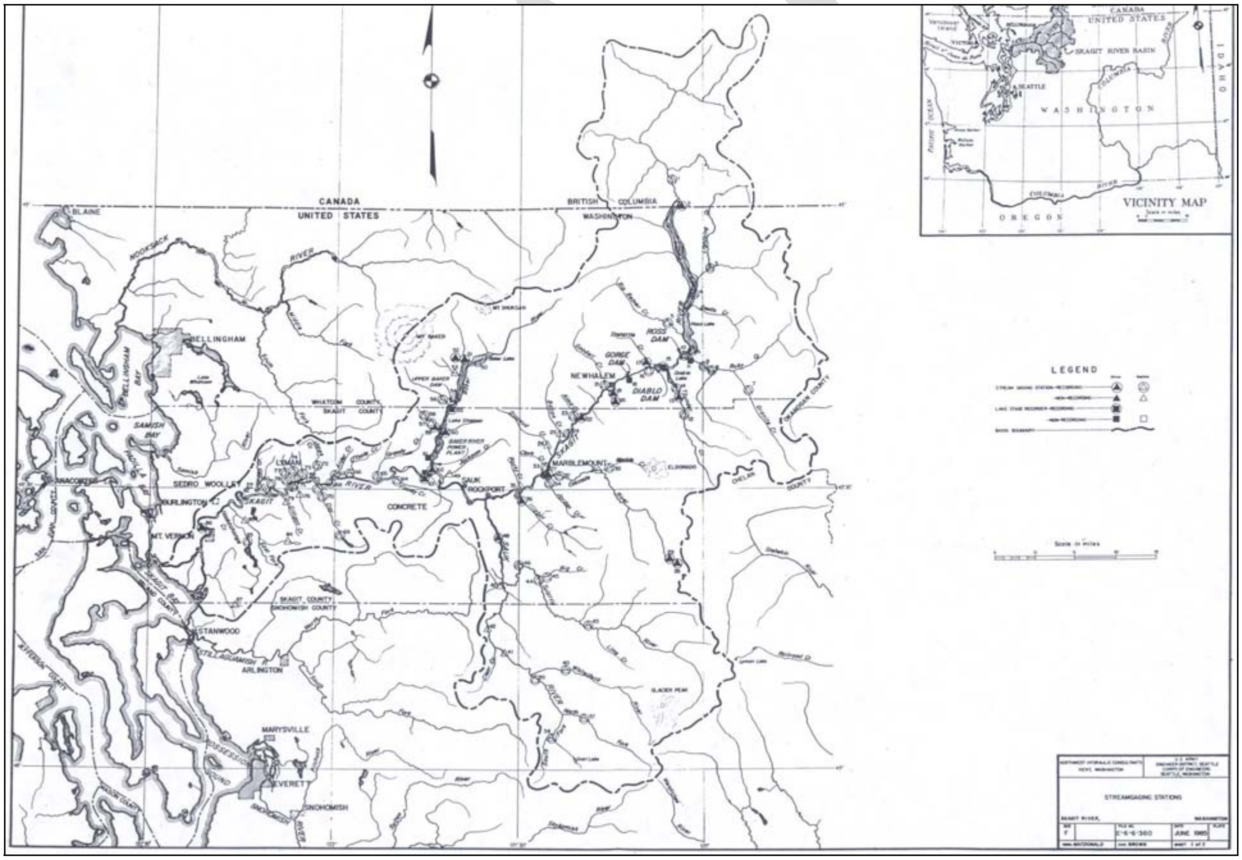

Figure 1 – Skagit River Basin Map

2.0 GENERAL BASIN CHARACTERISTICS

The Skagit River basin is located in the northwest corner of the State of Washington (see Figure 1). The northern end of the basin extends 28 miles into Canada. The Skagit River drainage area is 3,115 square miles, with slightly over half the area controlled by reservoirs. 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.

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, with 22 peaks higher than 8000 ft. Many of those peaks are topped by glaciers. 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 basin. The upper reaches of nearly all tributaries are situated in steep-walled mountain valleys. The middle and lower reaches of the tributaries are covered by timber.

Upstream of the Cascade River at RM 78, the Skagit River flows through a narrow, steep-walled canyon. From the Cascade River down to Sedro-Woolley (RM 23) the Skagit River flows in a l-mile to 3-mile wide valley. In this reach, the valley walls are moderately steep, timbered hillsides with few developments. Downstream of Sedro-Woolley, the river flows through the cities of Burlington and Mount Vernon, and then divides into North and South forks before discharging into Puget Sound. In this reach, the floodplain widens to a flat, fertile outwash plain that adjoins the Samish valley to the north and the Stillaguamish valley to the south.

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. 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. Glaciation exerted a powerful influence on the geomorphology of the Skagit River basin. Drainage patterns in the basin have many peculiar features, including long interconnected valleys, breached hydrologic divides, reversed dendritic segments, underfit streams, barbed tributaries, bisected valleys, and low-elevation mid-valley divides occupied by lakes and wetlands (Riedel et al. 2007).

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. 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.

Two volcanoes, Glacier Peak and Mt. Baker, are located in the upper watershed. Previous eruptions of Glacier Peak have generated lahars that traveled through the Skagit River to Puget Sound. Mt. Baker eruptions have deposited pyroclastic and lahar material in the Baker River watershed, but have not deposited substantial volumes material in the Skagit River floodplain (Gardner, et al, 1995). Future large eruptions could form thick fills of lahars and pyroclastic-flow deposits in the upper valleys near the volcano. Lahars from Glacier Peak could reach the delta, or there could be induced flooding due to temporary damming of watercourses in the upper watershed. Subsequent incision of volcanic deposits could fill riverbeds farther downstream with sediment for many years after the eruption, thereby affecting the capacity of stream channels and locally increasing flood heights (Waitt, et al, 1995).

2.3 Watershed Description

Headwaters of the contemporary Skagit River basin originate in a network of narrow, precipitous mountain canyons in Canada and flows south into the United States and then west for over 100 miles to Skagit Bay. The Skagit basin was likely much smaller prior to Quaternary glaciation. Geological evidence suggests overflow of proglacial lakes breached the North Cascades crest at Skagit Gorge and caused the lower Skagit River to capture upper Skagit valley (Riedel et al. 2007). The Skagit River falls rapidly from near 8,000 ft at its source in Canada to 1,600 ft at the head of Ross Reservoir at RM 128. Ross Reservoir and the associated Diablo (RM 101) and Gorge (RM 97) reservoirs reduce flood discharges, store spring snowmelt runoff, and trap sediment from 1,125 sq mi of the headwaters of the Skagit River.

From Gorge Dam to Newhalem (RM 94) the Skagit River plunges 250 ft in less than 3 miles. Downstream of Newhalem the river's slope flattens substantially to approximately 8 feet per mile between Newhalem and Concrete (RM 56). Numerous tributaries enter the Skagit River in this reach. Many of those tributaries are relatively small, consisting of steep heavily forested basins with drainage areas of less than 20 sq mi that discharge directly into the Skagit River. The largest tributaries to the Skagit River are the free-flowing Cascade and Sauk Rivers and the regulated Baker River.

The Cascade River has a drainage area of 185 square miles and enters the Skagit River at RM 78.1, just upstream of the town of Marblemount. The Cascade River runs for 29 river miles north and west from South Cascade Glacier on Sentinel Peak to the Skagit River. The basin ranges in elevation from 300 to 8,300 feet. The Cascade River is classified as a Wild and Scenic River. The basin is mostly forested and the river opens from a roughly 400-foot wide canyon at RM 3.3 to a 2800-foot wide floodplain at its mouth. The Cascade River is the second largest contributor to the sediment to the Skagit River.

The Sauk River is the largest tributary to the Skagit River and flows into it on the left bank at RM 67.2. The Sauk River is also designated a Wild and Scenic River. The Sauk River originates near Monte Cristo Peak and flows generally north for over 50 miles. The Sauk River has a drainage area of 732 miles, which is over 25% of the total drainage area of the Skagit River at their confluence. It is also approximately 50% of the total uncontrolled sediment contributing area in the basin. There are two large tributaries that flow into the Sauk River from Glacier Peak. The largest is the Suiattle River (346 square mile drainage area), which flows in from the east 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 east at River Mile 31.9. The elevations in the basin range from 10,541 feet to 210 feet at the mouth. The high elevation headwater areas have sparse vegetation and several peaks are glaciated. The middle and lower watershed is forested. The lower reaches of the rivers have braided and meandering channels with unstable banks. The Sauk River watershed is the largest contributor to the sediment to the Skagit River.

The Baker River enters the Skagit River from the north at RM 56.5, at the town of Concrete. The Baker River has a drainage area of 298 sq mi. The basin has several high peaks including Mount Baker, Mount Shuksan, Whatcom Peak, and Bacon Peak. The runoff from 297 sq mi drains into Lake Shannon or Baker Lake. The temporary storage of flood discharges in those lakes greatly reduces flood peaks and the sediment yield from the Baker River.

From Concrete (RM 56) to Sedro-Woolley (RM 23) a few small tributaries enter the Skagit River from both banks. Those tributaries originate in the forested, lower elevation foothills of the Cascade Mountains. Potentially larger tributary flows from Mount Baker are intercepted by the South Fork of the Nooksack River. The valley floor has somewhat irregular topography and is typically a half-mile to a mile wide. Most of the valley floor is utilized for agriculture.

Downstream from Sedro-Woolley (RM 23), the Skagit River crosses a broad outwash plain before discharging into Skagit Bay in Puget Sound. The floodplain stretches north-south about l9 miles, from Samish Bay on the north, to Camano Island on the south. The floodplain is a rich agricultural area. The cities of Burlington, Mount Vernon and La Conner are located on this floodplain. Nookachamps Creek is the only significant tributary in this reach. Immediately downstream from Mount Vernon, the river divides into two distributaries, the North and South forks. These two distributaries carry about 60 percent and 40 percent of the normal flows of the Skagit River, respectively.

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 varies markedly throughout the basin due to elevation and topography. 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. An average annual 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.

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 6 inches at Anacortes to 525 inches at Mount Baker Lodge.

Major storm activity occurs during the winter when the basin is subject to rather frequent ocean storms that can bring heavy rain or snow to the mountains. The type and timing of precipitation in the mountains influences the basin’s sediment production. Rain on bare ground is expected to produce more sediment erosion than typical rain-on-snow events and regional snowmelt events, especially when intense rains fall on saturated ground. Significant rain-on-frozen-ground events are rare and are not likely important generators of sediment west of the Cascade Crest. The understanding of severe winter weather systems is improving (Jones et al. 2004), but there is insufficient sediment data to attempt to determine the most significant sediment producing storm conditions in the Skagit Basin.

2.5 Hydrology

This report summarizes the Skagit River hydrology. A more detailed explanation of the hydrology is given in the Skagit River Hydrology Report that is also part of this Skagit River Flood Damage Reduction Study.

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 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 receded. Glacial melt continues to contribute to the baseflows during this period.

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 cause streamflows to rise rapidly. Streamflows also recede rapidly 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.

Annual runoff varies throughout the Skagit basin. The average annual runoff at the following streamgage stations reflects that variation; Skagit River at the Newhalem, 51.1 inches, Sauk River Near Sauk, 83.0 inches, Baker River at Upper Baker, 131.0 inches, Baker River at Concrete, 121.8 inches, and Skagit River near Mount Vernon, 73.2 inches. The watershed above Ross Dam, located in the rain shadow of western mountains that shield the basin from winter storms, has an annual runoff of only 45.6 inches.

3.0 SEDIMENT BUDGET

A sediment budget is an important component for understanding the sedimentation processes that help shape a river system and how potential flood control measures could impact the river environment (Vanoni 1975; USACE 1995; Thorne et al. 1997; Garcia 2008). An ideal sediment budget accounts for the major sources of sediment and identifies the location, timing, and material size distribution of the sediment moving through a river system. The practical level of detail incorporated into a sediment budget depends its purpose and the extent of available data (Reid and Dunne 1996). In the Skagit River basin there is insufficient data to construct a highly detailed conclusive sediment budget, but a preliminary sediment budget can be developed from existing information to help further the understanding of the alluvial response of the Skagit River system.

3.1 Methodology

The large variety of sediment yield methods can be placed into two broad categories: methods based on direct measurement and mathematical methods (USACE 1995). These methods may also be called the hydraulic and geomorphic methods. The annual sediment yield for the Skagit River Basin was estimated using each approach. The hydraulic method calculates the annual sediment discharge in the river using directly measured sediment loads and gives information about the sediment size and timing of the sediment yield. The geomorphic method estimates the annual sediment yield from upland areas based on catchment properties and provides information about the sources of sediment in the river system.

The geomorphic method estimates the annual basin sediment budget based on geology, land use and erosion processes present in the basin (Swanson, et al, 1982; Reid and Dunne 1996). The first step in this method is to identify the dominant erosion processes. Field measurements or aerial photography are then used to measure the sediment produced by a sampling of those erosion processes, usually measured over a period of years. The measured erosion rates are then applied to the entire basin to estimate the average annual sediment budget.

The hydraulic method combines a sediment load curve (a numerical relationship between sediment discharge and water discharge) with observed water discharge data to calculate an annual sediment transport. This method requires streamflow and sediment transport measurements at one or more locations in the river system. The importance of high flow events on overall sediment yield can be determined from this method.

3.2 Basin Sediment Budgets

This analysis applies the geomorphic method to Skagit River sub-basins to estimate average annual sediment budgets for each sub-basin and the entire watershed. A comprehensive assessment and inventory of sediment sources and yield does not exist for the Skagit River basin. Paulson (1997) developed annual sediment budgets for 10 Skagit River sub-basins. Paulson examined three erosion processes; mass wasting, surface erosion of roads and soil creep. Of those, mass wasting was found to be the dominant erosion process. Paulson then investigated the failure mechanisms, and geologic and land use influences on mass wasting. Three mass failure mechanisms, shallow-rapid landslides, debris flows and earth slumps were identified. It was determined that debris flows and earth slumps delivered over 75 percent of the mobilized material to the streams. Paulson's results agree with other studies conducted west of the Cascades that found mass wasting to be a dominant source of sediment in steep watersheds (Benda and Dunne 1997; Montgomery et al. 1998).

An average annual sediment budget was developed for this study, based on Paulson's work (1997). There is not adequate information available for the remainder of the basin to perform the detailed analysis of geology and land use that Paulson performed in the 10 sub-basins. Therefore sediment yields were extrapolated to other sub-basins based on proximity to one of Paulson's sub-basins. Table 1 lists the average annual sub-basin sediment yields estimated for this analysis.

Table 1. Skagit River Basin Average Annual Sediment Budget by Sub-basin derived from results obtained by Paulson (1997).

Sub-basin	Sediment Contributing Drainages in Mi^2	Non-Contributing Drainages in Mi^2	Annual Sediment Yield Yds^3/Mi^2	Annual Basin Sediment Yield in Yds^3
Upstream of Gorge Dam		1159		
Skagit u/s of Cascade River	228		280	63,840
Cascade River	185		160	29,600
Jackman Creek	24		3800*	91,200
North side tributaries	40		280	11,200
Illabot Creek	42		160*	6,720
Sauk River	732		400	292,800
Baker River		297		
Finney Creek	52		800*	41,600
South side tributaries	90		260	23,400
East Fork Nookachamps Creek	36		260	9,360
Lower Valley Floor		160		
North side tributaries	70		460	32,200
Basin Totals	1,499	1,616		601,920

* Basin yield taken directly from Paulson, 1997.

Nichols (personnel communications, 2006) recommended sediment yields would be significantly higher from glaciated areas. It was decided to add those source areas as a separate item in the sediment budget. Table 2 shows the glaciated drainage areas, estimated from maps and aerial photographs, which would contribute to the sediment yield from the Skagit Basin. Nichols (2006) estimated the glaciated areas would produce 2,600 tons/sq mi/yr or around 1,900 cu yds/sq mi/yr. Thus the 56 sq mi of glaciated area listed in Table 2 could add about 100,000 cu yds/yr of sediment.

Table 2. Glaciated drainage areas that contribute to the Skagit River Basin sediment budget.

Sub-basin	Glaciated Area in Sq Mi
White Chuck River (Sauk)	6
Suiattle River (Sauk)	15
Cascade River	23
Newhalem Creek	2
Ladder Creek	1
Goodell Creek	7
Bacon Creek	2
Basin Total	56

The average annual sediment budget for the Skagit River Basin, based on key geomorphic processes that are shaping the watershed, is estimated to be between 600,000 and 700,000 cu yds/yr. Nearly half the sediment is produced by the Sauk River sub-basin, the largest free-flowing tributary to the Skagit River. The high sediment yield from Jackman Creek demonstrates the sensitivity of this type of analysis, as about 50 percent of the sub-basin yield came from one large mass failure (Paulson, 1997). That one large failure also highlights the limitation of focusing on average annual sediment values, as the equivalent of several years of sediment can be delivered in a single large event.

3.3 Fluvial Sediment Budget

In this analysis the average annual sediment yield for the Skagit River was calculated from streamflow and suspended sediment data collected by the USGS at their Mount Vernon gaging station and by Pentec (2002). Suspended sediment data collected from 1971 to 1993, 2001, and 2006 were used to define a sediment load curve, the numerical relationship between water discharge and the sediment transport rate. The sediment load curve was then combined with daily discharges from 1940 through 2004 to calculate daily and annual fluvial sediment transport. As is explained below, this method contains some uncertainty in the sediment transport parameters because of the limited amount of available sediment data.

Prior to this study, Skagit River suspended sediment data had been collected between 1971 and 1993 by the USGS. A review of that data found there was no information available for discharges above 50,000 cfs. This was considered a significant limitation given that the highest 1 percent of the daily discharge record all exceeded 50,000 cfs, ranging up to a maximum of 142,000 cfs, and flood peaks can exceed 200,000 cfs. As a result, the Corps collaborated with the USGS to collect suspended sediment data from a large storm in November 2006. The five samples collected in November 2006 were from discharges ranging from 63,000 cfs to nearly 120,000 cfs. The complete suspended sediment data set and the best fit power function suspended sediment load curve are shown on Figure 2.

The impact of the November 2006 data on the suspended sediment load curve can be seen in Figure 2 by comparing the USACE 2008 curve to the Collins 1998 curve. The Collins 1998 curve is based on the 1971-1993 USGS data (Collins, 1998). The UASCE 2008 curve is about three times higher than the Collins curve for discharges over 20,000 cfs, however, the Collins curve is about three times higher for discharges less than 15,000 cfs. The differences between these two curves highlight the uncertainty commonly found in sediment load curves. The uncertainty comes from the scatter in the 1971-1993 data for discharges less than 50,000 cfs and from the limited amount of data available for discharges over 50,000 cfs. Several years of intensive suspended sediment sampling, especially during high discharges, would be necessary to significantly reduce the uncertainty in the sediment load curve. Because of the limitations of the 1971-1993 data, Collins (1998) recommended his curve was suitable for showing general patterns of sediment yields, but not for accurately calculating yields. The USACE 2008 curve is slightly better, because it incorporates the November 2006 high discharge data, but still has a high degree of uncertainty, and should also be used consistent with Collins' recommendation.

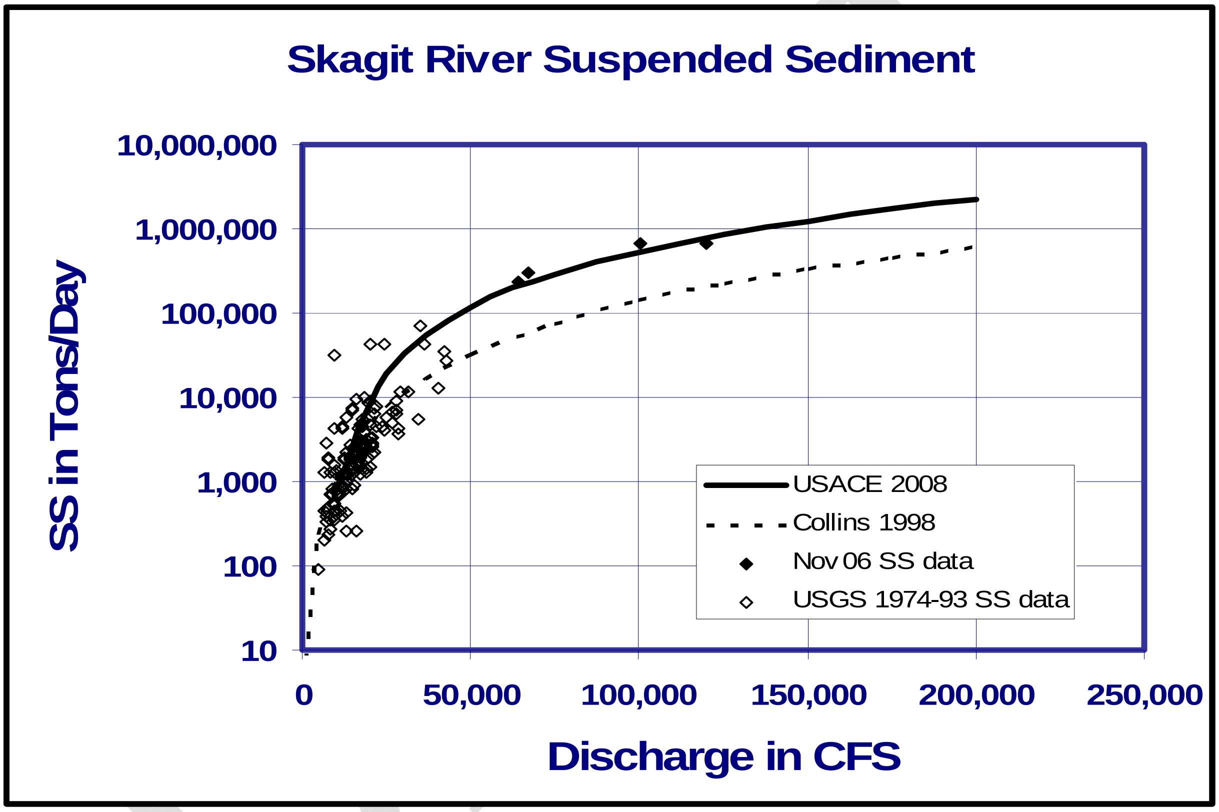

Figure 2. Suspended sediment load curves for the Skagit River at Mount Vernon. The difference between the two suspended sediment load curves is mainly due to the incorporation of the November 2006 data into the USACE 2008 sediment load curve analysis.

The USACE 2008 suspended sediment load curve was combined with the daily discharges from the USGS gage at Mount Vernon to compute daily and annual suspended sediment yields for the period 1940-2004. This method resulted in an average annual suspended sediment yield of 3.8 million tons (mt)/yr, or 2.8 million cubic yards (mcy)/yr. This is approximately four times the annual yield estimated by the basin sediment budget method. It is also more than double the 1.7 mt/yr estimated by Collins (1998).

The yearly suspended sediment yield results are shown on Figure 3. There is over an order of magnitude difference between the highest and lowest annual sediment yields. The highest annual yield was in WY 1991, 10.4 mt, and the lowest in WY 2001, 0.4 mt. Those two years are also the highest and lowest recorded runoff years during the period of record.

The calculated daily sediment yields were analyzed to determine how the average annual sediment delivery was distributed over the range of discharges. The results of that analysis are summarized in Table 3. The importance of floods to the sediment budget is evidenced by the highest 1 percent of the daily water discharges producing 21 percent of the average annual suspended sediment yield. It is also notable that the nine days in the period of record with discharges over 100,000 cfs are estimated to have produced a total of over 5 mcy of suspended sediment, about 3 percent of the period of record total. The highest single day was November 25, 1990, with calculated sediment yield of over 0.75 mcy.

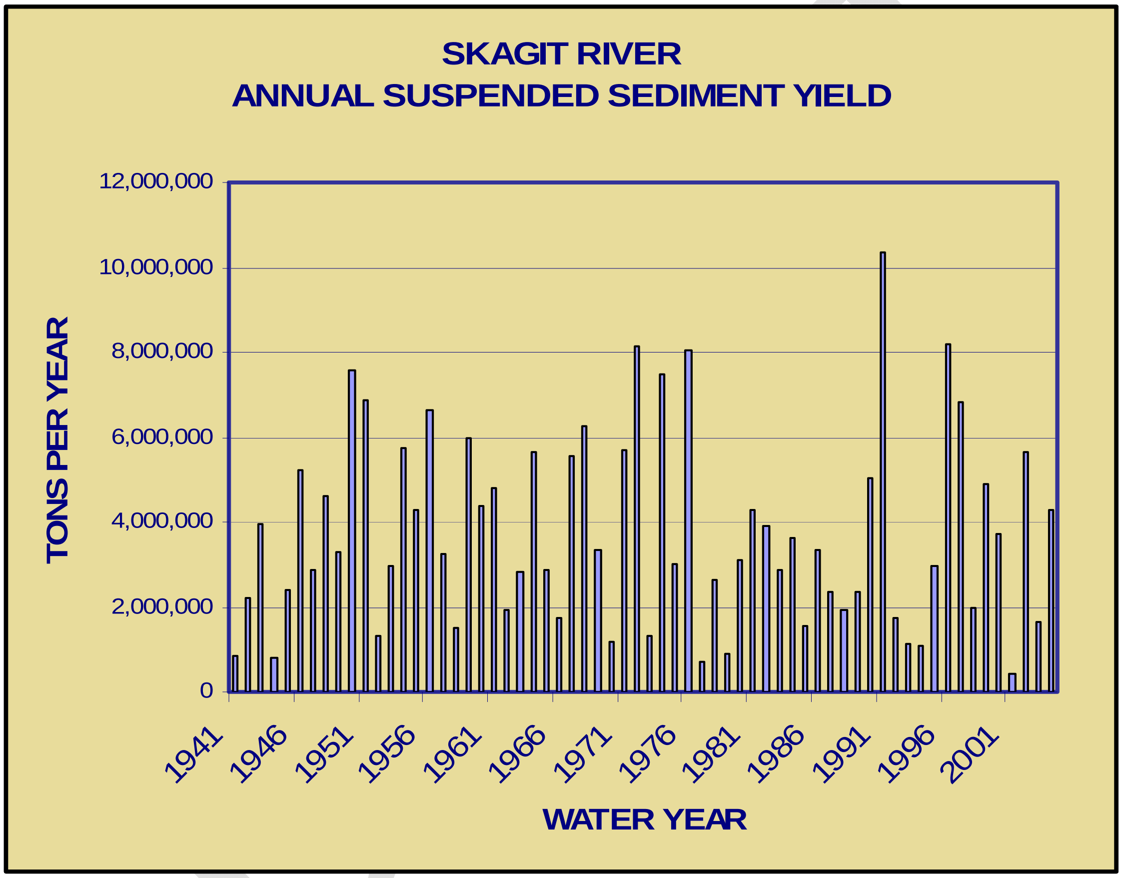

Figure 3. Calculated annual Skagit River suspended sediment discharges at Mount Vernon.

Table 3. Skagit River suspended sediment yield relative to magnitude and duration of water discharge.

Percent of Time Discharge is Exceed	Minimum Discharge in CFS	Suspended Sediment Yield		Percent of Average Annual Sediment Yield
		Tons/Year	MCY/Year	
1	50,600	780,000	0.6	21

10	27,200	2,400,000	1.8	63
50	14,500	3,700,000	2.7	98

The grain size distribution for the suspended sediment also has a large amount of scatter in the data, but shows a general trend of becoming finer as the discharge increases. With reference to Table 3, the sand percentage for the discharges between 14,500 and 27,200 cfs is estimated to be 70 percent, with an observed range of 3-90percent; for discharges between 27,200 and 50,600 cfs, the sand portion is estimated to be 50 percent, with a range of 40-77 percent; and for discharges exceeding 50,700 cfs, the sand portion is estimated to be 40 percent, with a range of 30-55 percent. Combining those percentages with the suspended sediment yields in Table 3 results in an average annual sand discharge at Mount Vernon of approximately 1.4 mcy/yr, which is half of the total annual suspended sediment yield. The remaining 50 percent of the suspended sediment yield at this location is silt and clay.

Bedload is a significant, but unexplored process in the Skagit River. Bedload has not been measured and its contribution to the annual sediment budget of the river is unknown. Bedload is also an important geomorphic process, as it is capable of moving the gravel and cobbles found in the riverbed.

3.4 Sediment Budget Conclusions

The average annual sediment yield estimates have a wide range; from 0.6-0.7 mcy/yr (0.8-0.9 mt/yr) for the basin geomorphic sediment budget, up to 2.8 mcy/yr for the fluvial hydraulic sediment budget. Both methods have a substantial amount of uncertainty in their estimates. The basin sediment budget currently does not account for all erosion processes active in the basin, nor have all the sub-basins been examined. The uncertainty in the fluvial sediment budget comes from relying on data with a fair amount of scatter and few high discharge measurements. The two methods take very different approaches and produce very different sediment budgets, however, both methods identified the importance of intense, short-term events (mass failures and floods) to sediment production.

The importance of intense, short-term events suggests that some of the difference in yields estimated by the two methods may be on account of the October 2003 storm. That storm was an unusually large storm that washed out roads and bridges in the upper Skagit River basin. The full extent of sediment producing disturbances, such as landslides, debris flows and bank erosion, caused by the storm has not been quantified. The November 2006 storm was the first of comparable magnitude following the October 2003 storm. It is possible that sediment sources created in 2003, and therefore not accounted for in the basin sediment budget, could have contributed to the suspended sediment measured in November 2006. This could have raised the 2006 suspended sediment concentrations to levels higher than pre-2003 levels. If this is the case, sediment yields can be expected to decline toward pre-2003 levels in a few years as the new sediment sources are depleted. Continued suspended sediment monitoring during large storms would be required to identify any long-term trends in sediment yields.

The estimated 0.8-3.8 million tons/yr sediment yield equates to 530-2,500 tons/ sq mi/yr from the 1,500 sq mi of the Skagit basin that is not regulated by dams. This Skagit River range is consistent with the regional range of 830-2,500 tons/sq mi/yr of sediment from glacially-fed rivers compiled by R2 Resources (2004) for Puget Sound Energy.

A comprehensive, long-term monitoring program of watershed erosion processes and suspended sediment measurements would be required to refine the Skagit River sediment budgets and reduce the level of uncertainty. Such a comprehensive sediment analysis is not considered necessary to evaluate the potential impacts of the measures under consideration in this Flood Damage Reduction Feasibility Study. No actions are being contemplated within the sediment source areas of the upper watershed and only the peaks of the flood hydrographs might be diverted or stored by flood control measures under consideration.

4.0 FLUVIAL GEOMORPHOLOGY

The Skagit River can be divided into five geomorphic reaches. In the upper basin the Skagit River occupies the narrow, steep-walled canyon upstream of the Cascade River. The middle river extends from the confluence of the Cascade River downstream to Sedro-Woolley. As the valley floor widens through this reach and the channel becomes more sinuous and complex. The lower river runs from Sedro-Woolley to the estuary. The lower river is confined to a single channel with hardened banklines. Downstream of Mount Vernon, the river splits into two distributary estuary channels, before discharging into Skagit Bay on Puget Sound.

4.1 Upper River

The upper reach covers the channel upstream of the Cascade River (RM 78). The channel form in this reach is controlled by the steep North Cascade Mountain geology. Most of the channel upstream of Gorge Dam (RM 97) is submerged by reservoirs. From Gorge Dam downstream to the Cascade River (RM 78), the river flows freely through a narrow bedrock confined channel in a series of rapids and deep pools. The Skagit River has a slope of 10 ft/mi in this lower reach. The riverbed is composed of bedrock, boulders, cobbles and gravel.

4.2 Middle River

The middle reach extends from the Cascade River downstream to near Burlington (approximately RM 19). This is the most active stretch of the river, with complex channel forms and only intermittent bank protection. The lower part of this reach was described by Pentec (2002) in the Phase 1 geomorphology report for this Skagit River Flood Damage Reduction Feasibility Study.

In this reach the river flows on a mountain valley floor that gradually widens in the downstream direction. The Cascade and Sauk rivers contribute large sediment loads to this reach of the Skagit River. The riverbed in the Cascade-Baker river reach is composed of boulders, cobbles, and gravel. The stream gradient falls from over 6 ft/mi upstream of Concrete to about 2 ft/mi upstream of Sedro-Woolley (approximately RM 23) and then steepens again to around 5 ft/mi at the downstream end of the reach. The bed becomes finer downstream and is mostly gravel with some sand near Sedro-Woolley. The floodplain soils tend to be sand, silt and clay.

The channel begins to meander and becomes more complex downstream of the Sauk River. Side channels become more frequent as the valley widens and the slope flattens between Hamilton and Sedro-Woolley. There are numerous side channels, oxbows and overbank erosion scars created during large floods of the past. Some meanders have been cutoff. Bank protection is intermittent throughout the entire reach, generally occurring along Highway 20 or adjacent to riverside communities.

Pentec (2002) mapped the 1894 and 1998 river channels downstream of Hamilton and identified a highly active channel migration zone approximately 2 miles wide between Hamilton and Sedro-Woolley. Between RM 24 and RM 19 the river occupies an active channel 1,000-1,600 feet wide, but there is no active meander zone. The riverbanks consist of alluvial materials and are generally 20-30 ft from top of bank to the submerged toe of the slope. Downstream of RM 22, the river had a meander zone approximately 2 miles wide in 1894, but there is currently little channel migration as most of the banks are now protected by revetments.

Large woody debris (LWD) is common in the middle river reach (Pentec, 2002). LWD exists along the shoreline, both in water and as recruitable trees. Concentrations of LWD can be found at the upstream end of islands, such as those at RM's 35 and 58, or the entrance to side channels, such as at RM 64.

Changes in bed elevations in between RM 19.4 and 22.4 were analyzed by WEST (2000) by comparing 1975 and 1999 channel cross-sections. Those results, listed in Table 4, show a bed elevation rise of 2 ft or more at 5 of 6 cross-sections. Those increases must be viewed with caution as most of those cross-sections are located in a river reach that has a wide channel and an unstable alignment that make cross-section comparisons difficult. Those channel conditions are however consistent with what would be expected in a depositional river channel, which is what the cross-sections indicate and what USACE reported in 1978.

Table 4. Skagit River Bed Elevation Changes for Selected Cross-sections Surveyed in 1975 and 1999 (WEST, 2000).

Reach	River Station (miles)	Change in Thalweg (feet)	Average Change in Bed (feet)
Skagit R.	19.4	2.8	2.4
Skagit R.	20	-0.7	2.7
Skagit R.*	20.9	4.2	4.0
Skagit R.*	21.6	-1.1	1.9
Skagit R.*	21.9	-1.6	2.4
Skagit R.*	22.4	-6	-2.8

* Cross sections are questionable, they do not appear to be surveyed at the same locations.

4.3 Lower River

The lower river runs from RM 19, slightly upstream of Burlington, downstream to RM 8, where the river splits into the North and South Forks. Within this reach the river occupies a single channel, typically 600-700 ft wide with 20-30 ft high banks. This reach has been extensively modified with levees, bank protection, and dredging over the past 100 years or more. Levees line both sides of the river, with minimal setback distances. The banks are continuously armored with riprap. No eroding banks were observed within this reach and the river occupies essentially the same location as 100 years ago (Pentec, 2002).

There is a limited amount of LWD in this reach. Most of the LWD that exists are individual pieces scattered along the riverbed. LWD does collect at bridge piers, especially during floods. Flood fight efforts usually remove the LWD from the bridge piers. There are a few small, isolated sources of LWD along the banks.

In this reach, the riverbed material changes from gravel to sand. Upstream of RM 17, the riverbed is a mixture of gravels and coarse sand. Downstream of RM 17, the bed generally consists of medium and coarse sands, with very little gravel or fine (silt or clay) material.

<u>4.3.1 Bed Elevation Changes.</u> Bed elevation changes in this reach can be analyzed spatially and temporally. The cross-section analysis discussed in the Middle River reach was also done for this reach. That analysis gives an indication of the erosion/deposition trends through the reach between 1975 and 1999. There are also cross-section measurements taken by the USGS at the Mount Vernon stream gage. Those cross-sections were surveyed more frequently and offer a means of analyzing short-term bed changes at the gage at RM 15.8.

To evaluate bed elevation changes, the Corps had WEST Consultants (2000) compared Skagit River cross-sections surveyed in 1975 and 1999. The results of that comparison are summarized in Table 5. The WEST findings showed that the majority of the locations in the lower river reach have aggraded, and only two have degraded. There was wide variation in the amount of aggradation, with increases ranging from 0.1 to 3.7 ft. The average increase in overall bed elevation was 1.4 ft for the 25 year time period.

Table 5. Skagit River Bed Elevation Changes for Selected Cross-sections Surveyed in 1975 and 1999 (WEST, 2000).

Reach	River Station (miles)	Change in Thalweg (feet)	Average Change in Bed (feet)
Skagit R.	10.1	10.6	3.7
Skagit R.	10.6	4.3	0.9
Skagit R.	11.2	2.4	0.6
Skagit R.	11.7	5.2	1.8
Skagit R.	12.4	-1.5	1.5
Skagit R.	12.9	3.9	1.0
Skagit R.	13.1	1.9	1.6
Skagit R.	13.8	-0.2	1.3
Skagit R.	14	-1.3	2.2
Skagit R.	15	-2.2	0.1
Skagit R.	15.1	3.3	2.3
Skagit R.	15.9	1.6	2.6
Skagit R.	16.2	2	0.2
Skagit R.	16.6	2.4	2.4
Skagit R.	16.8	2.1	2.2
Skagit R.	17	-1	-1.5
Skagit R.**	17.5	1.7	-6.0
Skagit R.	17.9	4.2	2.0
Skagit R.	18.5	3.2	1.2
Average***		2.3	1.4

** Cross-section is questionable, it do not appear to have been surveyed at the same locations.
*** Does not include the cross-section 17.5 that is questionable.

The 1975-1999 aggradation rates can be roughly compared to the Corps' 1978 aggradation estimate to identify depositional trends. The 1978 USACE report gave an average infill rate downstream of Sedro-Woolley of 33.4 cu yds/sq mi/yr between 1931 and 1978 (USACE, 1978). That rate equates to an estimated total of 2.5 mcy of deposition in the channels downstream of Sedro-Woolley over the 47 year period. Exact dimensions of those channels are not known, but using approximations based on recent surveys, the 2.5 mcy could have produce an average bed elevation increase of around 1 ft (0.02 ft/yr) for all the main channels downstream of Sedro-Woolley. The 1.4 ft (0.06 ft/yr) of average aggradation in the 25 years between 1975 and 1999 in this lower river reach is approximately three times the estimated rate derived from the Corps' 1978 information. Reasons for the apparent increase in aggradation rate are unknown. Several factors could have contributed to the increase, including inconsistencies in the river reaches, the termination of sand and gravel mining in the 1980s, the large floods in 1991, or increased sediment yields from upstream.

The USGS routinely surveys the riverbed when measuring Skagit River discharges at Mount Vernon (RM 15.8). Those surveys provide an opportunity to evaluate bed elevation changes occurring at an annual or shorter time frame at that location. For this analysis the USGS (Mastin, 2006) provided survey data and average bed elevations for selected surveys between 1960 and 2005. To complement the bed elevation analysis, the stage/discharge curves for a subset of those surveys were used to evaluate water surface elevation changes for 10,000 cfs. The average bed and water surface elevations are shown in Figure 4.

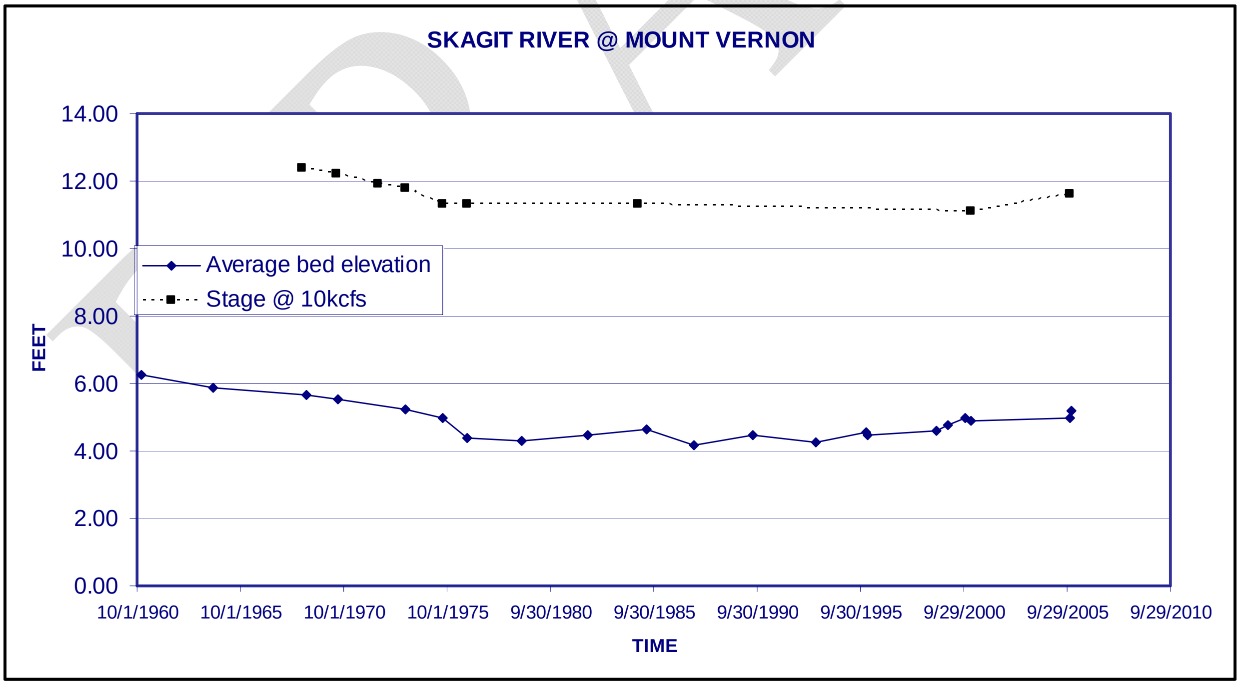

Figure 4. The average bed elevation and stage for 10,000 cfs are shown for the USGS streamgaging station on the Skagit River at Mount Vernon.

The record can be divided into three separate time periods based on the bed elevation change trends. There is a persistent decline in the average bed elevation from 1960 to 1976 that totals -1.9 ft. From 1976 to 1996 the bed elevations show small fluctuations that resulted in an overall rise of only 0.1 ft. The record does not show any unusual bed elevation change as a result of the high discharges and sediment yield in WY 1991. Then from 1996 to 2005 the average bed elevation rose 0.7 ft. This time period includes WY 2001, the lowest sediment yield year during the period of record. USACE (1978) reported a very similar -1.6 ft change in bed elevation at this location between 1959 and 1976. USACE also reported that the decline had been proceeded by an increase of 2.1 ft between 1940 and 1959.

The bed elevation changes and calculated sediment yields were visually compared to see if there was a relationship between bed changes and the magnitude or timing of the sediment yields. In Figure 5 the bed elevation changes at the USGS Mount Vernon gage are plotted along with the 3-year running average sediment yield for 1943-2005. A 3-year running average was used to smooth the sediment yield data and make it easier to identify temporal trends. There does not appear to be any relationship between the bed elevation changes and sediment yields.

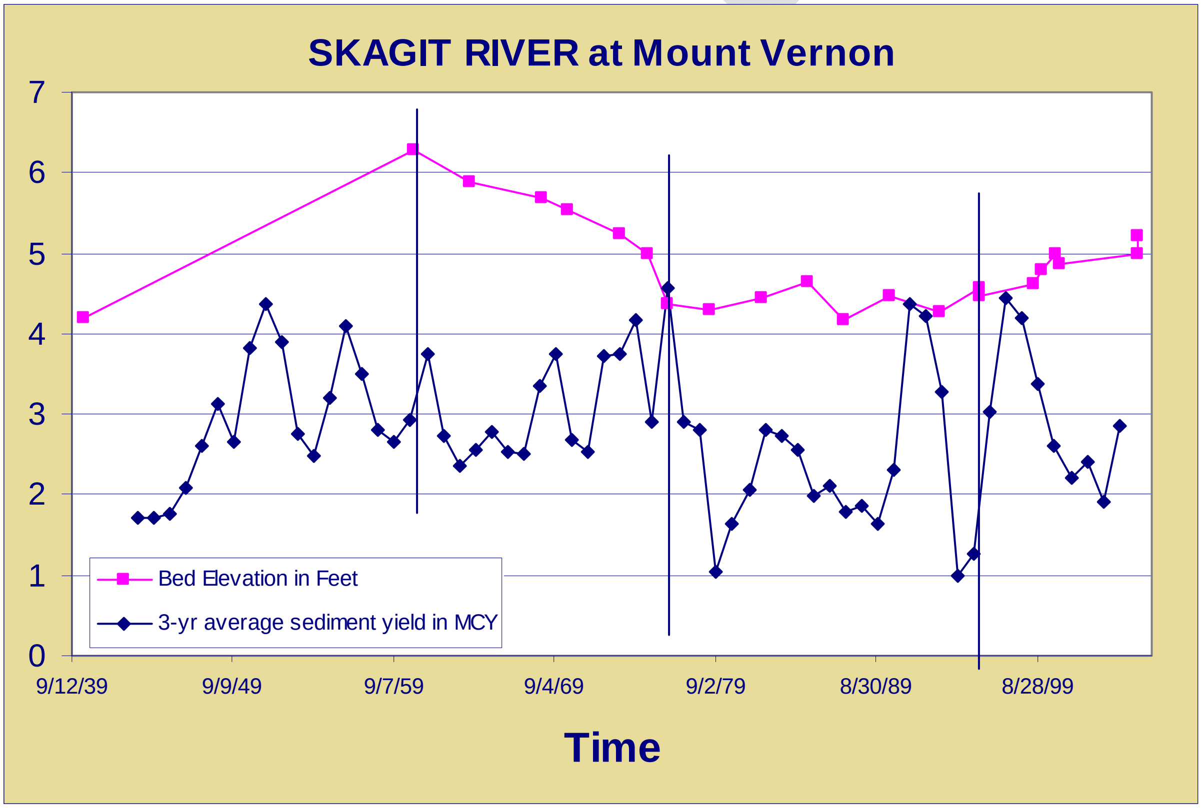

Figure 5. Bed elevations and sediment yield for the Skagit River at Mount Vernon.

Another interesting comparison is the bed elevation changes measured at the gaging station site by the two different surveys. During the 1975-1999 time period, the Corps' two cross-sections surveyed at the USGS station showed a -1.5 ft change, while the USGS data shows a change of -0.3 ft. While these differ in magnitude, they both indicate a decline in average bed elevation at this site. These declines are in contrast to the cross-section surveys overall average bed elevation change of +1.4 ft. However, the relatively consistent result at the gaging site does suggest the broader, overall depositional trend shown by the cross-sections is also reliable.

4.4 Estuary Channels

This reach includes the North and South Forks from their split with the main stem at RM 8, downstream to Skagit Bay in Puget Sound. The flows in these channels are influenced by both river discharges and tidal flows. The mean tide range of 12 ft in Skagit Bay generates large variations in the magnitude and direction of flows in the estuary channels (Philip Williams and Associates (PWA), and Skagit River System Cooperative (SRSC), 2004). The estuary channels and floodplains have been extensively altered by human activities (Collins, 1998).

4.4.1 North Fork. The North Fork carries about 60 percent of the Skagit River discharge. Upstream of about RM 2, the channel is confined by levees and high ground. Channel widths are typically 350-500 ft and the banks are around 15-20 ft high. Bed material samples identified a medium/coarse sand bed, with the D_{50} decreasing from 0.6 mm near RM 9 to 0.3 mm near the mouth (Pentec, 2002).

Bed elevation changes were measured by comparing North Fork cross-sections surveyed in 1975 and 1999 (WEST, 2000). The findings showed that the majority of the stations have aggraded, and only one had degraded. The results of that comparison are summarized in Tables 6. The North Fork had an average increase in overall bed elevations of 1.6 ft. This trend is consistent with that found in the South Fork and lower river channels.

Table 6. North Fork Skagit River Bed Elevation Changes for Selected Cross-sections Surveyed in 1975 and 1999 (WEST, 2000).

Reach	River Mile	Change in Thalweg (feet)	Average Change in Bed (feet)
NF Skagit R.	4.5	1.6	2.3
NF Skagit R.	4.75	4.2	2.8
NF Skagit R.	5.5	3	2.6
NF Skagit R.	6.2	10.4	1.1
NF Skagit R.	6.6	3	1.9
NF Skagit R.	7.2	0.5	0.8
NF Skagit R.**	7.33	3.9	2.9
NF Skagit R.	7.9	2.4	1.3
NF Skagit R.	8.1	2.5	1.1
NF Skagit R.	8.29	-3.7	-0.7
NF Skagit R.	8.85	2.2	2.3
Average***		2.6	1.6

** Cross sections are questionable, they do not appear to be surveyed at the same locations.
*** Does not include cross sections that are questionable.

Bankline vegetation along the North Fork generally consists of narrow bands of small trees and scrubs with isolated patches of larger trees, such as those near RM 4. There are no significant sources of LWD. LWD is scarce within most of the North Fork channel. The only significant accumulations of LWD occur at the upstream ends of the islands located near the mouth of the channel.

Two large channels, Dry Slough and Brown's Slough, used to branch off from the North Fork and flow south across Fir Island, but were cut off when the levees were built in the early 1900's. Both channels now have tide gates to control flows. Downstream of RM 2 several small channels divert flow into Skagit Bay before the North Fork enters the Bay at McGlinn Island.

4.4.2 South Fork. The South Fork has a more complex channel network than the North Fork. It occupies a single channel that varies from 400-900 feet wide downstream to RM 5.5 and then branches into three channels, Freshwater Slough, Steamboat Slough, and the main South Fork channel. Each of these channels branch into multiple channels as they approach Skagit Bay, creating a network of interconnected channels and islands. The South Fork channel complex carries approximately 40 percent of the total Skagit River flow.

Bed elevation changes along the single-channel reach of the South Fork were measured by comparing cross-sections surveyed in 1975 and 1999 (WEST, 2000). The results of that comparison are summarized in Table 7. The findings showed that all of the stations have aggraded. The South Fork had an average increase in overall bed elevations of 1.0 ft, with a range of 0.4 to 1.8 ft. This trend is consistent with that found in the North Fork and lower river channels. No bed elevation comparison was made downstream of RM 5.8.

Table 7. North Fork Skagit River Bed Elevation Changes for Selected Cross-sections Surveyed in 1975 and 1999 (WEST, 2000).

Reach	River Station (miles)	Change in Thalweg (feet)	Average Change in Bed (feet)
SF Skagit R.	5.8	0.3	1.8
SF Skagit R.	6.3	-0.4	0.9
SF Skagit R.**	6.95	4.4	0.1
SF Skagit R.	7.8	-0.5	0.5
SF Skagit R.	8.75	1.9	1.4
SF Skagit R.	9.25	-2.4	0.4
Average***		-0.2	1.0

** Cross sections are questionable, they do not appear to be surveyed at the same locations.
*** Does not include cross sections that are questionable.

The average bed material size in the South Fork is 0.56 mm, coarse sand. Similar to the North Fork, the D_{50} of the bed material decreases in the downstream direction, ranging from 0.8 mm near RM 8 to 0.3 mm near the mouth (Pentec, 2002).

The South Fork, while also constrained by levees, does not have continuous bank protection along its banks. There are expanses of riparian forests that provide a local supply of LWD to the channel. LWD is present through much of the main South Fork channel and the upstream end of Freshwater Slough. In several locations, LWD has been deposited on mid-channel bars. Pentec (2002) suggested the upstream growth of these bars is influenced by the accumulations of LWD.

4.5 Nearshore

The Skagit River nearshore covers an area approximately 8 miles long, north to south, and 2.5 to 5 miles wide, with shallow tidal flats extending nearly to Whidbey Island. This nearshore area could be divided into sub-areas based on any number of factors, such as fish or plant habitats, islands, or tidal channels. For this geomorphic analysis, it makes sense to follow Collins' (1998) lead and separate it into the North Fork Delta, South Fork Delta and Fir Island Delta. Each delta includes several habitat features, including shallow tidal flats, eelgrass, marshes, blind tidal channels, and distributary channels that are influenced by the presence or lack of river hydraulic and sediment processes. The deltas are separated from Whidbey Island by a deep channel along the eastern edge of the island.

4.5.1 North Fork Delta. The active North Fork Delta covers approximately 4,500 acres, generally west and south from the main channel mouth. The western edge of the delta is only 0.5 mile from Whidbey Island. The southern edge is not a distinct boundary, but is located in the vicinity of Craft Island, about 2 miles south of the main channel mouth. The northward expansion of the delta is cutoff by a rock jetty that is just over a mile long and runs between McGlinn and Goat islands. The jetty separates the North Fork Delta from Swinomish Channel and restricts sediment movement to the north.

Since the completion of the Skagit River levee systems, sediment discharges have been concentrated at the mouths of the North and South forks. Sand from the Skagit River is deposited throughout the 4,500 acres of the North Fork Delta, while silts and clays are transport beyond the delta. Sediment cores taken by the USGS on the delta have found several feet of recent sand deposits overlay older mud deposits (Grossman, 2008). Aerial photos available on Google Earth and Microsoft Live Search Maps, indicate the main North Fork channel delivers sediment to the northern part of the delta and the distributary channels supply sediment to the southern half of the North Fork Delta. Deposition appears to be greatest near the mouth of the main channel, as there are networks of small channels flowing west and south away from the mouth. The deposition has created new marsh habitat in the delta, replacing some of the marsh lost due to levees and agricultural development.

Marsh islands cover approximately 640 acres along the northeast edge of the delta. Collins (1998) indicated these marshes expanded slowly between 1889 and 1937, but then grow more rapidly between 1937 and 1991. The increased growth rate was attributed to an increase in the portion of Skagit River flow, and presumably sediment, carried by the North Fork channel. PWA and SRSC (2004) determined that these marshes had grown by 229 acres, an increase of over 50 percent, between 1954 and 2002. Pentec (2002) also concluded the islands were growing, based on observations of river sediments deposited around islands. The islands are separated by distributary channel from the North Fork Skagit River. The islands also contain a limited amount of blind tidal channels, dead-end channels that are formed by and convey tidal flows. Collins, found blind tidal channels made up only 4% of the marsh area. This small amount of the blind tidal channels is due to the small size of the islands (PWA and SRSC, 2004).

Sullivan Slough is a 3,000 acre marsh, located just north of the mouth of the river. Collins (1998) indicates the slough was once a major distributary channel of the Skagit River. The area was highly modified and the marsh area reduced between 1874 and 1940. Sediment from the Skagit River may have contributed to the aggradation during that period, but the current drainage pattern in Sullivan Slough indicates the area is now an independent blind slough complex.

Other interesting features of the delta include the presence of LWD around the islands and patches of eelgrass in the southern corner of the North Fork Delta (Grossman, 2005). The eelgrass is located far from the main channel mouth, where deposition would be the least. The USGS, in partnership with other agencies (including the SRSC), is studying the impact of sediment deposition on the eelgrass.

4.5.2 South Fork Delta. The active South Fork Delta is larger and more complex than the North Fork Delta. The South Fork Delta covers an area of around 13,000 acres in Skagit Bay. It is bordered on the south by the West Pass of the Stillaguamish River. The tidal flats extend 4 miles west, to approximately 1.2 miles from Whidbey Island. The northern boundary is not clearly defined, but generally runs west from the mouth of Freshwater Slough.

As with the North Fork Delta, sand from the Skagit River has been deposited over the South Fork Delta and the silts and clays transported away. Recent sand deposits overlay older mud deposits (Grossman, 2008). Deposition was most rapid between 1889 and 1937 when most of the marshes formed (Collins, 1998). Aerial photos available on Google Earth and Microsoft Live Search Maps, suggest the highest deposition is currently occurring at the mouth of Freshwater Slough, where an unstable, non-vegetated, low-tide island complex has developed.

Marsh islands cover approximately 2,000 acres, extending over a mile up along the main distributary channels. Collins (1998) indicated these marshes expanded most rapidly between 1889 and 1937. Growth continued after 1937, but at a much slower rate. PWA and SRSC (2004) determined that these marshes had grown by 518 acres between 1954 and 2002. This is nearly twice the rate of marsh growth as was observed in the North Fork Delta during the same time period. This higher growth rate was produced despite the South Fork carrying less water and sediment than the North Fork. The South Fork Delta islands are large and have well developed drainage networks. Collins (1998) estimated that blind tidal channels made up 7 percent of the marsh area in 1991. LWD is very sparse on the marshes, even along the shorelines.

Delta maps (Grossman, 2005) show fragmented patches of eelgrass occur within an approximately 3,000 acre area on the west side of the delta. Grossman concluded that the eelgrass fragmentation has been caused by sediment deposition following the concentration of Skagit River discharges in the North and South Fork channels.

4.5.3 Fir Island Delta. The Fir Island Delta is located between the North and South Fork deltas. The Fir Island Delta covers an area of around 5,000 acres in the center of Skagit Bay. The tidal flats extend 2.5 miles west, to about 0.75 miles from Whidbey Island. This area does not have any significant sources of freshwater or riverine sediment. The tidal flats are covered with sand that originates from the North or South forks.

There are approximately 500 acres of marsh in the Fir Island Delta. The marsh is located on a narrow, 4 mile stretch of the mainland shoreline. About 3 percent of the marsh is composed of blind tidal channels. There are levees along the landward side that have cut-off large portions of the marsh and the associated channel network (Collins, 1998). The marsh area has declined due to erosion and land subsidence; both processes are aggravated by the lack of sediment from the river. Collins (1998) estimated about 200 acres of erosion between 1937 and 1991, and PWA and SRSC (2004) measured 160 acres of marsh loss between 1954 and 2002. Most of the Fir Island shoreline contains accumulations of LWD.

Delta maps (Grossman, 2005) show the Fir Island Delta contains nearly 1,500 acres of continuous eelgrass habitat along the western edge of the delta. Apparently because of the lack of distinct channels and sediment deposition, this patch of eelgrass has not been fragmented as has happened to the eelgrass habitat in North and South deltas.

5.0 DATA GAPS

There are numerous data gaps that would have to be filled to thoroughly define the Skagit River's sediment budget and fluvial geomorphology. Some of the most important investigations required to fill those data gaps are:

- Inventory all significant erosion processes and sediment sources active in all sub-basins
- Identify the gradation of sediments produced in each sub-basin
- Monitor suspended sediment and bedload transport in the main stem and major tributaries
- Continue to re-survey channel cross-sections every 10 years or so
- Refine geomorphic analysis using a time series of aerial photographs
- Improve the understanding of relationships between subbasin sediment production and channel aggradation through watershed sediment yield modeling and sediment transport modeling.

These investigations would be very expensive and would require years to complete. Such a comprehensive investigation is not considered necessary to evaluate the potential impacts of the measures under consideration in this Flood Damage Reduction Feasibility Study. However, detailed studies are being conducted by other groups, such as the SRSC, USGS, and Skagit Watershed Council, to support habitat restoration efforts in the lower Skagit River, estuary, and nearshore. The results of those studies will be reviewed as they become available and the results considered in evaluating potential project impacts.

6.0 SEDIMENTATION CONCLUSIONS

Based on the results of the above sediment budget and fluvial geomorphology analyses, the Skagit River's sediment regime can be fairly well defined. There remains some uncertainty about precise annual values, but long-term trends are clear.

The Skagit River channel is fairly stable with the most migration occurring in the middle reach. Channel alignment in the upper basin is controlled by natural geology, while the lower river and estuary channels are controlled by levees and bank protection. The middle reach has only intermittent bank protection and the active migration zone is up to 2 miles wide. The estuary and nearshore islands are growing, but the Fir Island shoreline is eroding.

The average annual sediment yield at Mount Vernon is in the range of 0.6 to 2.8 mcy/yr. The major sources of sediment are the Cascade and Sauk rivers. Approximately half the basin does not contribute sediment because the sediment is stored in reservoirs. Large storms, those with daily discharges above 50,000 cfs, are a major factor in sediment production, causing upper basin land disturbances and producing an estimated 21 percent of the average annual sediment yield.

Upstream of RM 17, the Skagit riverbed is composed of gravel, cobble, and boulders. Downstream of RM 17 the riverbed and nearshore delta bottom are mainly sand. The 2.8 mcy/yr annual suspended sediment yield at Mount Vernon is composed of approximately 50 percent sand, 50 percent silt and clay. Most of the sand, and all the silt and clay are transported through the lower river and into Skagit Bay.

Since 1931, there has been a consistent long-term trend of sediment deposition in the channels downstream of Sedro-Woolley. This has resulted in an overall average bed elevation increase of approximately 2 1/4 ft since 1931. The bed upstream of RM 15.8 appears to be rising slightly faster than the overall average. Sand deposition has also been occurring in the estuary and on the delta. Islands and marsh habitat have been growing at the mouths of the North and South Forks.

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