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Toutle/Cowlitz River Sediment Budget

The Biedenharn Group, LLC

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1.0 INTRODUCTION

1.1 Background

Following the dramatic eruption of Mount St. Helens on 18 May 1980 and the deposition of approximately 3 billion cubic yards of primarily sand and gravel material in the upper 17 miles of the North Fork of the Toutle River, significant urban and industrial flooding occurred along the lower 20 miles of the Cowlitz River and the Columbia River's navigation channel was blocked between river miles (RM) 60 and 72. Subsequent mudflows and sedimentation problems along the lower Toutle and Cowlitz Rivers from 1981 to 1986 required the investigation and implementation of permanent measures by the U.S. Army Corps of Engineers (USACE) to address the long term impacts of the Mount St. Helens eruption.

The Mount St. Helens (MSH) Project was formulated to control the movement of large amounts of sediment downstream from the debris avalanche resulting from the May 18, 1980 eruption and maintain a congressionally authorized level of flood protection along the lower Cowlitz River. Other significant sources of sediment in the Toutle watershed have also been identified as contributing to the overall supply to the Cowlitz River. The increase in sediment available for transport downstream to the Cowlitz River has contributed to decreasing levels of flood protection on the lower twenty miles of the Cowlitz River due to loss of channel conveyance and hydrologic trends in the basin. Figure 1.1 is a vicinity map of the Toutle and Cowlitz Rivers.

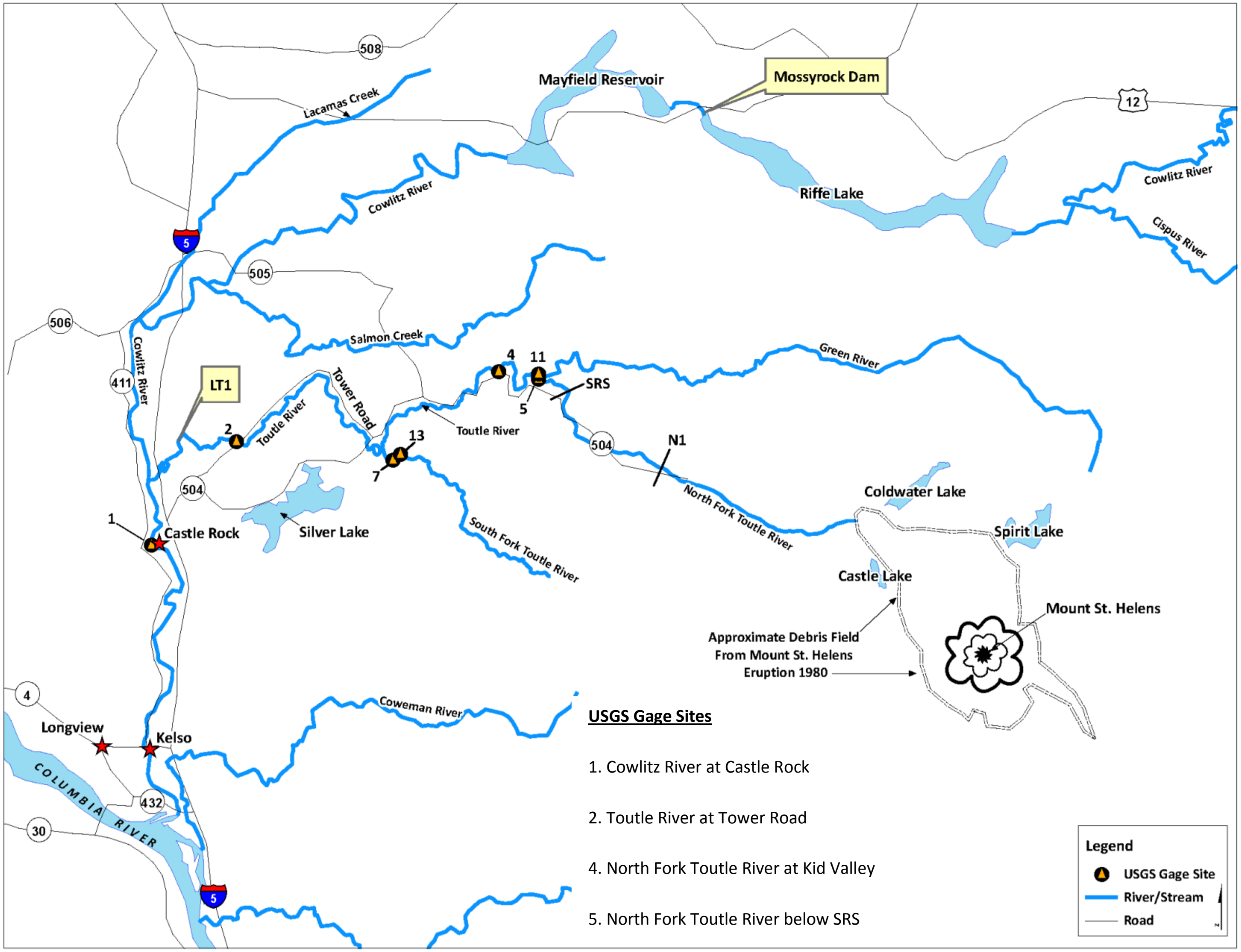


Figure 1.1 Project Vicinity Map

1.2 Project Description

To address immediate sediment and debris problems immediately following the eruption, two debris retaining structures were constructed on the Toutle River system. The North Fork (N-1) structure was constructed in 1980 at the toe of the debris avalanche, 6,100 feet in length 43 feet in height with an impoundment capacity of 6 M cubic yards. N-1 breached several times as flow overtopped the structure after dredging behind the structure was terminated in 1981. S-1 was a temporary structure located on the South Fork, 600 feet in length and 20 feet in height. It was removed in 1982 to allow fish migration. In addition, dredged material basins were located at LT-1 and LT-3.

The primary elements of the Mount St. Helens Project (MSH), as described in the 2002 Design Documentation Report (USACE, Portland District 2002) are described in the following paragraphs.

- **Spirit Lake Outlet Tunnel** is a relief tunnel system to control lake water surface elevations from exceeding a safe level. Overtopping and failure of the eruption-deposited debris dam could cause severe downstream flooding. The tunnel is 8,460 feet in length and is designed to safely deliver the excess lake water to South Coldwater Creek.

- **The Sediment Retention Structure (SRS)** is an embankment that is 125 feet in height and 1,800 feet in length. The sediment dam is located at river mile 13.3 along the North Fork of the Toutle River. The SRS was designed to prevent medium sands and coarser sediment from being transported downstream to the lower Toutle and the Cowlitz Rivers. As one of the six primary elements of the Mount St. Helens project, construction of the SRS along the North Fork of the Toutle River began in October 1986. The SRS began impounding water in November 1987, though construction was not completed until December 1989. Components of the SRS include an ungated-overflow spillway (crest elevation 940 ft NGVD 1929); an unlined chute in the right abutment; and an outlet works of 30, 3-foot diameter pipes stacked in six (6) rows spaced 10 feet apart. Since construction, the SRS has continuously impounded sediment such that by 22 April 1998 all six tiers of pipes have been closed and all runoff is currently passed through the ungated-overflow spillway. Three time periods relative to the SRS are used throughout this report: (1) the period between the 1980 eruption and the construction of the SRS in 1988; (2) the period between the closing of the dam in 1988 to the point at which retained sediment reached the spillway crest in 1998; and (3) the period after the SRS has filled to the spillway crest to the present.

- **The Fish Collection Facility** was constructed as a mitigation feature for the SRS blocking the upstream migration of fish. Fish collected at the facility can be transported around the SRS and released in the upstream breeding streams. The facility was constructed 1.3 miles downstream of the SRS and 0.7 miles upstream of the Green River confluence with the North Folk of the Toutle River.

- **Levee Improvements** along the lower Cowlitz River (RM 1.3 to 7.0) were required to maintain flood control standards and appropriate levels of protection. The Castle Rock levee (left bank from RM 16.1 to 17.55), Lexington levee (right bank from RM 6.95 to 9.6), Kelso levee (left bank from RM 2.6 to 6.8) and Longview levee (right bank from RM 3.1 to 5.5) were specifically included. Dredging was authorized in both the Toutle and Cowlitz Rivers through the year 2035, and was intended to encompass emergency measures.

- **Base-Plus Dredging** refers to the base-level condition which corresponds to the nominal protection level available in the November and December 1983 period.

- **The McCorkle Creek Pump Station** Addition was required because emergency levee construction impacted drainage from McCorkle Creek into the Cowlitz River. Additional pumping conveyance was required to mitigate flooding along the Creek.

Each of the primary elements of the project has been constructed and is functioning as designed. As the level of sediment retained within the SRS has reached the level of the spillway crest (1998), sediment from the upstream avalanche plain has reached the lower Cowlitz River and this has required the resumption of maintenance dredging that had been unnecessary during the SRS filling period.

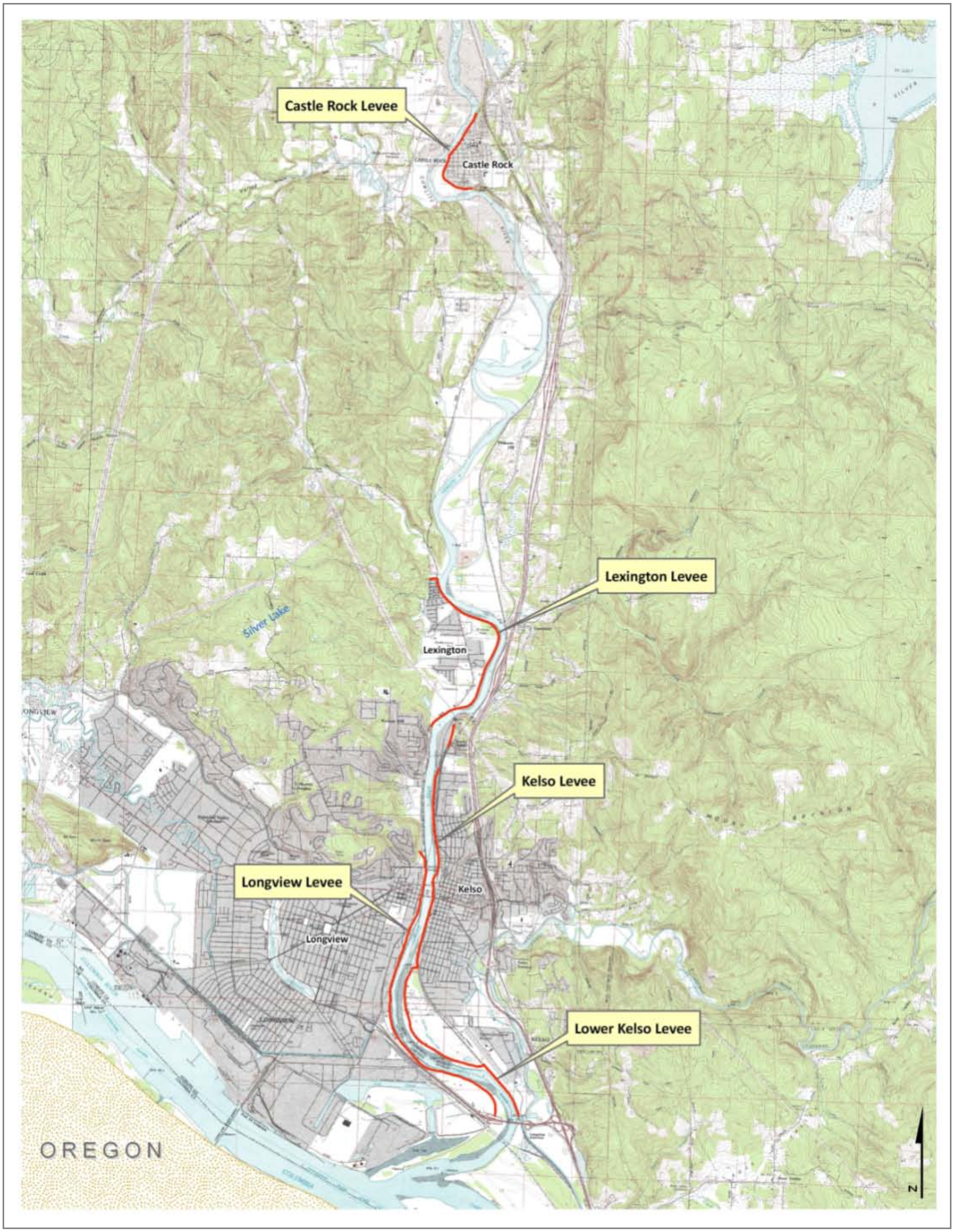


Figure 1.2 Cowlitz Levee Location Map

1.3 Purpose and Approach

The purpose of this report is to present a sediment budget that identifies the existing watershed sediment sources, pathways of sediment transport and sinks of temporary storage of sediment. The sediment budget estimates the volumes and transport rates of sediments in the Toutle watershed. In future studies, this sediment budget will provide a framework for identifying, screening and evaluating potential alternatives.

A sediment budget is an accounting of the sediment movement, into and out of, a selected location. In the Toutle / Cowlitz Rivers watershed (Figure 1.1) an accounting of the sediment load has been conducted beginning upstream within the ***debris avalanche plain*** along the North Fork of the Toutle River and continuing downstream to the ***mouth of the Cowlitz River*** adding estimated sediment loads from various sources along the way. Estimation of sediment sources was the result of careful examination of all available data within the system. Suspended sediment data, sediment samples, bathymetric data along the Cowlitz, aerial surveys, and ground survey are included in the information used to formulate appropriate sediment sources. Temporal density of the information is highly variable and in some cases the data is sparse. To develop a sediment budget with available data, judgments have been made of the usefulness of the data and relevance of the time periods over which the data is most valid. In the following chapters we will explain the sources of information and the variability of the information.

The Toutle/Cowlitz sediment budget network is comprised of seven reaches, as shown in Figure 1.1. The reaches were defined geographically by the locations of the SRS, USGS gages, and river confluences. Each reach is described below:

1. ***North Fork Toutle River extending from the debris avalanche downstream to the SRS***
2. ***North Fork Toutle River from the SRS to the Toutle confluence***
3. ***South Fork upstream of the USGS gage***
4. ***South Fork from the USGS gage downstream to the Toutle confluence***
5. ***Toutle River extending from the North and South confluence downstream to the USGS gage at Tower Road***
6. ***Toutle River from the USGS gage at Tower Road downstream to the Cowlitz River***
7. ***Cowlitz River from the Toutle to the Columbia River***

The sediment budget was formulated under the assumption that the North Fork, South Fork, and Toutle Rivers act as a conduit for efficiently moving sediment; mainly sands, silts, and clays; to the Cowlitz River. Local sinks have been observed in a few locations along the Toutle, North and South Fork Rivers; however, based on analysis of stream power, critical shear, suspended sediment data and field observations, these sinks are thought to be relatively small in comparison to the sediment sources. Sediment depositing in sink locations along the Toutle during dry hydrologic conditions will likely return to suspension and be delivered to the Cowlitz given time. Simulation of sinks or routing of sediment through the system to the Cowlitz requires a mobile bed sediment transport model, which was not included in the scope of this report.

In addition to the LiDAR and gage analyses necessary for the sediment budget, we have added a supplementary investigation of the historical survey data and gradation analyses of the sediment filling the Sediment Retention Structure (SRS). Also as supplementary information, we have provided a review of the dredging history in the Columbia River for the period beginning as eruption materials impacted the Columbia navigation project. Although these two supplemental topics were not directly utilized in the sediment budget, the perspective offered by the additional data is of significant value to the report.

1.4 Description of Toutle/Cowlitz Basin

The Cowlitz River Basin is located in the western slopes of the Cascade Mountains in the southwestern portion of Washington State with a total drainage area of 2,480 square miles. The Mayfield-Mossyrock reservoir system on the upper Cowlitz regulates 1,392 square miles of this area. The Cowlitz River flows generally south towards the confluence with the Columbia River at approximately river mile 68. The Toutle River, a tributary to the Cowlitz River at river mile 19.52, drains a mountainous portion of the Cowlitz River Basin, with headwaters on the northern and western flanks of Mount St. Helens, an active volcano. The Toutle River has three major tributaries: the South Fork, the North Fork, and the Green River. The landslide and volcanic blast of the 18 May 1980 eruption devastated a 232 square mile area north of the mountain, destroying vegetation and depositing volcanic debris (Christiansen and Peterson 1981). Mudflow tephra and blast deposits were also emplaced in several drainages south and east of the volcano (Dinehart 1992).

Altitudes in the Mount St. Helens area range from 8,365 feet at the present summit of the volcano to less than 10 feet above sea level near the mouth of the Cowlitz River. Precipitation ranges from 1140 millimeters per year (mm/yr) near the Columbia River to 3200 mm/yr on the upper slope of Mount St. Helens. Approximately 75% of the annual precipitation occurs between October and March, and about 95% of the recorded annual flood peaks have occurred between November and February (USACE 1984). Maximum flows are often the result of rain falling on snow pack.

Approximately 22 square mile of the 230 square mile blast zone has been replanted and is managed as commercial forestland. The remaining area of the blast zone, including the North Fork Toutle River Valley above Elk Rock, has been left relatively untouched and is within the Mount St. Helens National Volcanic Monument, managed by the U.S. Forest Service. The approximately 20 square miles of the debris avalanche, which is the major sediment source to the Toutle River, is located within the monument area (USACE 2002).

1.5 Sediment Budget Methodology

Development of a budget to estimate the amount of sediment delivered to the Cowlitz River from the Toutle River basin includes identification of potential sediment sources, and sinks, quantification of these data by grain size, and consideration of the uncertainty of the data. To facilitate the evaluation of appropriate sources and sinks, the Cowlitz-Toutle basin was subdivided into seven (7) major geographic segments, summarized in Table 1.1. Subdivision of the North Fork of the Toutle River is based on the location of the existing Sediment Retention Structure (SRS). Subdivisions of the Toutle River and the South Fork of the Toutle River are based on locations of existing USGS stream gages. Each geographic region will be evaluated independently in terms of relevant sources and sinks, input that will be used in the sediment budget. Sources of information used for each geographical unit vary and include gage data, aerial survey data, and hydrographic survey data. Each segment will be addressed in the following sections.

Table 1.1 Sediment sources and sinks used in the development of the sediment budget

Description		Data Source/Notes
North Fork Toutle River: Debris Avalanche to SRS		
Debris Avalanche Erosion	Coldwater Creek	1999-2007 Surface Comparison
	Castle Creek	
	Loowit	
	A - Debris Avalanche to Elk Rock	
	B - Elk Rock to N1	
SRS Deposition	C - Sediment Plane	1999-2007 Surface Comparison
	D - Sediment Plane	
	E - Sediment Plane	
Sources	Total Erosion	Sum of Debris Avalanche Erosion
Sinks	Total Deposition Behind SRS	Sum of Sediment Plane Deposition
Output from SRS	Output to North Fork Toutle River	Erosion - Deposition
North Fork Toutle River: SRS to Toutle River		
Input	Output from SRS	
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos
	Green River	Estimate from USGS Gage Data + 18% Unmeasured
Sinks		
Output	Output to Toutle River	
South Fork Toutle River: Upstream of USGS Gage		
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos
Sinks		
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured
South Fork Toutle River: Downstream of USGS Gage		
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured
Sources		
Sinks		
Output	Output to Toutle River	
Toutle River: Confluence of North Fork and South Fort to USGS Gage at Tower Road		
Input	Output from North Fork and South Fork	
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos
Sinks		
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rd	Compare Sediment Budget to Gage Data
Toutle River: USGS Gage at Tower Road to Cowlitz River		
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rd	Compare Sediment Budget to Gage Data
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos
Sinks		
Output	Output to Cowlitz River	
Cowlitz River: Toutle River to Columbia River		
Input	Input from Toutle River	
	Input from Upper Cowlitz	
Sources		
Sinks	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons
Output	Output to Columbia River	

1.6 Previous Studies

Dinehart (1998) and Simon (1999) provide rich sources of data pertaining to the channel morphology, sediment characteristics and transport rate of sediment moving from the areas directly affected by the volcanic eruption and moving downstream toward the lower Cowlitz River. Major et al. (2000), Major (2004) and Major and Mark (2006) provide an informative perspective of sediment yield and peak flow responses on a decadal scale. The first of his three papers close with the following prophetic quotation:

"If the 20-year perspective from Mount St. Helens can serve as a guide, yields from basins affected solely by hillslope disturbance will diminish rapidly, probably within tens of months, whereas yields from basins that experience dominantly channel disturbance will likely remain elevated for as much as several decades. Thus measures designed to mitigate sediment transport in the aftermath of severe explosive eruptions must remain functional for decades." Therefore, the need for long-term sustainability was advised early in the assessment and design for a lasting solution to the Mount St. Helens sediment yield.

WEST Consultants, Inc. (2002), under contract to the Portland District, USACE, conducted a study to predict the future sediment supply from the Toutle River system and evaluate the associated sediment transport characteristics of the Cowlitz River downstream of Toutle River confluence.

The Portland District, USACE has authored numerous engineering reports pertaining to the design of the major elements of the MSH. Annual hydrologic summaries are available for most years, as well as several river sedimentation studies. A listing of these documents is provided in the reference section of this report and pertinent documents are contained within the DVD attached to this report.

1.7 Data Collection

Extensive data sets from various sources have been collected by various agencies and researchers since the eruption. A significant effort was undertaken to compile and assess all available data. Based on this assessment, the best quality information was given the most weight in the sediment budget analysis and data sources were prioritized. The assessed uncertainty was a significant factor in prioritization.

1.7.1 Field Reconnaissance

Several field reconnaissance trips were made by members of the Portland District, USACE and by members of the Biedenharn Group, LLC team. In October, 2008 an extensive geo-reference video of the Cowlitz River, from the mouth to Mossy Rock Reservoir, and the Toutle River from the mouth, up the North and South Forks to Mount St. Helens was flown. The geo-referenced video was used to identify specific locations of bank instability along the Toutle and the North Fork of the Toutle Rivers. Sediment samples were obtained during December, 2008 by members of the Biedenharn Group, LLC and Portland District. The samples were processed at the laboratory facilities of Colorado State University.

1.7.2 Aerial Photography

Aerial photography collected for the current study includes the following:

- 1980 Aerial photography obtained from the USGS Earth Explorer Website
- 1981 Aerial photography of the South Fork Toutle River.
- 1984 Aerial photography covering a portion of the Toutle and North Fork Toutle Rivers.
- 1999 Aerial photography covering a majority of the Toutle River basin
- 2006 National Agriculture Imagery Program (NAIP) Aerial photography of the entire Toutle basin and lower Cowlitz River

Scanned copies of the 1981, 1984, and 1999 aerial photography were obtained from the Portland District and geo-rectified for use in GIS.

1.7.3 Survey Data

Survey data collected for the current study includes the following:

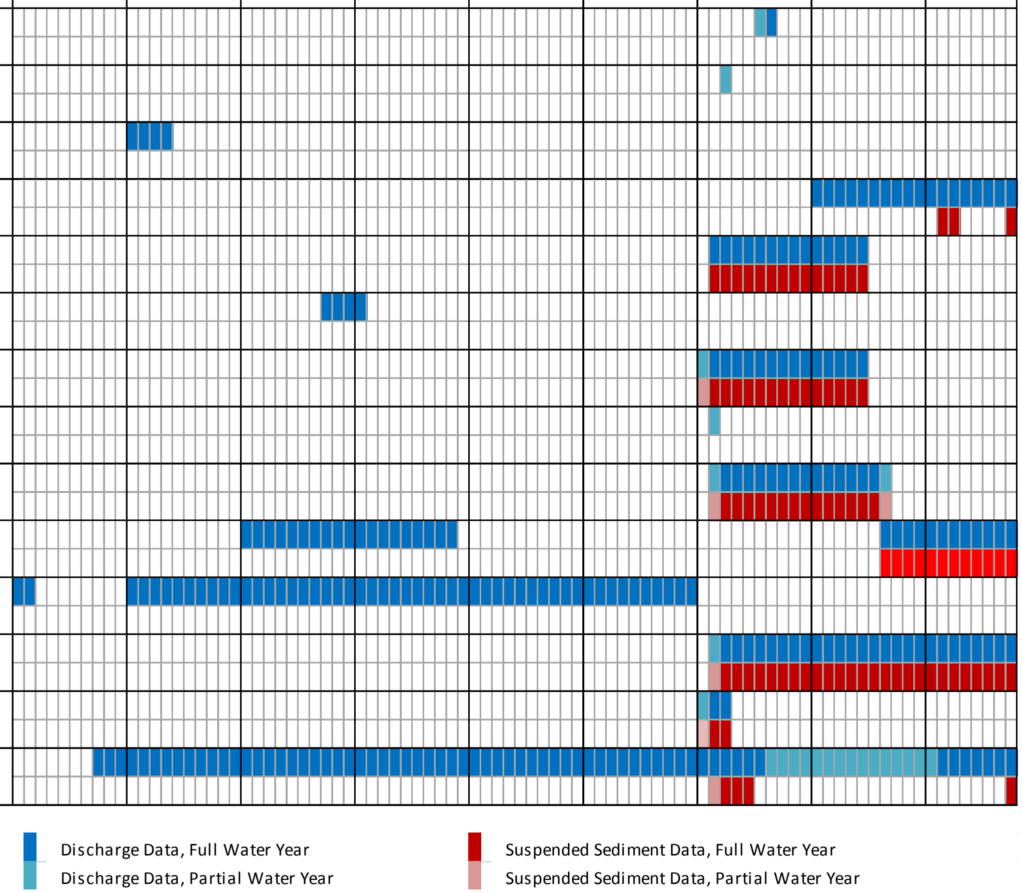
- Repeated cross section surveys provided by the USGS and collected between 1980 and 2007 throughout the basin.
- Contours digitized from 1950s and 1984 USGS quadrangle mapping covering the Mt. St. Helens debris avalanche. Digital files of the contours were obtained from the Portland District.
- Annually field surveyed cross sections located along a 5.4 mile reach of the sediment plain from years 1987 to 1998.
- Aerial photogrammetry collected through contract by the Portland District in 1987 and 1999. Coverage includes the debris avalanche and sediment deposition plain on the North Fork Toutle River above the SRS.
- LiDAR data was collected through contract by the Portland District. Some variation in the spatial extent of the data was evident; however, LiDAR was acquired in late 2004, 2006 and 2007.
- LiDAR collected in October 2003, December 2004, and October 2006 covering the sediment deposition plain on the North Fork Toutle River above the SRS
- LiDAR collected in October 2007 covering the entire North Fork Toutle River and debris avalanche, a portion of the South Fork Toutle River, and the Toutle River.
- Hydro-surveyed cross sections located on the lower 20 miles of the Cowlitz River collected in May 1990, August 1991, July 1992, Summer of 1996, August 2003, December 2006, and June of 2008.

1.7.4 USGS Gage Data

The USGS maintains an extensive network of gages in the basin. Over the period from about 1920 to present, 14 different gages have been utilized. Table 1.2 lists these gage location, and indicates the period of water and/or sediment discharge record for each gage. Figure 1.3 is a map showing gage locations. In addition to the USGS gages, several stage recording gages are maintained by NOAA on the lower Cowlitz, however, no discharge measurements are regularly made at these location and the sites are affected by the tide.

Table 1.2 USGS Gaging Stations and Periods of Record

Gage Name	USGS Gage No.	Drainage Area (mi^2)	Water Year: 1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000-2007
Coldwater Lake Canal near Spirit Lake	14240352	36.2									
North Fork Toutle River Below Maratta Creek near Spirit Lake	14240370	--									
North Fork Toutle River at St. Helens	14240500	124									
North Fork Toutle River Below SRS near Kid Valley	14240525	175									
Green River above Beaver Creek near Kid Valley	14240800	129									
Green River near Toutle	14241000	131									
North Fork Toutle River at Kid Valley	14241100	284									
South Fork Toutle River above Herrington Creek near Spotted Buck Mtn.	14241465	34.4									
South Fork Toutle River at Camp 12 near Toutle	14241490	117									
South Fork Toutle River at Toutle	14241500	120									
Toutle River near Silver Lake	14242500	474									
Toutle River at Tower Road	14242580	496									
Toutle River at Hwy. 99 Bridge near Castle Rock	14242690	511									
Cowlitz River at Castle Rock	14243000	2238									



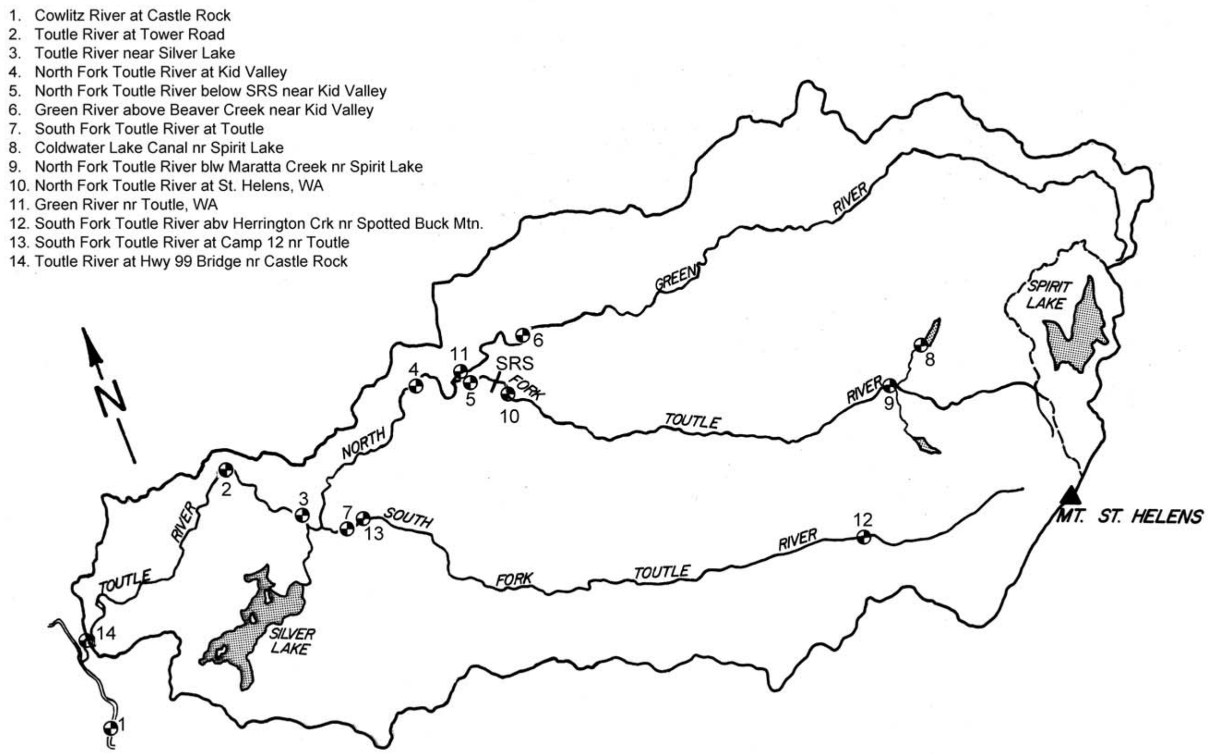


Figure 1.3 Watershed Map with USGS Gage Locations

1.7.5 Bed and Bank Material Gradations

Bed and bank material samples were compiled from previous studies and recent field work conducted by the Portland District and the Biedenharn Group. A list of previous studies providing bed material samples and a brief description is provided below.

- USACE Portland District, 1982, “Sediment Gradation Analysis Results, 1980-1988”: Summary of sediment samples taken during a period from 1980 to 1988 along the Cowlitz and Toutle Rivers.
- USACE Portland District, 1984, “Mt. St. Helens Cowlitz and Toutle Rivers Sedimentation Study 1984,” A summary of bed material gradations in the Cowlitz and Toutle Rivers is presented including statistical gradation plots (mean and standard deviation). Material gradations on the North Fork Toutle in the vicinity of the debris avalanche are of particular interest to the current study.
- USACE Portland District, 1988 to 2004, “Cowlitz River Basin Water Year Hydrologic Summary Reports” A series of reports produced every year by the Portland District that includes current year hydrology and sediment samples along the Cowlitz and Toutle Rivers.

- USACE Portland District, 1990, “Columbia River Channel Deepening: Reconnaissance Study” A series of sediment samples collected along the navigation channel of the Columbia River

- USACE Portland District, 1996, “Benthic invertebrates and sediment characteristics at 10 dredged material disposal areas (beach nourishment) in the lower Columbia River 1994-1995”

- USACE Portland District, 1997, “Channel Deepening along the Columbia River” Sediment samples collected in 1997 along the Navigation Channel of the Columbia River

- USACE Portland District, 2008, Sediment samples taken along the Navigation Channel in the Columbia River.

- USACE Portland District, 1990-2008, Records of dredging activity along the Lower Columbia River from river mile 45 to 72.

- Dinehart, R.L., 1998, “Sediment Transport at Gauging Stations near Mount ST. Helens, Washington, 1980 – 1990, Data Collection and Analysis”, USGS Professional Paper 1573: This study contains several bed material samples collected throughout the 1980s on the North Fork below the SRS, South Fork, Toutle and Cowlitz Rivers. Bed material samples presented in this report were not specifically used in the current study due to the dramatic channel response occurring during the 1980s as a result of the eruption.

- Simon, A., 1999, “Channel and Drainage-Basin Response of the Toutle River System in the Aftermath of the 1980 Eruption of Mount ST. Helens, Washington,” USGS Open-File Report 96-633: Includes an extensive set of bed material samples for the North Fork downstream of the SRS, the South Fork, and the Toutle River at locations coinciding with the USGS repeat cross sections.

Bed material data available on the Cowlitz River includes samples collected by the Portland District in 1992, 2000, 2005, and 2007. Additional bed material samples were collected on the Cowlitz River by the Biedenharn Group in 2007. Bed material samples were collected by the Portland District in 2005 on the Cowlitz River and in 2007 samples were collected on the North Toutle upstream of the SRS. Bed material samples were collected at various locations in the Toutle Watershed in December 2008 by the Portland District and the Biedenharn Group.

2.0 HYDROLOGIC AND HYDRAULIC ANALYSES

In this section, the hydrology of the area was briefly analyzed through a review of the record of maximum flow within the time period since eruption of Mt St Helens. Equally important are the records and analysis of responses of the relationship between river stage and discharge for the Toutle and Cowlitz Rivers within the period since the eruption. This analysis is presented as specific gage relationships. Although a sediment routing model is beyond the scope of this report, relationships are presented that compare stream power for the streams under review, and the relationship between hydraulic parameters on the streams to determine the distribution of sediment particle sizes that are moving in the system. The sediment budget methodology will establish the total sediment loads and applicable size fractions that move through the system, but sediment routing tools will be required if documentation of specific sediment sink areas along the streams in the system is needed.

2.1 Hydrology

Using the USGS gages, a graph of total annual discharge for two sites was developed. The greatest peak discharge for the Cowlitz River at Castle Rock and for the Toutle River at Tower Road was in 1996. Since 1996, the greatest discharge occurred in water year 2007. The total annual discharges for seven gages are compared in Figure 2.2.

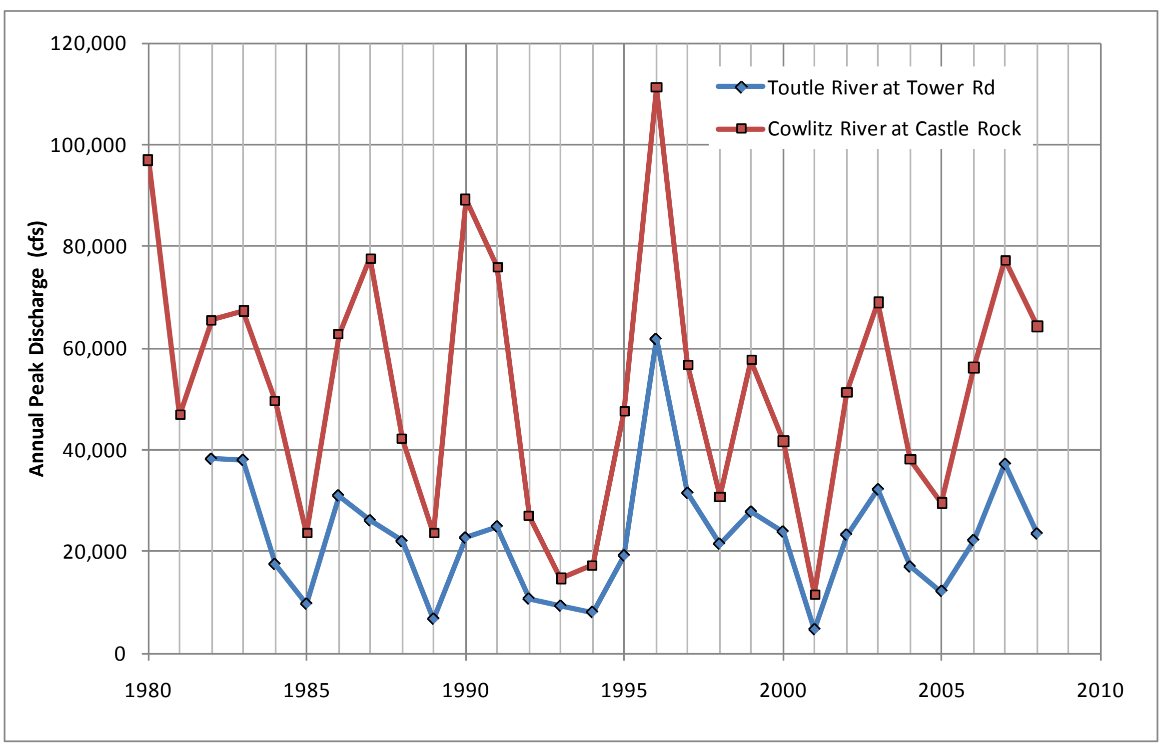


Figure 2.1 Annual peak discharges for the Toutle River at Tower Road and Cowlitz River at Castle Rock

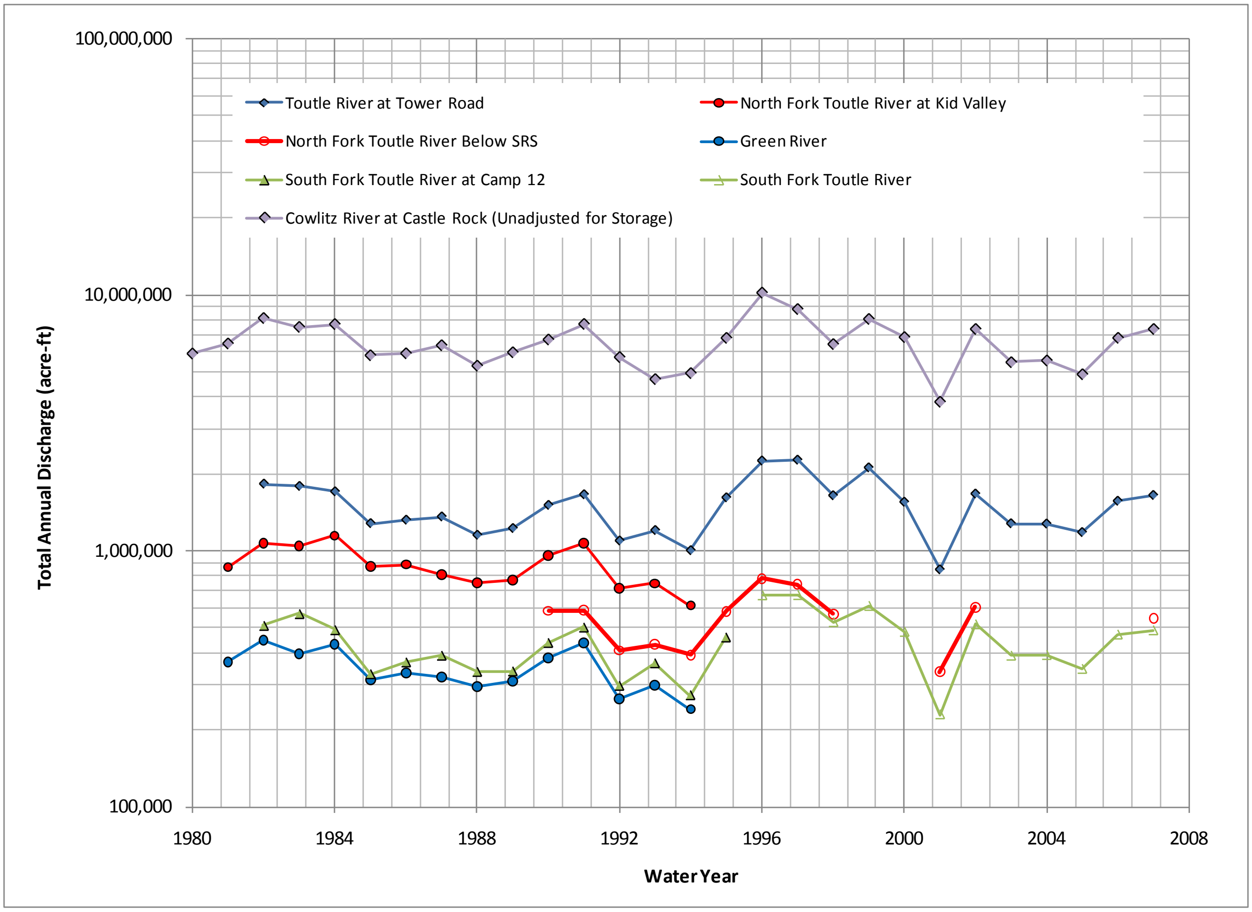


Figure 2.2 Total annual discharge for 7 USGS gage sites

2.2 Specific Gage Analysis

The specific gage record is a graph of stage for a specific discharge at a particular gaging location plotted against time. A channel is considered to be in dynamic equilibrium if the specific gage record shows no consistent increasing or decreasing trend over time, while an increasing or decreasing trend is indicative of an aggradational or degradational condition, respectively. Specific gage records were developed from the measured discharge data for the Toutle River at Tower Road, and the Cowlitz River at Castle Rock.

Figure 2.3 shows the specific gage record for the Toutle River at Tower Road. The specific gage record was developed for four different discharges (500 cfs, 1,000 cfs, 5,000 cfs, and 10,000 cfs). The specific gage record covers the period from March 1981 to January 2009. Therefore, there are no pre-eruption data at this gage. Examination of Figure 2.5 reveals several interesting trends. There is considerable variability in the stage trends for the first few years following the eruption. However, the peak stages appear to have occurred in late 1982 or early 1983. Following this period, there is a steady decrease in stage for all discharges, which reflects the continuing removal of sediment from the channel system.

This rapid decreasing trend continues through the late 1980s to early 1990s, after which the stages are fairly stable with perhaps a very slight downward trend. This data seems to suggest that most of the sediment accumulation in the Toutle following the eruption had been removed within about 10 years. These trends are supportive of the sediment decay trend suggested by Major (2004). It is also significant that there are no obvious changes in the stage trends associated with the construction and filling of the SRS. For instance, during the post 1998 period when spillway flows were supplying significantly more sediment to the downstream channel system, the specific gage trends remain stable. This suggests that most of the sediment coming out of the SRS is moving through the system and is not depositing in significant enough quantities to affect the stages at Tower Road.

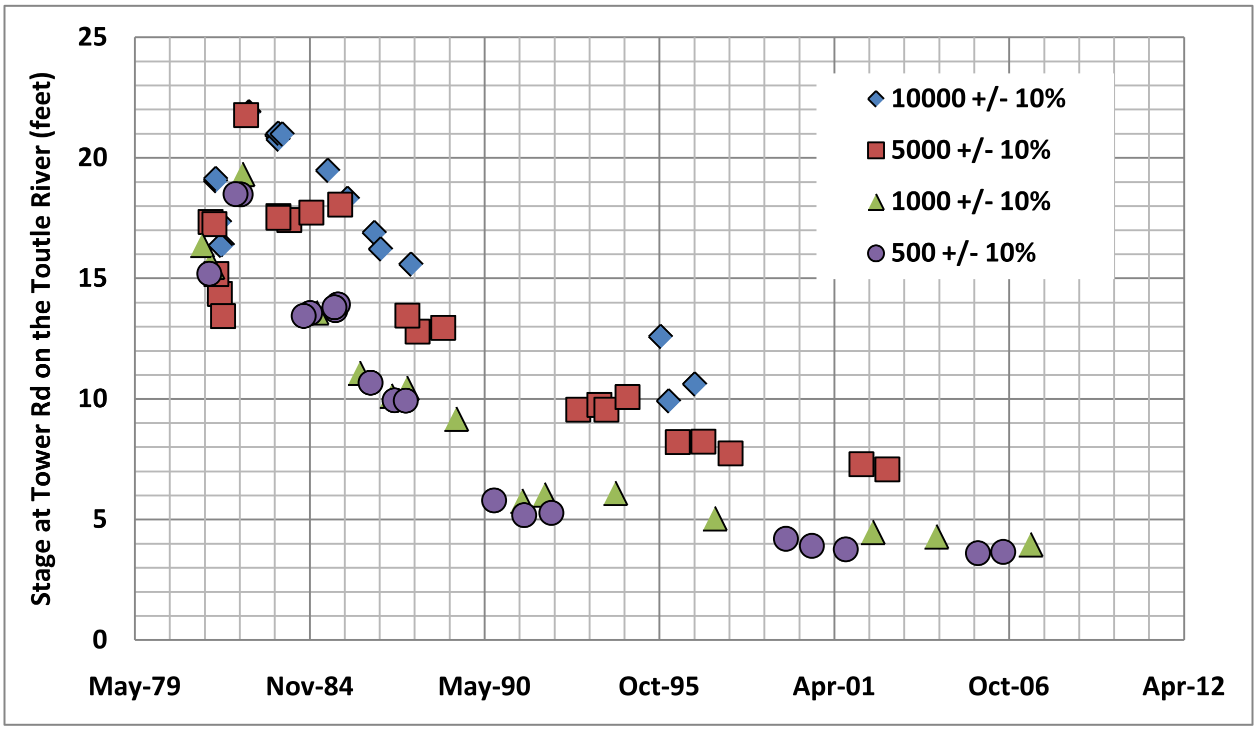


Figure 2.3 Specific gage for the Toutle River at Tower Road, 1980 – 2008

The specific gage record for the period 1974 to 2009 for the Cowlitz River at Castle Rock is shown in Figure 2.4. The discharges used in the development of this specific gage record were 8,000 cfs, 13,000 cfs, 25,000 cfs, and 40,000 cfs. Figure 2.4 shows that the 1980 eruption caused stages to increase by 10 feet or more at the lower discharges. For the first few years following the eruption, the specific gage trends are extremely variable with period of both scour and fill resulting from various factors such as dredging and hydrologic events. By the late 1980s to early 1990s, the specific gage record had stabilized, and for the past 10 to 15 years there have been no significant degradational or aggradational trends observed at either the low or high flows.

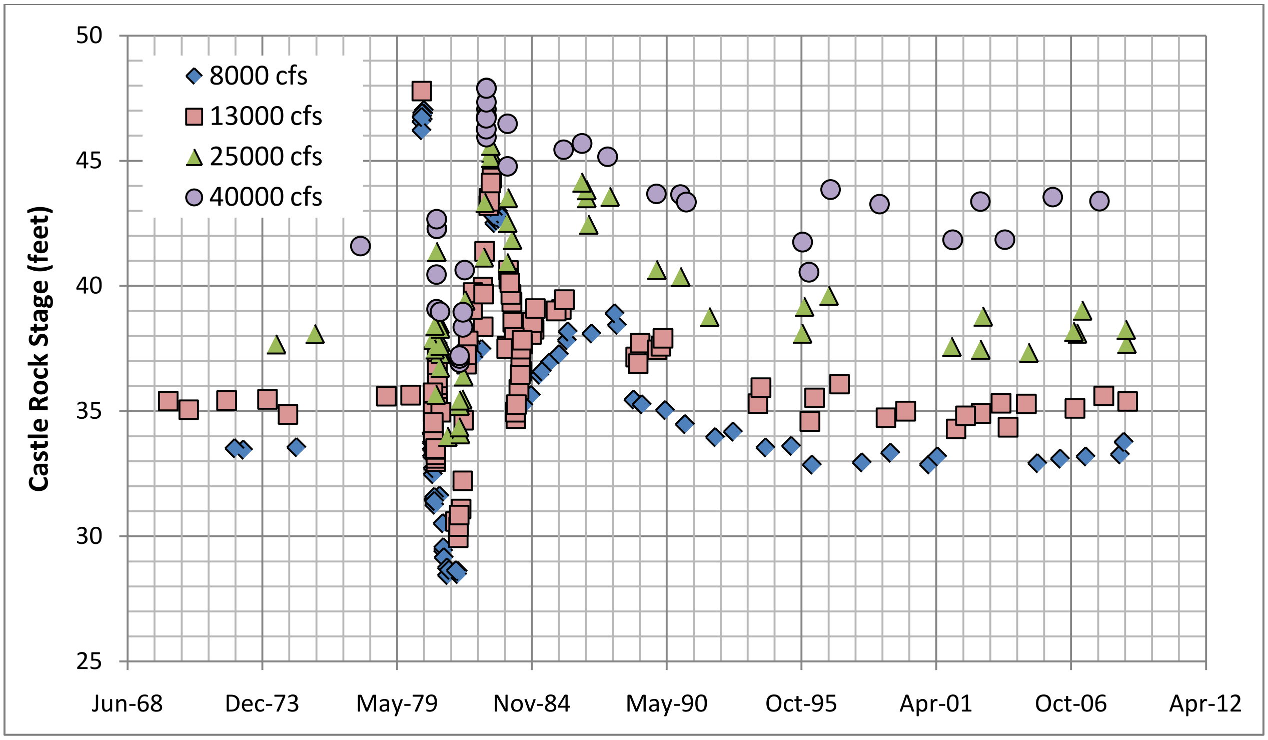


Figure 2.4 Specific Gage for the Cowlitz River at Castle Rock, 1970 - 2009

The Castle Rock specific gage reflects conditions about 17 miles upstream from the mouth of the Cowlitz. Because most of the observed sediment deposition occurs in the lower 10 miles of the river, it was felt that a specific gage record in the lower river was needed. Unfortunately, there was no gaging station on the lower river where discharge is consistently measured. An attempt was made to develop a specific gage record from the stage recording at the NOAA gage at Kelso by transposing the discharges from Castle Rock. However, there was such extreme uncertainty in the stage data and in transferring flow data from the Castle Rock gage that it was not considered being a reliable record.

2.3 Hydraulics

A one-dimensional steady flow hydraulic model of the Toutle and Cowlitz Rivers was developed from cross section geometry using 2007 LiDAR data for the North Fork, South Fork, and Toutle River. Cowlitz River cross section geometry was based on a combination of 2007 LiDAR data and 2008 bathymetry survey. Stream power and critical shear relationships were obtained from the one-dimensional hydraulics computations.

2.3.1 Stream Power Assessment

Characteristics of stream channels responding to instability has been related to specific stream power, which is computed as the product of the unit weight of water, discharge, and slope divided by the stream width, expressed as Watts per square meter (W/m^2). Brookes (1987) found that in streams destabilized by channelization (straightening) and then regained a stable sinuous pattern attained a stream power in the range of 100 W/m^2. Natural stable meandering channel may be found at stream power levels in the range of 10 to 35 W/m^2. Ranges for specific stream power as reported by Brookes (1987) can provide some insight to channel stability; however, natural riverine processes can cause specific stream power to vary significantly.

Figure 2.5 illustrates the variability of specific stream power for the Cowlitz-Toutle system. As shown, only the Cowlitz River is contained generally with the range of 10 to 100 W/m^2, whereas the Toutle River and North and South Forks range widely up to 1000 W/m^2 and drop to 10 W/m^2 at the downstream extent of each reach. The effect of the SRS on the North Fork above the SRS can be seen as the specific stream power drops below 10 W/m^2 near the SRS. Specific stream power values in the Cowlitz River below River Mile 3.0 also drop below 10 W/m^2. The lower Cowlitz River and the North Fork of the Toutle at the SRS are reaches that correspond to hydraulic conditions consistent with sedimentation.

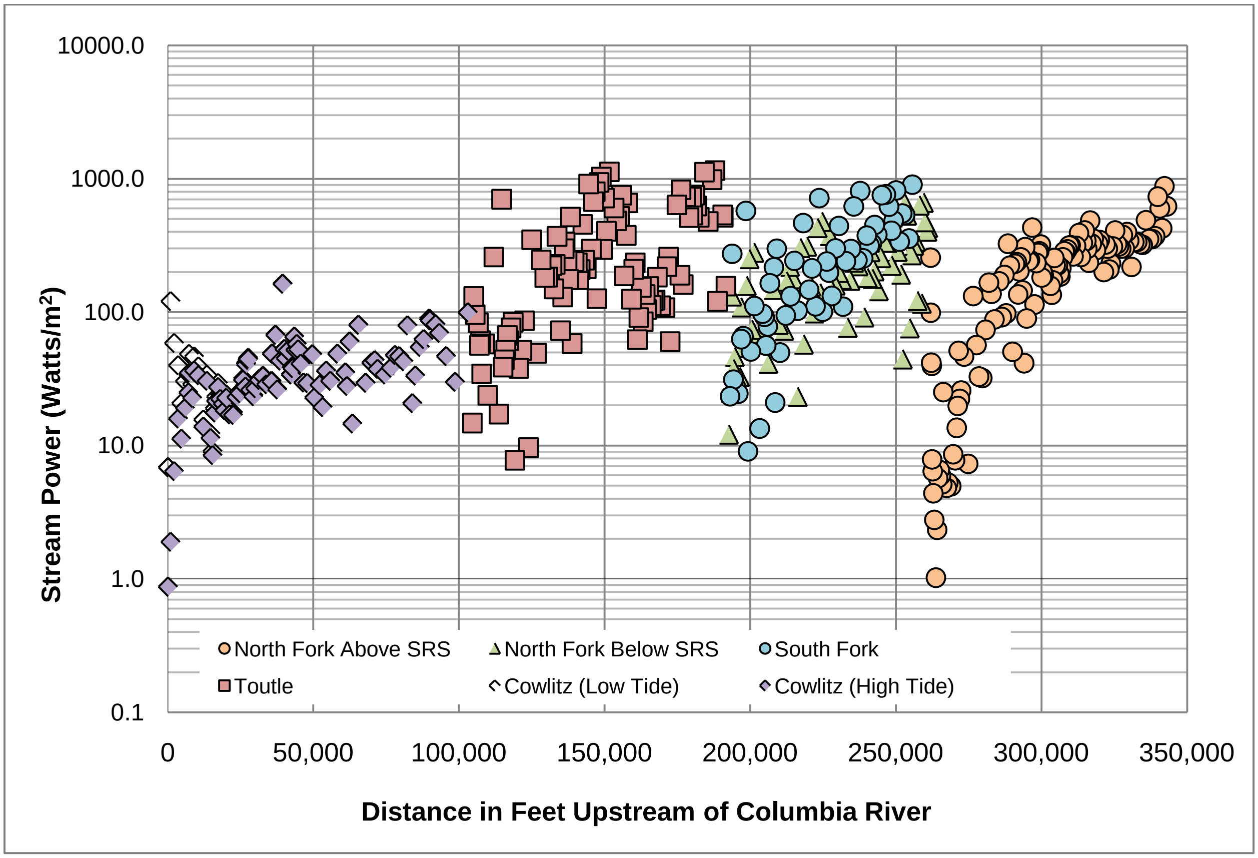


Figure 2.5 Specific stream power as a function of distance upstream of Columbia River

Figure 2.6 illustrates similar data, plotting channel slope versus bankfull discharge per unit width, with regions of specific stream power depicted. If an attainable threshold of specific stream power exists, above which sedimentation is no longer a problem, Figures 2.5 and 2.6 can be aids in managing channel morphology. Additional modeling will be required to identify possible useful thresholds.

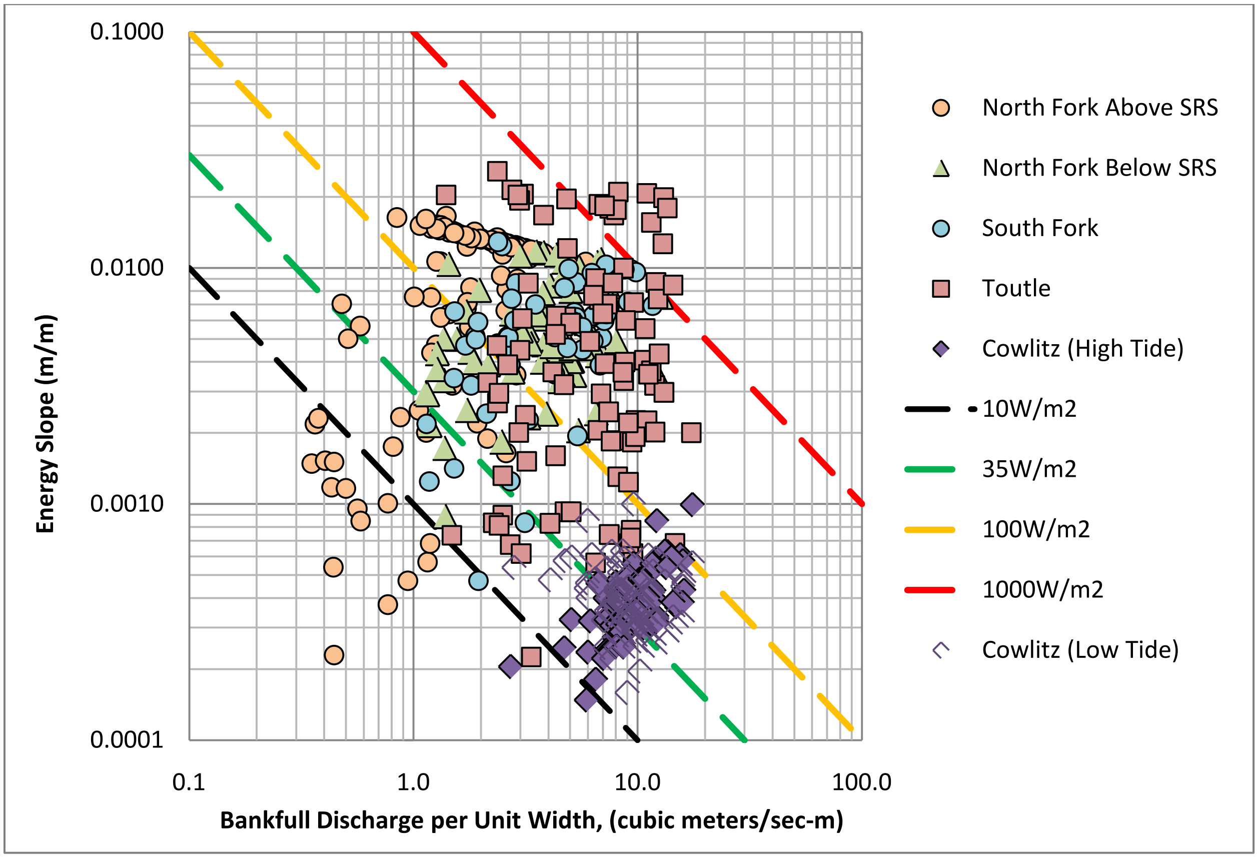


Figure 2.6 Energy slope versus bankfull discharge per unit width, with regions of specific stream power Indicated

2.3.2 Critical Shear Analysis

One of the major assumptions in conducting a sediment budget down the Toutle and Cowlitz River system is that all sizes of material can be mobilized. Equally important is the extent that various size particles are moved as bedload or suspension. In addition, the locations of any sinks and the range of particle sizes that could comprise possible sinks are important. The assumptions included in this analysis are those related to one-dimensional, uniform flow.

The Shields-Parker river sedimentation diagram (Garcia 2000, Garcia 1999), as shown in Figure 2.7, shows that for a given set of values of dimensionless shear and grain Reynolds number values, whether the particle will be in motion or not, and if the predominate motion is bed load or suspended load. As shown in the diagram, no motion occurs below the Shields curve, and no suspension occurs below the line of equal shear velocity and fall velocity.

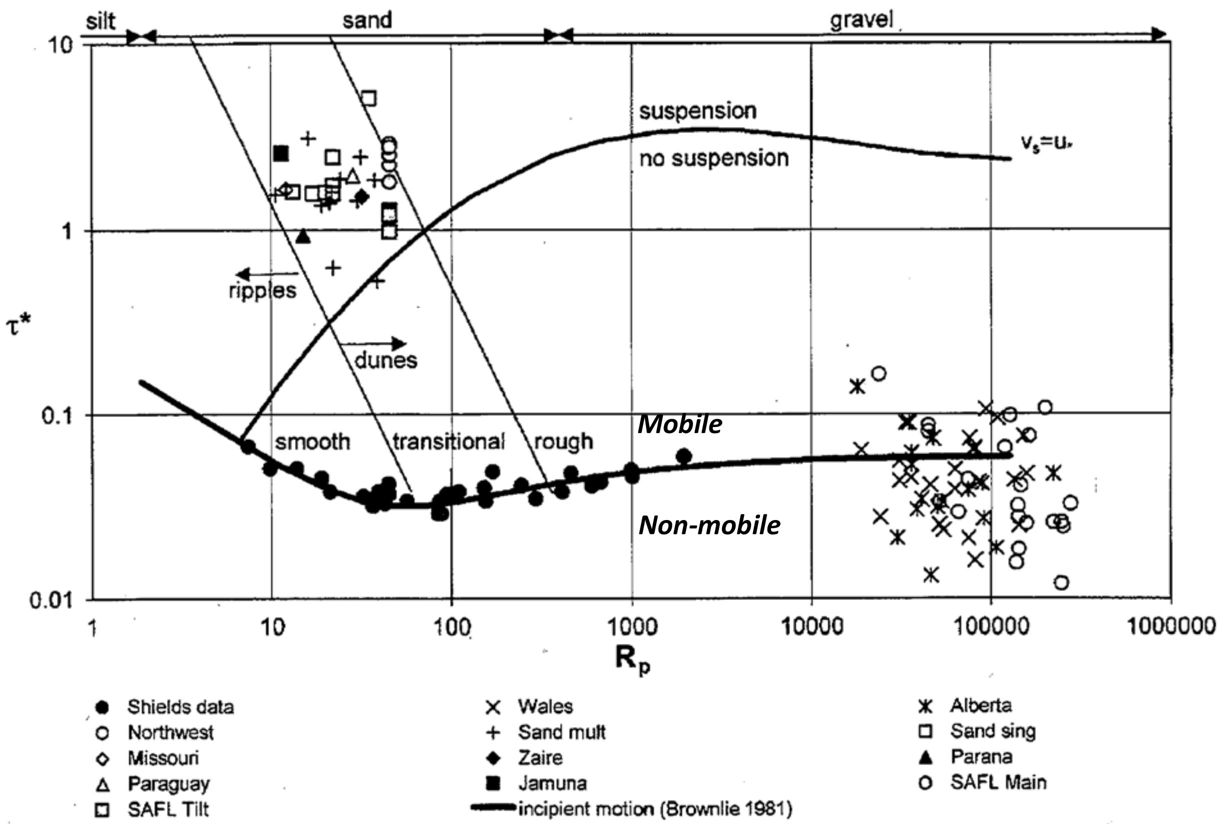


Figure 2.7 Shields-Parker river sedimentation diagram (after Garcia 2000)

Another diagram that can be used to characterize the same relationships is shown below, Figure 2.8. The x-axis is the ratio of dimensionless shear stress divided by dimensionless critical shear stress, and the y-axis is the shear velocity divided by particle fall velocity. The shear velocity was computed as the square root of the product of the hydraulic radius and slope. Dimensionless critical shear was assumed to be 0.03. These zones may be thought of in four quadrants: 1) in quadrant 1, there is no motion; 2) in quadrant 2, the particles are in motion moving as bed load; 3) in quadrant 3, the particles are in motion characterized as suspended load; and 4) in quadrant 4, the particles are not in motion. Each symbol represents a different particle size ranging from 0.0625 mm to 1 mm, with conditions taken for a series of twelve cross sections from the mouth of the Cowlitz River to river mile 2.5. The data indicates that as the particle size increases the portion of the load in suspension decreases, and the range of particle size without motion increases.

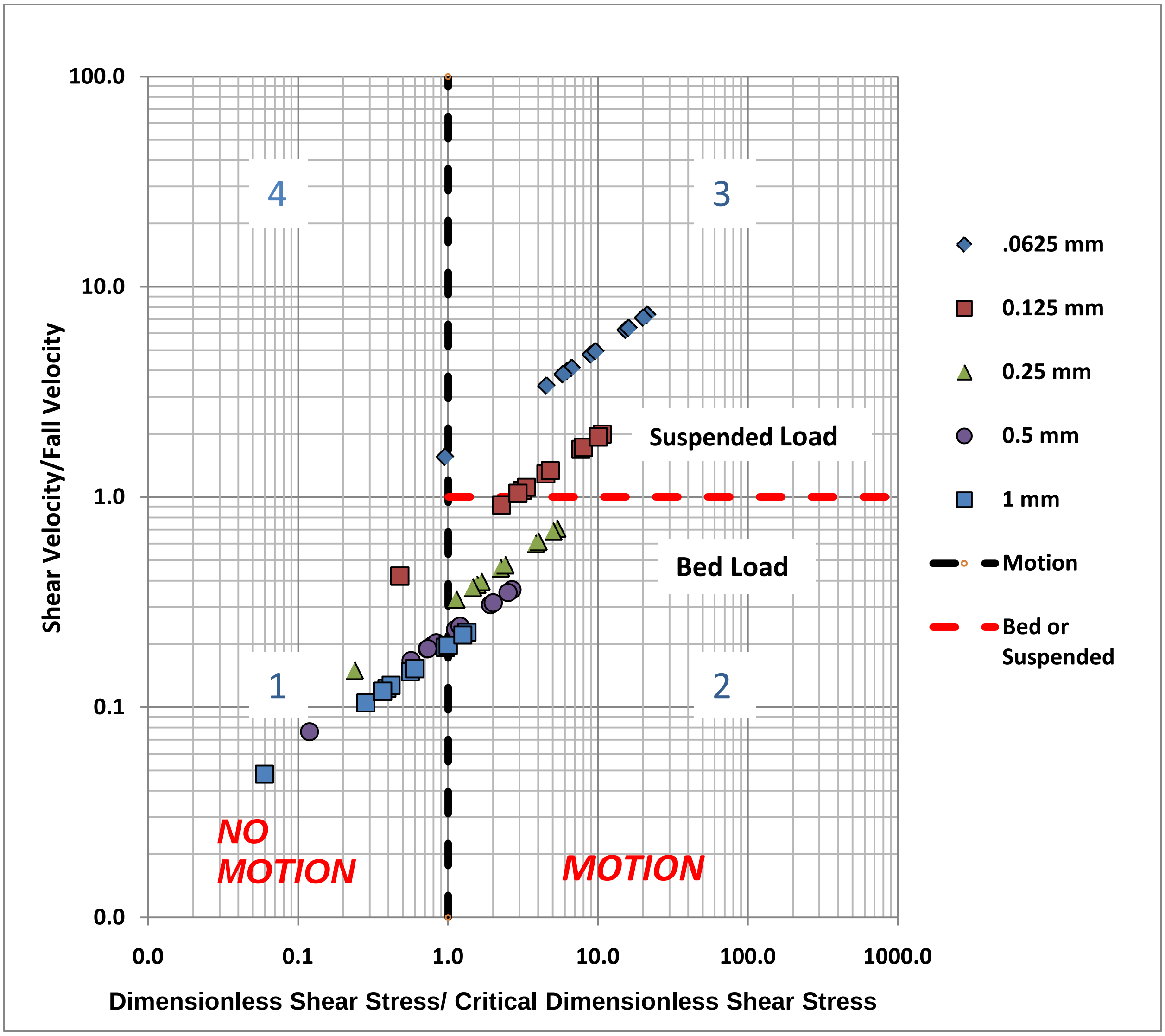


Figure 2.8 The shear stress ratio and shear velocity/fall velocity ratio combine to portray zones of motion, no motion, bed load and suspended load on the lower Cowlitz River.

Figure 2.9 is a graph of the same parameters as in Figure 2.8; however, the hydraulic characteristics utilized to develop this graph are the average hydraulic parameter values for each stream as listed. The Toutle River and tributaries exhibit similar characteristics, while the Cowlitz River exhibits lower values of shear ratio and velocity ratio. For average conditions on the Toutle River and tributaries, the sand-size particles remain in suspension and persistent sediment sinks would be expected to occur infrequently. In comparison, on the Cowlitz River, particles greater than 0.5 mm can be expected to move only in bed load and would be nearer to the no motion threshold. Particles moving as bedload are nearer the no-motion threshold and would be susceptible to sink deposition at local zones of low energy, for example, immediately upstream of the SRS or at the lower 5 to 7 miles of the Cowlitz.

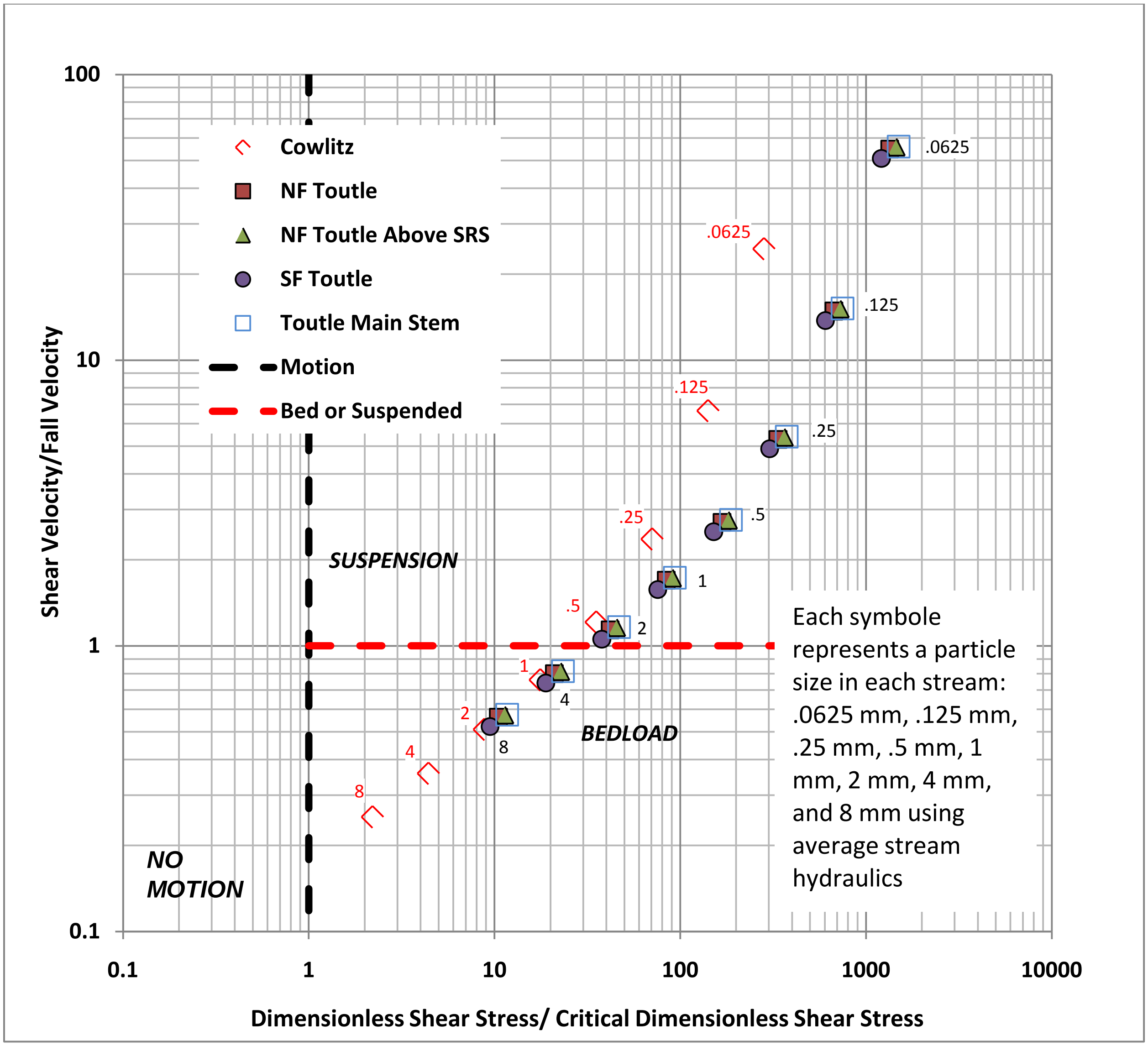


Figure 2.9 Average conditions for a range of particles are shown

3.0 SUSPENDED SEDIMENT DATA ANALYSIS

The USGS has collected a rich set of suspended sediment data that extends from prior to the Mount St. Helens eruption in the early 1980s and to the present. The following sections summarize that data, with some interpretation of findings related to the data.

3.1 Suspended Sediment Concentration

Measured sediment concentration has changed through time, as shown in Figure 3.1 for the Toutle River at Tower Road. The Tower Road gage is the most consistent suspended sediment data set for the Toutle River and tributaries that documents the evolving watershed since the 1980 eruption of Mount St. Helens. The data in Figure 3.1 indicates that sediment concentration was high during the period immediately following the eruption (1980 – 1987), and decreased during the next decade, 1988 – 1998, which may be related to the filling of the upstream SRS and to the decay of sediment availability from the 1980 eruption. Decay of sediment availability can be thought of as a combination of natural healing processes. After 1998 the sediment accumulation in the SRS had reached the crest of the spillway and an increase in suspended sediment concentration may be inferred; however, the variability of the data prevents a singular conclusion.

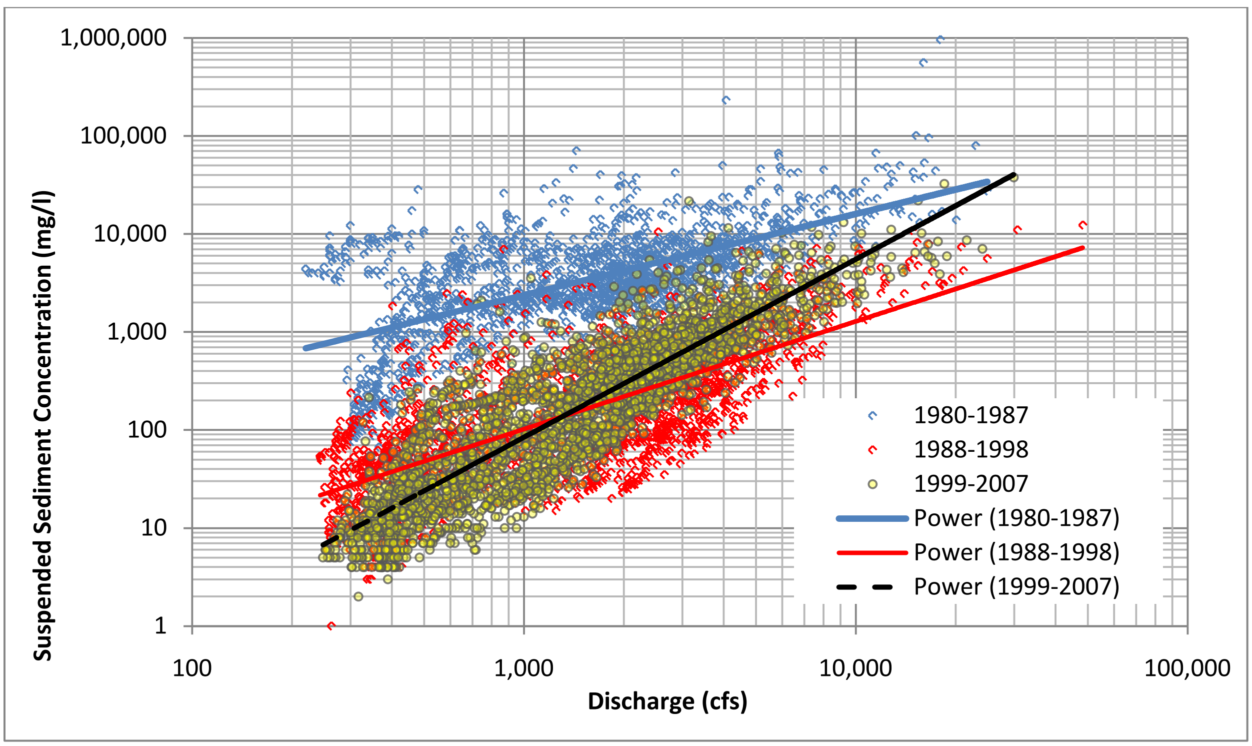


Figure 3.1 Suspended sediment concentration at the Toutle River at Tower Road gage, 1980 - 2007

3.2 Annual Suspended Sediment Data

Annual suspended sediment yield in the Cowlitz-Toutle system can be compared spatially and temporally. Table 3.1 and Figure 3.2 provide a basis for these comparisons. Table 3.1 provides the annual sediment yield in tons of sediment per year for each year that sampling occurred for six USGS gages in the Cowlitz-Toutle river system. Two years of high sediment yield, 1996 and 2007, are shown in red. Gage locations are shown in Figure 1.3.

Table 3.1 Annual Suspended Sediment

Water Year	Toutle River at Tower Road	North Fork Toutle River at Kid Valley	North Fork Toutle River Below SRS	Green River	South Fork	Cowlitz River at Castle Rock
	(tons/year)	*(tons/year)*	*(tons/year)*	*(tons/year)*	*(tons/year)*	*(tons/year)*
1980						
1981						26,942,811
1982	40,685,406	34,440,772		494,861	1,451,951	36,576,543
1983	39,738,740	29,250,990		181,228	1,616,656	33,977,610
1984	24,746,497	22,124,433		208,811	476,283	25,312,800
1985	9,373,687	9,120,850		36,141	41,502	
1986	7,630,324	7,986,256		277,111	189,388	
1987	8,769,228	6,950,704		78,804	605,993	
1988	2,200,707	974,505		76,458	424,064	
1989	773,065	372,517		16,225	218,990	
1990	2,378,125	827,494		88,301	964,046	
1991	2,609,865	1,037,696		81,713	932,002	
1992	742,732	266,622		15,226	409,389	
1993	449,278	155,425		6,960	547,632	
1994	162,478	102,998		6,160	43,675	
1995	1,520,254				522,754	
1996	6,536,196				2,774,549	
1997	3,040,196				2,004,010	
1998	1,996,635				1,385,456	
1999	5,057,821				1,224,242	
2000	3,017,381				324,901	
2001	367,097		101,813		16,664	
2002	3,704,975		2,011,237		872,200	
2003	2,384,742				155,998	
2004	1,284,376				175,018	
2005	1,309,443				220,091	
2006	2,693,096				226,727	
2007	12,565,689		7,028,662		3,555,263	13,162,998

Annual suspend sediment data for the Castle Rock gage for the period 1981 through 2007 is limited, as shown in Table 3.1. Only four coincident pairs of data are available for the Toutle River at Tower Road and for the Cowlitz River at Castle Rock. Even though the drainage area at Castle Rock gage on the Cowlitz River is much larger than the Tower Road gage on the Toutle River, the annual sediment yield between the two gages does not appear to increase. All four values of sediment yield for the Castle Rock gage are within an estimated variability (+or- 25%) for the Tower Road gage, suggesting that the increase in sediment supply from the upper Cowlitz River is insignificant. The Mossy Rock dam complex is upstream of the Toutle/Cowlitz confluence, which limits upstream sediment supply. Geo-referenced video inspection of bank instability for the Cowlitz River between the Mossy Rock dam and the Castle Rock gage indicated only minor instability. Although data is limited, we have assumed that sediment supply from the Cowlitz River upstream of the Toutle River confluence is insignificant.

Figure 3.2 graphically compares the suspended sediment yield per square mile of drainage area for each of six gages from within the Mt. Saint Helens eruption affected area with sediment yield from unaffected basins shown as black dashed lines (Major, 2000). For the pre-SRS period (1980 – 1988) the Toutle River at Tower Road decreased and by the end of the period, that gage approached the maximum sediment yield values of gages from unaffected areas within the Western Cascade Range. The Green River was not as dramatically affected by the eruption as the upper Toutle River and was not affected by the construction of the SRS. The Green River gage decreased during the period and continued decreasing until about 1994 when the gage was discontinued, with sediment yield falling below the mean values of the unaffected areas. Although at greater sediment yields, Muddy River follows similar trends as the Green and the Toutle River at Tower Road. Low sediment yield during the period of SRS filling (1988 – 1998) may be associated with relatively dry climatic conditions during the period, as well as the SRS filling for the Toutle and North Fork gages. Following 1994, the Toutle River gage at Tower Road resumed relatively high sediment concentrations reaching more than twice the maximum of the Western Cascade Range sediment yield values during the period ending in 2007. The data depicted in Figure 3.2 suggests that sediment yields fell rapidly following the eruption and have been affected by SRS construction and by climatic variation during the early 1990s to the present.

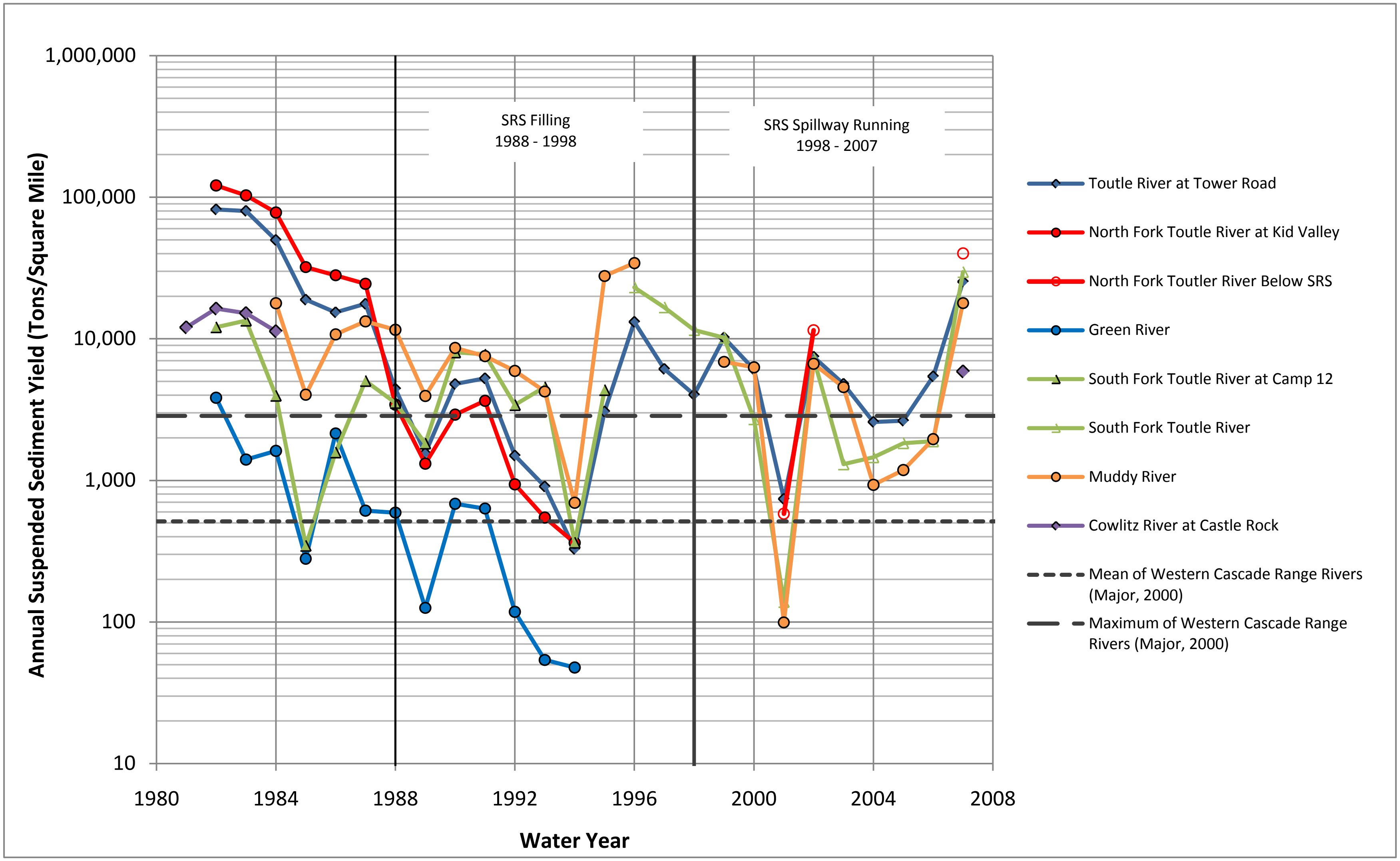


Figure 3.2 Annual sediment yield per square mile is shown for six gages within the affected watershed and are compared with non-affected watershed sediment yield.

The average annual mean water discharge, the average annual tons of suspended sediment per square mile of drainage area and the annual tons of suspended sediment per acre-feet of water discharge for three time periods based on the construction and subsequent filling of the SRS are given in Table 3.2. The effect of the SRS is clearly shown for the sediment yield in the 1999-2007 period, which is 1.8 times the prior period of SRS filling.

Table 3.2 Average Annual Water and Sediment Yield Statistics for Three Time Periods

Time Period	Toutle at Tower Road			
	Annual Water		Annual Suspended Sediment	
	mean cfs	acre-ft	tons/mi^2	tons/acre-ft
1982 - 1987	2,131	1,543,666	44,000	13.1
1988 - 1998	2,082	1,508,160	4,107	1.2
1999 - 2007	2,010	1,456,501	7,255	2.3

3.3 Suspended Sediment Gradations

Gradation distributions for suspended sediment samples were obtained from the USGS and were available only sporadically throughout the Cowlitz-Toutle watershed. Because of limited availability, gradation data from suspended sediment samples was used primarily as a comparison to the LiDAR-based, sediment budget results. However, along the Green River and the South Fork, where no other sediment gradation information exists, the suspended gradation data was used as a primary tool to distribute the respective sediment load.

3.3.1 North Fork Toutle River

Suspended sediment gradation data on the North Fork below the SRS included 38 samples collected between 2001 and 2009 and were only used for comparison to the sediment budget results. Table 3.3 provides the minimum, average, and maximum percent finer of the suspended sediment gradation data. All gradation samples are presented graphically in Figure 3.3. Trends lines are shown in Figure 3.3; however, due to the extreme variability in the data, the trends are statistically insignificant.

Table 3.3 Summary of North Fork Toutle Below SRS Suspended Sediment Gradations, 2001 - 2009

Statistic	0.0625mm	0.125mm	0.25mm	0.5mm	1mm	2mm
Min % Finer	23.7	55.1	81.2	96.9	98.8	99.5
Max % Finer	98.3	99.7	100.0	100.0	100.0	100.0
Ave % Finer	64.8	83.5	97.3	99.7	99.9	100.0
St dev	21.0	13.5	4.1	0.6	0.2	0.1
# of Samples	45	38	38	38	38	38

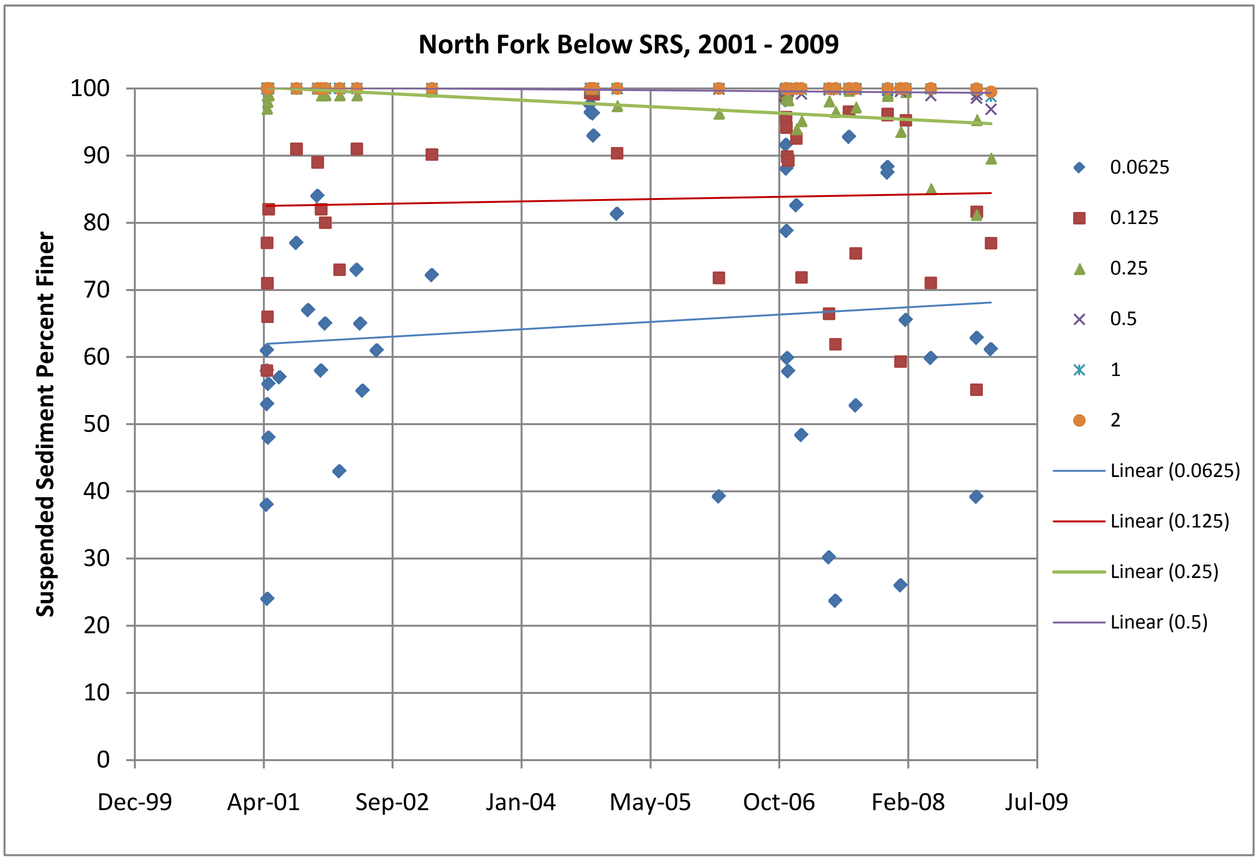


Figure 3.3 Suspended Sediment Gradations through time for the North Fork of the Toutle River below the SRS, 2001 - 200

3.3.2 Green River

Total sediment contributions from the Green River were estimated using gage records from the USGS. Gradation distributions for the suspended sediment along the Green River were used to distribute the total sediment load estimated from the gage data. Approximately 76 gradation samples were taken on the Green between 1981 and 1987. The average gradation was applied to the total annual suspended sediment to calculate a sediment load by grain size for input into the sediment budget. The minimum, average, and maximum of all Green River suspended sediment gradations samples is provided in Table 3.4. Green River suspended sediment gradations are plotted versus time in Figure 3.4.

Table 3.4 Summary of Green River Suspended Sediment Gradation Data, 1981 - 1987

Statistic	0.0625mm	0.125mm	0.25mm	0.5mm	1mm	2mm
Min % Finer	10.0	26.0	34.0	72.0	91.0	95.0
Max % Finer	99.0	100	100	100	100	100
Ave % Finer	43.8	57.4	75.1	90.6	97.8	98.9
St dev	19.8	16.9	14.3	6.8	2.4	1.3
# of Samples	164	79	78	73	63	35

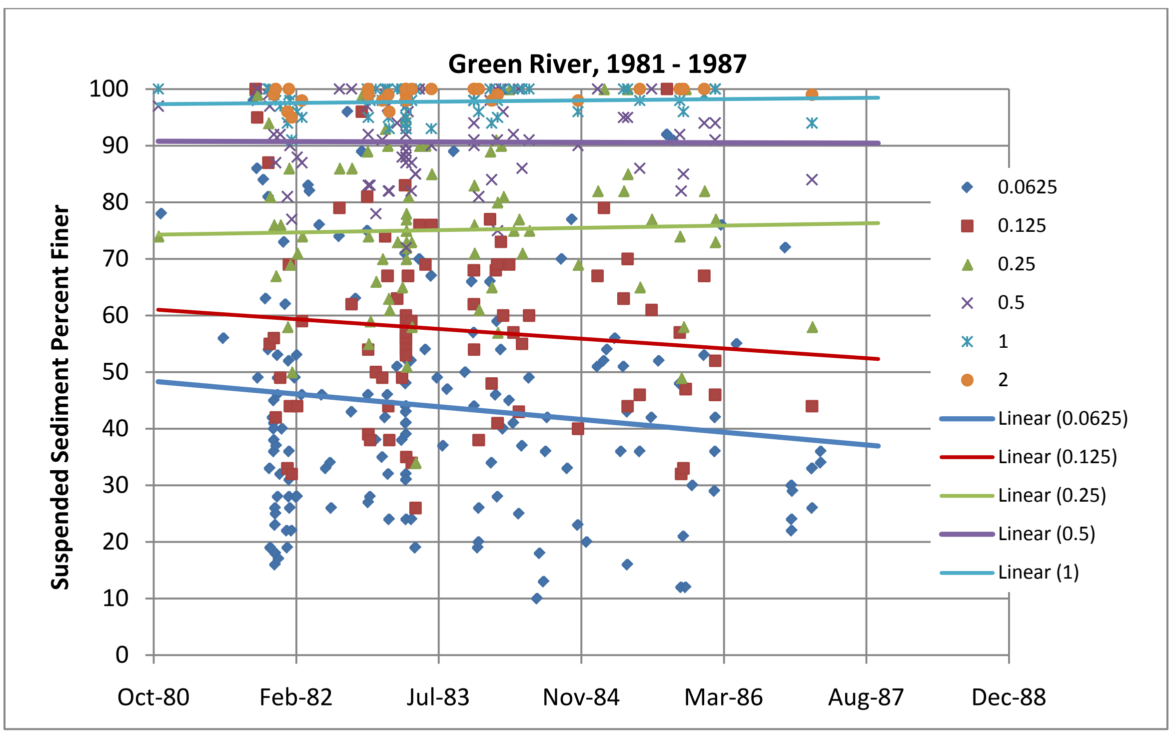


Figure 3.4 Suspended sediment gradation versus time for the Green River, 1981-1987

3.3.3 South Fork

At present, data has not been collected to directly quantify upstream sediment sources contributing to the South Fork Toutle River. Therefore, the annual suspended sediment data at the South Fork gage is utilized to estimate the sediment contribution to the Toutle River. The South Fork gradation data obtained from the USGS included 151 samples taken between 1980 and 1987 and 39 samples collected between 1998 and 2009. A data gap exists between 1987 and 1998. Average gradation values were computed for both time periods and are listed in Table 3.5. Graphs of gradation samples over both time periods are also presented in Figures 3.5 and 3.6. The estimate of the total sediment load was distributed by grain size using the available gradation data for the South Fork.

Table 3.5 Summary of Suspended Sediment Gradations for the South Fork Toutle River

Time Period	Statistic	0.0625mm	0.125mm	0.25mm	0.5mm	1mm	2mm
1980 – 1987	Min % Finer	1.0	1.0	3.0	29.0	91.0	99.0
	Max % Finer	100.0	100.0	100.0	100.0	100.0	100.0
	Ave % Finer	40.7	51.6	74.0	94.4	99.5	99.9
	St dev	24.7	26.4	22.8	10.6	1.3	0.2
	# of Samples	310	151	150	137	99	31
1999 – 2007	Min % Finer	1.0	3.9	21.7	66.8	95.8	98.6
	Max % Finer	98.3	99.4	99.8	100.0	100.0	100.0
	Ave % Finer	26.9	44.5	73.5	94.8	99.4	99.9
	St dev	19.9	23.7	20.2	7.3	1.0	0.3
	# of Samples	44	41	41	41	41	41

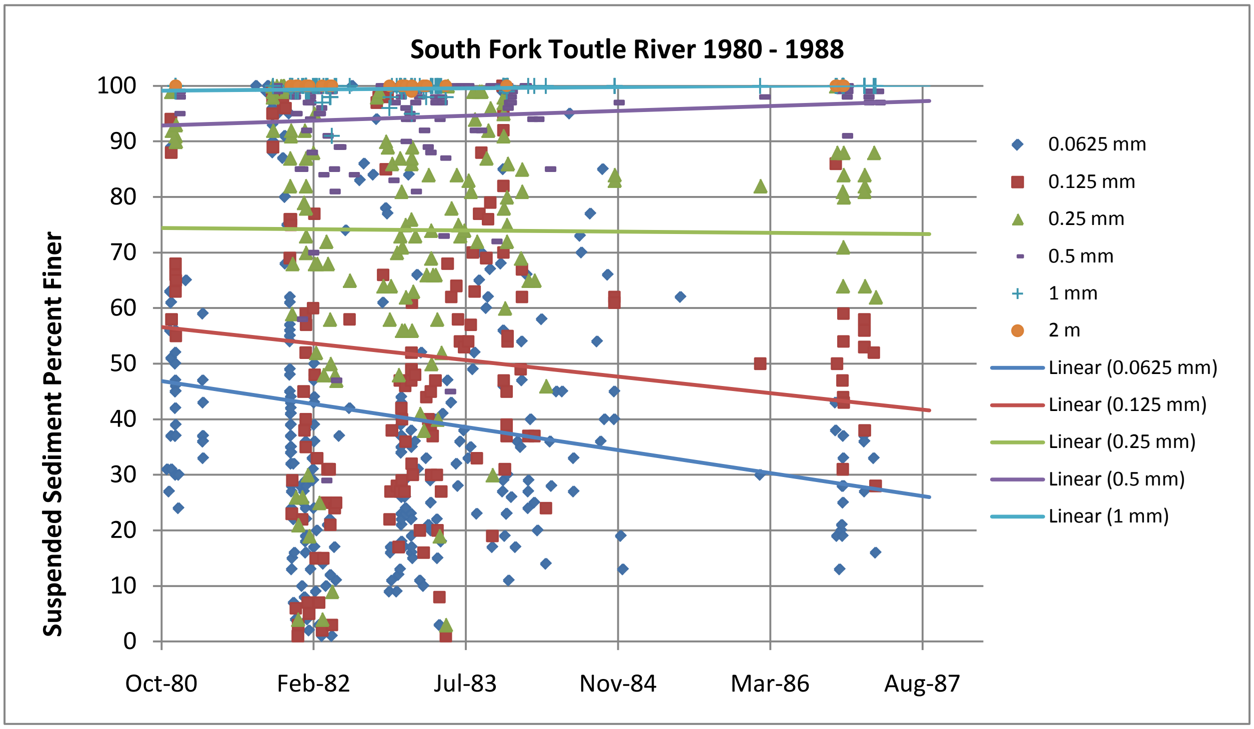


Figure 3.5 Suspended sediment gradations versus time for the South Fork Toutle gage, 1980-1988

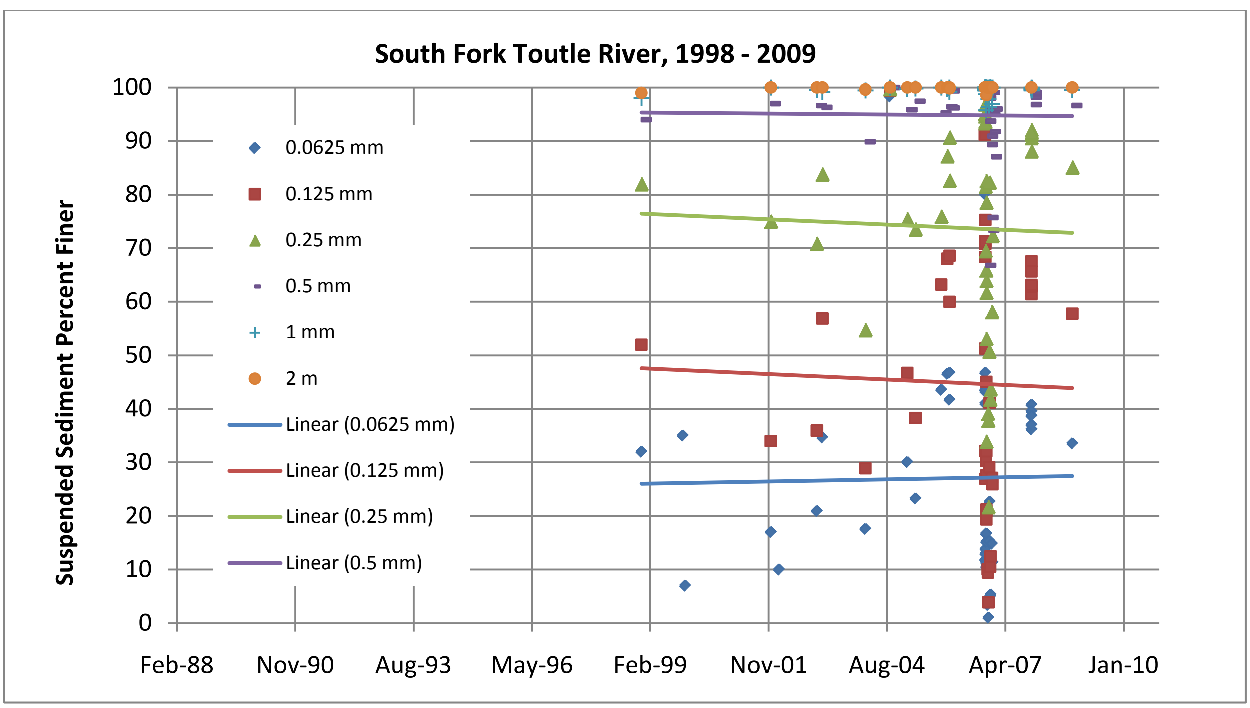


Figure 3.6 Suspended sediment gradations versus time for the South Fork gage, 1998-2009

3.3.4 Toutle River at Tower Road

The most extensive set of suspended sediment gradations exist for the Toutle River at Tower Road gage. The sample gradations were broken into three time periods for analysis: (1) 1981 – 1987 after the eruption and prior to the construction of the SRS; (2) 1988 – 1998 when the SRS was in Phase I of operation; and (3) from 1999 – 2007 during the SRS Phase II operation after the final tier of outlet pipes were closed and all runoff was diverted through the spillway. The number of gradation samples collected has decreased over the three time periods, as presented in Table 3.6. Average suspended sediment gradations for all three time periods are presented in Table 3.6 and graphical plots of the gradation samples over time are provided in Figures 3.7 through 3.9.

Table 3.6 Summary of Suspended Sediment Gradation Samples for the Toutle River at Tower Road Gage

Time Period	Statistic	0.0625mm	0.125mm	0.25mm	0.5mm	1mm	2mm
1981 - 1987	Min % Finer	4.0	17.0	37.0	64.0	81.0	92.0
	Max % Finer	92.0	97.0	99.0	100.0	100.0	100.0
	Ave % Finer	44.9	59.3	82.0	95.6	99.2	99.8
	St dev	15.1	14.7	11.3	5.1	2.0	1.1
	# of Samples	801	263	263	263	240	105
1988 – 1998	Min % Finer	21.0	17.0	54.0	88.0	96.0	98.0
	Max % Finer	89.0	95.0	97.0	100.0	100.0	100.0
	Ave % Finer	45.1	57.1	80.1	96.5	99.8	99.8
	St dev	17.5	17.8	11.4	3.2	0.7	0.7
	# of Samples	54	54	54	54	52	8
1999 – 2007	Min % Finer	13.9	32.6	55.0	83.1	98.5	98.8
	Max % Finer	100.0	100.0	100.0	100.0	100.0	100.0
	Ave % Finer	60.4	76.1	91.0	97.9	99.7	99.9
	St dev	21.7	16.3	9.3	3.3	0.4	0.2
	# of Samples	49	40	40	40	40	40

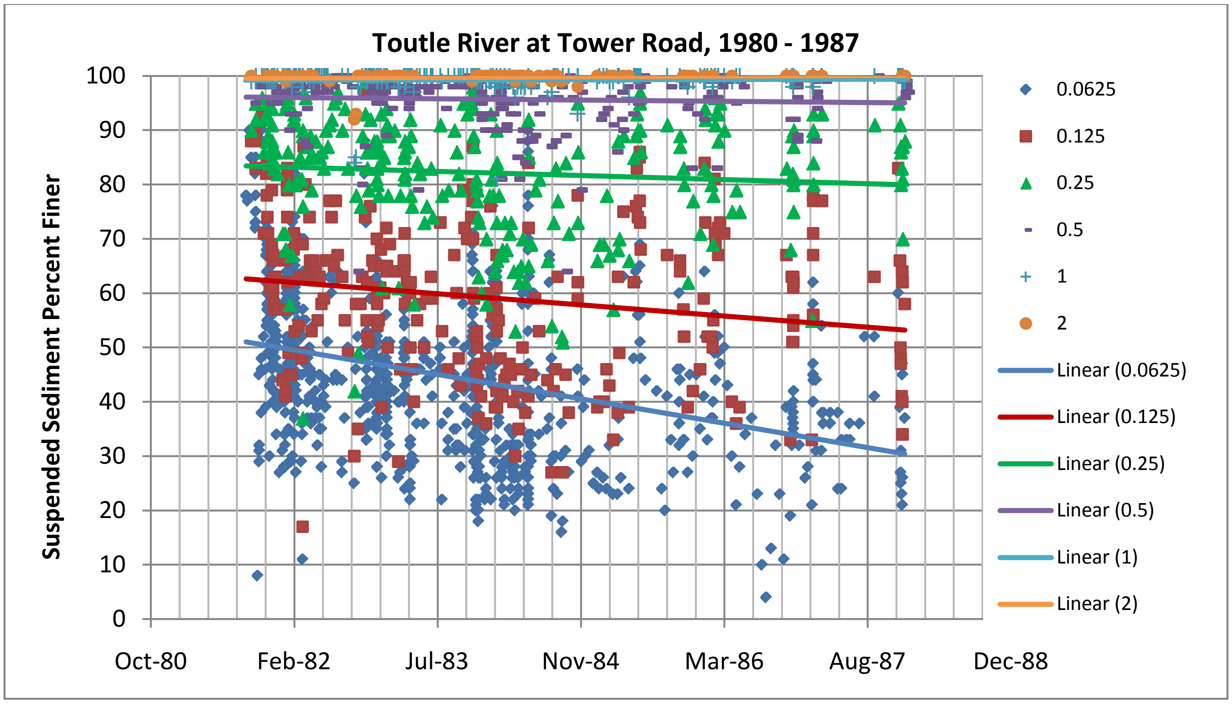


Figure 3.7 Suspended sediment gradations versus time for the Toutle River at Tower Road gage, 1980 – 1987 (pre-SRS construction)

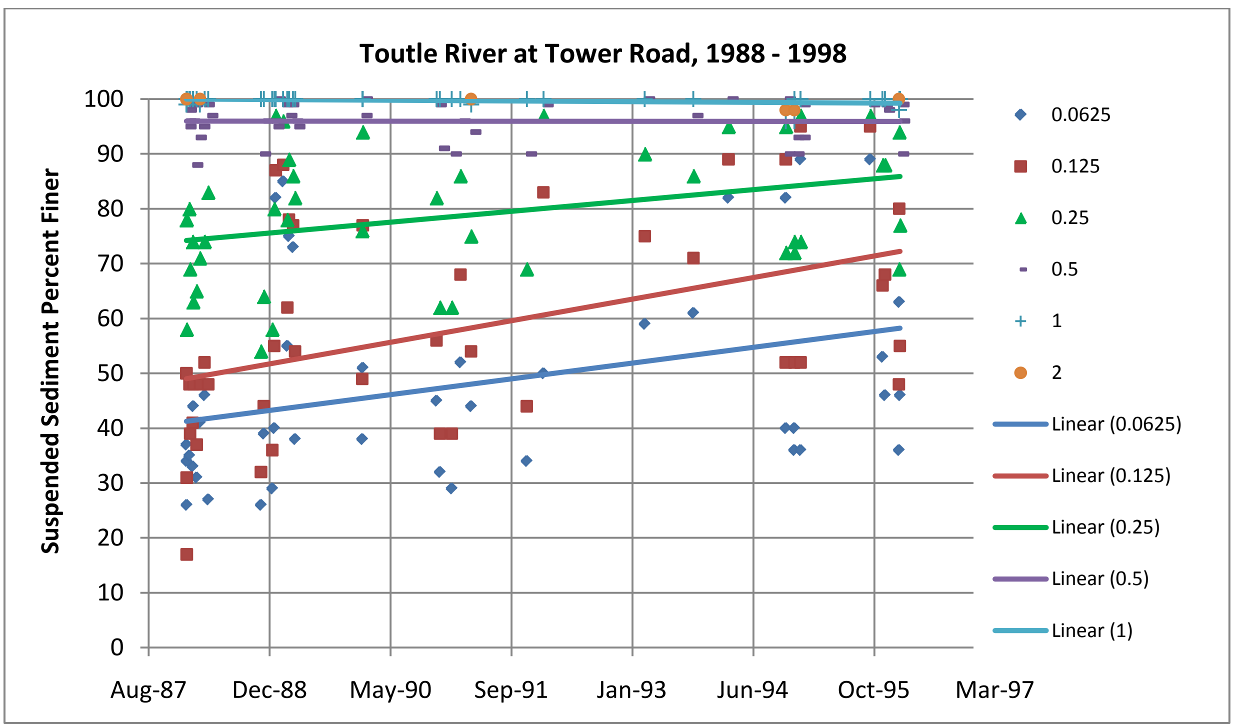


Figure 3.8 Suspended sediment gradations versus time for the Toutle River at Tower Road gage, 1988-1998 (SRS Phase 1 Operations)

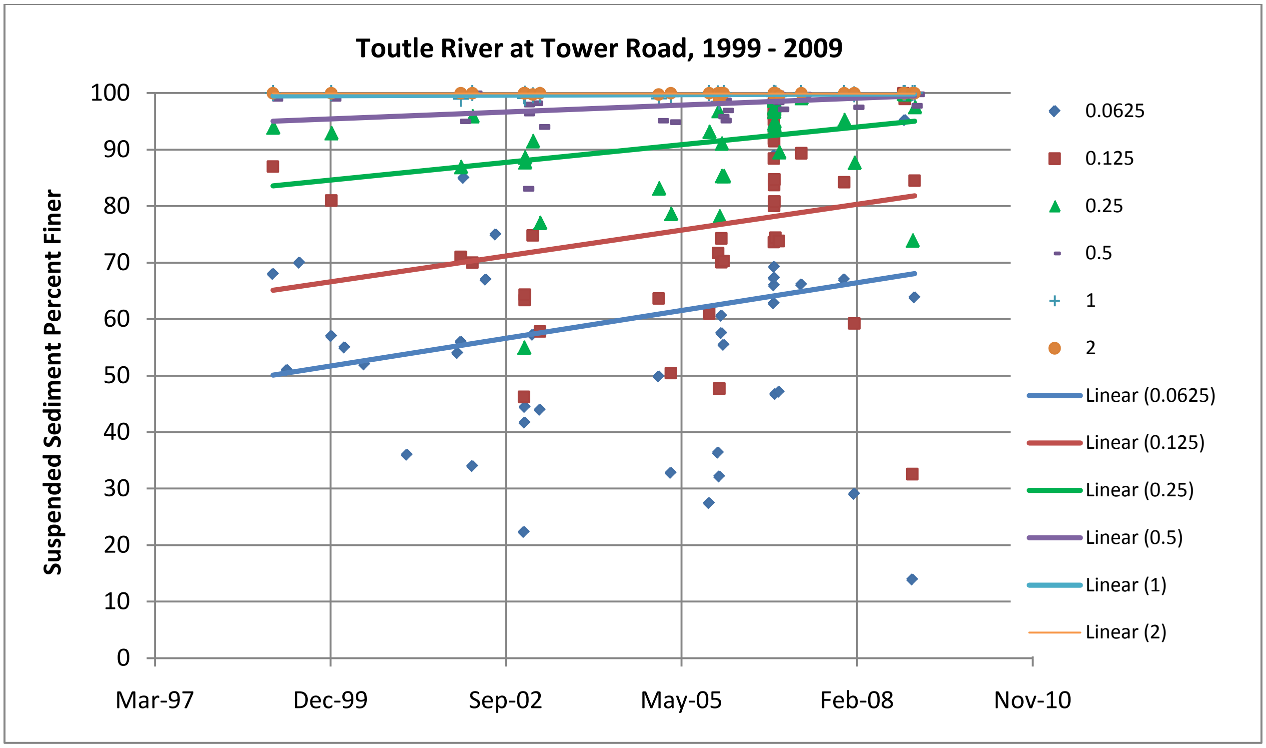


Figure 3.9 Suspended sediment gradations versus time for the Toutle River at Tower Road gage, 1999-2009 (SRS Phase II Operations)

3.3.5 Cowlitz at Castle Rock

There is limited suspended sediment data for the Cowlitz River at Castle Rock. Several samples were collected between 1980 and 1984 and a few collected from 2004 through 2007. The average suspended sediment gradations for both time periods are shown in Table 3.7. These data are also shown graphically in Figures 3.10 and 3.11.

Table 3.7 Summary of Suspended Sediment Gradations for the Cowlitz at Castle Rock Gage

Time Period	Statistic	0.0625mm	0.125mm	0.25mm	0.5mm	1mm	2mm
1980 - 1984	Min % Finer	1.0	2.0	5.0	40.0	90.0	97.0
	Max % Finer	99.0	100.0	100.0	100.0	100.0	100.0
	Ave % Finer	56.4	62.9	81.3	93.9	99.1	99.8
	St dev	24.2	23.9	20.0	10.3	1.8	0.7
	# of Samples	571	222	219	198	160	42
2004 - 2007	Min % Finer	20.0	33.7	55.7	78.8	95.9	99.8
	Max % Finer	85.1	97.9	99.8	100.0	100.0	100.0
	Ave % Finer	59.1	80.6	95.1	98.4	99.7	100.0
	St dev	13.4	13.2	9.7	4.5	0.9	0.0
	# of Samples	21	21	21	21	21	21

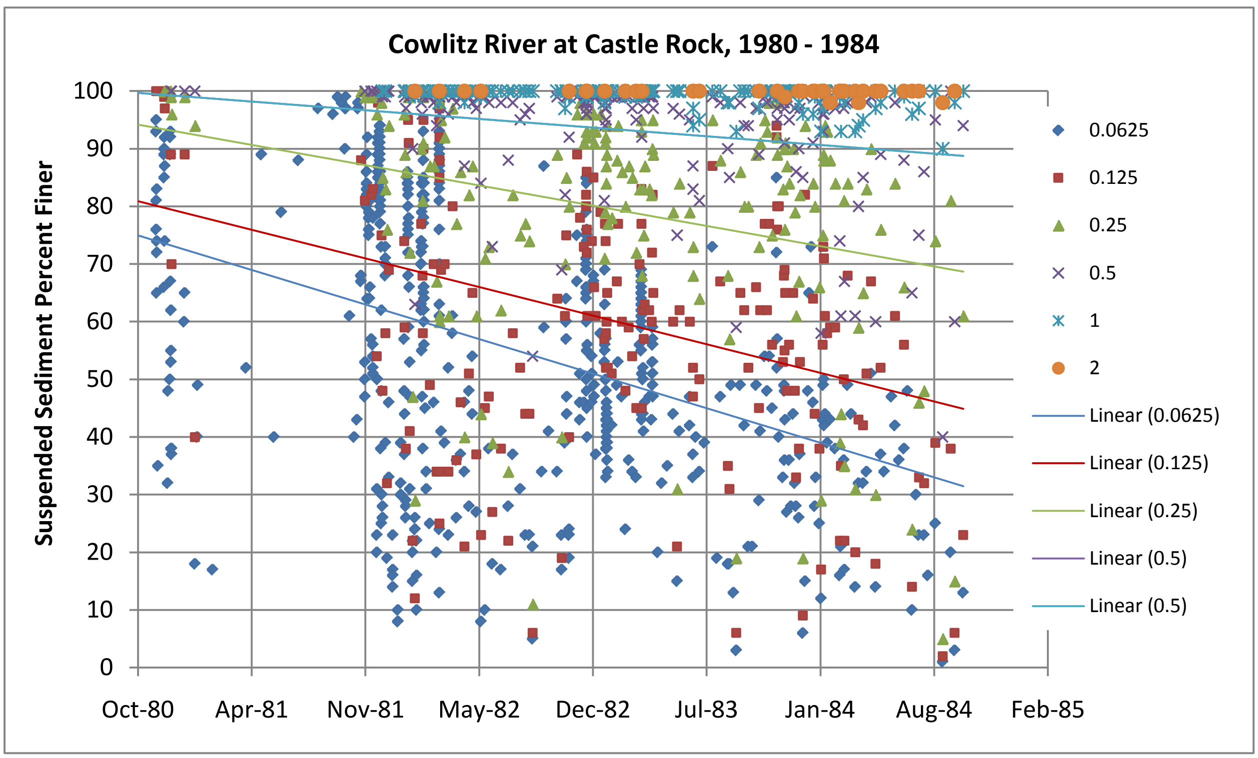


Figure 3.10 Suspended sediment gradations versus time for the Cowlitz River at Castle Rock, 1980-1984

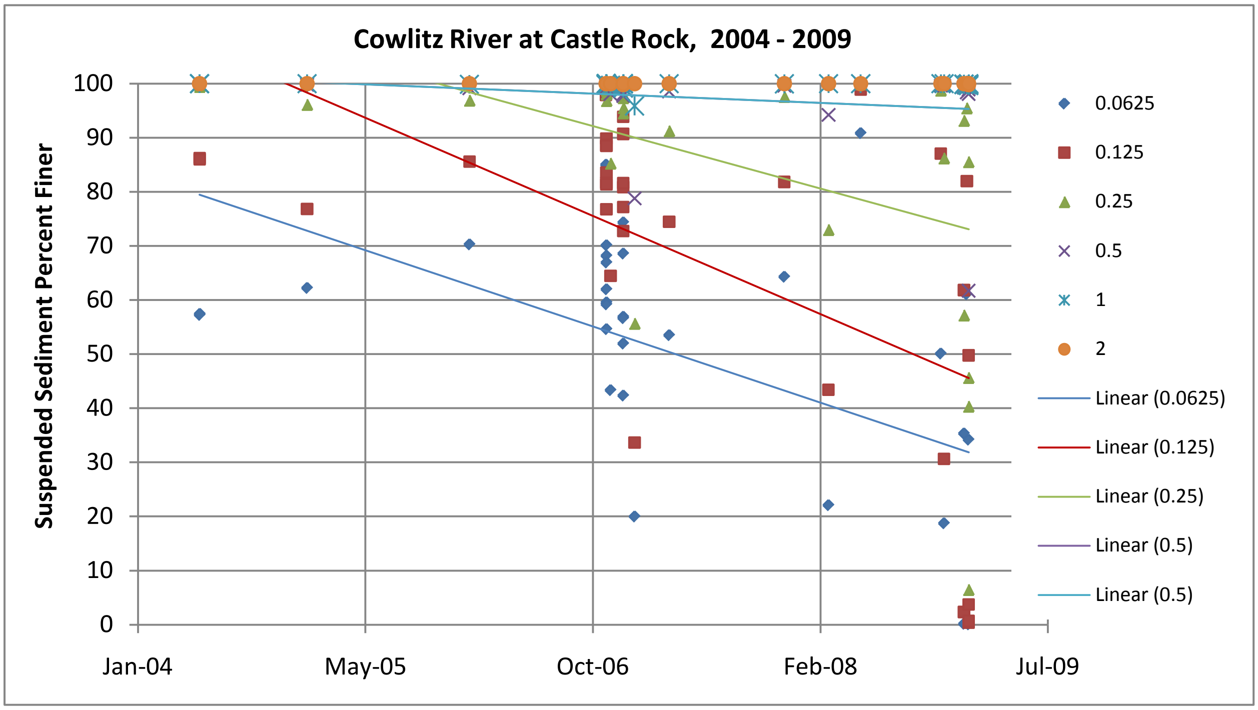


Figure 3.11 Suspended sediment gradations versus time for the Cowlitz River at Castle Rock, 2004-2009

3.4 Suspended Sediment Data Variability

The USGS sampling and analyses of discharge and sediment samples for the Mount St. Helens are held in high regard by all who use and appreciate the data. The following review of variability may aid in explaining the discrepancy in the quantity of medium to coarse sand sampled at the gage and the quantity of those particle sizes found in the sediment at the mouth of the Cowlitz River. A greater quantity of coarse-to-medium sand is found in problematic accumulations at the mouth of the Cowlitz River than is sampled at the Toutle River at Tower Road.

Figure 3.12 (Gray et al. 2009) shows the range of error in concentration that may result by sampling with stream velocity significantly greater or less than the velocity for which the sampler nozzle has been calibrated. The figure is for a nozzle calibrated at 5 feet per second, however, Gray et al. (2009) report that the FISP series of isokinetic samplers is calibrated to 3.9 feet per second. As shown, the curves of percentage of concentration error vary as a function of the ratio of mean intake nozzle velocity / mean stream velocity. An important factor is that the curves are also a function of the grain size, with the greatest error for a given velocity ratio being represented by the largest particle. This suggests that the suspended sediment gradation may be affected non-uniformly, to skew the gradation.

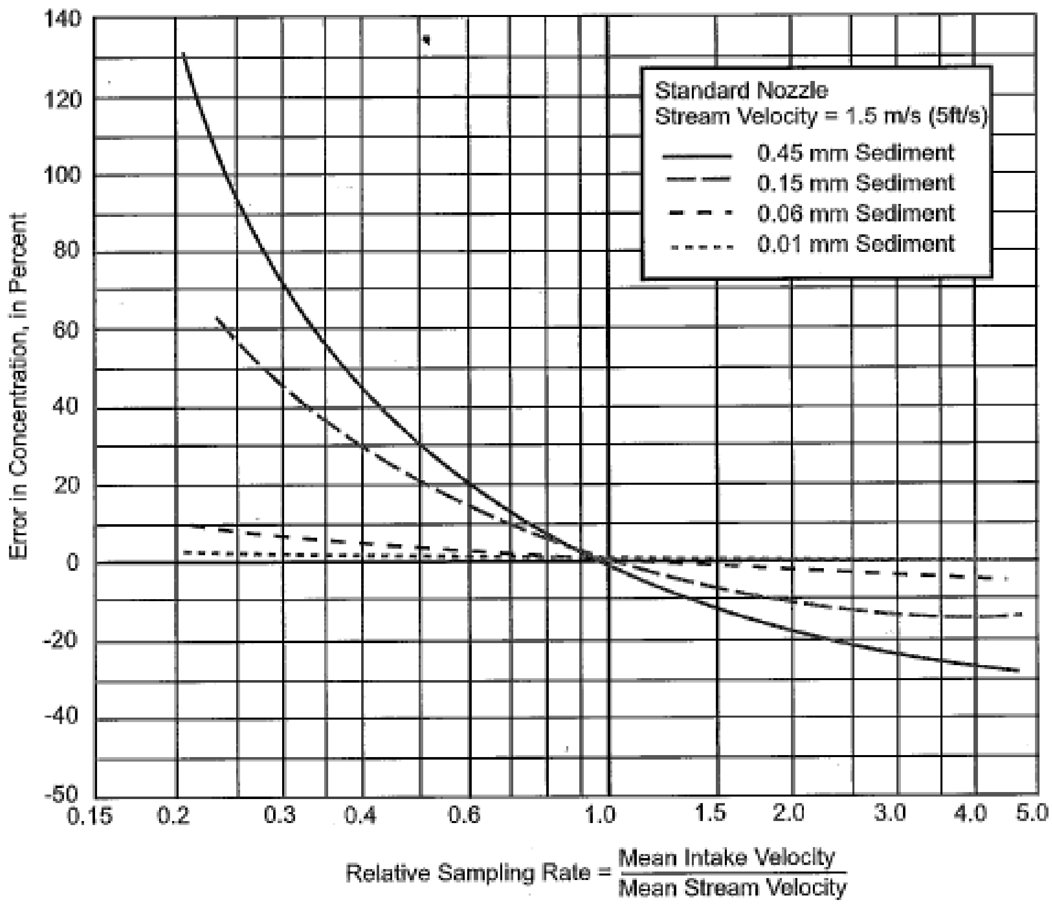


Figure 3.12 Taken from Gray et al. (2009). The original figure is from the Federal Interagency Sedimentation Project (1941) with the caption: Effect of sampling rate on measured sediment concentration for four sediment size distributions.

In addition to the variability that may occur in direct sampling of the suspended sediment, the USGS must also develop and estimate of the total sediment moving through a gaging cross-section from the sampling points data, and then these estimates must be extrapolated to annual sediment yield estimates. The method commonly used by the USGS (Porterfield 1972) is based on the development of interpolations between measured suspended sediment concentration values, using measured and estimated values to calculate suspended sediment discharges. This method necessitates the conversion of point sediment values to values representative of the entire cross section, using all available data. Gray and Francisco (2009) suggest that insufficient definition of the coefficients to transfer point data to be representative of the cross section, or misapplication can result in substantial errors in the derivation of daily suspended sediment discharge records.

Comparing the Porterfield (1972) interpolation method with a power-function-sediment-transport-rating-curve method has been investigated by several authors. Wailing (1977), using transport curves, found that annual loads could be overestimated by 30% even when the relationships were refined for seasonal and stage effects. Comparing ten USGS gauging stations and comparing the interpolation and rating curve methods, Gray and Francisco (2009) found the discrepancy to vary between -91% and 526%. The possible degree of uncertainly emphasizes the significant value of having experienced and expert evaluations of the collected data and of continued resources available to maintain equipment and personnel.

Spicer (2009), in a presentation to the study group, made the following comments pertaining to the uncertainty of suspended sediment records:

> *"Suspended sediment discharge is based on measured sample concentration and water discharge data. Water discharge uncertainty is usually in the +/- 10% range, but can be larger. Uncertainty in concentration is hard to assess. Samples are subject to several possible sources of error during the collection and handling process. The largest source is probably in applying coefficients to adjust point samples to cross section mean.*
>
> *It is probably realistic to think that annual suspended sediment discharge totals can be in error by 25%. The NF Toutle River 2008 final computed total was just over 4 million tons. 25% of that is 1 million tons. Presumably, use of turbidity and acoustic backscatter data could improve our ability to accurately measure suspended sediment, and possibly reduce the need for as many physical samples."*

The utilization of suspended sediment data should be encouraged as a supporting data set, to be used alone only when necessary. Consequently, even though the Toutle/Cowlitz sediment data is considered one of the best and most comprehensive data sets, variability exists in all measured suspended data. A variability of +/- 25% for suspended sediment discharge is utilized in this report. The sediment budget estimates were developed using both the USGS gaging data and the available LiDAR data, as is discussed in a subsequent section.

4.0 TERRAIN ANALYSIS AND SEDIMENT SOURCE/SINK DEVELOPMENT

4.1 USGS Repeat Cross Section Analysis

As part of Mount St. Helens monitoring efforts the USGS has conducted repeated surveys of cross sections located throughout the basin. Cross section surveys began shortly after the eruption and continued consistently throughout the 1980s. As channel response began to stabilize, surveys became less frequent during 1990s and 2000s. No surveys were conducted during the time periods of 1993 – 1995, and 2000 – 2003. All cross section survey data was obtained from the USGS; however, the spatial and temporal density of the recent surveys limits the usefulness of the data for assessing recent erosion rates. Analysis of the USGS repeated survey cross sections located throughout the basin was conducted and discussed in the WEST Report (April 2002). A map showing locations of the USGS cross sections is provided in Figure 4.1. A total of 21 cross sections that have been re-surveyed since the publication of the WEST report were analyzed. Table 4.1 includes a summary list of cross sections analyzed in the WEST report as well as cross sections included in the current study. It should be noted that cross section surveys have not been conducted on the North Fork Toutle River downstream of the SRS or the Toutle River since 1999. Analysis of the cross section survey data included producing plots of each cross section survey and calculating the cross sectional area, top width, and average depth (Figures 4.2 – 4.10).

Loowit Creek (Loo40) is located in the very active avalanche plane. Figure 4.2 shows the dramatic change in cross section from 2005 to 2007. The large sediment yield event occurred in November 2006. Profiles of the cross-sectional area of Loo40 and Loo33 are shown in Figure 4.3, and emphasize the dramatic change in area for the 2007 survey. In contrast the North Fork of the Toutle River (NF100) provides relatively little evidence of the effect of the November 06 event, showing more of a channel location shift as opposed to the accelerated incision of Loowit Creek. Profiles for NF100, NF110, NF120, NF130, NF300 and NF350 (Figures 4.5 and 4.6) show minor changes. On the upper South Fork of the Toutle River, renewed incision of 15 meters is evident from the cross section plot of Figure 4.7. Profiles of cross section area change confirm similar changes for SF615. Lower South Fork cross sections do not show similar response to the upper cross sections. These data suggest that, as expected, dramatic incision can be expected in the upper watersheds, while the lower portions of the watershed have evolved to a relatively stable profile.

Table 4.1 Summary of USGS Repeat Survey Cross Sections Analyzed by WEST and the Biedenharn Group

USGS Cross Section ID	Total # of Surveys	Surveys Post 2000	Analyzed by WEST (2002)	Analyzed by Biedenharn Group (2009)
Castle Creek: Debris Avalanche				
CA205	37	2007		X
Loowit: Debris Avalanche				
LO030	14	2004, 2007		X
LO033	7	2005, 2007		X
LO040	16	2005, 2007		X
North Fork Toutle River: Debris Avalanche				
NF100	52	2005, 2007	X	X
NF110	7	2006, 2007		X
NF120	36	2007	X	X
NF130	53	2007	X	X
NF300	26	2006	X	X
NF310	37	--	X	
NF320	66	--	X	
North Fork Toutle River: Upstream of N1				
NF345	37	--	X	
NF350	13	2006	X	X
NF375	45	--	X	
South Fork Toutle				
SF610	6	2004, 2007	X	X
SF615	5	2005, 2007		X
SF620	5	2005		X
SF640	7	--	X	
SF660	8	--	X	
SF675	6	--	X	
SF690	7	2004		X
SF695	6	2004		X
SF700	9	2004	X	X
SF710	7	2005		X
SF740	7	2005		X
SF745	10	2005	X	X
SF760	14	2005		X
SF770	7	2005		X

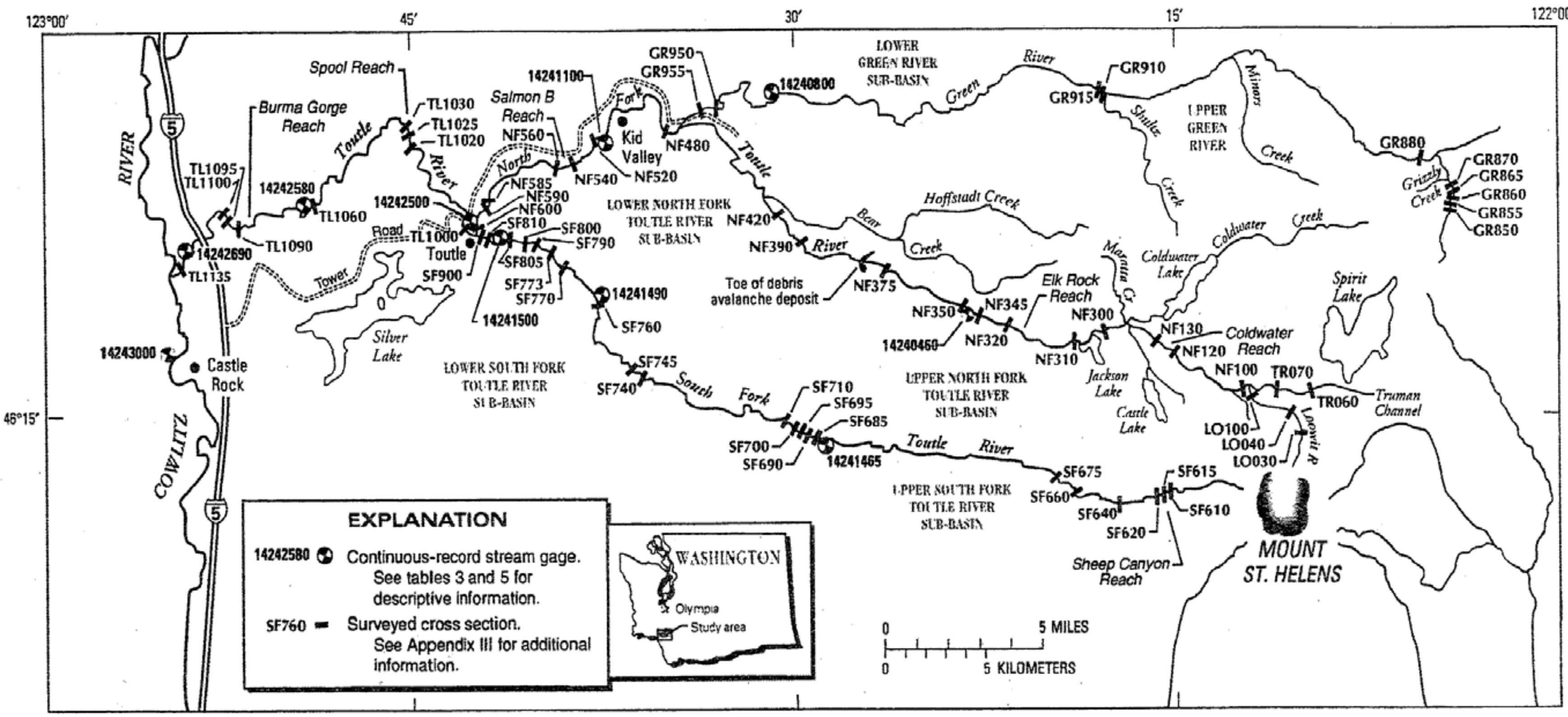


Figure 4.1 Repeat survey cross section location map

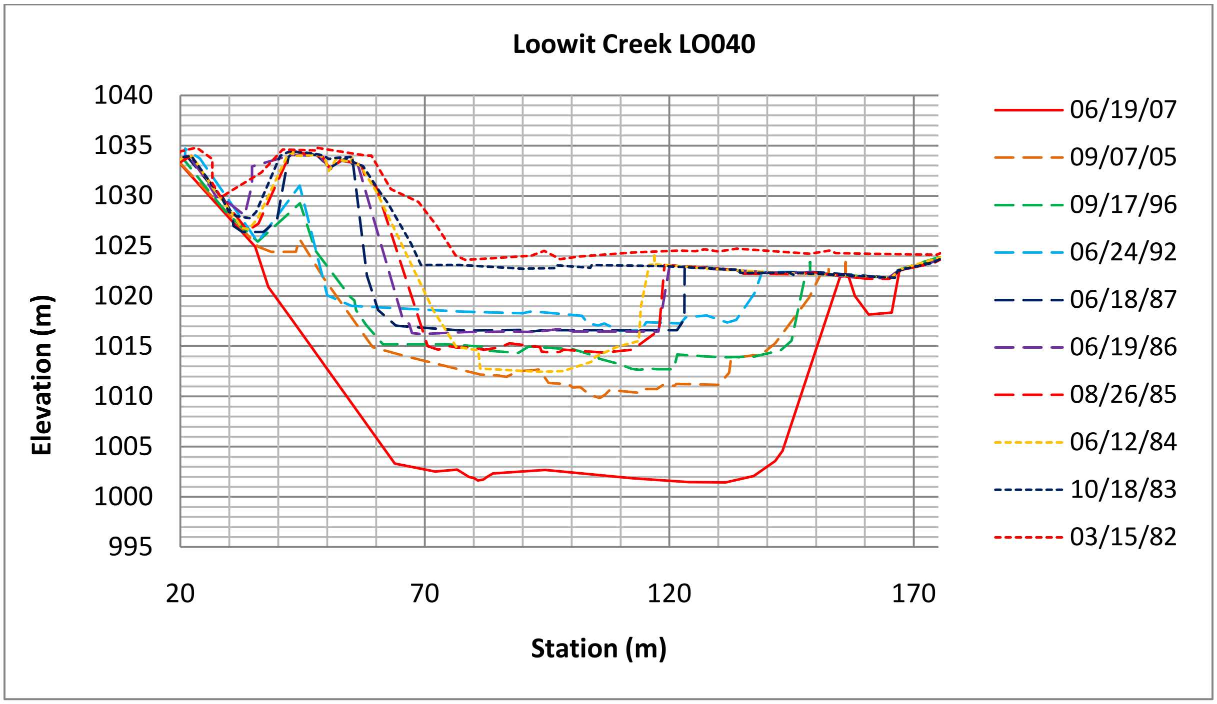


Figure 4.2 Loowit Creek Cross Section 40, 1982 – 2007

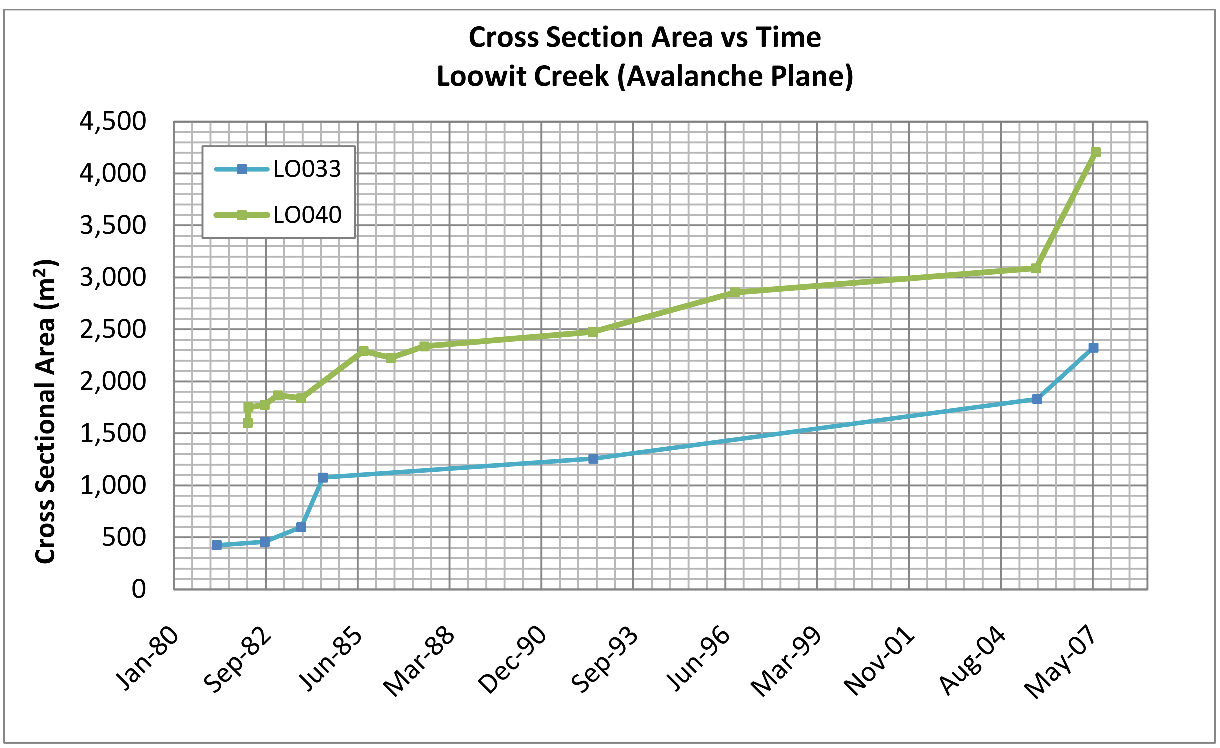


Figure 4.3 Cross sectional area versus time for Loowit Creek cross sections

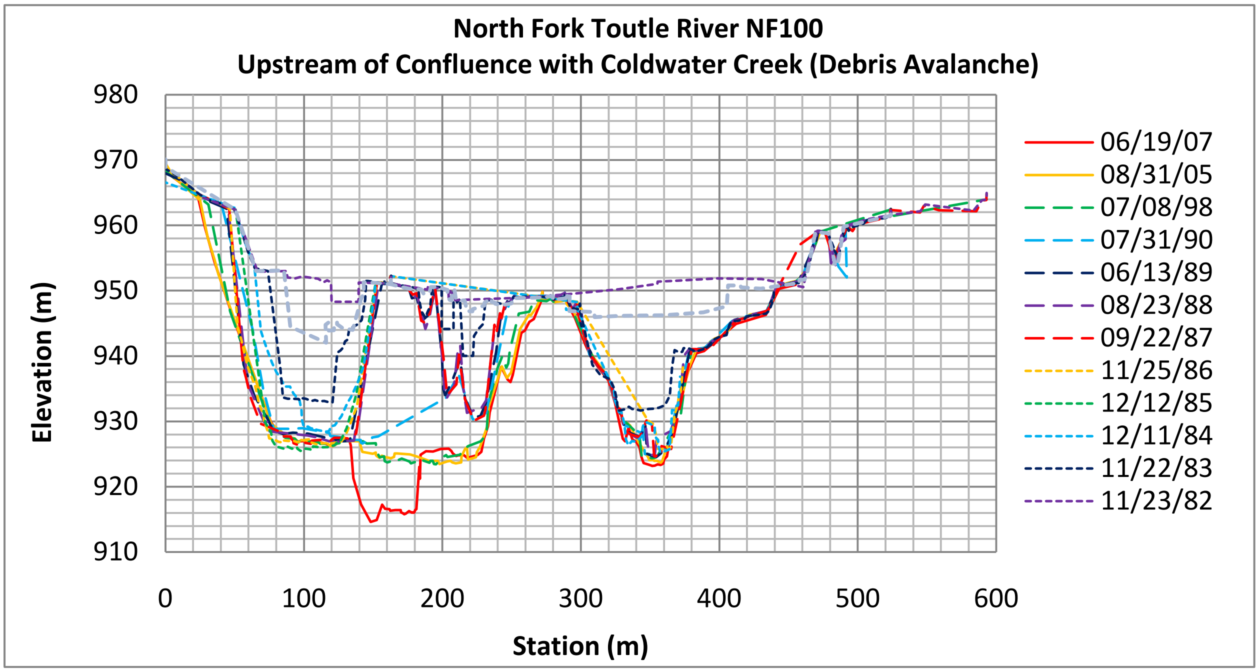


Figure 4. 4.4 North Fork Toutle River Upstream of Coldwater Creek, Cross Section 100, 1982 – 2007

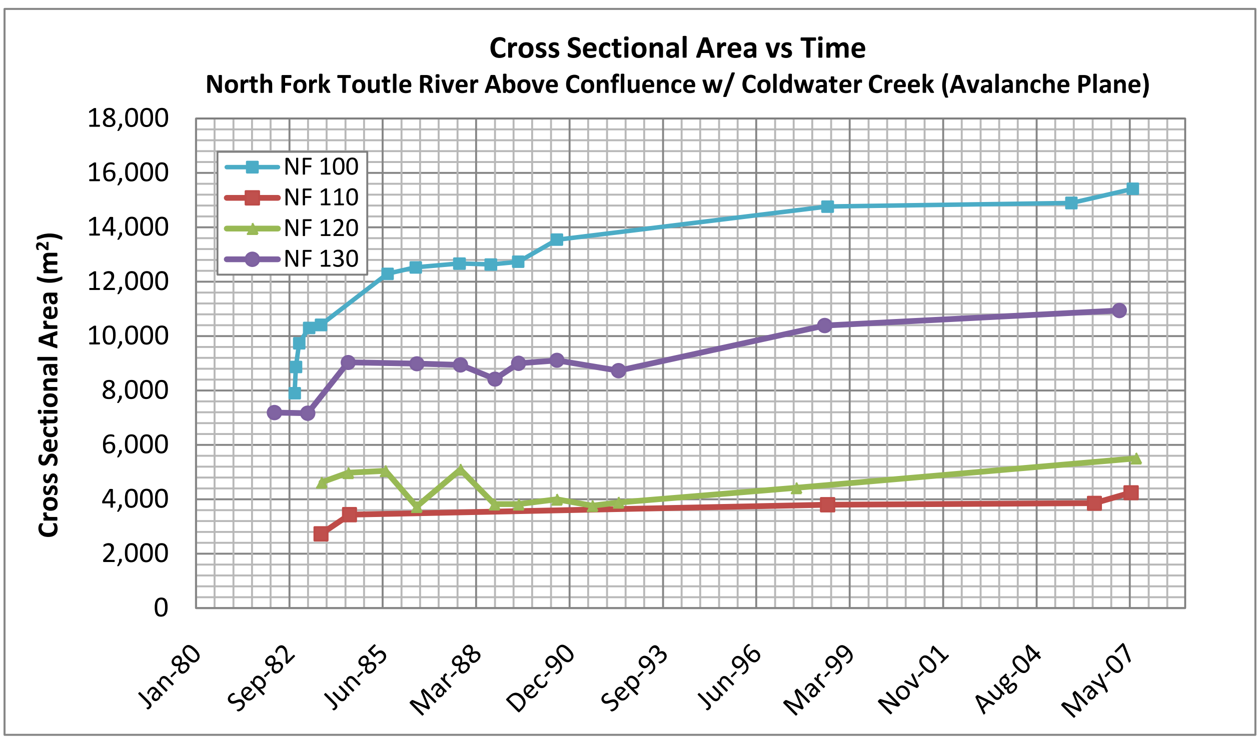


Figure 4.5 Cross sectional area versus time for upper North Fork Toutle River cross sections

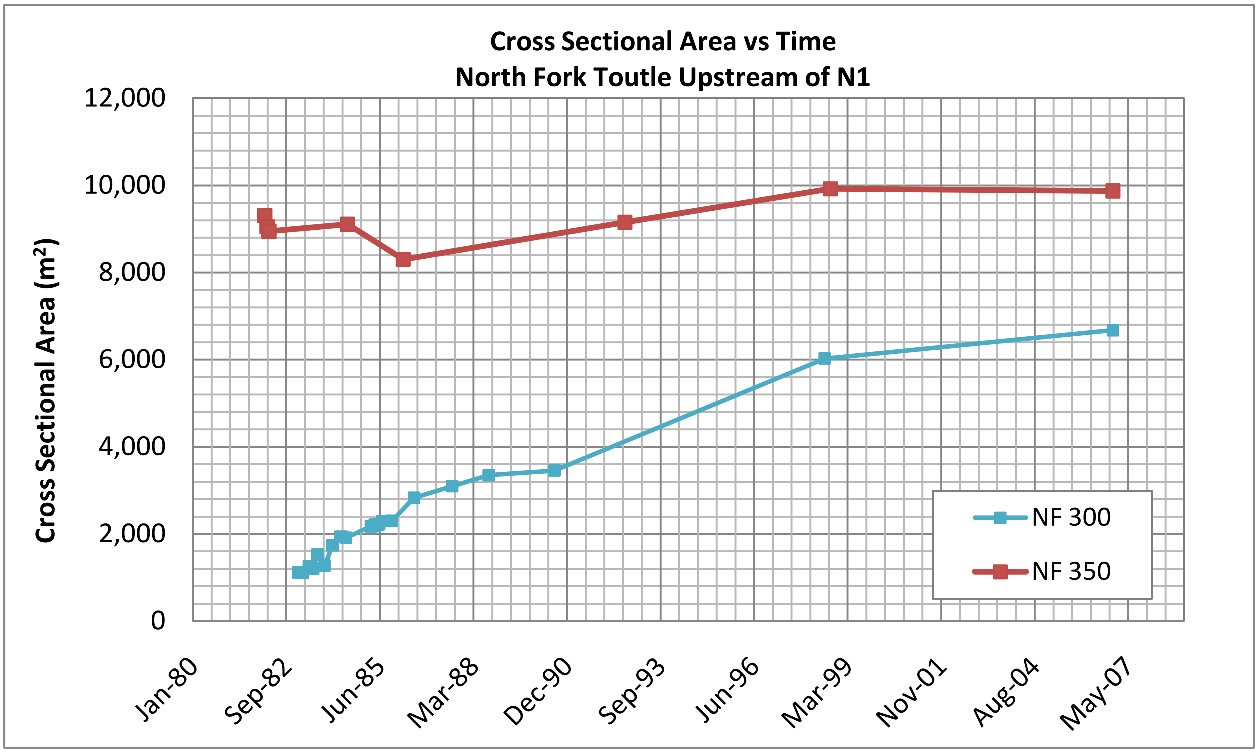


Figure 4.6 Cross sectional area versus time for North Fork Toutle River cross section upstream of N1

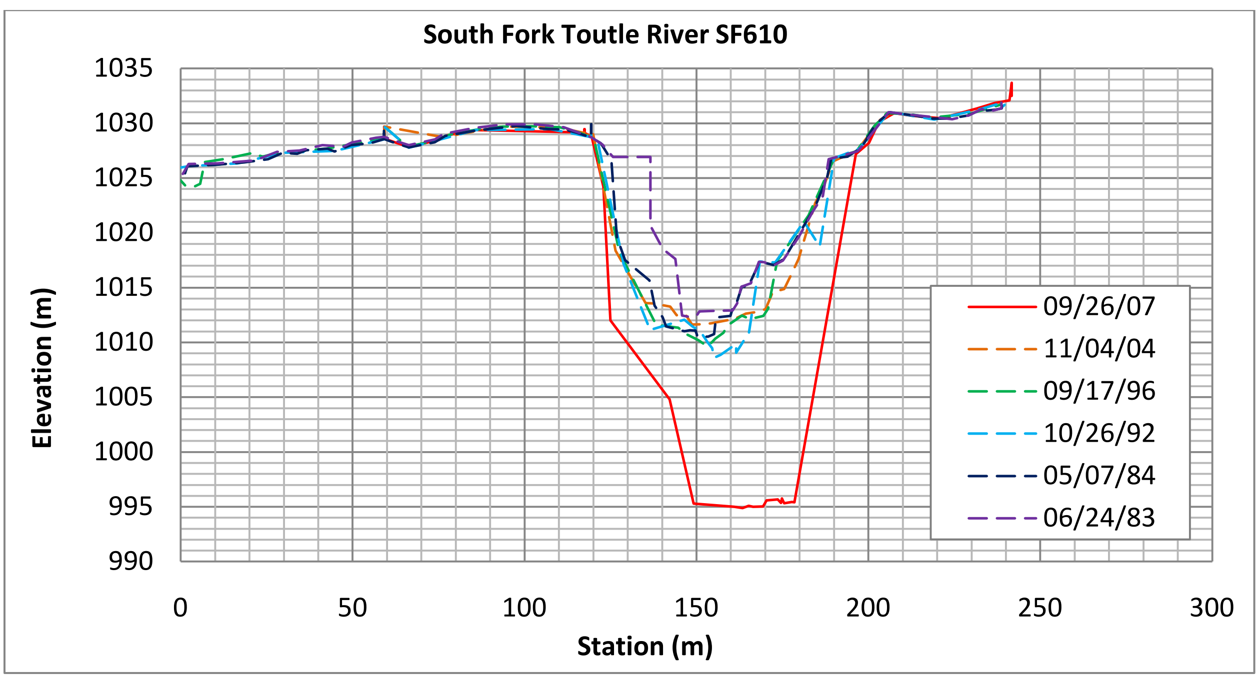


Figure 4.7 South Fork Toutle River Cross Section 610, 1983 - 2007

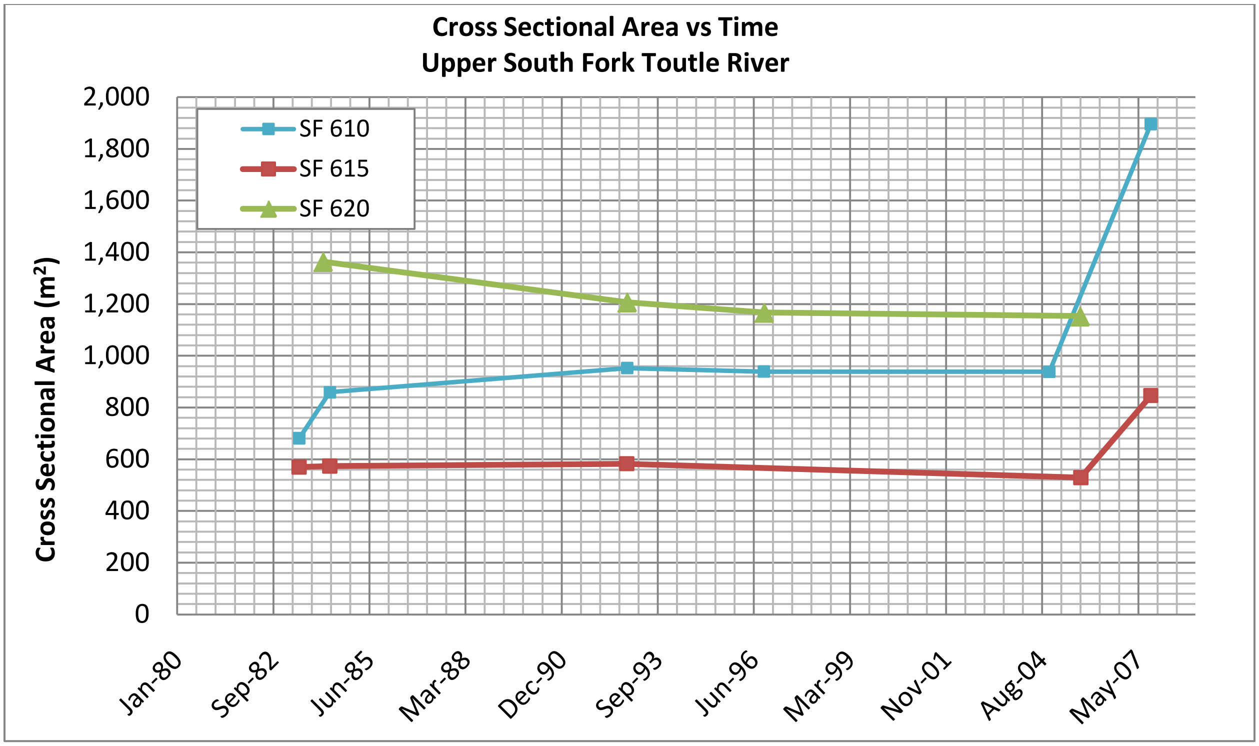


Figure 4.8 Cross sectional area versus time for upper South Fork Toutle River cross sections

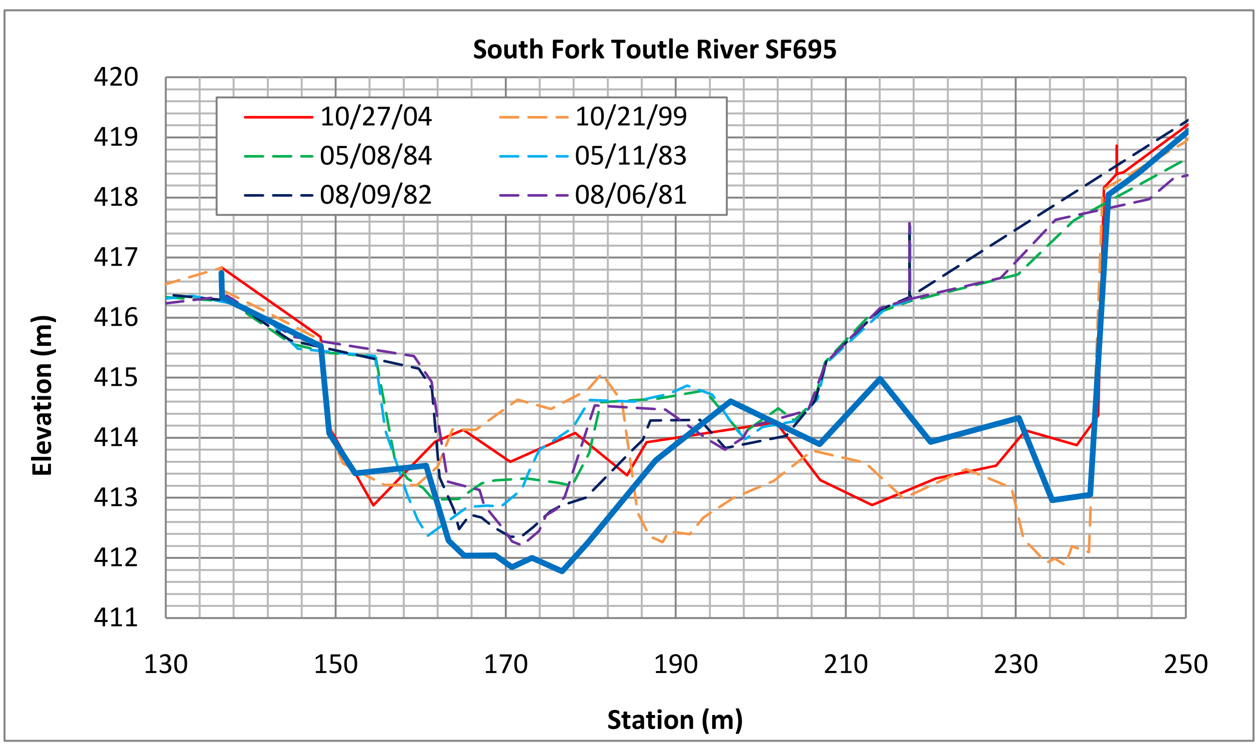


Figure 4.9 South Fork Toutle River Cross Section 695, 1981 - 2009

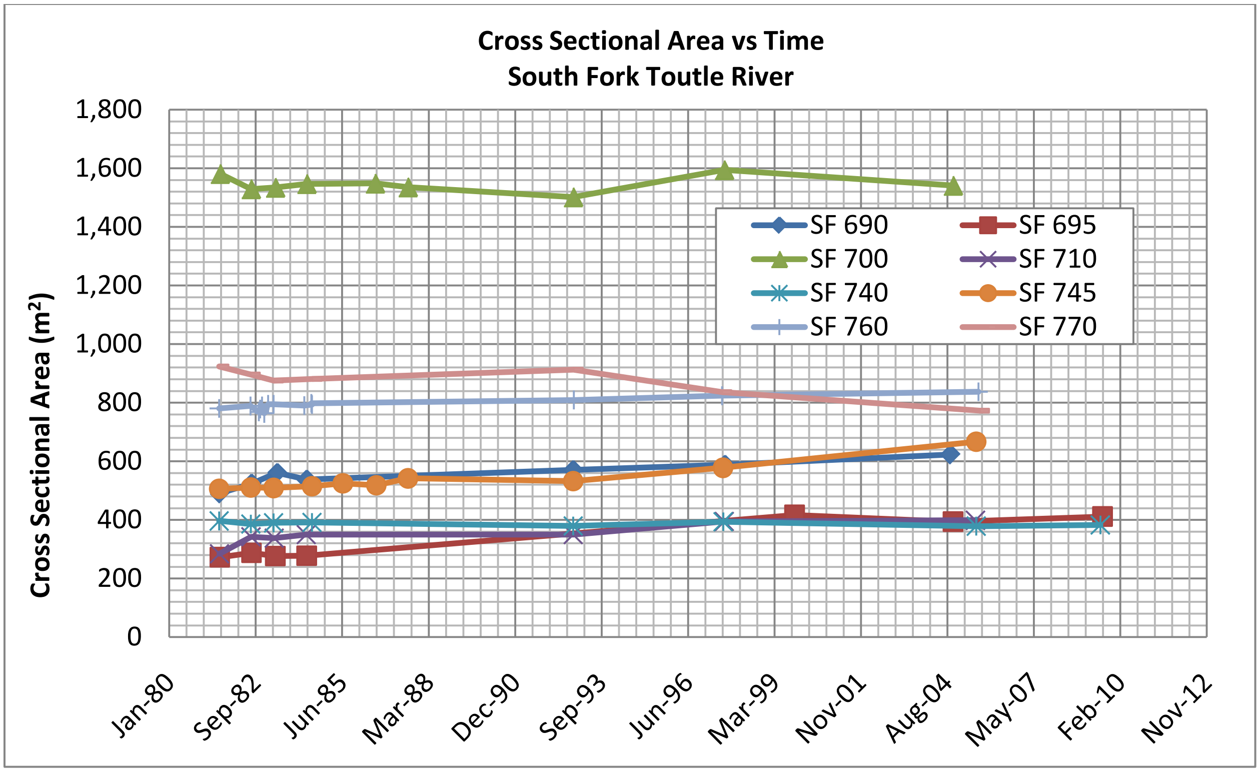


Figure 4.10 Cross sectional area versus time for lower South Fork Toutle River cross sections

4.2 Bank Erosion

A geo-referenced video recording was made of the October 2008 aerial reconnaissance. From a review of the geo-referenced video, a total of 68 bank erosion sites were identified along the North Fork Toutle below the SRS (11 sites), South Fork (40 sites), and Toutle (17 sites) Rivers. Once identified, historical aerial photography, channel geometry, and sample gradations of bank material were utilized to estimate bank erosion volumes and erosion rates by grain class for use in the sediment budget.

Extensive sets of historical aerial photography are available throughout the basin; however, not all sets have consistent spatial coverage. Historical photos taken in 1999 and 2006 were found to have the most complete coverage and were utilized for the bank erosion analysis. Digital scans of the 1999 aerial photography were obtained from the Portland District and geo-rectified to the 2006 National Agricultural Imagery Program (NAIP) photos. Channel bank lines in the vicinity of each bank erosion site were digitized from both sets of aerial photos. The surface area of the eroded banks was then calculated by comparing the digitized banklines between the different years. Depth of the eroded area was then estimated, from cross sections cut from 2007 LiDAR, and used to calculate a total volume. All volumes were converted to tons for use in the sediment budget. Figure 4.11 provides an example of a typical bank erosion site. It should be noted that bank movement was not always detectable from aerial photography for the bank erosion sites. Bank movement was detected at 48 of 68 sites (North Fork 9, South Fork 28, and Toutle 11). A summary table of the bank erosion occurring between 1999 and 2006, or water years 2000 through 2006, is provided in Table 4.2.

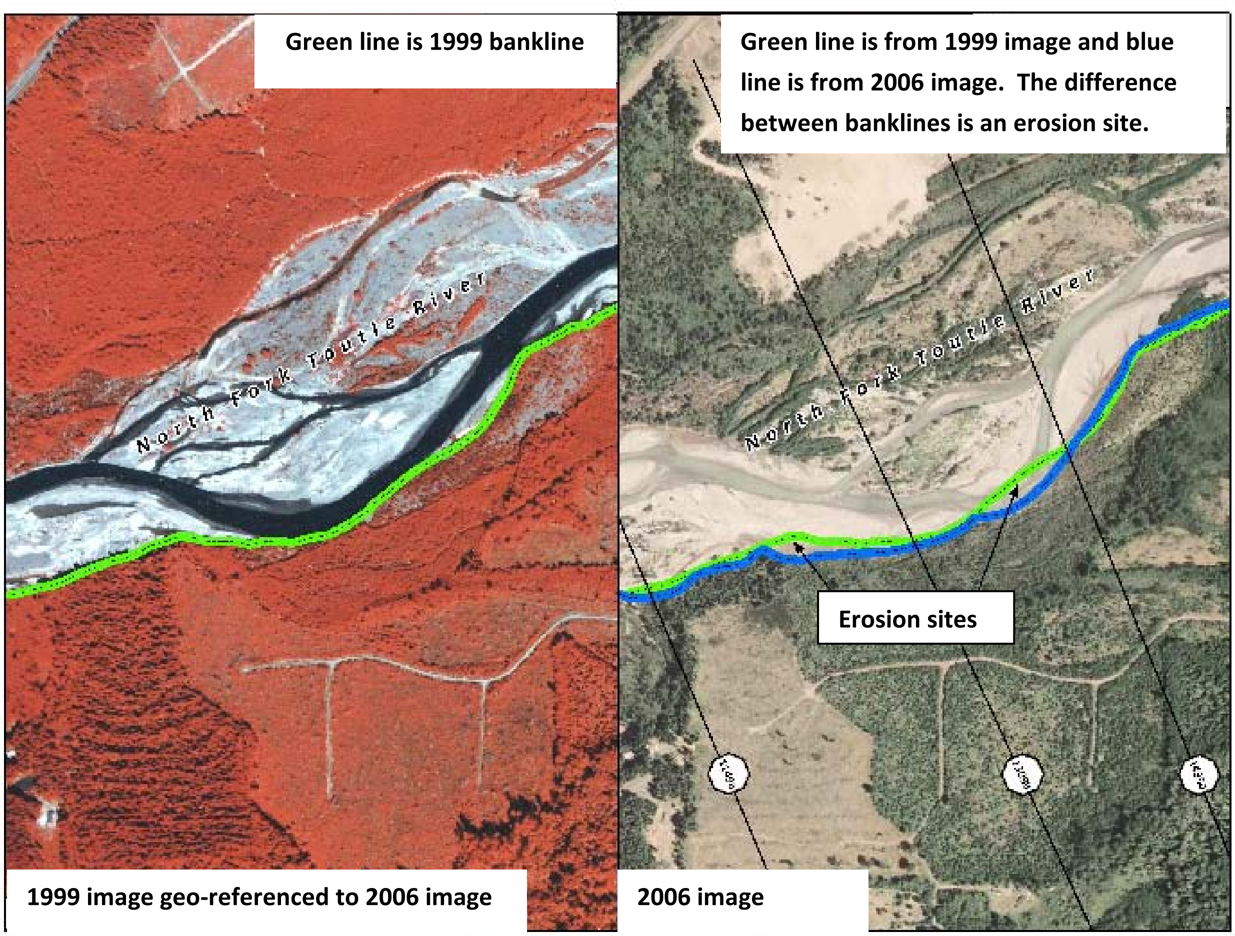


Figure 4.11 Example of Aerial Photo Comparison to Estimate Bank Erosion

The total bank erosion estimated for water years 2000 and 2006 was pro-rated annually based on the Toutle River at Tower Road peak annual discharge. Annual bank erosion quantities for water years before 2000 and after 2006 were estimated using the relationship between % of total bank erosion for 2000 – 2006 and Toutle River peak annual discharge, shown in Figure 4.12. Annual bank erosion quantities for water years 1999 – 2007 are presented in Table 4.3.

Table 4.2 Summary of Bank Erosion

Reach	Estimated Bank Erosion 1999 - 2006 (Tons) [A]	Average Bank Erosion Rate (Tons/Year)
North Fork Toutle Below SRS	616,835	88,119
South Fork Toutle River	1,163,989	166,284
Toutle River Upstream of Tower Road	112,450	16,064
Toutle River Downstream of Tower Road	497,046	71,007

[A] Volume converted to tons using 95 lb/ft^3

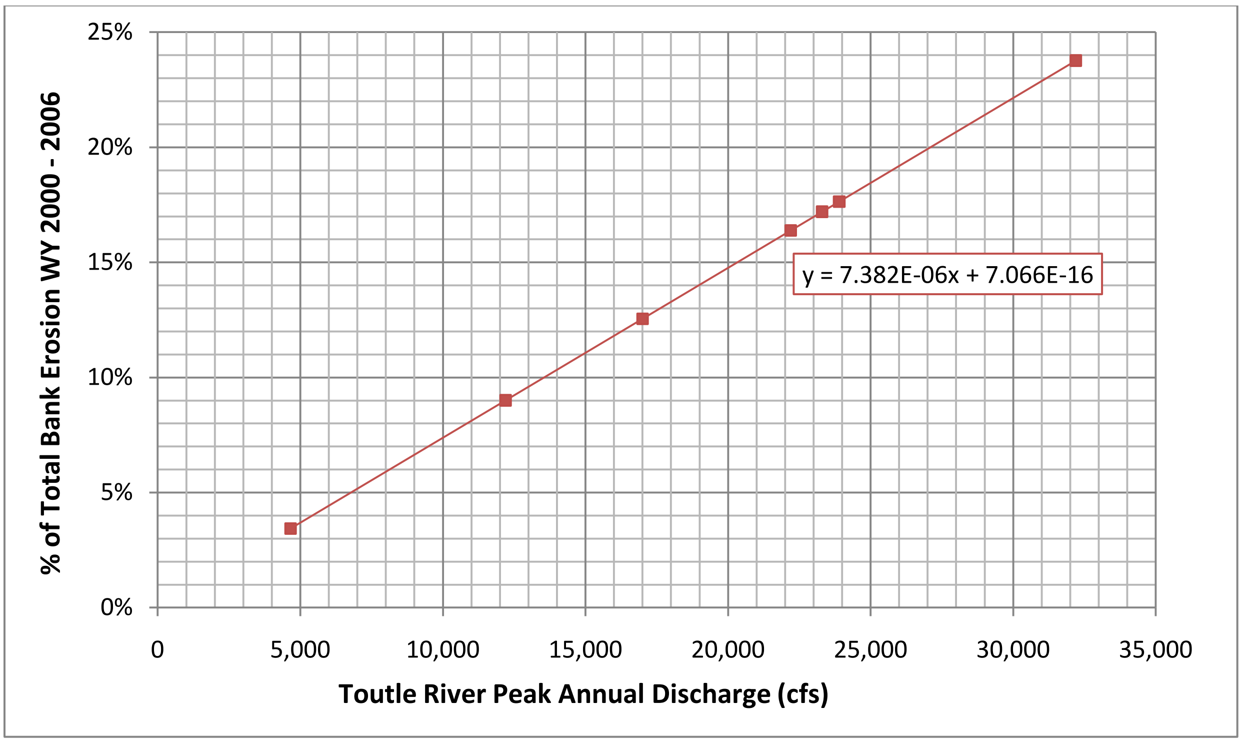


Figure 4.12 Percent of Total Bank Erosion WY 2000 – 2006 versus Toutle River Peak Annual Discharge

Table 4.3 Annual Bank Erosion for Water Years 1999 - 2007

Water Year	North Fork Toutle River Below the SRS	South Fork Toutle River	Toutle River U/S of Tower Road	Toutle River D/S of Tower Road
	(Tons)	(Tons)	(Tons)	(Tons)
1999	126,587	238,873	23,077	102,004
2000	108,828	205,362	19,840	87,694
2001	21,219	40,041	3,868	17,098
2002	106,096	200,207	19,342	85,492
2003	146,622	276,681	26,730	118,148
2004	77,409	146,074	14,112	62,376
2005	55,552	104,829	10,127	44,764
2006	101,087	190,755	18,428	81,456
2007	169,389	319,644	30,880	136,494

Bank erosion quantities were further broken down into grain size by applying the nearest bank material gradations collected in October of 2008 and presented in Figure 4.13. The sample designations BG1 through BG8 refer to samples collected by Biedenharn Group, LLC. Table 4.4 provides the total bank erosion calculated by grain size for the sediment budget time period including water years 2000 through 2007.

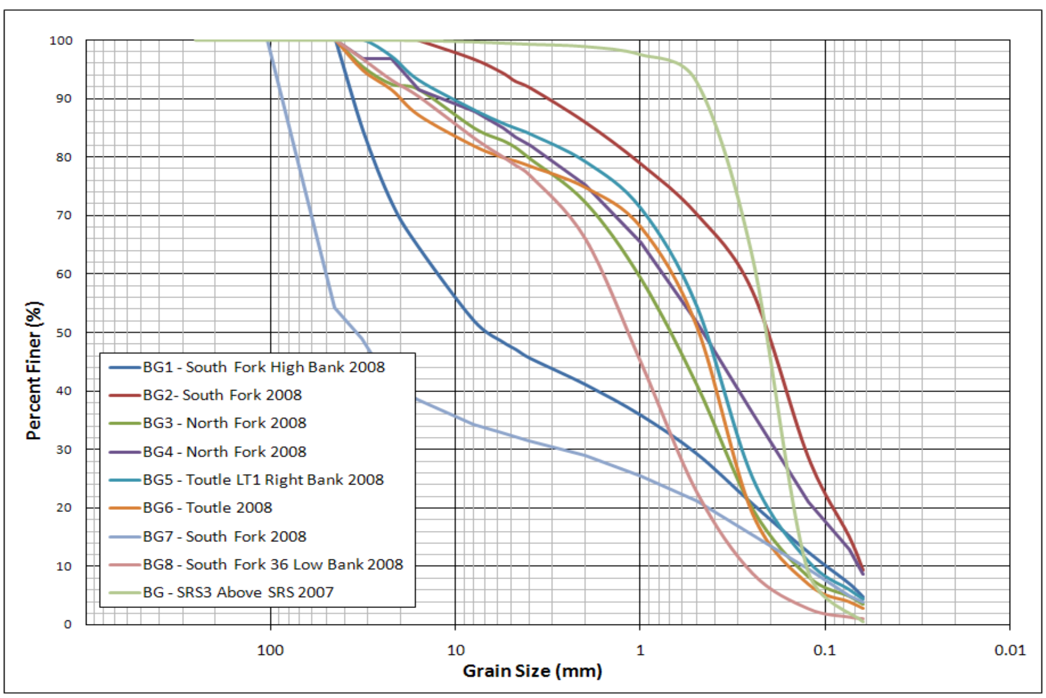


Figure 4.13 2008 Bank Material Gradations along the North Fork, South Fork, and Toutle River

Table 4.4 Total Bank Erosion by Grain Size for Water Years 2000 - 2007

Grain Size	North Fork Toutle River Below the SRS	South Fork Toutle River	Toutle River U/S of Tower Road	Toutle River D/S of Tower Road
(mm)	(M Tons)	(M Tons)	(M Tons)	(M Tons)
0.0625	0.03	0.05	0.012	0.03
0.125	0.04	0.10	0.018	0.04
0.25	0.09	0.18	0.022	0.09
0.5	0.17	0.20	0.022	0.19
1	0.14	0.27	0.020	0.11
2	0.10	0.26	0.014	0.05
4	0.06	0.14	0.010	0.03
8	0.04	0.09	0.008	0.03
16	0.05	0.09	0.005	0.03
32	0.03	0.07	0.008	0.04
64	0.04	0.04	0.005	0.00
128	0.00	0.00	0.000	0.00
Total	0.79	1.48	0.14	0.63

Accurately estimating bank erosion for over 68 sites throughout the watershed proved to be difficult given data limitations. The aerial photography method applied to the current study was carried out consistently for all bank erosion sites. Factors that may attribute to variability in the results include: accuracy of the rectification of the 1999 aerial photos, difficulty in identifying the channel banklines due to photo resolution and/or vegetation, limited cross section data to estimate bank height, and using a single bank gradation to represent the highly non-uniform banks. The variability of the bank erosion quantities was estimated to be + or – 35%.

4.3 Surface Comparisons of North Fork Toutle Basin above the SRS

Historical aerial survey data sets were found to be one of the most valuable sources of information to directly calculate volumes of erosion and deposition occurring on the debris avalanche and sediment plain upstream of the SRS. Total net change in volume was estimated by comparing digital surfaces for the eight sets of digital topography. Data sets available for analysis include:

- 1950s Contours digitized from USGS 15 minute quad mapping;
- 1984 Contours digitized from USGS 7.5 minute quad mapping;
- 1987 and 1999 Contours developed from aerial photographs; and
- 2003, 2004, 2006, and 2007 digital surface developed from LiDAR.

The extents of each data set vary, as shown in Figure 4.14. A total of eight surface comparisons were conducted based upon the coincident coverage of pairs of data. Direct comparison of the complete area upstream of the SRS cannot be developed for each year that a LiDAR flight is available, because the extent of the data sets varies significantly.

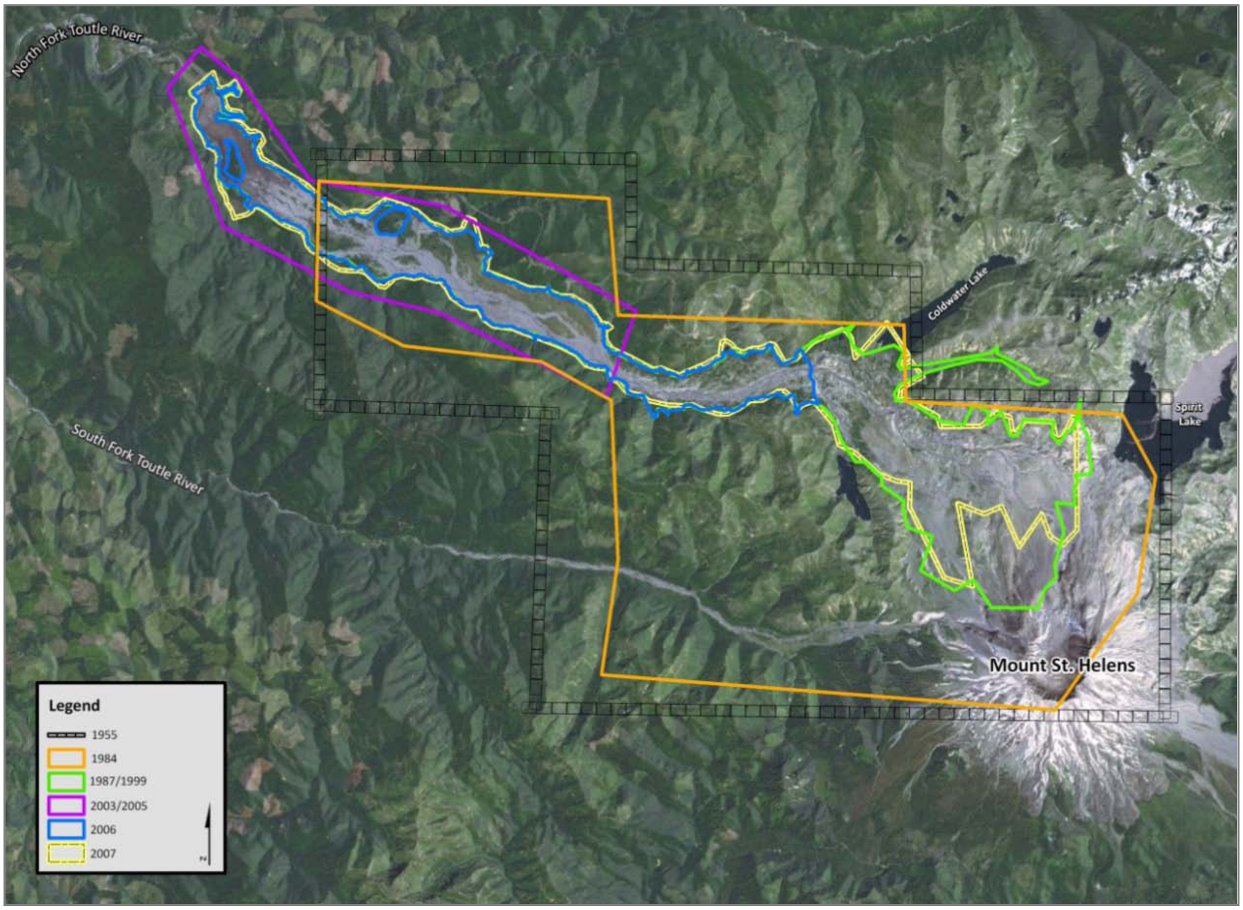


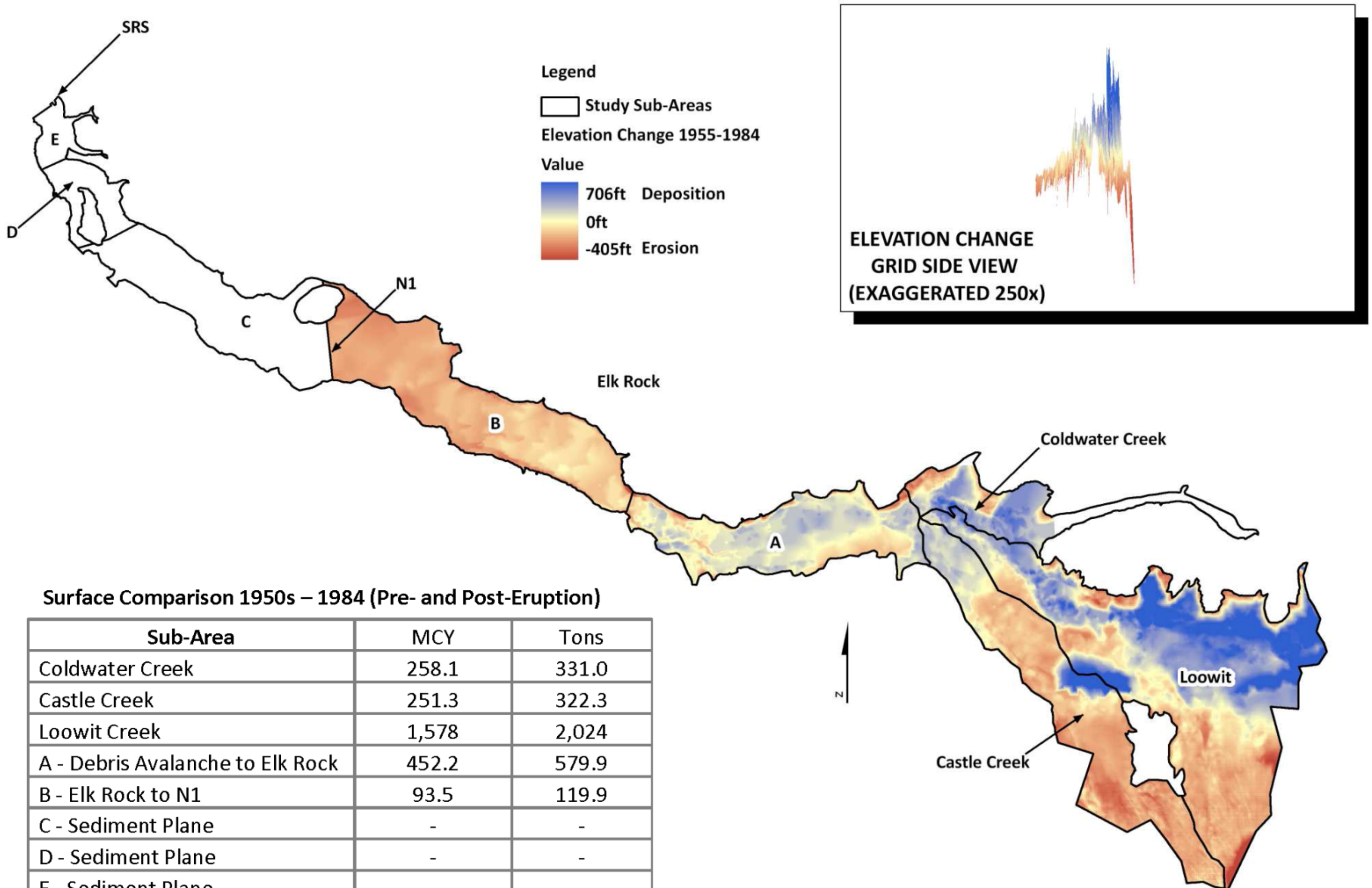
Figure 4.14 Extents of Aerial Survey Data for Available Data from 1955 to 2007

The surface comparisons were conducted by first converting each data set into a digital elevation model (DEM), or grid, having a cell resolution of 10' x 10'. Each DEM was then clipped to the area of interest. Volumes of erosion and deposition were then calculated by subtracting two selected DEMs. Results of each surface comparison were then divided spatially into eight sub-areas; three located in each drainage of the debris avalanche, two extending from the debris avalanche downstream to N1, and three located on the deposition between the SRS and N1.

Surface and volume calculations can be made only for the smaller coverage of the two LiDAR or photographic images utilized. The tables of sub-area volumes in each figure contain volume calculations only for the sub-areas having a coincident data set. Unfortunately, coincident data sets were not available, and the extent of data collected was not consistent.

4.3.1 Surface Comparison Results

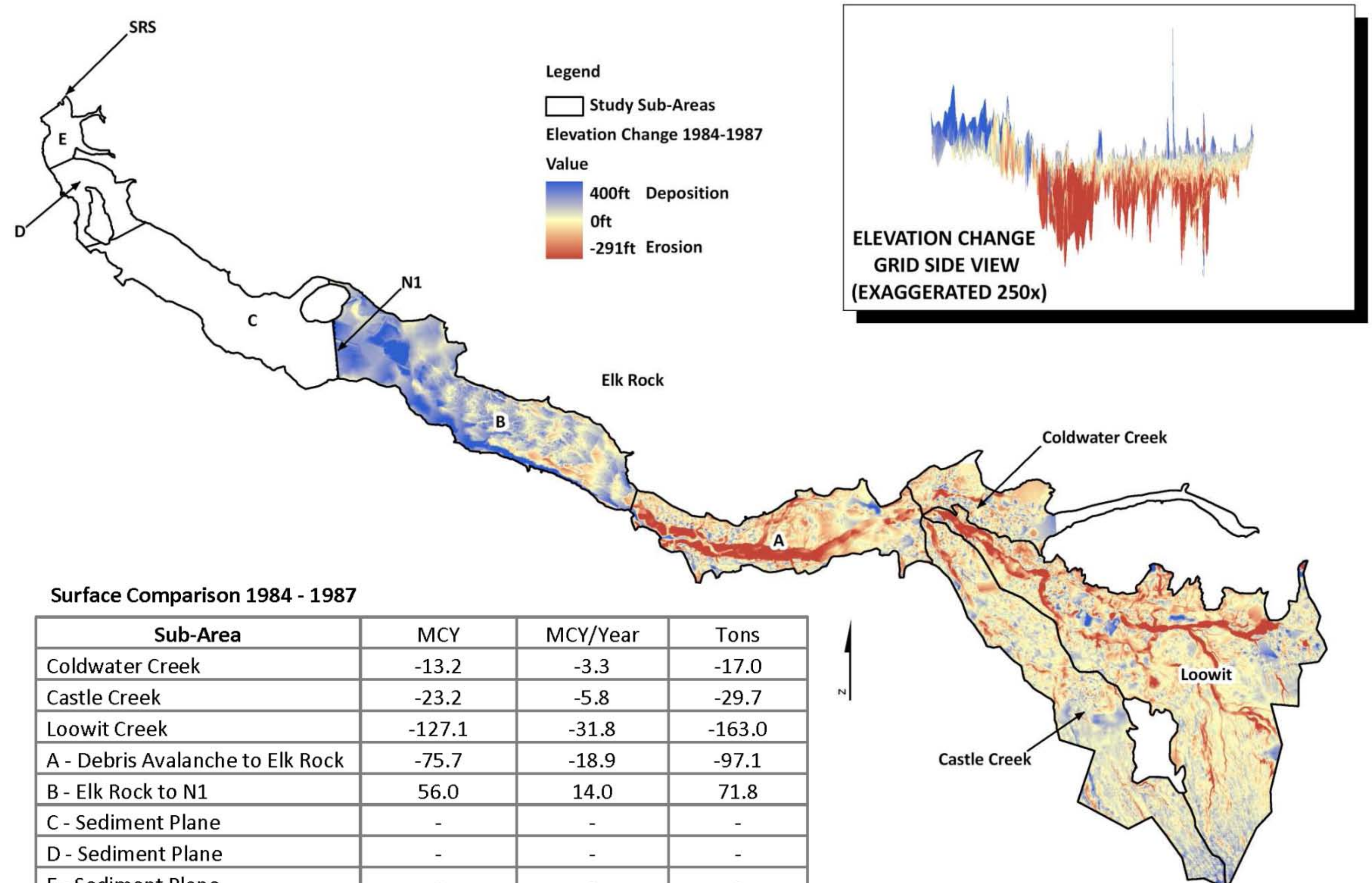
Results of the surface comparisons are presented in Figures 4.15 through 4.22. Each figure includes a color coded image of the change in elevation between surfaces; where blue and red indicate deposition and erosion, respectfully. The extents of the sub-area and a summary table of the volume calculations are also provided in Figures 4.15 through 4.22. All conversions from volume to mass were calculated using a unit weight 95 $lb/ft^{3.}$ A plot of the rate of change in volume calculated for each sub area over the various time periods is presented in Figure 4.23. Surface comparison results were utilized for independent analysis of the debris avalanche and sediment plain deposition for input to the sediment budget.



Surface Comparison 1950s – 1984 (Pre- and Post-Eruption)

Sub-Area	MCY	Tons
Coldwater Creek	258.1	331.0
Castle Creek	251.3	322.3
Loowit Creek	1,578	2,024
A - Debris Avalanche to Elk Rock	452.2	579.9
B - Elk Rock to N1	93.5	119.9
C - Sediment Plane	-	-
D - Sediment Plane	-	-
E - Sediment Plane	-	-
Total Erosion	-	-
Total Deposition	2,633	3,377

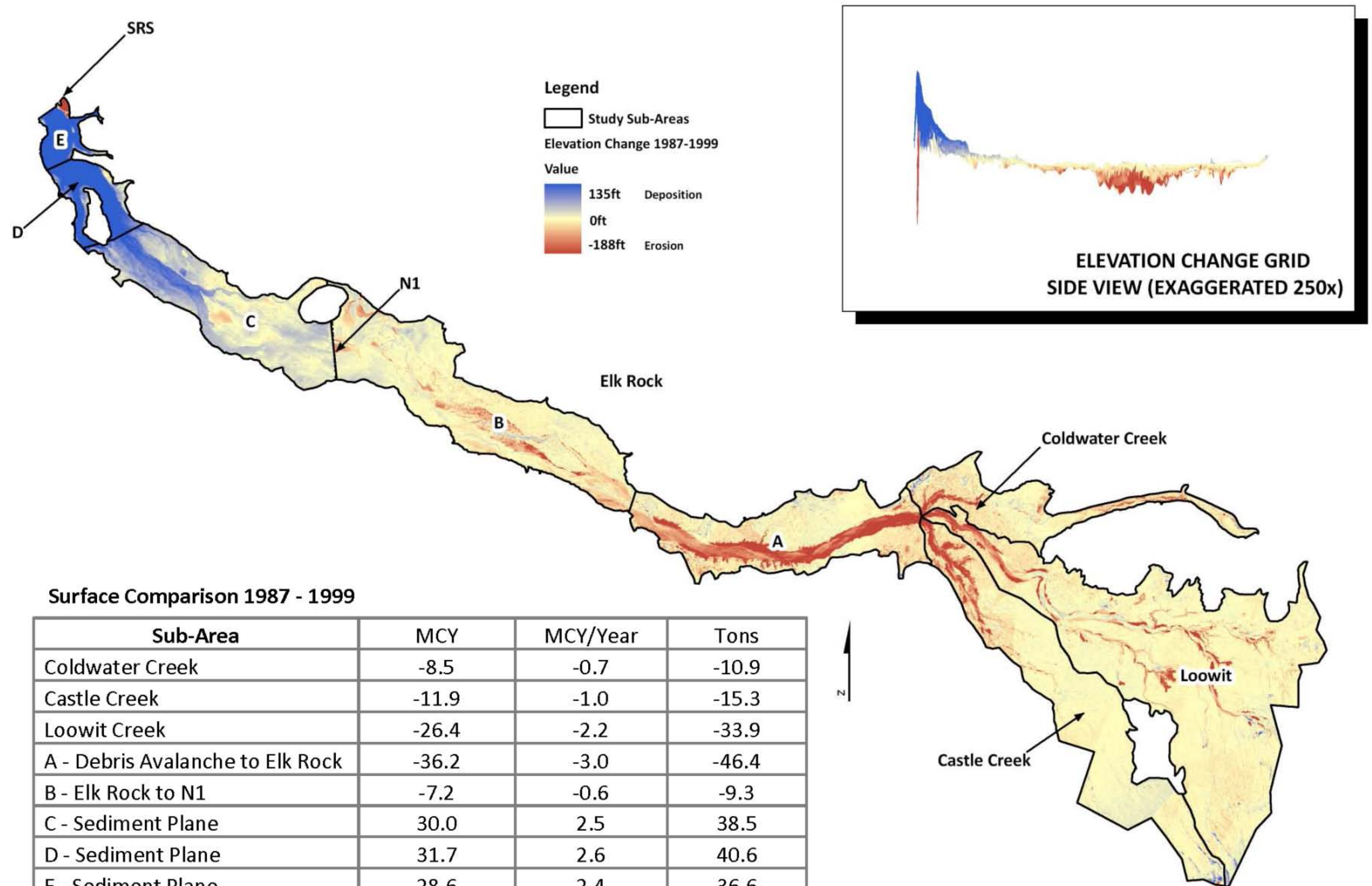
Figure 4.15 Surface Comparison of 1950s and 1984 Quadrangle Contour



Surface Comparison 1984 - 1987

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-13.2	-3.3	-17.0
Castle Creek	-23.2	-5.8	-29.7
Loowit Creek	-127.1	-31.8	-163.0
A - Debris Avalanche to Elk Rock	-75.7	-18.9	-97.1
B - Elk Rock to N1	56.0	14.0	71.8
C - Sediment Plane	-	-	-
D - Sediment Plane	-	-	-
E - Sediment Plane	-	-	-
Total Erosion	-239.2	-59.8	-306.8
Total Deposition	56.0	14.0	71.8

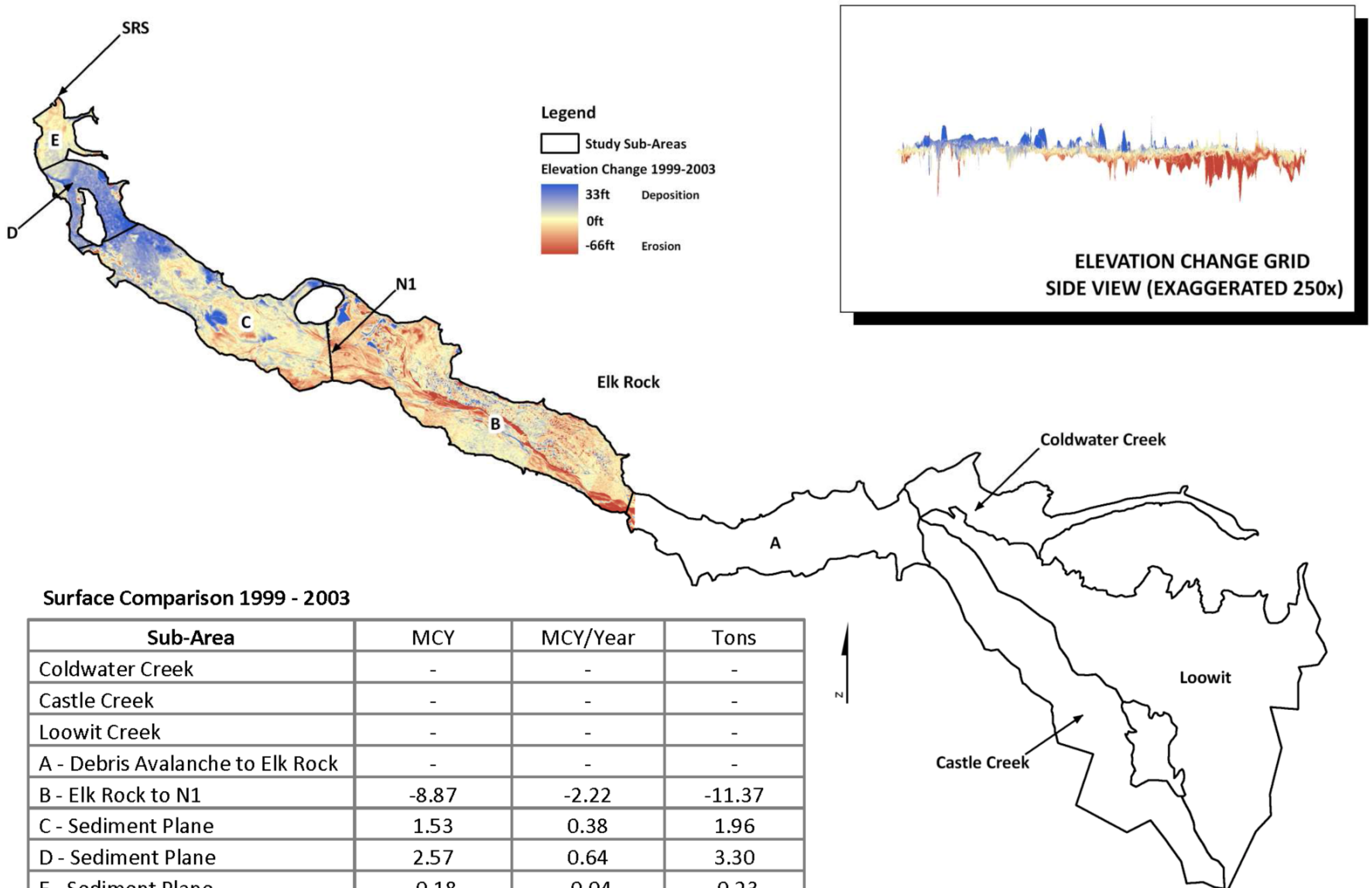
Figure 4.16 Surface Comparison of 1984 Quadrangle Contours and 1987 Photogrammetry



Surface Comparison 1987 - 1999

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-8.5	-0.7	-10.9
Castle Creek	-11.9	-1.0	-15.3
Loowit Creek	-26.4	-2.2	-33.9
A - Debris Avalanche to Elk Rock	-36.2	-3.0	-46.4
B - Elk Rock to N1	-7.2	-0.6	-9.3
C - Sediment Plane	30.0	2.5	38.5
D - Sediment Plane	31.7	2.6	40.6
E - Sediment Plane	28.6	2.4	36.6
Total Erosion	-90.2	-7.5	-115.7
Total Deposition	90.2	7.5	115.7

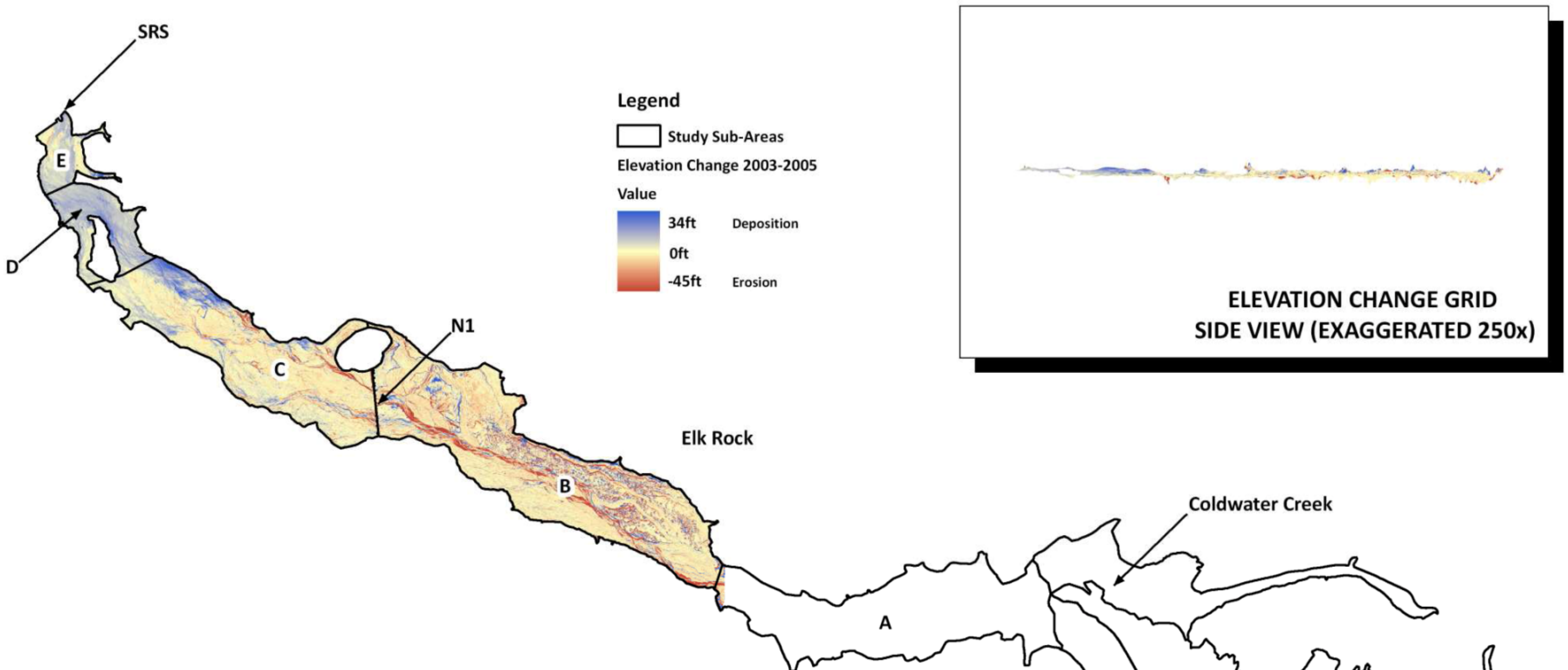
Figure 4.17 Surface Comparison of 1987 and 1999 Photogrammetry

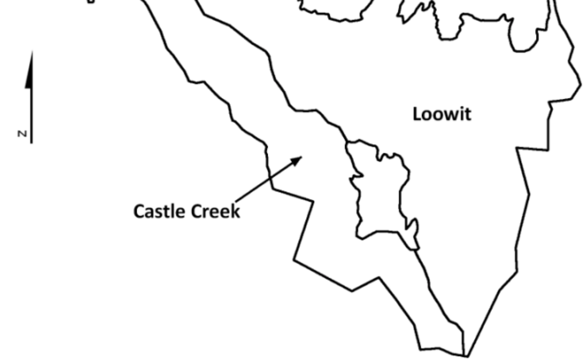


Surface Comparison 1999 - 2003

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-	-	-
Castle Creek	-	-	-
Loowit Creek	-	-	-
A - Debris Avalanche to Elk Rock	-	-	-
B - Elk Rock to N1	-8.87	-2.22	-11.37
C - Sediment Plane	1.53	0.38	1.96
D - Sediment Plane	2.57	0.64	3.30
E - Sediment Plane	-0.18	-0.04	-0.23
Total Erosion	-9.04	-2.26	-11.60
Total Deposition	4.10	1.03	5.26

Figure 4.18 Surface Comparison of 1999 Photogrammetry and 2003 LiDAR

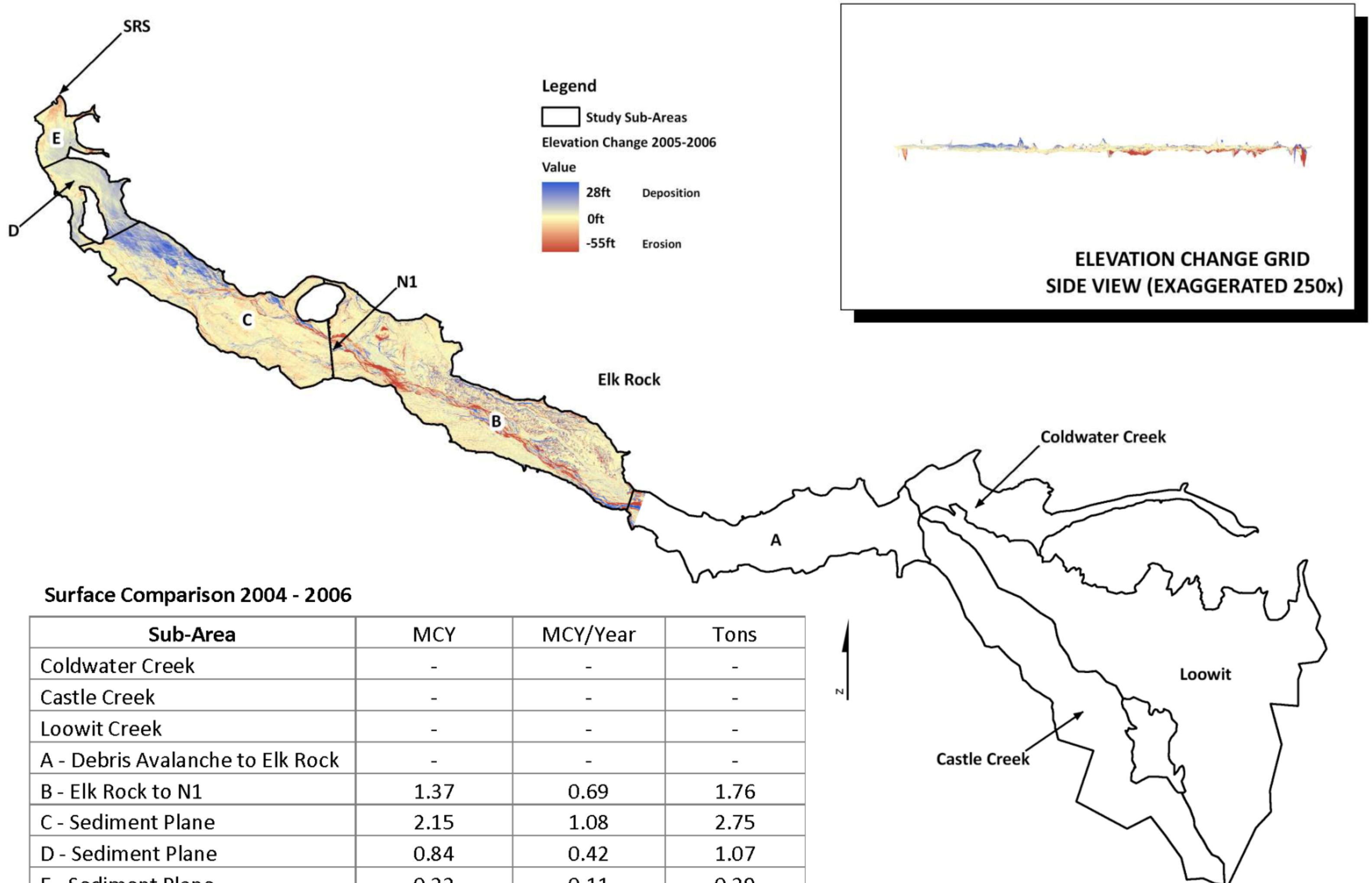




Surface Comparison 2003 - 2004

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-	-	-
Castle Creek	-	-	-
Loowit Creek	-	-	-
A - Debris Avalanche to Elk Rock	-	-	-
B - Elk Rock to N1	-2.18	-2.18	-2.79
C - Sediment Plane	-0.19	-0.19	-0.24
D - Sediment Plane	0.70	0.70	0.89
E - Sediment Plane	0.19	0.19	0.25
Total Erosion	-2.37	-2.37	-3.04
Total Deposition	0.89	0.89	1.14

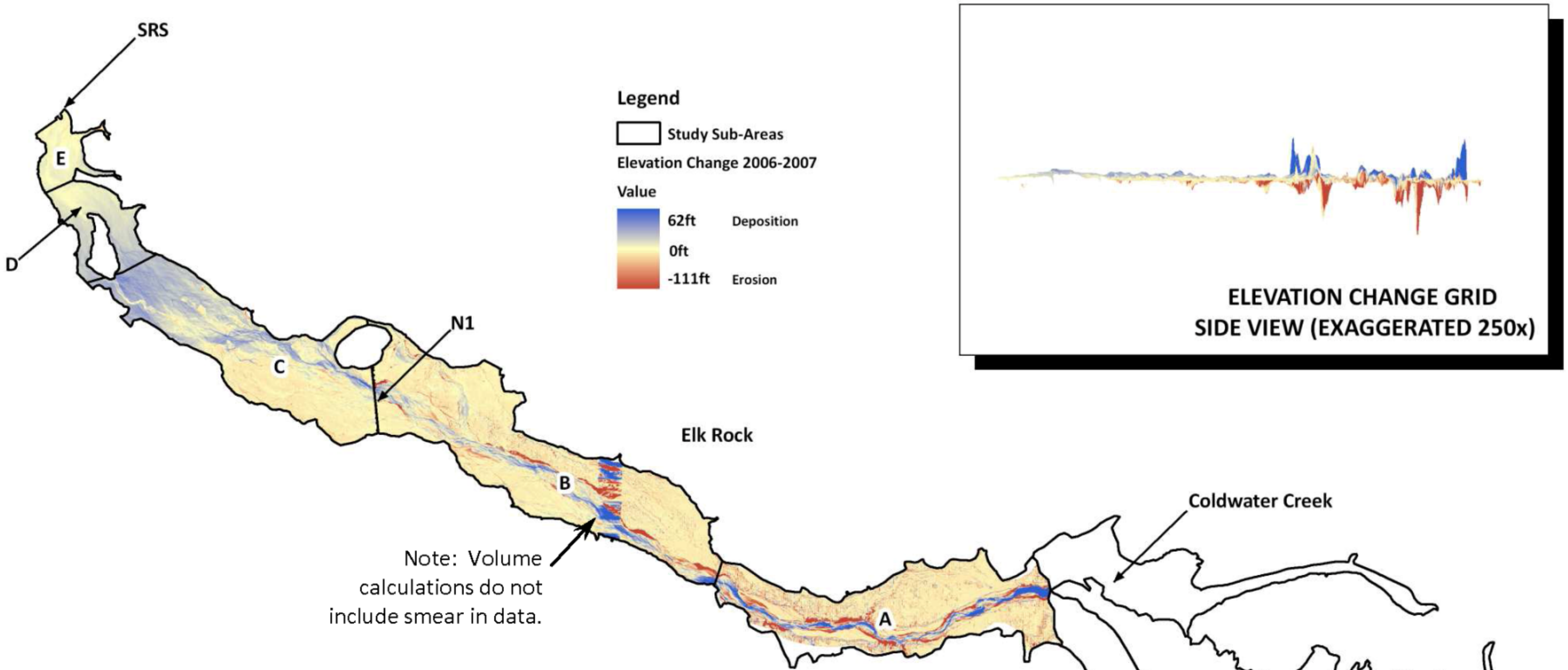
Figure 4.19 Surface Comparison of 2003 and 2004 LiDAR



Surface Comparison 2004 - 2006

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-	-	-
Castle Creek	-	-	-
Loowit Creek	-	-	-
A - Debris Avalanche to Elk Rock	-	-	-
B - Elk Rock to N1	1.37	0.69	1.76
C - Sediment Plane	2.15	1.08	2.75
D - Sediment Plane	0.84	0.42	1.07
E - Sediment Plane	0.22	0.11	0.29
Total Erosion	0.00	0.00	0.00
Total Deposition	4.58	2.29	5.87

Figure 4.20 Surface Comparison of 2004 and 2006 LiDAR



Surface Comparison 2006 - 2007

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-	-	-
Castle Creek	-	-	-
Loowit Creek	-	-	-
A - Debris Avalanche to Elk Rock	-1.65	-1.65	-2.12
B - Elk Rock to N1	-0.59	-0.59	-0.76
C - Sediment Plane	4.80	4.80	6.16
D - Sediment Plane	1.68	1.68	2.15
E - Sediment Plane	0.37	0.37	0.48
Total Erosion	-2.24	-2.24	-2.88
Total Deposition	6.85	6.85	8.79

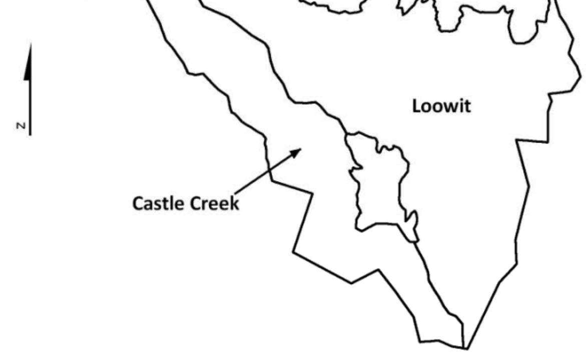
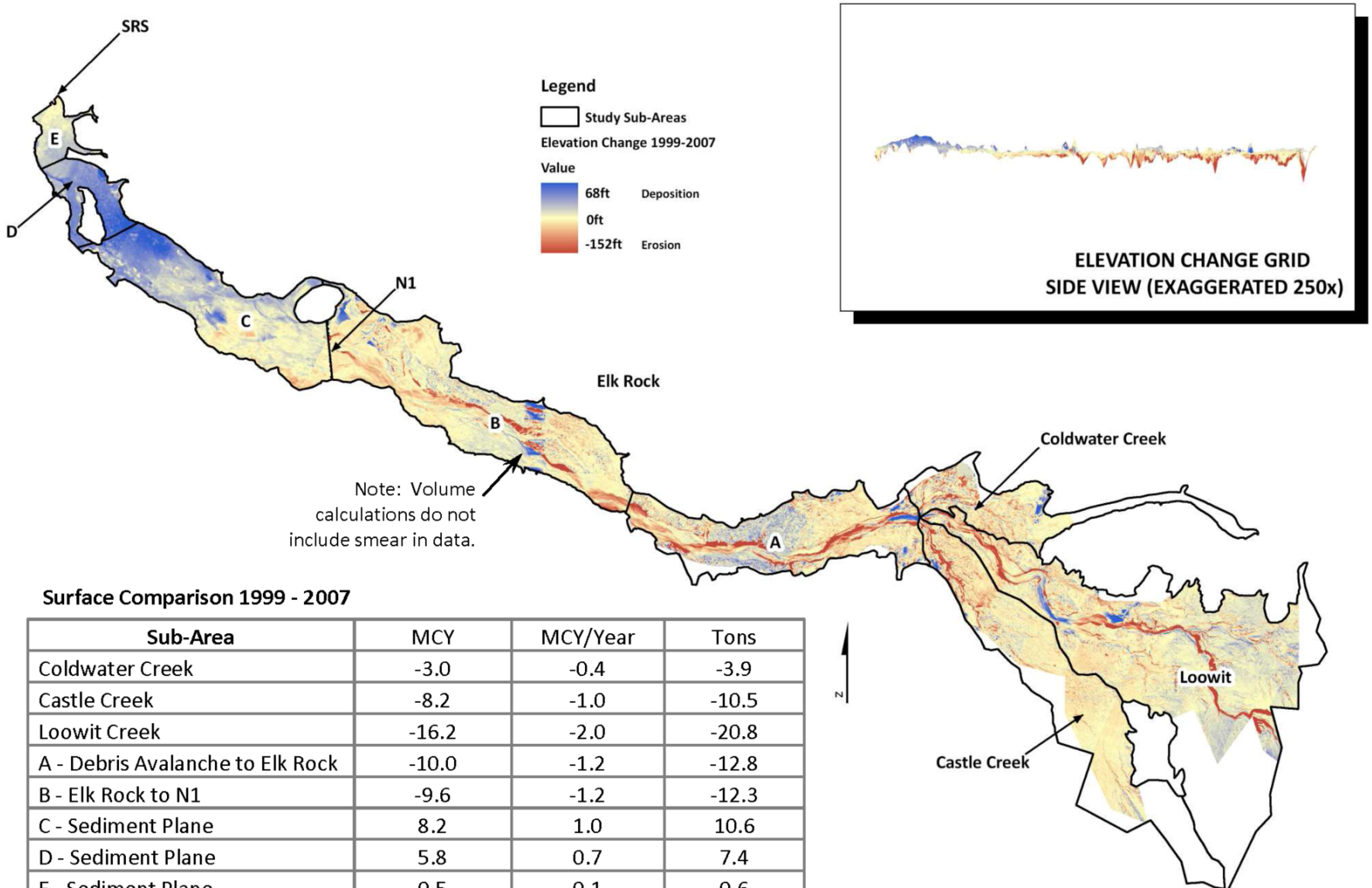


Figure 4.21 Surface Comparison of 2006 and 2007 LiDAR



Surface Comparison 1999 - 2007

Sub-Area	MCY	MCY/Year	Tons
Coldwater Creek	-3.0	-0.4	-3.9
Castle Creek	-8.2	-1.0	-10.5
Loowit Creek	-16.2	-2.0	-20.8
A - Debris Avalanche to Elk Rock	-10.0	-1.2	-12.8
B - Elk Rock to N1	-9.6	-1.2	-12.3
C - Sediment Plane	8.2	1.0	10.6
D - Sediment Plane	5.8	0.7	7.4
E - Sediment Plane	0.5	0.1	0.6
Total Erosion	-47.0	-5.9	-60.3
Total Deposition	14.5	1.8	18.6

Figure 4.22 Surface Comparison of 1999 Photogrammetry and 2007 LiDAR

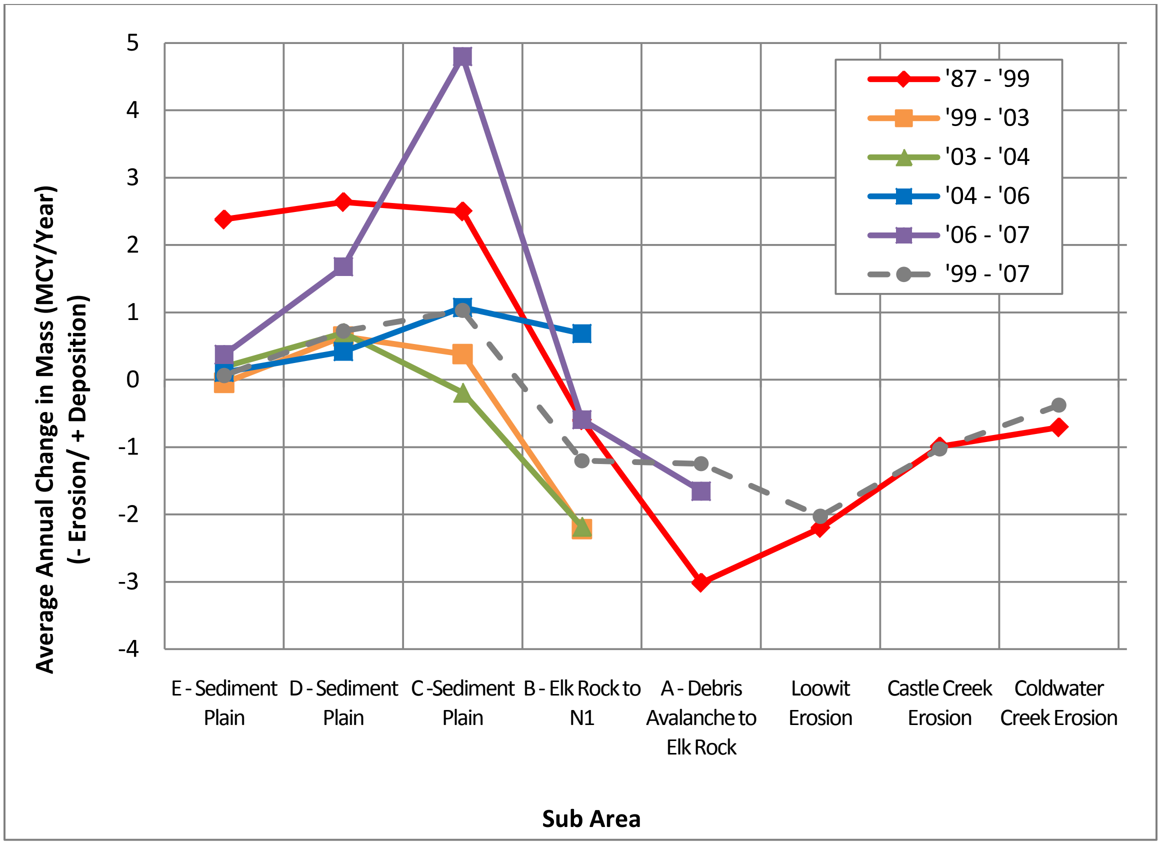


Figure 4.23 Average Annual Change in Mass Calculated from Surface Comparisons 1987 - 2007

4.3.2 Variability of Surface Comparison

Three main sources of inaccuracies contribute to variability in the results of the surface comparisons including: 1) accuracy of the original topographic data sets, 2) conversion of each data set to a DEM, and 3) the combination of two data sets.

The vertical and horizontal error in survey data is dependent upon the method and resolution by which it was collected. Standard accuracy of LiDAR data is approximately +/- 20 cm (or 0.65 feet). 2006 and 2007 LiDAR data obtained by the Portland District through contract was found to be accurate to +/- 0.2 feet.

An elevation assigned to each cell of a DEM is derived by averaging the elevation data within the area of a given cell, which in this analysis has a size of 100 square feet. Accuracy of a DEM can be increased by decreasing the cell size to adequately capture the accuracy of the original data set. A 10’ x 10’ cell size was determined to be an optimum selection for use with all data sets. Quantification of the error associated with the development of the DEM is unknown.

Certainty in the detection of change between two surfaces is dependent upon the combined error associated with each. An uncertainty analysis was conducted on all surface comparisons between 1987 and 2007. The analysis conservatively assumes that the combined vertical error of any two data sets used in the comparison is +/- 4 feet. Five sequences of 1,000 random numbers having a mean of 0.0 feet and a standard deviation of 2 feet were generated to represent error in any given cell of the surface comparison grids. The frequency of the vertical error, shown in Figure 4.24, was then distributed over the area of each surface comparison to determine a possible range of volume calculations.

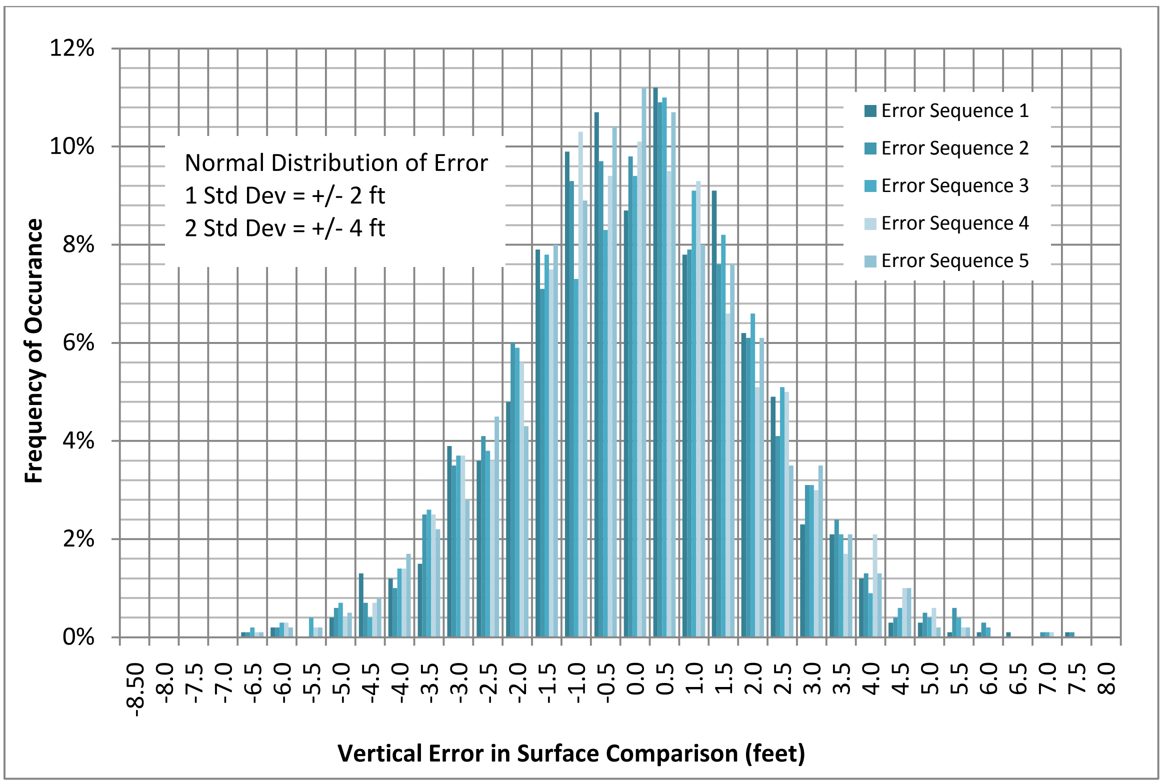


Figure 4.24 Distribution of Vertical Error in Surface Comparison Used in Uncertainty Analysis

The percentage of error associated with each surface comparison and sequence is listed in Table 4.5. It is apparent that as the time period increases the percentage of error decreases. Therefore, the most accurate surface comparisons are 1987 – 1999 and 1999 – 2007. The least accurate is the 2003 – 2004 comparison, which had the lowest change in volumes. Conservatively, all volumes computed by surface comparison between 1987 and 2007 have a range of +/- 15%.

Table 4.5 Possible Error in Surface Comparison Volumes

Surface Comparison	Error Sequence				
	# 1	# 2	# 3	# 4	# 5
1987 - 1999	0.2 %	0.6 %	0.2 %	0.3 %	0.6 %
1999 - 2003	1.3 %	3.4 %	1.4 %	1.4 %	2.8 %
2003 - 2004	5.4 %	14.4 %	5.7 %	7.1 %	13.8 %
2004 - 2006	1.9 %	5.0 %	2.0 %	2.5 %	4.8 %
2006 - 2007	2.3 %	6.2 %	2.4 %	2.9 %	5.7 %
1999 - 2007	0.4 %	1.1 %	0.4 %	0.5 %	1.1 %

4.4 Debris Avalanche Erosion

The area from the headwaters of the North Fork of the Toutle River, up to and including the Mt St Helens crater, down to the N-1 sediment retention structure generally constitutes the debris avalanche. This area includes Coldwater Creek, Castle Creek, Loowit Creek, and sub-areas A and B, as shown in Figure 4.15 to Figure 4.22. The debris avalanche is the primary source of sediment contributing to the Toutle/Cowlitz basin. An analysis of the debris avalanche erosion was conducted to estimate the volume of material available for erosion after the eruption, volume of material that has been eroded to date, and an estimate of future erosion volumes by 2035. Results of the analysis will be utilized as input to the sediment budget as well as provide insight into the past and current trends in erosion.

The surface comparisons presented in the previous section provided the basis to evaluate the change in volumes of the debris avalanche. Three distinct comparisons; 1984 to 1987, 1987 to 1999, and 1999 to 2007; provide similar coverage and an estimate of the change in erosion rates from the debris avalanche for the specific timeframe. A summary table of debris avalanche erosion occurring between 1984 and 2007 is provided in Table 4.6. The percent of erosion from each contributing sub-area is provided in Table 4.7.

Table 4.6 Debris Avalanche Erosion, 1984 - 1987

Surface Comparison	Water Years	Total Debris Avalanche Erosion			
		MCY	MCY/Year	MTons	MTons/Year
1984 – 1987	1985 - 1987	239.2	79.7	306.8	102.3
1987 – 1999	1988 - 1999	90.2	7.5	115.7	9.6
1999 – 2007	2000 - 2007	47.0	5.9	60.3	7.5

Table 4.7 Distribution of Debris Avalanche Erosion by Sub-Area, 1984 - 2007

	Surface Comparison		
	'84 –'87	'87 – '99	'99 – '07
Sub-Area	% of Total Erosion		
Coldwater Creek Erosion	6%	9%	6%
Castle Creek Erosion	10%	13%	17%
Loowit Erosion	53%	29%	34%
A - Debris Avalanche to Elk Rock	32%	40%	21%
B - Elk Rock to N1	0%	8%	20%

4.4.1 Annual Debris Avalanche Erosion

Computation of erosion from the debris avalanche supported the development of the final sediment budget by providing upstream sediment discharge boundary conditions. The sediment budget calculations were conducted for two time periods: water years 1988 – 1999, and 2000 – 2007. In addition to the total volume for each of the two time periods, the sediment budgets were also broken down annually for years 1999 through 2007 while still maintaining consistency with the longer time period budgets. To develop the annual sediment budgets, a method for pro-rating the debris avalanche erosion was developed using annual suspended sediment data and measured deposition behind the SRS. Using available data, yearly distribution of erosion from the debris avalanche was developed by summing the deposition occurring upstream of the SRS and measured suspended sediment moving past the SRS. A combination of the USGS suspended sediment data and measured SRS deposition was used to develop a method to pro-rate debris avalanche erosion. Suspended sediment samples were increased by 25 percent to account for unmeasured load not represented in the sample. The following equations were used to pro-rate the debris avalanche erosion (X) annually:

$$X_{year} = TL\ SS_{year} - SF\ SS_{year} + SRS_{year} \qquad \text{(Equation 4.1)}$$

Where:

Year	Water Year
X_{year}	Debris avalanche erosion for given water year
$TL\ SS_{year}$	Toutle at Tower Road annual suspended sediment + 25% unmeasured load
$SF\ SS_{year}$	South Fork annual suspended sediment + 25% unmeasured load
SRS_{year}	Annual deposition behind the SRS

$$X_T = TL\ SS_T - SF\ SS_T + SRS_T \qquad \text{(Equation 4.2)}$$

Where:

X_T	Debris avalanche erosion for given time period
T	Time Period of Surface Comparison (1988 – 1999, or 2000 – 2007)
TL SS_T	Toutle at Tower Road annual suspended sediment + 25% unmeasured load
SF SS_T	South Fork annual suspended sediment + 25% unmeasured load
SRS_T	Annual deposition behind the SRS

$$P_{year} = X_{year}/X_T \quad \text{(Equation 4.3)}$$

Where:

P	Pro-rating Percentage

$$E_{year} = P_{year} \times D_T \quad \text{(Equation 4.4)}$$

Where:

E	Annual Debris Avalanche Erosion (pro-rated)
D_T	Total debris avalanche erosion for a given time period calculated by surface comparison

The use of annual suspended sediment data in pro-rating the debris avalanche erosion was selected to mirror the annual trends in hydrology and erosion captured by the data. An example of the relationships between suspended sediment data and hydrology was shown in Figure 3.1 for the Toutle River gage at Tower Road. Annual suspended sediment data was not available consistently on the North Fork; therefore the difference between the South Fork and Toutle at Tower annual suspended sediment was calculated and used in Equation 4.1. Annual deposition occurring upstream of the SRS is discussed in detail in the following section. Data used in the calculations as well as the pro-rated annual debris avalanche erosion is provided in Table 4.8.

Table 4.8 Annual Debris Avalanche Erosion

Water Year	SRS Deposition	Toutle @ Tower SS + 25% Unmeasured	South Fork SS + 25% Unmeasured	TL SS - SF SS + SRS	Pro-Rating %	Debris Avalanche Erosion [A]	Annual Debris Avalanche Erosion [B]
	SRS	TL SS	SF SS	X	P	D	E
	(Tons)	(Tons)	(Tons)	(Tons)	%	Tons	Tons
1988	11,872,248	2,934,275	565,419	14,241,105	10.4%	115,737,360	12,022,967
1989	6,302,889	1,030,754	291,987	7,041,656	5.1%		5,944,875
1990	10,493,546	3,170,834	1,285,395	12,378,985	9.0%		10,450,883
1991	9,498,440	3,479,820	1,242,669	11,735,592	8.6%		9,907,702
1992	4,330,706	990,310	545,852	4,775,163	3.5%		4,031,403
1993	3,560,388	599,038	730,176	3,429,249	2.5%		2,895,123
1994	3,104,816	216,637	58,234	3,263,219	2.4%		2,754,953
1995	10,665,034	2,027,006	697,005	11,995,035	8.7%		10,126,736
1996	21,835,633	8,714,928	3,699,398	26,851,163	19.6%		22,668,932
1997	13,609,499	4,053,595	2,672,014	14,991,080	10.9%		12,656,129
1998	12,096,204	2,662,180	1,847,274	12,911,110	9.4%		10,900,126
1999	8,365,154	6,743,761	1,632,322	13,476,592	9.8%		11,377,532
2000	-2,838,613	4,023,174	433,201	751,361	1.6%	60,290,311	946,244
2001	-162,102	489,463	22,218	305,143	0.6%		384,289
2002	4,578,825	4,939,967	1,162,933	8,355,859	17.5%		10,523,145
2003	3,454,201	3,179,656	207,998	6,425,860	13.4%		8,092,556
2004	898,168	1,712,502	233,357	2,377,313	5.0%		2,993,925
2005	2,057,315	1,745,924	293,455	3,509,784	7.3%		4,420,128
2006	2,057,315	3,590,795	302,303	5,345,808	11.2%		6,732,368
2007	8,788,236	16,754,252	4,740,351	20,802,137	43.5%		26,197,656

[A] Debris avalanche erosion determined by surface comparison
[B] Estimated annual debris avalanche erosion by method of pro-rating

4.4.2 Debris Avalanche Erosion Rates and Decay

A comparison of debris avalanche erosion for the three time periods analyzed indicates a dramatic drop in the rate of erosion after 1987 and a slight decrease in erosion rates occurred between 1987 and 2007. Comparison of the erosion rates of 7.5 MCY/Year and 5.9 MCY/Year for 1987 – 1999 and 1999 – 2007, respectfully, must also be considered in the context of hydrology. The total water yield at Tower Road for both time periods was 18.7 million acre-feet for 1987 – 1999, and 11.0 million acre-feet for 2000 – 2007, a 40% difference. It should also be noted that both time periods experienced two significant storm events in 1996 and 2007. The 1996 event was determined to be a more intense event relative to 2007. The hydrologic trends of the two time periods coincide with the slight decrease seen in the debris avalanche erosion. Therefore, there is no solid evidence that decay has occurred in the past 20 years.

Erosion rates have been estimated and predicted for the project life in several other studies. Figure 4.25 shows a comparison of debris avalanche erosion rates for the period of 1980 to 2035 developed from these studies. Since significant decay (reduction in the rate of erosion) has not been detected with a high level of certainty for the past 20 years, the constant erosion rate of 5.9 MCY/Year was extended into the future to 2035, which compares closely to WEST (2002).

Annual debris avalanche erosion values from Table 4.8 were also utilized to produce projections to 2035. Annual erosion values from 2000 – 2007 were randomly selected to generate a 28 year sequence from 2008 to 2035. A total of 10,000 sequences were generated. The 5% and 95% exceedance values of the resulting 10,000 sequences of cumulative erosion were then determined to be the bounding projection. Forecasting by this method allows for erosion rates tied to hydrologic trends to be combined in all possible combinations, which eliminates uncertainty associated with possible wet, average, or dry year combinations. Figure 4.26 compares the cumulative annual projections for the period 1980 to 2035 with several other reports. Figure 4.27 draws a similar comparison for the period 2008 through 2035. Note that for 2008 though 2035, all projections are approaching a linear trend. Table 4.9 provides a summary of the debris avalanche erosion projections. Cumulative debris avalanche erosion predicted by 2035 ranges from 125 to 227 MCY, with a mean predicted value of 165 MCY.

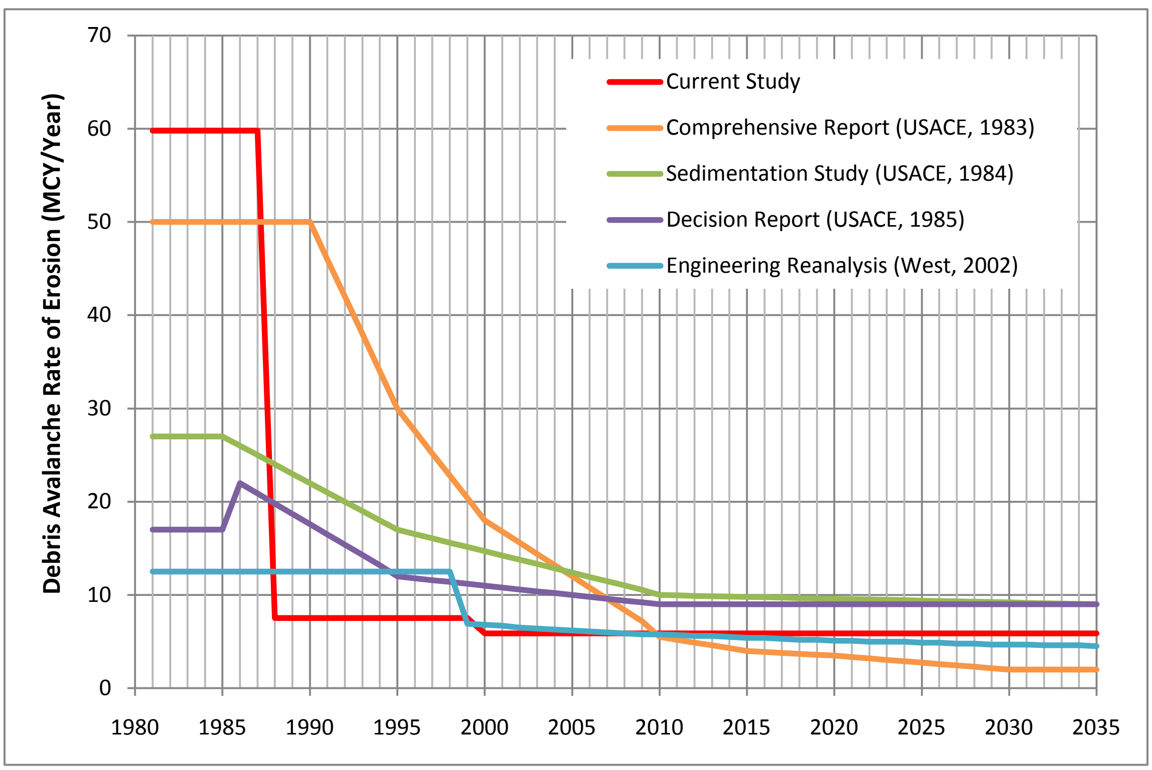


Figure 4.25 Comparison of Estimated Debris Avalanche Erosion Rates for 1981 - 2035

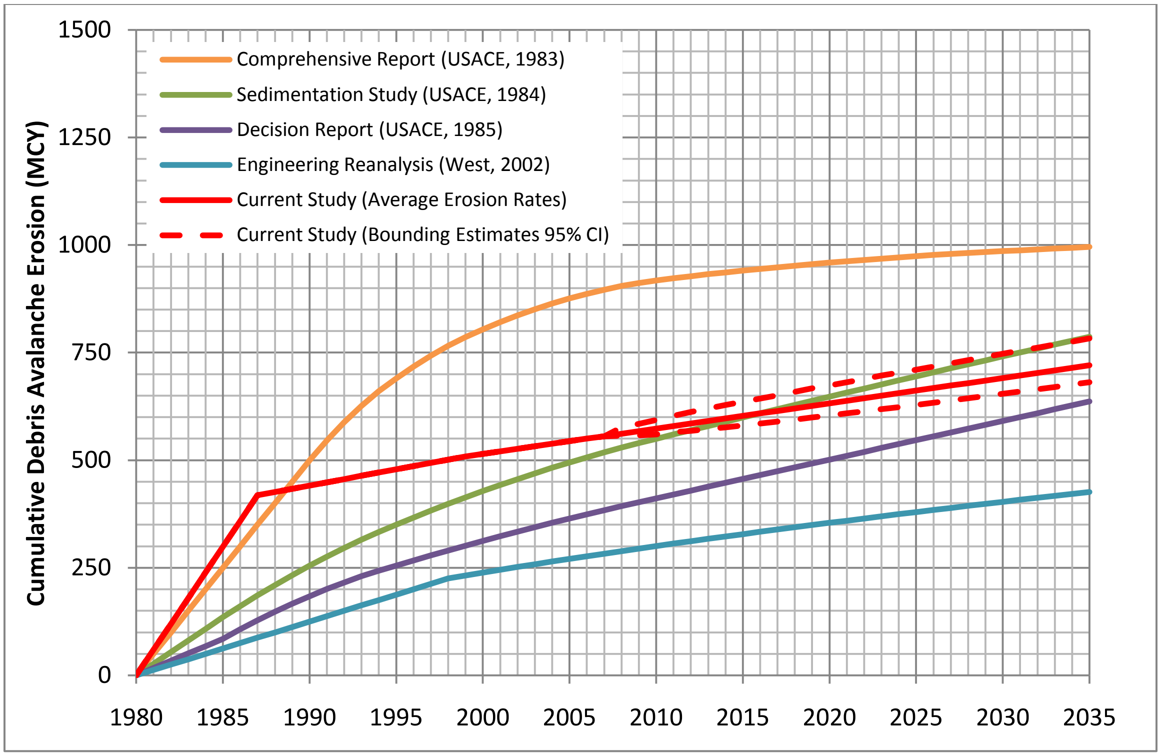


Figure 4.26 Comparison of Estimated Cumulative Debris Avalanche Erosion from 1981 – 2035

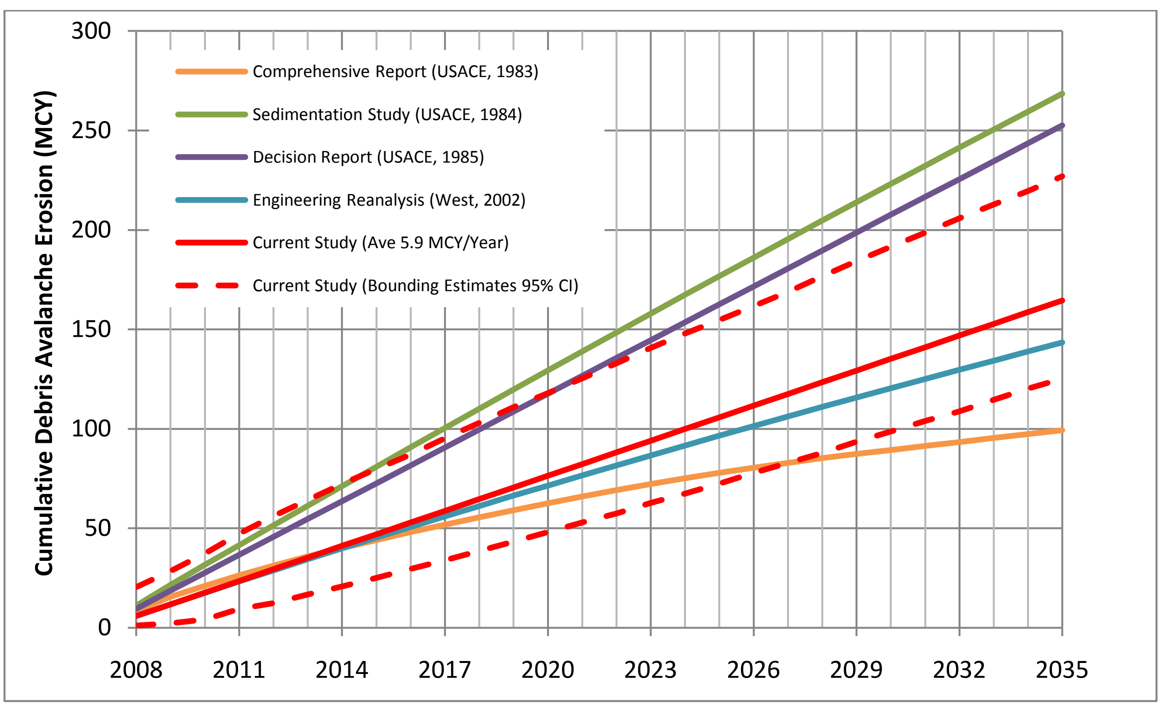


Figure 4.27 Comparison of Estimated Cumulative Debris Avalanche Erosion from 2008 – 2035

Table 4.9 Debris Avalanche Erosion Projections

Study	Total Erosion 1981 - 2035	Total Erosion 2008 - 2035
	(MCY)	(MCY)
Comprehensive Report (USACE, 1983)	1,000	100
Sedimentation Study (USACE, 1984)	750	269
Decision Report (USACE, 1985)	630	253
Engineering Reanalysis (West, 2002)	414	143
Current Study [A]	720	165

[A] Erosion rate of 5.9 MCY/Year assumed from 2008 - 2035

It has previously been estimated that just after the eruption the debris avalanche contained approximately 3 billion cubic yards of material. Results of the pre- and post-eruption surface comparison analysis indicate that 2.6 billion cubic yards of material remained in place by 1984. Table 4.10 provides an estimate of remaining material on the debris avalanche relative to the 1984 volume. Comparison of the volumes indicates that the debris avalanche will be a continual source of sediment well past the project life.

Table 4.10 Percent of Debris Avalanche Material Remaining

Time Period	Debris Avalanche Erosion [A, B]	Remaining Debris Avalanche Material [A]	% of Debris Avalanche Material Remaining [C]
	MCY	MCY	%
1984	--	2,633	--
1984 – 1987	239	2,394	91%
1987 – 1999	90	2,304	87%
1999 – 2007	47	2,257	86%
2007 – 2035	170	2,087	84%
2035 – 2050	94	1,993	82%
2050 – 2080	182	1,811	79%

[A] Volumes calculated by GIS surface comparison
[B] Erosion rate of 5.9 MCY/Year assumed after 2007
[C] % of Debris Avalanche Remaining relative to 1984

4.4.3 Debris Avalanche Gradations

The most extensive data set of gradations collected on the debris avalanche was found in the Cowlitz/Toutle Gradation Study (USACE, 1984). Gradation data existing in 1984 from a variety of sources was compiled, and additional samples were collected to supplement the existing data. Gradation data collected specifically for the 1984 investigation included 250 surface samples taken along 12 cross-sections between N-1 and Spirit Lake, and 28 samples taken from 21 backhoe pits in the active channel between N-1 and Coldwater Creek. In addition, approximately 90 backhoe samples were taken on the main stem and North Fork Toutle River. Most samples were 80 pound bag samples. The total data base included gradations for 3,070 samples.

A summary gradation curve from USACE (1984), including the mean and 2 standard deviations, representing debris avalanche samples collected between North Fork River Mile 19 and 36 is presented in Figure 4.28. The summary gradation was utilized as a starting point for estimating the debris avalanche erosion by grain size for the sediment budget. Estimates of debris avalanche erosion by grain size for input into the sediment budget will be further discussed in Section 4.6.

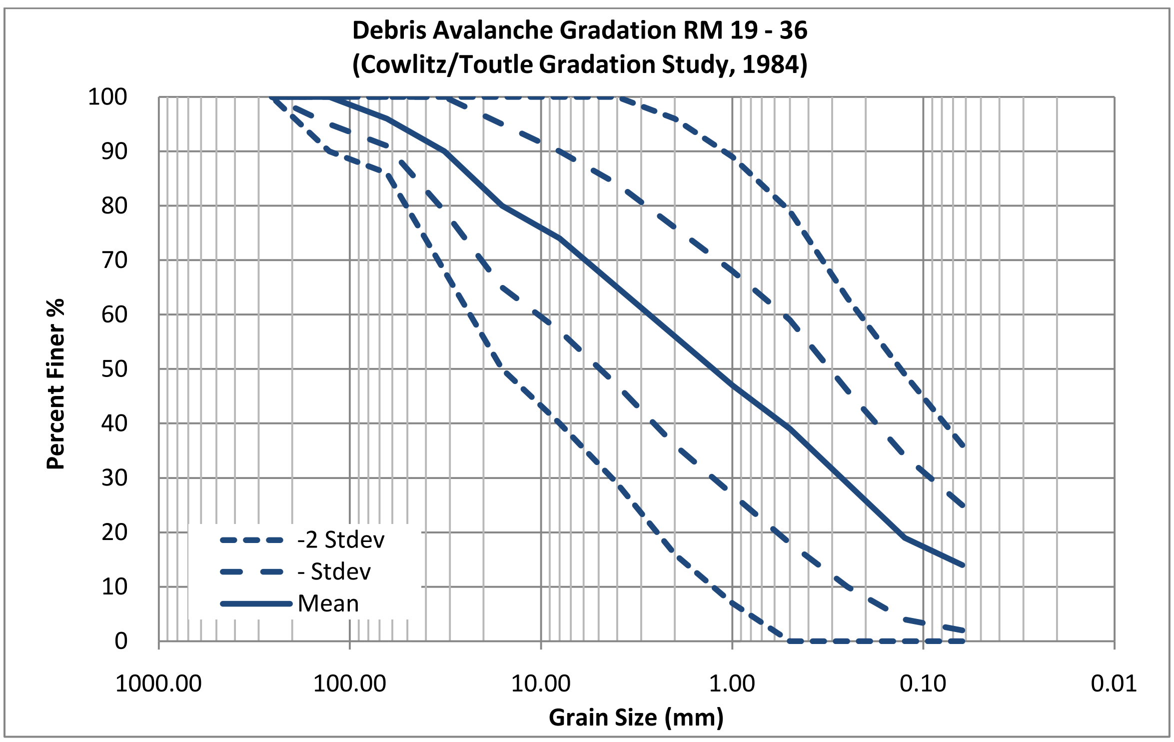


Figure 4.28 Average Debris Avalanche Material Gradations, Cowlitz/Toutle Gradation Study (USACE 1984)

4.5 SRS Sediment Plain Deposition

Since construction in 1988, the SRS has continuously captured sediment eroding from the debris avalanche. Deposition induced by the SRS has resulted in the development of an extensive sediment plain extending approximately seven miles upstream to the now defunct N-1 retention structure. As part of a monitoring program repeat cross section surveys and gradation samples have been collected on the sediment plane since 1988. This data has proven to be invaluable in development of depositional volumes by grain class for input into the sediment budget.

Quantification of annual deposition occurring behind the SRS on the sediment plain, and classification of the gradation is a key component to the sediment budget. Annual sediment plain deposition occurring during water years 1988 through 2007 were calculated using a combination of cross section survey data and the surface comparison presented in Section 4.3. An extensive set of gradations samples were also compiled and analyzed. Volume and gradation data was then combined to develop annual depositional volumes by grain size.

4.5.1 SRS Sediment Plain Deposition by End Area Method

A monitoring program, beginning just after construction of the SRS, of the SRS sediment plain has been consistently surveyed using twenty-five (25) cross sections since the construction of the SRS. Figure 4.29 identifies the locations of the discrete cross sections along the sediment plain upstream of the SRS, the distances between which are presented in Table 4.11. Yearly estimates of deposition volumes behind the SRS were part of an on-going effort to monitor the performance and modify the operation of the SRS.

To support the creation of the sediment budget, and to provide accurate information regarding major sources of sediment in the Toutle-Cowlitz system, an evaluation was performed on the total amount of sediment trapped by the SRS between 1987 and 2007. Cross sections were developed from surfaces created for each year from 1987 to 2007 to identify areas of degradation and aggradation. Figure 4.29 presents cross section alignment used in volume computations. Distances between cross sections are consistent with values in Table 4.11. Computation of volumes from net changes in sediment plain surfaces within a particular reach was achieved using a simple average end area method, with the total volume for a given year as the sum of each individual reach length's volume.

Data sources describing the sediment plain varied from 1987 to 2007. Generally, sources used to create surfaces of the sediment plain were derived from either photogrammetric aerial surveys, ground surveys (total station or GPS), or plane mounted LiDAR surveys. Table 4.12 summarizes the source of information used to create a surface describing the sediment plain from years 1987 to 2007.

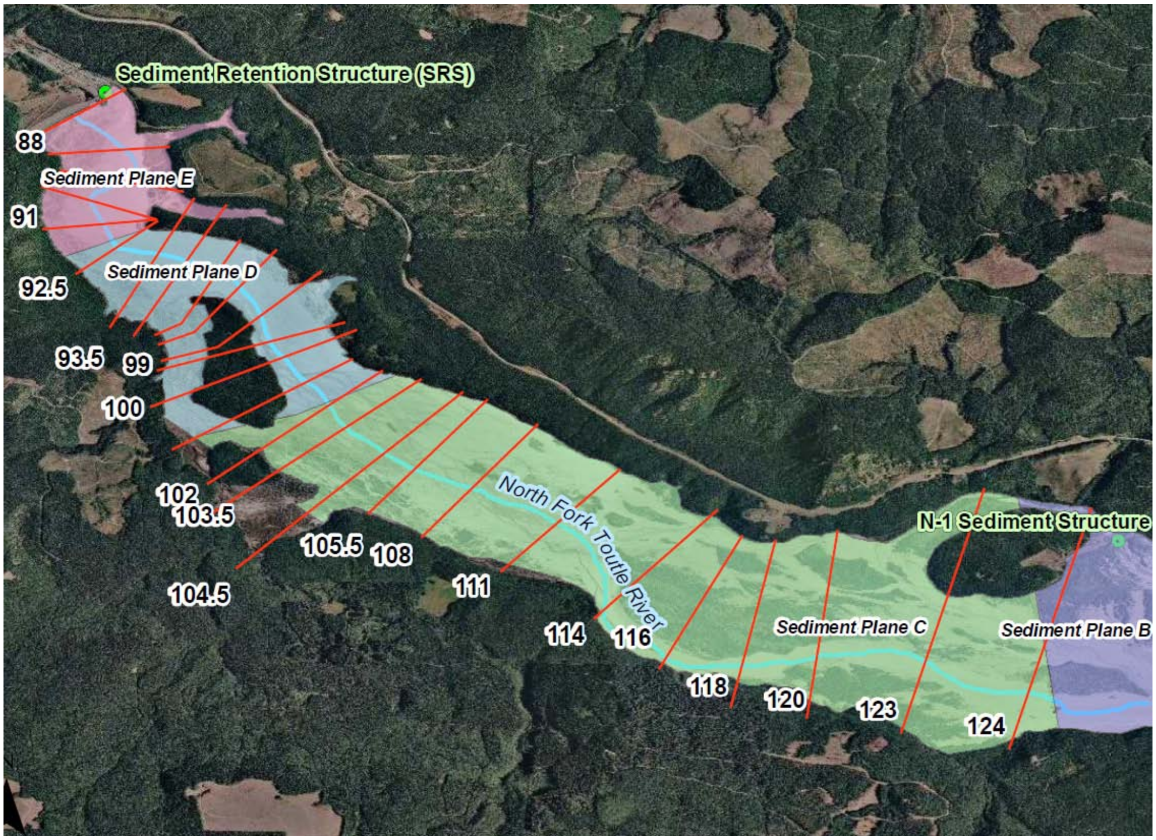


Figure 4.29 Cross Section Locations along the Sediment Plain upstream of the SRS

Table 4.11 Reach Lengths for Cross Sections within Sediment Plain

XS Name	RM	Reach Length (ft)	Cumulative Reach Length (ft)
123	19.9	2513	27390
120	19.4	1490	24877
118	19	1280	23387
116	18.7	1504	22107
114	18.3	2501	20603
111	17.6	2178	18102
108	17	1357	15924
105.5	16.7	802	14567
104.5	16.4	1144	13765
103.5	16.1	769	12621
102	15.9	879	11852
101	15.8	951	10973
100	15.6	558	10022
99	15.4	901	9464
98	15.3	989	8563
96	15.1	619	7574
95	14.9	764	6955
94	14.7	657	6191
93.5	14.5	872	5534
92.5	14.3	828	4662
91	14	670	3834
90	13.9f	793	3164
89	13.8	922	2371
88	13.6	1449	1449
87	13.5	0	0

Table 4.12 Sources of Information for Surfaces used in SRS Volume Computations

Year	Source of Information
1987	Raster Developed from Photogrammetry
1988	TIN Created from Total Station Survey
1989	TIN Created from Total Station Survey
1990	TIN Created from Total Station Survey
1991	TIN Created from Total Station Survey
1992	TIN Created from Total Station Survey
1993	TIN Created from Total Station Survey
1994	TIN Created from Total Station Survey
1995	TIN Created from Total Station Survey
1996	TIN Created from Total Station Survey
1997	TIN Created from Total Station Survey
1998	TIN Created from GPS Survey
1999	Raster Developed from Photogrammetry
2000	TIN Created from GPS Survey
2001	TIN Created from GPS Survey
2002	Not Available
2003	Raster Created from LiDAR
2004	Not Available
2005	Raster Created from LiDAR
2006	Raster Created from LiDAR
2007	Raster Created from LiDAR

Estimates of change in volume of the sediment plain were computed to support yearly monitoring efforts of the SRS and are summarized in the hydrologic summary reports. Previously computed values were compared to present computations of sediment volumes to verify consistent computational techniques, which were then applied in future years where previous computations are not available. Table 4.13 summarizes the computed net change in volume of the sediment plain from 1987 to 2007 and compares the computed results to the previously reported values from the Hydrologic Summary Reports.

Table 4.13 Summary of Net Volume Change in Sediment Plain

Year	Current Computations (MCY)	Hydrologic Summary Reports (MCY)
1987-1988	10.05	6.80
1988-1989	5.33	5.10
1989-1990	8.88	9.10
1990-1991	8.04	8.10
1991-1992	3.66	3.70
1992-1993	3.01	3.00
1993-1994	2.63	2.40
1994-1995	9.03	8.20
1995-1996	18.48	19.00
1996-1997	11.52	11.90
1997-1998	10.24	10.40
1998-1999	7.08	5.30
1999-2000	-2.44	0.10
2000-2001	-0.19	0.00
2001-2003	7.63	8.50
2003-2004	0.83	
2004-2006	3.67	
2006-2007	7.02	
Totals		
1987-2003	102.94	101.60
1987-2007	114.47	N/A

Data from Table 4.13 is represented graphically in **Error! Reference source not found.** where the net volume is plotted with respect to year and compared simultaneously with the reported maximum mean daily discharge just below the SRS (USGS Gage 14240525).

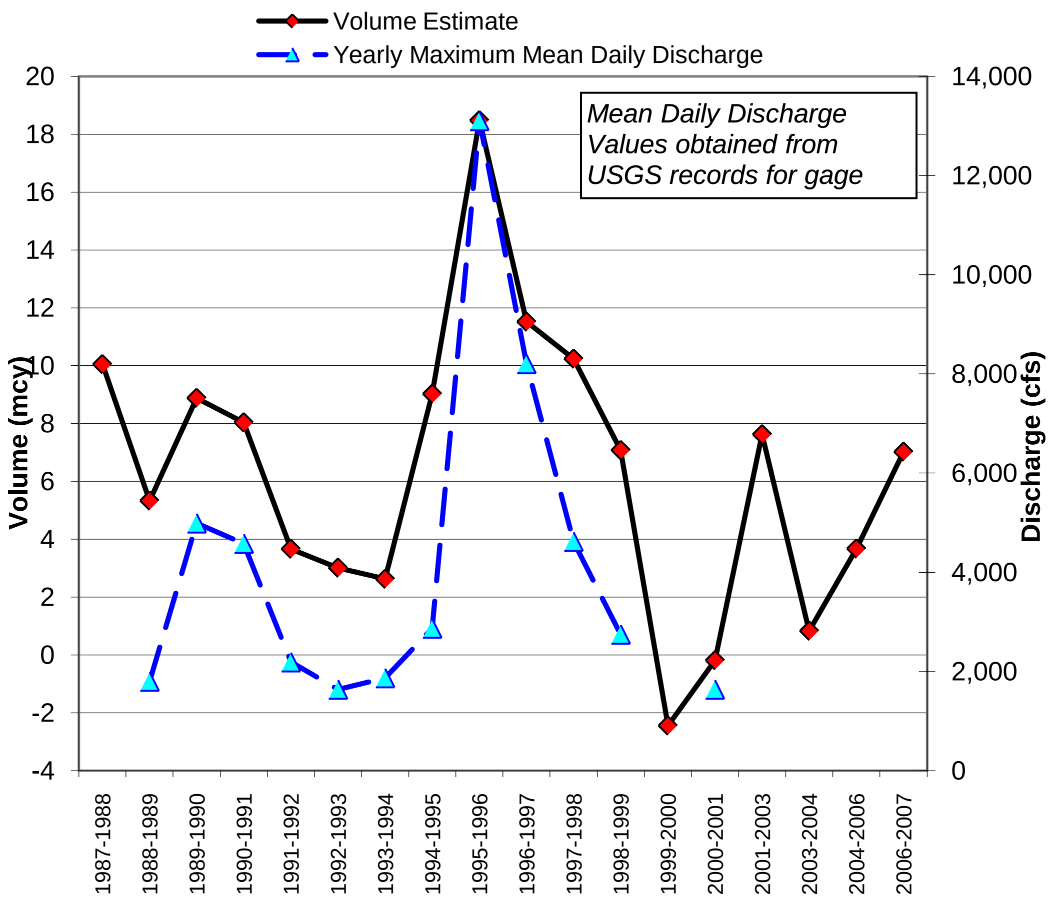


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Figure 4.30 Net Volume Change in Sediment Plain

Computation of the net change in sediment plain surfaces shown in Table 4.13 compares reasonably well to those values reported from previous hydrologic summary reports. For the period from 1987 to 2003 where hydrologic summary reports are available the difference between the computed volume and the reported volume is 1.34 MCY or 1.3 percent difference. Further, the fluctuation of the computed net change of the sediment plain surface is consistent to the record of maximum mean daily discharges reported by the USGS. Satisfactory validation of the computation of sediment volume fluctuations in the sediment plain supports the further use of the volume computations, along with the gradation data, for use as input in the sediment budget.

4.5.2 Sediment Plain Deposition by Surface Comparison

Depositional volumes computed by the end-area cross section method presented in the previous section were compared to results of the surface analysis presented in Section 4.3. Volumes computed by the cross section end-area method typically have more error due to the variability in terrain occurring between cross sections. Volume computations performed by surface analysis utilizing GIS provide more accurate results due to the continuous coverage of data. Surface comparison analysis was not available on an annual basis therefore values computed from the end-area cross section method were adjusted to account for differences between data sets. Table 4.15 provides a comparison of both data sets and the annual volumes utilized in the sediment budget. The difference in volumes between methods ranges from -2.5 to -27%, with the average end-area method yielding consistently larger volumes.

Table 4.14 Comparison of Annual Sediment Plain Deposition

<table>
<tr><th rowspan="2">Water Year</th><th>End-Area Cross Section Method</th><th>Surface Comparisons</th><th colspan="2">Adjusted for Use in Sediment Budget</th></tr>
<tr><th>MCY</th><th>MCY</th><th>MCY</th><th>M Tons</th></tr>
<tr><td>1988</td><td>10.05</td><td rowspan="12">90.24</td><td>9.26</td><td>11.87</td></tr>
<tr><td>1989</td><td>5.33</td><td>4.91</td><td>6.30</td></tr>
<tr><td>1990</td><td>8.88</td><td>8.18</td><td>10.49</td></tr>
<tr><td>1991</td><td>8.04</td><td>7.41</td><td>9.50</td></tr>
<tr><td>1992</td><td>3.66</td><td>3.38</td><td>4.33</td></tr>
<tr><td>1993</td><td>3.01</td><td>2.78</td><td>3.56</td></tr>
<tr><td>1994</td><td>2.63</td><td>2.42</td><td>3.10</td></tr>
<tr><td>1995</td><td>9.03</td><td>8.32</td><td>10.67</td></tr>
<tr><td>1996</td><td>18.48</td><td>17.03</td><td>21.84</td></tr>
<tr><td>1997</td><td>11.52</td><td>10.61</td><td>13.61</td></tr>
<tr><td>1998</td><td>10.24</td><td>9.43</td><td>12.10</td></tr>
<tr><td>1999</td><td>7.08</td><td>6.52</td><td>8.37</td></tr>
<tr><td>2000</td><td>-2.44</td><td rowspan="4">3.92</td><td>-2.21</td><td>-2.84</td></tr>
<tr><td>2001</td><td>-0.19</td><td>-0.13</td><td>-0.16</td></tr>
<tr><td>2002</td><td rowspan="2">7.63</td><td>3.57</td><td>4.58</td></tr>
<tr><td>2003</td><td>2.69</td><td>3.45</td></tr>
<tr><td>2004</td><td>0.83</td><td>0.70</td><td>0.70</td><td>0.90</td></tr>
<tr><td>2005</td><td rowspan="2">3.67</td><td rowspan="2">3.21</td><td>1.6</td><td>2.06</td></tr>
<tr><td>2006</td><td>1.6</td><td>2.06</td></tr>
<tr><td>2007</td><td>7.02</td><td>6.85</td><td>6.85</td><td>8.79</td></tr>
<tr><td colspan="5">Totals</td></tr>
<tr><td>1988 - 1999</td><td>97.94</td><td colspan="2">90.24</td><td>115.7</td></tr>
<tr><td>1999 - 2003</td><td>5.00</td><td colspan="2">3.92</td><td>5.0</td></tr>
<tr><td>2003 - 2004</td><td>0.83</td><td colspan="2">0.70</td><td>0.9</td></tr>
<tr><td>2004 - 2006</td><td>3.67</td><td colspan="2">3.21</td><td>4.1</td></tr>
<tr><td>2006 - 2007</td><td>7.02</td><td colspan="2">6.85</td><td>8.8</td></tr>
</table>

The sediment plain deposition values applied to the sediment budget were computed annually for sub-areas C, D, and E, identified in the surface comparison analysis (Table 4.16). Depositional volumes were broken into sub-areas to allow for the application of different gradations of material representing the coarsening observed in samples and field observations.

Table 4.15 Annual Sediment Plain Deposition by Sub-Area

Water Year	**Sub-Area C**	**Sub Area D**	**Sub Area E**
	M Tons	**M Tons**	**M Tons**
1988	6.03	3.20	2.50
1989	4.14	1.48	0.54
1990	3.16	4.86	2.47
1991	5.83	2.28	1.19
1992	1.41	1.88	1.03
1993	1.73	1.09	0.71
1994	1.21	1.38	0.50
1995	2.37	6.90	1.42
1996	6.31	8.24	7.36
1997	3.28	5.36	5.06
1998	1.94	2.36	8.01
1999	1.09	1.59	5.85
2000	-2.58	1.18	-1.44
2001	-0.16	0.00	0.00
2002	2.68	1.21	0.69
2003	2.02	0.91	0.52
2004	-0.24	0.89	0.25
2005	1.37	0.54	0.14
2006	1.37	0.54	0.14
2007	6.16	2.15	0.48

Note: + indicates deposition/-indicates erosion

4.5.3 Sediment Plain Gradations

In addition to computing depositional volume, annual estimates of SRS performance included sediment sampling. Although not entirely complete for the whole time period, gradation samples collected on the sediment plain for various years of the SRS operation have proven valuable in developing appropriate input for the sediment budget.

In the years following the eruption of Mount St. Helens in 1980, substantial efforts were extended to quantify and qualify deposits within the Toutle-Cowlitz system. Sediment samples taken by the U.S. Army Corps of Engineers (USACE) from 1980 to 1988 were compiled in the *Sediment Gradation Analysis Results, 1980-1988* document published in December 1988. Sediment samples taken by USACE after 1988 were generally compiled in hydrologic summaries of the respective water year reports. Additional sediment samples were taken by the Biedenharn Group in 2007. A compilation of gradation samples were used to support analysis of the sediment plain composition used to compute volumes per grain size for sediment accumulated behind the SRS. Table 4.16 lists the cross-section sampled during each of the years between 1987 and 2007.

The general approach used to characterize the size fraction of the sediment behind the SRS was to first normalize all the sediment samples to a common particle size gradation distribution and then assign a specific gradation at a given cross section for a given year. Normalizing the gradation was achieved, where necessary, by using a logarithmic interpolation routine to transfer an existing gradation size classes to that of the common desired particle size distribution.

After compiling all the available SRS gradation data, information gaps were identified at cross section locations for given years. Where sediment samples had not been taken, an estimated gradation was developed by creating representative sediment gradations from adjacent cross sections or years, and assigning the representative gradations to the areas lacking sampled data.

From the database of gradations, particle distribution parameters were computed to provide a sense of the spatial relationship of particle size between cross sections. The median (D50) grain size, computed for each cross section, was plotted versus river mile. As evident in Figure 4.31, the median grain size tends to increase with distance upstream of the SRS, although significant variability in grain size is evident.

Table 4.16 Available Gradation Data

Cross Section	1987	1989	1990	1991	1992	1997	1998	1999	2000	2007
123	X			X	X	X				
120	X			X	X					
118				X						
116	X			X	X					X
114				X	X					
111	X			X	X			X		
108				X	X	X		X		
105.5				X	X					
104.5				X	X	X				
103.5	X			X	X			X		
102				X	X		X			
101				X	X			X		
100			X	X	X					
99			X	X	X			X		
98			X	X	X					
96			X	X	X	X		X		
95	X	X	X	X						
94	X	X	X	X						
93.5	X	X	X	X						
92.5	X	X	X	X		X				
91	X	X	X							
90		X	X			X		X		
89		X	X	X	X					
88		X	X	X		X		X		
87	X		X	X					X	X

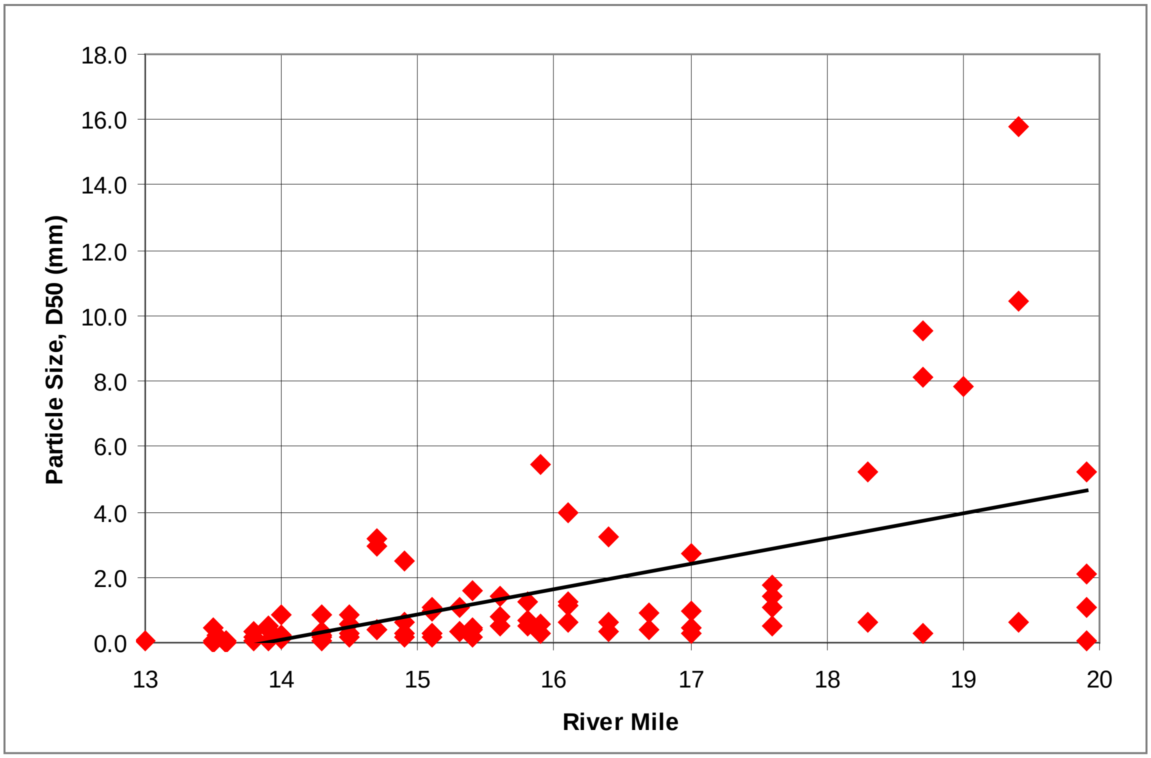

Figure 4.31 D50 of the SRS Sediment Plain with respect to River Mile

A review of the temporal trends of the gradation data revealed that, in general, there is a fining effect over time for the sediment behind the SRS. It is expected that construction of the SRS caused reduction of the hydraulic gradient upstream of the dam, thus depositing finer material along with coarse material. As sand accumulation increased with time the percentage of fine material deposited behind the dam also increases. Figure 4.32 illustrates this general fining effect. Considering that the sediment behind the dam reached the spillway elevation around 1998, it was expected that this fining effect would diminish from 1998 to 2007; however, this could not be verified due to lack of gradation data in these latter years.

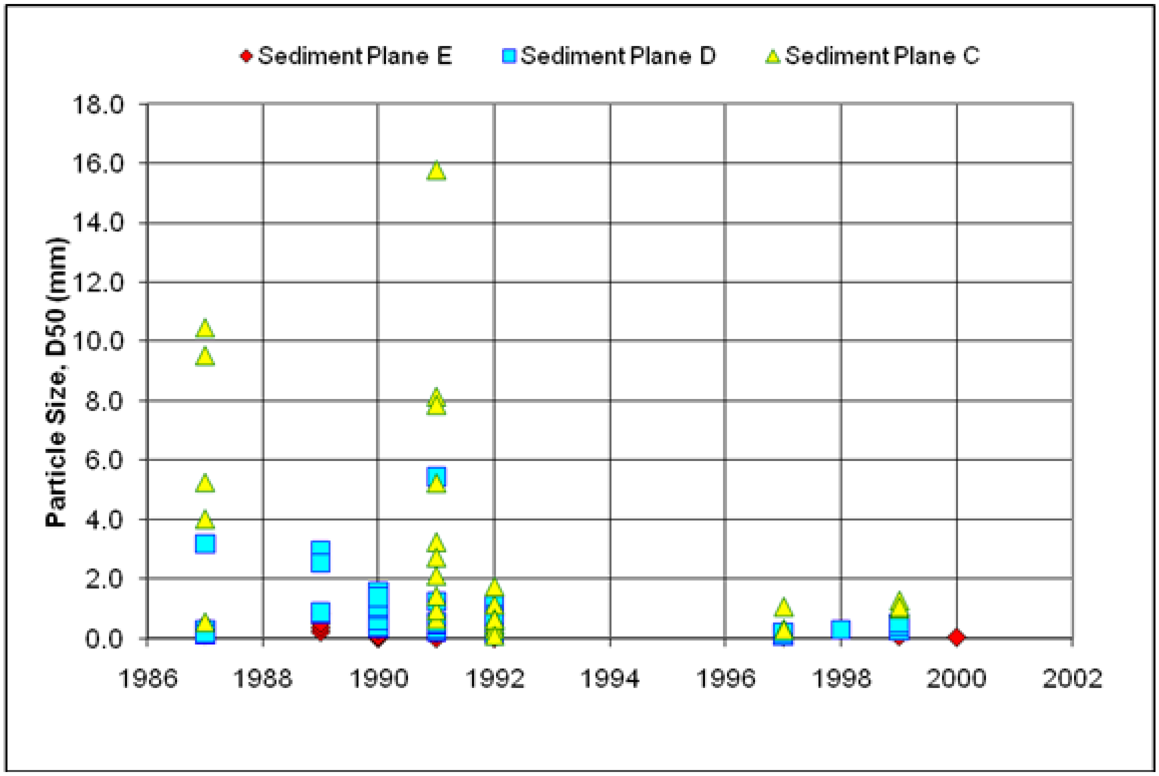

Figure 4.32 D50 along the SRS Sediment Plain with respect to Time

Using available sediment samples, as shown in Table 4.16, a composite database was created to provide sediment gradation data along the sediment plain from 1988 to 2007. This database was used to facilitate a volume estimate per grain size for the sediment plain. Using sampled data to fill in information data gaps resulted in a full dataset that was reasonably representative of general trends in the gradation data. This is shown for the D50 in Figure 4.33 where the full dataset is plotted with the original dataset.

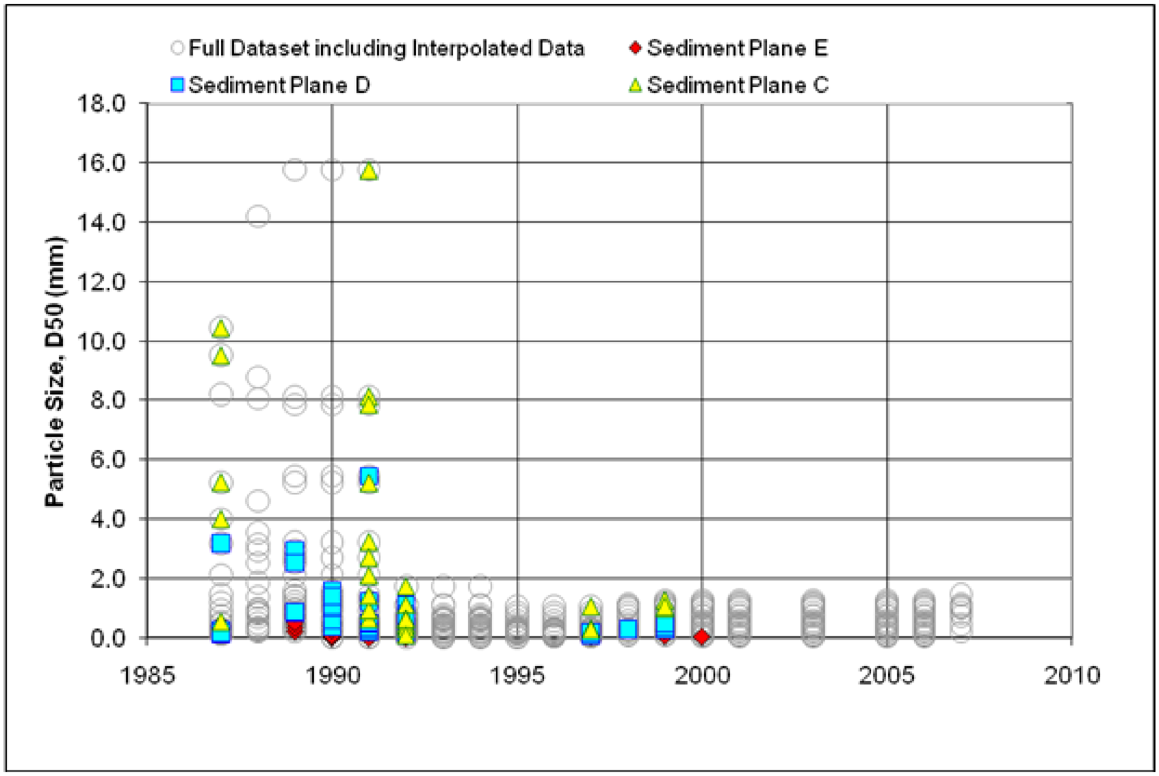

Figure 4.33 D50 of the SRS Sediment Plain with respect to Time, Full Dataset

From Figure 4.33 there appears to be significant fining in the D50 from 1991 to 1992. A review of the data indicated that the location of the samples was not consistent with previous samplings, which may bias the result. Comparing the actual samples collected in 1992 to the actual samples collected in 1997, there still appears to be an overall fining effect with respect to time.

The full gradation dataset, including interpolated data, was utilized to compute composite gradations, pro-rated by volume changes, for sub-areas C, D, and E of the sediment plain. The resulting composite gradation of material depositing behind the SRS for water years 1999 through 2007 and sediment plain sub-areas C, D, and E are shown in Figures 4.34 through 4.36. The resulting gradations were then applied to the depositional volumes provided in Table 4.15 for use in the sediment budget. It should be noted that gradations for water year 2001 are not shown in Figures 4.35 and 4.36 because the net change in volume was found to be zero.

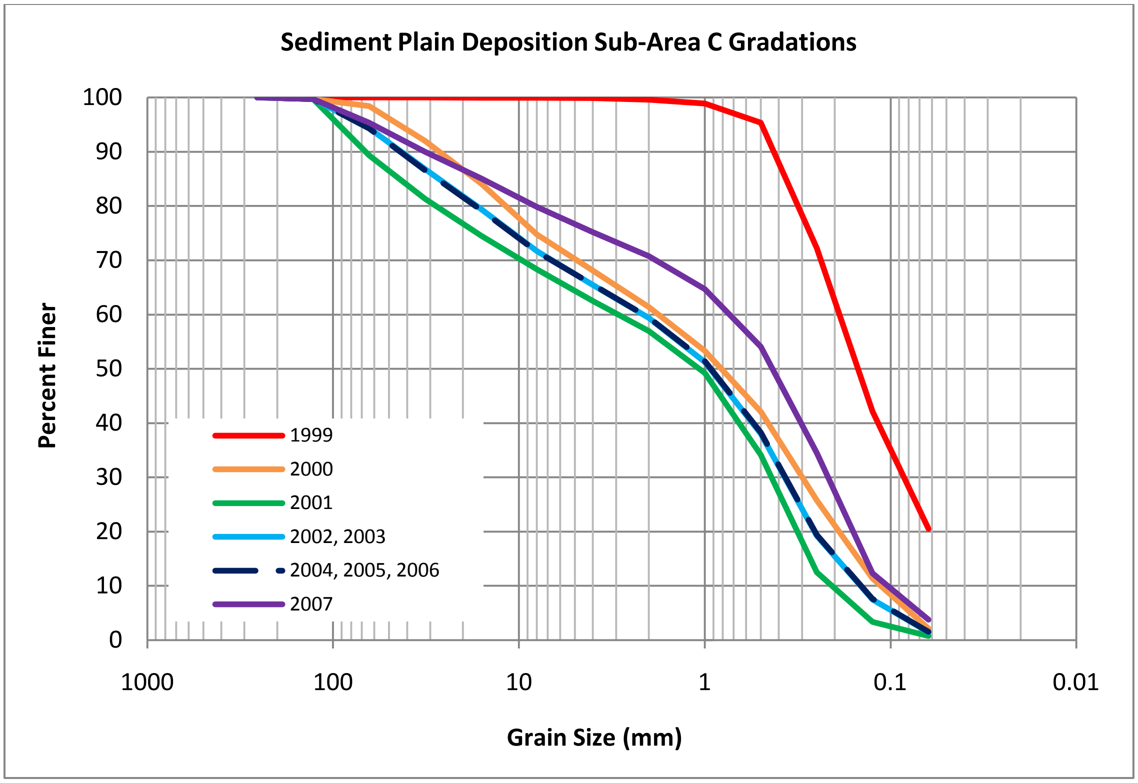

Figure 4.34 Gradation of sediment plain deposition for Sub-Area C

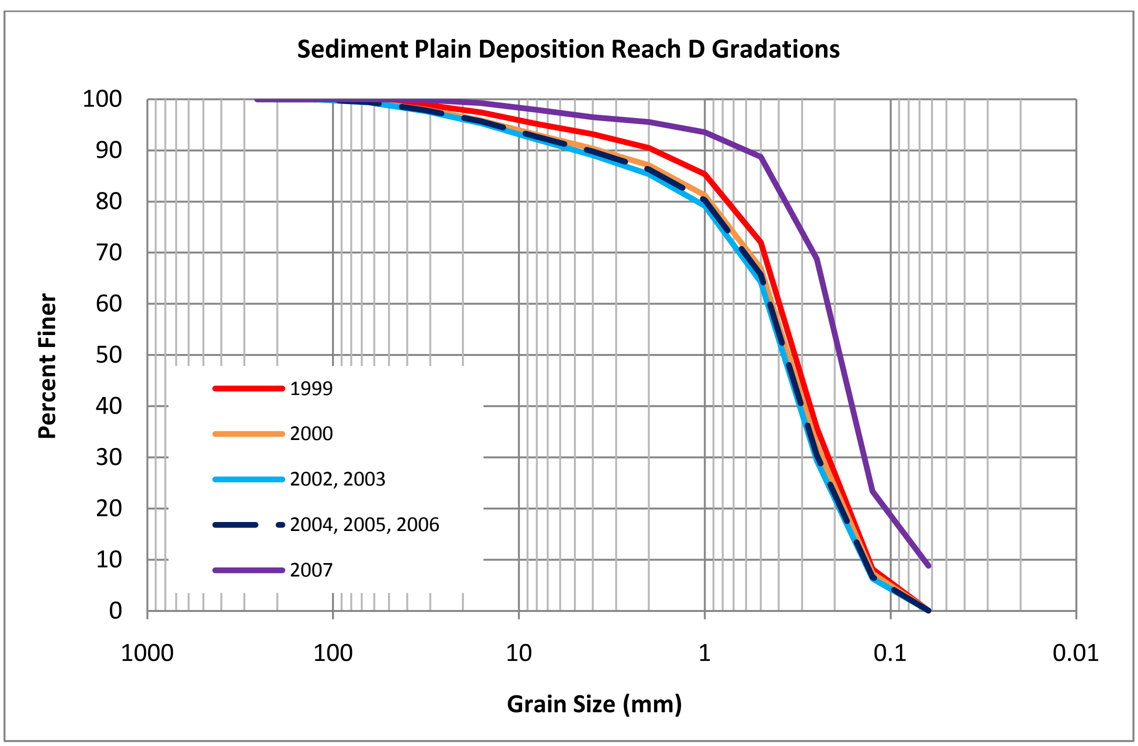

Figure 4.35 Gradation of sediment plain deposition for Sub-Area D

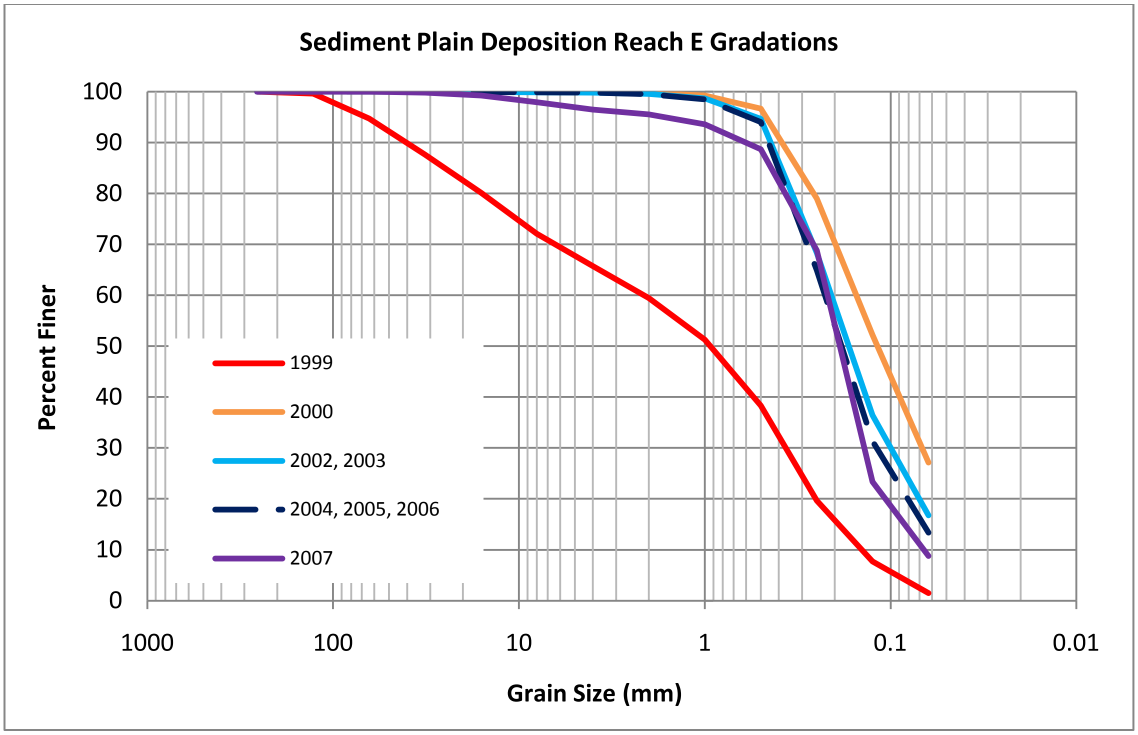

Figure 4.36 Gradation of sediment plain deposition for Sub-Area E

Analysis of gradation information combined with the annual volumes of deposition behind the SRS between 1988 and 1998, prior to sediment reaching the spillway crest, provides insight to the gradation of material eroding from the debris avalanche. The gradation of material deposited during 1988 – 1998 is presented in Figure 4.37, along with a comparison to the 1984 debris avalanche gradation samples. During the period in which the SRS was filling to the spillway crest it is likely that very fine sands, silts and clays were passing through the outlet works and into the lower North Fork. Given the passing of smaller grain sizes it is likely that the true gradation of material eroding from the debris avalanche, also shown in Figure 4.37, contains these smaller grain sizes. Therefore, a reasonable debris avalanche gradation for use in the sediment budget would have the same shape as the gradation computed for material depositing behind the SRS, however, more fine material would be evident. The gradation shown in red in Figure 4.37 was applied to the debris avalanche erosion and sediment plain sub-areas A and B volumes for input to the sediment budget.

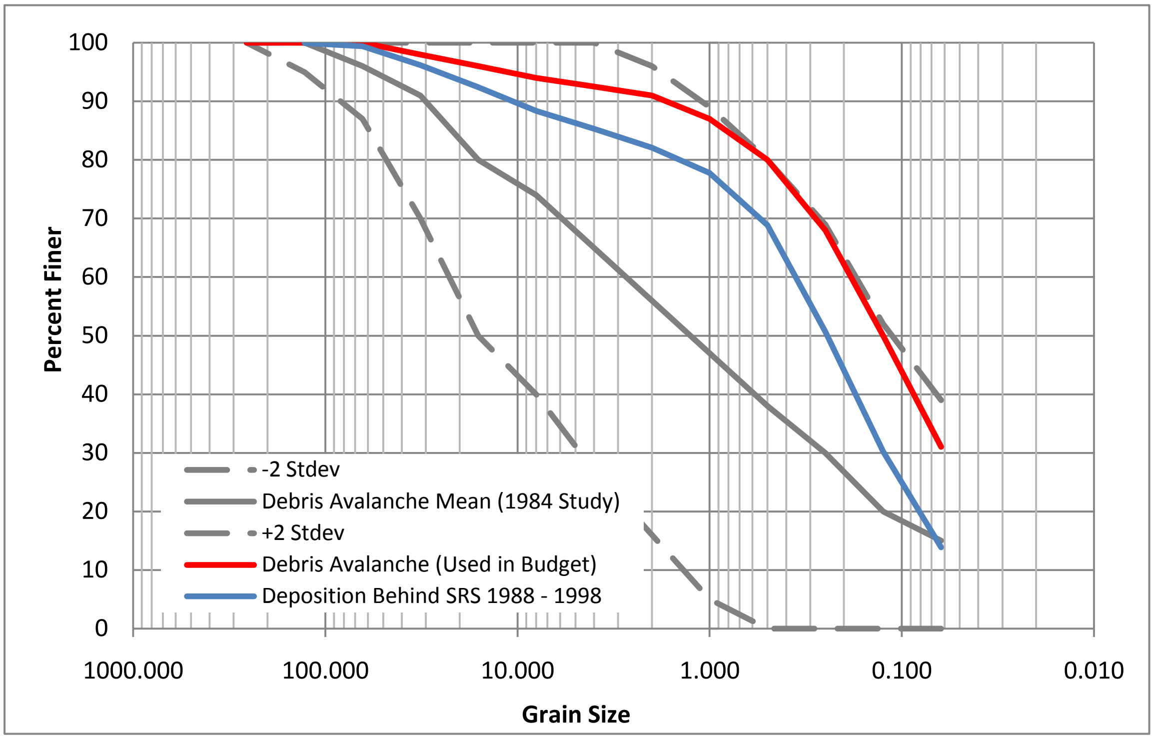

Figure 4.37 Gradation of material deposited behind SRS between 1988 - 1998

4.6 Sediment Output from the SRS

The SRS effectively trapped sediment during the first 10 years of operation until the closure of all outlet works in 1998, at which time flows began permanently passing through the spillway. For the past 10 years sediment moving through the spillway of the SRS has contributed to deposition of sands in the lower Cowlitz River. Figure 4.38 presents annual estimates from 1988 through 2007 of debris avalanche erosion, SRS sediment plain deposition, and the difference. Comparison of annual estimates of erosion and deposition verifies that between 1988 and 1998 the SRS was an effective sediment trap and between 1999 and 2007 sediment is clearly exiting through the spillway. Identification and quantification of sediment output from the SRS by grain size is a key component of sediment budget development.

Annual sediment output from the SRS was first calculated by computing the difference between debris avalanche erosion and sediment plain deposition by grain class for water years 1999 – 2007. Results of the calculations were reviewed by grain class and compared with field observations. Field observations and hydraulic calculations indicate that it is highly unlikely for gravel (>2mm) to be transported over the sediment plain and through the SRS spillway.

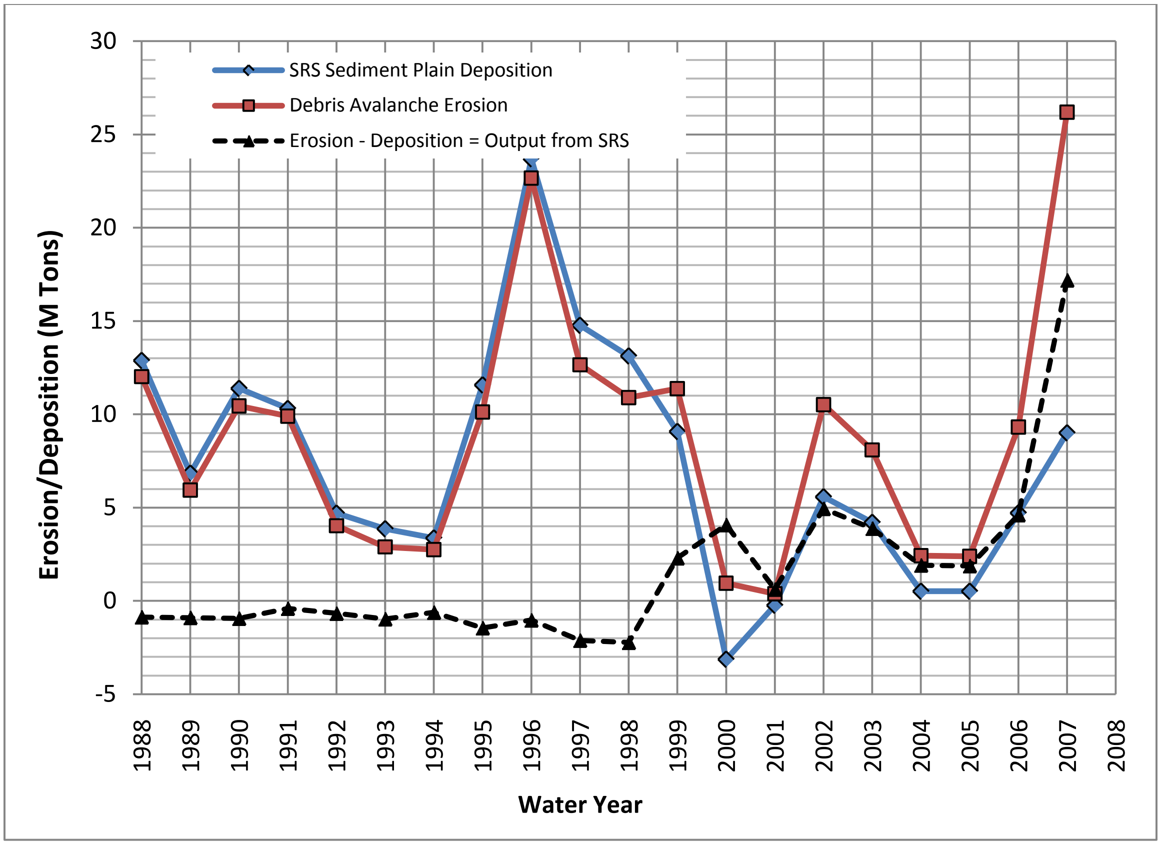

Figure 4.38 Annual Estimates of Debris Avalanche Erosion and SRS Deposition for WYs 1988 - 2007

During multiple site visits gravel was not observed to be present on the lower portion of the sediment plain or downstream of the SRS spillway. Furthermore, hydraulic calculations presented in Section 2.3 indicate that stream power and critical shear is not high enough to transport material in the gravel range over the sediment plain. Processes observed on the upper sediment plain indicate that gravel will be exchanged for sands or finer material as sediment moves downstream towards the spillway. Therefore, calculated sediment output from the SRS was adjusted to limit gravels from exiting the SRS while redistributing the volume of gravel to sands or finer material. Table 4.17 provides the annual debris avalanche erosion, SRS sediment plain deposition, calculated sediment output from the SRS, and the adjusted sediment output from the SRS all by grain size for water years 1999 through 2007. These calculations were used directly in each annual sediment budget. Sediment output from the SRS is shown graphically in Figures 4.39 and 4.40.

Table 4.17 Calculation of Sediment Output from the SRS

Total Erosion Upstream of SRS (M Tons)													
Water Year	**Silt/Clay**	**Sand**					**Gravel**						**Total**
	0.0625	**0.125**	**0.25**	**0.5**	**1**	**2**	**4**	**8**	**16**	**32**	**64**	**128**	
1999	3.53	2.16	2.05	1.37	0.80	0.46	0.23	0.17	0.17	0.17	0.17	0.09	11.38
2000	0.29	0.18	0.17	0.11	0.07	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.95
2001	0.12	0.07	0.07	0.05	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.38
2002	3.26	2.00	1.89	1.26	0.74	0.42	0.21	0.16	0.16	0.16	0.16	0.08	10.52
2003	2.51	1.54	1.46	0.97	0.57	0.32	0.16	0.12	0.12	0.12	0.12	0.06	8.09
2004	0.93	0.57	0.54	0.36	0.21	0.12	0.06	0.04	0.04	0.04	0.04	0.02	2.99
2005	1.37	0.84	0.80	0.53	0.31	0.18	0.09	0.07	0.07	0.07	0.07	0.03	4.42
2006	2.09	1.28	1.21	0.81	0.47	0.27	0.13	0.10	0.10	0.10	0.10	0.05	6.73
2007	8.12	4.98	4.72	3.14	1.83	1.05	0.52	0.39	0.39	0.39	0.39	0.20	26.20
Total Deposition Upstream of SRS (M Tons)													
Water Year	**Silt/Clay**	**Sand**					**Gravel**						**Total**
	0.0625	**0.125**	**0.25**	**0.5**	**1**	**2**	**4**	**8**	**16**	**32**	**64**	**128**	
1999	-0.31	-0.73	-1.47	-1.92	-1.01	-0.57	-0.41	-0.40	-0.51	-0.46	-0.43	-0.29	-8.53
2000	0.44	0.51	0.46	0.27	0.16	0.15	0.14	0.14	0.21	0.18	0.15	0.03	2.84
2001	0.00	0.00	0.01	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.16
2002	-0.16	-0.37	-0.81	-1.11	-0.56	-0.30	-0.21	-0.20	-0.25	-0.23	-0.22	-0.15	-4.58
2003	-0.12	-0.28	-0.61	-0.84	-0.42	-0.23	-0.16	-0.15	-0.19	-0.17	-0.17	-0.12	-3.45
2004	-0.04	-0.09	-0.26	-0.33	-0.11	-0.04	-0.02	-0.01	-0.01	0.00	0.00	0.01	-0.90
2005	-0.04	-0.14	-0.33	-0.48	-0.27	-0.15	-0.10	-0.10	-0.12	-0.11	-0.11	-0.08	-2.06
2006	-0.04	-0.14	-0.34	-0.49	-0.27	-0.14	-0.10	-0.10	-0.12	-0.11	-0.11	-0.08	-2.06
2007	-0.46	-0.91	-2.56	-1.73	-0.78	-0.42	-0.30	-0.32	-0.36	-0.32	-0.33	-0.27	-8.79

Note: + indicates erosion/- indicates deposition

Table 4.17 Calculation of Sediment Output from the SRS (Continued)

Sediment Output from SRS = Erosion - Deposition (M Tons)													
Water Year	Silt/Clay	Sand					Gravel						Total
	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	128	
1999	3.22	1.43	0.58	-0.56	-0.21	-0.11	-0.19	-0.23	-0.34	-0.29	-0.26	-0.20	2.84
2000	0.74	0.69	0.63	0.38	0.22	0.19	0.16	0.16	0.22	0.19	0.16	0.03	3.78
2001	0.12	0.08	0.08	0.08	0.05	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.55
2002	3.11	1.63	1.08	0.16	0.18	0.12	0.00	-0.05	-0.09	-0.07	-0.06	-0.07	5.94
2003	2.39	1.26	0.84	0.14	0.14	0.10	0.00	-0.03	-0.06	-0.05	-0.05	-0.05	4.64
2004	0.89	0.48	0.28	0.03	0.10	0.08	0.04	0.03	0.04	0.04	0.05	0.03	2.10
2005	1.33	0.70	0.46	0.05	0.04	0.03	-0.02	-0.04	-0.06	-0.05	-0.05	-0.04	2.36
2006	2.05	1.13	0.87	0.32	0.21	0.12	0.03	0.00	-0.02	-0.01	-0.01	-0.03	4.68
2007	7.66	4.07	2.16	1.41	1.05	0.62	0.23	0.07	0.04	0.07	0.06	-0.07	17.41
Adjusted Sediment Output from SRS = Erosion - Deposition (M Tons)													
Water Year	Silt/Clay	Sand					Gravel						Total
	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	128	
1999	1.75	0.78	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.84
2000	0.98	0.92	0.84	0.50	0.30	0.25	0.00	0.00	0.00	0.00	0.00	0.00	3.78
2001	0.15	0.10	0.10	0.10	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.55
2002	2.95	1.54	1.03	0.15	0.17	0.12	0.00	0.00	0.00	0.00	0.00	0.00	5.94
2003	2.28	1.20	0.80	0.13	0.14	0.09	0.00	0.00	0.00	0.00	0.00	0.00	4.64
2004	1.00	0.54	0.32	0.03	0.11	0.09	0.00	0.00	0.00	0.00	0.00	0.00	2.10
2005	1.20	0.63	0.42	0.04	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	2.36
2006	2.04	1.13	0.87	0.31	0.20	0.12	0.00	0.00	0.00	0.00	0.00	0.00	4.68
2007	7.86	4.17	2.21	1.45	1.08	0.64	0.00	0.00	0.00	0.00	0.00	0.00	17.41

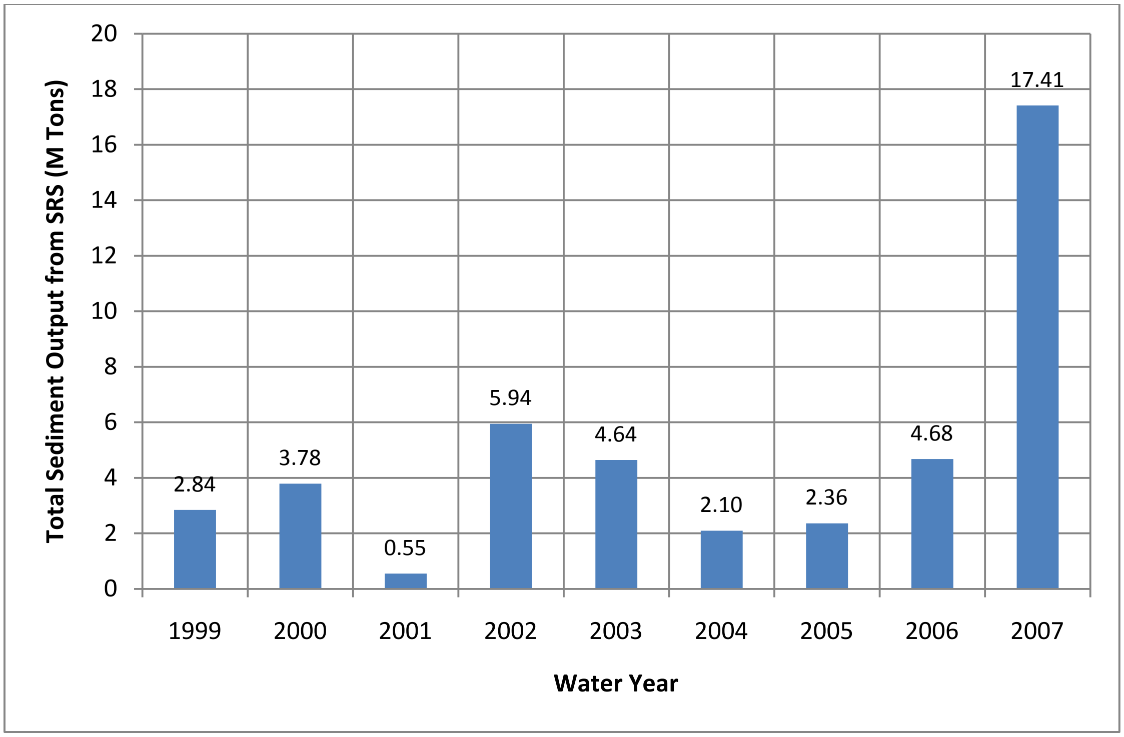

Figure 4.39 Total Sediment Output from the SRS for WYs 1999 - 2007

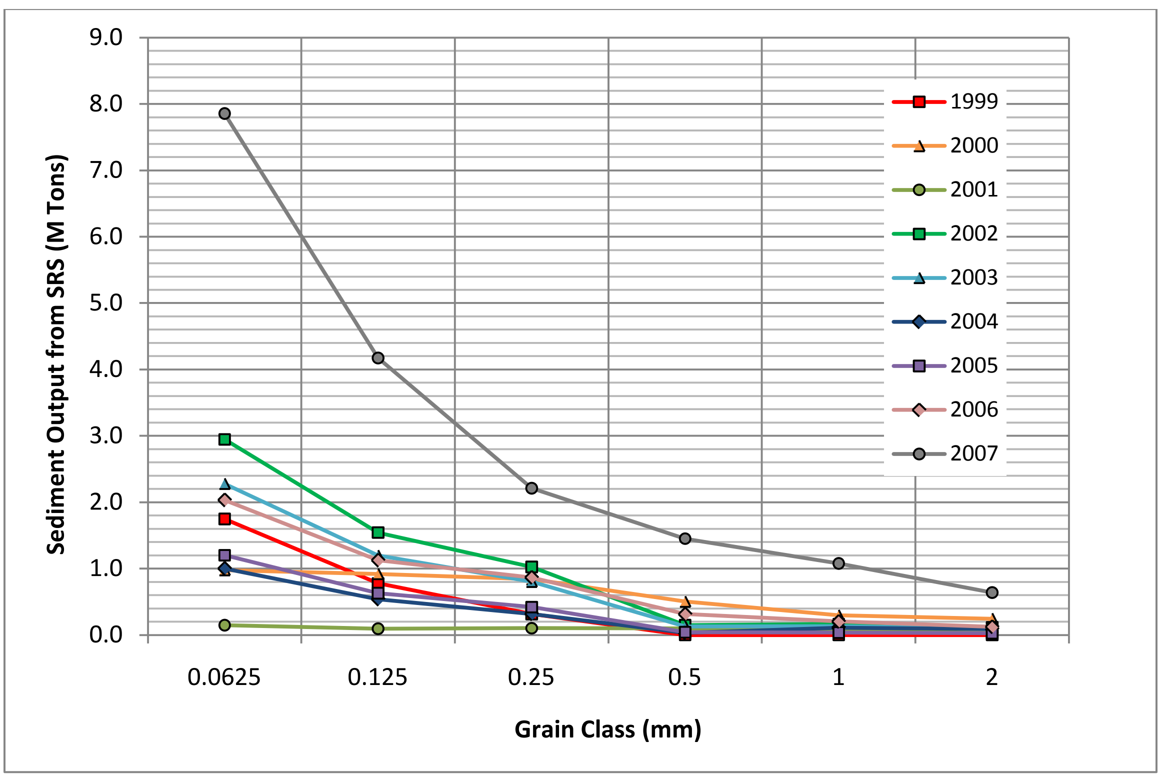

Figure 4.40 Sediment Output from the SRS by Grain Class for WYs 1999 – 2007

4.7 Toutle Watershed Sediment Sources

Sediment sources to the Toutle River include contributions from the North and South Fork Toutle Rivers as well as local bank erosion. All bank erosion sources to the Toutle are presented in Section 4.2. A summary of all sediment sources contributing to the Toutle River watershed as well as the methods of computation and variability are presented in Table 4.18. A detailed description of the North the South Fork sources are provided in the following sections.

Table 4.18 Summary of Sediment Sources to the Toutle River Watershed

Sediment Sources	Method of Computation	Variability
North Fork Toutle River		
Sediment Output from SRS	Comparison of debris avalanche erosion and sediment plain deposition computed by surface comparisons.	+/-15%
Green River	Estimated using suspended sediment rating curve of Green River gage data relative to Toutle at Tower Road gage plus 18% unmeasured load.	+/-25%
Bank Erosion Downstream of SRS	Identification of unstable banks using 1999 and 2006 aerial photograph comparison.	+/-35%
South Fork Toutle River		
Upstream Sediment Source	Estimated by comparing South Fork bank erosion and annual suspended sediment at the South Fork Gage # 14241500 plus 25% unmeasured load.	+/-25%
Bank Erosion	Identification of unstable banks using 1999 and 2006 aerial photograph comparison.	+/-35%
Toutle River		
Bank Erosion Upstream of Tower Road	Identification of unstable banks using 1999 and 2006 aerial photograph comparison.	+/-35%
Bank erosion Downstream of Tower Road	Identification of unstable banks using 1999 and 2006 aerial photograph comparison.	+/-35%

4.7.1 North Fork Toutle River

Three main sediment sources contribute to the North Fork Toutle River including: 1) sediment output from the SRS, 2) local bank erosion occurring downstream of the SRS, and 3) sediment delivery from the Green River. Development of items 1 and 2 for input to the sediment budget were presented in previous sections. Annual contributions by grain size from the Green River were estimated using USGS gage data. A rating curve relative to Tower Road, shown in Figure 4.41, was used to estimate annual suspended sediment for years in which data was not available on the Green River. Unmeasured load in the Green River is estimated to be 18% (Simon, 1999) and was added to each annual value. The average of all Green River suspended sediment gradation samples was used to estimate annual sediment by grain class.

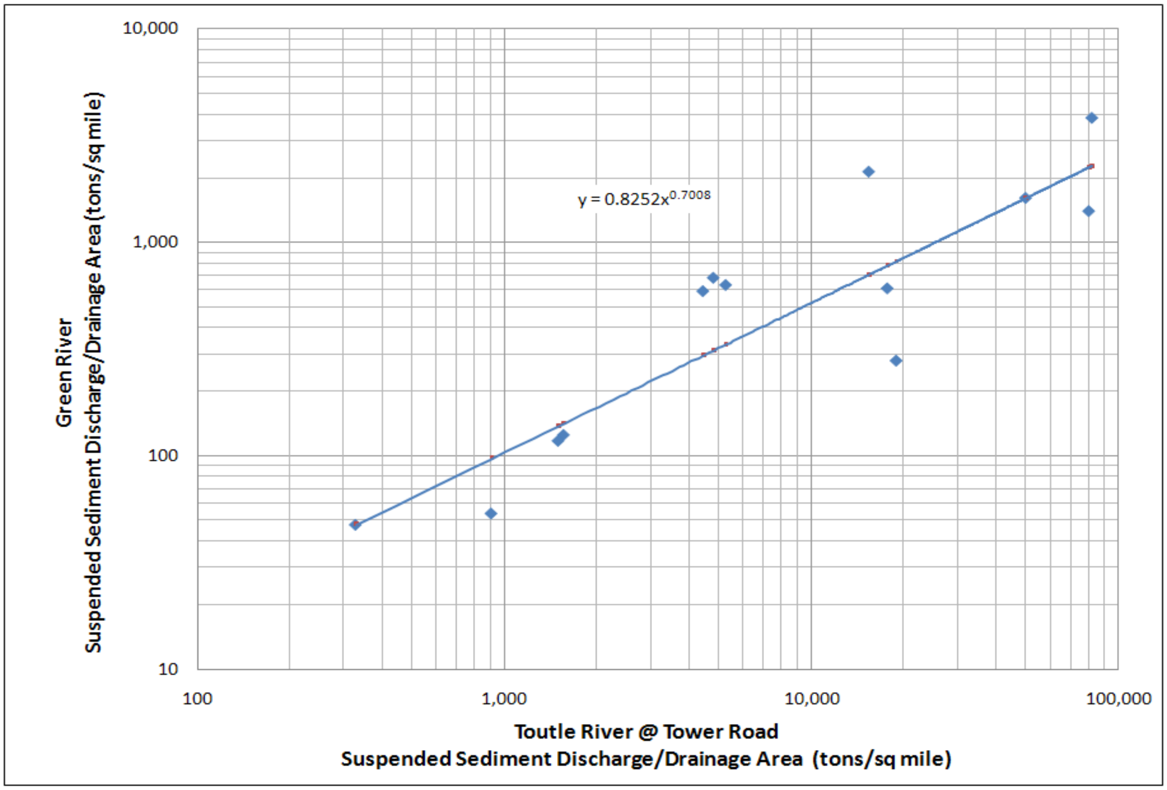

Figure 4.41 Green River vs. Toutle at Tower Road Suspended Sediment

4.7.2 South Fork Toutle River

Local sediment sources contributing to the South Fork River include an upstream sediment load and several bank erosion sites. Currently, there is no data available to estimate volumes of erosion occurring in the headwater of the South Fork. USGS repeat survey cross section data has not been collected in suitable temporal or spatial density to be used to estimate erosion volumes. Therefore, sediment output from the South Fork River was estimated using the USGS suspended sediment gage data. The gage is located near the Toutle confluence and downstream of all identified bank erosion sites. Comparison of the bank erosion quantities to gage data indicates that there is a significant contribution that is not accounted for in the bank erosion estimates, likely stemming from an upstream source. The upstream source was calculated in the sediment budget by this comparison.

Annual suspended sediment data plus a 25% unmeasured load was used as the contribution from the South Fork to the Toutle in the sediment budget. The average of suspended sediment gradation samples collected between 1999 and 2007 were applied to estimate the source by grain size.

4.8 Cowlitz River

Analysis of Cowlitz deposition and sediment quality is made possible by a rich dataset of bathymetric cross section and bed gradation data collected over the past 20 years. Following the completion of the major post-eruption dredging efforts on the lower Cowlitz River, a monitoring effort began whereby cross sections were surveyed between the Cowlitz confluence with the Columba and Toutle Rivers. A robust initial effort, presumably to determine effectiveness of the newly constructed SRS as well as response to channel dredging, yielded to less intensive surveys conducted to determine condition in response to large flood events and eventually to monitor observed deposition in the channel. Bed gradation data was collected throughout the study period with large reach-wide datasets developed in 1992 and 2005 and smaller bed gradation datasets collected intermittently. The dataset utilized in this Sediment Budget report is limited in scope to data from 1990 to present.

The analysis procedure utilized on the lower Cowlitz River makes best use of the available data as follows:

1. Sediment deposition volumes are calculated from the cross section datasets using an average-end-area method. The volumes are determined at the minimum reach spacing allowable given the multiple cross section datasets.
2. Volumes are modified as required to reflect dredging events occurring between datasets.
3. Deposition volumes are converted to mass.
4. A bed gradation is distributed to each reach according to representative time and proximity.
5. Masses are determined for each grain size for each reach.

A summary of datasets used for the lower Cowlitz sediment budget is shown in Table 4.19.

Table 4.19 Data Sets Utilized in Lower Cowlitz Sediment Budget Calculations

Cross Section Data	Volume Calculation	Gradation Data Applied
May 1990		
Aug 1991	Aug 1991 - May 1990	Aug 1992
July 1992	July 1992 - Aug 1991	Aug 1992
Summer 1996	Summer 1996 - July 1992	Aug 1992
Aug 2003	Aug 2003 - Summer 1996	Oct 2000
Dec 2006	Dec 2006 - Aug 2003	Summer 2005
Jun 2008	Jun 2008 - Dec 2006	Jan 2007 below RM 10, Summer 2005 above RM 10

4.8.1 Cowlitz Volume/Mass Analysis

A large number of cross section datasets have been collected over the past 20 years (Table 4.20). All known datasets were successfully retrieved for this analysis. While most cover the full extents of the study reach, extending from the Columbia to above the Toutle River, there were several sets that were spot-checks comprised of fewer than 10 cross sections or covering a reach smaller than the complete study reach. The spot-check data sets of 1998, 1999 and 2000 were sparse, and were excluded from the analysis. The April 2006 dataset had good coverage of the lower 10 Miles of the Cowlitz, but was ultimately not used due to the availability of a full reach dataset 8 months later in Dec 2006. The remaining group of seven full study reach datasets was used to calculate depositional volumes by on average-end-area method for six timeframes.

Table 4.20 All Lower Cowlitz Cross Section Datasets in Study Time Frame

Survey Data	Used in Analysis	Data Format
1989 Apr	No	HEC-2 model
1990 May	Yes	HEC-2 model
1991 Aug	Yes	HEC-2 model
1992 Jul	Yes	HEC-2 model
1996 Summer	Yes	Point data and HEC-RAS model
1998 Jun [1]	No	Excel station-elevation
1999 Jun [1]	No	Excel station-elevation
2000 Oct [1]	No	Excel station-elevation
2003 Aug	Yes	Point data and HEC-RAS model
2006 Apr [2]	No	Point data and HEC-RAS model
2006 Dec	Yes	Point data and HEC-RAS model
2008 Feb/Mar/May	Yes	Point data and HEC-RAS model

[1] Limited set of spot-check cross sections collected
[2] Cross sections collected only on the lower 10 miles of the Cowlitz

For years prior to 2003, a relatively consistent cross section alignment and labeling was utilized for cross sections on the Cowlitz River. Beginning in 2003, the location and river mile naming of each dataset began to vary. Since volume estimates made by the average-end-area method are very sensitive to reach length, great care was taken to verify the location of each cross section and only calculate volumes on reaches that represent the same geographical area. Reach length errors were found in some of the older datasets during this process. Ultimately, new reach lengths were cut using HEC-GeoRAS and the 2008 cross section alignment. The 2008 cross sections and river mile naming are shown in Figure 4.42. These lengths were enforced at geographically identical reaches of all datasets to ensure that the calculated volumes were not biased by erroneous older reach length data.

Sediment volume calculations extended between the uppermost and lowermost cross sections common to all geometries, RM 19.52 and RM 0.18. Calculated volumes were converted to mass by using the factor of 95 lbs/ft^3. Results from the depositional mass calculations are shown in Table 4.21. A total mass deposited or eroded is shown for each of the common reaches for each of the time frames between cross section surveys. Pulling the data apart to this level allows for maximum flexibility for future use, however it increases the opportunity to expose errors in the data. Future users are cautioned to examine the depositional trends in a reach longer than the minimum common reach to make conclusions. The minimum common reach approach is informative in that it demonstrates how the general depositional characteristics change along the study reach. If a single spike or oscillation is of interest, further investigation into the cross sections and terrain data may be warranted to verify the mechanisms.

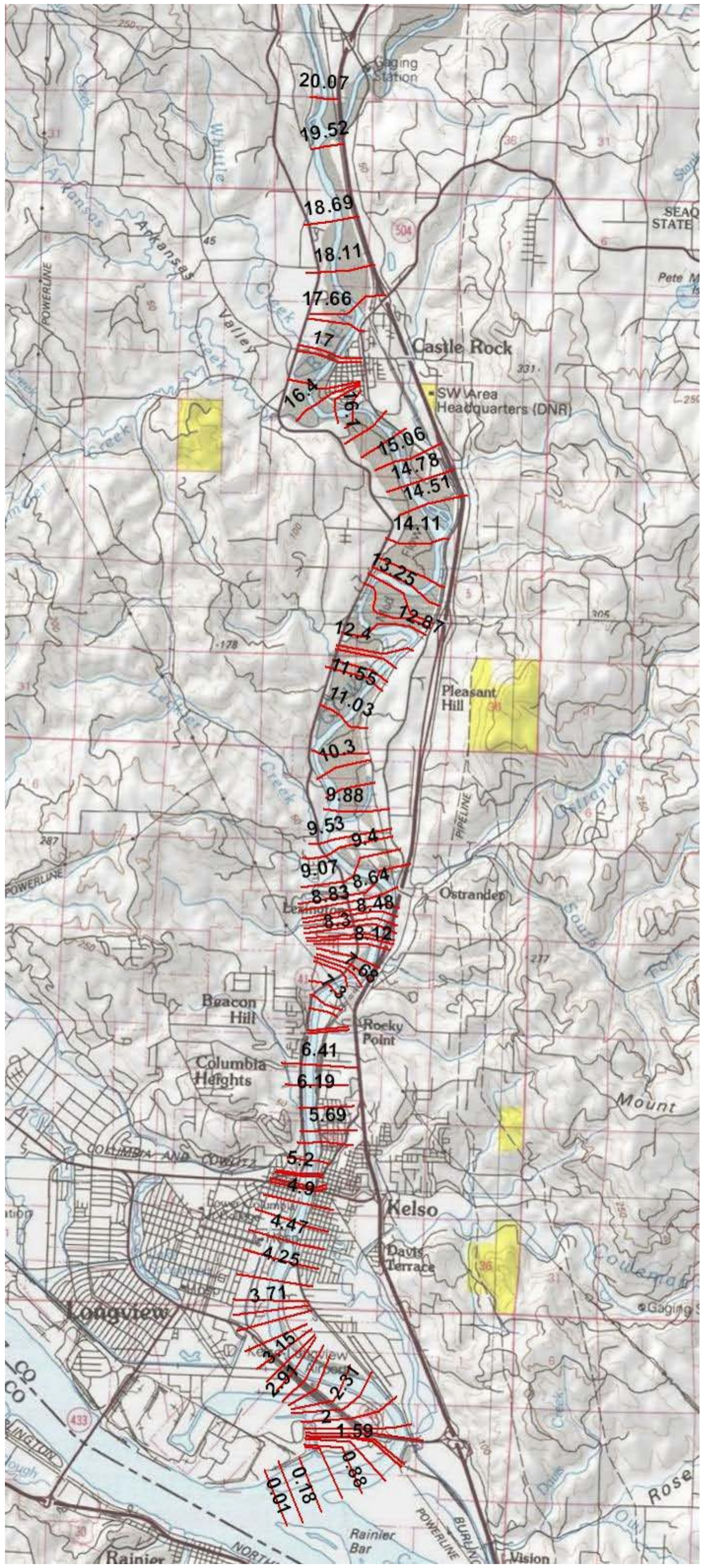

Figure 4.42 2008 Cowlitz Cross Section Locations and River Miles

Table 4.21 Deposition per Reach

2008 River Mile	Downstream Distance (miles)	Deposition Tons/Reach Aug 1991 - May 1990	Jul 1992 - Aug 1991	Summer 1996 - Jul 1992	Aug 2003 - Summer 1996	Dec 2006 - Aug 2003	Jun 2008 - Dec 2006
19.52	0.83	(96751)	40596	(65115)	7821	(82226)	104221
18.69	0.58	(18684)	(12187)	(68839)	30788	(12766)	77343
18.11	0.45	(36064)	(11132)	18725	(26360)	(4097)	8566
17.66	0.24	(13470)	3373	4304	(12228)	41	(13739)
17.42	2.09	(112849)	(8814)	44755	(376245)	40244	166087
15.33	1.87	(54355)	(44941)	2131	(155824)	182019	69977
13.46	0.59	34823	(77798)	166128	(17339)	125098	56445
12.87	0.86	159672	(75833)	343781	(155948)	151355	(10594)
12.01	0.18	16532	(13263)	22864	(61452)	79805	43348
11.83	0.28	2028	(15001)	15208	(22305)	54355	(3807)
11.55	1.67	36292	33271	46079	(25512)	116739	7780
9.88	0.48	48520	124	47341	(2917)	(95303)	82785
9.40	0.33	14277	(1283)	476	9145	(10966)	55597
9.07	0.43	1655	(2131)	9870	29733	21684	31368
8.64	0.41	45603	8690	(2379)	63501	(78088)	61307
8.23	0.42	14132	13139	(13035)	45975	26464	32506
7.81	0.81	76122	(24084)	9994	121829	(81936)	125181
7.00	0.59	20277	9145	10077	65818	9021	88309
6.41	0.72	(7718)	(8711)	58390	31740	81026	93606
5.69	1.01	(16077)	(12622)	83612	169501	(1386)	149203
4.68	0.43	(18332)	(7966)	81978	(14835)	29878	81874
4.25	0.45	(45437)	(18394)	85557	(26629)	35547	36706
3.80	0.53	21932	(63749)	71384	(26526)	(9766)	75750
3.27	0.49	(12001)	(68260)	132215	(56466)	18705	(41382)
2.78	0.47	(7097)	(68777)	125863	(57500)	63790	5731
2.31	0.60	159321	(198675)	76743	(56942)	84688	113532
1.71	0.37	(152162)	13159	(31202)	90109	6745	219439 [2]
1.34	0.67	(102441)	(92137)	(198509)	422200	(95282)	249352 [2]
0.67	0.67	(36437)	(56693)	(2633) [1]	(4608) [1]	333932	719641 [2]
0.18	0.00						
Totals		**(78,688)**	**(760,953)**	**1,075,761**	**(11,477)**	**989,319**	**2,686,129**

[1] The 1996 cross section survey did not extend downstream to RM 0.19. The tonnage calculated between 2003 and 1992 is distributed evenly based on time.
[2] Ending Feb 28, 2008: 227,272 CY of dredging occurred between 1990 cross sections 1.30 and 0.01 (approx). The dredging tonnage is distributed evenly below 1990 RM 1.3 (2008 RM 0.67) based on distance

An intuitive way to view the mass deposition in each reach is to normalize the deposition by reach length and time and plot tons/mile/year in the y-axis relative to river mile. Figures 4.43 and 4.44 depict the pre and post SRS-filling-to-spillway-crest period of deposition normalized in this manner respectively. The pre SRS-filling-to-spillway-crest period shows large rates of varying deposition and erosion near the Horseshoe Bend area at RM 12 – RM 13.5. This region has been active over the analysis period experiencing a significant amount of bank erosion and subsequent bank revetment following the high water events of 1996. The bank erosion resulted in a realignment of the reach and compression of the Horseshoe Bend meander. Meander scrolls apparent in the topography immediately upstream and downstream of Horseshoe Bend indicate the meander is actively moving downstream, however, the bend is pinned by a dredge spoil pile at the downstream point bar.

The tidal zone in the lower five miles of the Cowlitz River also shows larger than average rates of deposition and erosion. The timeframe post SRS-filling-to-spillway-crest experiences the highest rates of deposition seen in this analysis, in excess of 700,000 tons/mile/year in the lowest mile of the reach in the period between 2006 and 2008.

Based on the total deposition values for the six time frames available (Table 4.21), a state of quasi-equilibrium appears to have been reached between 1990 and 2003. During this period, deposition and erosion roughly balance both spatially and temporally, Figure 4.43. Following 2003, higher total deposition values are observed in the Cowlitz River with deposition rates in the lower two miles higher than all other observed rates achieved. Deposition rates between December 2006 and June 2008 are consistently high in the lower 10 miles with a moderately high rate of deposition observed in the upper 5 miles.

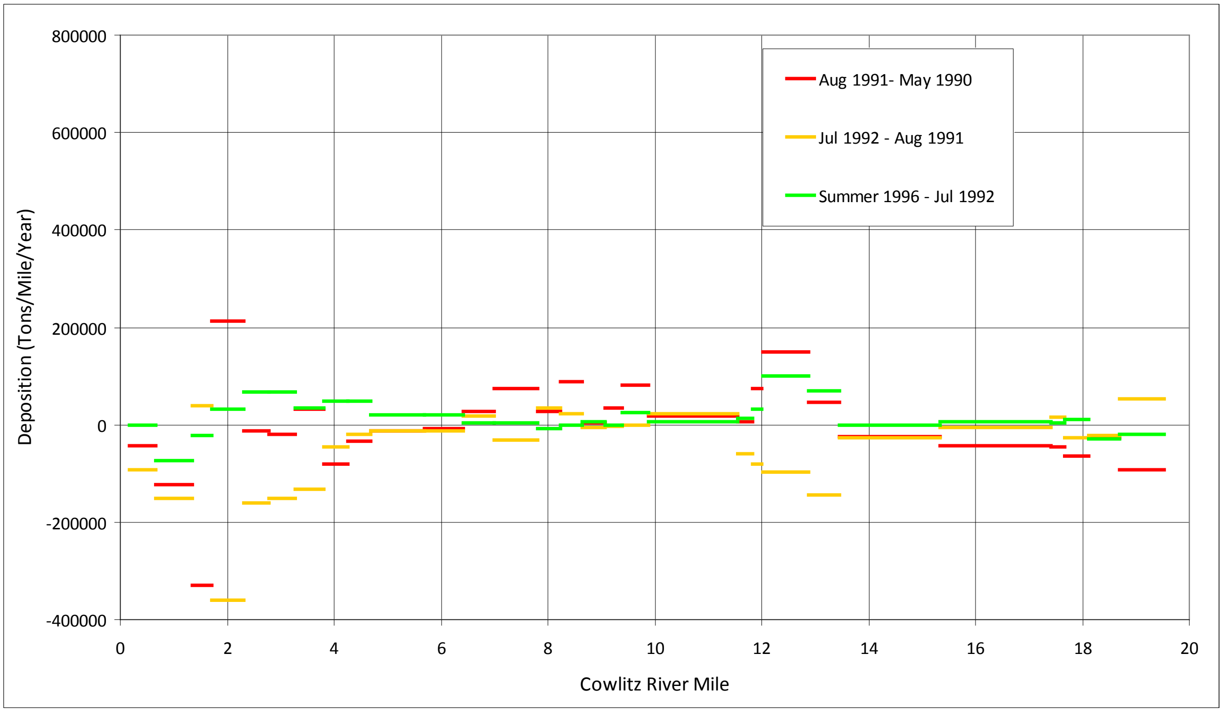

Figure 4.43 Cowlitz deposition for period prior to SRS filling to spillway

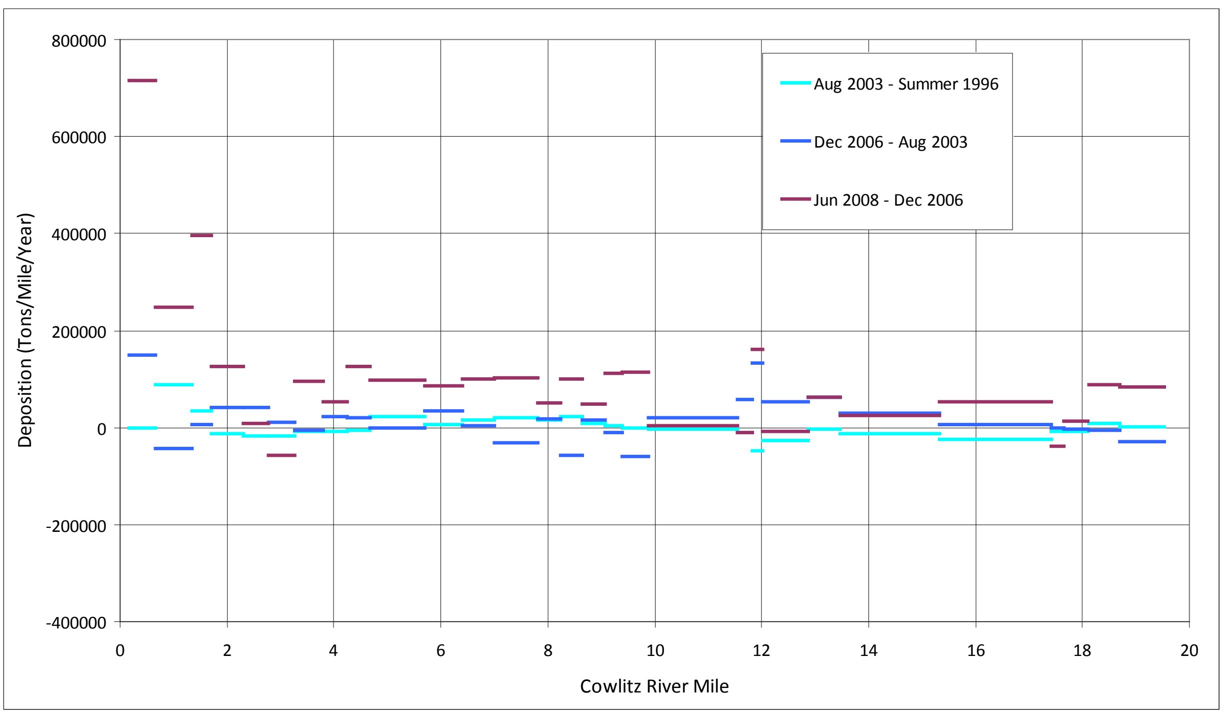

Figure 4.44 Cowlitz deposition for period post SRS filling to spillway

4.8.2 Cowlitz Bed Gradation Analysis

Multiple bed gradation data sets have been collected along the study reach between 1990 and 2008 (Table 4.22). Given the complexities of bed material sampling, more weight is given to the large groups of samples that exhibit clear trends. This speaks to the experience of the field personnel and provides confidence in the quality of the data set. Two very robust data sets from 1992 and 2005 cover the expanse of the study reach and provide important insights on gradation trends in the lower Cowlitz.

Table 4.22 Lower Cowlitz Bed Gradation Datasets

Bed Gradation Data	Number of Samples	Used in Analysis	Extents
1992 Aug	44	Yes	RM 0.0 to RM 19.7
2000 Oct	5	Yes	RM 1.1 to RM 15.5
2004 Jun-Aug	8	No	RM 1.1 to RM 18.8
2005	17	Yes	RM 1.7 to RM 19.8
2007 Jan	10	Yes	RM 0.3 to RM 8.5

Determining gradation of the Cowlitz sediment mass flux requires assignment of a gradation to each reach where a depositional or erosional mass has been calculated. Each of the gradation samples were reviewed for applicability. Repeat samples were removed as well as samples that clearly demonstrated bed armoring. Removal of armored samples in the upper reaches was done as the bed gradation did not represent the material that would deposit or erode from the stream. Samples were located along the river and assigned to the closest depositional reaches. In some cases, a single sample was assigned to several miles of river. In the case of the 1992 dataset, more samples were available than depositional reaches. In these situations the screened samples within a reach were averaged and applied. Application of the gradation was a simple distribution of the depositional mass to the gradations by the percent of mass retained by the screen. Figure 4.45 shows the D50 of the screened bed gradation dataset.

Application of gradations was straight forward for depositional reaches. A similar application of the bed gradation to upstream erosional reaches would result in gravel size material leaving the system; however, with few gravel size particles in the lower reaches, implementation of an erosional size threshold was necessary. Preliminary mobile bed RAS modeling indicates that very coarse sand trended depositional while coarse sand could be eroded from the bed and passed out into the Columbia. These results were used to determine a threshold size of 1.0 mm; particles larger than 1.0 mm were not allowed erode from the bed and leave the system. This threshold is supported by the critical shear analysis presented in section 2.2.2. For erosional reaches with grain sizes larger than the threshold, a new distribution was calculated for the material smaller than 1.0 mm proportioning the remaining fractions to account for 100% of the erosional mass. One limitation with this approach is that it will not transport material. Erosion of material larger the 1.0 mm does occur in the upper reaches, but it tends to redeposit in the Cowlitz before it reaches the Columbia. This approach is limited to removing any material eroded from the system. Under these assumptions, a 1.0 mm threshold is appropriate.

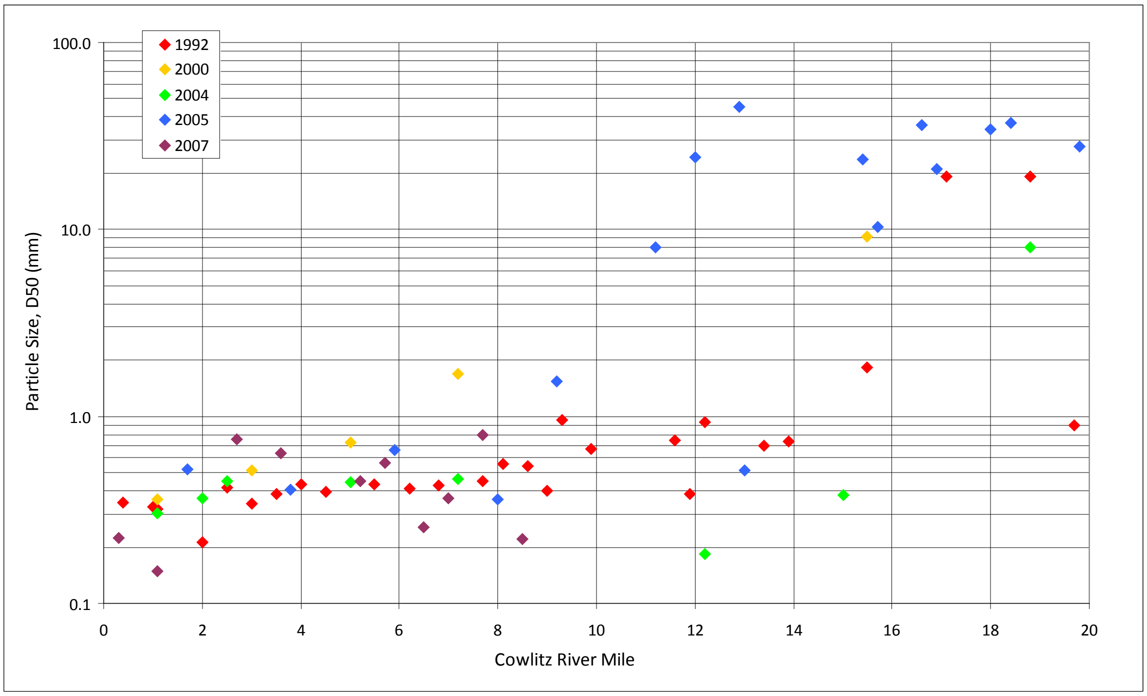

Figure 4.45 D50 of Bed Gradation Samples

Total deposition and erosion per grain size for each period between surveys is shown in Figure 4.46. The bimodal grain size aspect observed in the D50 analysis is again present. A significant deposition of coarse gravels occurs. For the sand size particles, the 2006 – 2008 period stands out from the other periods with a high mass of fine sands depositing in the system. For all other periods, the material in flux was medium and coarse sands. Tables 4.23 through 4.28 provide the mass flux per grain size, per reach, per time period.

The fate of gravels in the system has been a lingering question that Figure 4.54 can help answer. Two dominant D50 trends arise medium sands in the lower reaches and coarse gravels in the upper reaches. Gravels are certainly present in the Toutle and upper Cowlitz systems and are observed passing the Castle Rock USGS station. With no gravels present in the lowest parts of the Cowlitz, we have presumed that there has been a steady accumulation of gravels in the upper reaches. The data indicates that the stream bed between RM 11 and 15 has changed from a sand bed to a gravel bed between 1992 and 2005 or in other words, a gravel wedge may be moving downstream through the lower Cowlitz River and is currently near RM 11. The significance of this change is that gravel bed channels are more stable than sand bed channels. As the gravel wedge moves downstream, any measure intended to induce transport must take into account the changing bed conditions. An alternative hypothesis to consider is the possibility that the apparent coarsening of the bed in 2005 may be a result of the gravel being exposed during that time period. It may be that the gravel was there in the previous time periods, but was covered by sands at the time the samples were collected. We know, for example, that sands periodically move over the gravel at Castle Rock. Perhaps a monitoring program to sample the bed several times a year to determine bed material changes with time in this area should be considered.

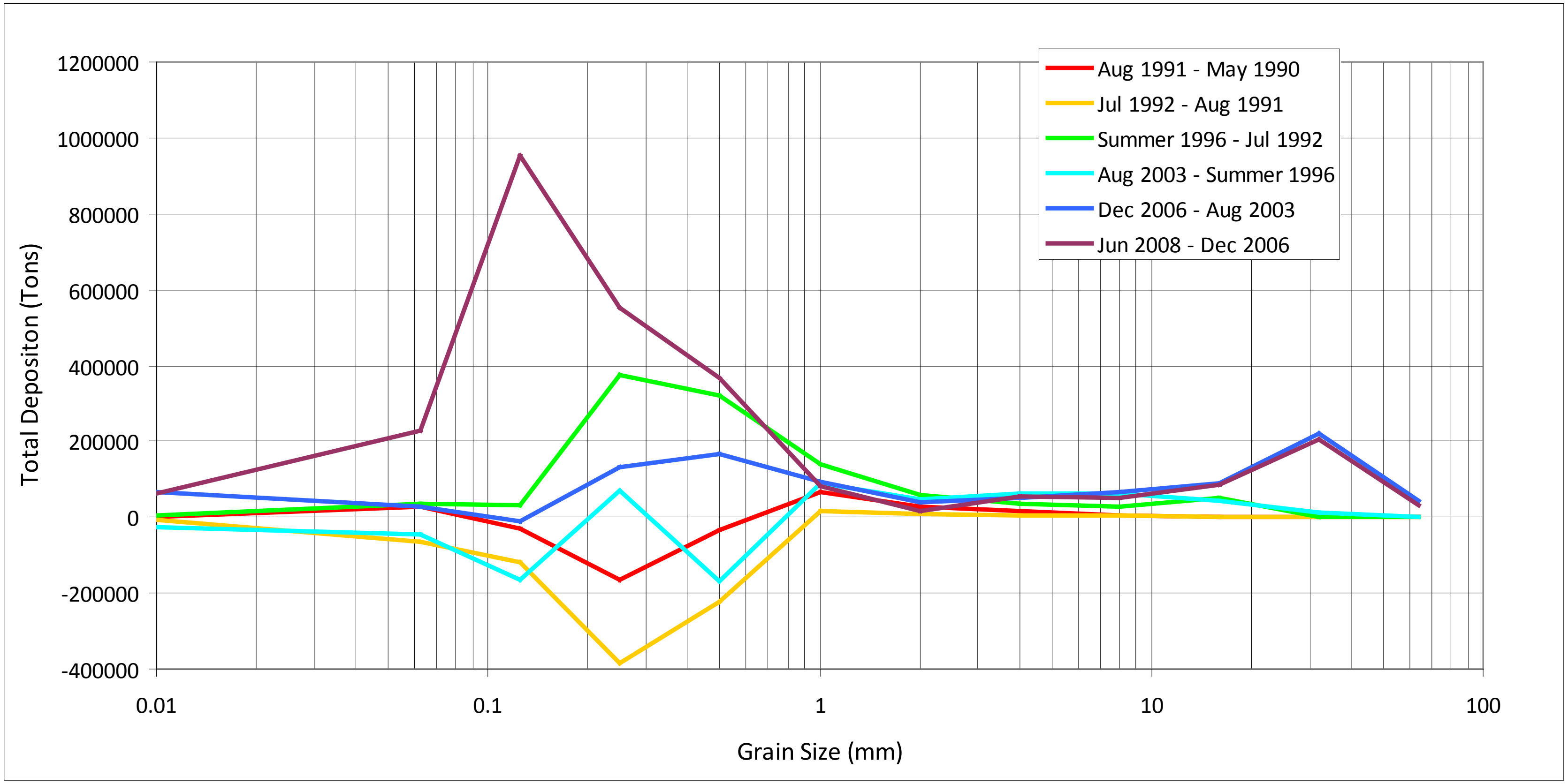

Figure 4.46 Total Deposition per Grain Size for Each Time Period

Table 4.23 Aug 1991 – May 1990 Deposition by Grain Size

		Aug 1991 - May 1990 Deposition Tons/Reach/Grain Size											
2008 River Mile	Downstream Distance (miles)	128 to 64	64 to 32	32 to 16	16 to 8	8 to 4	4 to 2	2 to 1	1 to 0.5	0.5 to 0.25	0.25 to 0.125	0.125 to 0.625	< 0.0625
19.52	0.83	0	0	0	0	0	0	0	(58225)	(36086)	(1569)	(349)	(523)
18.69	0.58	0	0	0	0	0	0	0	(15078)	(3278)	0	(328)	0
18.11	0.45	0	0	0	0	0	0	0	(29105)	(6327)	0	(633)	0
17.66	0.24	0	0	0	0	0	0	0	(5657)	(6196)	(1347)	(269)	0
17.42	2.09	0	0	0	0	0	0	0	(47396)	(51910)	(11285)	(2257)	0
15.33	1.87	0	0	0	0	0	0	0	(32869)	(20348)	(474)	(474)	(190)
13.46	0.59	0	0	0	35	383	1602	7626	17133	7800	174	0	70
12.87	0.86	0	0	479	2555	7904	12558	20678	68555	45347	1038	80	479
12.01	0.18	0	0	17	512	959	2017	4133	5869	2877	132	0	17
11.83	0.28	0	0	0	0	0	0	4	420	1553	49	0	2
11.55	1.67	0	0	12	569	1016	2553	7174	15908	8674	290	12	85
9.88	0.48	0	0	0	388	776	2232	7375	23678	13149	728	49	146
9.40	0.33	0	0	528	1628	1056	1085	2484	5582	1770	114	14	14
9.07	0.43	0	0	50	45	22	36	109	291	849	245	3	5
8.64	0.41	0	0	0	137	274	958	5016	18743	18378	1961	46	91
8.23	0.42	0	0	99	127	297	678	1569	5031	5568	735	14	14
7.81	0.81	0	0	0	38	495	1561	5252	25273	38328	3806	1180	190
7.00	0.59	0	0	0	81	182	406	1054	6073	10260	2129	51	41
6.41	0.72	0	0	0	0	0	0	0	(2429)	(4452)	(780)	(24)	(32)
5.69	1.01	0	0	0	0	0	0	0	(3939)	(10268)	(1509)	(294)	(67)
4.68	0.43	0	0	0	0	0	0	0	(3954)	(13040)	(1298)	(20)	(20)
4.25	0.45	0	0	0	0	0	0	0	(13430)	(27602)	(1327)	(2973)	(106)
3.80	0.53	0	0	0	0	22	66	461	4891	14870	175	1426	22
3.27	0.49	0	0	0	0	0	0	0	(1836)	(6291)	(3604)	(243)	(27)
2.78	0.47	0	0	0	0	0	0	0	(2201)	(4261)	(261)	(366)	(7)
2.31	0.60	0	0	0	80	1514	3425	5178	12825	46123	45964	39432	4780
1.71	0.37	0	0	0	0	0	0	0	(12296)	(98213)	(35197)	(4304)	(2152)
1.34	0.67	0	0	0	0	0	0	0	(10244)	(66169)	(24669)	(1150)	(209)
0.67	0.49	0	0	0	0	0	0	0	(3710)	(26942)	(4904)	(826)	(55)
0.18	0.00												
	Totals	**0**	**0**	**1,184**	**6,194**	**14,899**	**29,176**	**68,113**	**(32,098)**	**(165,837)**	**(30,684)**	**27,797**	**2,566**

Note: + Values indicate deposition/ ( ) indicate erosion

Table 4.24 July 1992 - Aug 1991 Deposition by Grain Size

		Jul 1992 - Aug 1991 Deposition Tons/Reach/Grain Size											
2008 River Mile	Downstream Distance (miles)	128 to 64	64 to 32	32 to 16	16 to 8	8 to 4	4 to 2	2 to 1	1 to 0.5	0.5 to 0.25	0.25 to 0.125	0.125 to 0.625	< 0.0625
19.52	0.83	0	0	447	2761	4628	4750	5480	13559	8403	365	81	122
18.69	0.58	0	0	0	0	0	0	0	(9835)	(2138)	0	(214)	0
18.11	0.45	0	0	0	0	0	0	0	(8984)	(1953)	0	(195)	0
17.66	0.24	0	0	2287	553	179	108	78	71	78	17	3	0
17.42	2.09	0	0	0	0	0	0	0	(3702)	(4055)	(881)	(176)	0
15.33	1.87	0	0	0	0	0	0	0	(27176)	(16823)	(392)	(392)	(157)
13.46	0.59	0	0	0	0	0	0	0	(52941)	(24103)	(538)	0	(215)
12.87	0.86	0	0	0	0	0	0	0	(45011)	(29773)	(681)	(52)	(315)
12.01	0.18	0	0	0	0	0	0	0	(8752)	(4289)	(197)	0	(25)
11.83	0.28	0	0	0	0	0	0	0	(3111)	(11514)	(361)	0	(15)
11.55	1.67	0	0	11	521	932	2340	6577	14584	7952	266	11	78
9.88	0.48	0	0	0	1	2	6	19	61	34	2	0	0
9.40	0.33	0	0	0	0	0	0	0	(955)	(303)	(20)	(2)	(2)
9.07	0.43	0	0	0	0	0	0	0	(445)	(1298)	(375)	(5)	(8)
8.64	0.41	0	0	0	26	52	182	956	3572	3502	374	9	17
8.23	0.42	0	0	92	118	276	631	1458	4677	5177	683	13	13
7.81	0.81	0	0	0	0	0	0	0	(8850)	(13422)	(1333)	(413)	(67)
7.00	0.59	0	0	0	37	82	183	476	2739	4628	960	23	18
6.41	0.72	0	0	0	0	0	0	0	(2742)	(5025)	(880)	(28)	(37)
5.69	1.01	0	0	0	0	0	0	0	(3092)	(8061)	(1185)	(231)	(52)
4.68	0.43	0	0	0	0	0	0	0	(1718)	(5666)	(564)	(9)	(9)
4.25	0.45	0	0	0	0	0	0	0	(5437)	(11174)	(537)	(1203)	(43)
3.80	0.53	0	0	0	0	0	0	0	(14581)	(44330)	(523)	(4250)	(65)
3.27	0.49	0	0	0	0	0	0	0	(10442)	(35781)	(20501)	(1382)	(154)
2.78	0.47	0	0	0	0	0	0	0	(21335)	(41295)	(2531)	(3544)	(72)
2.31	0.60	0	0	0	0	0	0	0	(17087)	(61449)	(61237)	(52534)	(6368)
1.71	0.37	0	0	0	0	13	13	105	1053	8409	3014	368	184
1.34	0.67	0	0	0	0	0	0	0	(9214)	(59513)	(22188)	(1034)	(188)
0.67	0.49	0	0	0	0	0	0	0	(5772)	(41920)	(7630)	(1286)	(86)
0.18	0.00												
	Totals	**0**	**0**	**2,836**	**4,017**	**6,164**	**8,213**	**15,149**	**(220,867)**	**(385,705)**	**(116,873)**	**(66,442)**	**(7,444)**

Note: + Values indicate deposition/ ( ) indicate erosion

Table 4.25 Summer 1997 - July 1992 Deposition by Grain Size

		Summer 1996 - Jul 1992 Deposition Tons/Reach/Grain Size											
2008 River Mile	Downstream Distance (miles)	128 to 64	64 to 32	32 to 16	16 to 8	8 to 4	4 to 2	2 to 1	1 to 0.5	0.5 to 0.25	0.25 to 0.125	0.125 to 0.625	< 0.0625
19.52	0.83	0	0	0	0	0	0	0	(39186)	(24286)	(1056)	(235)	(352)
18.69	0.58	0	0	0	0	0	0	0	(55554)	(12077)	0	(1208)	0
18.11	0.45	0	0	12846	3015	693	599	506	861	187	0	19	0
17.66	0.24	0	0	2918	706	228	138	99	90	99	22	4	0
17.42	2.09	0	0	30344	7340	2372	1432	1029	940	1029	224	45	0
15.33	1.87	0	0	268	269	221	268	291	492	305	7	7	3
13.46	0.59	0	0	0	166	1827	7642	36382	81735	37213	831	0	332
12.87	0.86	0	0	1031	5500	17017	27038	44520	147602	97634	2235	172	1031
12.01	0.18	0	0	23	709	1326	2789	5716	8117	3978	183	0	23
11.83	0.28	0	0	0	0	0	0	30	3148	11649	365	0	15
11.55	1.67	0	0	15	722	1290	3241	9108	20198	11013	369	15	108
9.88	0.48	0	0	0	379	757	2178	7196	23102	12829	710	47	142
9.40	0.33	0	0	18	54	35	36	83	186	59	4	0	0
9.07	0.43	0	0	296	266	128	217	651	1737	5063	1461	20	30
8.64	0.41	0	0	0	0	0	0	0	(1137)	(1115)	(119)	(3)	(6)
8.23	0.42	0	0	0	0	0	0	0	(5772)	(6388)	(843)	(16)	(16)
7.81	0.81	0	0	0	5	65	205	690	3318	5032	500	155	25
7.00	0.59	0	0	0	40	91	202	524	3018	5099	1058	25	20
6.41	0.72	0	0	0	117	175	467	2160	17459	31998	5605	175	234
5.69	1.01	0	0	530	4989	3930	2982	4069	16444	42865	6299	1226	279
4.68	0.43	0	0	0	164	984	1722	3853	16232	53531	5329	82	82
4.25	0.45	0	0	684	1112	1454	2909	6160	21646	44490	2139	4791	171
3.80	0.53	0	0	0	0	71	214	1499	15919	48398	571	4640	71
3.27	0.49	0	0	1454	1058	926	3041	8197	17981	61612	35302	2380	264
2.78	0.47	0	0	0	0	252	881	5035	37130	71868	4405	6167	126
2.31	0.60	0	0	0	38	729	1650	2494	6178	22217	22140	18994	2302
1.71	0.37	0	0	0	0	0	0	0	(2521)	(20139)	(7217)	(882)	(441)
1.34	0.67	0	0	0	0	0	0	0	(19851)	(12128221)	(47804)	(2228)	(405)
0.67	0.49	0	0	0	0	0	0	0	(268)	(1947)	(354)	(60)	(4)
0.18	0.00												
	Totals	**0**	**0**	**50,427**	**26,650**	**34,572**	**59,851**	**140,293**	**319,243**	**373,996**	**32,362**	**34,334**	**4,035**

Note: + Values indicate deposition/ ( ) indicate erosion

Table 4.26 Aug 2003 - Summer 1997 Deposition by Grain Size

		Aug 2003 - Summer 1996 Deposition Tons/Reach/Grain Size											
2008 River Mile	Downstream Distance (miles)	128 to 64	64 to 32	32 to 16	16 to 8	8 to 4	4 to 2	2 to 1	1 to 0.5	0.5 to 0.25	0.25 to 0.125	0.125 to 0.625	< 0.0625
19.52	0.83	0	917	1737	1545	822	596	712	634	201	361	157	140
18.69	0.58	0	3608	6836	6083	3237	2347	2803	2495	792	1420	617	550
18.11	0.45	0	0	0	0	0	0	0	(11197)	(3555)	(6373)	(2768)	(2467)
17.66	0.24	0	0	0	0	0	0	0	(5194)	(1649)	(2956)	(1284)	(1144)
17.42	2.09	0	0	0	0	0	0	0		(50741)	(90961)	(39509)	(35211)
15.33	1.87	0	0	0	0	0	0	0	(66192)	(21015)	(37672)	(16363)	(14583)
13.46	0.59	0	0	0	0	0	0	0	(7365)	(2338)	(4192)	(1821)	(1623)
12.87	0.86	0	0	0	0	0	0	0	(66245)	(21032)	(37702)	(16376)	(14594)
12.01	0.18	0	0	0	0	0	0	0	(26104)	(8288)	(14857)	(6453)	(5751)
11.83	0.28	0	0	0	0	0	0	0	(9475)	(3008)	(5392)	(2342)	(2087)
11.55	1.67	0	0	0	0	0	0	0	(10837)	(3441)	(6168)	(2679)	(2388)
9.88	0.48	0	0	0	0	0	0	0	(2032)	(628)	(172)	(56)	(29)
9.40	0.33	0	241	828	1227	1072	839	1513	2385	737	203	66	35
9.07	0.43	0	785	2692	3988	3484	2728	4919	7756	2397	658	213	113
8.64	0.41	0	1676	5748	8517	7442	5827	10505	16563	5120	1406	455	240
8.23	0.42	0	1214	4162	6167	5388	4219	7606	11992	3707	1018	330	174
7.81	0.81	0	3216	11028	16341	14277	11179	20154	31778	9823	2698	873	461
7.00	0.59	0	1738	5958	8828	7713	6039	10888	17168	5307	1458	472	249
6.41	0.72	0	838	2873	4257	3720	2912	5251	8279	2559	703	228	120
5.69	1.01	0	0	0	5353	15303	11633	24217	61629	46001	4440	517	408
4.68	0.43	0	0	0	0	0	0	0	(8091)	(6040)	(583)	(68)	(54)
4.25	0.45	0	0	0	0	0	0	0	(14524)	(10841)	(1046)	(122)	(96)
3.80	0.53	0	0	0	0	0	0	0	(11724)	(13657)	(998)	(110)	(37)
3.27	0.49	0	0	0	0	0	0	0	(24956)	(29072)	(2124)	(235)	(78)
2.78	0.47	0	0	0	0	0	0	0	(25414)	(29605)	(2163)	(239)	(80)
2.31	0.60	0	0	0	0	0	0	0	(25167)	(29317)	(2142)	(237)	(79)
1.71	0.37	0	0	0	0	7	28	390	25592	40675	6659	7384	9374
1.34	0.67	0	0	0	0	35	131	1828	119909	190580	31200	34597	43920
0.67	0.49	0	0	0	0	0	0	0	(1315)	(2090)	(342)	(379)	(482)
0.18	0.00												
	Totals	**0**	**14,233**	**41,862**	**62,306**	**62,500**	**48,478**	**90,786**	**(169,476)**	**71,585**	**(163,619)**	**(45,133)**	**(24,999)**

Note: + Values indicate deposition/ ( ) indicate erosion

Table 4.27 Dec 2006 - Aug 2003 Deposition by Grain Size

		Dec 2006 - Aug 2003 Deposition Tons/Reach/Grain Size											
2008 River Mile	Downstream Distance (miles)	128 to 64	64 to 32	32 to 16	16 to 8	8 to 4	4 to 2	2 to 1	1 to 0.5	0.5 to 0.25	0.25 to 0.125	0.125 to 0.625	< 0.0625
19.52	0.83	0	0	0	0	0	0	0	(19622)	(24294)	(26163)	(10278)	(1869)
18.69	0.58	0	0	0	0	0	0	0	(5873)	(5362)	(766)	(638)	(128)
18.11	0.45	0	0	0	0	0	0	0	(525)	(945)	(1226)	(1015)	(385)
17.66	0.24	6	16	8	2	1	1	1	1	1	1	1	0
17.42	2.09	0	15776	7244	4870	2455	684	966	2616	4910	604	80	40
15.33	1.87	9101	62068	45323	18930	11467	5279	3822	8737	13105	2730	1456	0
13.46	0.59	0	26271	4253	5504	5129	6005	7005	8757	9758	8256	13385	30774
12.87	0.86	0	31784	5146	6660	6206	7265	8476	10595	11806	9989	16195	37233
12.01	0.18	18275	42776	4150	4868	2394	559	319	718	4070	1277	319	80
11.83	0.28	15763	8316	7718	5109	2772	1033	1522	4022	5055	2229	652	163
11.55	1.67	0	30235	14592	13542	8405	4319	4553	7471	13542	12024	6537	1518
9.88	0.48	0	0	0	0	0	0	0	(38212)	(48902)	(5004)	(2047)	(1137)
9.40	0.33	0	0	0	0	0	0	0	(4397)	(5627)	(576)	(236)	(131)
9.07	0.43	0	347	2472	2862	2255	1800	2862	3643	4662	477	195	108
8.64	0.41	0	0	0	0	0	0	0	(20044)	(33824)	(22967)	(1169)	(84)
8.23	0.42	0	0	26	26	106	291	1270	6351	10718	7278	370	26
7.81	0.81	0	0	0	0	0	0	0	(21032)	(35491)	(24099)	(1227)	(88)
7.00	0.59	0	0	0	0	72	180	1362	4862	2400	108	27	9
6.41	0.72	0	0	0	0	648	1621	12235	43673	21553	972	243	81
5.69	1.01	0	0	0	0	0	0	0	(910)	(449)	(20)	(5)	(2)
4.68	0.43	0	0	0	0	239	598	4512	16104	7947	359	90	30
4.25	0.45	0	0	0	0	0	178	2239	10913	14503	7323	391	0
3.80	0.53	0	0	0	0	0	0	0	(3217)	(4275)	(2159)	(115)	0
3.27	0.49	0	0	0	0	0	94	1178	5742	7632	3853	206	0
2.78	0.47	0	255	0	383	1084	1467	5422	24623	26920	2743	893	0
2.31	0.60	0	339	0	508	1440	1948	7199	32690	35738	3642	1186	0
1.71	0.37	0	27	0	40	115	155	573	2604	2847	290	94	0
1.34	0.67	0	0	0	0	0	0	0	(42519)	(46484)	(4737)	(1542)	0
0.67	0.49	0	1336	0	2004	5677	7680	28384	128898	140919	14359	4675	0
0.18	0.00												
	Totals	**43,146**	**219,546**	**90,933**	**65,309**	**50,465**	**41,156**	**93,902**	**166,670**	**132,430**	**(9,201)**	**28,724**	**66,241**

Note: + Values indicate deposition/ ( ) indicate erosion

Table 4.28 Jun 2008 - Dec 2006 Deposition by Grain Size

		Jun 2008 - Dec 2006 Deposition Tons/Reach/Grain Size											
2008 River Mile	Downstream Distance (miles)	128 to 64	64 to 32	32 to 16	16 to 8	8 to 4	4 to 2	2 to 1	1 to 0.5	0.5 to 0.25	0.25 to 0.125	0.125 to 0.625	< 0.0625
19.52	0.83	10005	37936	20219	10943	6566	4169	5211	2189	2710	2918	1146	208
18.69	0.58	8662	37821	11215	5337	2630	1624	2320	3558	3248	464	387	77
18.11	0.45	1336	3281	1619	488	274	308	257	128	231	300	248	94
17.66	0.24	0	0	0	0	0	0	0	(1761)	(3170)	(4110)	(3405)	(1292)
17.42	2.09	0	65106	29896	20096	10131	2823	3986	10796	20263	2491	332	166
15.33	1.87	3499	23862	17424	7278	4409	2029	1470	3359	5038	1050	560	0
13.46	0.59	0	11853	1919	2484	2314	2709	3161	3951	4403	3725	6040	13885
12.87	0.86	0	0	0	0	0	0	0	(1308)	(1457)	(1233)	(1999)	(4596)
12.01	0.18	9927	23234	2254	2644	1300	303	173	390	2211	694	173	43
11.83	0.28	0	0	0	0	0	0	0	(1263)	(1588)	(700)	(205)	(51)
11.55	1.67	0	2015	972	902	560	288	303	498	902	801	436	101
9.88	0.48	0	0	0	0	497	0	1159	18378	13246	47030	1639	836
9.40	0.33	0	0	0	0	334	0	778	12342	8895	31584	1101	562
9.07	0.43	0	0	0	0	188	0	439	6964	5019	17820	621	317
8.64	0.41	0	0	0	0	368	0	858	13610	9809	34829	1214	619
8.23	0.42	0	0	0	0	2828	98	7639	17455	3881	426	72	107
7.81	0.81	0	0	0	0	3130	0	4131	26538	64468	25750	989	175
7.00	0.59	0	0	0	0	618	0	8124	18986	17044	38150	2685	2702
6.41	0.72	0	0	0	0	10484	468	12512	28425	10403	19601	3463	8250
5.69	1.01	0	0	0	0	2984	0	9698	54608	48939	29632	2193	1149
4.68	0.43	0	0	0	0	1637	0	6877	49452	22843	589	74	401
4.25	0.45	0	0	0	0	734	0	3083	22170	10241	264	33	180
3.80	0.53	0	0	0	0	1515	0	6363	45753	21134	545	68	371
3.27	0.49	0	0	0	0	0	0	0	(31022)	(7545)	(1525)	(495)	(794)
2.78	0.47	0	0	0	0	298	0	1312	3089	751	152	49	79
2.31	0.60	0	0	0	0	0	0	227	3633	6812	61988	34877	5994
1.71	0.37	0	0	0	0	0	0	439	7022	13166	119814	67412	11586
1.34	0.67	0	0	0	0	0	0	499	7979	14961	136146	76601	13166
0.67	0.49	0	0	0	0	0	0	1439	41020	255472	382633	30945	8132
0.18	0.00												
	Totals	**33,429**	**205,109**	**85,518**	**50,172**	**53,799**	**14,820**	**82,461**	**366,940**	**552,329**	**951,828**	**227,253**	**62,470**

Note: + Values indicate deposition/ ( ) indicate erosion

Net deposition or erosion by grain class presented in Tables 4.23 through 4.28 was pro-rated annually for water years 1999 through 2007 for use in the sediment budget between the Columbia and Toutle Rivers. Table 4.29 shows the pro-rated Cowlitz deposition or erosion used as input to the sediment budget. It should be noted that sediment contribution from the Cowlitz River to the sediment budget upstream of the Toutle River were considered negligible and entered as zero in all water years analyzed.

Table 4.29 Cowlitz River Annual Deposition/Erosion by Grain Size, Input to Sediment Budget from Columbia to Toutle River

Water Year	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	128	Total
	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)	(Tons)
1999	3,485	6,307	22,896	-10,085	23,687	-12,710	-6,787	-8,750	-8,723	-5,861	-1,993	0	1,469
2000	3,485	6,307	22,896	-10,085	23,687	-12,710	-6,787	-8,750	-8,723	-5,861	-1,993	0	1,469
2001	3,485	6,307	22,896	-10,085	23,687	-12,710	-6,787	-8,750	-8,723	-5,861	-1,993	0	1,469
2002	3,485	6,307	22,896	-10,085	23,687	-12,710	-6,787	-8,750	-8,723	-5,861	-1,993	0	1,469
2003	-200	4,195	20,903	-15,626	12,816	-16,043	-8,118	-10,336	-11,054	-9,779	-12,756	-2,157	-48,155
2004	-19,872	-8,617	2,760	-39,729	-50,001	-28,171	-12,347	-15,140	-19,593	-27,280	-65,864	-12,944	-296,796
2005	-19,872	-8,617	2,760	-39,729	-50,001	-28,171	-12,347	-15,140	-19,593	-27,280	-65,864	-12,944	-296,796
2006	-19,872	-8,617	2,760	-39,729	-50,001	-28,171	-12,347	-15,140	-19,593	-27,280	-65,864	-12,944	-296,796
2007	-37,670	-126,425	-523,045	-310,403	-210,151	-50,049	-10,209	-32,113	-30,860	-51,582	-123,787	-20,543	-1,526,837

Note: + indicates erosion/- indicates deposition

4.8.3 Recommendations for Future Data Collection

Deposition rates in the lower Cowlitz River have increased since 2003 according to this analysis. The most recent analysis period, 2006 – 2008, showed the highest depositional rates of all analysis periods. While the highest rates were in the lower two miles, a high persistent depositional rate is observed in the lower ten miles and again in the upper 5. Continued monitoring in the form of surveying cross sections is warranted as conditions in the lower Cowlitz River are changing with increased deposition. Cross section surveys should serve the modeling purposes, but repeating locations previously surveyed facilitated this mass change analysis allowing for additional detail throughout the study reach.

Bed material gradations are changing in the lower Cowlitz. A gravel wedge is potentially moving downstream and presently transitions to a sand bed river at approximately RM 11. When bed gradation data sets are collected, no less than 1 sample per mile should be taken and the sampling should extend from the confluence with the Columbia to the confluence with the Toutle. The data should be collected by experienced personnel in one sampling effort in an effort to help establish clear trends in bed gradation.

4.8.4 Variability of Cowlitz Deposition

Given the nature of hydrographic survey and the average-end-area method for volume calculation in meandering river, we suggest the variability of the Cowlitz deposition analysis to be +/-20%

Stream bed gradation sampling in the sandy lower reaches of the Cowlitz has higher certainty of reflecting the depositional gradation than sampling in the upper gravel reaches where sorting can occur. Spatial and temporal distribution of the gradation data is good relative to most engineering applications of this nature. The limitations of internal transport in the budget calculation method requiring a global erosion threshold reduces certainty of correct distribution. Uncertainty with the gradation distribution of mass deposition and erosion is determined by judgment to be +/- 30 %.

5.0 SEDIMENT BUDGET

A sediment budget is an accounting of the sediment movement, into and out of, a site on the landscape. In the Toutle / Cowlitz Rivers watershed an accounting of the sediment load has been conducted beginning upstream within the debris avalanche along the North Fork of the Toutle River and continuing downstream to the mouth of the Cowlitz River adding estimated sediment loads from various sources along the way. Estimation of sediment sources was the result of careful examination of all available data within the system. Suspended sediment data, sediment samples, bathymetric data along the Cowlitz, aerial surveys, and ground survey are included in the information used to formulate appropriate sediment sources. Temporal density of the information is highly variable and in some cases the data is sparse. To develop a sediment budget with available data, judgments have been made of the usefulness of the data and relevance of the time periods over which the data is most valid. In prior chapters the sources of information and the uncertainty of applying the information has been explained. Much of the data has been collected with an immediate purpose other than the development of a sediment budget; dredging surveys for example were collected for the purpose of evaluating the navigation channel geometry. Future management of the data acquisition resources could, perhaps, be enhanced by consideration of how the data is being applied for longer term estimates of river response to upstream sediment supplies. A sediment budget was developed by combining independently estimated sediment sources and sinks. The Toutle/Cowlitz sediment budget network is comprised of seven reaches. The reaches were defined geographically by the locations of the SRS, USGS gages, and river confluences. Each reach is described below:

1. North Fork Toutle River extending from the debris avalanche downstream to the SRS
2. North Fork Toutle River from the SRS to the Toutle confluence
3. South Fork upstream of the USGS gage
4. South Fork from the USGS gage downstream to the Toutle confluence
5. Toutle River extending from the North and South confluence downstream to the USGS gage at Tower Road
6. Toutle River from the USGS gage at Tower Road downstream to the Cowlitz River
7. Cowlitz River from the Toutle to the Columbia River

Separate sediment budgets were calculated for various time periods based upon the available data. A longer time period sediment budget including water years 2000 – 2007 was developed as well as nine annual budgets for water years 1999 through 2007. The sediment budget was limited to this time period due to the conditions occurring as a result of sediment passing through the spillway of the SRS, which began in 1998. It is thought that under a no-action scenario the SRS will continue to operate in a similar manner as the structure has functioned since it filled circa 1998.

The sediment budget was formulated under the assumption that the North Fork, South Fork, and Toutle Rivers act as a conduit for efficiently moving sediment; mainly sands, silts, and clays; to the Cowlitz River. Local sinks have been observed in a few locations along the Toutle, North, and South Fork Rivers; however, based upon analysis of stream power, critical shear, suspended sediment data and field observations, these sinks are thought to be relatively small in comparison to the sediment sources. Sediment depositing in sink locations along the Toutle during dry hydrologic conditions will likely return to suspension and be delivered to the Cowlitz given time. Locations of local sinks may account for some error in annual sediment budgets for years in which flows are relatively lower; however, this should have only a minor effect at moderate to higher flow years or on the larger time period budget. Investigation and development of data to support quantification and timing of sinks was not part of this study. Simulation of sinks or routing of sediment through the system to the Cowlitz requires a mobile bed sediment transport model, which was not included in the scope of this report.

5.1 Sediment Budget Results

The sediment budgets were calculated by mass (tons) and by grain size. The sediment budgets (Tables 5.1 through 5.9) appear as tabular spreadsheets with sediment sources and sinks listed along the left column. Description and data sources follow in the second and third columns. The remaining columns provide the total sediment quantity for each line of data and are then divided by particle size. All values are determined arithmetically; particle routing considering mass and hydraulic capacity is not included in the sediment budgets shown in Table 5.1 through Table 5.9**.**

Table 5.9 is the sediment budget from the avalanche plain to the mouth of the Cowlitz River for the period 2000 through 2007. This period was selected based on the LiDAR data available in the sediment avalanche plain, and is judged to have the highest quality data in the upper watershed and most complete data set available. Annual sediment budgets are necessary to coordinate with downstream data sets, especially survey data in the lower Cowlitz River and for planning purposes. Tables 5.1 through 5.10 present annual sediment budgets, which to some extent contain data that is based on the 2000 through 2007 avalanche plain LiDAR data. Chapter 4 summarizes the development of all data sets used in the sediment budget analyses.

Table 5.10 is a summary of the Toutle River basin sediment sources. Figure 5.1 shows that output of sediment from the SRS is the largest single contributor of the total sediment sources contributing to the basin, averaging 79.4% of the total sediment sources. Upstream sediment input to the South Fork Toutle River was identified as the next largest contributor with an average contribution of 13.3%. Table 5.12 and Figures 5.2 and 5.3 portray the annual supply of sediment by particle size at the mouth of the Toutle River.

Table 5.1 Toutle/Cowlitz Sediment Budget for Water Year 1999

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 1999

					Silts			Sand					Gravel			Cobble	
					CM	VFS	FS	MS	CS	VCS	VFG	FG	MG	CG	VCG	SC	LC
				Total	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
	Description	Data Source/Notes	Variabiliy	Tons	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1987-1999 Surface Comparison Prorated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	1,070,272	331,784	203,352	192,649	128,433	74,919	42,811	21,405	16,054	16,054	16,054	16,054	8,027	2,676
	Castle Creek		+/-15%	1,501,241	465,385	285,236	270,223	180,149	105,087	60,050	30,025	22,519	22,519	22,519	22,519	11,259	3,753
	Loowit		+/-15%	3,332,371	1,033,035	633,151	599,827	399,885	233,266	133,295	66,647	49,986	49,986	49,986	49,986	24,993	8,331
	A - Debris Avalanche to Elk Rock		+/-15%	4,563,086	1,414,557	866,986	821,355	547,570	319,416	182,523	91,262	68,446	68,446	68,446	68,446	34,223	11,408
	B - Elk Rock to N1		+/-15%	910,562	282,274	173,007	163,901	109,267	63,739	36,422	18,211	13,658	13,658	13,658	13,658	6,829	2,276
SRS Sediment Plain	C - Sediment Plain	1999-2000 Surface Comparison	+/-15%	(1,090,363)	(223,514)	(236,290)	(327,559)	(252,428)	(38,331)	(8,092)	(2,891)	(510)	(483)	(266)	0	0	0
	D - Sediment Plain		+/-15%	(1,591,267)	(378)	(130,006)	(438,694)	(577,234)	(211,978)	(81,019)	(43,341)	(31,701)	(35,459)	(24,540)	(13,988)	(2,930)	0
	E - Sediment Plain		+/-15%	(5,852,504)	(85,999)	(363,799)	(700,158)	(1,092,329)	(758,794)	(476,838)	(368,237)	(371,984)	(471,530)	(438,691)	(416,981)	(286,970)	(20,195)
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		11,377,532	3,527,035	2,161,731	2,047,956	1,365,304	796,427	455,101	227,551	170,663	170,663	170,663	170,663	85,331	28,444
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(8,534,135)	(309,891)	(730,096)	(1,466,410)	(1,921,990)	(1,009,103)	(565,949)	(414,469)	(404,195)	(507,471)	(463,496)	(430,969)	(289,899)	(20,195)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		2,843,397	3,217,143	1,431,635	581,545	(556,687)	(212,676)	(110,848)	(186,918)	(233,532)	(336,808)	(292,833)	(260,306)	(204,568)	8,249
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		2,843,397	1,748,958	778,290	316,149	0	0	0	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	126,587	4,374	6,014	14,651	26,869	22,901	16,584	9,519	6,596	8,394	4,861	5,824	0	
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	83,689	36,675	11,398	14,801	12,985	5,970	1,860						0	
Sinks																	
Output	Output to Toutle River			3,053,673	1,790,008	795,702	345,601	39,854	28,871	18,443	9,519	6,596	8,394	4,861	5,824	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		1,393,449	430,600	272,698	443,585	315,428	31,325	-32,028	-22,762	-14,213	-14,458	-11,037	-5,689	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	238,873	8,072	15,720	28,987	32,664	43,839	41,433	22,762	14,213	14,458	11,037	5,689		
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	1,632,322	438,673	288,418	472,572	348,092	75,164	9,405	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		1,700,481	438,673	288,418	472,572	348,092	75,164	9,405	22,762	14,213	14,458	11,037	5,689	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			1,700,481	438,673	288,418	472,572	348,092	75,164	9,405	22,762	14,213	14,458	11,037	5,689	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			4,754,154	2,228,680	1,084,120	818,172	387,945	104,035	27,848	32,281	20,809	22,852	15,898	11,513	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	23,077	2,010	2,837	3,517	3,587	3,151	2,283	1,547	1,341	842	1,209	752	0	
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		4,777,231	2,230,690	1,086,956	821,689	391,532	107,186	30,131	33,829	22,150	23,694	17,107	12,265	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		4,777,231	2,230,690	1,086,956	821,689	391,532	107,186	30,131	33,829	22,150	23,694	17,107	12,265	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	102,004	4,347	6,385	14,321	30,159	17,017	8,068	4,754	4,101	5,215	7,108	528	0	
Sinks																	
Output	Output to Cowlitz River			4,879,235	2,235,038	1,093,342	836,010	421,691	124,203	38,199	38,583	26,252	28,909	24,215	12,793	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			4,879,235	2,235,038	1,093,342	836,010	421,691	124,203	38,199	38,583	26,252	28,909	24,215	12,793	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	1,469	3,485	6,307	22,896	(10,085)	23,687	(12,710)	(6,787)	(8,750)	(8,723)	(5,861)	(1,993)	0	
Output	Output to Columbia River			4,880,704	2,238,523	1,099,649	858,906	411,607	147,890	25,489	31,796	17,502	20,186	18,355	10,800	0	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.2 Toutle/Cowlitz Sediment Budget Water Year 2000

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2000

	Description	Data Source/Notes	Variability	Total Tons	Silts CM	Sand VFS	Sand FS	Sand MS	Sand CS	Sand VCS	Gravel VFG	Gravel FG	Gravel MG	Gravel CG	Gravel VCG	Cobble SC	Cobble LC
					0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
					Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	60,626	18,794	11,519	10,913	7,275	4,244	2,425	1,213	909	909	909	909	455	152
	Castle Creek		+/-15%	165,323	51,250	31,411	29,758	19,839	11,573	6,613	3,306	2,480	2,480	2,480	2,480	1,240	413
	Loowit		+/-15%	326,163	101,110	61,971	58,709	39,140	22,831	13,047	6,523	4,892	4,892	4,892	4,892	2,446	815
	A - Debris Avalanche to Elk Rock		+/-15%	200,555	62,172	38,105	36,100	24,067	14,039	8,022	4,011	3,008	3,008	3,008	3,008	1,504	501
	B - Elk Rock to N1		+/-15%	193,577	60,009	36,780	34,844	23,229	13,550	7,743	3,872	2,904	2,904	2,904	2,904	1,452	484
SRS Sediment Plain	C - Sediment Plain	1999-2000 Surface Comparison	+/-15%	2,581,281	54,359	238,722	372,190	420,833	289,276	209,530	172,719	173,108	240,936	202,547	166,907	33,003	7,152
	D - Sediment Plain		+/-15%	(1,180,031)	(755)	(85,516)	(294,929)	(408,932)	(168,611)	(69,012)	(38,659)	(31,248)	(33,708)	(25,086)	(16,797)	(6,778)	0
	E - Sediment Plain		+/-15%	1,437,363	389,875	360,504	385,717	253,712	36,921	7,363	2,623	376	175	97	0	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		946,244	293,336	179,786	170,324	113,549	66,237	37,850	18,925	14,194	14,194	14,194	14,194	7,097	2,366
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		2,838,613	443,479	513,710	462,977	265,613	157,586	147,882	136,683	142,236	207,403	177,557	150,110	26,224	7,152
Output from SRS	Sediment Output from SRS	Erosion - Deposition		3,784,857	736,815	693,496	633,301	379,162	223,823	185,732	155,608	156,430	221,597	191,751	164,304	33,321	9,518
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		3,784,857	977,706	920,225	840,350	503,124	296,998	246,454	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	108,828	3,761	5,170	12,595	23,099	19,688	14,257	8,184	5,671	7,216	4,179	5,007	0	
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	58,270	25,536	7,936	10,305	9,041	4,157	1,295							
Sinks																	
Output	Output to Toutle River			3,951,955	1,007,002	933,331	863,251	535,264	320,843	262,006	8,184	5,671	7,216	4,179	5,007	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		227,838	109,479	63,029	100,495	64,298	-17,741	-33,124	-19,569	-12,219	-12,430	-9,488	-4,891	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	205,362	6,940	13,514	24,920	28,081	37,689	35,620	19,569	12,219	12,430	9,488	4,891	0	
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	433,201	116,419	76,543	125,415	92,380	19,948	2,496	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		491,798	116,419	76,543	125,415	92,380	19,948	2,496	19,569	12,219	12,430	9,488	4,891	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			491,798	116,419	76,543	125,415	92,380	19,948	2,496	19,569	12,219	12,430	9,488	4,891	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			4,443,753	1,123,421	1,009,874	988,666	627,644	340,791	264,502	27,753	17,890	19,646	13,668	9,898	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	19,840	1,728	2,439	3,024	3,084	2,709	1,962	1,330	1,153	724	1,040	647	0	
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		4,463,592	1,125,150	1,012,313	991,690	630,727	343,500	266,464	29,083	19,043	20,370	14,708	10,545	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		4,463,592	1,125,150	1,012,313	991,690	630,727	343,500	266,464	29,083	19,043	20,370	14,708	10,545	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	87,694	3,737	5,489	12,312	25,928	14,630	6,936	4,087	3,526	4,483	6,111	454	0	
Sinks																	
Output	Output to Cowlitz River			4,551,286	1,128,887	1,017,803	1,004,001	656,656	358,130	273,400	33,170	22,569	24,853	20,818	10,998	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			4,551,286	1,128,887	1,017,803	1,004,001	656,656	358,130	273,400	33,170	22,569	24,853	20,818	10,998	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	1,469	3,485	6,307	22,896	(10,085)	23,687	(12,710)	(6,787)	(8,750)	(8,723)	(5,861)	(1,993)	0	
Output	Output to Columbia River			4,552,755	1,132,372	1,024,110	1,026,898	646,571	381,817	260,690	26,384	13,819	16,131	14,958	9,006	0	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.3 Toutle/Cowlitz Sediment Budget WY 2001

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2001

					Silts			Sand					Gravel			Cobble	
					CM	VFS	FS	MS	CS	VCS	VFG	FG	MG	CG	VCG	SC	LC
				Total	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
	Description	Data Source/Notes	Variabiliy	Tons	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	24,621	7,633	4,678	4,432	2,955	1,723	985	492	369	369	369	369	185	62
	Castle Creek		+/-15%	67,141	20,814	12,757	12,085	8,057	4,700	2,686	1,343	1,007	1,007	1,007	1,007	504	168
	Loowit		+/-15%	132,461	41,063	25,168	23,843	15,895	9,272	5,298	2,649	1,987	1,987	1,987	1,987	993	331
	A - Debris Avalanche to Elk Rock		+/-15%	81,449	25,249	15,475	14,661	9,774	5,701	3,258	1,629	1,222	1,222	1,222	1,222	611	204
	B - Elk Rock to N1		+/-15%	78,616	24,371	14,937	14,151	9,434	5,503	3,145	1,572	1,179	1,179	1,179	1,179	590	197
SRS Sediment Plain	C - Sediment Plain	2000-2001 Surface Comparison	+/-15%	162,102	1,188	4,268	14,775	35,142	24,464	12,546	8,937	9,429	10,069	11,008	13,032	16,808	437
	D - Sediment Plain		+/-15%	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	E - Sediment Plain		+/-15%	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		384,289	119,129	73,015	69,172	46,115	26,900	15,372	7,686	5,764	5,764	5,764	5,764	2,882	961
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		162,102	1,188	4,268	14,775	35,142	24,464	12,546	8,937	9,429	10,069	11,008	13,032	16,808	437
Output from SRS	Sediment Output from SRS	Erosion - Deposition		546,391	120,317	77,283	83,947	81,256	51,364	27,917	16,622	15,194	15,833	16,773	18,797	19,691	1,397
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		546,391	148,705	95,517	103,753	100,428	63,483	34,504	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	21,219	733	1,008	2,456	4,504	3,839	2,780	1,596	1,106	1,407	815	976	0	0
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	13,313	5,834	1,813	2,354	2,066	950	296							
Sinks																	
Output	Output to Toutle River			580,923	155,272	98,339	108,564	106,997	68,272	37,580	1,596	1,106	1,407	815	976	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		-17,823	4,618	1,291	1,573	-737	-6,325	-6,817	-3,816	-2,382	-2,424	-1,850	-954	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	40,041	1,353	2,635	4,859	5,475	7,349	6,945	3,816	2,382	2,424	1,850	954		
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	22,218	5,971	3,926	6,432	4,738	1,023	128	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		33,643	5,971	3,926	6,432	4,738	1,023	128	3,816	2,382	2,424	1,850	954	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			33,643	5,971	3,926	6,432	4,738	1,023	128	3,816	2,382	2,424	1,850	954	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			614,566	161,243	102,264	114,996	111,735	69,295	37,708	5,411	3,488	3,831	2,665	1,930	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	3,868	337	476	590	601	528	383	259	225	141	203	126	0	0
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		618,435	161,580	102,740	115,586	112,337	69,823	38,090	5,671	3,713	3,972	2,868	2,056	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		618,435	161,580	102,740	115,586	112,337	69,823	38,090	5,671	3,713	3,972	2,868	2,056	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	17,098	729	1,070	2,400	5,055	2,852	1,352	797	688	874	1,191	88	0	0
Sinks																	
Output	Output to Cowlitz River			635,533	162,309	103,810	117,986	117,392	72,675	39,443	6,468	4,400	4,846	4,059	2,144	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			635,533	162,309	103,810	117,986	117,392	72,675	39,443	6,468	4,400	4,846	4,059	2,144	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	1,469	3,485	6,307	22,896	(10,085)	23,687	(12,710)	(6,787)	(8,750)	(8,723)	(5,861)	(1,993)	0	0
Output	Output to Columbia River			637,002	165,795	110,118	140,882	107,308	96,363	26,733	(319)	(4,350)	(3,877)	(1,802)	152	0	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.4 Toutle/Cowlitz Sediment Budget WY 2002

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2002

	Description	Data Source/Notes	Variabiliy	Total	Silts	Sand					Gravel					Cobble	
				Tons	CM 0.0625 Ton	VFS 0.125 Ton	FS 0.25 Ton	MS 0.5 Ton	CS 1 Ton	VCS 2 Ton	VFG 4 Ton	FG 8 Ton	MG 16 Ton	CG 32 Ton	VCG 63 Ton	SC 128 Ton	LC 256 Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	674,215	209,007	128,101	121,359	80,906	47,195	26,969	13,484	10,113	10,113	10,113	10,113	5,057	1,686
	Castle Creek		+/-15%	1,838,556	569,952	349,326	330,940	220,627	128,699	73,542	36,771	27,578	27,578	27,578	27,578	13,789	4,596
	Loowit		+/-15%	3,627,243	1,124,445	689,176	652,904	435,269	253,907	145,090	72,545	54,409	54,409	54,409	54,409	27,204	9,068
	A - Debris Avalanche to Elk Rock		+/-15%	2,230,366	691,414	423,770	401,466	267,644	156,126	89,215	44,607	33,455	33,455	33,455	33,455	16,728	5,576
	B - Elk Rock to N1		+/-15%	2,152,765	667,357	409,025	387,498	258,332	150,694	86,111	43,055	32,291	32,291	32,291	32,291	16,146	5,382
SRS Sediment Plain	C - Sediment Plain	57% of 2001-2003 Surface Comparison	+/-15%	(2,680,136)	(39,284)	(161,075)	(314,649)	(503,820)	(354,126)	(217,920)	(164,185)	(166,220)	(207,986)	(198,028)	(201,494)	(144,487)	(6,864)
	D - Sediment Plain		+/-15%	(1,208,326)	(913)	(75,332)	(278,831)	(421,860)	(179,572)	(75,060)	(44,014)	(37,494)	(38,219)	(28,772)	(20,233)	(8,027)	0
	E - Sediment Plain		+/-15%	(690,363)	(115,543)	(136,215)	(220,057)	(181,529)	(27,883)	(5,975)	(2,136)	(393)	(407)	(224)	0	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		10,523,145	3,262,175	1,999,398	1,894,166	1,262,777	736,620	420,926	210,463	157,847	157,847	157,847	157,847	78,924	26,308
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(4,578,825)	(155,740)	(372,622)	(813,536)	(1,107,209)	(561,581)	(298,954)	(210,336)	(204,107)	(246,612)	(227,025)	(221,727)	(152,513)	(6,864)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		5,944,320	3,106,436	1,626,776	1,080,630	155,569	175,039	121,972	127	(46,260)	(88,765)	(69,177)	(63,880)	(73,590)	19,444
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		5,944,320	2,946,762	1,543,158	1,025,085	147,572	166,042	115,702	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	106,096	3,666	5,040	12,279	22,520	19,194	13,899	7,978	5,528	7,035	4,075	4,882	0	0
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	67,287	29,487	9,164	11,900	10,440	4,800	1,495							
Sinks																	
Output	Output to Toutle River			6,117,703	2,979,915	1,557,363	1,049,264	180,532	190,035	131,097	7,978	5,528	7,035	4,075	4,882	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		962,726	305,762	192,306	312,385	220,618	16,807	-28,026	-19,078	-11,912	-12,118	-9,250	-4,768	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	200,207	6,766	13,175	24,295	27,376	36,743	34,726	19,078	11,912	12,118	9,250	4,768		
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	1,162,933	312,528	205,481	336,679	247,995	53,550	6,700	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		1,220,059	312,528	205,481	336,679	247,995	53,550	6,700	19,078	11,912	12,118	9,250	4,768	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			1,220,059	312,528	205,481	336,679	247,995	53,550	6,700	19,078	11,912	12,118	9,250	4,768	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			7,337,763	3,292,444	1,762,843	1,385,943	428,526	243,585	137,797	27,056	17,441	19,153	13,325	9,649	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	19,342	1,685	2,378	2,948	3,006	2,641	1,913	1,297	1,124	706	1,014	630	0	0
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		7,357,104	3,294,129	1,765,221	1,388,891	431,533	246,227	139,710	28,353	18,565	19,859	14,338	10,280	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		7,357,104	3,294,129	1,765,221	1,388,891	431,533	246,227	139,710	28,353	18,565	19,859	14,338	10,280	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	85,492	3,644	5,352	12,002	25,277	14,262	6,762	3,985	3,438	4,371	5,957	442	0	0
Sinks																	
Output	Output to Cowlitz River			7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			7,442,596	3,297,772	1,770,572	1,400,893	456,810	260,489	146,472	32,338	22,002	24,230	20,296	10,722	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	1,469	3,485	6,307	22,896	(10,085)	23,687	(12,710)	(6,787)	(8,750)	(8,723)	(5,861)	(1,993)	0	0
Output	Output to Columbia River			7,444,065	3,301,258	1,776,880	1,423,790	446,726	284,176	133,762	25,551	13,252	15,507	14,435	8,729	0	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.5 Toutle/Cowlitz Sediment Budget WY 2003

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2003

					Silts	Sand					Gravel					Cobble	
				Total	CM	VFS	FS	MS	CS	VCS	VFG	FG	MG	CG	VCG	SC	LC
					0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
	Description	Data Source/Notes	Variabiliy	Tons	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	518,487	160,731	98,513	93,328	62,218	36,294	20,739	10,370	7,777	7,777	7,777	7,777	3,889	1,296
	Castle Creek		+/-15%	1,413,894	438,307	268,640	254,501	169,667	98,973	56,556	28,278	21,208	21,208	21,208	21,208	10,604	3,535
	Loowit		+/-15%	2,789,439	864,726	529,993	502,099	334,733	195,261	111,578	55,789	41,842	41,842	41,842	41,842	20,921	6,974
	A - Debris Avalanche to Elk Rock		+/-15%	1,715,206	531,714	325,889	308,737	205,825	120,064	68,608	34,304	25,728	25,728	25,728	25,728	12,864	4,288
	B - Elk Rock to N1		+/-15%	1,655,529	513,214	314,551	297,995	198,664	115,887	66,221	33,111	24,833	24,833	24,833	24,833	12,416	4,139
SRS Sediment Plain	C - Sediment Plain	43% of 2001-2003 Surface Comparison	+/-15%	(2,021,857)	(29,635)	(121,513)	(237,366)	(380,075)	(267,148)	(164,395)	(123,859)	(125,394)	(156,902)	(149,390)	(152,005)	(108,999)	(5,178)
	D - Sediment Plain		+/-15%	(911,544)	(688)	(56,829)	(210,346)	(318,245)	(135,467)	(56,624)	(33,204)	(28,285)	(28,832)	(21,705)	(15,263)	(6,055)	0
	E - Sediment Plain		+/-15%	(520,800)	(87,164)	(102,759)	(166,008)	(136,943)	(21,035)	(4,507)	(1,611)	(297)	(307)	(169)	0	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		8,092,556	2,508,692	1,537,586	1,456,660	971,107	566,479	323,702	161,851	121,388	121,388	121,388	121,388	60,694	20,231
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(3,454,201)	(117,488)	(281,101)	(613,720)	(835,263)	(423,649)	(225,527)	(158,674)	(153,975)	(186,040)	(171,264)	(167,268)	(115,054)	(5,178)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		4,638,355	2,391,205	1,256,485	842,940	135,844	142,830	98,175	3,177	(32,587)	(64,652)	(49,876)	(45,879)	(54,360)	15,054
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		4,638,355	2,278,645	1,197,339	803,261	129,449	136,106	93,554	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	146,622	5,067	6,966	16,970	31,121	26,525	19,208	11,026	7,640	9,722	5,631	6,746	0	0
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	49,411	21,654	6,730	8,738	7,666	3,525	1,098							
Sinks																	
Output	Output to Toutle River			4,834,388	2,305,365	1,211,035	828,969	168,237	166,157	113,861	11,026	7,640	9,722	5,631	6,746	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		-68,683	46,547	18,544	26,643	6,522	-41,200	-46,792	-26,365	-16,463	-16,747	-12,784	-6,589	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	276,681	9,350	18,207	33,575	37,834	50,778	47,991	26,365	16,463	16,747	12,784	6,589	0	0
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	207,998	55,898	36,751	60,217	44,355	9,578	1,198	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		286,944	55,898	36,751	60,217	44,355	9,578	1,198	26,365	16,463	16,747	12,784	6,589	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			286,944	55,898	36,751	60,217	44,355	9,578	1,198	26,365	16,463	16,747	12,784	6,589	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			5,121,333	2,361,263	1,247,786	889,186	212,593	175,734	115,059	37,390	24,103	26,469	18,414	13,335	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	26,730	2,328	3,286	4,074	4,155	3,650	2,644	1,792	1,554	975	1,401	871	0	0
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		5,148,062	2,363,591	1,251,072	893,260	216,747	179,384	117,703	39,183	25,656	27,444	19,815	14,206	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		5,148,062	2,363,591	1,251,072	893,260	216,747	179,384	117,703	39,183	25,656	27,444	19,815	14,206	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	118,148	5,035	7,396	16,587	34,933	19,710	9,345	5,507	4,751	6,040	8,233	611	0	0
Sinks																	
Output	Output to Cowlitz River			5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			5,266,210	2,368,627	1,258,468	909,847	251,680	199,094	127,048	44,690	30,407	33,485	28,048	14,818	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	(48,155)	(200)	4,195	20,903	(15,626)	12,816	(16,043)	(8,118)	(10,336)	(11,054)	(9,779)	(12,756)	(2,157)	0
Output	Output to Columbia River			5,218,055	2,368,427	1,262,663	930,750	236,054	211,910	111,004	36,572	20,071	22,431	18,269	2,061	(2,157)	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.6 Toutle/Cowlitz Sediment Budget WY 2004

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2004

	Description		Data Source/Notes	Variability	Total Tons	Silts	Sand					Gravel					Cobble	
						CM	VFS	FS	MS	CS	VCS	VFG	FG	MG	CG	VCG	SC	LC
						0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
						Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																		
	Coldwater Creek		1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	191,820	59,464	36,446	34,528	23,018	13,427	7,673	3,836	2,877	2,877	2,877	2,877	1,439	480
	Castle Creek			+/-15%	523,085	162,156	99,386	94,155	62,770	36,616	20,923	10,462	7,846	7,846	7,846	7,846	3,923	1,308
Debris Avalanche	Loowit			+/-15%	1,031,982	319,914	196,077	185,757	123,838	72,239	41,279	20,640	15,480	15,480	15,480	15,480	7,740	2,580
	A - Debris Avalanche to Elk Rock			+/-15%	634,558	196,713	120,566	114,220	76,147	44,419	25,382	12,691	9,518	9,518	9,518	9,518	4,759	1,586
	B - Elk Rock to N1			+/-15%	612,480	189,869	116,371	110,246	73,498	42,874	24,499	12,250	9,187	9,187	9,187	9,187	4,594	1,531
	C - Sediment Plain			+/-15%	242,797	3,559	14,592	28,504	45,642	32,081	19,742	14,874	15,058	18,842	17,940	18,254	13,089	622
SRS Sediment Plain	D - Sediment Plain		Average of 2003-2004 Surface Comparison	+/-15%	(894,411)	(676)	(55,761)	(206,392)	(312,263)	(132,921)	(55,560)	(32,580)	(27,753)	(28,290)	(21,297)	(14,976)	(5,942)	0
	E - Sediment Plain			+/-15%	(246,554)	(41,265)	(48,648)	(78,591)	(64,831)	(9,958)	(2,134)	(763)	(141)	(145)	(80)	0	0	0
Sources	Debris Avalanche Erosion		Net Erosion from Debris Avalanche		2,993,925	928,117	568,846	538,906	359,271	209,575	119,757	59,878	44,909	44,909	44,909	44,909	22,454	7,485
Sinks	Total Deposition Behind SRS		Net Deposition on Sediment Plain		(898,168)	(38,382)	(89,817)	(256,478)	(331,453)	(110,798)	(37,952)	(18,469)	(12,836)	(9,593)	(3,438)	3,277	7,148	622
Output from SRS	Sediment Output from SRS		Erosion - Deposition		2,095,756	889,735	479,029	282,428	27,818	98,777	81,805	41,410	32,073	35,315	41,471	48,186	29,602	8,107
North Fork Toutle River: SRS to Toutle River																		
Input	Output from SRS to North Fork Toutle River		Adjusted for sand/gravel exchange		2,095,756	1,002,730	539,865	318,296	31,351	111,321	92,194	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle		Est. & pro-rated from 99-06 Aerial Photos	+/-35%	77,409	2,675	3,678	8,959	16,431	14,004	10,141	5,821	4,034	5,133	2,973	3,562	0	0
	Green River		Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	32,024	14,034	4,362	5,663	4,969	2,285	712							
Sinks																		
Output	Output to Toutle River				2,205,189	1,019,439	547,904	332,918	52,751	127,610	103,047	5,821	4,034	5,133	2,973	3,562	0	0
South Fork Toutle River: Upstream of USGS Gage																		
Input	Upstream Source = Gage - Bank Erosion		Upstream Source Data Unavaliable		87,283	57,776	31,620	49,833	29,789	-16,063	-23,992	-13,919	-8,691	-8,841	-6,749	-3,479	0	0
Sources	Bank Erosion South Fork		Est. & pro-rated from 99-06 Aerial Photos	+/-35%	146,074	4,936	9,613	17,726	19,974	26,808	25,337	13,919	8,691	8,841	6,749	3,479	0	0
Sinks																		
Output	@ USGS Gage # 14241500 South Fork		USGS Gage + 25% Unmeasured	+/-25%	233,357	62,713	41,232	67,559	49,763	10,745	1,345	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																		
Input	@ USGS Gage # 14241500 South Fork		USGS Gage + 25% Unmeasured		275,037	62,713	41,232	67,559	49,763	10,745	1,345	13,919	8,691	8,841	6,749	3,479	0	0
Sources																		
Sinks																		
Output	Output to Toutle River				275,037	62,713	41,232	67,559	49,763	10,745	1,345	13,919	8,691	8,841	6,749	3,479	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																		
Input	Output from North Fork and South Fork				2,480,226	1,082,151	589,136	400,477	102,514	138,355	104,391	19,740	12,725	13,974	9,722	7,040	0	0
Sources	Toutle Bank Erosion Above Tower		Est. & pro-rated from 99-06 Aerial Photos	+/-35%	14,112	1,229	1,735	2,151	2,193	1,927	1,396	946	820	515	739	460	0	0
Sinks																		
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc		Compare Sediment Budget to Gage Data		2,494,338	1,083,380	590,871	402,628	104,707	140,282	105,787	20,687	13,545	14,489	10,461	7,500	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																		
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc		Compare Sediment Budget to Gage Data		2,494,338	1,083,380	590,871	402,628	104,707	140,282	105,787	20,687	13,545	14,489	10,461	7,500	0	0
Sources	Toutle Bank Erosion Below Tower		Est. & pro-rated from 99-06 Aerial Photos	+/-35%	62,376	2,658	3,905	8,757	18,443	10,406	4,934	2,907	2,508	3,189	4,346	323	0	0
Sinks																		
Output	Output to Cowlitz River				2,556,714	1,086,039	594,775	411,385	123,150	150,688	110,721	23,594	16,053	17,678	14,808	7,823	0	0
Cowlitz River: Toutle River to Columbia River																		
Input	Input from Toutle River				2,556,714	1,086,039	594,775	411,385	123,150	150,688	110,721	23,594	16,053	17,678	14,808	7,823	0	0
	Input from Upper Cowlitz				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources					0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion		Hydro-Survey Comparisons	+/-30%	(296,796)	(19,872)	(8,617)	2,760	(39,729)	(50,001)	(28,171)	(12,347)	(15,140)	(19,593)	(27,280)	(65,864)	(12,944)	0
Output	Output to Columbia River				2,259,918	1,066,167	586,158	414,145	83,421	100,687	82,550	11,247	914	(1,914)	(12,472)	(58,041)	(12,944)	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.7 Toutle/Cowlitz Sediment Budget WY 2005

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2005

	Description	Data Source/Notes	Variabiliy	Total Tons	Silts	Sand					Gravel					Cobble	
					CM	VFS	FS	MS	CS	VCS	VFG	FG	MG	CG	VCG	SC	LC
					0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
					Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	283,196	87,791	53,807	50,975	33,984	19,824	11,328	5,664	4,248	4,248	4,248	4,248	2,124	708
	Castle Creek		+/-15%	772,265	239,402	146,730	139,008	92,672	54,059	30,891	15,445	11,584	11,584	11,584	11,584	5,792	1,931
	Loowit		+/-15%	1,523,583	472,311	289,481	274,245	182,830	106,651	60,943	30,472	22,854	22,854	22,854	22,854	11,427	3,809
	A - Debris Avalanche to Elk Rock		+/-15%	936,840	290,420	178,000	168,631	112,421	65,579	37,474	18,737	14,053	14,053	14,053	14,053	7,026	2,342
	B - Elk Rock to N1		+/-15%	904,245	280,316	171,807	162,764	108,509	63,297	36,170	18,085	13,564	13,564	13,564	13,564	6,782	2,261
SRS Sediment Plain	C - Sediment Plain	Average of 2004-2006 Surface Comparison	+/-15%	(1,376,559)	(20,177)	(82,731)	(161,608)	(258,770)	(181,885)	(111,927)	(84,328)	(85,373)	(106,825)	(101,710)	(103,491)	(74,211)	(3,525)
	D - Sediment Plain		+/-15%	(537,154)	(406)	(33,488)	(123,952)	(187,535)	(79,828)	(33,367)	(19,566)	(16,668)	(16,990)	(12,790)	(8,994)	(3,568)	0
	E - Sediment Plain		+/-15%	(143,602)	(24,034)	(28,334)	(45,774)	(37,760)	(5,800)	(1,243)	(444)	(82)	(85)	(47)	0	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		4,420,128	1,370,240	839,824	795,623	530,415	309,409	176,805	88,403	66,302	66,302	66,302	66,302	33,151	11,050
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(2,057,315)	(44,617)	(144,553)	(331,335)	(484,065)	(267,512)	(146,537)	(104,339)	(102,122)	(123,899)	(114,547)	(112,485)	(77,779)	(3,525)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		2,362,813	1,325,623	695,271	464,288	46,351	41,897	30,268	(15,936)	(35,821)	(57,597)	(48,246)	(46,183)	(44,628)	7,525
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		2,362,813	1,202,981	630,947	421,334	42,062	38,021	27,468	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	55,552	1,920	2,639	6,429	11,791	10,050	7,278	4,177	2,895	3,684	2,133	2,556	0	0
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	32,461	14,225	4,421	5,741	5,036	2,316	721							
Sinks																	
Output	Output to Toutle River			2,450,826	1,219,126	638,007	433,504	58,890	50,386	35,467	4,177	2,895	3,684	2,133	2,556	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		188,626	75,321	44,953	72,237	48,245	-5,726	-16,492	-9,989	-6,237	-6,345	-4,843	-2,497	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	104,829	3,543	6,898	12,721	14,334	19,239	18,183	9,989	6,237	6,345	4,843	2,497	0	0
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	293,455	78,863	51,851	84,958	62,579	13,513	1,691	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		323,366	78,863	51,851	84,958	62,579	13,513	1,691	9,989	6,237	6,345	4,843	2,497	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			323,366	78,863	51,851	84,958	62,579	13,513	1,691	9,989	6,237	6,345	4,843	2,497	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			2,774,193	1,297,990	689,858	518,462	121,469	63,899	37,158	14,167	9,132	10,029	6,977	5,053	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	10,127	882	1,245	1,543	1,574	1,383	1,002	679	589	370	531	330	0	0
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		2,784,320	1,298,872	691,103	520,005	123,043	65,282	38,159	14,846	9,721	10,398	7,508	5,383	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		2,784,320	1,298,872	691,103	520,005	123,043	65,282	38,159	14,846	9,721	10,398	7,508	5,383	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	44,764	1,908	2,802	6,285	13,235	7,468	3,541	2,087	1,800	2,289	3,119	232	0	0
Sinks																	
Output	Output to Cowlitz River			2,829,084	1,300,779	693,906	526,290	136,279	72,750	41,700	16,932	11,521	12,687	10,627	5,614	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			2,829,084	1,300,779	693,906	526,290	136,279	72,750	41,700	16,932	11,521	12,687	10,627	5,614	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	(296,796)	(19,872)	(8,617)	2,760	(39,729)	(50,001)	(28,171)	(12,347)	(15,140)	(19,593)	(27,280)	(65,864)	(12,944)	0
Output	Output to Columbia River			2,532,288	1,280,907	685,288	529,050	96,550	22,749	13,529	4,585	(3,619)	(6,906)	(16,653)	(60,250)	(12,944)	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.8 Toutle/Cowlitz Sediment Budget WY 2006

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2006

	Description	Data Source/Notes	Variabiliy	Total Tons	Silts CM 0.0625 Ton	Sand VFS 0.125 Ton	FS 0.25 Ton	MS 0.5 Ton	CS 1 Ton	VCS 2 Ton	Gravel VFG 4 Ton	FG 8 Ton	MG 16 Ton	CG 32 Ton	VCG 63 Ton	Cobble SC 128 Ton	LC 256 Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Lidar Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	431,341	133,716	81,955	77,641	51,761	30,194	17,254	8,627	6,470	6,470	6,470	6,470	3,235	1,078
	Castle Creek		+/-15%	1,176,248	364,637	223,487	211,725	141,150	82,337	47,050	23,525	17,644	17,644	17,644	17,644	8,822	2,941
	Loowit		+/-15%	2,320,593	719,384	440,913	417,707	278,471	162,441	92,824	46,412	34,809	34,809	34,809	34,809	17,404	5,801
	A - Debris Avalanche to Elk Rock		+/-15%	1,426,916	442,344	271,114	256,845	171,230	99,884	57,077	28,538	21,404	21,404	21,404	21,404	10,702	3,567
	B - Elk Rock to N1		+/-15%	1,377,270	426,954	261,681	247,909	165,272	96,409	55,091	27,545	20,659	20,659	20,659	20,659	10,330	3,443
SRS Sediment Plain	C - Sediment Plain	Average of 2004-2006 Surface Comparison	+/-15%	(1,376,559)	(20,662)	(83,949)	(162,233)	(259,855)	(180,898)	(110,742)	(83,169)	(84,243)	(105,198)	(101,120)	(106,146)	(74,336)	(4,008)
	D - Sediment Plain		+/-15%	(537,154)	(354)	(35,212)	(127,897)	(189,569)	(78,305)	(32,263)	(18,681)	(15,489)	(16,022)	(11,979)	(8,275)	(3,108)	0
	E - Sediment Plain		+/-15%	(143,602)	(19,205)	(25,837)	(48,160)	(41,843)	(6,439)	(1,385)	(495)	(92)	(95)	(52)	0	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		6,732,368	2,087,034	1,279,150	1,211,826	807,884	471,266	269,295	134,647	100,986	100,986	100,986	100,986	50,493	16,831
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(2,057,315)	(40,221)	(144,998)	(338,291)	(491,267)	(265,642)	(144,389)	(102,345)	(99,824)	(121,315)	(113,152)	(114,421)	(77,444)	(4,008)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		4,675,052	2,046,813	1,134,152	873,536	316,617	205,624	124,906	32,303	1,162	(20,330)	(12,166)	(13,435)	(26,951)	12,823
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		4,675,052	2,035,235	1,127,736	868,594	314,826	204,461	124,199	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	101,087	3,493	4,802	11,700	21,456	18,288	13,243	7,601	5,267	6,703	3,882	4,651	0	0
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	53,807	23,580	7,328	9,516	8,349	3,839	1,196							
Sinks																	
Output	Output to Toutle River			4,829,946	2,062,309	1,139,867	889,810	344,631	226,587	138,638	7,601	5,267	6,703	3,882	4,651	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		111,548	74,795	40,861	64,372	38,382	-21,088	-31,345	-18,177	-11,350	-11,546	-8,814	-4,543	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	190,755	6,446	12,553	23,148	26,084	35,008	33,087	18,177	11,350	11,546	8,814	4,543	0	0
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	302,303	81,241	53,414	87,519	64,466	13,920	1,742	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		356,732	81,241	53,414	87,519	64,466	13,920	1,742	18,177	11,350	11,546	8,814	4,543	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			356,732	81,241	53,414	87,519	64,466	13,920	1,742	18,177	11,350	11,546	8,814	4,543	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			5,186,678	2,143,550	1,193,282	977,329	409,097	240,507	140,380	25,779	16,617	18,249	12,696	9,194	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	18,428	1,605	2,265	2,809	2,864	2,516	1,823	1,236	1,071	672	966	601	0	0
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		5,205,107	2,145,155	1,195,547	980,138	411,961	243,023	142,203	27,014	17,688	18,921	13,661	9,795	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		5,205,107	2,145,155	1,195,547	980,138	411,961	243,023	142,203	27,014	17,688	18,921	13,661	9,795	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	81,456	3,472	5,099	11,436	24,084	13,589	6,443	3,797	3,275	4,164	5,676	421	0	
Sinks																	
Output	Output to Cowlitz River			5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			5,286,563	2,148,627	1,200,646	991,573	436,045	256,612	148,645	30,811	20,964	23,086	19,337	10,216	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	(296,796)	(19,872)	(8,617)	2,760	(39,729)	(50,001)	(28,171)	(12,347)	(15,140)	(19,593)	(27,280)	(65,864)	(12,944)	0
Output	Output to Columbia River			4,989,767	2,128,755	1,192,029	994,334	396,316	206,611	120,475	18,464	5,824	3,493	(7,942)	(55,648)	(12,944)	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.9 Toutle/Cowlitz Sediment Budget WY 2007

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2007

					Silts	Sand					Gravel					Cobble	
					CM	VFS	FS	MS	CS	VCS	VFG	FG	MG	CG	VCG	SC	LC
				Total	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	63	128	256
	Description	Data Source/Notes	Variabiliy	Tons	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton	Ton
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Surface Comparison Pro-rated by: Tower SS-South Fork SS + SRS Deposition	+/-15%	1,678,475	520,327	318,910	302,126	201,417	117,493	67,139	33,570	25,177	25,177	25,177	25,177	12,589	4,196
	Castle Creek		+/-15%	4,577,135	1,418,912	869,656	823,884	549,256	320,399	183,085	91,543	68,657	68,657	68,657	68,657	34,329	11,443
	Loowit		+/-15%	9,030,120	2,799,337	1,715,723	1,625,422	1,083,614	632,108	361,205	180,602	135,452	135,452	135,452	135,452	67,726	22,575
	A - Debris Avalanche to Elk Rock		+/-15%	5,552,558	1,721,293	1,054,986	999,460	666,307	388,679	222,102	111,051	83,288	83,288	83,288	83,288	41,644	13,881
	B - Elk Rock to N1		+/-15%	5,359,368	1,661,404	1,018,280	964,686	643,124	375,156	214,375	107,187	80,391	80,391	80,391	80,391	40,195	13,398
SRS Sediment Plain	C - Sediment Plain	2006-2007 Surface Comparison	+/-15%	(6,156,997)	(232,924)	(526,552)	(1,364,819)	(1,205,429)	(654,646)	(371,611)	(272,223)	(287,367)	(322,557)	(302,614)	(329,636)	(269,684)	(16,937)
	D - Sediment Plain		+/-15%	(2,151,180)	(189,053)	(313,635)	(977,252)	(428,185)	(104,727)	(42,457)	(20,572)	(30,253)	(28,854)	(12,964)	(3,227)	0	0
	E - Sediment Plain		+/-15%	(480,059)	(42,189)	(69,991)	(218,084)	(95,554)	(23,371)	(9,475)	(4,591)	(6,751)	(6,439)	(2,893)	(720)	0	0
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		26,197,656	8,121,273	4,977,555	4,715,578	3,143,719	1,833,836	1,047,906	523,953	392,965	392,965	392,965	392,965	196,482	65,494
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(8,788,236)	(464,166)	(910,178)	(2,560,156)	(1,729,168)	(782,743)	(423,543)	(297,386)	(324,371)	(357,850)	(318,471)	(333,583)	(269,684)	(16,937)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		17,409,420	7,657,108	4,067,377	2,155,422	1,414,551	1,051,093	624,363	226,567	68,594	35,114	74,493	59,382	(73,201)	48,557
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		17,409,420	7,855,420	4,172,719	2,211,246	1,451,186	1,078,315	640,534	0	0	0	0	0	0	0
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	169,389	5,854	8,047	19,605	35,954	30,644	22,191	12,738	8,826	11,232	6,505	7,794	0	0
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	158,366	69,401	21,569	28,007	24,571	11,298	3,519							
Sinks																	
Output	Output to Toutle River			17,737,175	7,930,675	4,202,335	2,258,858	1,511,712	1,120,257	666,244	12,738	8,826	11,232	6,505	7,794	0	0
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		4,420,707	1,263,126	816,545	1,333,585	967,168	159,618	-28,130	-30,459	-19,019	-19,347	-14,769	-7,612	0	0
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	319,644	10,802	21,035	38,788	43,708	58,662	55,442	30,459	19,019	19,347	14,769	7,612	0	0
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	4,740,351	1,273,928	837,580	1,372,373	1,010,876	218,280	27,313	0	0	0	0	0	0	0
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		4,831,557	1,273,928	837,580	1,372,373	1,010,876	218,280	27,313	30,459	19,019	19,347	14,769	7,612	0	0
Sources																	
Sinks																	
Output	Output to Toutle River			4,831,557	1,273,928	837,580	1,372,373	1,010,876	218,280	27,313	30,459	19,019	19,347	14,769	7,612	0	0
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			22,568,731	9,204,603	5,039,915	3,631,231	2,522,588	1,338,537	693,557	43,196	27,845	30,579	21,274	15,406	0	0
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	30,880	2,690	3,796	4,706	4,800	4,217	3,054	2,071	1,795	1,127	1,618	1,006	0	0
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		22,599,611	9,207,293	5,043,711	3,635,937	2,527,388	1,342,754	696,611	45,267	29,640	31,706	22,892	16,412	0	0
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		22,599,611	9,207,293	5,043,711	3,635,937	2,527,388	1,342,754	696,611	45,267	29,640	31,706	22,892	16,412	0	0
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	136,494	5,817	8,544	19,163	40,357	22,771	10,796	6,362	5,488	6,978	9,511	706	0	0
Sinks																	
Output	Output to Cowlitz River			22,736,105	9,213,110	5,052,256	3,655,100	2,567,745	1,365,525	707,407	51,629	35,128	38,684	32,403	17,119	0	0
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			22,736,105	9,213,110	5,052,256	3,655,100	2,567,745	1,365,525	707,407	51,629	35,128	38,684	32,403	17,119	0	0
	Input from Upper Cowlitz			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sources				0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	(1,526,837)	(37,670)	(126,425)	(523,045)	(310,403)	(210,151)	(50,049)	(10,209)	(32,113)	(30,860)	(51,582)	(123,787)	(20,543)	0
Output	Output to Columbia River			21,209,269	9,175,440	4,925,830	3,132,054	2,257,342	1,155,374	657,358	41,420	3,016	7,824	(19,178)	(106,668)	(20,543)	0

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.10 Toutle/Cowlitz Sediment Budget WY 2000 - 2007

Toutle/Cowlitz River Sediment Budget
From Debris Avalanche to Columbia River
WY 2000 through 2007

					Silts	Sand					Gravel					Cobble	
	Description	Data Source/Notes	Variabiliy	Total M Tons	CM 0.0625 M Tons	VFS 0.125 M Tons	FS 0.25 M Tons	MS 0.5 M Tons	CS 1 M Tons	VCS 2 M Tons	VFG 4 M Tons	FG 8 M Tons	MG 16 M Tons	CG 32 M Tons	VCG 63 M Tons	SC 128 M Tons	LC 256 M Tons
North Fork Toutle River: Debris Avalanche to SRS																	
Debris Avalanche	Coldwater Creek	1999-2007 Surface Comparison	+/-15%	3.86	1.20	0.73	0.70	0.46	0.27	0.15	0.08	0.06	0.06	0.06	0.06	0.03	0.01
	Castle Creek		+/-15%	10.53	3.27	2.00	1.90	1.26	0.74	0.42	0.21	0.16	0.16	0.16	0.16	0.08	0.03
	Loowit		+/-15%	20.78	6.44	3.95	3.74	2.49	1.45	0.83	0.42	0.31	0.31	0.31	0.31	0.16	0.05
	A - Debris Avalanche to Elk Rock		+/-15%	12.78	3.96	2.43	2.30	1.53	0.89	0.51	0.26	0.19	0.19	0.19	0.19	0.10	0.03
	B - Elk Rock to N1		+/-15%	12.33	3.82	2.34	2.22	1.48	0.86	0.49	0.25	0.19	0.19	0.19	0.19	0.09	0.03
SRS Sediment Plain	C - Sediment Plain	1999-2007 Surface Comparison	+/-15%	(10.63)	(0.28)	(0.72)	(1.83)	(2.11)	(1.29)	(0.73)	(0.53)	(0.55)	(0.63)	(0.62)	(0.70)	(0.61)	(0.03)
	D - Sediment Plain		+/-15%	(7.42)	(0.19)	(0.66)	(2.22)	(2.27)	(0.88)	(0.36)	(0.21)	(0.19)	(0.19)	(0.13)	(0.09)	(0.03)	0.00
	E - Sediment Plain		+/-15%	(0.79)	0.07	(0.05)	(0.39)	(0.31)	(0.06)	(0.02)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	0.00	0.00
Sources	Debris Avalanche Erosion	Net Erosion from Debris Avalanche		60.3	18.7	11.5	10.9	7.2	4.2	2.4	1.2	0.9	0.9	0.9	0.9	0.5	0.2
Sinks	Total Deposition Behind SRS	Net Deposition on Sediment Plain		(18.8)	(0.4)	(1.4)	(4.4)	(4.7)	(2.2)	(1.1)	(0.7)	(0.7)	(0.8)	(0.8)	(0.8)	(0.6)	(0.0)
Output from SRS	Sediment Output from SRS	Erosion - Deposition		41.5	18.3	10.0	6.4	2.5	2.0	1.3	0.5	0.2	0.1	0.1	0.1	(0.2)	0.1
North Fork Toutle River: SRS to Toutle River																	
Input	Output from SRS to North Fork Toutle River	Adjusted for sand/gravel exchange		41.46	18.43	10.22	6.59	2.73	2.11	1.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sources	Bank Erosion North Fork Toutle	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	0.79	0.03	0.04	0.09	0.17	0.14	0.10	0.06	0.04	0.05	0.03	0.04	0.00	0.00
	Green River	Estimate from USGS Gage Data + 18% Unmeasured	+/-35%	0.46	0.20	0.06	0.08	0.07	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sinks																	
Output	Output to Toutle River			42.71	18.66	10.32	6.76	2.97	2.28	1.49	0.06	0.04	0.05	0.03	0.04	0.00	0.00
South Fork Toutle River: Upstream of USGS Gage																	
Input	Upstream Source = Gage - Bank Erosion	Upstream Source Data Unavaliable		5.91	1.94	1.21	1.96	1.37	0.07	(0.21)	(0.14)	(0.09)	(0.09)	(0.07)	(0.04)	0.00	0.00
Sources	Bank Erosion South Fork	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	1.48	0.05	0.10	0.18	0.20	0.27	0.26	0.14	0.09	0.09	0.07	0.04	0.00	0.00
Sinks																	
Output	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured	+/-25%	7.39	1.99	1.31	2.14	1.58	0.341	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Fork Toutle River: Downstream of USGS Gage																	
Input	@ USGS Gage # 14241500 South Fork	USGS Gage + 25% Unmeasured		7.82	1.99	1.31	2.14	1.58	0.34	0.04	0.14	0.09	0.09	0.07	0.04	0.00	0.00
Sources				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sinks				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Output	Output to Toutle River			7.82	1.99	1.31	2.14	1.58	0.34	0.04	0.14	0.09	0.09	0.07	0.04	0.00	0.00
Toutle River: Confluence of North Fork and South Fork to USGS Gage at Tower Road																	
Input	Output from North Fork and South Fork			50.53	20.65	11.63	8.90	4.55	2.62	1.54	0.20	0.13	0.14	0.10	0.07	0.00	0.00
Sources	Toutle Bank Erosion Above Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	0.14	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Sinks																	
Output at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		50.67	20.66	11.64	8.93	4.57	2.64	1.55	0.21	0.14	0.15	0.11	0.08	0.00	0.00
Toutle River: USGS Gage at Tower Road to Cowlitz River																	
Input at Tower Rd	@ USGS Gage # 14242580 Toutle at Tower Rc	Compare Sediment Budget to Gage Data		50.67	20.66	11.64	8.93	4.57	2.64	1.55	0.21	0.14	0.15	0.11	0.08	0.00	0.00
Sources	Toutle Bank Erosion Below Tower	Est. & pro-rated from 99-06 Aerial Photos	+/-35%	0.63	0.03	0.04	0.09	0.19	0.11	0.05	0.03	0.03	0.03	0.04	0.00	0.00	0.00
Sinks																	
Output	Output to Cowlitz River			51.30	20.68	11.68	9.02	4.76	2.75	1.60	0.24	0.16	0.18	0.15	0.08	0.00	0.00
Cowlitz River: Toutle River to Columbia River																	
Input	Input from Toutle River			51.30	20.68	11.68	9.02	4.76	2.75	1.60	0.24	0.16	0.18	0.15	0.08	0.00	0.00
	Input from Upper Cowlitz			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sources				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sink/Source	Cowlitz River Deposition/Erosion	Hydro-Survey Comparisons	+/-30%	(2.46)	(0.09)	(0.13)	(0.43)	(0.48)	(0.28)	(0.19)	(0.08)	(0.11)	(0.13)	(0.16)	(0.34)	(0.06)	0.00
Output	Output to Columbia River			48.84	20.60	11.55	8.59	4.28	2.47	1.41	0.16	0.05	0.05	(0.01)	(0.26)	(0.06)	0.00

(Note: Negative values indicate deposition or sinks, Positive values indicate erosion or sources)

Table 5.11 Summary of Toutle Basin Sediment Sources

Source	1999	2000	2001	2002	2003	2004	2005	2006	2007	Total
	Sediment Source (Million Tons)									
Output from the SRS	2.84	3.78	0.55	5.94	4.64	2.10	2.36	4.68	17.41	44.30
Green River	0.08	0.06	0.01	0.07	0.05	0.03	0.03	0.05	0.16	0.55
North Fork Bank Erosion	0.13	0.11	0.02	0.11	0.15	0.08	0.06	0.10	0.17	0.91
South Fork Upstream Source	1.39	0.23	0.00	0.96	0.00	0.09	0.19	0.11	4.42	7.39
South Fork Bank Erosion	0.24	0.21	0.04	0.20	0.28	0.15	0.10	0.19	0.32	1.72
Toutle Bank Erosion U/S Tower Road	0.02	0.02	0.00	0.02	0.03	0.01	0.01	0.02	0.03	0.17
Toutle Bank Erosion D/S Tower Road	0.10	0.09	0.02	0.09	0.12	0.06	0.04	0.08	0.14	0.74
Total	**4.81**	**4.49**	**0.64**	**7.39**	**5.26**	**2.52**	**2.80**	**5.23**	**22.64**	**55.78**
	% of Total									
Output from the SRS	59.1	84.2	85.1	80.5	88.2	83.3	84.4	89.4	76.9	79.4%
Green River	1.7	1.3	2.1	0.9	0.9	1.3	1.2	1.0	0.7	1.0%
North Fork Bank Erosion	2.6	2.4	3.3	1.4	2.8	3.1	2.0	1.9	0.7	1.6%
South Fork Upstream Source	29.0	5.1	0.0	13.0	0.0	3.5	6.7	2.1	19.5	13.3%
South Fork Bank Erosion	5.0	4.6	6.2	2.7	5.3	5.8	3.7	3.6	1.4	3.1%
Toutle Bank Erosion U/S Tower Road	0.5	0.4	0.6	0.3	0.5	0.6	0.4	0.4	0.1	0.3%
Toutle Bank Erosion D/S Tower Road	2.1	2.0	2.7	1.2	2.2	2.5	1.6	1.6	0.6	1.3%

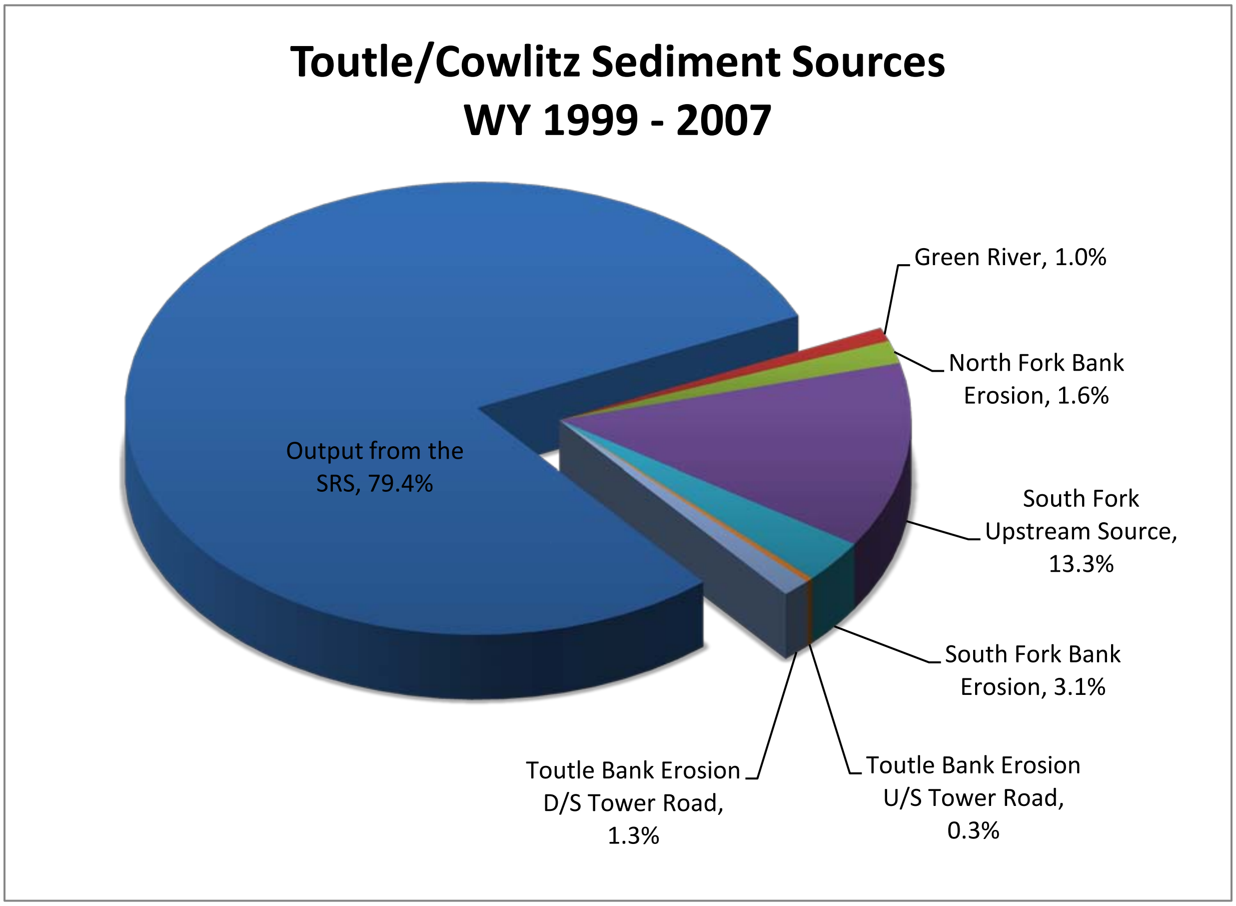

Figure 5.1 Toutle/Cowlitz Sediment Source Breakdown for Water Years 1999 through 2007

Table 5.12 Annual Sediment Load at Mouth of Toutle River by Grain Size

Water Year	Silt/Clay	Sand					Gravel					Total
	0.0625	0.125	0.25	0.5	1	2	4	8	16	32	64	
1999	2.24	1.09	0.84	0.42	0.12	0.04	0.04	0.03	0.03	0.02	0.01	4.88
2000	1.13	1.02	1.00	0.66	0.36	0.27	0.03	0.02	0.02	0.02	0.01	4.55
2001	0.16	0.10	0.12	0.12	0.07	0.04	0.01	0.00	0.00	0.00	0.00	0.79
2002	3.30	1.77	1.40	0.46	0.26	0.15	0.03	0.02	0.02	0.02	0.01	7.44
2003	2.37	1.26	0.91	0.25	0.20	0.13	0.04	0.03	0.03	0.03	0.01	5.27
2004	1.09	0.59	0.41	0.12	0.15	0.11	0.02	0.02	0.02	0.01	0.01	0.00
2005	1.30	0.69	0.53	0.14	0.07	0.04	0.02	0.01	0.01	0.01	0.01	0.00
2006	2.15	1.20	0.99	0.44	0.26	0.15	0.03	0.02	0.02	0.02	0.01	0.00
2007	9.21	5.05	3.66	2.57	1.37	0.71	0.05	0.04	0.04	0.03	0.02	22.74

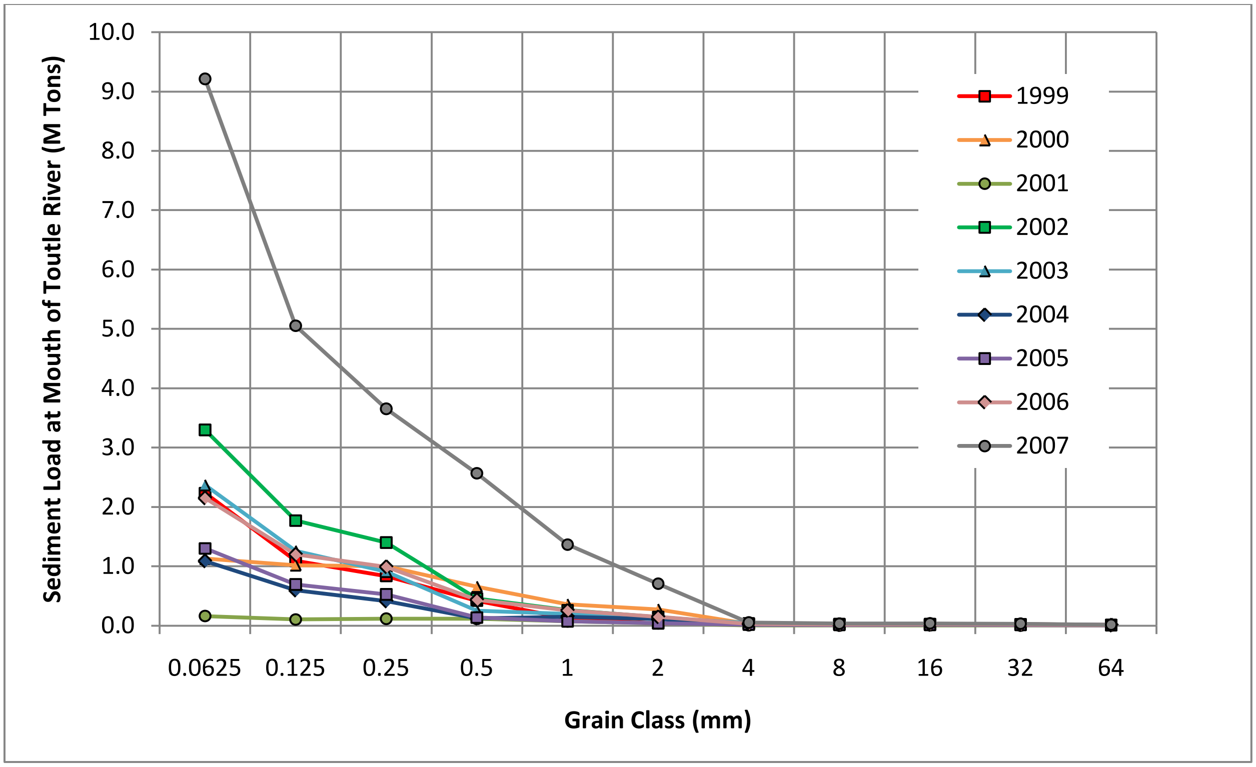

Figure 5.2 Annual Sediment Load by Grain Class at Mouth of Toutle River, 1999 – 2007

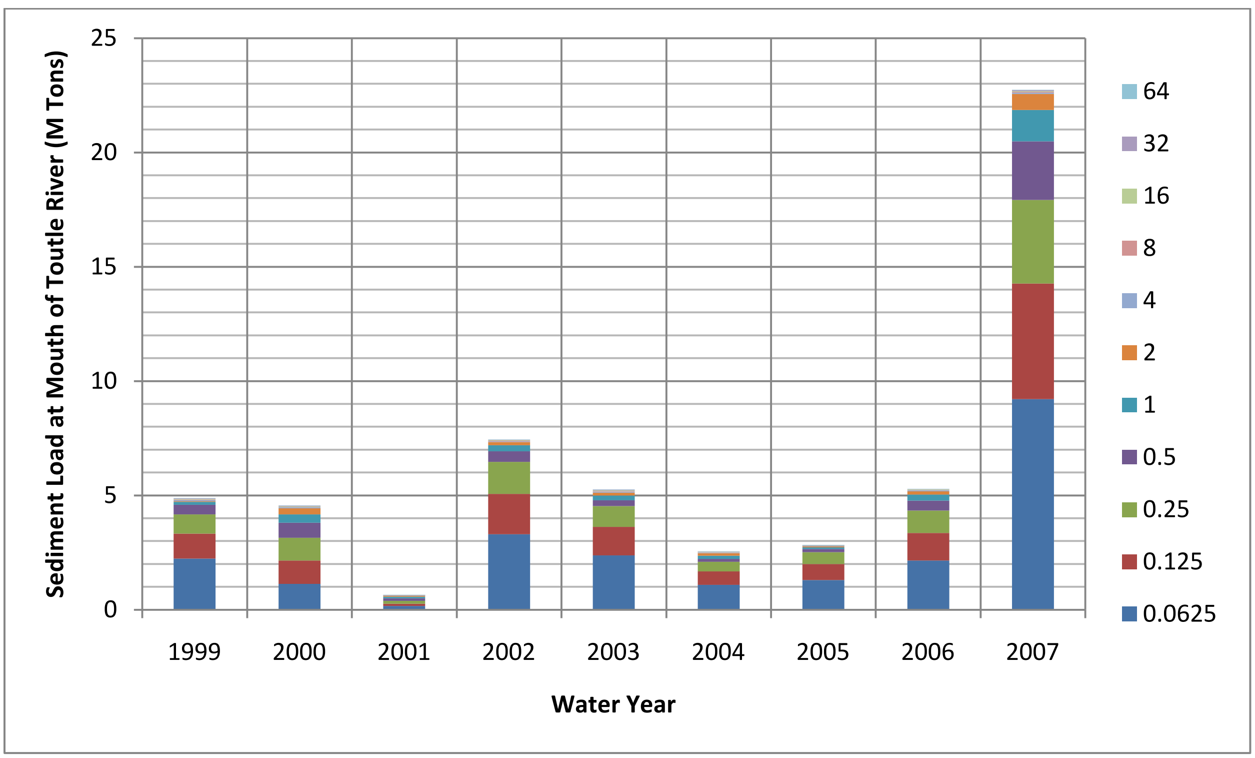

Figure 5.3 Total Sediment Load at Mouth of Toutle River

5.2 Comparison to USGS Gage Data

The sediment budget results were compared to USGS suspended sediment gage data, as shown in Figures 5.4 through 5.10. The gage data is shown with 25% unmeasured load added as well as error bars representing +/- 25%. A comparison of the annual suspended sediment at Tower Road to the load calculated in the sediment budget for sands, silts, and clays is shown in Figure 5.2.

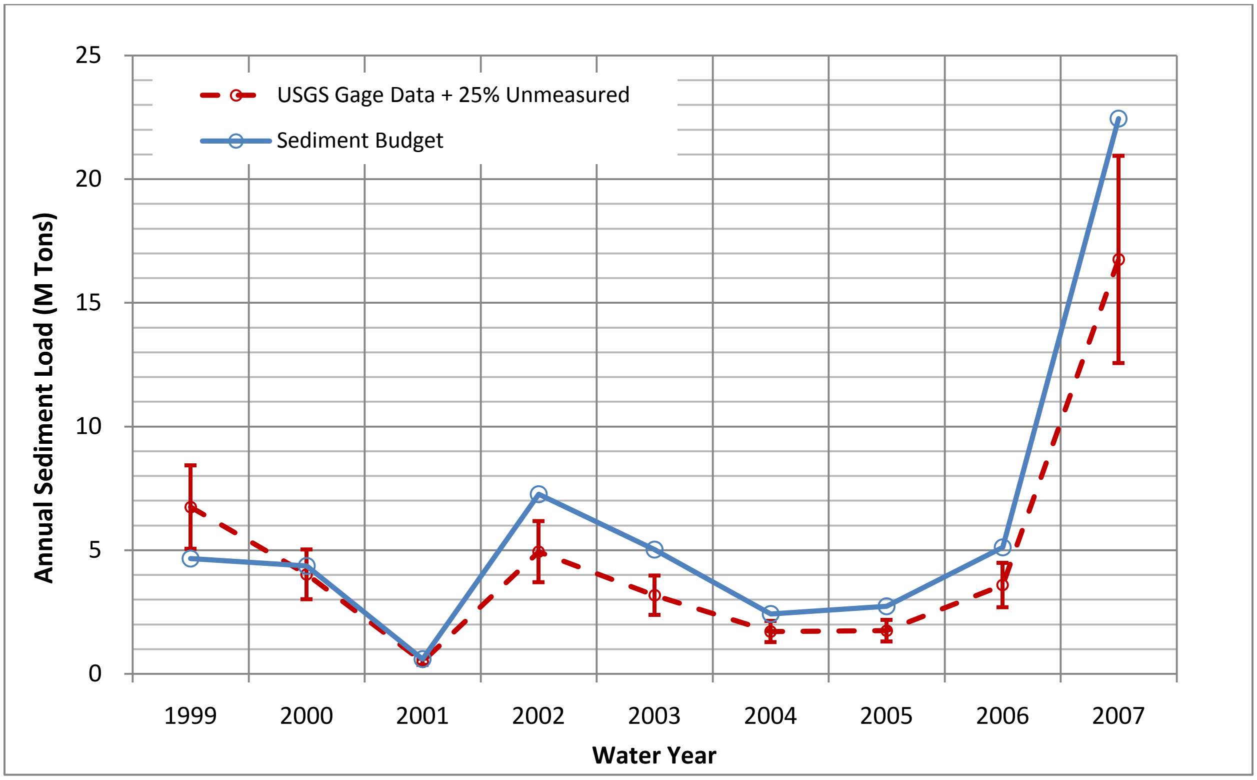

Figure 5.4 Comparison of Sediment Budget and USGS Gage Data, Toutle River Sediment Load for Sands and Finer at Tower Road

A comparison of the USGS gage data and sediment budget by grain size was also conducted. Figures 5.5 through 5.10 show the sediment budget results and USGS gage data with 25% unmeasured load and 25% error bars. In most comparisons the sediment budget produces higher values of sands between 0.5 and 2mm (medium to coarse sands). Medium and coarse sands are found to be contributing to the aggradation in the lower Cowlitz and a majority of very fine sands and silts are likely moving through the Cowlitz to the Columbia. The annual USGS gage data was divided into grain classes by applying the average suspended sediment gradation for 2000 – 2007, which may be an unwarranted assumption for the comparisons.

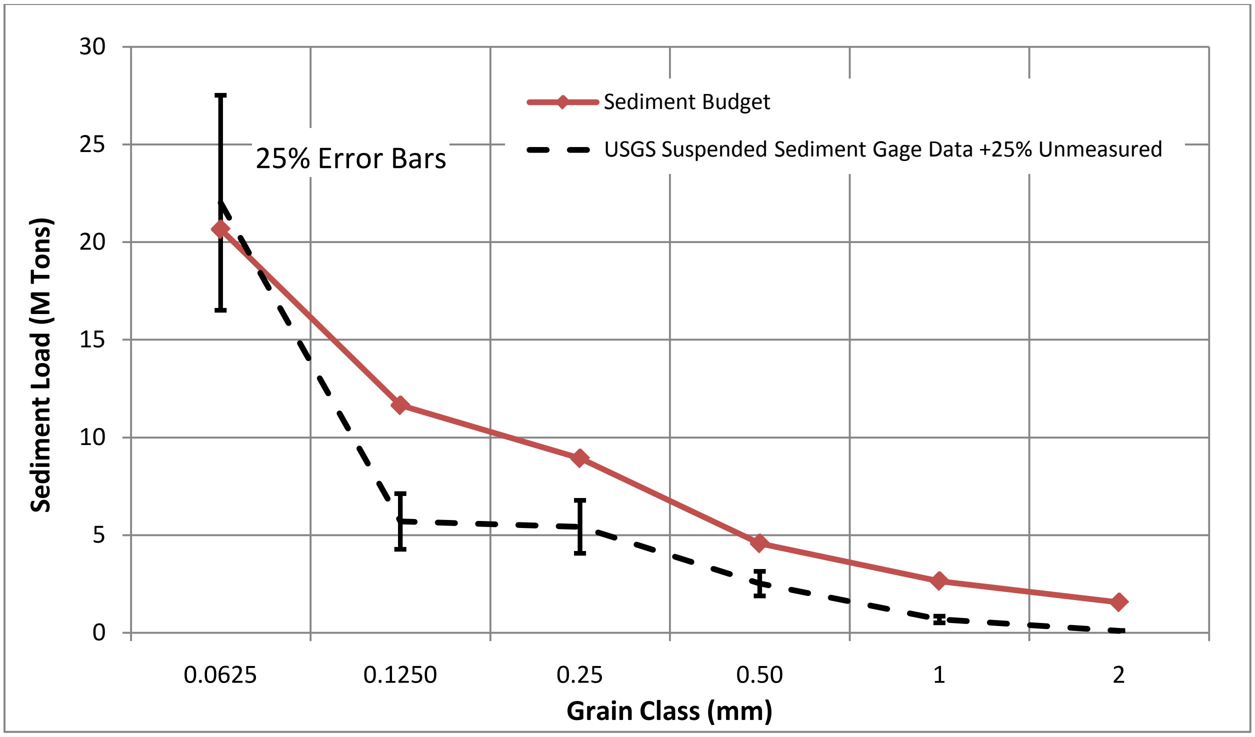

Figure 5.5 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, Toutle at Tower Road WY 2000 - 2007

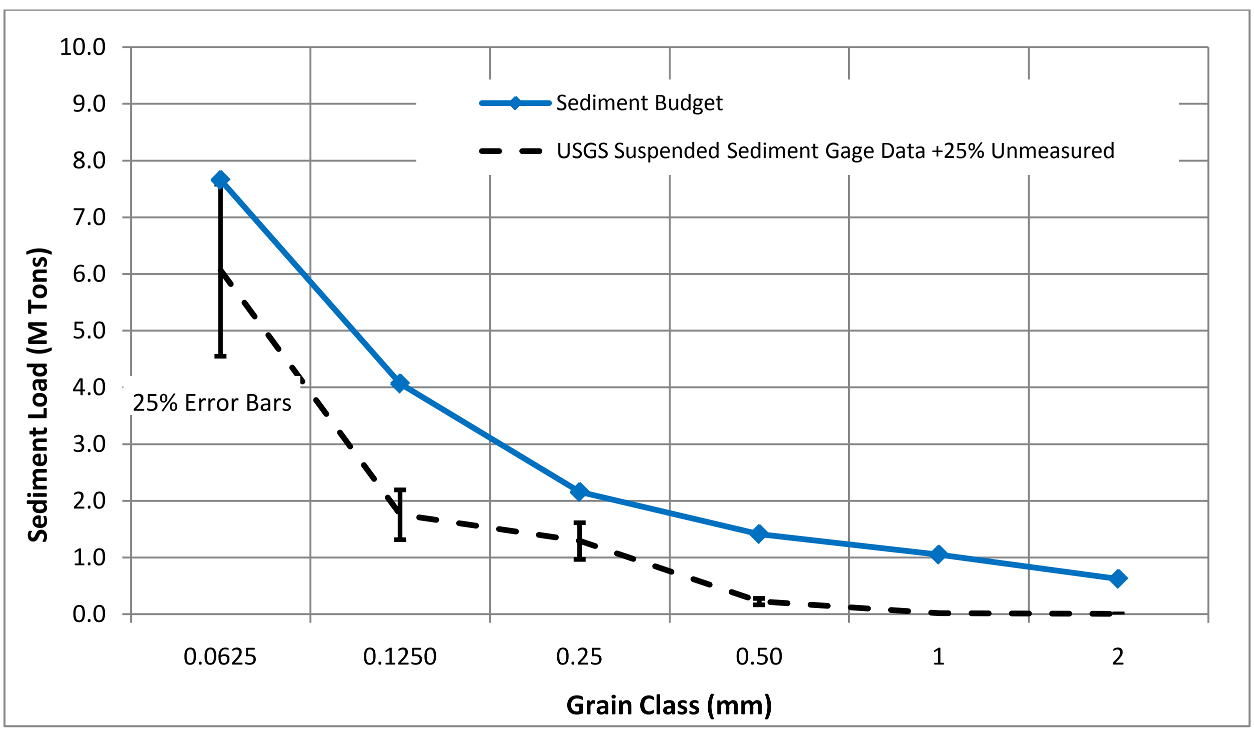

Figure 5.6 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, North Fork Below SRS WY 2007

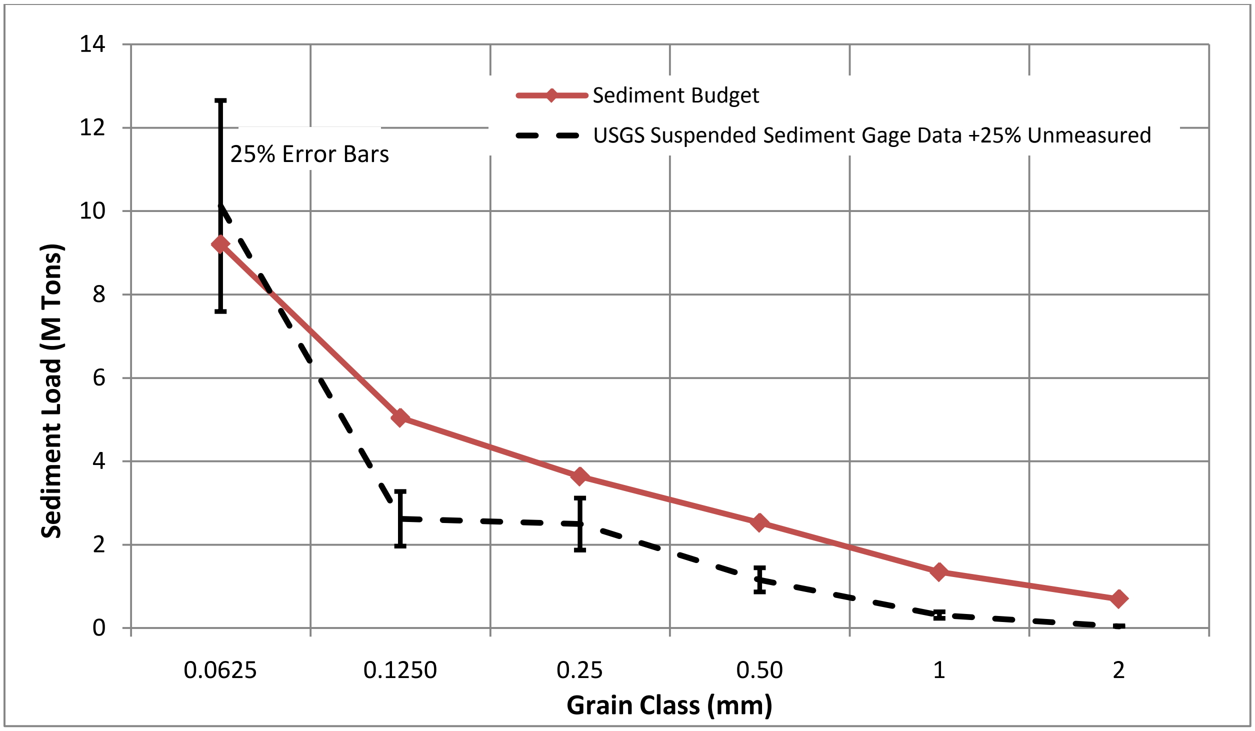

Figure 5.7 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, Toutle at Tower Road WY 2007

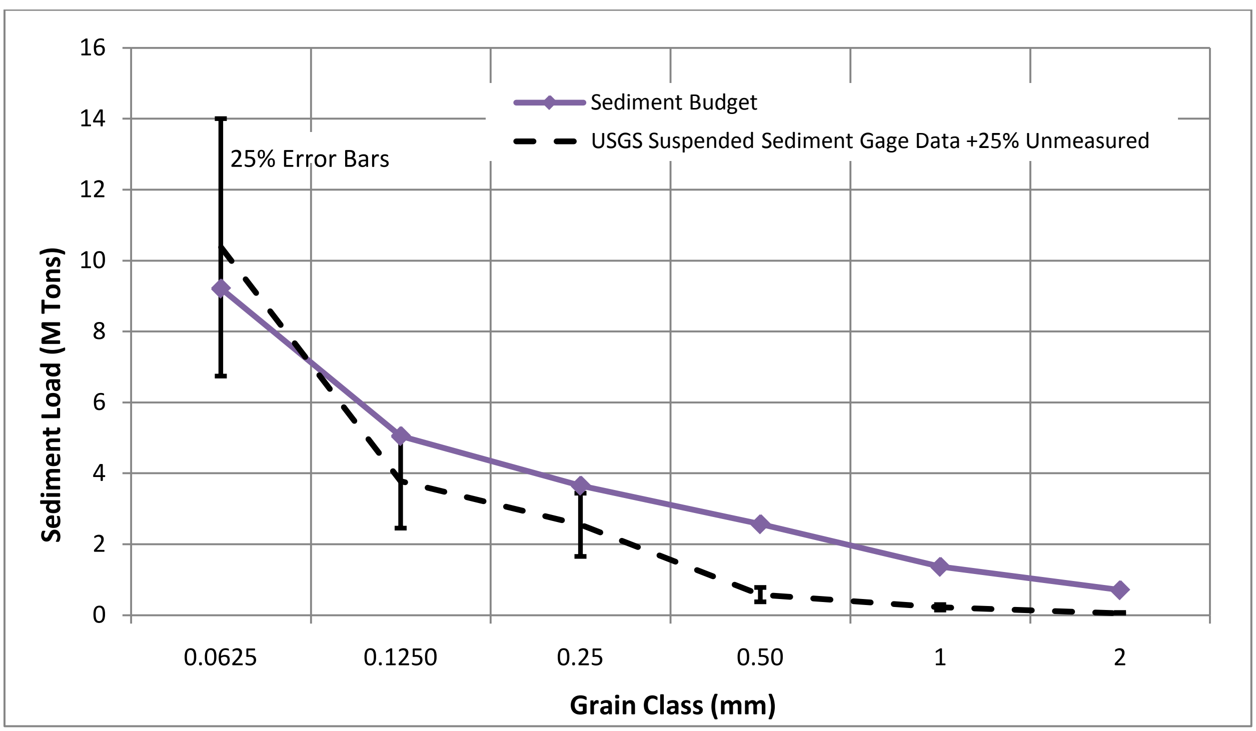

Figure 5.8 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, Cowlitz River at Castle Rock WY 2007

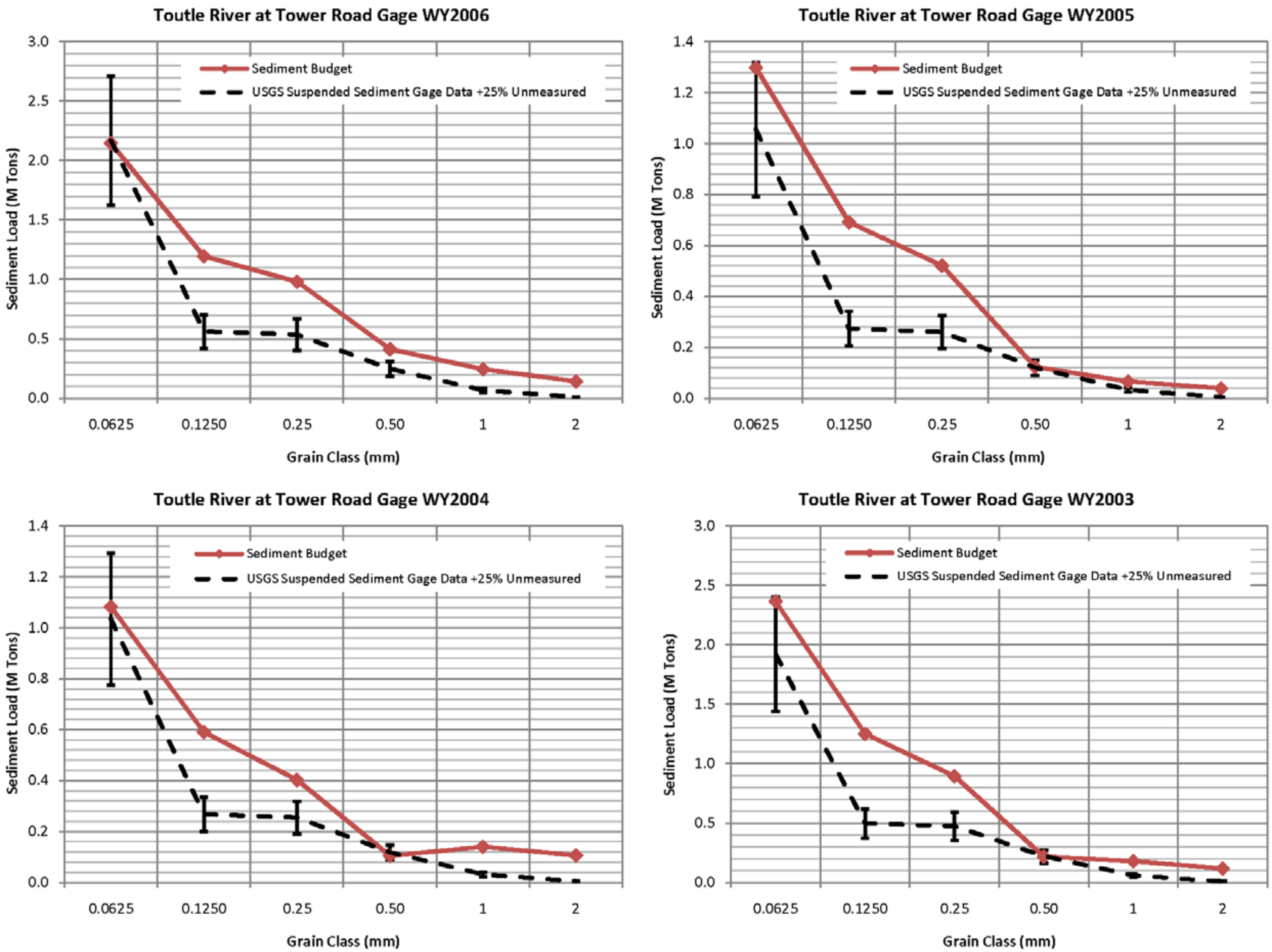

Figure 5.9 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, Toutle at Tower Road WYs 2003 - 2006

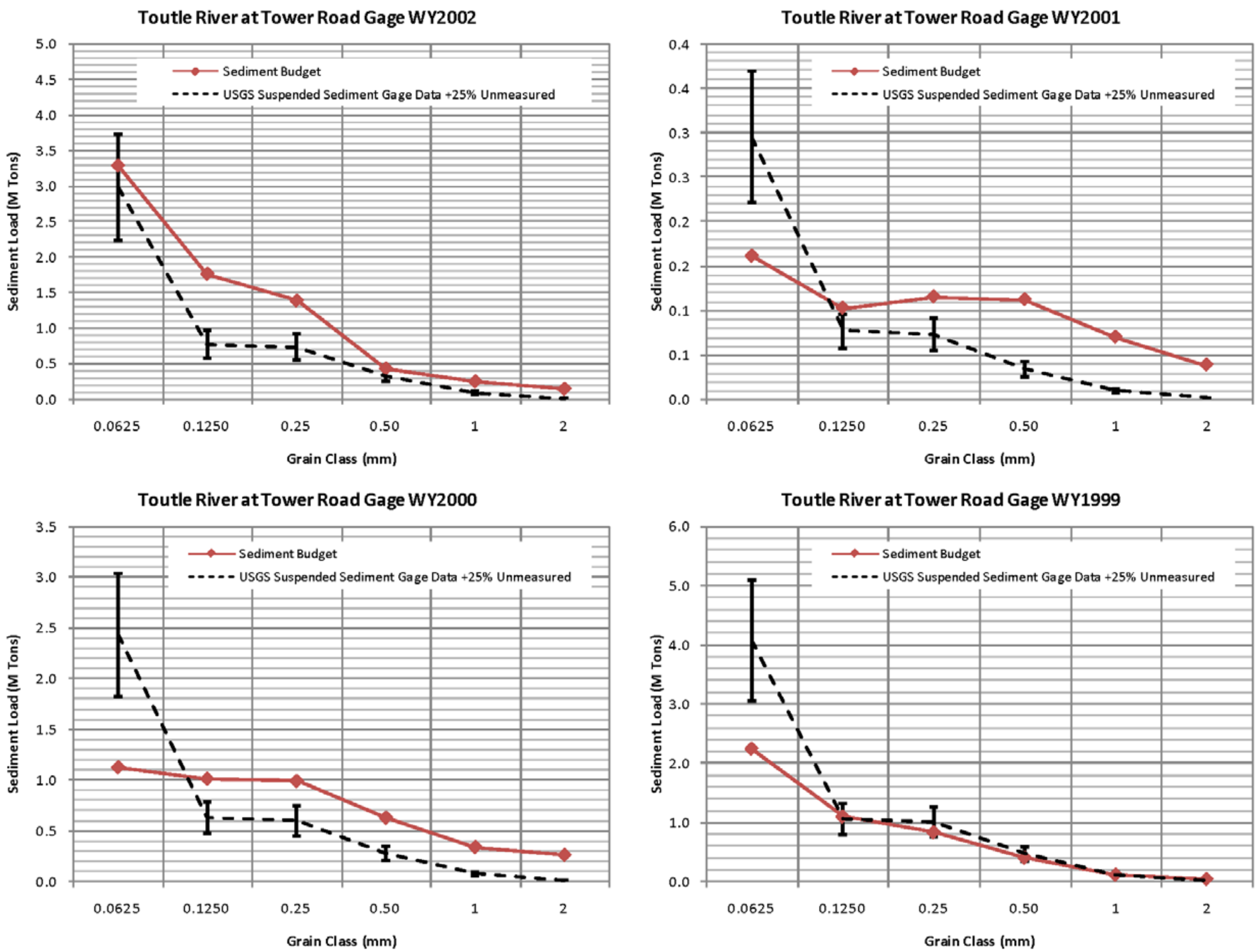

Figure 5.10 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, Toutle at Tower Road WYs 1999 - 2002

5.3 Uncertainty Analysis

A main goal in the development of the Toutle/Cowlitz sediment budget was to estimate the total annual sediment load at the mouth of the Toutle River for water years 1999 – 2007 to gain insight into how much and what size of sediment is depositing in the lower Cowlitz River. Development of input to the Toutle/Cowlitz sediment budget is certainly not an exact science and therefore, results should include an evaluation of uncertainty.

Each individual input to the Toutle/Cowlitz sediment budget was developed with as much accuracy as possible given limitation of available data sources and method by which input was developed. A value of variability (e.g. +/-25%) was assigned to each individual sediment budget input and an uncertainty analysis was conducted to present a range of total sediment load at the mouth of the Toutle River. Two analyses were conducted: the first uncertainty analysis involved variation associated with the total magnitudes of each sediment sources and the second includes a combination of variation in the total magnitudes of each sediment source as well as debris avalanche and sediment plain gradation inputs.

Uncertainty of the total sediment load at the mouth of the Toutle River was first conducted by varying each sediment source input. Each source input to the sediment budget was assigned a percentage of uncertainty as indicated by column three of Table 5.12. These values are supported by discussions in Chapter 4. A matrix of sixteen combinations of low, mean, and high values for each sediment source was applied to each annual sediment budget, and a sediment yield at the mouth of the Toutle River was computed. The matrix of sediment source combinations is shown in Table 5.13. The combinations mainly focused on the uncertainty in the debris avalanche and sediment plain because output from the SRS accounts for approximately 80% of the total sediment load to the Toutle/Cowlitz system.

Table 5.13 Sediment Budget Uncertainty Analysis Matrix

Sediment Budget Input	Description	Variability	Uncertainty Matrix (Magnitude: L = Low, M = Mean, H = High)															
			1*	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
North Fork Toutle: Debris Avalanche to SRS																		
Debris Avalanche Erosion	Coldwater Creek	+/-15%	M	L	H	L	L	L	M	M	M	H	H	H	L	L	H	H
	Castle Creek	+/-15%	M	L	H	L	L	L	M	M	M	H	H	H	L	L	H	H
	Loowit	+/-15%	M	L	H	L	L	L	M	M	M	H	H	H	L	L	H	H
	A - Debris Avalanche to Elk Rock	+/-15%	M	L	H	L	L	L	M	M	M	H	H	H	L	L	H	H
	B - Elk Rock to N1	+/-15%	M	L	H	L	L	L	M	M	M	H	H	H	L	L	H	H
SRS Deposition	C - Sediment Plain	+/-15%	M	L	H	L	M	H	L	M	H	L	M	H	H	H	L	L
	D - Sediment Plain	+/-15%	M	L	H	L	M	H	L	M	H	L	M	H	H	H	L	L
	E - Sediment Plain	+/-15%	M	L	H	L	M	H	L	M	H	L	M	H	H	H	L	L
North Fork Toutle: SRS to Toutle River																		
Local sources	Bank Erosion North Fork Toutle	+/-35%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H
	USGS Gage # 14240800 Green River	+/-25%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H
South Fork Toutle: Upstream of Gage																		
Local sources	Bank Erosion South Fork	+/-35%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H
Output	USGS Gage # 14241500 South Fork	+/-25%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H
Toutle River: NF/SF to Tower Road																		
Local Source	Toutle Bank Erosion Above Tower	+/-35%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H
Toutle River: Tower to Cowlitz																		
Local Sources	Toutle Bank Erosion Below Tower	+/-35%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H
Cowlitz River: Toutle to Columbia																		
Sink/Source	Cowlitz River Deposition/Erosion	+/-35%	M	L	H	M	M	M	M	M	M	M	M	M	L	H	L	H

* Mean sediment budget

Summary results of the load calculated (M tons) at the mouth of the Toutle River for the matrix is provided in Table 5.14 and in graphical form in Figure 5.11. For comparison Figure 5.11 also includes the USGS suspended sediment gage data at Tower Road with 25% error bars. The calculated uncertainty in the total sediment load at the mouth of the Toutle River was found to range from +/-17% to a maximum value of +/-72%. The total budget from 2000 – 2007 had an uncertainty of +/-28%.

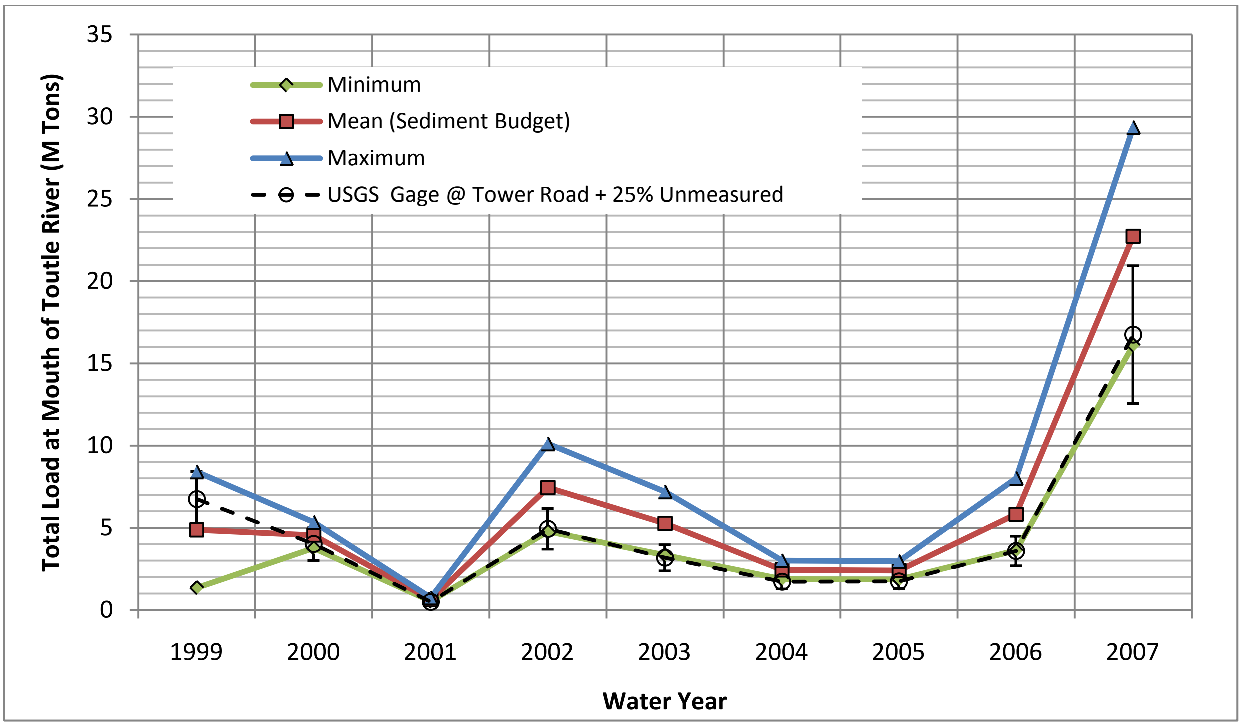

Figure 5.11 Uncertainty Analysis Minimum, Mean, and Maximum Total Sediment Load at Mouth of Toutle River (shown with measured suspended sediment data at Tower Road).

Table 5.14 Summary of Uncertainty in Magnitude of Total Sediment Load at Mouth of Toutle River

Matrix ID	1*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Uncertainty
Water Year	Total Sediment Load at Mouth of Toutle River (M Tons)																
1999	4.9	3.9	5.9	4.5	3.2	1.9	6.2	4.9	3.6	7.9	6.6	5.3	1.4	2.4	7.3	8.4	+/- 72%
2000	4.6	3.8	5.3	4.0	4.4	4.8	4.1	4.6	5.0	4.3	4.7	5.1	4.6	5.1	4.1	4.5	+/- 17%
2001	0.6	0.5	0.8	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.7	+/- 17%
2002	7.4	6.2	8.7	6.6	5.9	5.2	8.1	7.4	6.8	9.7	9.0	8.3	4.8	5.6	9.3	10.1	+/- 36%
2003	5.3	4.4	6.2	4.6	4.1	3.5	5.8	5.3	4.8	7.0	6.5	6.0	3.3	3.7	6.8	7.2	+/- 37%
2004	2.6	2.1	3.0	2.2	2.1	2.0	2.7	2.6	2.4	3.1	3.0	2.9	1.8	2.1	3.0	2.6	+/- 28%
2005	2.8	2.3	3.3	2.5	2.2	1.9	3.1	2.8	2.5	3.8	3.5	3.2	1.7	2.0	3.7	2.8	+/- 39%
2006	5.3	4.4	6.2	4.6	4.3	4.0	5.6	5.3	5.0	6.6	6.3	6.0	3.8	4.1	6.4	5.3	+/- 28%
2007	22.7	18.8	26.7	20.1	18.8	17.5	24.1	22.7	21.4	28.0	26.7	25.3	16.1	18.9	26.6	29.4	+/- 29%
2000-2007	51.3	42.4	60.2	45.1	42.3	39.4	54.1	51.3	48.5	63.2	60.3	57.5	36.8	42.1	60.5	65.8	+/- 28%

*Sediment Budget

Cells highlighted in green indicate the minimum value of the uncertainty results, blue indicate maximum values.

Further review of the analysis results indicate that larger uncertainty is associated with values of sediment load at the mouth of the Toutle in individual grain classes. Even though gradation inputs to the sediment budget were held constant for the uncertainty analysis variation in the total magnitude does affect individual grain classes in different ways. This can be attributed to the primary limitation of the sediment budget methodology in that hydraulic routing of particles is not included. This limitation makes estimates of coarser fractions especially susceptible to error. Figure 5.12 shows the variation by grain class of the sediment load at the mouth of the Toutle River for the 2000-2007 sediment budget. Uncertainty in the sediment load by grain class varies from year to year and ranges from +/-20% to as much as +/-210%.

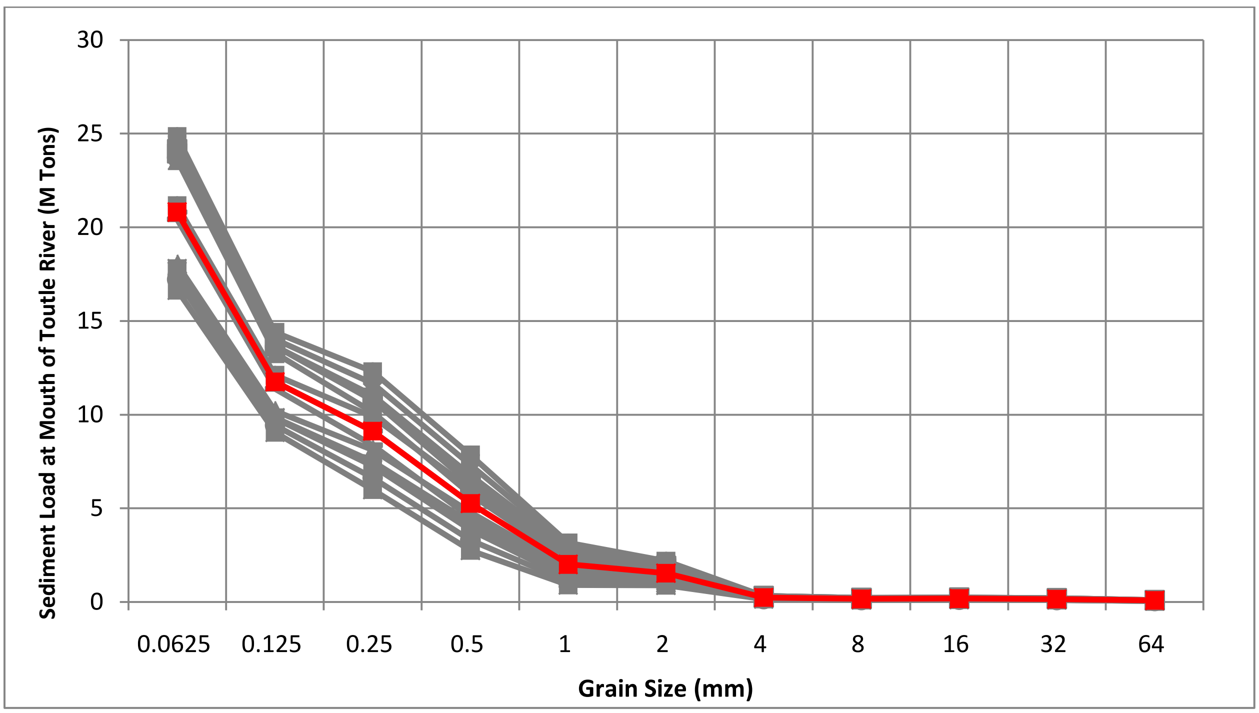

Figure 5.12 Sediment Load at Mouth of Toutle River for WY 2000 – 2007. The red line indicates the 2000–2007 sediment budget results and grey lines indicate the range of uncertainty.

An additional uncertainty analysis was conducted by varying the sediment source inputs as well as incorporating variation in the gradation input of the debris avalanche erosion and sediment plain deposition. Sediment output from the SRS is the largest contributor to the Toutle/Cowlitz system and that gradation is highly dependent upon the selection of input gradations. Other input gradations to the sediment budget were not incorporated into the uncertainty analysis due to the relatively small magnitudes of the sediment output from the SRS (80% of the total sediment input). Varying gradations for the debris avalanche, sub-areas A and B, and sediment plain sub-areas C, D, and E are provided in Figures 5.13 through 5.16. The matrix of sediment source and gradation combinations is shown in Table 5.15.

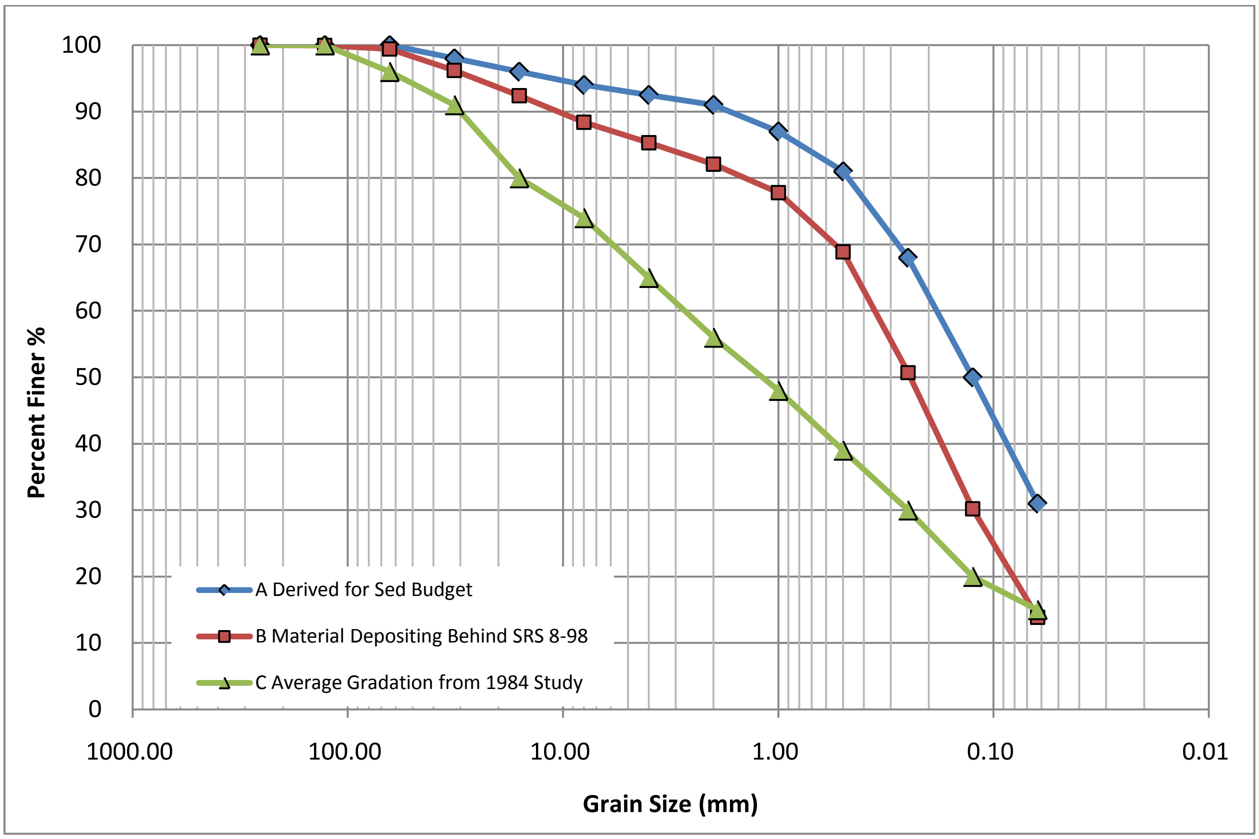

Figure 5.13 Debris Avalanche and Sub-Areas A and B Gradations Used in Uncertainty Analysis

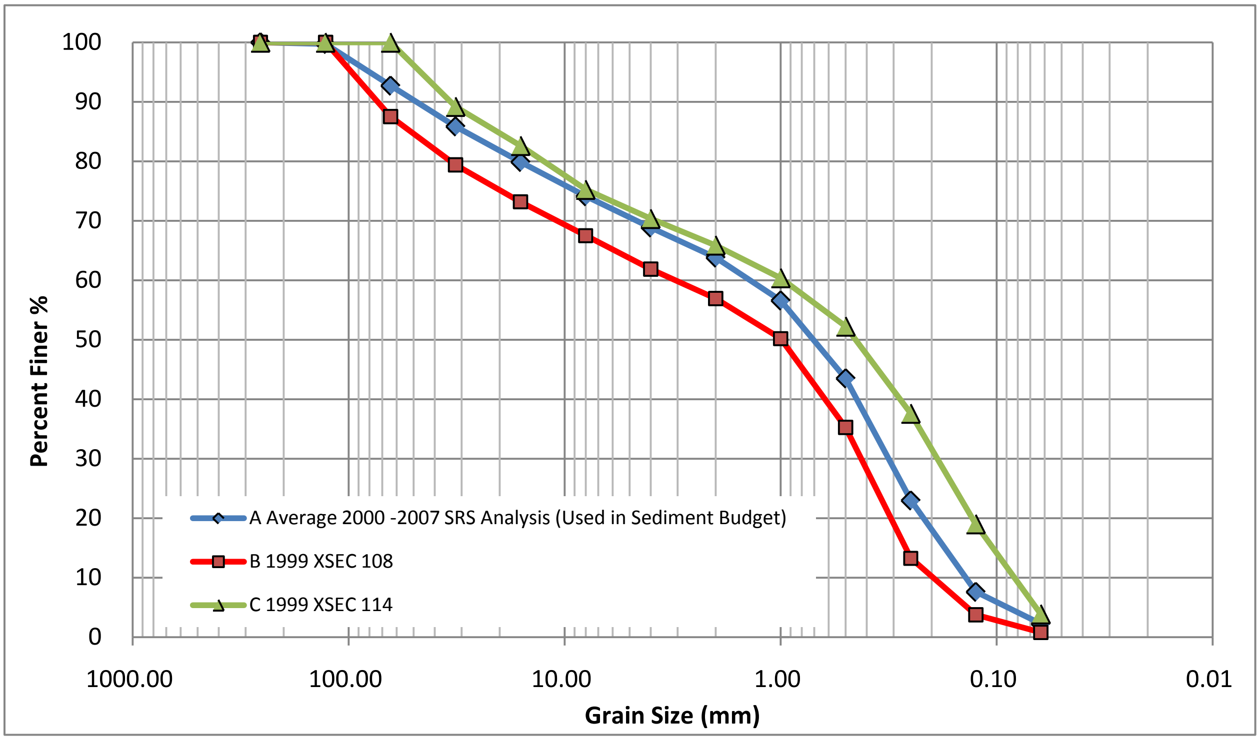

Figure 5.14 Sediment Plain Sub-Area C Gradations Used in Uncertainty Analysis

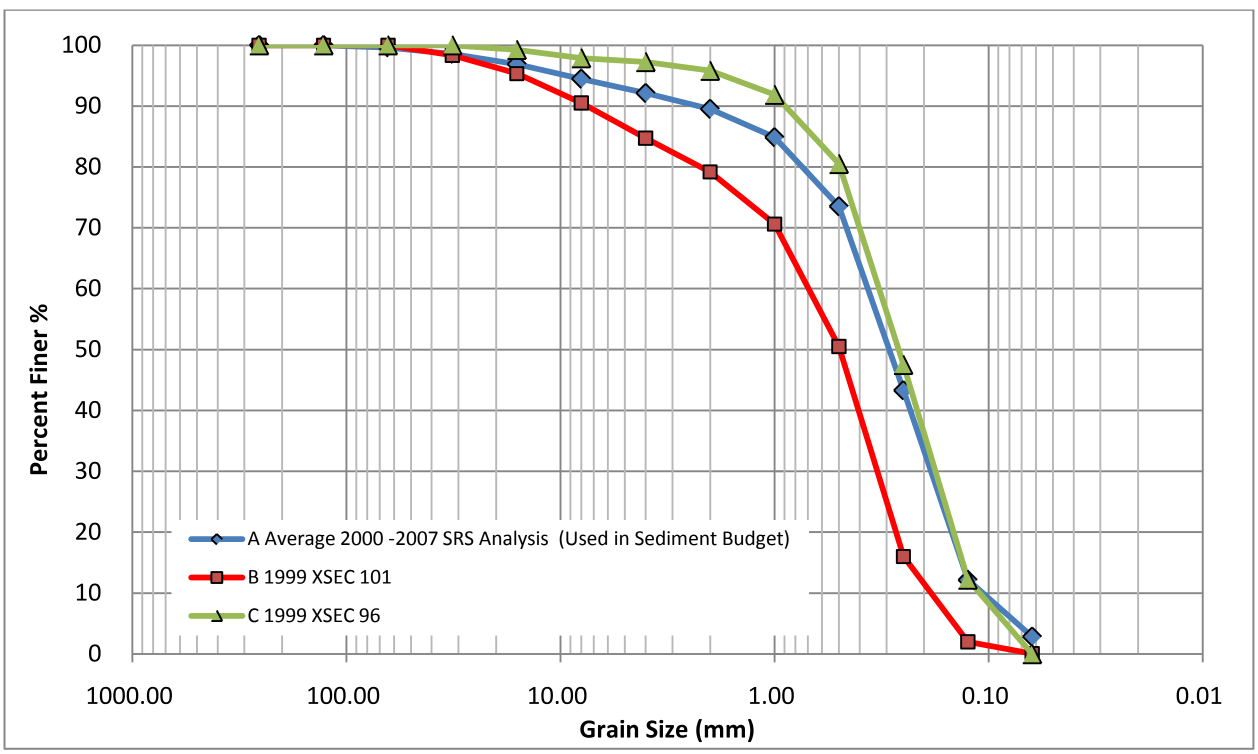

Figure 5.15 Sediment Plain Sub-Area D Gradations Used in Uncertainty Analysis

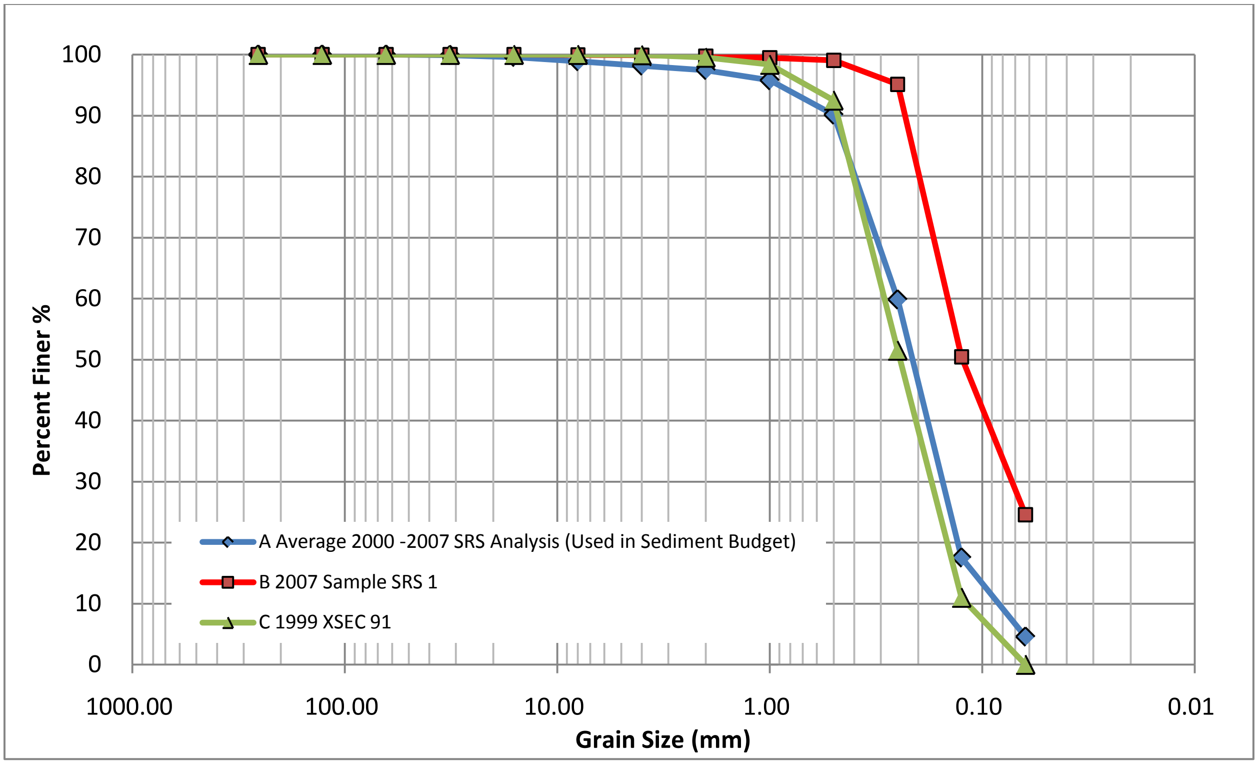

Figure 5.16 Sediment Plain Sub-Area E Gradations Used in Uncertainty Analysis

Table 5.15 Sediment Budget Uncertainty Matrix, Variation in Magnitudes and Gradations

Sediment Budget Input	Description	Variability	Uncertainty Matrix (Magnitude: L = Low, M = Mean, H = High, Gradations A, B, C See Figures X)																										
			17*	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
North Fork Toutle: Debris Avalanche to SRS																													
Debris Avalanche Erosion	Coldwater Creek	+/-15%	MA	MA	MA	MB	MB	MB	MC	MC	MC	LA	LA	LA	LB	LB	LB	LC	LC	LC	HA	HA	HA	HB	HB	HB	HC	HC	HC
	Castle Creek	+/-15%	MA	MA	MA	MB	MB	MB	MC	MC	MC	LA	LA	LA	LB	LB	LB	LC	LC	LC	HA	HA	HA	HB	HB	HB	HC	HC	HC
	Loowit	+/-15%	MA	MA	MA	MB	MB	MB	MC	MC	MC	LA	LA	LA	LB	LB	LB	LC	LC	LC	HA	HA	HA	HB	HB	HB	HC	HC	HC
	A - Debris Avalanche to Elk Rock	+/-15%	MA	MA	MA	MB	MB	MB	MC	MC	MC	LA	LA	LA	LB	LB	LB	LC	LC	LC	HA	HA	HA	HB	HB	HB	HC	HC	HC
	B - Elk Rock to N1	+/-15%	MA	MA	MA	MB	MB	MB	MC	MC	MC	LA	LA	LA	LB	LB	LB	LC	LC	LC	HA	HA	HA	HB	HB	HB	HC	HC	HC
SRS Deposition	C - Sediment Plain	+/-15%	MA	MB	MC	MA	MB	MC	MA	MB	MC	HA	HB	HC	HA	HB	HC	HA	HB	HC	LA	LB	LC	LA	LB	LC	LA	LB	LC
	D - Sediment Plain	+/-15%	MA	MB	MC	MA	MB	MC	MA	MB	MC	HA	HB	HC	HA	HB	HC	HA	HB	HC	LA	LB	LC	LA	LB	LC	LA	LB	LC
	E - Sediment Plain	+/-15%	MA	MB	MC	MA	MB	MC	MA	MB	MC	HA	HB	HC	HA	HB	HC	HA	HB	HC	LA	LB	LC	LA	LB	LC	LA	LB	LC
North Fork Toutle: SRS to Toutle River																													
Local sources	Bank Erosion North Fork Toutle	+/-35%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H
	USGS Gage # 14240800 Green River	+/-25%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H
South Fork Toutle: Upstream of Gage																													
Local sources	Bank Erosion South Fork	+/-35%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H
Output	USGS Gage # 14241500 South Fork	+/-25%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H
Toutle River: NF/SF to Tower Road																													
Local Source	Toutle Bank Erosion Above Tower	+/-35%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H
Toutle River: Tower to Cowlitz																													
Local Sources	Toutle Bank Erosion Below Tower	+/-35%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H
Cowlitz River: Toutle to Columbia																													
Sink/Source	Cowlitz River Deposition/Erosion	+/-35%	M	M	M	M	M	M	M	M	M	L	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	H

* Mean sediment budget

Results of the uncertainty matrix associated with variation in magnitude of sediment sources and debris avalanche and sediment plain gradations indicate that the sediment budget results by grain class are highly sensitive to inputs. Table 5.15 shows the maximum percent variation from the mean sediment budget for each grain class in the sand range. Results show that the uncertainty in the sediment load per grain class can be as high as 602%. Figure 5.16 presents uncertainty in the sediment load by grain class at the mouth of the Toutle for the water year 2000 – 2007 sediment budget, which has a maximum percent difference of 114%. Annual sediment budgets have a much higher uncertainty by grain class when compared to the longer term budget (2000 – 2007). This can be attributed to the primary limitation of the sediment budget methodology in that hydraulic routing of particles is not included.

Table 5.16 Maximum % Difference in the Total Load at the Mouth of the Toutle River by Grain Size from Uncertainty Matrix ID 17 – 43.

	Maximum % Difference from Mean					
Water Year	**0.0625**	**0.125**	**0.25**	**0.5**	**1**	**2**
1999	**106%**	60%	248%	203%	158%	144%
2000	56%	32%	35%	67%	30%	64%
2001	54%	56%	41%	38%	59%	83%
2002	82%	181%	251%	382%	187%	**227%**
2003	80%	189%	**277%**	**431%**	187%	207%
2004	82%	79%	306%	602%	123%	191%
2005	95%	229%	285%	501%	240%	262%
2006	51%	107%	93%	121%	143%	167%
2007	49%	104%	86%	111%	145%	170%
2000 - 2007	56%	55%	70%	114%	101%	97%

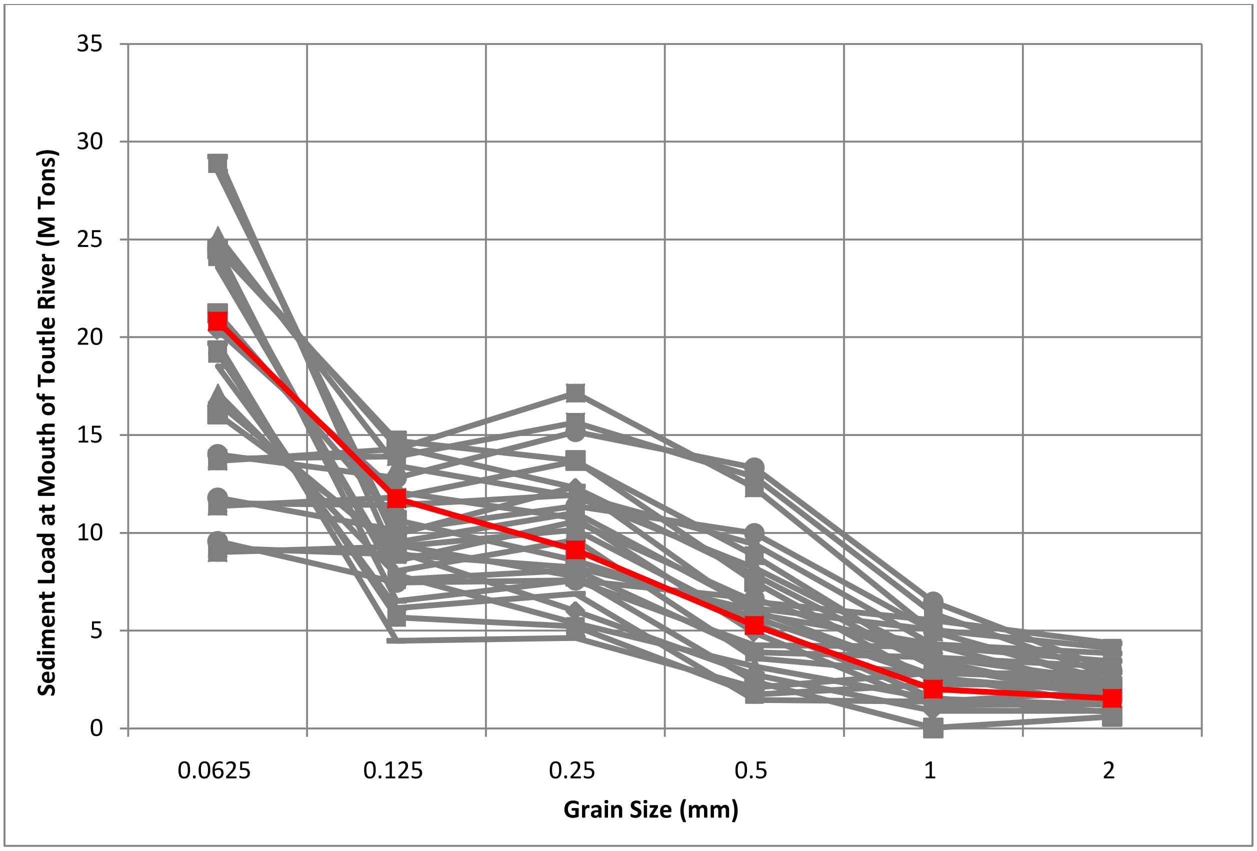

Figure 5.17 Sediment Load at Mouth of Toutle River for WY 2000 – 2007. The red line indicates the 2000–2007 sediment budget results and grey lines indicate the range of uncertainty associated with source and gradation inputs.

5.4 Forecasting of Sediment Load at Mouth of Toutle River

Estimates of the cumulative sediment load at the mouth of the Toutle River through 2035 were made utilizing the range of total sediment load calculated for water years 1999 through 2007 (Table 5.17) and a Monte Carlo bootstrapping simulation. The low and high values listed in Table 5.17 are the bounding results of the uncertainty analysis and the mean value is from the sediment budget. Different sequence combinations of the low, mean and high values for the past nine years (1999 – 2007) were formulated to represent the 28 predictive years (2008 – 2035) to estimate a possible range of cumulative sediment loads at the mouth of the Toutle River by 2035. It should be noted that utilization of the past nine years for future predictions has limitations associated with applying past erosion and deposition rates occurring in the system. Use of a more robust sediment routing model above the SRS would be recommended to improve the accuracy of the forecasting.

A random number generation analysis tool in Excel was used to generate 10,000 sequences of the 28 years, each made of a combination of the range of values for the past nine years. 10,000 sequences were generated to ensure that a reasonable range of possible combinations of years was analyzed. The selected annual sediment load for each selected year in all sequences was then utilized to calculate the cumulative sediment load by 2035. Table 5.18 provides an example of a few of the 28 year sequences generated. The first column in the table is a list of the years for which a prediction is being made, the second column is a list of the sequence combination of the nine years, the third column is one of the three ranges of the total annual sediment load corresponding to the selected year, and the fourth column lists the cumulative sediment load. The percent exceedance of the cumulative load in 2035 relative to all 10,000 sequences was also calculated. The last two rows of Table 5.18 gives an example of the rank and percent exceedance calculations.

Table 5.17 Minimum, Mean, and Maximum Total Annual Sediment Load at Mouth of Toutle River

Water Year	Total Sediment Load at Mouth of Toutle River (M Tons)		
	Low (L)	Mean (M)	High (H)
1999	1.35	4.88	8.41
2000	3.76	4.55	5.33
2001	0.53	0.64	0.75
2002	4.78	7.44	10.10
2003	3.34	5.27	7.19
2004	1.84	2.56	3.28
2005	1.73	2.83	3.93
2006	3.79	5.29	6.78
2007	16.10	22.74	29.40

Table 5.18 Example of Predictive Sequences

Sequence #	1	2	--	10,000	1	2	--	10,000	1	2	--	10,000
Forecast Year	**Selected Water Year (1999 – 2007)**				**Total Annual Load at Mouth of Toutle (M Tons)** [A]				**Cumulative Total Load at Mouth of Toutle (M Tons)**			
2008	2000 H	2000 L	--	2003 H	5.33	3.76	--	7.19	5.33	3.76	--	7.19
2009	2006 L	2004 M	--	1999 L	3.79	2.56	--	1.35	9.12	6.32	--	8.54
2010	1999 M	2004 M	--	2003 M	4.88	2.56	--	5.27	14.00	8.88	--	13.81
2011	2005 H	2001 L	--	2004 M	3.93	0.53	--	2.56	17.93	9.41	--	16.37
2012	2004 L	2003 H	--	2004 H	1.84	7.19	--	3.28	19.77	16.60	--	19.65
2013	2004 L	2006 M	--	2001 L	1.84	5.29	--	0.53	21.61	21.89	--	20.18
2014	2001 M	2006 H	--	2006 H	0.64	6.78	--	6.78	22.25	28.67	--	26.96
2015	2002 M	2000 M	--	2005 L	7.44	4.55	--	1.73	29.69	33.22	--	28.69
2016	2005 M	1999 L	--	2003 L	2.83	1.35	--	3.34	32.52	34.57	--	32.03
2017	1999 M	2005 H	--	2004 M	4.88	3.93	--	2.56	37.40	38.50	--	34.59
2018	2001 M	2000 H	--	2002 L	0.64	5.33	--	4.78	38.03	43.83	--	39.37
2019	2004 M	2005 M	--	2006 L	2.56	2.83	--	3.79	40.59	46.66	--	43.16
2020	2002 L	2007 H	--	2006 L	4.78	29.40	--	3.79	45.37	76.06	--	46.95
2021	1999 L	2006 M	--	2001 M	1.35	5.29	--	0.64	46.72	81.35	--	47.58
2022	2004 H	2004 H	--	1999 H	3.28	3.28	--	8.41	50.00	84.63	--	55.99
2023	2000 H	2001 L	--	2004 H	5.33	0.53	--	3.28	55.33	85.15	--	59.27
2024	2000 L	2007 M	--	2000 L	3.76	22.74	--	3.76	59.09	107.89	--	63.03
2025	2006 M	2001 M	--	2000 M	5.29	0.64	--	4.55	64.38	108.53	--	67.58
2026	2003 H	2004 M	--	2004 M	7.19	2.56	--	2.56	71.57	111.09	--	70.14
2027	2007 L	2006 L	--	2006 L	16.10	3.79	--	3.79	87.67	114.88	--	73.93
2028	2006 L	2001 L	--	2007 L	3.79	0.53	--	16.10	91.46	115.40	--	90.03
2029	2000 M	2003 L	--	2002 L	4.55	3.34	--	4.78	96.01	118.74	--	94.81
2030	2004 H	1999 M	--	2000 M	3.28	4.88	--	4.55	99.29	123.62	--	99.36
2031	2003 L	2004 M	--	2000 L	3.34	2.56	--	3.76	102.63	126.18	--	103.12
2032	2007 M	2005 H	--	1999 H	22.74	3.93	--	8.41	125.37	130.11	--	111.53
2033	2003 L	2005 M	--	2004 M	3.34	2.83	--	2.56	128.71	132.94	--	114.09
2034	1999 L	2002 M	--	2000 H	1.35	7.44	--	5.33	130.06	140.38	--	119.42
2035	2007 M	2002 M	--	2002 L	22.74	7.44	--	4.78	**152.80**	**147.82**	--	**124.20**
Rank of 10,000									7,188	7,722	**--**	9,440
% Exceedance									72%	77%	**--**	94%

[A] Total sediment load at mouth of Toutle River, see Table 5.17.

Sequences representing the minimum, maximum and exceedance frequencies at 5% increments between 5% and 95% of the cumulative load at the mouth of the Toutle River in 2035 were queried from the forecasting analysis, and are presented graphically in Figure 5.18. The minimum, maximum, 5%, and 95% exceedance sequences are shown in Table 5.19. The total range of cumulative sediment loads predicted by 2035 was determined to be 81 to 373 million tons and a 95% limit ranges from 123 to 237 million tons. The mean cumulative sediment load by 2035 was estimated to be 173 million tons. Figure 5.19 shows the minimum, maximum, 5% and 95% exceedance sequences calculated for all years from 2008 through 2035. The method by which the forecasting was conducted provides a range of results that account for uncertainty in hydrologic patterns (wet, average, or dry years).

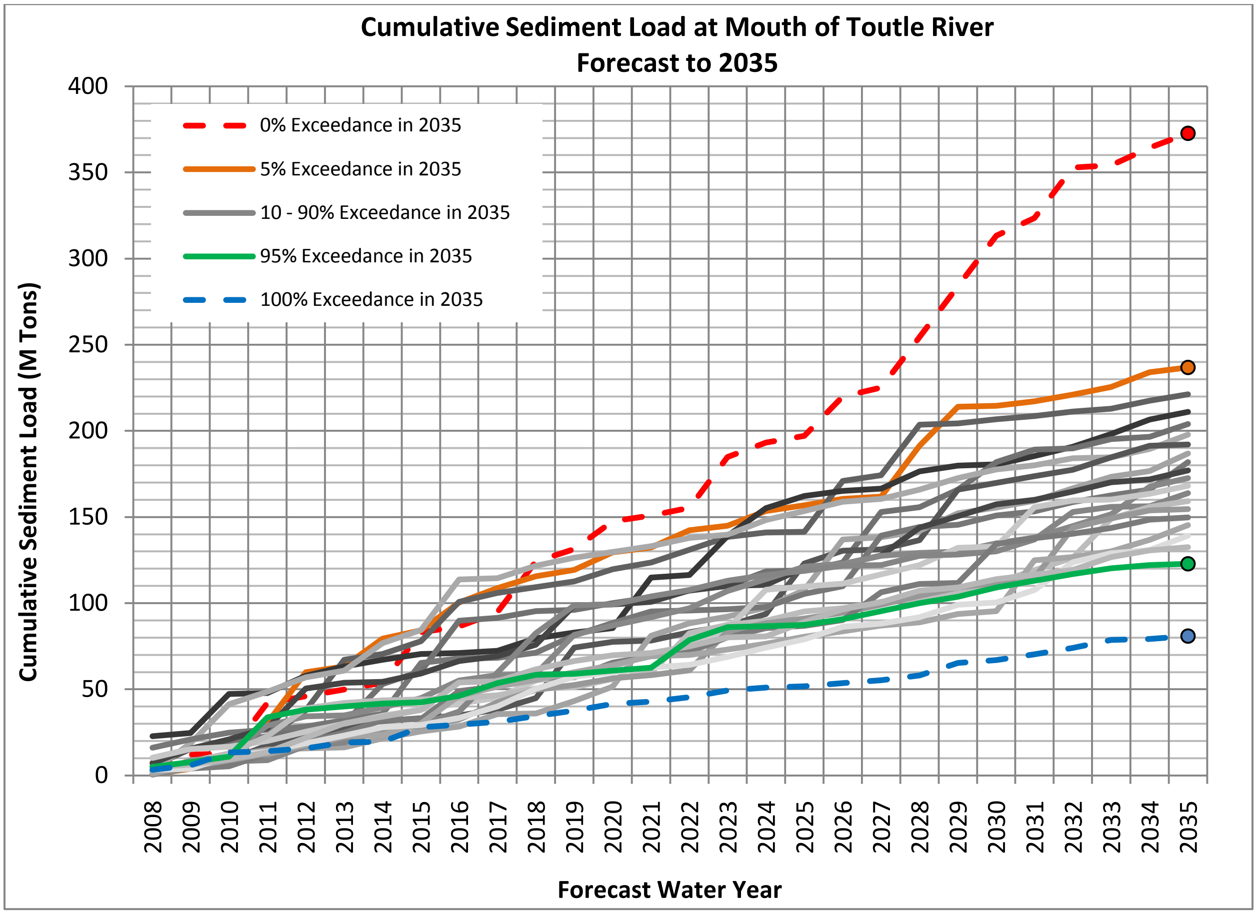

Figure 5.18 Forecast of the Total Sediment Load at the Mouth of the Toutle River by 2035

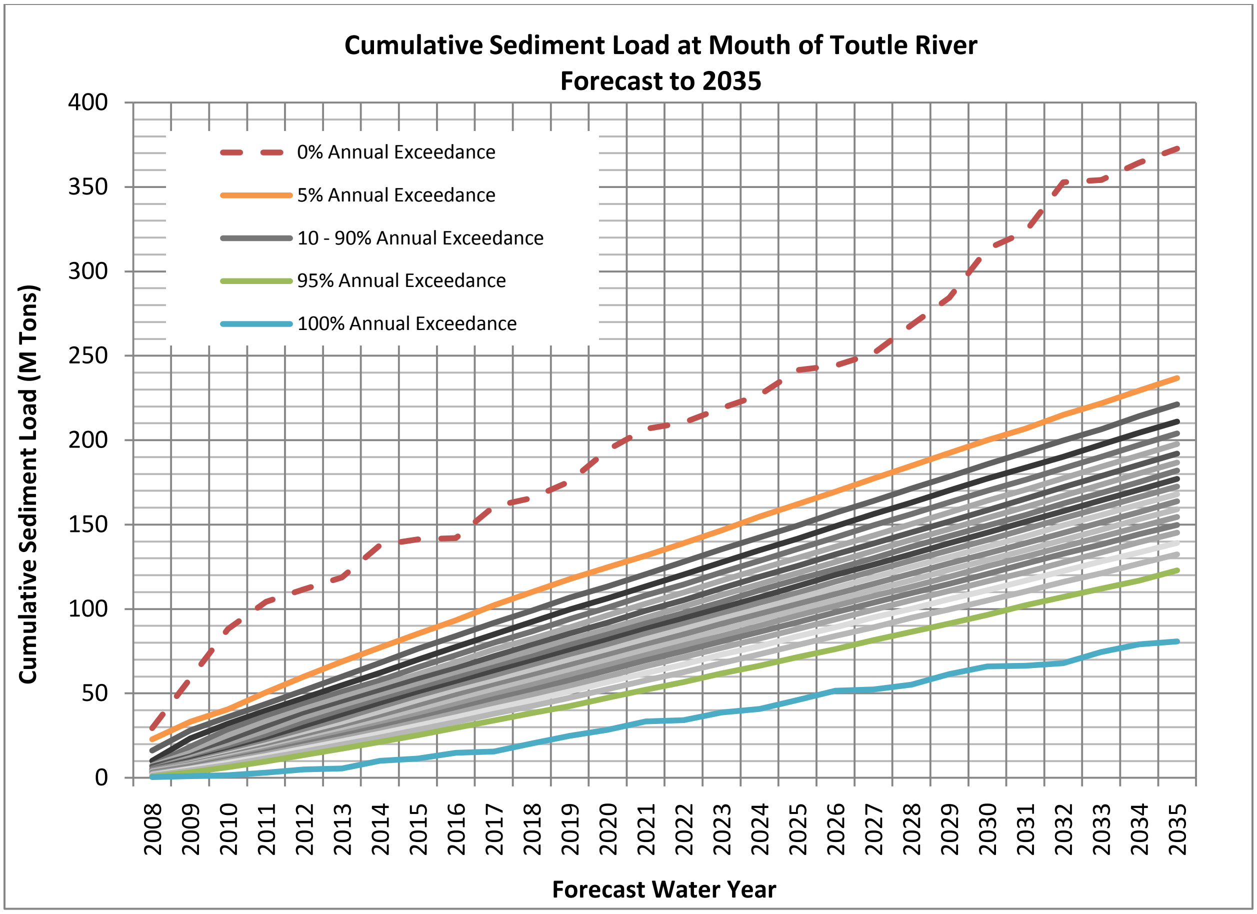

Figure 5.19 Annual Forecast of the Total Sediment Load at the Mouth of the Toutle River from 2008 through 2035

Table 5.19 Minimum, Maximum, 5%, and 95% Exceedance Forecasting Sequences

Forecast Water Year	Minimum		95% Exceedance		5% Exceedance		Maximum	
	WY	Cumulative Sediment Load (M Tons)	WY	Cumulative Sediment Load (M Tons)	WY	Cumulative Sediment Load (M Tons)	WY	Cumulative Sediment Load (M Tons)
2008	2003 L	3.3	1999 M	4.9	2001 M	0.6	2003 H	7.2
2009	2004 M	5.9	2005 M	7.7	2004 H	3.9	1999 M	12.1
2010	2002 M	13.3	2004 H	11.0	2005 H	7.8	2001 M	12.7
2011	2001 M	14.0	2007 M	33.7	2007 M	30.6	2007 H	42.1
2012	2004 L	15.8	2000 M	38.3	2007 H	60.0	2005 H	46.0
2013	2004 H	19.1	2005 L	40.0	2003 L	63.3	2005 H	50.0
2014	2001 L	19.6	2005 L	41.7	2007 L	79.4	2000 L	53.7
2015	1999 H	28.0	2001 M	42.4	1999 M	84.3	2007 H	83.1
2016	1999 L	29.4	2006 L	46.2	2007 L	100.4	2004 H	86.4
2017	2005 L	31.1	2002 M	53.6	1999 H	108.8	1999 H	94.8
2018	2004 H	34.4	2002 L	58.4	2006 H	115.6	2007 H	124.2
2019	2003 L	37.7	2001 M	59.0	2006 L	119.4	2003 H	131.4
2020	2000 L	41.5	2005 L	60.8	2002 H	129.5	2007 L	147.5
2021	1999 L	42.8	2004 L	62.6	2005 M	132.3	2003 L	150.8
2022	2004 M	45.4	2007 L	78.7	2002 H	142.4	2000 M	155.4
2023	2005 H	49.3	2002 M	86.1	2004 M	145.0	2007 H	184.8
2024	2005 L	51.1	2001 L	86.7	1999 H	153.4	1999 H	193.2
2025	2001 H	51.8	2001 H	87.4	2003 L	156.7	2005 H	197.1
2026	2005 L	53.5	2004 H	90.7	2006 L	160.5	2007 M	219.9
2027	2005 L	55.3	2002 L	95.5	1999 L	161.9	2003 M	225.1
2028	2005 M	58.1	2000 M	100.0	2007 H	191.3	2007 H	254.5
2029	2003 H	65.3	2000 L	103.8	2007 M	214.0	2007 H	283.9
2030	2005 L	67.0	2006 M	109.1	2001 L	214.5	2007 H	313.3
2031	2004 H	70.3	2005 H	113.0	2004 M	217.1	2002 H	323.4
2032	2000 L	74.1	2005 H	116.9	2005 H	221.0	2007 H	352.8
2033	2000 M	78.6	2003 L	120.3	2000 M	225.6	1999 L	354.2
2034	2001 L	79.1	2004 L	122.1	1999 H	234.0	2002 H	364.3
2035	**2005 L**	**80.9**	**2001 H**	**122.8**	**2005 M**	**236.8**	**1999 H**	**372.7**

5.5 Conclusions and Recommendations

Key results and conclusions of the analyses presented in this report are summarized in the following list:

- Evidence of decay in the rate of debris avalanche erosion was not found to be significant in available data collected during the past 20 years. Cumulative debris avalanche erosion predicted by 2035 ranges from 125 to 227 MCY, with a mean value of 165 MCY. Calculation of debris avalanche erosion was conducted using surface comparisons that were found to have an uncertainty of +/- 15%.

- The SRS filled to the spillway crest with sediment in 1998 and since then sediment moving through the spillway comprises approximately 79% of the total sediment sources contributing to the Toutle/Cowlitz system. Sediment output from the SRS from 1999 – 2007 was estimated to be comprised of approximately 46% silts and clays, 40% fine sands, 6% medium sands, and 8% coarse sands.

- Upstream sediment supply to the South Fork was found to be the second largest contributor to the Toutle/Cowlitz system accounting for approximately 13%.

- The total sediment load delivered to the Cowlitz River at the mouth of the Toutle River during water years 1999 through 2007 was estimated by the sediment budget to be 56.2 million tons and was comprised of 41% silts and clays, 40% fine sands, 9% medium sands, 8% coarse sands, and 2% gravel. Uncertainty associated with the total load ranges from +/- 17% and +/-72%, with an average uncertainty of 28%. Uncertainty in the load by grain size is considerably larger.

- The cumulative sediment load delivery at the mouth of the Toutle River, with uncertainty incorporated, is predicted to be between 81 and 373 million tons. The 5% and 95% confidence limits range from 123 to 237 million tons with a mean value of 173 million tons.

- The sediment budget methodology provides an efficient, first-approximation method for estimating total sediment yield along a river system.

- Primary limitations in the method are the temporal density of the data relative to the temporal density of the estimates required, and the inability of the method to include hydraulic sediment routing by grain size. Sediment routing models should be considered in the portion of the watershed upstream of the SRS, and in the Cowlitz River.

- The sediment budget was formulated under the assumption that the North Fork, South Fork, and Toutle Rivers act as a conduit for efficiently moving sediment, mainly sands, silts, and clays, to the Cowlitz River. Local sediment sinks have been observed in a few locations along the Toutle, North, and South Fork Rivers, however, based upon analysis of stream power, critical shear, suspended sediment data and field observations, these sinks are thought to be relatively small in comparison to the sediment sources.

- Sediment deposition rates in the lower Cowlitz River have increased since 2003. The most recent analysis period, 2006 – 2008, showed the highest depositional rates of all analysis periods. The high depositional rates observed between 2006 and 2008 are likely due to very high sediment loadings associated with the November 2006 storm event and subsequent dredging activities and likely do not represent a steep rising trend in deposition. While the highest rates were in the lower two miles, a high persistent depositional rate is observed in the lower ten miles and again in the upper 5 miles.

- Sediment deposition occurring in the lower Cowlitz was found to be primarily medium and coarse sands. Discrepancies were found between the quantity of medium to coarse sand sampled by USGS gages and the quantity of those particles found in the sediment at the mouth of the Cowlitz River.

- Although much of the data has been collected with some immediate purpose, (for example the dredging surveys), future management of the data acquisition resources could, perhaps, be enhanced by consideration of how the data is being applied for longer term modeling.

- Approximately 40% of the predicted sediment yield at the mouth of the Toutle River is in the silt and clay range.

- It should be noted that the Sediment Budget analyses and results do not take into account mudslides or lahars.

6.0 References

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