DEVELOPING A SEDIMENT BUDGET OF THE COWLITZ SYSTEM

David S. Biedenharn, Hydraulic Engineer, Biedenharn Group, LLC, Vicksburg, MS, biedenharngroup@yahoo.com; Paul Sclafani, USACE, Portland District, Portland OR, Paul.Sclfani@usace.army.mil; Matt Fraver, USACE, Portland District, Portland OR, Matthew.R.Fraver@usace.army.mil; Michelle Martin, Hydraulic Engineer, Anderson Consulting Engineers, Inc, Fort Collins, CO, mlmartin@acewater.com; and Chester C. Watson, Hyd Engineer, Biedenharn Group, LLC, Vicksburg, MS, chester@chestercwatson.com

Abstract The Cowlitz and Toutle River watersheds have been dramatically altered by the 1980 volcanic eruption of Mount St. Helens, and the resulting measures constructed to protect the public and control the extraordinary volumes of sediment mobilized by the 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. A key component of this study is the development of a sediment budget that identifies the existing watershed sediment sources, pathways and sinks. The sediment budget estimates the volumes and transport rates of sediments in the Toutle watershed and the near and long term range of possible effects on the Cowlitz and Columbia Rivers. Data used in the development of the sediment budget included, historical surveys of the debris avalanche area and streams, USGS measured suspended sediment data on the North Fork Toutle, South Fork Toutle, Toutle and Cowlitz Rivers, bed and bank material gradations throughout the system, and estimates of bank erosion from comparative aerial photography. The sediment budget provides a framework for identifying, screening and evaluating potential alternatives.

The cumulative sediment load delivery forecast out to 2035, with uncertainty incorporated, at the mouth of the Toutle River is predicted to be between 81 and 373 million tons. The total 95% limit ranges from 123 to 237 million tons for the same period. 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.

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. Figure 1 is a vicinity map of the Toutle and Cowlitz Rivers.

The purpose of this paper is to discuss a sediment budget developed to identify the existing watershed sediment sources, pathways of sediment transport and sinks of temporary storage of sediment.

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 (Figure 1) 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. 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, LIDAR, 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.

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. A sediment budget was developed by combining independently estimated sediment sources and sinks. The Toutle/Cowlitz sediment budget network is comprised of seven reaches, as shown in Table 1.

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 2000 through 2007. For this paper, the results of the sediment budget for the 2000 – 2007 time period are discussed. 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 (Sediment Retention Structure), which began in 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 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. 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. 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.

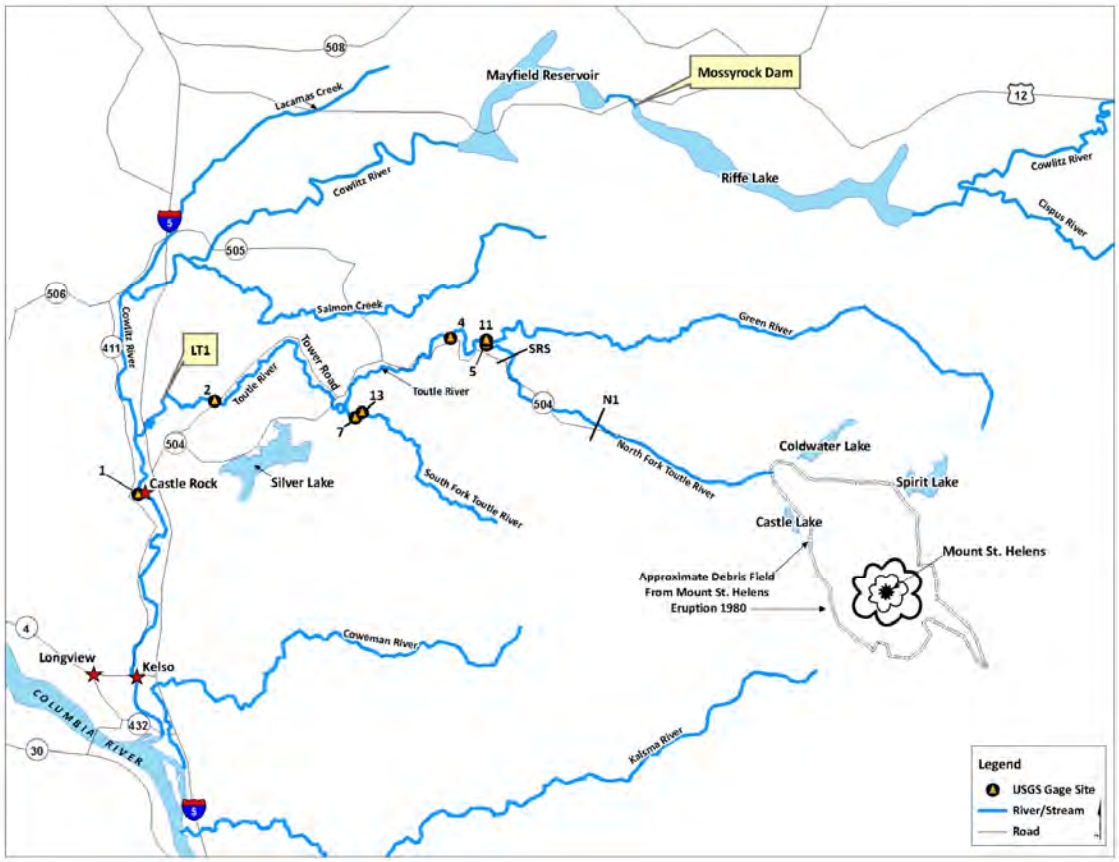

Figure 1 Toutle-Cowlitz Rivers vicinity map.

Figure 2 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%. Figure 3 portrays the annual supply of sediment for each year by particle size at the mouth of the Toutle River.

The sediment budget results were compared to USGS suspended sediment gage data, as shown in Figure 4. The gage data is shown with 25% unmeasured load added as well as +/-25% error. A comparison of the USGS gage data and sediment budget by grain size was also conducted. Figure 5 shows the sediment budget results and USGS gage data with 25% unmeasured load and +/-25% error bars by grain size. 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.

Table 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	

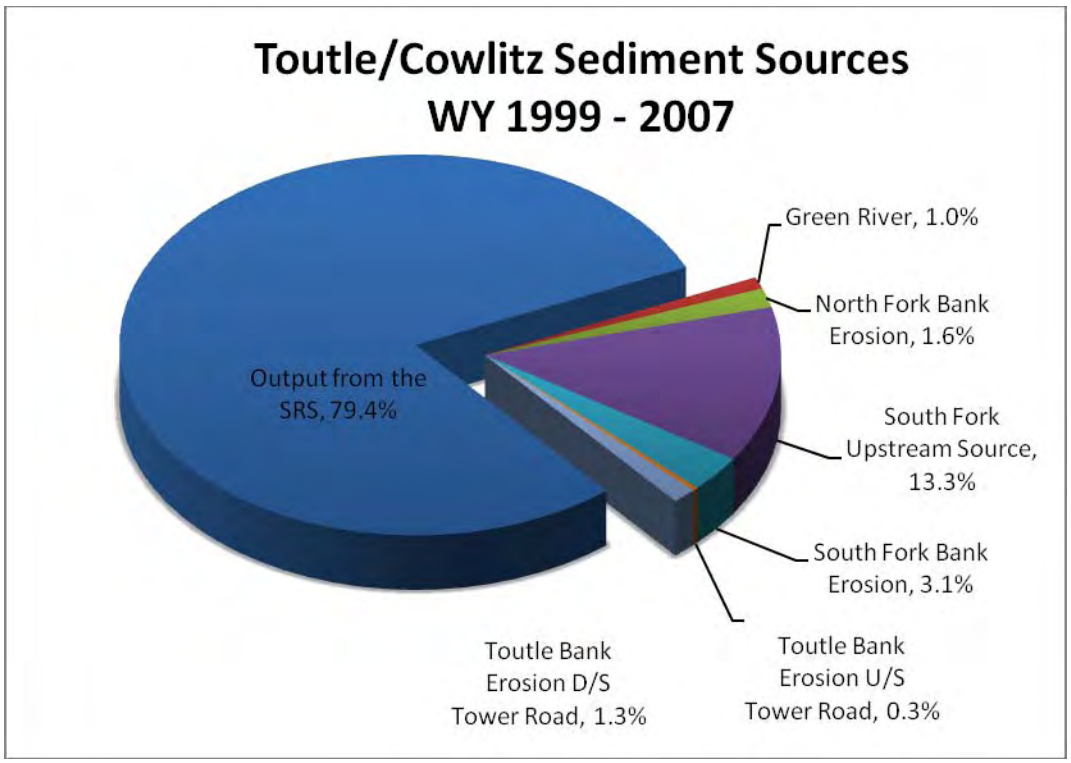

Figure 2 Toutle/Cowlitz Sediment Source Breakdown for Water Years 1999 through 2007.

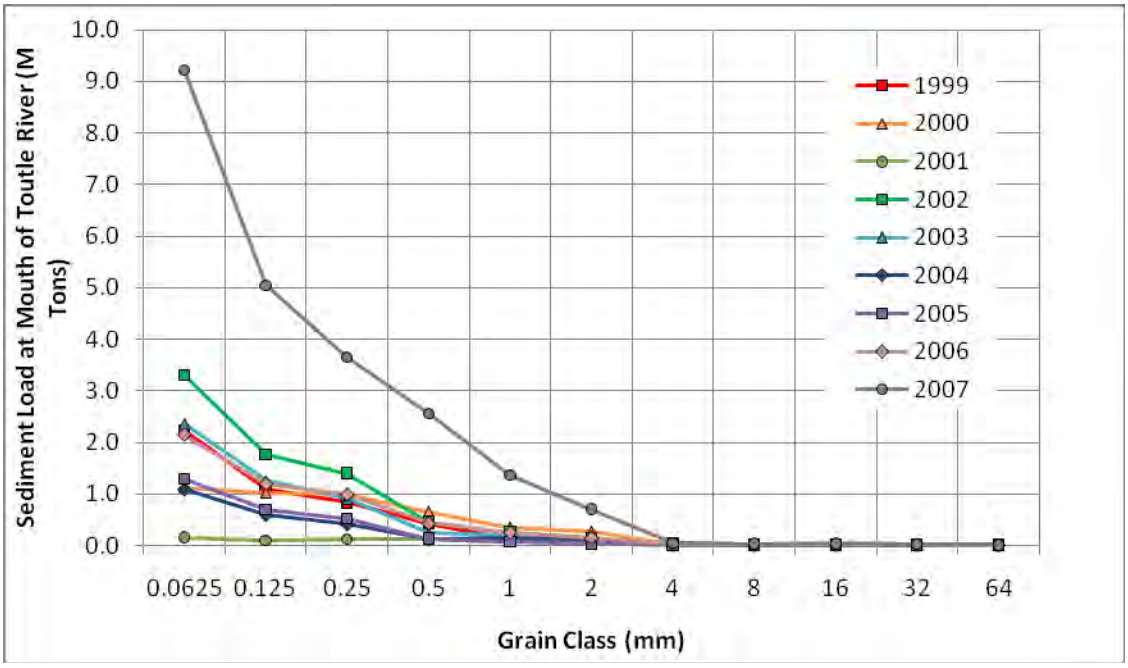

Figure 3 Annual Sediment Load by Grain Class at Mouth of Toutle River, 1999 – 2007.

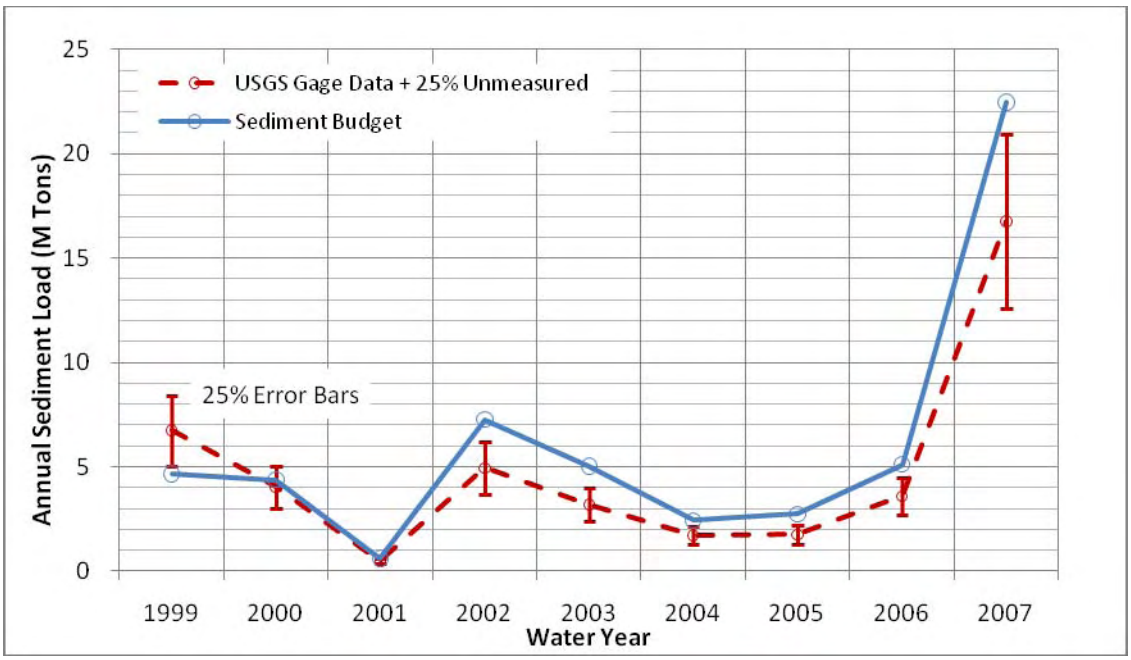

Figure 4 Comparison of Sediment Budget and USGS Gage Data, Toutle River Sediment Load for Sands and Finer at Tower Road.

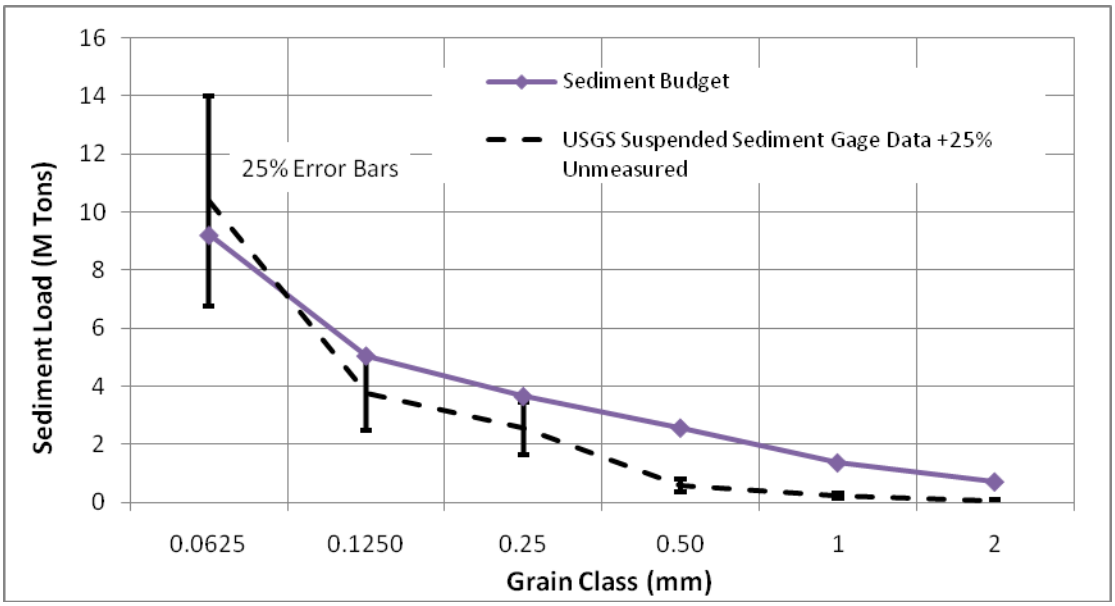

Figure 5 Comparison of Sediment Budget and USGS Suspended Sediment Gage Data, Cowlitz River at Castle Rock WY 2007.

UNCERTAINTY ANALYSIS

A primary 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 2000 – 2007 to gain insight into the quantity and size of sediment depositing in the lower Cowlitz River. Development of input to the Toutle/Cowlitz sediment budget is an approximation with uncertainty; therefore, use of the results without an evaluation of uncertainty is irresponsible.

Each individual input to the Toutle/Cowlitz sediment budget was developed with as much accuracy as possible, given limitations of available data sources and methods by which input was developed. Table 2 provides the estimates of uncertainty for each input. 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 source, and the second includes a combination of variations 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, and then 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 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.

Summary results of the sediment load calculated (M tons) at the mouth of the Toutle River for the matrix are provided in Figure 6. The calculated uncertainty in the total sediment load at the mouth of the Toutle River on a yearly basis was found to range from +/-17% to a maximum value of +/-72%. The total budget from 2000 – 2007 had an uncertainty of +/-28%.

Review of the analysis results indicates 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 7 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%.

Table 2 Sediment budget uncertainty estimates.

Sediment Budget Inputs	Description	Uncertainty
North Fork Toutle: Debris Avalanche to SRS		
Debris Avalanche Erosion	Coldwater Creek to N1	+/- 15%
SRS Deposition	Sediment Plain, N1 to SRS	+/- 15%
North Fork Toutle: SRS to Toutle River		
Local Sources	Bank Erosion North Fork Toutle	+/- 35%
	USGS Gage Green River	+/- 25%
South Fork Toutle Upstream of Gage		
Local Sources	Bank Erosion South Fork Toutle	+/- 35%
Output	USGS Gage South Fork Toutle	+/- 25%
Toutle River NF/SF to Tower Road		
Local Source	Toutle Bank Erosion above Tower	+/- 35%
Toutle River: Tower to Cowlitz		
Local Sources	Toutle Bank Erosion below Tower	+/- 35%
Cowlitz River; Toutle to Columbia		
Sink/Source	Cowlitz Deposition/Erosion	+/- 35%

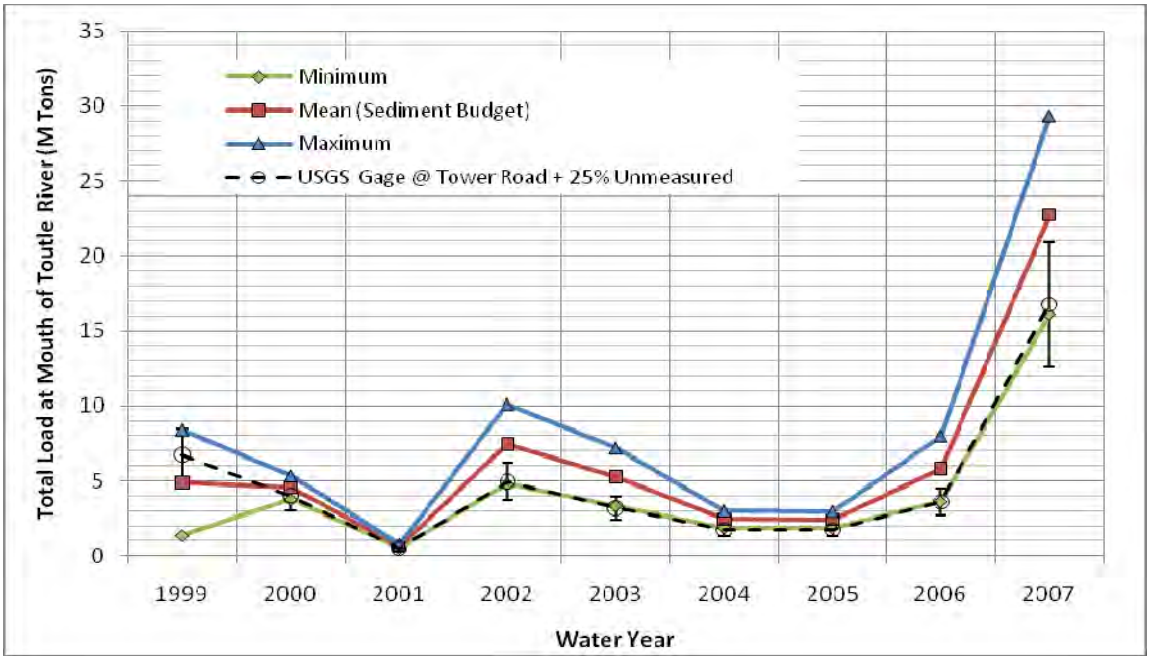

Figure 6 Uncertainty Analysis Minimum, Mean, and Maximum Total Sediment Load at Mouth of Toutle River (shown with measured suspended sediment data at Tower with +/- 25% error bars).

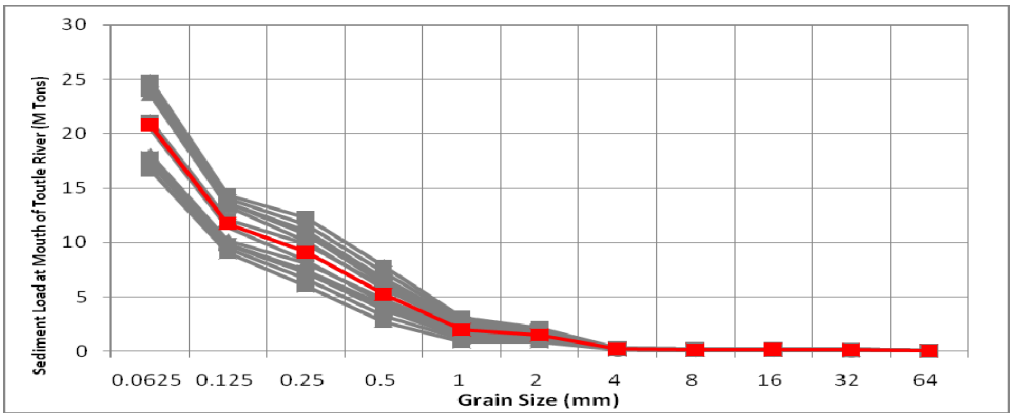

Figure 7 Sediment Load at Mouth of Toutle River for WY 2000 – 2007. The red line indicates the 2000–2007 sediment budget results and grey lines indicate the range of uncertainty.

An additional uncertainty analysis was conducted by varying the sediment source inputs incorporating variation in the gradation 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 compared to the SRS (80% of the total sediment input).

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. Results show that the uncertainty in the sediment load per grain class can be as high as 602%. Figure 8 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).

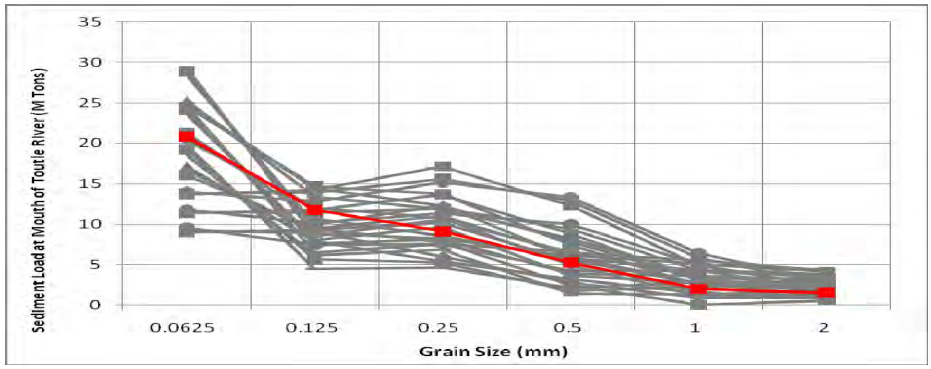

Figure 8 Sediment Load at Mouth of Toutle River for WY 2000 – 2007. The red line indicates the 2000–2007 sediment budget results and grey lines indicate the range of uncertainty associated with source and gradation inputs.

FORECASTING OF SEDIMENT LOAD AT THE MOUTH OF THE TOUTLE RIVER

Estimates of the cumulative sediment load at the mouth of the Toutle River through 2035 were made utilizing the range (low, medium, high) of total sediment load calculated for water years 2000 through 2007 and a Monte Carlo bootstrapping simulation. 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. 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. 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 9. 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.

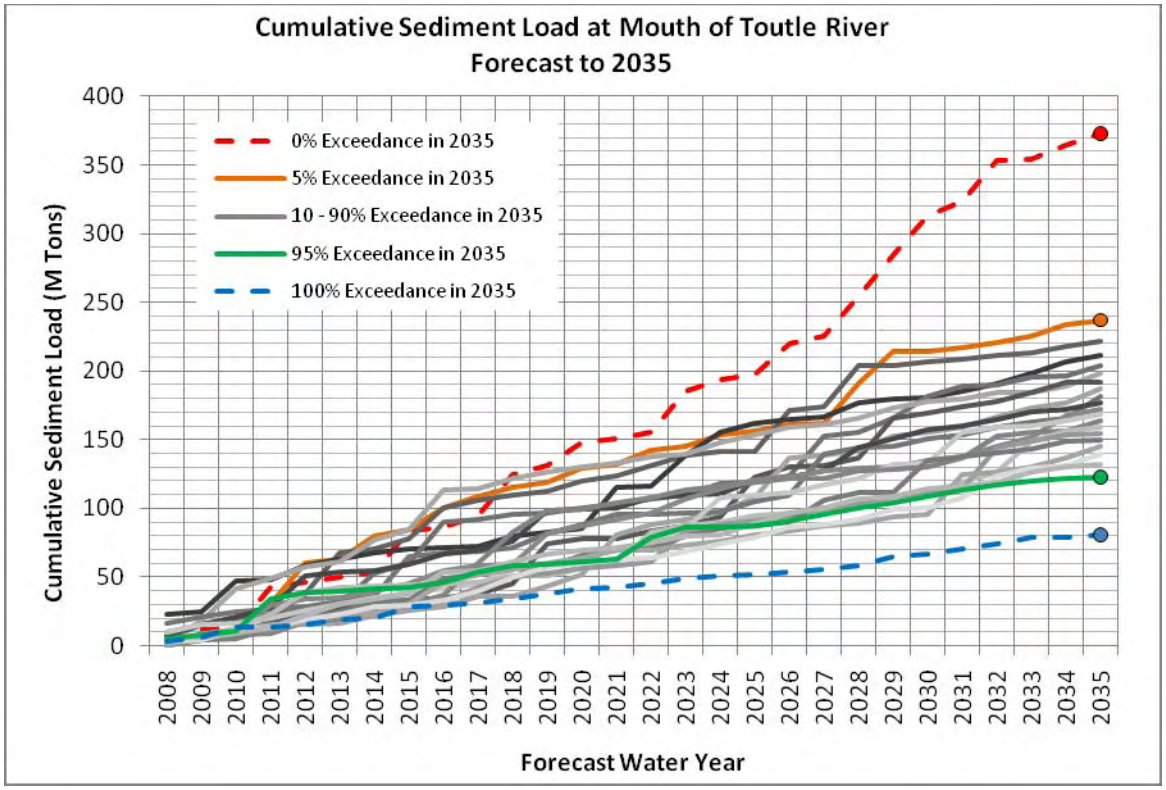

Figure 9 Forecast of the Total Sediment Load at the Mouth of the Toutle River by 2035.

CONCLUSIONS

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

- 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.
- 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, with uncertainty incorporated, at the mouth of the Toutle River is predicted to be between 81 and 373 million tons. The total 95% limit ranges from 123 to 237 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.

REFERENCES

Gray, J., Glysson, D. and Edwards, T. 2009. Suspended-sediment samplers and sampling methods, in Sedimentation Engineering (Marcello Garcia), ASCE

Gray, John R. and Simoes, Francisco J. M., 2009. Estimating sediment discharge, in Sedimentation Engineering (Marcello Garcia), ASCE

Porterfield, G., 1972. Book 3, Chapter C3, Computation of fluvial-sediment discharge. Techniques of water resources investigation, U.S. Geological Survey

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

Wailing, D. E., 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Research. 13(3), 531-538.