Prepared in cooperation with the Federal Emergency Management Agency and
Snohomish County Department of Public Works

Preliminary Assessment of Aggradation Potential in the North Fork Stillaguamish River Downstream of the State Route 530 Landslide near Oso, Washington

Scientific Investigations Report 2015–5173

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph showing downstream view of the North Fork Stillaguamish River where it incised back into the SR 530 Landslide deposit near Oso, Washington. (Photograph by Christopher S. Magirl, U.S. Geological Survey, May 15, 2014)

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Power	
watts per square meter (W/m^3)	0.005290	BTU per square foot per minute [(BTU/ft^2)/min]

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Preliminary Assessment of Aggradation Potential in the North Fork Stillaguamish River Downstream of the State Route 530 Landslide near Oso, Washington

By Christopher S. Magirl[1], Mackenzie K. Keith[1], Scott W. Anderson[1], Jim E. O'Connor[1], Robert Aldrich[2], and Mark C. Mastin[1]

Abstract

On March 22, 2014, the State Route 530 Landslide near Oso, Washington, traveled almost 2 kilometers (km), destroyed more than 40 structures, and impounded the North Fork Stillaguamish River to a depth of 8 meters (m) and volume of 3.3×10^6 cubic meters (m^3). The landslide killed 43 people. After overtopping and establishing a new channel through the landslide, the river incised into the landslide deposit over the course of 10 weeks draining the impoundment lake and mobilizing an estimated 280,000±56,000 m^3 of predominantly sand-sized and finer sediment. During the first 4 weeks after the landslide, this eroded sediment caused downstream riverbed aggradation of 1–2 m within 1 km of the landslide and 0.4 m aggradation at Whitman Road Bridge, 3.5 km downstream. Winter high flows in 2014–15 were anticipated to mobilize an additional 220,000±44,000 m^3 of sediment, potentially causing additional aggradation and exacerbating flood risk downstream of the landslide. Analysis of unit stream power and bed-material transport capacity along 35 km of the river corridor indicated that most fine-grained sediment will transport out of the North Fork Stillaguamish River, although some localized additional aggradation was possible. This new aggradation was not likely to exceed 0.1 m except in reaches within a few kilometers downstream of the landslide, where additional aggradation of up to 0.5 m is possible. Alternative river response scenarios, including continued mass wasting from the landslide scarp, major channel migration or avulsion, or the formation of large downstream wood jams, although unlikely, could result in reaches of significant local aggradation or channel change.

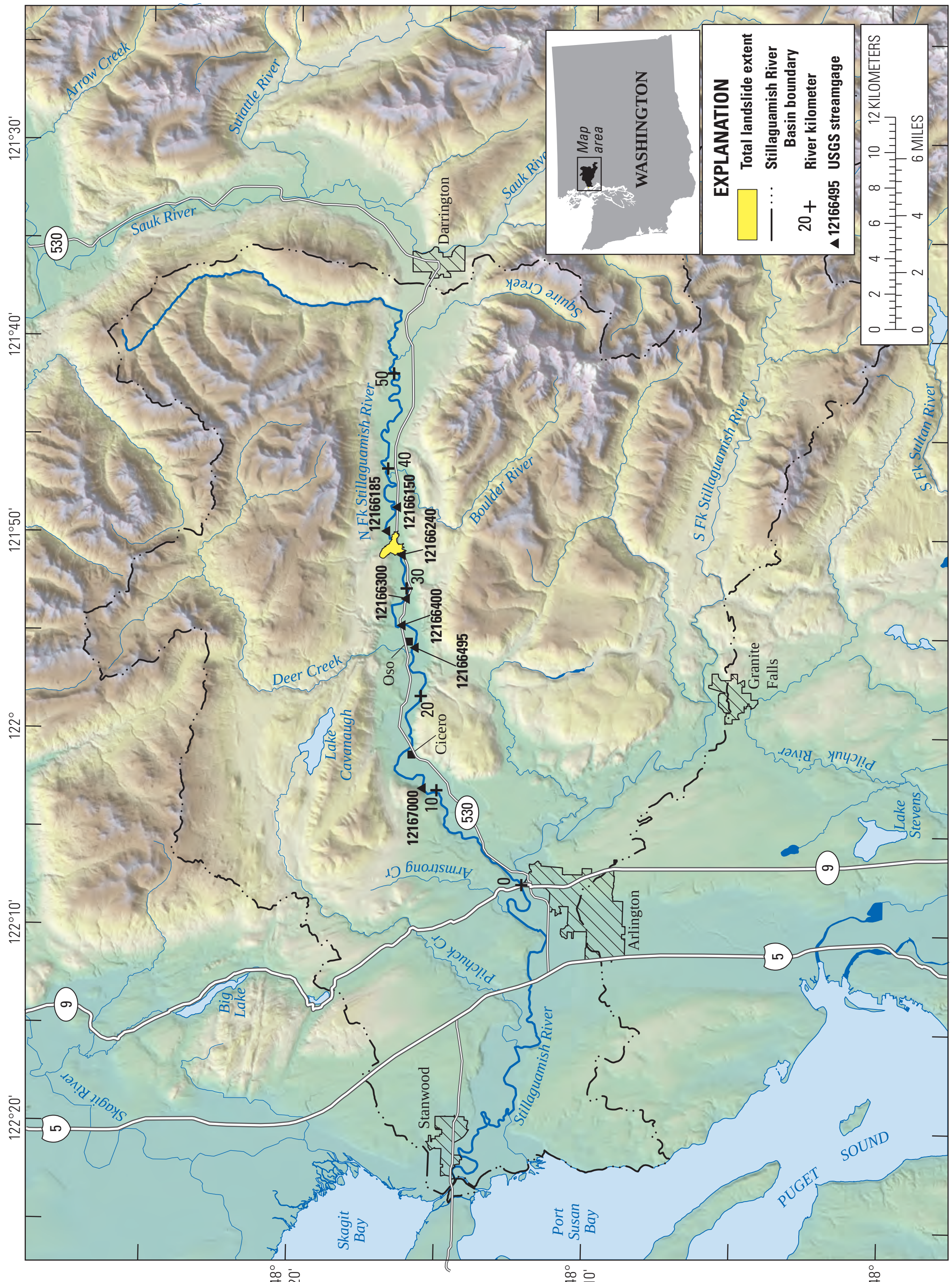
[1]U.S. Geological Survey.

[2]Snohomish County Public Works.

Introduction

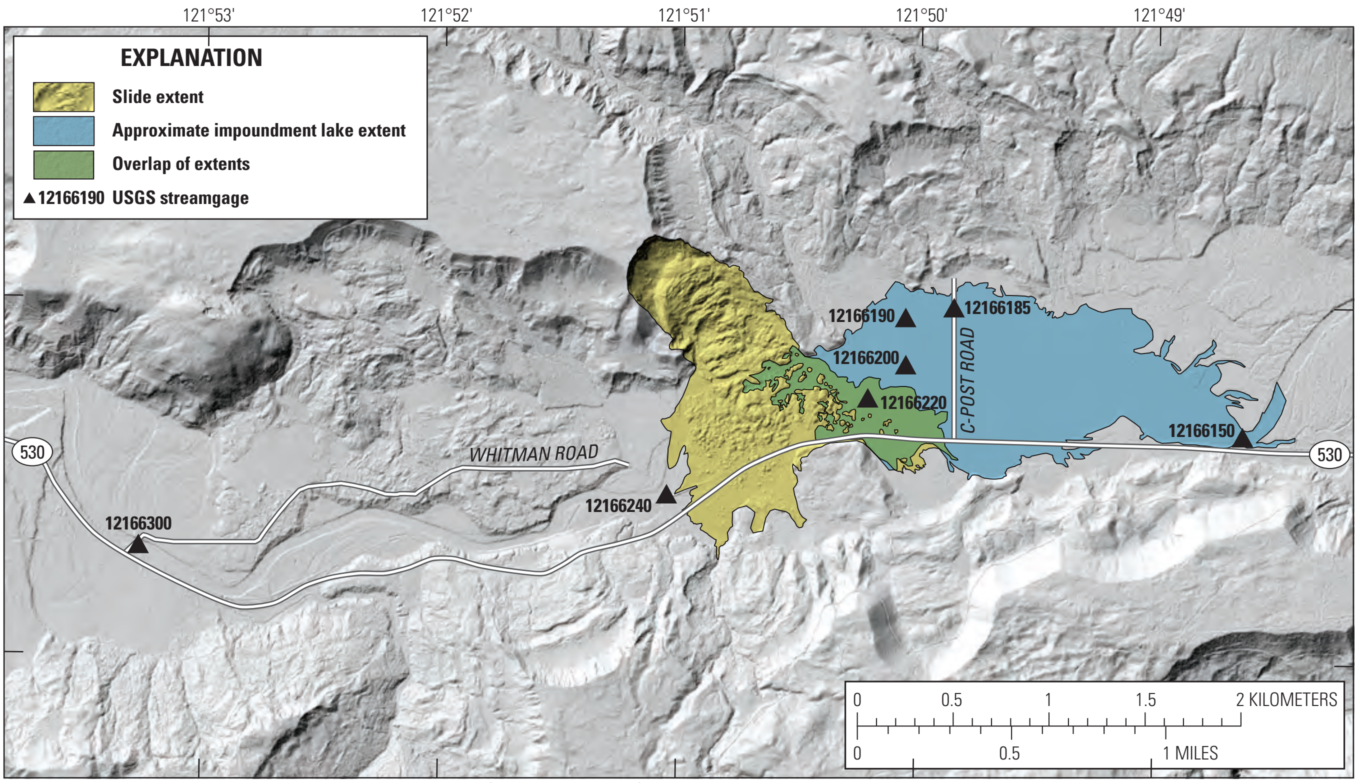
On March 22, 2014, an 8×10^6 cubic meter (m^3) landslide (Iverson and others, 2015) originating from a 190 m bluff of unconsolidated glacial till moved almost 2 km across the flood plain of the North Fork Stillaguamish River 6 km east of Oso, Washington (fig. 1). The destructive landslide traveled from north to south across the river and through a rural neighborhood, destroyed more than 40 structures, traversed a 1.4-km section of Washington State Route 530 (SR 530), and killed 43 people. The landslide covered about 1 square kilometer (km^2) of the valley bottom with deposits as thick as 20 m. The SR 530 Landslide (hereinafter landslide) dammed the North Fork Stillaguamish River by 8 m, forming an impoundment lake about 3 km long, 1.5 km^2 in area, and 3.3×10^6 m^3 in volume (fig. 2). After 25 hours, the impoundment lake overtopped the landslide deposit in a topographically low trough establishing a new river-channel location. Because of the relatively shallow slope of the new river channel through the landslide deposit, the rate of erosion was moderate without the rapid dam breaching and outburst flood sometimes associated with landslide-dammed impoundments (Costa and Schuster, 1988; Korup, 2002; O'Connor and Beebee, 2009).

From March 23 through May 2014, the new river channel slowly incised into the landslide deposit. To aid the search-and-recovery effort, a pilot channel through the eastern section of the landslide was excavated in early April by Snohomish County, its consultants, and cooperating agencies. This channel accelerated river incision and expedited the drainage of the impoundment lake. By June 1, 2014, there was no longer a pool within the impoundment for river flows less than about 57 m^3/s (2,000 ft^3/s). Some degree of impoundment, however, was expected to reappear during high winter flows as the relatively narrow channel through the landslide deposit exerted hydraulic control on the upstream river reach.



Base map modified from U.S. Geological Survey digital data (10-meter resolution) and other digital data, various scales. Coordinate reference system: UTM Zone 10N, North American Datum of 1983

Figure 1. Stillaguamish River Basin, the North Fork Stillaguamish River, U.S. Geological Survey streamgages, and the location of the State Route 530 Landslide near Oso, Washington, March 22, 2014.



Base map modified Puget Sound Lidar Consortium digital data (1-meter resolution), U.S. Geological Survey digital data (10-meter resolution), and other digital data, various scales.
Coordinate reference system: UTM Zone 10N, North American Datum of 1983

Figure 2. Lidar-derived topography showing extent of the State Route 530 Landslide, the maximum extent of impoundment lake, and U.S. Geological Survey (USGS) rapid-deployment streamgages in operation near the landslide.

In summer of 2014, we anticipated that larger flows during the 2014–15 winter flood season would progressively widen and incise the river channel through the landslide deposit toward a future equilibrium condition with a quasi-stable hydraulic geometry.

The evolution of localized accumulations of alluvium deposited from geomorphic disturbances, also known as sediment waves, is well studied in the geomorphology literature (Gilbert, 1917; Nicholas and others, 1995; Lisle and others, 2001; James, 2006; Lisle, 2008). Fine-grained sediment eroded by the river from the landslide traveled as far as Port Susan Bay in Puget Sound in the days and weeks following the event, but some portion of the bedload, composed of sands and gravels, accumulated in the river reach downstream of the landslide. Localized aggradation, followed by incision, was expected to continue in the 2014–15 flood season. Flume studies, mechanistic theory, and landslide case studies (Lisle, 2008) indicate that sediment waves composed of coarser grained material (that is, sands, gravels, and cobbles) in mountainous rivers with Froude numbers greater than 0.4 evolve primarily though dispersion; whereby sediment from the newly added deposit transports downstream and causes aggradation, and background bedload in the river accumulates just upstream of the new sediment deposit because of localized decrease in transport capacity. If the landslide sediment wave is dispersion dominant, river reaches within a few kilometers downstream and upstream of the landslide will be most strongly affected by aggradation and effects farther downstream will be negligibly small. In contrast, where the sediment deposit is dominated by sands and finer particles and Froude number is less than 0.4, the sediment wave evolves with both dispersion and translation. If sediment-wave dispersion and translation occurs, reaches far from the landslide may accumulate detectable quantities of new sediment.

To assess the potential for anticipated aggradation in the North Fork Stillaguamish River during the 2014–15 flood season, the Federal Emergency Management Agency and Snohomish County Department of Public Works requested the U.S. Geological Survey (USGS) to investigate the potential of aggradation downstream of the landslide, thus identifying potential increases in flood risk as the sediment wave evolves. The assessment in this report was completed largely using data and analysis completed in summer of 2014.

Purpose and Scope

This report represents a preliminary assessment of aggradation potential in the river reach downstream of the landslide using datasets and models available during summer of 2014, before the 2014–15 flood season. This report is neither a comprehensive analysis of sediment transport in the North Fork Stillaguamish River nor is it intended to precisely estimate the depth of aggradation. Instead, this report identifies river reaches prone to aggradation and offers preliminary analysis to estimate a range of expected aggradation depths. With more data and analysis, the models and approaches discussed herein may be updated, improved, and finalized in future reports.

Description of Study Area

The North Fork Stillaguamish River drains 736 km^2 of the Cascade Range of western Washington and joins the South Fork Stillaguamish River near Arlington becoming the Stillaguamish River, which flows into Port Susan Bay in Puget Sound near Stanwood (Collings and Hill, 1973; Embrey, 1987; Beechie and others, 2001) (fig. 1). Compared to other rivers in the greater Puget Sound watershed (Konrad, 2015), the North Fork Stillaguamish River drains a lower elevation catchment with maximum basin elevation of 2,078 m (6,820 ft) and a mean basin elevation of 625 m (2,050 ft) (U.S. Geological Survey, 2014).

The North Fork Stillaguamish River flows down an alluvial-controlled corridor comprised of late Pleistocene and Holocene sediment with few bedrock outcrops (Dragovich and others, 2003). Active geologic processes, including landslides from adjacent bluffs (Haugerud, 2014), lahars, and eruptive deposits from Glacier Peak (Beechie and others, 2001; Dragovich and others, 2003) and major drainage realignments (Beechie and others, 2001), presumably increase the lateral instability of the river channel through geologic time frames. This lateral instability may have been reduced from anthropogenic revetments and development; the river channel is now predominantly single threaded. Ubiquitous point, lateral, and mid-channel bars act as sources and sinks of likely active bedload of gravels and cobbles transported during peak-flow events. Boulders deposited in many bars throughout the river corridor indicate that, for large floods, the river has the competence to transport sizeable clasts. Sand is prevalent throughout the bar substrate indicating a relatively ample supply of background sediment. At modest flows, non-cohesive sand-sized sediment is likely the dominant sediment class in bedload transport.

Flooding on the river is caused by heavy winter rainfall associated with atmospheric rivers (Neiman and others, 2011), and Henn and others (2015) determined that the 21–45-day period preceding the landslide had anomalously high precipitation with return periods that ranged from 2 to 88 years, depending on the analytical approach. Streamflow gaging on the North Fork Stillaguamish River near Arlington (USGS streamgage 12167000) began in 1928. Sumioka and others (1998) reported 0.5 (2-year), 0.04 (25-year), and 0.01 (100-year) exceedance probabilities of annual peak flows (annual exceedance probability; AEP) during water years 1929–96 to be 646 m^3/s (22,800 ft^3/s), 1,020 m^3/s (35,900 ft^3/s), and 1,140 m^3/s (40,300 ft^3/s), respectively. However, the five largest peak-flow events during the period of record occurred after 2002. Using all 85 systematic annual peak flows from 1929 to 2013, a Log Pearson Type III analysis (U.S. Interagency Advisory Committee on Water Data, 1982) that used a multiple Grubbs-Beck low outlier test, a weighted station and regional skew value, and a final estimate weighted with the regional regression estimate (Sumioka and others, 1998) yields updated estimates of the 0.5 , 0.04, and 0.01 AEP events to be 678 m^3/s (24,000 ft^3/s), 1,160 m^3/s (41,100 ft^3/s), and 1,350 m^3/s (47,700 ft^3/s), respectively.

A river centerline convention was established based on the 2013 channel location: river kilometer (RKM) 0.0 was positioned at the confluence of the North and South Forks Stillaguamish River near Arlington. The landslide affected a section of the river from RKMs 34.1 to 32.7. Just after the landslide, the USGS installed streamgages at Whitman Road Bridge at RKM 29.2 (12166300, North Fork Stillaguamish River near Oso) and upstream of the landslide at RKM 36.2 (12166150, North Fork Stillaguamish River near Swede Heaven) (table 1; fig. 2). A stage-only gage was installed at RKM 34.8 on C-Post Bridge (12166185, North Fork Stillaguamish River at C-Post Bridge near Oso). From March 28 to May 31, three floating buoys provided stage-only data from the impoundment lake (12166190, North Fork Stillaguamish River Northeast Pooled Slide Area near Oso; 12166200, North Fork Stillaguamish River East Pooled Slide Area near Oso; 12166220, North Fork Stillaguamish River Southwest Pooled Slide Area near Oso). Another stage-only streamgage was later installed at RKM 32.3 just downstream of the landslide (12166240, North Fork Stillaguamish River at Rowan). The main stem streamgage (12167000, North Fork Stillaguamish River near Arlington) is located at RKM 11.1. Deer Creek, the largest tributary to the North Fork Stillaguamish River, enters at Oso, at RKM 23.9.

As of summer 2014, the river flowed through a 1-km long section of landslide deposit composed of 10–20-m tall hummocky terrain sourced from the bluff bounding the northern extent of the flood plain and consisting of re-deposited Pleistocene glacial till, glacial outwash, and lacustrine units (Dragovich and others, 2003). Of seven auger samples of the landslide deposit, four samples were finer than 2 mm and three samples were predominantly fine grained with all samples containing at least 85 percent finer than 2 mm (Keaton and others, 2014). We presumed this sand-sized sediment of the landslide deposit was the dominant size class in bedload transport during high flows as the incision channel deepened and widened. The river also flows past a larger landslide deposit 2 km downstream of the SR 530 Landslide with similar hummocky terrain informally known as the Rowan landslide (Dragovich and others, 2003; Iverson and others, 2015). The age of the Rowan landslide is unknown, but it likely predates European settlement of the valley.

Table 1. Discharge or stage-only streamgages installed by the U.S. Geological Survey along the North Fork Stillaguamish River, Washington.

[**Abbreviation:** km^2, square kilometer]

Streamgage No.	Streamgage name	River kilometer	Drainage area (km^2)	Provisional data used
12166150	North Fork Stillaguamish River near Swede Heaven	36.2	344	Stage, discharge
12166185	North Fork Stillaguamish River at C-Post Bridge near Oso	34.8	373	Stage only
12166190	North Fork Stillaguamish River Northeast Pooled Slide Area near Oso	34.4	394	Stage only
12166200	North Fork Stillaguamish River East Pooled Slide Area near Oso	34.4	394	Stage only
12166220	North Fork Stillaguamish River Southwest Pooled Slide Area near Oso	34.4	394	Stage only
12166240	North Fork Stillaguamish River at Rowan	32.3	398	Stage only
12166300	North Fork Stillaguamish River near Oso	29.2	416	Stage, discharge
12167000	North Fork Stillaguamish River near Arlington	11.1	679	Stage, discharge

Methods to Determine Aggradation Potential

The general methodological framework of this study was built around four primary tasks: (1) calculating the volume of sediment eroded from the landslide through the summer of 2014 and anticipated erosion volumes during the 2014–15 flood season, (2) analyzing longitudinal diversion in unit stream power downstream of the landslide to indicate reaches with a propensity to aggrade or incise, (3) analyzing bed-material-transport capacity of the river during high flows to identify downstream reaches prone to aggradation, and (4) assessing downstream aggradation potential in the context of sediment waves.

High-resolution digital elevation models (DEMs), aerial imagery, and one-dimensional hydraulic modeling (Hydrologic Engineering Center River Analysis System; HEC-RAS) were used with stream-power and transport-capacity theory to identify reaches of the North Fork Stillaguamish River downstream of the SR 530 Landslide prone to aggradation in the 2014–15 flood season. Increased discharge with winter rains was expected to widen and incise the river channel into the landslide deposit mobilizing sediment. Some of this sediment was likely retained in the downstream channel, causing some degree of aggradation.

Hydrologic conditions were analyzed using provisional discharge and stage data from the USGS streamgages. The impoundment water volume was calculated from the deficit discharge measured at the downstream streamgage and confirmed with hypsometric analysis of DEMs. Aerial imagery and DEMs also were used to determine extent of the impoundment. The evolution of the water-surface elevation of the impoundment lake was determined after March 28 using the four USGS stage-only streamgages installed in the impoundment lake and stage data from the streamgages to de-trend fluctuations of the hydrograph. Manual survey measurements of the impoundment-lake elevation were made by Snohomish County, March 24–27 (D. Lucas, Snohomish County, written commun., 2014).

Calculating Erosion Volumes

The volume of sediment eroded from the landslide by the river was calculated using DEM data, bathymetric data, and aerial imagery for two periods: March 24–April 6 and April 6–July 1, 2014 (table 2). The Puget Sound Lidar Consortium acquired high-resolution light and detection ranging (lidar) data of the North Fork Stillaguamish River valley from April to July 2013. After the landslide, the Washington State Department of Transportation (WSDOT) commissioned and processed two lidar overflights of the

Table 2. Lidar and aerial imagery used in the assessment of aggradation potential in the North Fork Stillaguamish River downstream of the State Route 530 Landslide near Oso, Washington.

[**Abbreviations:** Lidar, light detection and ranging; PSLC, Puget Sound Lidar Consortium; WSDOT, Washington State Department of Transportation]

Date	Data format	Source	Horizontal resolution (meters)
04-17-13 to 07-31-13	Lidar	PSLC	1 × 1
03-24-14	Lidar	WSDOT	1 × 1
03-24-14	Aerial imagery	WSDOT	0.3 × 0.3
04-01-14	Aerial imagery	WSDOT	0.08 × 0.08
04-06-14	Lidar	WSDOT	1 × 1
04-14-14	Aerial imagery	WSDOT	0.08 × 0.08
05-01-14	Aerial imagery	WSDOT	0.08 × 0.08
07-01-14	Aerial imagery	WSDOT	0.08 × 0.08

landslide area on March 24 and April 6, 2014. The lidar data from March 24 did not penetrate the surface of the impoundment lake but provided elevation data of the deposit above the level of the impoundment and the river water-surface elevation downstream of the landslide. Bathymetric data were collected in the impoundment lake in early April by Snohomish County and its consultant, David Evans and Associates, Inc. WSDOT and David Evans and Associates, Inc. (J. Dasler, David Evans and Associates, Inc., written commun., 2014), combined the April 6 lidar data with the surveyed bathymetry and available 2013 lidar data to construct a comprehensive DEM of the landslide deposit as of April 6. WSDOT also acquired high-resolution aerial imagery on July 1, 2014, showing the progress of river incision and widening. Aerial imagery from April 1, April 14, and May 1, 2014, also was used for geomorphic interpretation of the river corridor near the landslide (table 2).

Sediment volume eroded from the landslide deposit between March 24 and April 6 was determined by comparing DEM-generated cross sections for those dates spaced at 50-m segments along the July 1 river centerline. For the March 24 DEM, the westernmost cross sections were unaffected by the impoundment, allowing direct comparison with the April 6 DEM to calculate volume change. The easternmost March 24 cross sections were in an area free of river incision before April 6. For cross sections in the middle of the deposit, where incision occurred before April 6 and where the presence of the impoundment lake precluded precise determination of the submerged topography, the terrestrial surface was estimated using exposed hummocks adjacent to the future river channel and intermediate aerial imagery collected by WSDOT on April 1.

To calculate sediment volume eroded from April 6 to July 1, the same cross sections were analyzed, assuming the river incised a prismatic trapezoidal shape from the landslide deposit with linear side slopes and wetted bottom width and exposed top widths determined with the high-resolution July 1 imagery. The water-surface elevation of the bottom of the trapezoid was determined using survey data of river elevation collected by Snohomish County on August 6 (K. Hanson, Snohomish County, written commun., 2014). Turbidity data collected downstream indicated negligible incision occurred between July 1 and August 6. Based on a reasonable range of potential future side slopes, an anticipated degree of channel migration and adjustment, and geomorphic judgment, we estimated the uncertainty of the sediment volume change calculations reported here to be about 20 percent.

To assess the potential downstream aggradation in the 2014–15 flood season, we estimated the sediment volume likely to be eroded from the landslide under a future equilibrium condition. This estimate entailed assuming (1) the river channel will remain in its summer 2014 alignment, (2) the width of the river will approach the mean width of the river where it flows adjacent to the Rowan landslide 2-km downstream, (3) the side slopes will retreat to 34 degrees, an angle of repose typical of loose, unconsolidated colluvium (Allen, 2001), and (4) the water-surface elevation of the river will approach the pre-slide river profile. This postulated future condition was compared to the river morphology on July 1 to estimate the volume of sediment expected to mobilize in the 2014–15 flood season.

Calculating Unit Stream Power

Unit stream power in watts per square meter, ω, was calculated along the North Fork Stillaguamish River using the equation (Bagnold, 1966):

$$\omega = \frac{\rho g Q S}{w} , \tag{1}$$

where

- ρ is the density of water, assumed to be 1,000 kg/m^3;
- g is the gravity constant, taken to be 9.81 m/s^2 ;
- Q is the discharge, taken here to be the discharge of the 0.5 AEP peak-flow event;
- S is the energy slope; and
- w is the active, unvegetated channel width.

The 0.5 AEP peak flow was calculated at the USGS streamgage near Arlington (12167000). This 0.5 AEP peak flow was hydrologically scaled to the full river corridor (accounting for changes in flow resulting from tributaries entering along the 55-km long study reach) using the relative variability of mean annual discharge from the National Hydrologic Dataset (NHD) linked to the NHDPlus dataset, a hydrologically conditioned DEM with 30-m resolution (U.S. Environmental Protection Agency, 2008). Energy slope of the river long profile for the 0.5 AEP discharge was determined using Hydrologic Engineering Center's River Analysis System (HEC-RAS) Version 4.1 (U.S. Army Corps of Engineers, 2010a, 2010b, 2010c) one-dimensional, steady-state, step-backwater model constructed for 56 km of the North Fork Stillaguamish River by the Federal Emergency Management Agency and the U.S. Army Corps of Engineers (T. Perkins, Federal Emergency Management Agency, and T. Ball, U.S. Army Corps of Engineers, written commun., 2014). The HEC-RAS model constructed for the analysis assumed an idealized trapezoidal shape and standard hydraulic depth (updated bathymetric data were unavailable), contained cursory bridge geometry data, was neither calibrated nor validated, and was never intended to provide precise estimates of water-surface elevation. Instead, the model was used as an analytical tool to estimate relative values of energy grade and hydraulic influence in the river corridor in order to estimate stream power and transport capacity at a coarse resolution. Using the energy elevation predicted at HEC-RAS cross sections, energy slope was calculated using a weighted mean at 500-m river segments. The average active-channel width for each 500-m segment was determined by digitizing the unvegetated portion of the river channel (Wallick and others, 2011) using imagery from the 2011 National Agriculture Imagery Program (U.S. Department of Agriculture, 2011).

Calculating Bed-Material Transport Capacity

Bed-material transport capacity was calculated with the aid of the U.S. Forest Service Bedload Assessment of Gravelbed Rivers (BAGS) macro-enabled spreadsheet (Pitlick and others, 2009; Wilcock and others, 2009) in a manner similar to that of Wallick and others (2010, 2011). BAGS required several inputs for this preliminary analysis, including bed-material size distribution, cross-section geometry, discharge, and energy slope (from hydraulic modeling). Field measurements of bed-material size and cross-section geometry, discharge, and energy slope from the HEC-RAS model were applied to the bed-material transport equations of Parker (1990a, 1990b) and Wilcock and Crowe (2003) using BAGS software. These two sediment-transport equations are good for gravel-bedded rivers with ample sand supply as observed in the North Fork Stillaguamish River and have been successfully used in gravel-bedded rivers in Oregon (Wallick and others, 2010, 2011). For this study, transport capacity was assumed to be a suitable proxy for actual bed-material transport because the assumption of unlimited sediment supply (Pitlick and others, 2009) was likely valid in the 2014–15 flood season.

For the BAGS calculations, we primarily used grain-size information collected at five locations along the North Fork Stillaguamish River in 2014 (table 3) using a modified Wolman (1954) pebble count method. Additional grain-size data collected between 2005 and 2009 (J. Brown, Stillaguamish Tribe of Indians, written commun., 2014) were used, where needed, to supplement data collected in July 2014. Another set of pebble-count data were collected from the landslide deposit in the hummocky terrain adjacent the river to determine the size of sediment prone to mobilization in the 2014–15 flood season. Although we observed occasional cobble- and boulder-sized particles spaced throughout the landslide deposit, the material adjacent the river channel subject to future erosion was predominantly sand sized and smaller. Three Wolman pebble counts performed on the hummocky terrain just south of the river channel on May 15, 2014, indicated that 67 percent of the surficial deposits were 2 mm or finer (table 3).

Bed-material transport was calculated for three flow scenarios—the 0.5 AEP peak flow, one-half the 0.5 AEP peak flow, and one-quarter 0.5 AEP peak flow. As noted in section, "Calculating Unit Stream Power," peak-flow values were scaled along the length of the river corridor using mean-annual flow from the NHDPlus dataset. For each of the flow scenarios, we calculated the corresponding hydraulic conditions with the HEC-RAS model, assuming steady-state and subcritical flow. Hydraulic results for each of the three discharge scenarios became the input for the BAGS calculations, which were taken from just downstream of the landslide at RKMs 32.7–16.2.

Table 3. Summary of grain-size distributions used to simulate bed-material transport along the North Fork Stillaguamish River, Washington.

[**Percent finer than:** Categories are in millimeters]

Grain-size distribution identifier	River kilometer	Descripiton	Date	Source	Percent finer than								
					2.0	4.0	8.0	16.0	32	64	128	256	512
USGS1	35.0–34.7	Composite of three pebble counts collected near C-Post Road Bridge	2014	U.S. Geological Survey	39	40	40	46	66	89	100	100	100
USGS_LSD	33.2	Composite of three pebble counts from top of hummocky terrain of landslide deposit just south of river channel	05-15-14	U.S. Geological Survey	67	3	2	3	3	0	0	0	0
RP9	32.7	Composite of two pebble counts	2005, 2006	Stillaguamish Tribe of Indians	0	14	20	36	56	74	87	97.5	100
RP8	32.4	Composite of two pebble counts	2005, 2006	Stillaguamish Tribe of Indians	0	36	44	56	69	81	92	95	100
RP7	31.9	Composite of two pebble counts	2005, 2009	Stillaguamish Tribe of Indians	0	23	26	36	46	59	78	93	100
RP4/5	30.4	Composite of three pebble counts	2005, 2005, 2008	Stillaguamish Tribe of Indians	0	15	19	24	38	54	76	87	100
RP2	29.7	One pebble count	2005	Stillaguamish Tribe of Indians	0	39	43	50	63	80	92	96	100
USGS2	29.3–29.1	Composite of three pebble counts collected near Whitman Road Bridge	2014	U.S. Geological Survey	15	22	27	37	51	77	94	99	99
USGS3	26.5	One pebble count collected near the upstream SR530 Bridge	2014	U.S. Geological Survey	25	25	26	32	49	69	98	100	100
USGS4	24.3	One pebble count collected near 221st Avenue bridge	2014	U.S. Geological Survey	1	1	2	17	59	87	100	100	100
USGS5	16.3–16.0	Composite of three pebble counts collected near the downstream SR530 Bridge near Cicero	2014	U.S. Geological Survey	16	21	28	38	63	91	100	100	100

Assessing Aggradation Potential in the Context of Sediment Waves

River reaches where unit stream power or transport capacity transitions from large to small values represent areas with greater relative potential for aggradation. Full sediment-transport analyses are required to fully estimate the depth of anticipated aggradation and are beyond the scope of this study; however, using insight from sediment-wave dynamics on mountainous rivers elsewhere (Lisle, 2008) and by projecting the downstream distribution of anticipated sediment erosion during the coming flood season, estimates of the magnitude of aggradation depth in different reaches is possible.

Relative change in stage at Whitman Road Bridge from March to July 2014 was determined using the shift in the stage-discharge rating as measured by USGS (Rantz, 1982). Although not a direct measurement of aggradation, changes in stage at a streamgage have been used as a proxy for aggradation (Smelser and Schmidt, 1998; Juracek and Fitzpatrick, 2009; Czuba and others, 2010).

To gain insight in sediment-wave behavior, the dimensionless Froude number, *Fr*, for an irregular, low-gradient channel with steady, one-dimensional flow was calculated using discharge measurements made from March to June at the Whitman Road Bridge streamgage and the equation (Henderson, 1966):

$$Fr = \sqrt{\frac{Q^2 B}{g A^3}}\ , \qquad (2)$$

where

- B is the top width of the wetted channel; and
- A is the cross-sectional area of the wetted channel.

Sediment Erosion Volumes

From March 22 to July 1, 2014, discharge values in the North Fork Stillaguamish River were typical for late spring and early summer. As measured near Arlington, discharge ranged from 28.1 m^3/s (994 ft^3/s) to 264 m^3/s (9,340 ft^3/s) through the end of May with three peaks greater than 170 m^3/s (6,000 ft^3/s) (fig. 3).

Before the landslide, the low-flow water-surface elevation at C-Post Bridge (12166185; fig. 1), based on 2013 lidar, was about 83.4 m (273.6 ft). Just after the landslide, the water-surface elevation of the impoundment increased steeply to 89.3 m (293 ft) on March 23 (fig. 3). Aerial imagery and DEM data indicated that the impoundment lake extended about 4 km upstream of the landslide. The volume of water in the impoundment was estimated to be about 3.3×10^6 m^3. By April 1, the impoundment elevation declined to 86.9 m (285 ft). Through the middle of April, the impoundment declined by only about 0.5 m. The completion of the pilot channel in middle April, combined with a series of moderate flow events, promoted erosion of the landslide deposit and lowering of the impoundment lake to about 83.9 m (275.3 ft) by May 1. Continued, but less rapid, incision reduced the lake level to 83.4 m (273.6 ft) by late May, effectively eliminating the impoundment at low discharge (fig. 3).

Measurements of the water-surface elevation of the river through the landslide showed the upstream progression of the erosion knickpoint with time (fig. 4). At the apex of the landslide deposit, the maximum impoundment water depth (that is, the increase in water-surface elevation relative to pre-slide river conditions) was about 8 m (fig. 4). By March 24, the river had topped the landslide deposit and the erosion knickpoint was effectively in the center of the deposit about 1,000 m downstream of C-Post Bridge. The landslide deposit extended to 2,000 m downstream of C-Post Bridge, but landslide sediment eroded by the new river on March 23 and 24 quickly filled the downstream river channel 1–2 m at least as far as 2,500 m downstream of C-Post Bridge. By April 6, the knickpoint moved upstream another 200 m, and the river naturally incised into the deposit as much as 5 m. At the downstream end of the landslide deposit, April 6 net aggradation was still 1–2 m. By August 6, the knickpoint was about 700 m from C-Post Bridge and the river had further incised with an elevation only about 1.5 m higher than the pre-slide water-surface elevation. At the downstream extent of the landslide deposit between 1,500 and 2,000 m downstream of C-Post Bridge, the river was nearly back to its pre-slide elevation indicating the continued evolution of the sediment wave (fig. 4).

From March 24 to April 6 and from April 6 to July 1, 120,000±24,000 m^3 and 160,000±32,000 m^3, respectively, eroded from the landslide deposit. The total sediment eroded from March 24 to July 1 was 280,000±56,000 m^3. Sediment erosion as a consequence of future channel incision and widening to an equilibrated geometry is projected to total 220,000±44,000 m^3. Without additional mass wasting from the landslide scarp or major channel migration or avulsions, the total volume of sediment eroded by the river is expected to be about 500,000±100,000 m^3, or 6 percent of the total slide volume of 8×10^6 m^3.

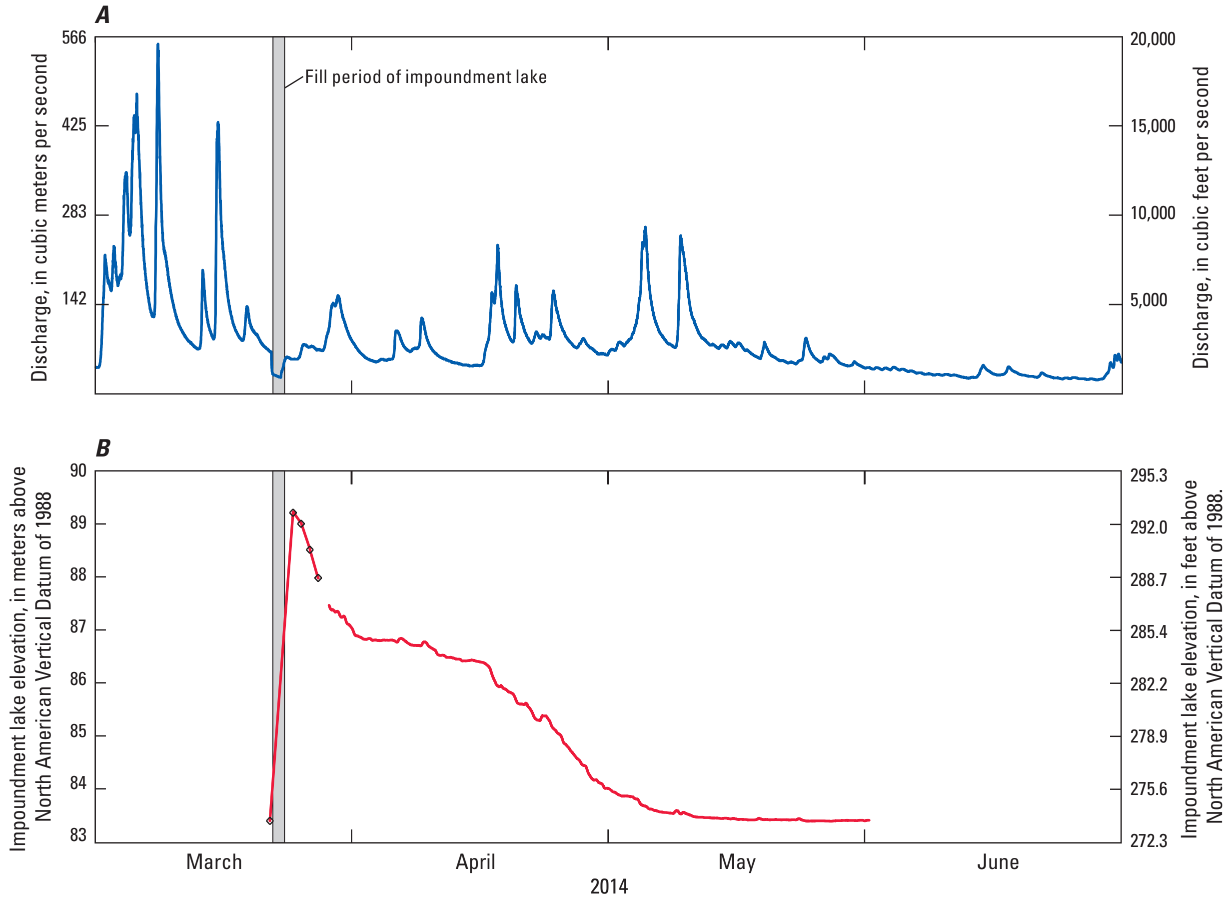


Figure 3. Discharge values plotted at 15-minute intervals for the North Fork Stillaguamish River near Arlington (12167000) (*A*) and impoundment lake elevation (*B*), March 1 to July 1, 2014, near Oso, Washington. Manual survey measurements of the impoundment lake elevation from March 24 to 27 are shown in *B* as data points; the data gap represents the transition from manual measurements to continuous gaging.

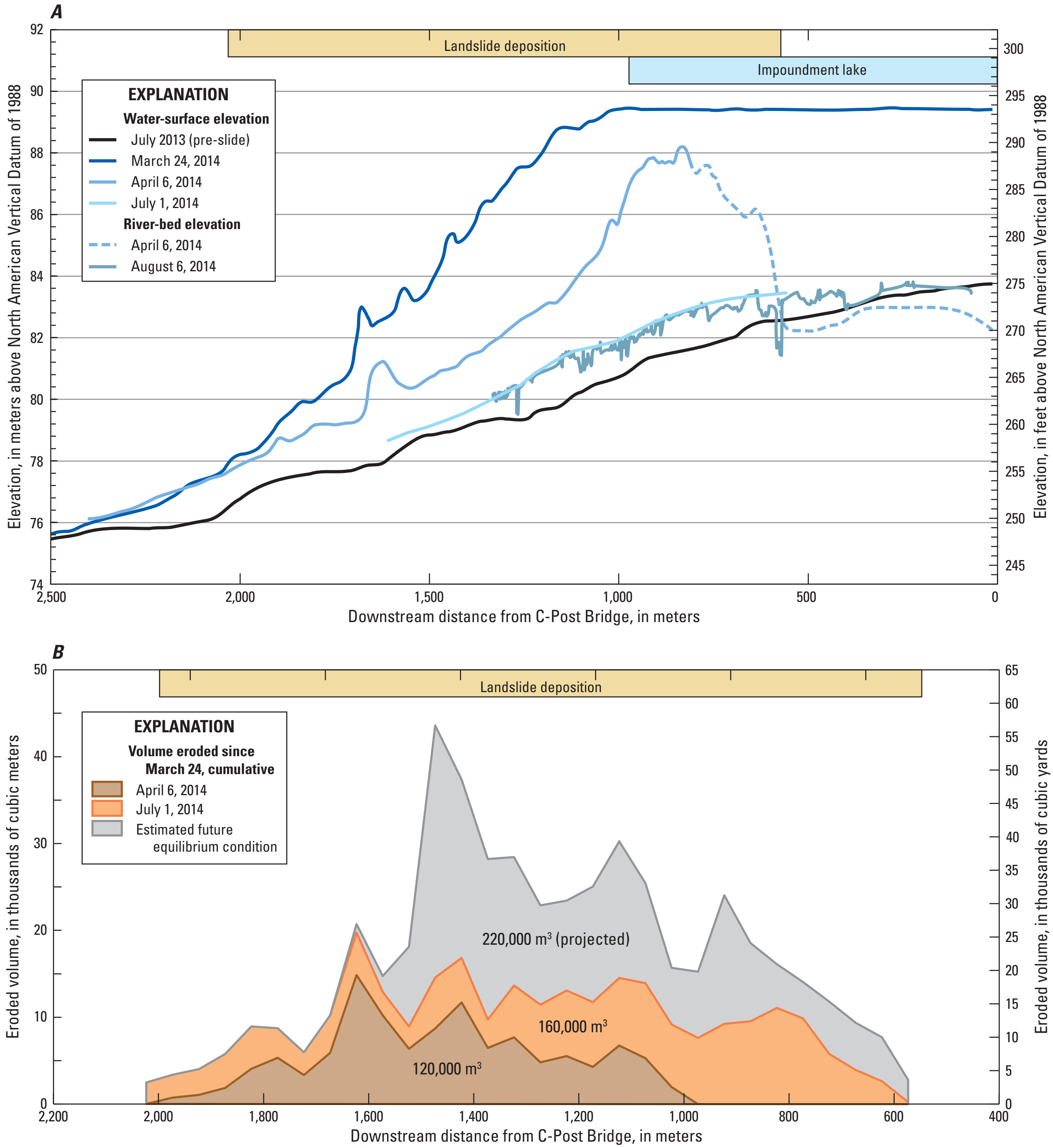


Figure 4. Landslide-deposition and water-surface elevation (*A*) and sediment volume eroded from landslide deposition relative to distance downstream (*B*) of C-Post Bridge, near Oso, Washington. Graph *B* also shows the projected sediment erosion from the deposit under a future equilibrium condition assuming the river channel remains in its July 1 location. Uncertainty of the volume projections in graph *B* is 20 percent.

Downstream Aggradation Potential

The sediment eroded from the landslide—likely totaling about 500,000±100,000 m^3 in the near term—was expected to contribute to downstream channel aggradation. If all of that mobilized sediment remained in lower 40 km of the North Fork Stillaguamish River, the channel would aggrade by an average of 0.25 m, assuming a 50-m wide active channel, but this is an unrealistic overestimate because most sediment will be transported out of the study reach toward Port Susan Bay in Puget Sound and patterns of aggradation will vary temporally and spatially as the sediment moves downstream encountering complex reach-specific hydraulic conditions. Unit stream power and bed-material transport capacity analyses provide spatially explicit estimates of potential aggradation.

Energy Slope and Unit Stream Power

In the lower 40 km of the North Fork Stillaguamish River, pre-slide, active-channel widths varied from 43 to 133 m, with the narrowest river reach adjacent to the Rowan landslide near RKM 31.6 (fig. 5). Sparse pebble-count data indicated that typical median particle size near the SR 530 Landslide ranges from 10 to 50 mm. Post-slide energy slope in the river was relatively constant with values of about 0.002 from RKMs 5 to 20 (fig. 5). Locally, energy slope increased to near 0.004 at the confluence with the South Fork Stillaguamish River and 0.0052 near the SR 530 Bridge east of Oso. At the slide, the energy slope was a maximum value of 0.009, and slope approached 0.0 in the impoundment lake. Before the SR 530 Landslide, unit stream power ranged from 50 to 280 W/m^2, with localized peaks near the Rowan landslide and near the SR 530 Bridge east of Oso due to narrowing of the active channel. Unit stream power also increased downstream of Deer Creek with increasing discharge. After the landslide, unit stream power was affected from RKMs 30 to 39. The peak post-slide unit stream power was 380 W/m^2 at the downstream section of the landslide, and unit stream power in the impoundment lake was near zero (fig. 5).

Bed-Material Transport Capacity

Results of the BAGS-calculated bed-material transport capacity from the Parker (1990a, 1990b) and Wilcock and Crowe (2003) equations showed decreasing capacity in the river reach 2 km downstream of the landslide, with a localized minimum near RKM 30.5 (fig. 6). Transport capacity generally increased from RKM 30.5 downstream to Whitman Road Bridge then decreases toward the SR 530 Bridge east of Oso with localized minimum values near RKMs 28.8 and 26.8. At the SR 530 Bridge east of Oso (RKM 26.4), trends in transport capacity are complex with a localized maximum at the bridge. The SR 530 Bridge east of Oso is co-located with an early 20th-century railroad bridge (now named the Whitehorse Trail) constructed with relatively narrow bridge abutments that constrict the river and likely cause the transport-capacity localized maximum. The transport-capacity data indicate the bridge will not be a location with pronounced aggradation. Between the SR 530 Bridge and Deer Creek, there are localized transport-capacity minima. The Parker (1990a, 1990b) equation indicates a minimum near RKM 26 and the Wilcock and Crowe (2003) equation indicates a minimum near RKM 24.3. Transport capacity increased at the Deer Creek confluence because of increased discharge. The analysis indicated a general decreasing transport-capacity trend downstream of Deer Creek to about RKM 16 (fig. 6). The localized transport-capacity minima likely reflected natural decreases in slope or increased active-channel width in particular reaches; however, anthropogenic influences, particularly the early 20th-century railroad bridge with its relatively narrow abutments, also affect transport-capacity values locally.

Notably, simulated transport rates reflected the river capacity to move bed material at a coarse resolution; actual transport rates will vary with available sediment supply and geomorphic response. Estimates of bed-material-transport rates of the analytical approach used in this study are notoriously approximate (Pitlick and others, 2009; Wallick and others, 2010, 2011) due to complexities in the sediment-transport process and river mechanics. Modeled transport capacities also vary with transport equation used, input flow, grain-size, and energy slope data. The hydraulic model was constructed as a cursory tool that provided a first-order estimate of sediment-transport potential, and datasets used to build the model were incomplete. The simulated transport rates, therefore, represented first-order approximations of how the system might respond and were not intended to represent precise prediction of river-system behavior. Transport-rate predictions would improve with more grain-size data, improved energy slope estimates, and a refined hydraulic model.

Zones of Potential Aggradation

Longitudinal differences in unit stream power and transport capacity along the river corridor can indicate areas prone to aggradation. With continued river erosion of the landslide deposit, increased bedload would presumably be in transport with the potential for localized aggradation in reaches with decreasing unit stream power or transport capacity.

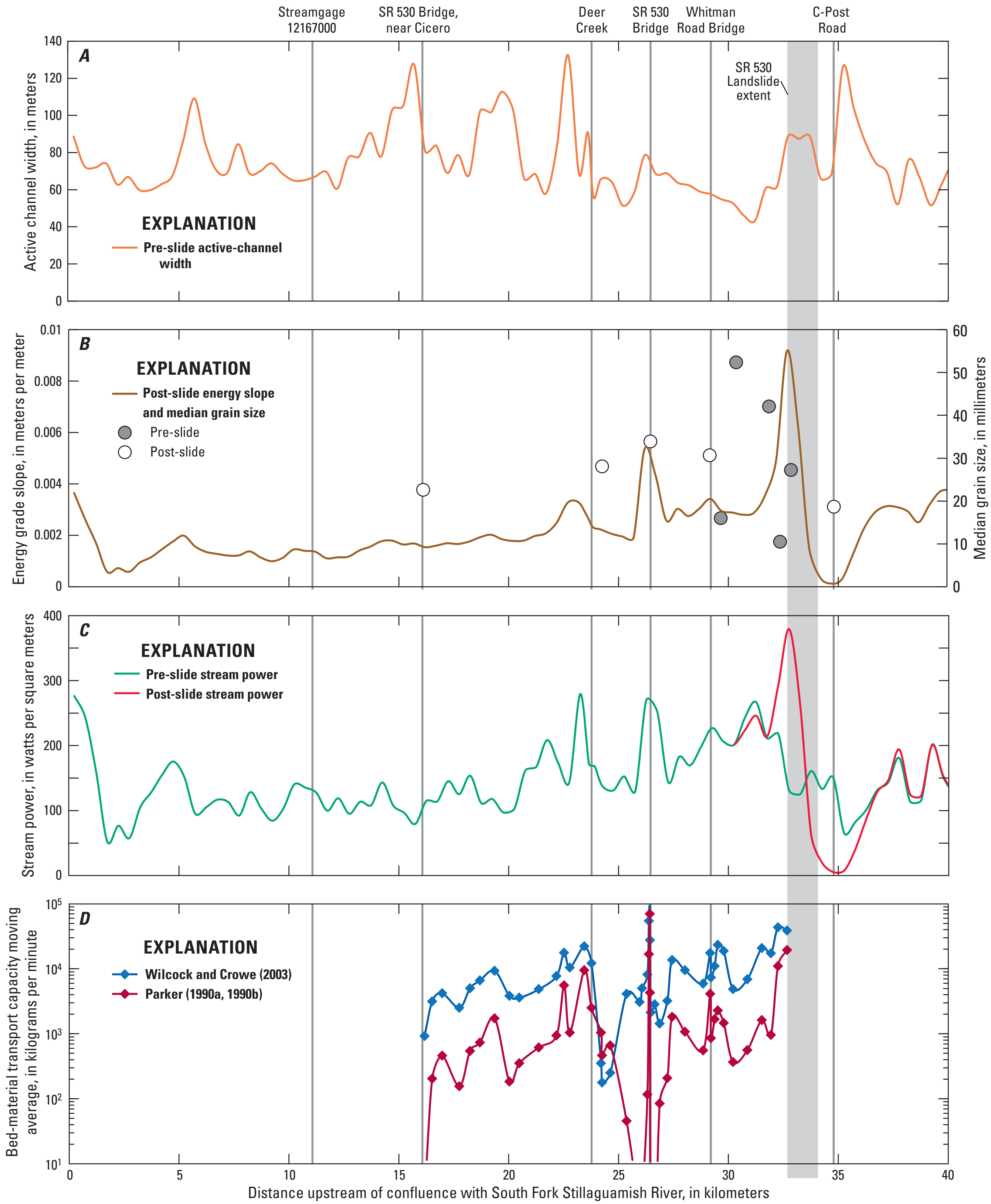


Figure 5. (*A*) Pre-slide active channel width, (*B*) post-slide energy grade slope and median grain size, (*C*) pre- and post-slide unit stream power, and (*D*) bed-material transport capacity for the 0.5 annual exceedance probability peak-flow event for the North Fork Stillaguamish River, Washington.

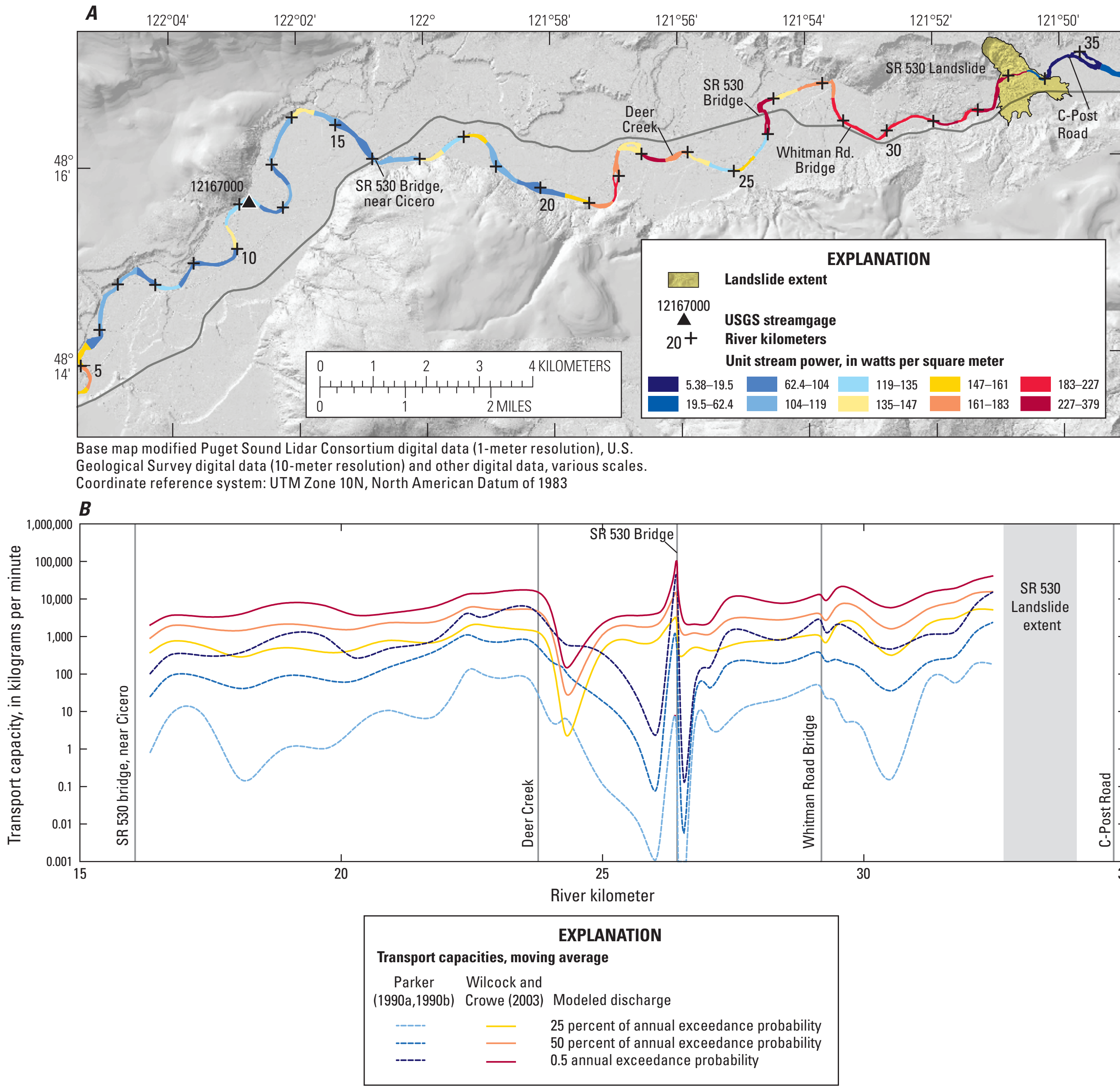


Figure 6. North Fork Stillaguamish River showing unit stream power by 500-meter reach intervals downstream of the State Route 530 Landslide (*A*) and bed-material transport capacity from RKM 16 to RKM 33 (*B*).

Just downstream of the landslide, in the reach from RKM 32.5 downstream to 27.3, unit stream power decreased from 380 to 140 W/m^2, thus indicating the potential for aggradation (fig. 5). Analysis of transport capacity showed decreasing transport capacity downstream to RKM 30.2 then a slight increase until local minima present near RKM 28.2 and 26.2 (fig. 6). Considering analysis of both unit stream power and transport capacity, river reaches from the landslide downstream to RKM 30.2 and near RKM 28.8 and 26.8 were expected to be most likely to experience measurable aggradation. Farther downstream, the river reach between the SR 530 Bridge east of Oso (RKM 26.4) and Deer Creek (RKM 23.9) could have experienced measurable aggradation as this reach showed both decreasing unit stream power and transport capacity. Similarly, river reaches near RKM 20 and RKMs 6–16 could see localized aggradation, although the amount of aggradation in these downstream reaches would likely be small compared to reaches immediately downstream of the landslide.

In sediment-wave studies, pulses of sediment commonly translate, disperse, or exhibit both characteristics (fig. 7). Lisle (2008) suggested that sediment waves both disperse and translate when *Fr* is less than 0.4 and the sediment wave material is dominated by sand and is finer than the existing bed material. For the landslide, the sediment mobilized from the deposit is predominantly sand. Moreover, *Fr* at the Whitman Road Bridge streamgage, measured on 11 occasions from March 25 to June 24, averaged 0.30 and ranged from 0.18 to 0.44. Thus, the sediment wave would be expected to disperse downstream with some degree of translation. In this instance, we expected the river reach closest to the landslide to experience the most aggradation.

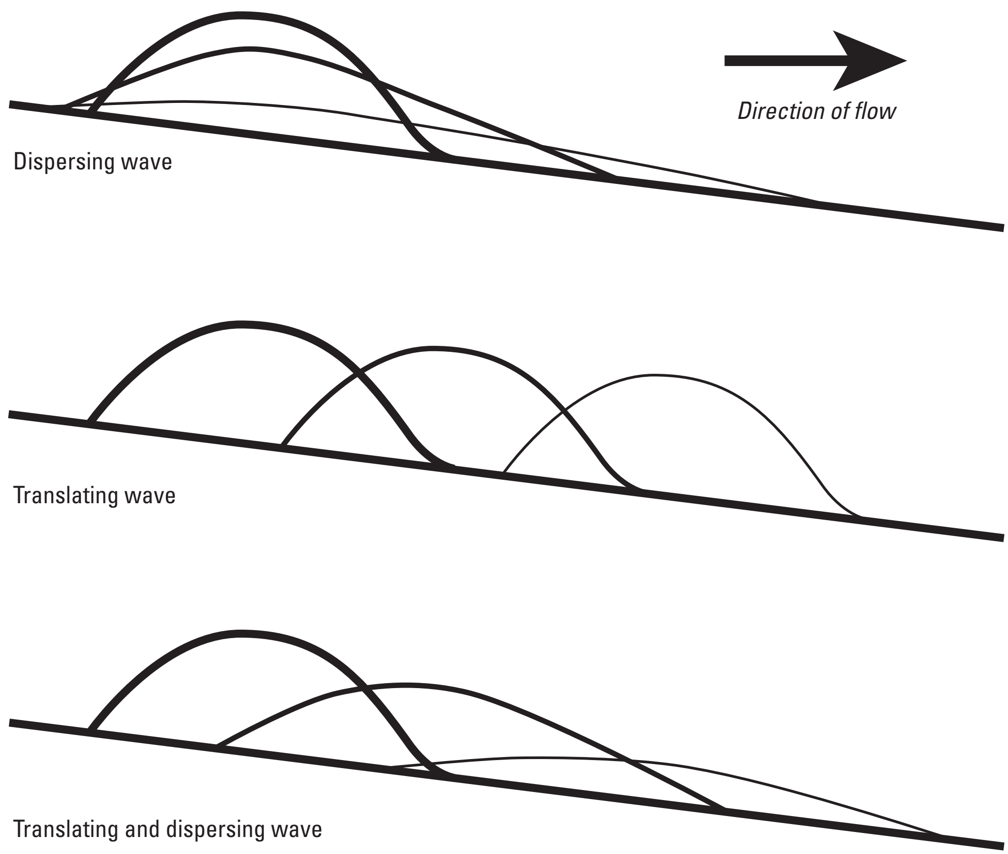


Figure 7. Conceptual model of typical sediment-wave dynamics in mountainous rivers, from Lisle (2008).

Post-slide lidar and aerial photographs help confirm that the sediment wave was primarily dispersive. The lidar DEMs in March and April showed aggradation of 1–2 m at 2,000–2,500 m downstream of C-Post Bridge (fig. 4), this was confirmed with aerial-imagery analysis indicating the burial of a 1–2 m glacial erratic boulder in the river near RKM 32.4. By July 1, the river in this reach had incised back down into the aggraded river bed almost to the pre-slide river elevation. At the Whitman Road Bridge streamgage, analysis of the data indicated that from late March to late April, the stage shift in water-surface elevation for comparable flows increased about +0.4 m (fig. 8). Then, from May to July, the stage shift decreased to about +0.25 m relative to pre-slide river conditions. This river response at the streamgage is consistent with downstream translation and dispersion of a sediment wave, similar to that described by Lisle (2008).

Before July 1, 280,000±56,000 m^3 of sediment was eroded from the landslide and entered the channel, with the most pronounced downstream river response occurring in March and April. As the river continues to widen and incise through the deposit with future high flows, another 220,000±44,000 m^3 of sediment is expected to mobilize. Deposition of this additional sediment as bed material is expected to more strongly affect the water-surface elevation of smaller and intermediate flows (0.1 or 0.2 AEP peak-flow events) as opposed to larger floods (0.01 or 0.02 AEP peak-flow events). Larger events convey flood waters through the flood plain and also would readily mobilize the finer grained material sourced from the landslide into suspension and off the bed, thus mitigating influence of aggradation. In addition, for reaches nearest the landslide, a series of smaller peak-flow events greater than the largest flows seen since the landslide (283 m^3/s or 10,000 ft^3/s) but less than the 0.5 AEP peak-flow event (about 678 m^3/s or 24,000 ft^3/s), would lead to greater aggradation than if a 0.1 or 0.2 AEP event were to occur early in the flood season, which would likely transport mobilized sediment far downstream.

Although it is difficult to predict the depth of downstream aggradation, a worst case scenario was considered whereby all 220,000 m^3 of sediment from the landslide mobilizes in a single event, then immediately deposits in the relatively low transport-capacity reach between RKMs 30.2 and 31.9. Over the 1.7-km long reach, active-channel widths average 50 m. Assuming 20 percent of the mobilized sediment moves as bedload and covers the bed uniformly, the total depth of aggradation would be about 0.5 m. However, such focused aggradation is unlikely; spreading the same volume of eroded sediment over the several kilometers of depositional reaches downstream of the landslide would produce maximum aggradation of less than 0.2 m. Notably, this depth of potential aggradation is less than that documented just downstream of the landslide using the March 24 and April 6 lidar data (fig. 4), indicating that the worst aggradation from the landslide in the first 1.7 km had likely already occurred in the weeks following the event.

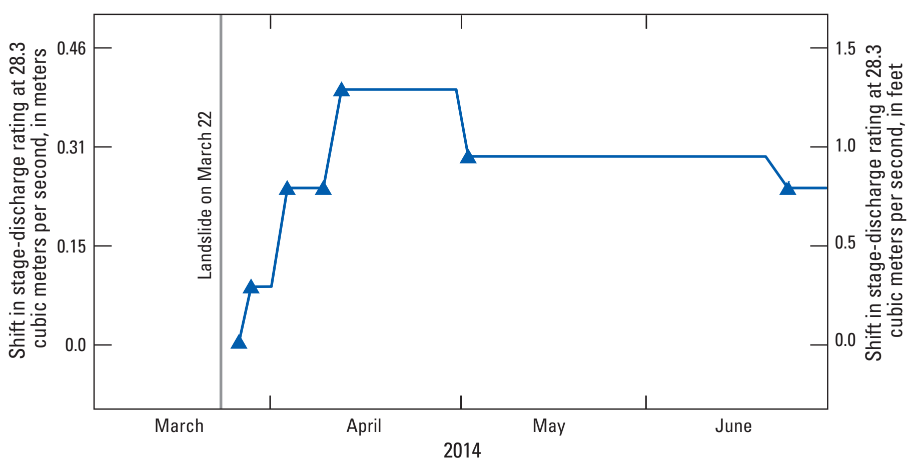


Figure 8. Shifts in stage-discharge rating at the U.S. Geological Survey streamgage North Fork Stillaguamish River near Oso (12166300), Washington, March 28–July 1, 2014.

Additional Flood Risk Issues

The previous analysis assumes the river channel through the landslide does not migrate substantively or avulse to a new location, reflecting a likely anticipated river response in the 2014–15 flood season. However, other river-behavior scenarios were possible. New mass movements from the landslide scarp caused by heavy winter rain saturating the unvegetated hillslope could affect river response. Such mass movements include small-scale slumping of clay-rich lacustrine deposits adjacent to the river, debris flows entering the incised channel causing new impoundments, or large-scale remobilization of the landslide mass, which could increase the volume of sediment transported downstream relative to anticipated 220,000±44,000 m^3.

If large mass movements again dam the river, a new channel could erode through a different section of the landslide deposit mobilizing more sediment and increasing the amount of downstream aggradation; however, rapid dam breaching from a new channel avulsion is unlikely due to the low gradient of the deposit in the flood plain. In contrast, if a debris flow entered the narrow incision channel, an impoundment as deep as 8 m could conceivably reform upstream of the debris-flow deposit. The gradient of the river overtopping a localized debris-flow deposit could be relatively steep, causing rapid erosion and impoundment outburst flood. This sequence of events that could lead to rapid breeching is unlikely, but the hazards associated with this scenario and potential effects to downstream residents are significant.

In addition to sediment, large woody debris transported from the landslide deposit could accumulate on downstream bridges, gravel bars, or boulder-dominated riffles causing localized increases in water-surface elevation during high flows or redirecting the momentum of the flowing river into revetments or low areas of the flood plain. Most of the landslide-derived large woody debris prone to downstream movement was likely transported out of the reach during spring flows, but large peak events in the winter will likely mobilize additional wood.

Our analysis assumed much of the sediment-wave behavior would be dispersive, affecting river reaches close to the landslide more than downstream reaches. There is a possibility, however that sand load will travel several kilometers and accumulate in sandy reaches. In the North Fork Stillaguamish River, the reaches near RKMs 2–3 and RKMs 6–9 may accumulate sand in detectable quantities. Although beyond the scope of this study, the main stem Stillaguamish River near Stanwood contains sand-dominant reaches that also could be prone to new sand accumulation sourced from the landslide.

Conclusions

On March 22, 2014, the State Route 530 Landslide near Oso, Washington, caused 43 fatalities and released a major pulse of sand-dominated sediment into the North Fork Stillaguamish River. This sediment was expected to affect channel geomorphology and potentially increase flood risk in the 2014–15 flood season. Using a combination of aerial imagery, high-resolution digital elevation models, hydraulic models; and principles of sediment-wave behavior, stream power, and bed-material transport theory, we completed a preliminary assessment of aggradation potential in the river channel downstream of the landslide in summer of 2014.

From March 24 to April 6 and from April 6 to July 1, an estimated 120,000±24,000 cubic meters (m^3) and 160,000±32,000 m^3 of sediment, respectively, eroded from the landslide deposit. The cumulative sediment eroded from March 24 to July 1 was 280,000±56,000 m^3. Assuming the river remains in its current location, incises down to an elevation similar to the pre-slide elevation, and widens to about 43 meters (m) (the width of the active channel downstream adjacent the larger Rowan landslide deposit), another 220,000±44,000 m^3 of sediment was expected to mobilize during the 2014–15 flood season. If the river remains in its current location through the landslide deposit, the total volume of sediment eroded by the river is expected to be about 500,000±100,000 m^3, or 6 percent of the total slide volume of 8×10^6 m^3.

In the weeks following the landslide, 1–2 m of new sedimentation was documented just downstream of the landslide and 0.4 m of aggradation was documented at the Whitman Road Bridge, 3.5 kilometers (km) downstream of the landslide. By July 1, incision in the reach just downstream of the landslide brought the river water surface back to nearly its pre-slide elevation.

Analysis of unit stream power and bed-material transport capacity indicated that in the 2014–15 flood season, the river reach 1.7 km downstream of the landslide would see the most additional aggradation, with other reaches near river kilometers (RKM) 28.8, 26.8, and RKM 26.4–23.9 also being prone to aggradation. The depth of accumulation was expected to be less than 0.1 m, although the reach just downstream of the landslide could have as much as 0.5 m of aggradation, a depth less than the aggradation documented in the weeks immediately following the event.

In this study, we focused on the most likely river scenarios in the 2014–15 flood season, but geomorphic and hydraulic conditions could create alternative, albeit less likely, scenarios of river response. Sand mobilized by the landslide could translate far downstream as a sediment wave accumulating in deposits that could affect flood-conveyance capacity. Reaches of the North Fork Stillaguamish River near RKMs 2–3 and 6–9 could see detectable sand accumulation, and reaches in the main stem Stillaguamish River near Stanwood also could experience localized sand accumulation. New mass wasting from the landslide scarp could increase the volume of sediment anticipated to mobilize. Less likely, but potentially more hazardous, a new mass movement at the landslide could partially or completely block the new river channel through the landslide deposit, reforming the impoundment lake with the possibility of rapid breaching and release of an outburst flood downstream.

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