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EVOLUTION AND TIMING OF SUSPENDED-SEDIMENT TRANSPORT FOLLOWING THE 1980 MOUNT ST. HELENS ERUPTION

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Abstract: Continuous monitoring of streamflow and suspended-sediment discharges from disturbed basins following the catastrophic 1980 eruption of Mount St. Helens reveals when, and under what conditions, sediment redistribution occurs following a major landscape disturbance. The redistributed sediment includes material deposited by the eruption as well as centuries-old sediment that has been remobilized from storage. Suspended-sediment yields, as much as 10^4 Mg/km^2/yr shortly after the eruption, declined nonlinearly in all basins for more than a decade. Yet, after 20 years, suspended-sediment yields from some basins remain 10-100 times greater than typical background values. Suspended sediment is transported dominantly by stormflows; more than 50% of the suspended–sediment load is transported in 1 to 4 weeks each year. Very large floods ($p<0.01$) have transported as much as 50% of the annual suspended-sediment load in a single day from some basins. Although large stormflows can transport quantitatively significant volumes of sediment, the majority of the annual suspended-sediment load is transported by common stormflows. On average, about half of the annual suspended-sediment load is transported by stormflows that have return intervals of less than 1.5 years. Discharges smaller than mean annual flow transport #10% of the annual suspended-sediment load. Two decades of monitoring suspended-sediment discharges and channel geometry changes in the aftermath of the catastrophic Mount St. Helens eruption demonstrate the long-term instability of eruption-generated detritus and show that geomorphically significant evolution of disturbed watersheds generally proceeds under commonplace hydrologic conditions.

INTRODUCTION

Explosive volcanic eruptions can severely disrupt water and sediment fluxes in watersheds. Geomorphic and hydrologic responses to disturbances caused by explosive volcanic eruptions commonly are rapid and dramatic, and as a result posteruption sediment yields can greatly exceed preeruption yields (Major et al., 2000). Disruptions of watershed hydrology and geomorphology by volcanic eruptions are particularly significant because subsequent prolonged sediment transport can cause environmental, social, and economic damages that equal or exceed those caused directly by an eruption (e.g., Mercado et al., 1996). Despite the significance of sediment redistribution following explosive eruptions (or other substantial landscape disturbances) there is a dearth of global long-term data to adequately address such fundamental questions as: (1) How does sediment yield evolve following major landscape disturbance? (2) How long does excess sediment yield persist above background level? (3) Does sediment yield evolve monotonically with time, or is there significant temporal variation? (4) Does volcanogenic disturbance process greatly influence consequent sediment yield? (5) What is the influence of hydrology on geomorphic evolution of a disturbed landscape? (6) When, and under what conditions, is sediment typically redistributed? In this paper, I present a summary perspective of nearly 20 years of suspended-sediment yield in the aftermath of the 1980 Mount St. Helens eruption, and examine the timing and hydrologic conditions of sediment transport. I focus on suspended sediment because bedload data are limited and suspended sediment averaged ≥ 80% of the total sediment discharge (Lehre et al., 1983; Simon, 1999).

VOLCANOGENIC LANDSCAPE DISTURBANCE

The catastrophic 1980 eruption of Mount St. Helens affected some watersheds severely, others mildly (Lipman and Mullineaux, 1981). Watersheds proximally north of the volcano underwent the most severe disturbance (Fig. 1). A large debris avalanche deposited 2.5 km^3 of debris in the upper North Fork Toutle River valley (Glicken, 1998), and a consequent directed blast ravaged 600 km^2 of rugged terrain and blanketed the landscape with up to 1 m of gravelly to silty sand tephra (Hoblitt et al., 1981; Waitt, 1981). The avalanche deposit buried 60 km^2 of valley to a mean depth of 45 m and severed surface drainage between the upper and lower North Fork Toutle River watershed (Lehre et al., 1983; Janda et al., 1984). Local liquefaction of that deposit spawned the North Fork Toutle River lahar (Janda et al., 1981; Fairchild, 1987). Fallout from the eruption column blanketed proximal areas east-northeast of the volcano with silty-sand and gravel tephra to tens of centimeters (Waitt and Dzurisin, 1981). On the volcano=s western, southern, and eastern flanks, pyroclastic currents triggered lahars that flowed many tens of kilometers, but deposited only tens of centimeters to a few meters of coarse, gravelly sand on valley floors and floodplains (Janda et al., 1981; Pierson, 1985; Major and Voight, 1986; Fairchild, 1987; Scott, 1988). The eruption and its aftermath are particularly well suited for an analysis of the issues outlined above because: (1) the eruption was a single event composed of a mosaic of volcanogenic processes; (2) sediment was distributed broadly and abruptly across the landscape; (3) water and sediment fluxes have been systematically monitored for nearly two decades, and (4) there has been an increase in precipitation and runoff in the past several years in response to a possible climatic shift (e.g., Mantua et al., 1997).

SEDIMENT YIELD

After the eruption, streamgaging stations were established to monitor discharges of water and suspended sediment from basins affected by the blast current, debris avalanche, and lahars (Dinehart, 1998). Annual suspended-sediment yields, monitored at five stations along the larger rivers draining Mount St. Helens (Fig. 1), were as much as 500 times greater than probable background level, and generally declined nonlinearly for more than a decade (Fig. 2; Major et al., 2000). Long-term monitoring of suspended sediment demonstrates that magnitudes of erosion and sediment release are greatly influenced by volcanogenic disturbance process and streamflows, and that yields do not decline smoothly with time but are punctuated by excursions (Fig. 2).

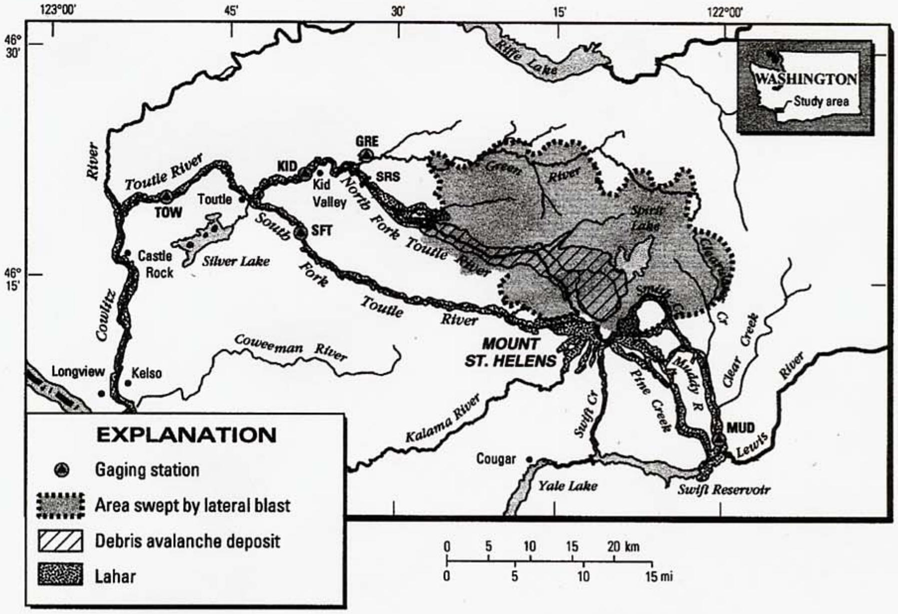

Figure 1. Effects of Mount St. Helens 1980 eruption and location of streamgaging stations. TOW, KID, SFT, MUD, GRE are gaging stations. SRS, sediment retention structure. (After Major et al., 2000).

Basin-Specific Transport: From 1980 to 1999, the Toutle River transported more than 300 x 10^6 Mg (1 Mg = 1 metric ton) of suspended sediment past TOW gage (Fig. 1). Nearly half of that sediment was transported by syneruptive lahars (Dinehart, 1998; Major et al., 2000). Erosion associated with drainage development across the avalanche deposit (Lehre et al., 1983; Janda et al., 1984) as well as bank erosion along the North Fork Toutle River downstream of the avalanche deposit (Meyer and Janda, 1986) contributed to the enormous sediment discharges measured along the lower North Fork Toutle River at KID and along the lower Toutle River at TOW (Figs. 1 and 2).

A sediment retention structure (SRS) constructed upstream from KID (Fig. 1) impounds most of the sediment eroded from the avalanche deposit (US Army Corps of Engineers, 1984). The dam began trapping sediment in November 1987 (WY 1988), and by 1999 had trapped ~100 x 10^6 Mg of sediment (US Army Corps of Engineers, 2000). Downstream of the dam, subsequent sediment discharges measured at KID and TOW plummeted, and as a result the KID gage was decommissioned in 1994. Monitoring of annual sediment accumulation behind the dam, combined with assumptions about the percentage of sediment transported as bedload (Major et al., 2000), indicate that sediment was released from the debris-avalanche deposit more slowly than estimated from projection of the sediment-yield trend through 1987 (Fig. 3; Major et al., 2000). Twenty years after emplacement, the average annual suspended-sediment yield from the debris-avalanche deposit remains about 10^4 Mg/km^2, 100 times greater than the background levels typical of many western Cascades rivers.

Suspended-sediment yields from two lahar-affected basins (South Fork Toutle and Muddy; Fig. 1) are substantially less than from the avalanche deposit (Fig. 2). From 1982 to 1999, stormflows transported about 15 x 10^6 and 20 x 10^6 Mg of suspended sediment from the South Fork Toutle and Muddy River basins, respectively. From 1982 to 1985, yields from these basins dropped rapidly (Fig. 2), but the average yield then reached a plateau at about 10^3 Mg/km^2, 10 times greater than typical background level.

The Green River (Fig. 1), affected solely by the blast current, transported the least suspended sediment. From 1982 to 1994, stormflow transported 1.4 x 10^6 Mg of suspended sediment from the basin. With minor fluctuations, the annual suspended-sediment yield from Green River basin declined persistently; within five years it had returned to levels typical of western Cascades rivers, and by 1994 was as little as 15 Mg/km^2 (Fig. 2), at which time the station was shut down.

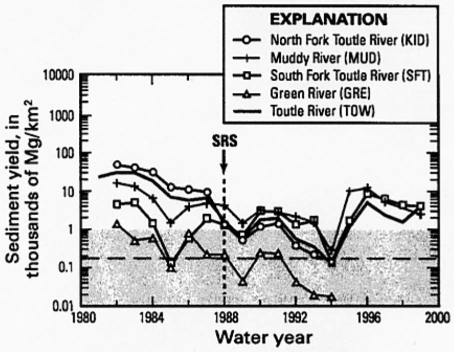

Figure 2. Annual suspended-sediment yields at Mount St. Helens. See Figure 1 for basin disturbances and station locations. Shaded region depicts range of, and dashed line depicts mean value of, mean annual yields of several western Cascade Range rivers (US Geological Survey , 2000). (After Major et al., 2000).

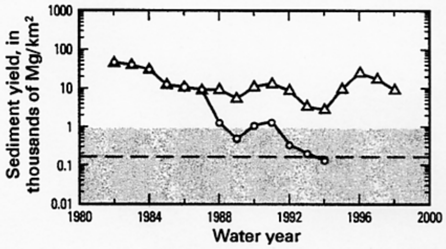

Figure 3. Annual suspended-sediment yield at KID projected (triangles) in absence of sediment dam. Measured yield (circles) shown for comparison. See Figure 2 for additional information. (After Major et al., 2000).

Effects of streamflow: A 20-year perspective on suspended-sediment yield at Mount St. Helens shows that broad hydrologic trends can significantly perturb sediment discharge and substantially lengthen extrapolated recovery times (Figs. 2 and 3; Major et al., 2000). Sediment discharges in consecutive wet years (1995-1999) demonstrate that dormant sediment at Mount St. Helens remains mobile, and that suspended-sediment yields in several basins remain far from equilibrium. From 1995 to 1999, mean annual discharges in most basins were about 40%-50% greater than those during 1981 to 1994 (Major et al., 2000). As a result, suspended-sediment yields from the North Fork Toutle, South Fork Toutle, and Muddy River basins increased as much as 10-50 times and approached or exceeded average values measured within a few years after the eruption (Figs. 2 and 3; Major et al., 2000).

TIMING AND DISCHARGE CONDITIONS OF SEDIMENT TRANSPORT

Transit Times of Suspended Sediment: Analysis of transit times of suspended sediment from basins at Mount St. Helens shows that the majority of annual suspended-sediment transport occurs during limited periods of a few weeks or less. More than 50% of the annual suspended sediment in the North Fork Toutle and Toutle Rivers has been transported in 10-27 days during the period of study, whereas 50% of the suspended-sediment transport occurs in less than one week in the South Fork Toutle, Green, and Muddy River basins (Table 1). Comparable transit times are observed in regional basins unaffected by the eruption (e.g., Chehalis River; Table 1), but in those basins, sediment loads pale in comparison to those from basins affected by the Mount St. Helens eruption.

Suspended-sediment is transported dominantly by seasonal stormflows. Individual large floods can be particularly significant. For example, the 1996 suspended-sediment yield from Muddy River basin was about 75% of the maximum annual yield recorded in 1982, and 50% of the 1996 annual yield was transported in a single day. The impact of an individual flood is further highlighted by comparing suspended-sediment yields and annual runoff in 1996 and 1997. In the Muddy, Toutle, and South Fork Toutle basins, the 1997 annual runoff equaled or exceeded that of 1996 (Major et al., 2000), yet the 1996 sediment yields were 40%-140% greater as the result of a single large flood.

Table 1. Summary of mean transit times (days ∀ 1s) for percentages of annual suspended-sediment discharges.

River (gage)	Period	50%	60%	75%	90%
Toutle (TOW)	1981-1998	16 ∀ 13	27 ∀ 21	55 ∀ 37	119 ∀ 59
	1981-1987	25 ∀ 17	40 ∀ 26	77 ∀ 45	149 ∀ 67
	1988-1998	11 ∀ 6	18 ∀ 10	41 ∀ 23	101 ∀ 48
NFk Toutle (KID)	1982-1994	25 ∀ 15	40 ∀ 22	77 ∀ 35	150 ∀ 45
	1982-1987	24 ∀ 12	39 ∀ 19	79 ∀ 32	156 ∀ 43
	1988-1994	27 ∀ 18	41 ∀ 26	75 ∀ 39	145 ∀ 49
SFk Toutle (SFT)	1982-1998	5 ∀ 2	7 ∀ 2	12 ∀ 4	28 ∀ 10
Green (GRE)	1982-1994	5 ∀ 3	8 ∀ 5	18 ∀ 12	50 ∀ 33
Muddy (MUD)	1982-1996	7 ∀ 4	11 ∀ 6	24 ∀ 12	66 ∀ 25
Chehalis	1962-1971	18 ∀ 4	24 ∀ 5	41 ∀ 8	79 ∀ 11

Transport Discharge Conditions: While individual stormflows can transport quantitatively significant amounts of sediment, they may not be the most geomorphically effective flows over the long term (Wolman and Miller, 1960). To assess a long term perspective of water discharge and its relation to suspended-sediment transport in the aftermath of the Mount St. Helens eruption, I have examined suspended-sediment transport with respect to mean annual flow, mean annual flood (average maximum discharge), and bankfull discharge. Despite considerable noise, the cumulative percentage of transported suspended sediment increases with increasing water discharge (Fig. 4). Table 2 summarizes the water discharge (Q_{50}), culled from Figure 4, below which 50% of the cumulative suspended-sediment load is transported. For example, on average, half of the suspended sediment transported from the South Fork Toutle basin is moved by water discharges less than or equal to 5000 cfs. Table 2 also summarizes the approximate return interval of discharges of magnitude Q_{50}, and compares this discharge to the magnitude of the mean annual flow and the mean annual flood. In all cases, Q_{50} is several times greater than the mean annual flow, a fraction of the mean annual flood, and has a return

Table 2. Water discharges for 50% cumulative suspended-sediment transport.

River	Q_{50} (cfs)	~return interval (years)	Q_{mean} (cfs)	$Q_{mean\ flood}$ (cfs)	$Q_{bankfull}$ (cfs)	times mean flow	times mean flood
Toutle							
overall	8600	< 1.1	2060	19760	13850	4.2	.44
pre-SRS	7115	< 1.1	--	--	--	3.5	.36
post-SRS	10185	< 1.25	--	--	--	4.9	.52
NFk Toutle							
overall	3700		1070	13180	--	3.5	.28
pre-SRS	4090		--	--	--	3.8	.31
post-SRS	3220		--	--	--	3.0	.24
SFk Toutle	4990	< 1.4	610	8100	5240	8.2	.62
Green	2905	< 1.25	502	6090	3765	5.8	.48
Muddy	4845	< 1.4	863	8080	5350	5.6	.60

Table 3. Approximate percentages of suspended-sediment load transported by various water discharges.

River	$Q < Q_{mean}$	$Q < Q_{mean\ flood}$	$Q < Q_{bankfull}$
Toutle			
overall	11	100	80
pre-SRS	13	100	99
post-SRS	9	99	70
NFk Toutle			
overall	12	100	--
pre-SRS	11	100	--
post-SRS	14	100	--
SFk Toutle	3	83	53
Green	5.5	100	66
Muddy	6.5	85	56

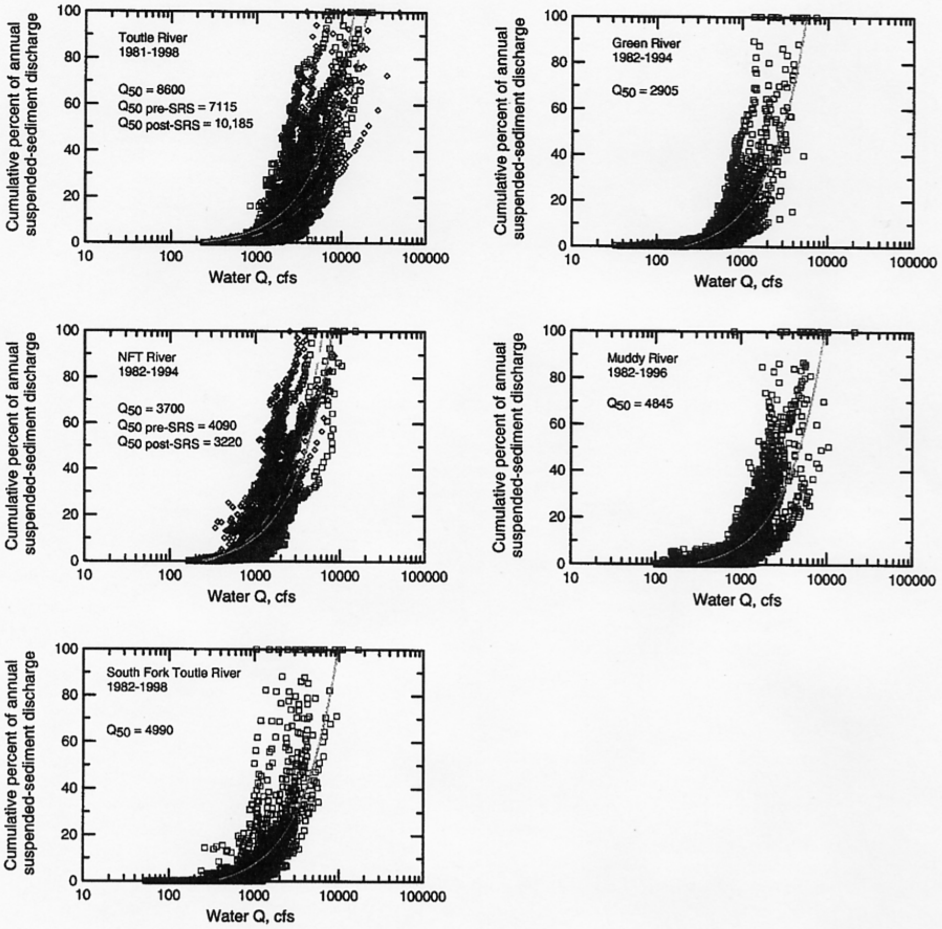

Figure 4. Cumulative percentage of annual suspended-sediment transport versus water discharge. Scatterplot represents a 5-point moving average of water discharge. Solid lines represent linear regression model. Q_{50} is the discharge (in cfs) below which 50% of cumulative annual suspended sediment is transported. Plots for the Toutle and North Fork Toutle Rivers show linear regressions for pre- and post-sediment-retention-dam periods.

interval of less than 1.5 years. These data highlight the importance of stormflows on suspended-sediment transport; discharges smaller than the mean annual flow transport#10% of the annual suspended-sediment load (Table 3).

A calculation of the approximate percentage of suspended sediment transported annually at bankfull discharge provides an assessment of the relative importance of stormflow magnitudes on sediment redistribution. For this analysis, bankfull discharge is approximated as the discharge having a return interval of about 1.5 years (Dunne and Leopold, 1978). Adopting this definition for bankfull discharge shows that discharges less than or equal to bankfull are responsible for transporting more than 50 percent of the annual suspended-sediment load for the period of study (Table 3), and thus are the discharges that are most effective over time.

CONCLUSIONS

Sediment yields in the aftermath of explosive volcanic eruptions typically decline nonlinearly as physical and vegetative controls diminish sediment supply (e.g., Pierson et al., 1992; Janda et al., 1996; Major et al., 2000). At Mount St. Helens, suspended-sediment yields dropped rapidly over the first few years, but then slowed over the next decade. However, spatial and temporal perturbations resulting from hydrologic fluctuations are likely to punctuate, or even temporarily reverse, long-term trends, which complicates projection of time to equilibrium. Suspended sediment at Mount St. Helens is transported mainly by episodic stormflows having return intervals# 1.5 years. However, infrequent large ($p<0.01$) stormflows have transported significantly large amounts of sediment.

Twenty years after the eruption of Mount St. Helens, suspended-sediment yields remain 1 to 2 orders of magnitude above typical background levels in basins where mass-flow sediments were deposited in channels. In basins where the geomorphic impact was dominantly hillslope disturbance, suspended-sediment yields returned to background level within five years. The perspective of suspended-sediment transport in the aftermath of significant landscape disturbance at Mount St. Helens demonstrates the long-term instability of eruption-generated detritus, and shows that measures designed to mitigate sediment transport in the aftermath of severe explosive eruptions must remain functional for decades.

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