Sediment yield following severe volcanic disturbance—A two-decade perspective from Mount St. Helens

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ABSTRACT

Explosive volcanic eruptions perturb water and sediment fluxes in watersheds; consequently, posteruption sediment yields can exceed pre-eruption yields by several orders of magnitude. Annual suspended-sediment yields following the catastrophic 1980 Mount St. Helens eruption were as much as 500 times greater than typical background level, and they generally declined nonlinearly for more than a decade. Although sediment yields responded primarily to type and degree of disturbance, streamflow fluctuations significantly affected sediment-yield trends. Consecutive years (1995–1999) of above-average discharge reversed the nonlinear decline and rejuvenated yields to average values measured within a few years of the eruption. After 20 yr, the average annual suspended-sediment yield from the 1980 debris-avalanche deposit remains 100 times (10^4 Mg [megagrams]/km^2) above typical background level (~10^2 Mg/km^2). Within five years of the eruption, annual yields from valleys coated by lahar deposits roughly plateaued, and average yields remain about 10 times (10^3 Mg/km^2) above background level. Yield from a basin devastated solely by a blast pyroclastic current diminished to background level within five years. These data demonstrate long-term instability of eruption-generated detritus, and show that effective mitigation measures must remain functional for decades.

Keywords: sediment yield, volcano, Mount St. Helens, geomorphology.

INTRODUCTION

Explosive volcanic eruptions disrupt watershed hydrology and geomorphology. Erosional response to severe volcanic disturbance is commonly rapid and dramatic; as a consequence, posteruption sediment yields can greatly exceed pre-eruption yields. Annual sediment fluxes from basins affected by explosive eruptions commonly range from 10^3 to 10^6 Mg (megagrams)/km^2 (Table 1[1]) ranking them among Earth's greatest sediment producers (Milliman and Syvitski, 1992). Prolonged excessive sediment transport after an eruption can cause environmental and socioeconomic harm equaling or exceeding that caused directly by an eruption (e.g., Mercado et al., 1996). Unfortunately, scarcity of long-term data hinders assessment of recovery times from extraordinary posteruption sediment yield.

Sediment and streamflow measurements following the catastrophic 1980 eruption of Mount St. Helens provide a unique opportunity to assess decadal-scale yields after abrupt emplacement of sediment across a landscape. The eruption variously affected several watersheds (Fig. 1), and it occurred shortly after the onset of a relatively dry period (of ~20 yr duration) in the Pacific Northwest (Mantua et al., 1997), followed in the late 1990s by above-average mean annual streamflow. We can therefore demonstrate the effects of disturbance process and hydrologic trends on sediment yields. We present a nearly two-decade record of suspended-sediment discharge following the eruption, and establish a conceptual model for posteruption sedimentary response to a severe explosive eruption. We restrict our discussion to suspended-sediment yield because bedload data are limited and suspended sediment averaged ≥80% of the total sediment yield (Lehre et al., 1983; Simon, 1999).

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[1]GSA Data Repository item 200087, Tables 1–3, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

1980 MOUNT ST. HELENS ERUPTION

The catastrophic 1980 Mount St. Helens eruption affected some watersheds severely, others mildly. Watersheds north of the volcano underwent the most severe disturbance and the greatest accumulation of new, loose sediment from deposition by a 2.5 km^3 debris avalanche (Glicken, 1998) and a consequent directed blast (Hoblitt et al., 1981; Waitt, 1981). The blast pyroclastic current destroyed vegetation across ~600 km^2 of rugged terrain (Fig. 1), and blanketed the landscape with <1 cm 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 lower and upper North Fork Toutle River watershed (Fig. 1) (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 a plinian eruption column blanketed proximal areas east-northeast of the volcano with silty-sand and gravel tephra fall 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 flood plains (Janda et al., 1981; Pierson, 1985; Major and Voight, 1986; Fairchild, 1987; Scott, 1988).

SEDIMENT YIELD

Data Collection Sites

After the eruption, stations were established to measure discharges of water and suspended sediment along the larger rivers draining Mount St. Helens. Some stations operated briefly, or gathered data intermittently. Five stations (Fig. 1; Table 2; see footnote 1) provided continuous records for more than a decade (1982–1994) after the eruption; three of those stations remain operational. Two stations are located below the debris-avalanche deposit: one along the lower North Fork Toutle River (KID in Fig. 1) and another along the lower Toutle River (TOW in Fig. 1). KID measured discharges from the North Fork Toutle and Green Rivers; TOW measurements include discharges from the entire Toutle River watershed (Fig. 1). The South Fork Toutle (SFT) and Muddy River (MUD) stations (Fig. 1) measured discharges from basins affected primarily by large lahars. The Green River (GRE) station (Fig. 1) measured discharge from a basin affected solely by the blast pyroclastic current.

Sediment Discharge from the Toutle River Basin

From 1980 to 1999, the Toutle River transported more than 300 × 10^6 Mg of suspended sediment past TOW. Syneruptive lahars in 1980 transported 140 × 10^6 Mg of sediment (Dinehart, 1998), and another in 1982 transported ~3 × 10^6 Mg of sediment (Dinehart, 1998). Syneruptive lahars therefore transported nearly half of the suspended sediment thus far mobilized from the Toutle River basin; stormflow discharge transported most of the remainder (163 × 10^6 mg).

Data Repository item 200087 contains additional material related to this article.

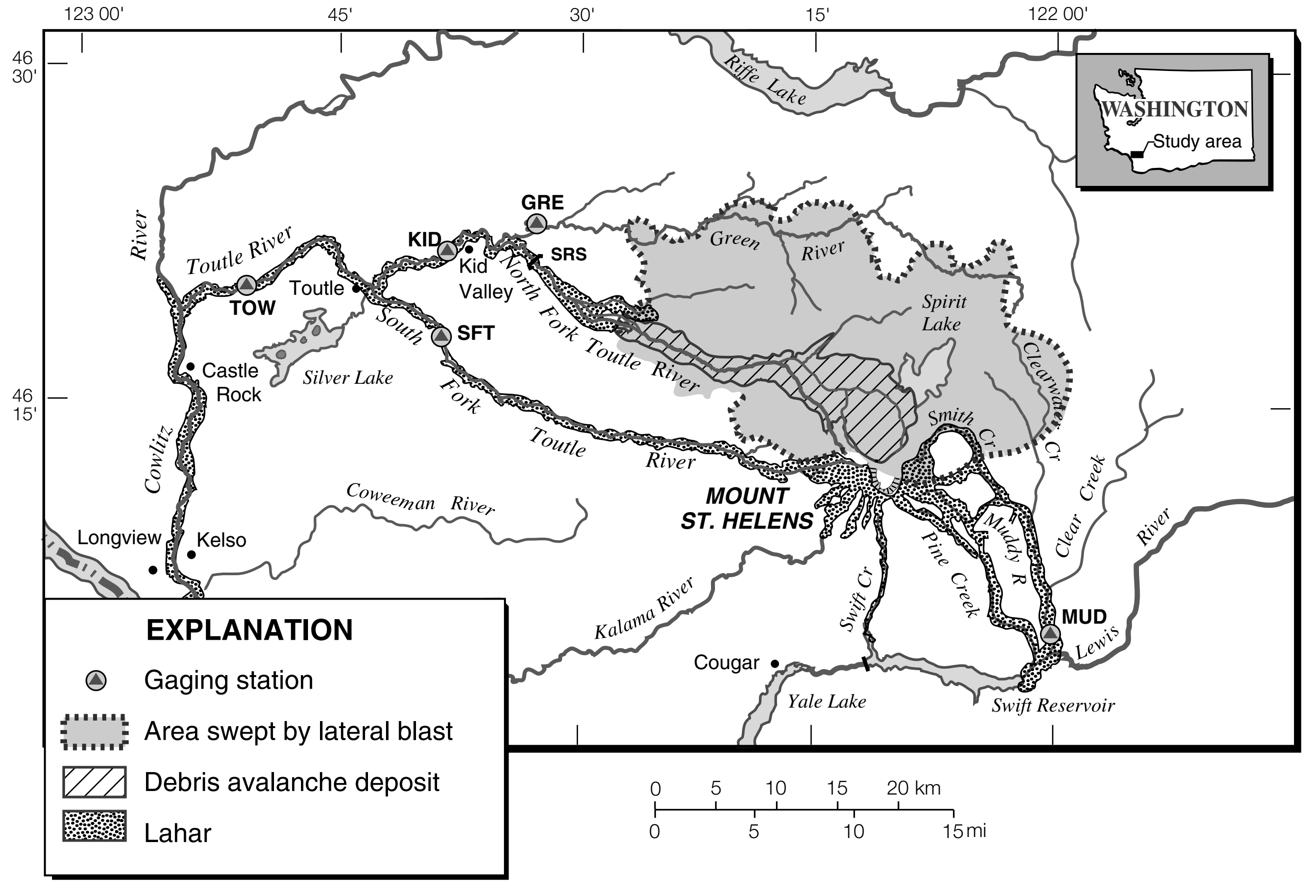

Figure 1. Effects of Mount St. Helens 1980 eruption and location of gaging stations. Stations: TOW—lower Toutle River, KID—lower North Fork Toutle River, SFT—South Fork Toutle River, MUD—Muddy River, GRE—Green River. SRS—Sediment retention structure.

Yield from Debris-Avalanche Deposit

Erosion associated with drainage development across the avalanche deposit dominated sediment transport in the Toutle basin immediately after the eruption (Lehre et al., 1983; Janda et al., 1984). Bank erosion along tens of kilometers of the Toutle River valley below the avalanche deposit (Meyer and Janda, 1986) mobilized older sediment held in storage. As a result, suspended-sediment yields at stations KID and TOW initially were as much as 500 times greater than yields typical for western Cascade Range rivers (Fig. 2; Table 3; see footnote 1). Average annual suspended-sediment yield past station KID from 1982 to 1984 was 38 000 Mg/km^2; peak annual yield reached 46 000 Mg/km^2. At station TOW, the average annual yield from 1981 to 1984 was 25 000 mg/km^2, and peak annual yield reached 30 000 Mg/km^2.

A large sediment retention dam constructed above KID (Fig. 1) curtails sediment delivery downstream from the avalanche deposit (U.S. Army Corps of Engineers, 1984). The dam began trapping sediment in November 1987, and by 1999 it had trapped ~100×10^6 Mg of sediment (U.S. Army Corps of Engineers, 2000). Below the dam, sediment discharges measured at KID and TOW plummeted (<2000 Mg/km^2; Table 3—see footnote 1). Owing to trap efficiency of the dam, KID was decommissioned in 1994.

To estimate long-term suspended-sediment discharge from the debris-avalanche deposit, we computed projected suspended-sediment yield past KID in the absence of the dam. We computed projected yields by reducing the annual sediment mass trapped behind the dam (U.S. Army Corps of Engineers, 2000) by 20%, an approximation of the bedload (Lehre et al., 1983; Simon, 1999), then added the remainder to the measured suspended-sediment discharge at KID. We estimated post-1994 loads by adding the calculated suspended-sediment load trapped behind the dam to 70% of the difference between suspended-sediment discharges measured at TOW and SFT, on the basis of historical relations between discharges measured at KID and the discharge difference between those two sites. Our calculations indicate that sediment eroded from the avalanche deposit more slowly than estimated from projection of the sediment-yield trend measured through 1987 (Fig. 3). Between 1985 and 1992 the average annual suspended-sediment yield from the avalanche deposit hovered around 10 000 Mg/km^2. Yield then dropped to about 3000 Mg/km^2 by 1994, still 10 times above pre-eruption conditions. As of 1999 only about 12% (~450×10^6 Mg) of the avalanche-deposit mass had been eroded. About half of the eroded mass (~215×10^6 Mg) was removed within hours of deposit emplacement by the North Fork Toutle lahar (Fairchild and Wigmosta, 1983), and about 20% (~100×10^6 Mg; Lehre et al., 1983) eroded fluvially during the first year after the eruption. Thus, nearly 70% of the sediment eroded from the debris-avalanche deposit was removed within one year of the eruption.

Yields from Lahar-Affected Basins

The suspended-sediment yields from two lahar-affected basins (South Fork Toutle and Muddy) are substantially less than from the avalanche deposit. Suspended-sediment discharges from each channel are equivalent to about 10% of the load (exclusive of the 1980 lahars) that has passed TOW. From 1982 to 1999, stormflows transported about 15×10^6 and 20×10^6 Mg of suspended sediment from the South Fork Toutle and Muddy River basins, respectively (Table 3; see footnote 1). From 1982 to 1985, yields from these basins dropped rapidly, but average yield then reached a plateau at about 10^3 Mg/km^2, 10 times greater than that typical for western Cascade Range rivers, for the next decade (Fig. 2).

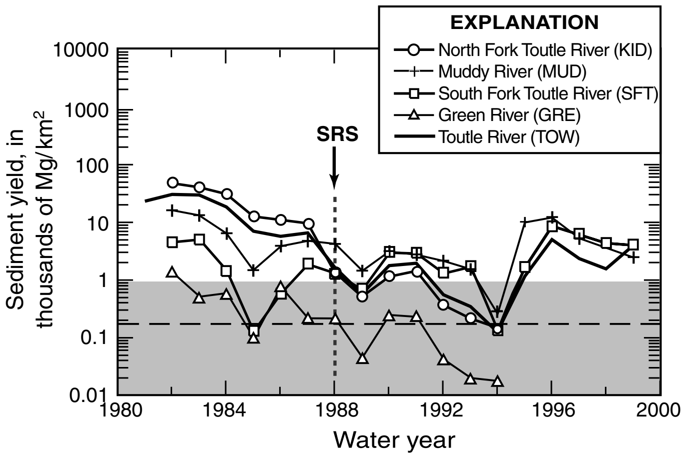

Figure 2. Annual suspended-sediment yields at Mount St. Helens. See Figure 1 for basin disturbances and station locations. Shaded region depicts range of, and dashed line depicts mean value of, mean annual yields of several western Cascade Range rivers (U.S. Geological Survey, 2000).

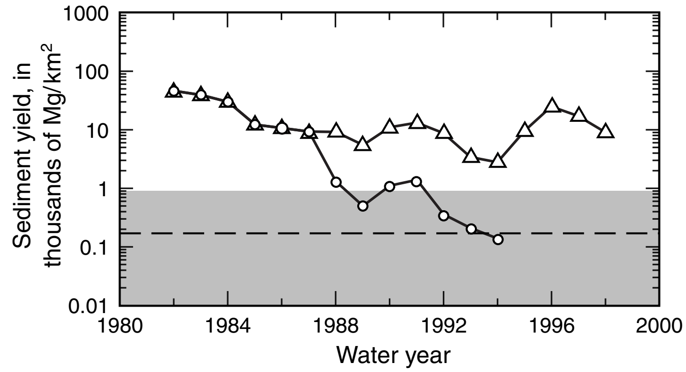

Figure 3. Annual suspended-sediment yield at KID projected (triangles) in absence of sediment dam. Measured yield (circles) shown for comparison. Dam began trapping sediment in late 1987. See Figure 2 for additional information.

Yield from Blast-Affected Basin

The Green River transported the least suspended sediment. From 1982 to 1994, stormflow transported 1.4×10^6 Mg of suspended sediment from the basin (Table 3; see footnote 1), which was <1% of the suspended-sediment load that passed TOW and <20% of that transported from the lahar-affected basins. Annual yield from this basin exceeded 1300 Mg/km^2 in 1982, then dropped below 1000 Mg/km^2. With minor fluctuations, the annual suspended-sediment yield from the Green River basin declined persistently until, in 1994, it diminished to as little as 15 Mg/km^2 (Fig. 2). Such low yield is within the range typical of Cascades streams; consequently, the station was decommissioned.

Effects of Streamflow Variation

Suspended-sediment yields from most basins at Mount St. Helens declined nonlinearly for more than a decade after the eruption, a response commonly observed in disturbed geomorphic systems (Graf, 1977). Extrapolating this trend (from 1981–1994) suggests recovery to pre-eruption sediment yields within 10 yr (Green River) to 40 yr (North Fork Toutle) after the eruption (Figs. 2 and 3). However, extrapolating trends of even this length can be misleading. The 20-yr perspective on sediment yield at Mount St. Helens shows that broad hydrologic trends (Table 3; see footnote 1) can significantly perturb sediment discharge and substantially lengthen extrapolated recovery times (Figs. 2 and 3).

Sediment discharges in consecutive wet years (1995–1999) demonstrate that dormant sediment at Mount St. Helens remains mobile, and that 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 (Table 3; see footnote 1). Suspended-sediment yields from the North Fork Toutle, South Fork Toutle, and Muddy basins increased as much as 10–50 times and approached or exceeded values measured within a few years of the eruption (Figs. 2 and 3; Table 3; see footnote 1), a reversal of nonlinear decline. Average yields from 1995 to 1999 in those three basins ranged from 40% to 100% of the average yields from 1981 to 1984, and exceeded the average yields from 1984 to 1987. Average sediment yield at TOW, although enhanced, was less affected owing to sediment retention upstream.

Individual floods as well as broad hydrologic trends can significantly affect sediment yields. Large floods disproportionately entrain and transport sediment stored in channels. For example, the 1996 suspended-sediment yield from Muddy River basin was 75% of the maximum yield recorded in 1982, and 50% of the 1996 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 (Table 3; see footnote 1), yet the 1996 sediment yields were 40%–140% greater as a result of a single large flood.

DISCUSSION

A nearly 20-yr record of suspended-sediment transport following the 1980 Mount St. Helens eruption reveals a landscape responding over several time scales. Suspended-sediment yields at Mount St. Helens peaked within 2 to 3 yr after the catastrophic eruption, then declined nonlinearly for more than a decade. After 5 yr, yields remained relatively constant (10–100 times above background level) or slowly declined over the next decade. The decline is persistent but punctuated by fluctuations that are broadly discharge dependent. The Green River basin, however, returned to pre-eruption level within 5 yr. The onset of amplified water discharges in 1995 abruptly increased suspended sediment released from the basins, and record floods in 1996 generated sediment yields typical of the first 4 yr after the eruption. Continued wet years have maintained rejuvenated yields equivalent to the average yields of the early to mid 1980s.

On the basis of the suspended-sediment record documented at Mount St. Helens as well as on limited sediment yields reported in the aftermath of explosive eruptions elsewhere (Table 1; see footnote 1), we suggest the following conceptual model for watershed response to explosive volcanic eruption. Deposition of tephra and channel detritus perturbs surface water runoff, which triggers rapid and massive erosion and leads to enhanced sediment yield. The type and thickness of sediment deposited by an eruption, its distribution on the landscape, and its susceptibility to erosion play key roles influencing its spatial and temporal redistribution. Fresh volcanic debris erodes through rapid extension of drainage networks, similar to that observed in badlands topography (e.g., Howard, 1999). Network initiation leads to sediment yields that typically are orders of magnitude above pre-eruption yields. Erosion rates and sediment yields decline as drainage networks extend, integrate, and diminish hydrologic contributing areas and slope gradients. Once established, channels in valley fill undergo complex cycles of incision, aggradation, and widening (e.g., Meyer and Martinson, 1989; Punongbayan et al., 1996). Typically, channel adjustments are rapidly dominated by widening (Meyer and Martinson, 1989; Simon, 1999). Consequently, channel adjustments become discharge dependent, and sediment entrainment relies primarily on bank collapse during trench widening, rather than on bed scour. If bank instability persists, high sediment yield persists. When bank instability declines, sediment yield declines. At Mount St. Helens, channel adjustments on the debris avalanche (Bart, 1999; Simon, 1999) and in lahar-affected basins have persisted, especially in the steeper upstream reaches, and sediment yields from these basins remain elevated. Erosion of tephra-mantled hillslopes typically subsides within several months as overland flow, bioturbation, freeze-thaw, and erosional sorting disrupt low-permeability tephra, stabilize rills, and armor inter-rill regions (Swanson et al., 1983; Kadomura et al., 1983; Collins and Dunne, 1986; Leavesley et al., 1989). Thus, hillslope sediment yields diminish to background levels rapidly. At Mount St. Helens, the Green River basin yield attests to rapid stabilization of hillslope sediment.

Climate variations affect sediment yields by affecting river discharge. At Mount St. Helens, elevated mean annual discharge increased mean river stage and caused rivers to spread across or avulse within their valleys and undermine banks. Until channels adjust to the higher average flows, rejuvenated sediment yields should persist. Sediment discharges from volcanoes in settings that are significantly wetter than the Pacific Northwest may exceed those observed at Mount St. Helens, but they should follow a general pattern of nonlinear decline following an explosive eruption (e.g., Janda et al., 1996).

CONCLUSIONS

Sediment yields in the aftermath of explosive volcanic eruptions typically decline nonlinearly as physical and vegetative controls diminish sediment supply. 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. If the 20-yr perspective from Mount St. Helens can serve as a guide, yields from basins affected solely by hillslope disturbance will diminish rapidly, probably within tens of months, whereas yields from basins that experience dominantly channel disturbance will likely remain elevated for as much as several decades. Thus, measures designed to mitigate sediment transport in the aftermath of severe explosive eruptions must remain functional for decades.

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