WATER RESOURCES
IMPACT

POST-ERUPTION HYDROLOGY AND SEDIMENT TRANSPORT IN VOLCANIC RIVER SYSTEMS

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INTRODUCTION

Explosive volcanic eruptions are a type of landscape disturbance that can profoundly alter river system hydrology and sediment transport. Explosive eruptions can damage, destroy, bury, or obliterate vegetation, and cover vast tracts of landscape with centimeters to tens of centimeters of gravelly to silty sediment known as tephra or volcanic ash. They can also fill river valleys with great quantities of gravelly sand (Figure 1), which can obliterate watershed divides, disrupt drainage patterns, or modify channel size, shape, pattern, and structure. Such landscape disturbances affect runoff, erosion, and flow routing, and cause accelerated landscape adjustments that greatly affect sediment transport and deposition (e.g., Waldron, 1967; Kadomura *et al.*, 1983; Janda *et al.*, 1984; Punongbayan *et al.*, 1996; Major *et al.*, 2000; Hayes *et al.*, 2002; Manville, 2002). Hydrologic, sedimentologic, and geomorphic responses to major explosive eruptions can be dramatic, widespread, and persistent, and present enormous challenges to those entrusted with managing disturbance response. Here I provide a brief overview of hydrologic and geomorphic impacts of explosive eruptions on volcanic river systems, provide examples of system responses, and highlight a few strategies that have been used to manage post-eruption sediment transport.

HYDROLOGIC AND GEOMORPHIC CONSEQUENCES OF VOLCANIC DISTURBANCES

Landscape changes caused by explosive volcanic eruptions can have dramatic hydrologic and hydraulic consequences. Volcanic eruptions, like forest practices (Jones, 2000), wildfires (Moody and Martin, 2001), and other disturbances (e.g., Knox, 2001), can affect the major storage components of the water balance and alter the character, timing, magnitude, and duration of runoff. Damage and destruction of vegetation alters canopy storage by reducing or eliminating interception, increasing precipitation throughfall, and reducing evapotranspiration. It also alters snowpack water storage in mid-latitude to high-latitude basins by affecting snowpack accumulation and melt dynamics. Changes in throughfall, snowmelt, and evapotranspiration in turn affect soil water storage. In addition to the consequences of vegetation changes, tephra deposits commonly reduce soil infiltration capacity, sometimes to as little as a few mm per hour (Leavesley *et al.*, 1989). Such hydrologic changes typically increase surface runoff and reduce the travel time of overland flow from hillslopes to channels. Thus post-eruption runoff initially gets to channels faster and in greater quantity than pre-eruption runoff.

Eruptions, and subsequent sediment transport, can impact river channel hydraulics as well as hillslope hydrology. Drainage patterns must redevelop on thick valley fills that obliterate existing valley structure (Figure 1), and piracy can occur. Consequent sediment transport delivers fine sediment downstream, which commonly aggrades and paves channel beds. Also, in many volcanic river systems worldwide, large volcanic debris flows ream out vegetation along river corridors and displace, shorten, straighten, and smooth river channels (e.g., Janda *et al.*, 1984). Therefore, post-eruption runoff commonly is routed through channels more powerfully and efficiently until channels recover characteristics of pre-eruption structure. Initially, for a given rainfall, the magnitudes of post-eruption peakflows are larger than those of pre-eruption peakflows.

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Effects of Volcanic Disturbances on Peakflow Discharges

A sparse number of studies show that post-eruption hydrographs are temporarily flashier, and that peakflow discharges temporarily have greater magnitudes and recur more frequently than comparable pre-eruption discharges. Post-eruption peakflow discharges in basins disturbed by the Mount St. Helens eruption, for example, were disproportionately larger than those from basins undisturbed. Hydraulic modeling shortly after the 1980 eruption suggested that the character of unit hydrographs changed dramatically. Modeled peaks of post-eruption two-hour unit hydrographs were as much as 70 percent greater, and rates of rise were as much as 30 percent faster, than peaks of pre-eruption unit hydrographs (Orwig and Mathison, 1982). Major *et al.* (2001) showed that post-eruption peakflow discharges from basins having drainage areas of 300-1,200 km^2 at Mount St. Helens exceeded pre-eruption discharges by as much as 30 to 70 percent for about five years. After five years, the magnitudes of pre- and post-eruption peakflow discharges generally did not differ significantly, although some differences were detected as much as 15 to 20 years after eruption during a period of wetter than normal conditions. Recurrence frequency as well as discharge magnitude at Mount St. Helens also increased temporarily. Basins severely disturbed by the eruption typically had maximum discharges larger than those expected about once every 10 to more than 25 years through 1983, and discharges smaller than those expected once every five

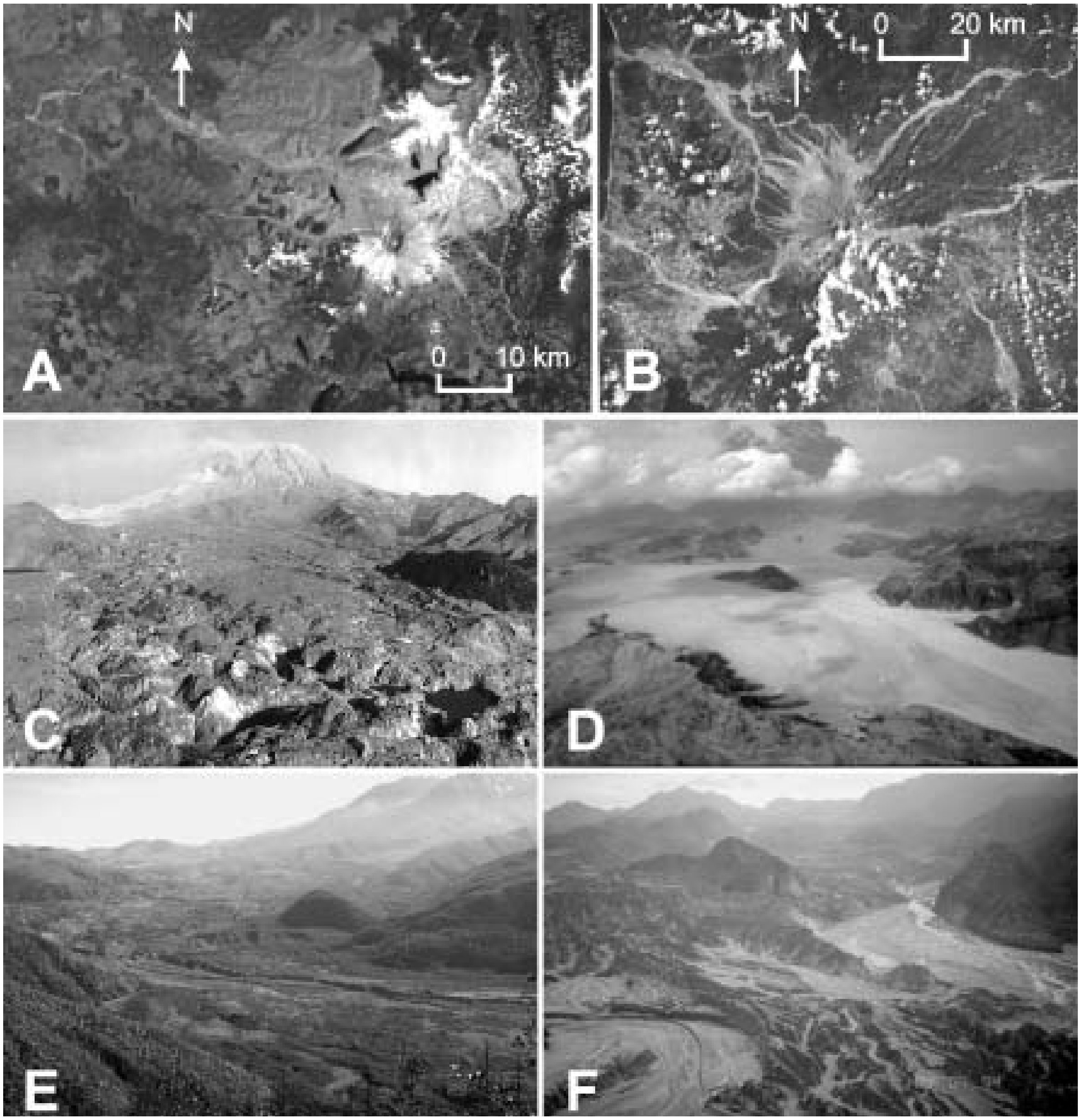

Figure 1. (A) Landsat Image (1983) of Area Affected by 1980 Mount St. Helens Eruption. Note denuded basins impacted by directed volcanic blast and tephra fall north of volcano, channels affected by far-traveled debris flows, valley immediately north of volcano crater filled with landslide debris, and lakes formed when landslide truncated tributary valleys. (B) Space Shuttle Photograph (1992) of Area Affected by 1991 Mount Pinatubo Eruption. Note area close to volcano affected by extensive pyroclastic flows and tephra fall, and channels affected by debris flows. (C) Hummocky Landslide Deposit (mean depth = 45 m) That Fills North Fork Toutle River Valley North of Mount St. Helens (June 1980). (Photograph by Harry Glicken) (D) Pyroclastic Valley Fill (>100 m thick) on Western Side of Mount Pinatubo (June 1991). (Photograph by R.P. Hoblitt, USGS) Note the lack of drainage integration immediately after deposit emplacement in (C) and (D). (E) Erosion and Channel Development on Mount St. Helens Landslide Deposit (July 2002). (Photograph by T.C. Pierson, USGS) (F) Dissection of Pyroclastic Valley Fill at Mount Pinatubo (September 1994). Note island in center of photo for reference. (Photograph by C.G. Newhall, USGS)

years in 1984 and 1985. In contrast, basins undisturbed by the eruption generally had maximum discharges smaller than those expected to occur about once every five years through 1985. After 1985, recurrences of specific discharge magnitudes in most disturbed and undisturbed basins were similar.

The type of disturbance influenced the magnitude of change of post-eruption peakflow discharge at Mount St. Helens. Basins having mainly disturbed hillslopes (destroyed vegetation and tephra fall) exhibited the least amplified discharge peaks, and they generally had the shortest recovery times to conditions characteristic of pre-eruption hydrology compared to basins having severely disturbed channels and hillslopes.

Effects of Volcanic Disturbances on Channel Morphology and Sediment Transport

Changes in channel morphology and sediment transport are the most dramatic responses of volcanic river systems to eruptions. Enhanced surface runoff, amplified discharges, and vast supplies of easily erodible sediment lead to rapid and extraordinary channel change and sediment transport. After an eruption, channels commonly follow complex cycles of incision, aggradation, and widening (e.g., Meyer and Martinson, 1989). Depending upon the nature and degree of disturbance, channels can incise and aggrade by tens of meters and widen by hundreds of meters (Figures 1 and 2) within months or even during single storm cycles (e.g., Rodolfo, 1989; Punongbayan *et al.*, 1996). Such dramatic geomorphic changes can lead to post-eruption sediment yields (sediment load normalized by basin area or unit runoff) that are several hundred times greater than pre-eruption yields (Figure 3) (Major *et al.*, 2000; Hayes *et al.*, 2002). But how long do such extraordinary yields last? At Mount St. Helens, extraordinary post-eruption suspended-sediment yields declined nonlinearly for more than a decade, but then increased abruptly in response to greater than normal runoff in the late 1990s (Figure 3). Even after 20 years yields in some basins remain 10 to 100 times greater than pre-eruption values (Major *et al.*, 2000).

At many volcanoes, extraordinary sediment yields result predominantly from debris flows that are triggered by intense rainfall, snowmelt, or breaching of impounded waters. However, post-eruption fluvial transport can be important, and fluctuations in annual runoff can strongly affect sediment yields (Figure 3). Generally, fluvial transport occurs during moderate to large floods, but substantial post-eruption transport has been observed under relatively low discharges along highly disturbed channels. At Mount Pinatubo, low discharge to moderate discharge transport accounted for as much as 25 percent of annual sediment yields six years after eruption (Hayes *et al.*, 2002). Hayes *et al.* (2002) attributed high transport rates by low magnitude discharges to an unlimited supply of volcanic sediment deposited in channels and an enhanced mobility of particles moving over smooth, fine grained beds.

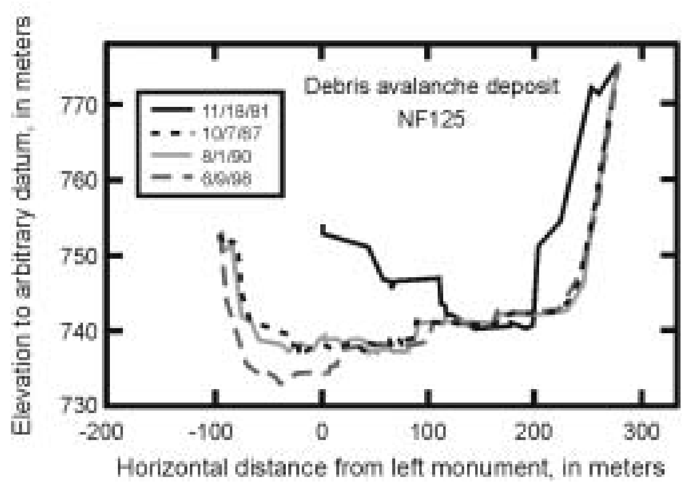

Figure 2. Example Time Series of Channel Cross-Section Development on Mount St. Helens Landslide Deposit. Section is Near Westernmost Lake on North Side of the Valley Seen in Figure 1a.

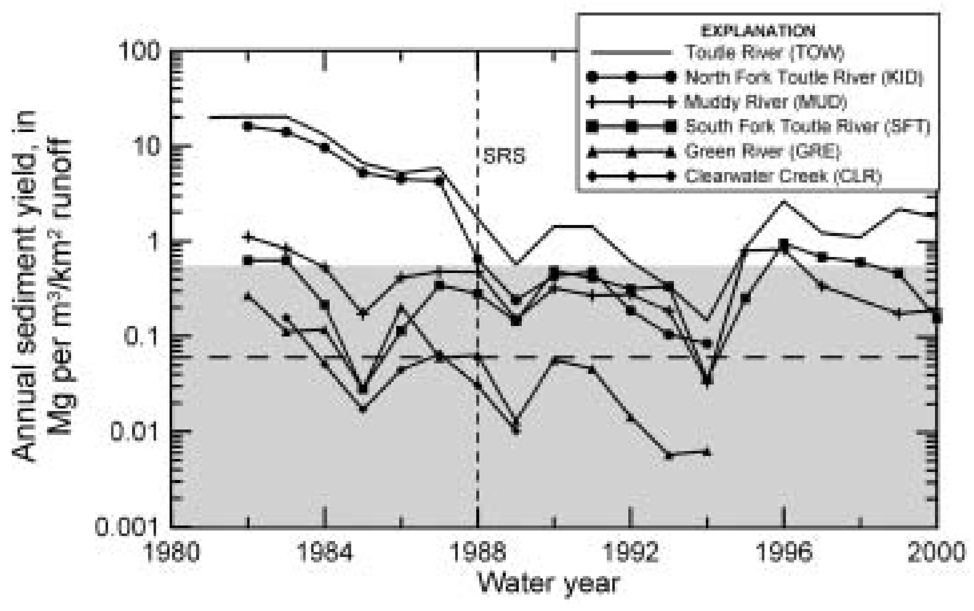

Figure 3. Annual Suspended Sediment Yields at Mount St. Helens. TOW and KID are gages that measure transport from large landslide deposit; MUD and SFT are gages that measure transport from channels affected by large volcanic debris flows; GRE and CLR are gages that measure transport from basins affected solely by a directed volcanic blast and tephra fall. The shaded region depicts the range of, and horizontal dashed line depicts median value of, mean annual suspended sediment yields from several western Cascades Range rivers. The horizontal dashed line serves as a proxy for pre-eruption sediment yields. The vertical dashed line identifies closure of a large sediment retention structure (SRS; cf. Figure 4c) that significantly diminished downstream transport measured at KID and TOW (modified from Major *et al.*, 2000).

Predominant post-eruption fluvial transport at Mount St. Helens contrasts with predominant debris flow transport at many other volcanoes, especially those in tropical climates (e.g., Waldron, 1967; Janda *et al.*, 1996; Rodolfo, 1989; Suwa and Yamakoshi, 1999; Lavigne *et al.*, 2000). Predominant fluvial transport and a dearth of debris flows at Mount St. Helens is primarily a consequence of low to moderate storm intensities that characterize the regional climate. Low intensity, long duration rainfall at Mount St. Helens favors fluvial, rather than debris flow, transport.

The magnitude and duration of accelerated landscape adjustment and extraordinary sediment transport varies with the nature of volcanic impact. At Mount St. Helens, as elsewhere, basins having channels severely disturbed by large landslides, pyroclastic flows (hot, dry avalanches), or debris flows discharged greater sediment loads for a longer period of time than did basins having mainly disturbed hillslopes (Figure 3). The amount of sediment supplied from tephra covered hillslopes diminished rapidly after rill networks exposed permeable substrates and stabilized (Collins and Dunne, 1986). As a consequence, abnormal sediment discharges from basins having mainly disturbed hillslopes declined rapidly and returned to pre-eruption levels within tens of months, whereas abnormal sediment discharges from basins having severely disturbed channels have persisted for decades (Figure 3).

STRATEGIES FOR MANAGING SEDIMENT TRANSPORT

Strategies for managing and mitigating problems and hazards posed by sediment transport in volcanic river systems generally fall into one of four categories: (1) dredging sediment accumulated on channel beds; (2) constructing dams to inhibit sediment migration; (3) modifying channels to facilitate sediment transport; or (4) developing warning systems to alert the downstream populace of impending debris flows. Costs to mitigate problems associated with post-eruption sediment transport are very expensive; they can tax resources in developed countries and can overwhelm those of developing countries. Since 1980, mitigation costs at Mount St. Helens have exceeded $1 billion. The most commonly employed strategy for managing sediment transport involves dam construction. In Japan, Indonesia, and the Philippines, for example, numerous small dams have been built to trap sediment (Figure 4). Sediment behind these dams must be dredged periodically for them to remain effective. At Mount St. Helens, a large (190 million m^3 capacity) sediment retention structure was constructed on the North Fork Toutle River to keep sediment eroded from a voluminous (2.5 km^3) landslide deposit out of downstream channel reaches (Figure 4). In basins subject to recurrent debris flows, such as at Sakurajima volcano in Japan, river channels have been paved with concrete to reduce roughness, prevent lateral migration, and facilitate transport efficiency (Figure 4). Seismic systems that detect the acoustic signatures of debris flows and transmit warnings to downstream communities have been employed successfully at volcanoes worldwide, especially in areas where engineered defensive structures are too costly (e.g., LaHusen, 1996).

CONCLUSIONS

Explosive volcanic eruptions directly impact watersheds by damaging or destroying vegetation and depositing large volumes of easily erodible sediment on hillslopes and in channels. Such disturbances commonly decrease infiltration, reduce channel roughness, and increase runoff. Subsequent precipitation consequently results in peakflow discharges that are temporarily amplified by tens of percent, and in persistent sediment transport that can increase as much as 100-fold for decades.

Post-eruption hydrologic and sediment-transport responses in volcanic river systems have different temporal characteristics. The chief effects of hydrologic changes (demonstrably increased runoff and discharge) appear to diminish relatively rapidly after an eruption (perhaps several tens of months), whereas abnormal sediment transport is more persistent and can last for decades. The magnitude and duration of extraordinary post-eruption sediment transport varies mainly with the nature of volcanic impact. Sediment transport is greater and more persistent from basins having severely disturbed channels than from basins having mainly disturbed hillslopes. Temporal patterns of sediment transport are also affected by hydrologic fluctuations. Punctuation, and even temporary reversal, of decadal scale trends of suspended sediment transport at Mount St. Helens highlight the sensitivity of volcanically disturbed river systems to hydrologic variations. Therefore, measures designed to mitigate posteruption sediment transport need to remain functional for decades. To effectively mitigate the hydrologic and geomorphic problems associated with explosive volcanic eruptions, land managers and emergency planners need to recognize the characteristic differences in the magnitudes and time scales of the responses of the major geomorphic systems.

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REFERENCES

Collins, B.D. and T. Dunne, 1986. Erosion of Tephra From the 1980 Eruption of Mount St. Helens. Geological Society of America Bulletin 97:896-905.

Hayes, S.K., D.R. Montgomery, and C.G. Newhall, 2002. Fluvial Sediment Transport and Deposition Following the 1991 Eruption of Mount Pinatubo. Geomorphology 45:211-224.

Janda, R.J., D.F. Meyer, and D. Childers, 1984. Sedimentation and Geomorphic Changes During and Following the 1980-1983 Eruptions of Mount St. Helens, Washington. Shin Sabo 37(2):10-21; 37(3):5-19.

Janda, R.J., A.S. Daag, P.J. Delos-Reyes, C.G. Newhall, T.C. Pierson, R.S. Punongbayan, K.S. Rodolfo, R.U. Solidum, and J.V. Umbal, 1996. Assessment and Response to Lahar Hazard Around Mount Pinatubo, 1991-1993. *In:* Fire and Mud –

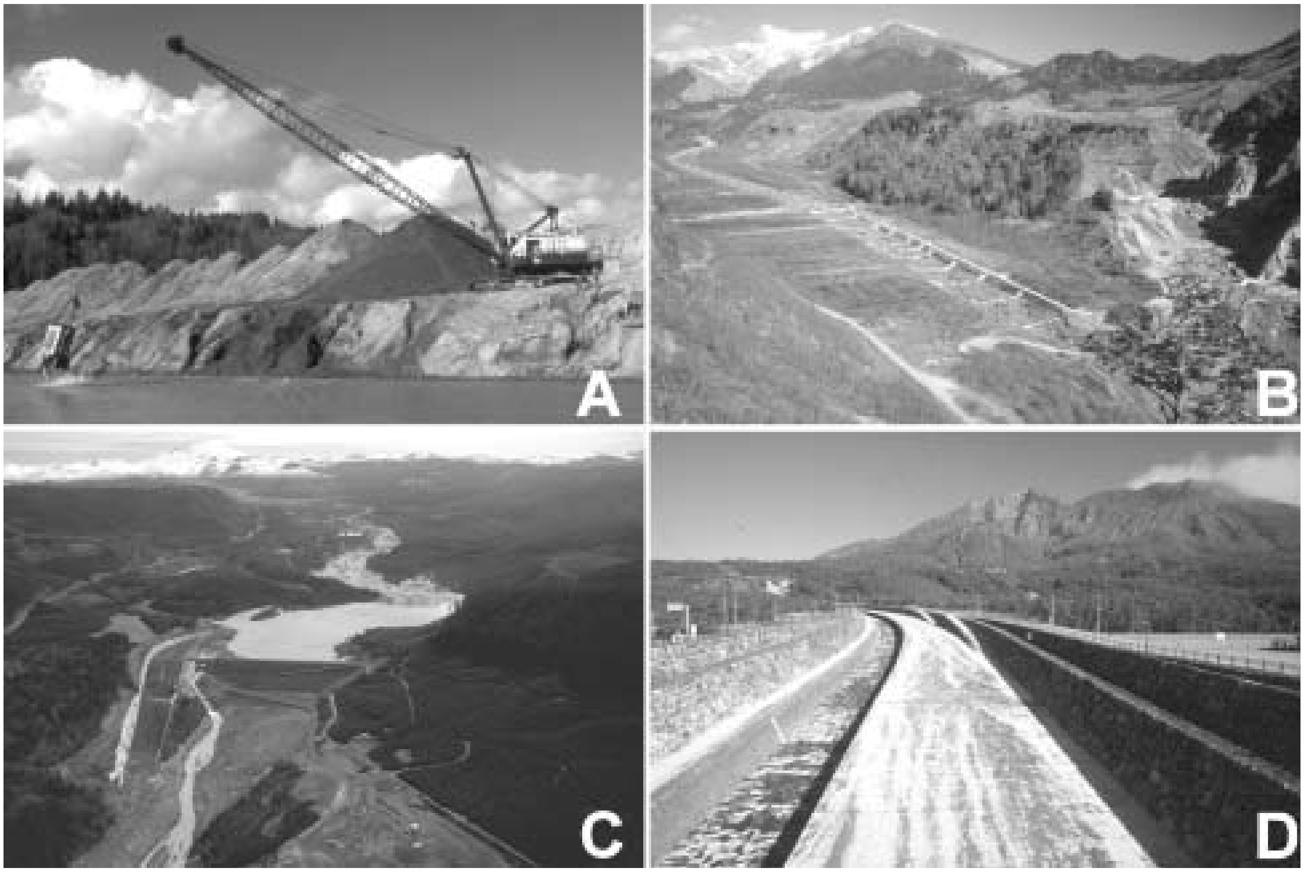

Figure 4. Strategies for Mitigating Post-Eruption Sediment Transport and Deposition. (A) Channel dredging at Mount St. Helens. (Photograph by Lyn Topinka, USGS) (B) Numerous small check dams lining channel near Mount Ontake, Japan. (C) Large sediment retention structure at Mount St. Helens. (Photograph by Bill Johnson, USACOE) (D) Channel paved with concrete to facilitate debris flow transport along the lower Nojiri River, Sakurajima volcano, Japan.

Eruptions and Lahars of Mount Pinatubo, Philippines, C.G. Newhall and R.S. Punongbayan (Editors). University of Washington Press, pp. 107-140.

Jones, J.A., 2000. Hydrologic Processes and Peak Discharge Response to Forest Removal, Regrowth, and Roads in 10 Small Experimental Basins, Western Cascades, Oregon. Water Resources Research 36:2621-2642.

Kadomura, H., T. Imagawa, and H. Yamamoto, 1983. Eruption-Induced Rapid Erosion and Mass Movements on Usu Volcano. Zeitschrift für Geomorphologie, Supplement Band 46:123-142.

Knox, J.C., 2001. Agricultural Influence on Landscape Sensitivity in the Upper Mississippi River Valley. Catena 42:193-224.

LaHusen, R.G., 1996. Detecting Debris Flows Using Ground Vibrations. U.S. Geological Survey Fact Sheet 236-96.

Lavigne, F., J.C. Thouret, B. Voight, H. Suwa, and A. Sumaryono, 2000. Lahars at Merapi Volcano, Central Java – An Overview. Journal of Volcanology and Geothermal Research 100:423-456.

Leavesley, G.H., G.C. Lusby, and R.W. Lichty, 1989. Infiltration and Erosion Characteristics of Selected Tephra Deposits From the 1980 Eruption of Mount St. Helens, Washington, USA. Hydrological Sciences Journal 34:339-353.

Major, J.J., T.C. Pierson, R.L. Dinehart, and J.E. Costa, 2000. Sediment Yield Following Severe Volcanic Disturbance – A Two Decade Perspective From Mount St. Helens. Geology 28:819-822.

Major, J.J., L.E. Mark, and K.R. Spicer, 2001. Response of Peak-flow Discharges to the Catastrophic 1980 Mount St. Helens Eruption. EOS 82(47):F511.

Manville, V., 2002. Sedimentary and Geomorphic Responses to Ignimbrite Emplacement – Readjustment of the Waikato River After the A.D. 181 Taupo Eruption, New Zealand. Journal of Geology 110:519-541.

Meyer, D.F. and H.A. Martinson, 1989. Rates and Processes of Channel Development and Recovery Following the 1980 Eruption of Mount St. Helens, Washington. Hydrological Sciences Journal 34:115-127.

Moody, J.A. and D.A. Martin, 2001. Initial Hydrologic and Geomorphic Response Following a Wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26:1049-1070.

Orwig, C.E., and J.M. Mathison, 1982. Forecasting Considerations in Mount St. Helens Affected Rivers. *In:* Proceedings of Mount St. Helens Effects on Water Resources. State of Washington Water Resources Center, Pullman, Washington, pp. 272-292.

Punongbayan, R.S., C.G. Newhall, and R.P. Hoblitt, 1996. Photographic Record of Rapid Geomorphic Change at Mount Pinatubo, 1991-1994. *In:* Fire and Mud – Eruptions and Lahars of Mount Pinatubo, Philippines, C.G. Newhall and R.S. Punongbayan (Editors). University of Washington Press, pp. 21-66.

Rodolfo, K.S., 1989. Origin and Early Evolution of Lahar Channel at Mabinit, Mayon Volcano, Philippines. Geological Society of America Bulletin 101:414-426.

Suwa, H. and T. Yamakoshi, 1999. Sediment Discharge by Storm Runoff at Volcanic Torrents Affected by Eruption. Zeitschrift für Geomorphologie, Supplement Band 114:63-88.

Waldron, H.H., 1967. Debris Flow and Erosion Control Problems Caused by the Ash Eruptions of Irazú Volcano, Costa Rica. U.S. Geological Survey Bulletin 1241-I.

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