Spatial and temporal patterns in fluvial recovery following volcanic eruptions: Channel response to basin-wide sediment loading at Mount Pinatubo, Philippines

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ABSTRACT

The June 1991 eruption of Mount Pinatubo, Philippines, was one of the largest volcanic eruptions of the twentieth century, emplacing 5–6 km^3 of pyroclastic-flow material on the flanks of the volcano. The combination of abundant, relatively fine-grained, easily erodible material and intense tropical rainfall led to numerous lahars immediately following the eruption. Even after major lahars ended, sediment yields in some basins remained orders of magnitude above pre-eruption levels. Using data collected from 1996 through 2003, we investigated five basins that experienced varying amounts of sediment loading in the 1991 eruption, from 1% to 33% of the basin area covered by valley-filling pyroclastic-flow deposits. From measurements of flow and bed characteristics made through time, we developed a general conceptual model for channel recovery following basin-wide sediment loading. Initially, finer-grained sediment and pumice are mobilized preferentially through selective transport. Once the bed is coarse enough for gravel-size clasts to interact with one another, clast structures develop, increasing form roughness and critical shear stress and inhibiting initial clast mobility. As sediment inputs continue to decline, the channel incises into valley bottom sediments, progressively armoring through winnowing. At Pinatubo, incision and armoring occur first as dry season phenomena due to reduced sediment inputs, eventually moving to year-round low-flow bed stability. Observed timing of the onset of in-channel biological recovery suggests that reestablishment of channel stability helps catalyze aquatic ecosystem recovery.

Keywords: Pinatubo, sediment transport, sediment supply, fluvial, volcanoes.

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INTRODUCTION

Hazards from volcanic eruptions with abundant fine-grained pyroclastic-flow material last well beyond the actual eruptive event. Following an eruption, easily erodible sediment and greater surface runoff create extremely high sediment yields in rivers draining active volcanoes. Sediment yields orders of magnitude higher than average world rivers have been measured at Mount St. Helens (Pearson, 1986; Dinehart, 1998; Major et al., 2000; Major, 2004), Mount Usu (Kadomura et al. 1983), Galunggung (Hirao and Yoshida, 1989), and Mount Pinatubo (Umbal, 1997; Tuñgol, 2002) in years immediately following major eruptions (Fig. 1). Much of the initial high sediment yield can be attributed to lahars, but even after lahar activity has ceased, sediment yields may remain elevated (Major et al., 2000; Hayes et al., 2002; Major, 2004).

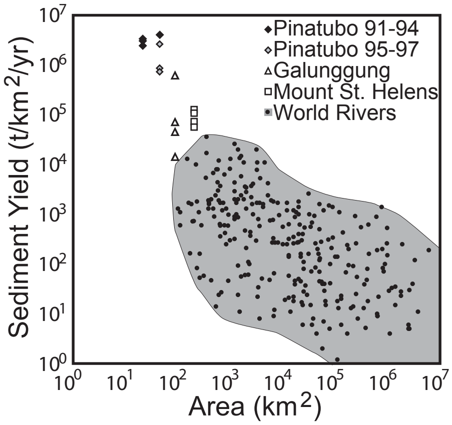

Figure 1. Sediment yields on volcanically disturbed rivers as compared to normal world rivers. Shown here are sediment yields from Galunggung Volcano in Indonesia (Hirao and Yoshida, 1989), the North Fork Toutle River at Mount St. Helens (Pearson, 1986), and the Pasig-Potrero River at Mount Pinatubo (Umbal, 1997; Tuñgol, 2002) in the four years following a major eruption. Pinatubo also has years 1995–1997 plotted to show how sediment yields are declining. Sediment yields from normal world rivers come from Milliman and Syvitski (1992).

Pyroclastic-flow and tephra-fall material inundating the surrounding landscape can severely impact watersheds. On hillslopes, loss of vegetation and blanketing by tephra leads to reduced infiltration rates and flashier responses to storms (Segerstrom, 1950; Waldron, 1967; Kadomura et al., 1983; Janda et al., 1984a; Yamamoto, 1984; Leavesley et al., 1989; Shimokawa et al., 1989). Abundant fine-grained material is easily mobilized from hillslopes into rills and channels. In valleys, pyroclastic flows can temporarily bury preexisting drainage networks or permanently reorganize drainage basin boundaries. In addition, abundant erodible material coupled with greater surface runoff often lead to the development of volcanic debris flows and hyperconcentrated flows, referred to collectively as lahars.

Watershed recovery from volcanic disturbance represents an important process, yet only a few studies were conducted on the hydrologic effects of eruptions prior to the May 1980 eruption of Mount St. Helens. One of the first comprehensive studies of long-term geomorphic recovery of an eruptive landscape was on Paricutín Volcano in Mexico (Segerstrom, 1950, 1960, 1966). Paricutín first erupted in 1943, with activity continuing through 1952. At Paricutín, many features described in later eruptions were documented including destruction of vegetation, reduced infiltration rates related to ash crusting, increased mass movements, extensive rill erosion, and development of debris-laden stream flows. Like lahars at other volcanoes (Janda et al., 1984b; Tuñgol, 2002), many debris flows scoured down below the pre-eruption surface, incorporating older sediments

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with new eruptive materials. By 1965, the area achieved relative stability, and farmers reoccupied most low-lying areas around the edifice. Landscape stability and recovery in these lower areas was attributed primarily to revegetation.

Irazú Volcano in Costa Rica erupted ash from 1963 to 1965. Waldron (1967) documented erosion of ash deposits with particular emphasis on debris flow hazards and mitigation efforts. Similar to Paricutín, ash surfaces crusted, reducing infiltration rates and increasing runoff rates to as high as 95%–100% during high-intensity rainfall events. Initially most ash erosion occurred through rilling and headward erosion of gullies. In the second year, channel erosion became more severe, leading to oversteepened banks, which reactivated old landslides and formed new ones. Debris flows were common, with more than 90 during the 1964 rainy season alone. Much of Waldron's work focuses on these flows, downstream hazards associated with them, and mitigation efforts.

The May 1980 eruption of Mount St. Helens generated some of the first comprehensive, long-term, detailed studies of geomorphic impact of volcanic eruptions on neighboring watersheds, with continued monitoring to the present. During the May 18th eruption, a lateral blast denuded over 550 km^2, and 0.19 km^3 of easily erodible tephra was deposited over relatively steep terrain. In addition, 2.8 km^3 of debris avalanche material composed mostly of sand and fine gravel was emplaced in the North Fork Toutle River basin (Janda et al., 1984b). Detailed studies documented intense sheet wash and rill erosion on hillslopes in the year following the eruption. By the second year, sheet and rill erosion had dramatically declined due to changes in hillslope hydrology (Collins et al., 1983; Lehre et al., 1983; Collins and Dunne, 1986). In river valleys, lahars moved through many major tributaries of the Toutle and Lewis Rivers, transporting sediment from low-order watersheds, scouring the bed, and eroding main channel banks. Much of the sediment eroded from channels was pre-eruption alluvium and colluvium (Janda et al., 1984b). In the debris avalanche valley fill, the newly forming channel network went through four stages: (1) headward extension of the channel network, (2) incision, (3) channel widening and aggradation, and (4) alternating periods of aggradation and scour (Janda et al., 1984b; Pearson, 1986).

Since Mount St. Helens, studies on Mount Usu, Unzen, and Sakurajima in Japan (Kadomura et al., 1983; Shimokawa and Taniguchi, 1983; Chinen and Kadomura, 1986; Mizuyama and Kobashi, 1996), Mount Galunggung in Indonesia (Hamidi, 1989; Hirao and Yoshida, 1989), and Mayon Volcano and Mount Pinatubo in the Philippines (Rodolfo, 1989; Rodolfo and Arguden, 1991; Daag, 1994; Newhall and Punongbayan, 1996; Tuñgol, 2002) have addressed landscape disturbance and recovery from volcanic eruptions. A significant fraction of this research concentrates on the time immediately following eruptions, when disturbance to the hydrologic system is greatest. In many cases, reduced infiltration rates and excess sediment contributed to lahar activity and immediate downstream hazards for the local populace. At Mount Pinatubo, for example, major lahars in the first year affected 364 villages, home to 2.1 million people (Mercado et al., 1996).

Relatively little research has focused on the time after the initial lahar phase has passed and sediment transport is controlled by nonlahar fluvial processes. During this period rivers may no longer be dominated by lahar activity, but sediment yields remain far above pre-eruptive levels. Sediment yields on the Pasig-Potrero River at Mount Pinatubo six years after the eruption were still two orders of magnitude higher than pre-eruption yields (JICA, 1978; Hayes et al., 2002). Almost 20 yr after the eruption of Mount St. Helens, suspended sediment yields in the area draining the debris avalanche deposit remained two orders of magnitude higher than pre-eruption background values (Major et al., 2000; Major, 2004). At both volcanoes, hydrologic hazards including excess sedimentation and downstream flooding are still concerns years to decades after major eruptions. The time scale over which fluvial recovery will occur is still not well constrained. Long after the initial eruption, volcanically disturbed rivers can continue to be a significant threat to communities.

Our study investigates watershed recovery on the east flank of Mount Pinatubo following the June 1991 eruption, focusing on the time after major lahar activity ceased. Not only does Pinatubo offer an excellent opportunity to study fluvial recovery from an eruption, but it also offers a unique window into dynamics of sediment-laden rivers in general. Many mountain watersheds in tectonically active areas are dominated by discrete, often substantial, inputs of sediment from hillslope disturbances. These landslide-derived sediment pulses can constitute a major portion of the sediment budget (Dietrich and Dunne, 1978; Swanson et al., 1982; Pearce and Watson, 1986; Benda and Dunne, 1987). Sediment loading also occurs from anthropogenic sources, such as mining debris or sediment released during dam removal (Gilbert, 1917; Pickup et al., 1983; Knighton, 1989). However, the dynamics of how a large sediment input is processed and moved downstream are still being studied (Meade, 1985; Madej and Ozaki, 1996; Lisle et al., 1997, 2001; Madej, 2001; Cui et al., 2003a, 2003b).

In the case of Mount Pinatubo, the excess sediment load is extreme. The behavior of a system when subjected to such an intense disturbance should help elucidate the relationships important in systems with less intense disturbances. By studying how a volcanically impacted landscape is affected by a substantial increase in sediment load and how the geomorphic systems process, remove, or stabilize that excess sediment, we are better able to infer how watersheds experiencing episodic sediment loading may behave.

We examined a series of watersheds with varying amounts of sediment loading and thus different rates of sediment remobilization and eventual recovery and stabilization of the watershed. Recovery can take on many forms and is subject to many definitions. Here, we are concerned mostly with the physical recovery of the stream channel. We consider a channel recovered when it can support the reestablishment of an aquatic ecosystem of pre-eruption complexity. In some cases, the channel will be able to return to pre-eruption conditions (similar grain size, roughness, and lateral mobility rates) although perhaps with more terrace or valley bottom storage than before. In other cases, a new equilibrium condition may be reached. In both cases, however, physical recovery implies a degree of channel stability that requires evacuation or stabilization of the bulk of the excess sediment load and the reduction of significant lateral and vertical channel adjustments.

We begin by reviewing the potential response of fluvial systems to the introduction of abundant fine-grained sediment and how channels might adjust as sediment input declines. We then describe recovery processes at Pinatubo, drawing on data and observations from five basins with varying impact from the eruption. This multi-basin approach is used both to illustrate the importance of the degree of initial impact and as a form of space-for-time substitution. We also use one basin as a case study, following the Pasig-Potrero River from 1996 through 2003. Based on the parallel implications of these two approaches, we propose a conceptual framework to explain trends in channel recovery following massive sedimentation events.

THEORETICAL CONTEXT

As sediment inputs increase, a fluvial system can adjust by increasing storage through channel or valley bottom aggradation or by increasing sediment transport rates. If the river is supply limited and able to transport all sediment that enters the system, then an increase in sediment input can directly translate into an increase in sediment transport without necessitating adjustments in storage. If the sediment load far exceeds the transport capacity, as it did at Pinatubo after the eruption, then adjustments in geometry or substrate within the channel or valley bottom will result in changes in sediment storage or transport or both. We consider here the case of increased sediment transport.

Sediment transport is a function of excess basal shear stress, which is the total basal shear stress generated by a flow minus the portion removed through turbulent dissipation from roughness elements. The portion of the excess shear stress available to move sediment may be reduced further by a critical value that must be overcome to initiate motion. The remaining effective shear stress will increase if either the total shear stress increases, through an increase in depth, slope, or discharge, or if the critical shear stress or roughness decreases. Sediment transport rates can also change if the sediment being transported has a different grain size distribution than the substrate before sediment loading. Under conditions of selective transport, finer sediments mobilize at lower flow conditions than coarser clasts and thus can be evacuated at higher rates than coarser material (Komar, 1987). In addition, as sand content in mixtures increases, transport rates of both sand and gravel may increase by orders of magnitude (Wilcock et al., 2001; Wilcock and Kenworthy, 2002). Thus, the addition of large amounts of sand may enhance overall sediment transport.

After an initial sediment loading event, as sediment inputs decline through time, the reverse conditions apply and either a decrease in storage or transport rates must occur. In order to decrease the sediment transport rate, the effective shear stress should decrease, either through lower total basal shear stress or higher critical shear stress or roughness. Channel widening, increased sinuosity, slope adjustments through downstream aggradation and upstream incision, or lower discharge can all reduce total basal shear stress. An increase in surface grain size or the introduction of bedforms, pebble clusters, or obstructions like vegetation or large woody debris will increase the roughness. All of these factors will lower the excess shear stress. The effective shear stress can be reduced further by raising the critical shear stress. Increasing surface grain size and particle interactions can raise the critical shear stress. Because of all the degrees of freedom outlined above, it is hard to predict from first principles exactly how a channel will accommodate decreasing sediment inputs and the order and sequencing of expected changes. We do, however, have an idea of what types of changes to expect in a system under a decreasing sediment supply.

STUDY AREA

Mount Pinatubo is located ~100 km northwest of Manila on the island of Luzon, Philippines. In June 1991, Mount Pinatubo erupted, emplacing 5–6 km^3 of pyroclastic-flow material on the volcanic flanks. River valleys were partially buried with as much as 200 m of loose pyroclastic debris (Scott et al., 1996b).

The climate at Mount Pinatubo is tropical and monsoonal, with distinct rainy and dry seasons. Clark Air Base on the lower east flank of the volcano receives an average annual rainfall of 1,950 mm, 60% of which falls during the summer months of July, August, and September (Scott et al., 1996a). This rainfall often comes in very intense storms, which, coupled with loose sediment deposited during the eruption, led to major lahars following the eruption on all rivers draining the volcano. Over time, the threshold rainfall necessary to trigger a lahar has risen, reducing lahar frequency (Tuñgol, 2002).

Sediment yields immediately following the eruption were several orders of magnitude higher than normal (Fig. 1). Initial estimates of total sediment yield made using standard techniques (U.S. Army Corps of Engineers, 1994) were lower than actual yields, by close to an order of magnitude. Initial U.S. Geological Survey estimates were closer but were still ~50% too low (Pierson et al., 1992). Yields declined nonlinearly during the first four years following the eruption, with minor variations to the overall declining trend occurring due to local events such as stream captures or lake break-out floods (Umbal, 1997; Tuñgol, 2002) (Fig. 2). Estimates made by Umbal (1997) have sediment yields continuing to decline exponentially. Due to a lack of sediment yield data after 1997, however, it is unclear how the trend will continue.

East flank basins were variably affected, with 1% to 33% of each basin covered with pyroclastic-flow deposits. Our study focuses on five rivers on the east side of the volcano, which are, in order from the most impacted to the least, the Sacobia, Pasig-Potrero, O'Donnell, Gumain, and Porac Rivers (Fig. 3). Table 1 shows the size and relative volcanic impact in terms of the percent area covered by valley-filling primary pyroclastic-flow deposits.

The Pasig-Potrero and Sacobia Rivers have a unique history involving a massive stream capture event in October 1993. At the time of the eruption, the Sacobia River basin extended into the area now occupied by the 1991 crater. The Pasig-Potrero River initiated several kilometers downstream. In October 1993, the Pasig-Potrero River captured the upper half of the Sacobia basin, doubling the basin area of the Pasig-Potrero while halving that of the Sacobia (Punongbayan et al., 1994). Since this capture occurred after three rainy seasons, a substantial amount of sediment had already left the upper Sacobia River basin (Daag, 1994), and the Pasig-Potrero inherited transport capacity (increased discharge) without a commensurate increase in sediment load from the upper watershed. At the end of the 1992 lahar season, the upper Sacobia basin had an estimated 12×10^6 m^3 of sediment per km^2 of basin area, while the Pasig-Potrero basin had 18×10^6 m^3/km^2 (Daag, 1994). Although the Pasig-Potrero River did have a sharp increase in

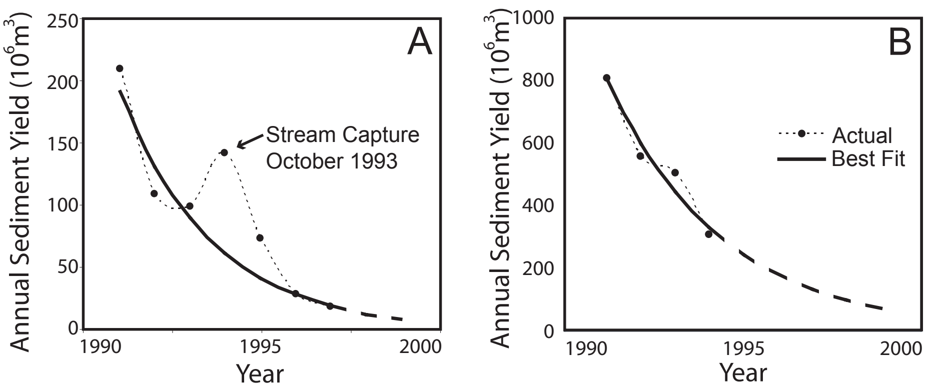

Figure 2. Sediment yields from (A) the Sacobia-Pasig-Abacan River system, and (B) Mount Pinatubo overall. Yields generally followed an exponential decline in the years following the eruption. Data for 1991–1994 and the "best fit" exponential line estimating future yields are from Umbal (1997). Data from 1995 to 1997 come from Tuñgol (2002) and are for the Pasig-Potrero River system only. All data are based on mapping of lahar deposits. On the Sacobia-Pasig-Abacan, a stream capture event in October 1993 led to temporarily elevated sediment yields in 1994. Pre-eruption sediment yields on the Pasig-Potrero River were <1×10^6 m^3 (JICA, 1978).

sediment yield immediately following the stream capture event, the increase was transient, and now the Pasig-Potrero River is adjusting more rapidly than the Sacobia River.

The sediment-laden rivers of Pinatubo have several interesting features (Fig. 4). During the rainy season they are shallow and highly braided, with braids ranging in size from a few centimeters in width to tens of meters, all of which actively transport sediment. Transport occurs as a moving carpet of sand and fine gravel over a smooth bed. Gravel clasts roll or slide independently over the predominantly sand bed. Any clast that becomes stationary in an active channel is quickly scoured around, sinks into the bed, and is buried, thus maintaining a smooth bed. Flow is often super-critical, and transient antidunes are present. During high flows, the water level may rise high enough to completely fill the valley bottom, and channel-spanning roll waves pulse downstream. Many of these characteristics are beginning to change, and it is these adjustments that we are seeking to document and understand.

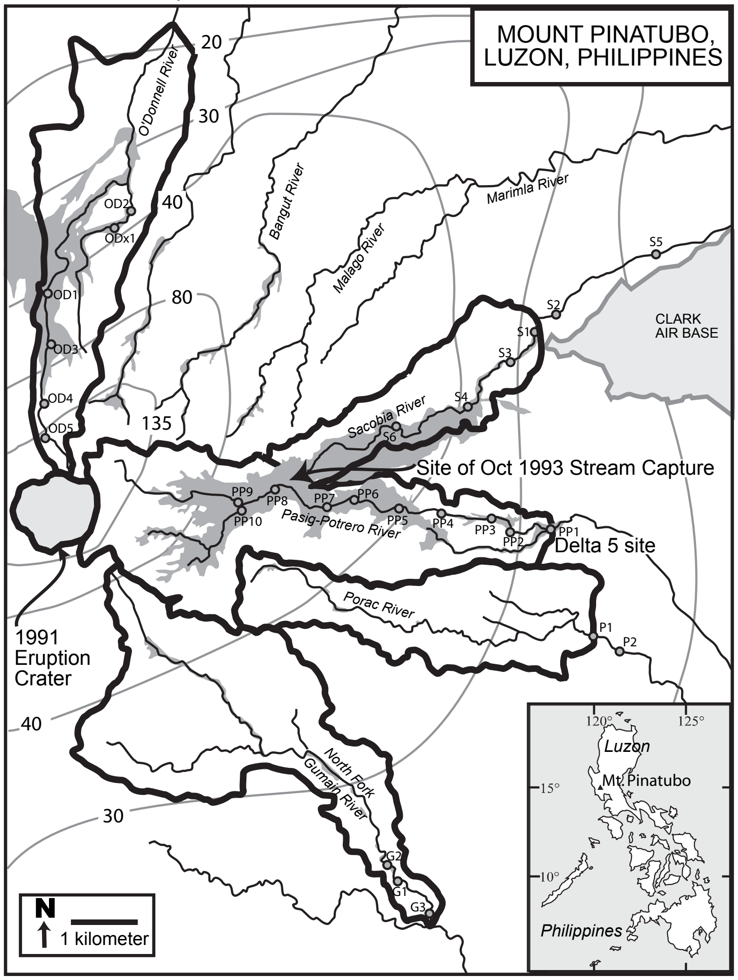

Figure 3. Eastern half of Mount Pinatubo showing major rivers draining the east and north flanks of the volcano. Watershed boundaries for the five study basins are delineated. Circles mark field sites. Massive valley-filling primary pyroclastic-flow deposits from the June 1991 eruption are shaded (Scott et al., 1996b), and isopach lines represent cumulative tephra fall deposits in centimeters (Paladio-Melosantos et al., 1996).

METHODS

We use data collected from 1996 through 2003 to examine evidence of sediment removal and document channel response in each basin (Table DR1).[1] We focus on adjustments in the channel bed including grain size, roughness, and the presence/absence of bedforms or clast structures. In some rivers we are tracking changes in low-flow sediment mobility or transport through time. Although our focus is on the physical recovery of the channel system, we noted signs of ecologic recovery—or lack thereof—within the channel and valley bottom.

Cross-Sectional Surveys

Survey lines were established in 1997 at or near the alluvial fan head in four of the five basins in our study area (Panfil et al., 1998). We established an additional cross section upstream of the fan head on the O'Donnell River in 2001. Table DR1 shows when cross sections were established and reoccupied for each river. During each survey, we measured bed topography across the valley bottom using an auto level and stadia rod. Depth and mean downstream velocity were measured at equally spaced intervals in active channels. We measured mean velocity using a Swoffer current meter in later surveys.

TABLE 1. BASIN CHARACTERISTICS

Basin	Basin area† in 1991 (km²)	Area† covered by pyroclastic-flow deposits‡ (km²)	Basin covered by pyroclastic-flow deposits‡ (%)
Sacobia	42.5 (19)§	12.3	29
Pasig-Potrero	22.7 (45)§	7.5	33
O'Donnell#	37	6.8	18
Gumain#	41	2.0	5
Porac	30.8	0.3	1

†Data are from Daag, 1994; Major et al., 1996; Janda et al., 1996; and Scott et al., 1996b. Basin areas are for post-eruption conditions in 1991 upstream of alluvial fan heads: Pasig-Potrero River above 240 m (PP1 site), Sacobia River above 200 m (S1 site), O'Donnell River above 240 m, Gumain River above 60 m (G3 site), and Porac River above 120 m (P1 site).
‡Area and percent basin covered by pyroclastic-flow deposits refers specifically to valley-filling primary pyroclastic-flow deposits.
§In October 1993, a stream-capture event occurred, diverting the upper Sacobia River basin into the Pasig-Potrero River basin. Drainage areas following the capture are given in parentheses.
#We considered only the west fork of the O'Donnell River and the north fork of the Gumain River.

[1]GSA Data Repository item 2005027, data summary, is available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

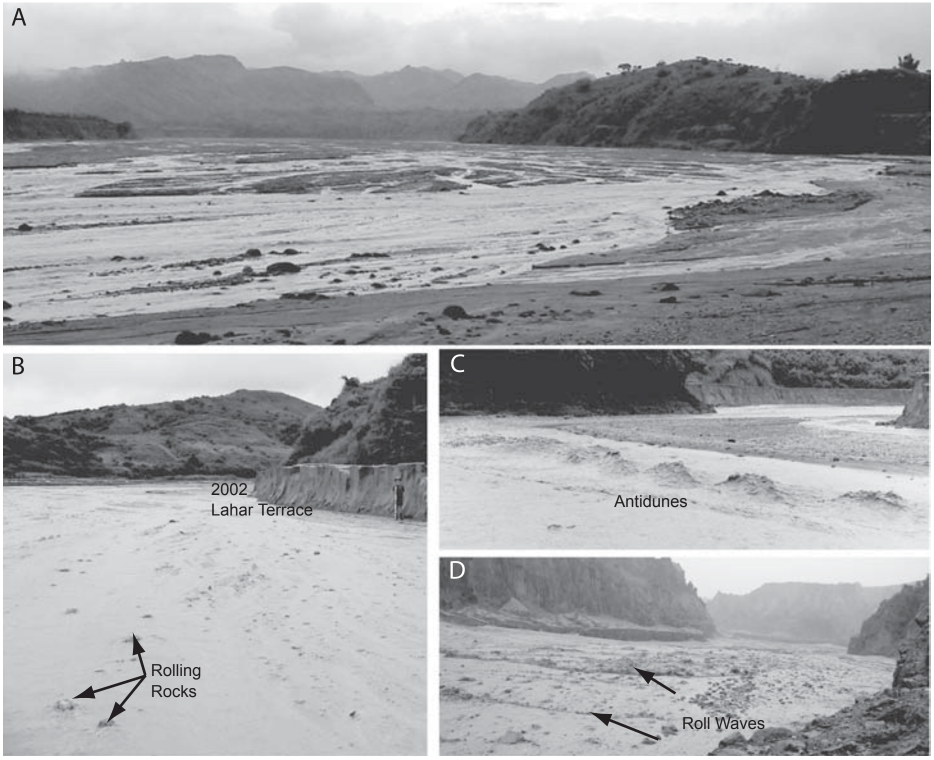

Figure 4. Photos from the (A) Pasig-Potrero, (B) and (C) Sacobia, and (D) O'Donnell Rivers illustrating several of the unique features of rivers that were severely impacted in the 1991 eruption. (A) Channels are often wide and braided with dozens of active braids, from widths of a few centimeters up to tens of meters, all transporting sediment. (B) Many of the larger clasts can be seen sticking up out of the flow and rolling or sliding along a smooth carpet of moving sand and fine pebbles. (C) Flow is often supercritical, and antidunes are common. (D) Roll waves can be seen moving downstream under all flow conditions, although they become larger and more frequent during high flow events. This event had roll waves with amplitudes up to one meter.

Early surveys used a stopwatch to measure surface velocity from which we approximated mean velocity as 80% of the surface velocity. At each survey site we measured water surface slope using the level and stadia. Surface grain size distributions were obtained through Wolman pebble counts (Wolman, 1954). To track bed surface composition, clasts ≥4 mm in diameter were categorized as lithic or pumice.

Longitudinal Surveys

On the three rivers with the most sediment loading we measured bed surface long profiles from the alluvial fan head as far upstream as possible. These data were coupled with a reconnaissance survey done in 1996 on the Pasig-Potrero River by J. Stock. We used a laser range finder with built-in inclinometer to measure bed elevation and slope at points spaced 50–100 m apart along the river. With this spacing, the range finder has uncertainties of ± 0.06 m in the horizontal and ± 0.14 m in the vertical. Given this, we do not use the profile elevation data to show absolute changes in bed elevation, but we do consider that slopes integrated over several hundred meters are accurate and can be compared between years.

In addition to measuring longitudinal bed elevation, we also conducted Wolman pebble counts every 1–2 km. We noted clast type (lithic versus pumice) for all clasts ≥4 mm diameter to document lithologic composition of the bed surface.

On the O'Donnell River we surveyed 10.9 km upstream, all the way to the headwaters of the channel at the crater wall. On the Sacobia River, we could survey 8.0 km upstream of the alluvial fan head in the dry season, to a spring emanating from a cliff, but in the rainy season we were limited to the lower 5 km. A 16.0 km stretch of the Pasig-Potrero River was surveyed, including 7.3 km on the alluvial fan for comparison.

Sediment Mobility and Transport

In channels with highly mobile clasts, we conducted surveys to quantify conditions necessary for sediment mobility. We surveyed four sites on the Pasig-Potrero and Sacobia Rivers repeatedly from 1997 through 2002 (Table DR1). Surveys from 1997 are presented in Montgomery et al. (1999). In these surveys, we measured the diameter of clasts that were either mobile or stationary, noted clast composition (lithic or pumice), and measured water depth. Clasts were designated as mobile only if they were actively moving at the time of measurement. Although these surveys neglect variations in important parameters like flow velocity, we sampled across entire braids to ensure a range of flow conditions.

By 2000, low bars within the active braidplain were becoming weakly armored, leading to more grain interactions in channels flowing across bars. To assess the importance of these clast interactions, we surveyed braids flowing across bars separately from braids not associated with bars. During the winter of 2001, we also conducted a clast mobility survey in what we termed "clear-water channels." These braids had visibly low suspended sediment concentrations and few mobile clasts ≥4 mm. Many were groundwater-fed, and we could trace them to their source in the river bed. The average velocity measured in one of these braids was 0.4 m/s, swift enough to mobilize and transport coarser sediment in exposed positions, but only small amounts of sand were mobile.

On the Pasig-Potrero River, we also measured sediment transport rates during low-flow conditions in the rainy season of 2001. We compare sediment transport rating curves with a similar study undertaken by Hayes et al. (2002) during the 1997 and 1998 rainy seasons. Bedload and suspended load were measured over the course of a four-week period in August and September 2001. We sampled both suspended load and bedload using the equal-width increment technique as outlined in Edwards and Glysson (1999). For suspended load, we obtained vertically integrated bulk samples with a U. S. Geological Survey DH-48 sampler with a 1/4 inch (0.64 cm) opening. Bedload was measured using a handheld modified U. S. Geological Survey Elwha pressure-difference sampler with a 200 mm × 100 mm opening and 1 mm mesh bag. Bedload transport was computed assuming a 100% sampler efficiency (Hayes et al., 2002).

For each suspended load sample, we used the average of three separate passes across the channel. For bedload discharge, we collected samples on two separate passes across the channel. One of the two samples was dried, weighed, and sieved. We measured discharge immediately before and after sample collection to ensure flow conditions remained constant. If the discharge changed more than 30%, transport data were discarded.

TABLE 2. SUMMARY OF BASIN RESULTS 1997–98 AND 2000–02

	Porac	Gumain	O'Donnell	Pasig-Potrero	Sacobia
% Pumice†					
1997–98	4%	0%	N.D.	75%	86%
2000–02	1%	0%	68%	53%	93%
Surface grain size†					
D_{50} 1997–98	–3.7 φ (13 mm)	–5.9 φ (60 mm)	N.D.	–2.8 φ (7 mm)	–2.3 φ (5 mm)
D_{50} 2000–02	–6.2 φ (74 mm)	–6.6 φ (97 mm)	–2.3 φ (5 mm)	–1.8 φ (3 mm)	–1.3 φ (2.5 mm)
D_{90} 1997–98	–7.6 φ (194 mm)	–8.2 φ (294 mm)	N.D.	–5.3 φ (39 mm)	–5.0 φ (32 mm)
D_{90} 2000–02	–7.9 φ (239 mm)	–8.3 φ (315 mm)	–5.1 φ (34 mm)	–5.2 φ (37 mm)	–4.6 φ (24 mm)
Roughness‡					
n 1997–98§	0.078	0.064	N.D.	0.024	0.013
n 2000–02	N.D.	0.067	0.035	0.023	0.023
C_f 1997–98§	19	17	N.D.	82	288
C_f 2000–02	N.D.	16	28	90	85
Aggradation/ Degradation (m)#					
August 1997 storm	<0.5	<0.5	N.D.	–12.6 (–7.9 to –17.3)	–2.1 (–1.6 to +2.3)
1997–2000	<0.5	–1.7 (–1.5 to –1.8)	N.D.	+12.7 (8.9–16.5)	+3.1 (+2.6 to +3.5)
2000–2001	N.D.	–0.9 (–0.8 to –1.0)	N.D.	+2.6 (2.0–3.1)	–0.1 (–0.5 to +0.8)

Note: Values listed are averages for all cross sections near the alluvial fan head measured during the given time interval. N.D.—no data.

†Surface grain size and % pumice come from Wolman surface pebble counts.

‡Roughness parameters (Manning's n, $n = R_h^{2/3} S^{1/2} v^{-1}$, and coefficient of friction, $C_f = \rho v^2 \tau_b^{-1}$) were back-calculated from flow measurements at each cross section. Here, R_h is the hydraulic radius, S is water surface slope, v is mean velocity, ρ is water density, and τ_b is the total basal shear stress.

§Velocities from 1997 and 1998 were adjusted to shift from measured thalweg to mean cross-sectional values.

#Valley bottom aggradation/degradation refers to the overall change in the thalweg or active braid-plain elevation between cross sections. The number listed is an average of all cross sections with the range from all cross sections given in parentheses.

TABLE 3. SUMMARY OF BASIN OBSERVATIONS

	Lateral mobility†	Bed morphology/Clast interactions‡	Signs of ecological recovery§
Porac	Low mobility: Channel cross sections stable from 1997 to 2000; stable during 1997 storm event	Armored bed	Vegetated banks; fish and macroinvertebrates present by 2000
Gumain	High mobility during 1997 storm event; Low to moderate mobility 1997–2001	Armored bed	Light vegetation on 1997 terrace surfaces by 2000; Fish returned by 2001
O'Donnell	High mobility during rainy season—wide, shallow, and braided; As of 2001, many reaches have moderate mobility during dry season	Pebble clusters and patchy armor in rainy season; Some reaches fully armored during dry season	Very light vegetation in rill fields and terrace surfaces by 2001; some algae in river during dry season; upper 2 km have valley bottom vegetation, frogs and macroinvertebrates by 2002
Pasig-Potrero	High mobility during rainy season—wide, shallow, and braided; As of 2001, many upper basin reaches have moderate mobility in dry season	Pebble clusters and patchy armor in rainy season; Some upper basin reaches armored during dry season	Very light vegetation in rill fields and terrace surfaces by 2001; some algae in river during dry season; nothing in active channel area during rainy season by 2002
Sacobia	High mobility year-round—wide, shallow, and braided	Patchy armor on bars composed mostly of pumice—fairly ineffective when flow reaches bar tops	Light vegetation in rill fields and terrace surfaces by 2001; nothing in active channel area during rainy season by 2002

†Lateral mobility is assessed based both on repeat surveys of cross sections and observations made during both the rainy and dry seasons. Lateral mobility is classified as low (incised and fairly stable), moderate (incised but still migrating rapidly across the valley bottom), and high (braided or incised but migrating tens of meters in a single event).

‡Bed morphology and clast interactions encompass observations of the presence or absence of surface armor, clast structures like pebble clusters or patches of armor, and variations between the rainy and dry seasons as of 2002.

§Signs of ecological recovery include observations of vegetation in the valley and within the active channel and the presence or absence of macroinvertebrates. Presence or absence of fish was usually assessed through conversations with local residents.

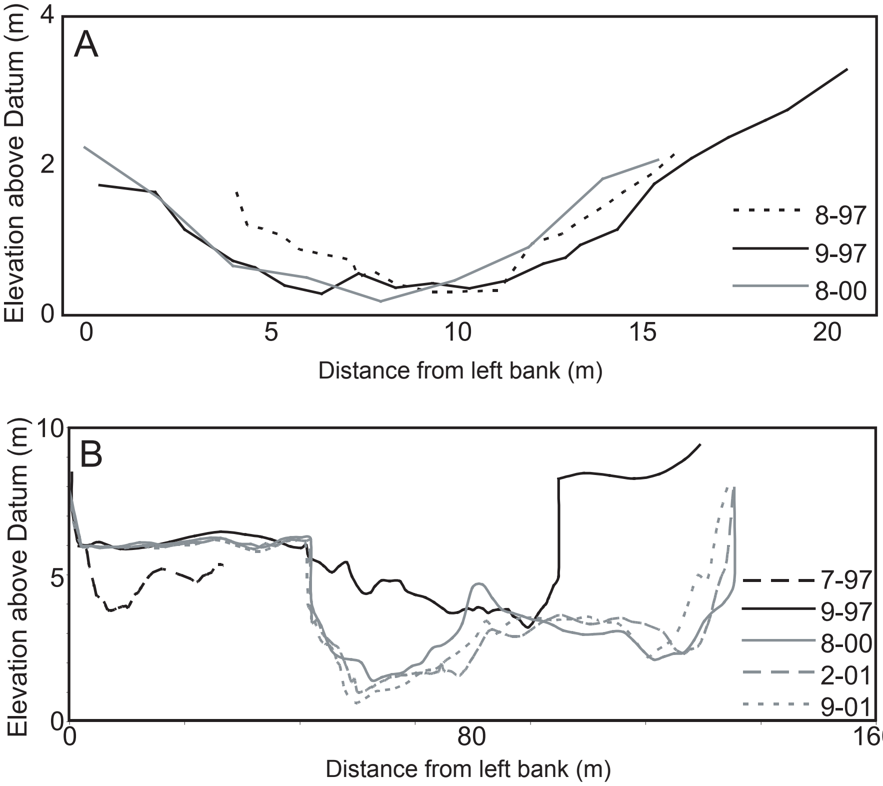

Figure 5. Cross-sectional surveys from the (A) Porac and (B) Gumain Rivers. Surveys of the Porac River site P1, taken before and after a 100-yr storm event in August 1997 with an additional survey taken in August 2000, show little lateral movement during either time period. Surveys of the Gumain River site G1 show substantial lateral movement and vertical incision during the same storm event in August 1997. Between August 1997 and August 2000, the channel continued to deepen and widen, but the cross section remained fairly stable both laterally and vertically from August 2000 through September 2001.

RESULTS

The degree of channel response and timescale of channel recovery varied directly with the initial sediment loading. Below we examine and review changes in the five study basins, with particular emphasis on 1997 through 2002. It is important to note that the basins were at different phases in the recovery process in 1997, a result of variations in initial sediment loading. Those basins with the least sediment loading had recovered more than those with more severe sediment loading. We discuss our observations on the bed surface, channel form, and flow and sediment transport processes in order from basins with the least to the greatest impact, or those farthest along the recovery process to those with less progress. All our results focus on the portion of the basin upstream of the alluvial fan head. In this context, references to the lower and upper basin are the lower and upper half of the basin upstream of the alluvial fan head. In some cases, river kilometers are used to denote locations within the basin upstream of the fan head. An overview of the results for each basin is given in Tables 2 and 3.

Porac River

The Porac River had only 1% of its basin covered by pyroclastic-flow deposits (Major et al., 1996), although >0.4 m of ash and tephra-fall blanketed upper basin hillslopes (Paladio-Melosantos et al., 1996). Lahars occurred in the summer of 1991. Helicopter flights in September 1991 found practically all pyroclastic-flow deposits gone by the end of the first rainy season (Pierson et al., 1992). Cross-sectional surveys at two sites upstream of the alluvial fan head on the Porac River began in August of 1997. On August 20, 1997, a storm with a 100-yr recurrence interval occurred on the east flank of Pinatubo (Tuñgol, 2002). Repeat surveys after the storm showed only minor changes in bed topography (Fig. 5A). In August 2000, surveys of site P1 found almost no changes in bed topography since 1997. Site P2 could not be compared directly to 1997 data due to the construction of a small dam below the site. In 1997, the P1 site was dominated by very coarse pebble gravel (average D_{50} of -5.5ϕ [45 mm]) and had high roughness values with an average Manning's n value of 0.08. Site P2 had a mean grain size in the granule range, with a D_{50} of -1.9ϕ (4 mm), and a Manning's n value of 0.03. By 2000, both cross sections had coarsened, with D_{50} values in the very coarse pebble to cobble range: -6.7ϕ (104 mm) and -5.6ϕ (49 mm) at sites P1 and P2, respectively. By 1997, the banks were fully vegetated. By 2000, algae, macroinvertebrates, snails, and fish had returned to the main channel.

Gumain River

The Gumain River had 5% of its basin area covered by pyroclastic-flow deposits (Janda et al., 1996). Lahars occurred during the 1991 rainy season. Helicopter flights in September 1991 showed only 20%–40% of the pyroclastic-flow deposits remaining in the upper Gumain valley (Pierson et al., 1992). No lahars were reported during the 1992 or 1993 rainy seasons (Janda et al., 1996).

Cross-sectional survey lines were established on three sites upstream of the alluvial fan head in August 1997. Repeat surveys at sites G1 and G3 after the storm of August 20, 1997, show substantial incision and lateral movement of the channel (Fig. 5B). In 2000 and 2001, repeat surveys were conducted on the same two sites. Site G1 had stabilized and showed little change other than some deepening of the thalweg from September 1997 through 2001. At site G3, the channel continued to migrate rapidly across the floodplain, moving by at least 18 m from 2000 to 2001.

The Gumain River bed is dominated by coarse pebble gravel to large cobbles. In 1997, surface D_{50} values measured on three cross sections ranged from -4.5 to -7.0ϕ (23–128 mm). Surface D_{50} values in 2000 and 2001 at sites G1 and G3 were coarser than 1997 values by an average of -1.1ϕ. Backcalculated Manning's n values ranged from 0.041 to 0.050 in 1997, and rose to 0.07 in 2001. We were unable to get accurate flow measurements on site G1 in 2001 due to backwater effects from a small dam erected just downstream from the site.

By 2000, sparse vegetation occupied a terrace formed during the August 20, 1997, event. The river bed was armored and rough with fairly clear water. In 2000, there was no evidence of either macroinvertebrates or fish in the river, but by 2001 locals reported that fish had returned to the main channel.

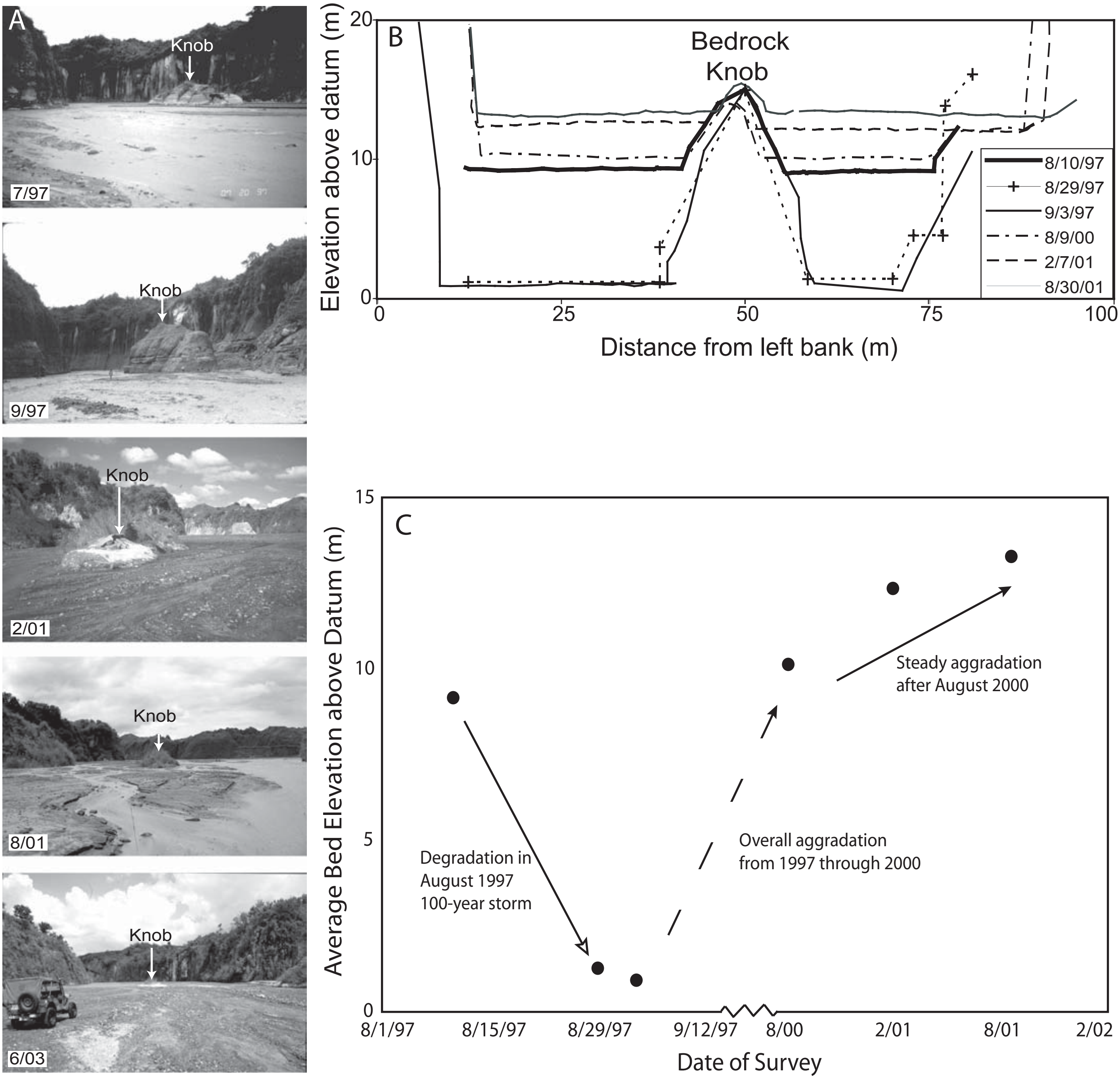

Figure 6. Pasig-Potrero River site PP2 ("Hanging Sabo"). PP2 has had steady aggradation following a dramatic event during a 100 yr storm in August 1997 (Tuñgol, 2002), which caused at least 8 m of degradation. Since then, the bed has aggraded 12 m. (A) Photo series showing scour and aggradation around a bedrock knob ("Hanging Sabo Rock"). There are people for scale in the 9/97 photo. (B) Surveys of the same river cross section from 1997 to 2001. (C) Detail of the bed elevation changes through time. Note the scale change between 1997 and 2000.

O'Donnell River

The O'Donnell River drains the north flank of Mount Pinatubo. The 1991 eruption covered 18% of the basin with pyroclastic-flow deposits. Major lahars occurred through 1994 (N. Tuñgol, personal commun.). The channel was not surveyed until 2000, at which point it was still wide, turbid, and braided at the fan head. The upper basin had coarsened considerably, leading to noticeable downstream fining (average D_{50} of -4.4ϕ [21 mm] in the upper 5 km versus -2.7ϕ (6 mm) in the lower 5 km). The channel bed is still very active during the rainy season, with a highly mobile bed. In summer 2001, bed elevation changes of at least 0.5 m were observed during a single storm.

During the 2001 dry season, reaches of the O'Donnell shifted from wide, shallow, and braided to a single, incised, armored channel. The reaches where this incision occurred stretched as far downstream as 2 km above the alluvial fan head. The flow had visibly low suspended sediment concentrations. In places where the valley constricts to a width of less than 12 m, the channel had cut down to bedrock. Algae were present in the main channel during the dry season but were confined mostly to hot springs in the upper basin. In the headwaters (uppermost 2 km), vegetation was present in the valley bottom, and several aquatic species were found including algae, macroinvertebrates, and frogs. In the lower basin, vegetation was limited to a few high terraces and rill fields, and no aquatic flora or fauna were observed in the main channel or valley bottom.

Pasig-Potrero River

Of the five study basins, the Pasig-Potrero River had the greatest sediment cover with ~33% of the basin area covered by valley-filling pyroclastic-flow deposits (Major et al., 1996) to depths as great as 200 m in the valley bottom (Scott et al., 1996b). The Pasig-Potrero River is currently wide, shallow, and braided with high sediment loads even at low flow. It is incised into its alluvial fan and continues to aggrade near the fan head (Fig. 6). By 2000, the long profile had developed a fairly consistent curvature upstream of the alluvial fan head. This is a change from 1996 when a segment 5–9 km above the fan head had a steady 3.5% gradient and no apparent curvature (Fig. 7).

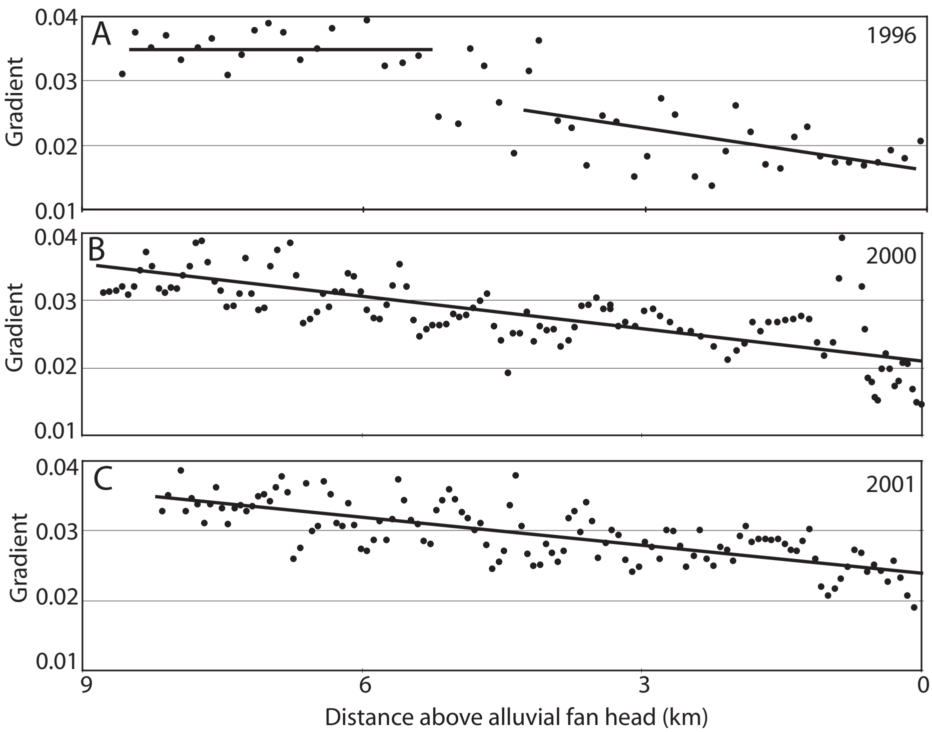

Figure 7. Longitudinal bed gradients on the Pasig-Potrero River. (A) In 1996, a reconnaissance survey was completed by J. Stock. Gradients were calculated an average of every 140 m, and a two-point moving average of those gradient data are plotted here. (B) In 2000, and (C) 2001, stream gradient was calculated every 75–100 m. Plotted here are three-point moving averages. In 1996, upper reaches had almost no curvature, as shown by a constant 3.5% slope. By 2000, a fairly consistent curvature had developed.

Major lahars continued on the Pasig-Potrero River through 1997. Since sediment yield measurements relied primarily on measuring lahar deposits or estimates of lahar flow volumes, we do not have sediment yield data after 1997 (Tuñgol, 2002). Hayes et al. (2002) measured sediment yield from nonlahar fluvial transport in 1997 and found that it was quite substantial, equal to one quarter of the total annual sediment yield. In 1997, the sediment yield was still two orders of magnitude higher than pre-eruption sediment yields measured at a sediment control (sabo) dam at site PP2, 2.5 km upstream of the alluvial fan head (JICA, 1978; Hayes et al., 2002).

Although we do not have direct measurements of sediment yield following 1997, we have indirect evidence of ongoing sediment evacuation from the upper Pasig-Potrero River. If pumice content is treated as a tracer of eruptive material, then by measuring pumice content along the length of the river through time, we can determine whether or not eruptive sediment being transported out of the basin is being replenished from the hillslopes. We found a distinct decrease in pumice content for clasts ≥4 mm, starting in the upper basin. By 2001 pumice content at the alluvial fan head had dropped to <30%, down from >95% in 1996 (Fig. 8A).

Surveys of surface grain size in the channel bottom show an overall increase in median grain size through time, starting in the upper basin (Fig. 8B). This pattern of a coarser upper basin and finer lower basin has led to systematic downstream fining, even though the channel overall is coarsening through time. Coupled with coarser surface grain size is an increase in bed organization. There are more pebble clusters and armor patches present within the Pasig-Potrero River now than there were at the end of the lahar phase. However, reach-averaged Manning's n roughness values did not change substantially from 1997 through 2001 (Table 2).

The effect of the pebble clusters and armor patches on sediment mobility is evident from the results of channel mobility surveys. In 1997, there was a fairly sharp delineation between mobility and stability for sediment in the active channel network (Fig. 9). Clasts were stable in water less than half their grain diameters, and any flow deeper than that would mobilize clasts (Montgomery et al., 1999). By 1998, there was some overlap between stable and mobile regions. The region of mobility did not change: clasts in water depths greater than approximately half their diameter could mobilize. However, the range of depths over which clasts could remain stable increased, and clasts could remain stable in water depths up to approximately one grain diameter. Thus, for many clasts there was a greater barrier to overcome for initiating mobility. In surveys after 1998, channels running across low bars with greater concentrations of pebble clusters and armor patches showed an even greater barrier to initial mobility. In these partially armored channels, clasts could remain stable at any depth, although the conditions under which clasts could mobilize were the same as in unarmored channels.

There were differences between lithic and pumice clast mobility in main channels from summer 2000 and winter 2001 surveys. In the transition zone between stability and mobility, there tend to be more mobile pumice than lithic clasts and more stable lithic then pumice clasts. The summer 2001 and 2002 surveys show no apparent lithologic differences.

The increase in clast stability also affects overall low-flow sediment transport. We found an increase in the critical shear stress, from <0.02 Pa in 1997–98 to 5 Pa in 2001. Otherwise, the bedload transport rating curves remained similar. It is difficult to compare suspended load measurements between 1997–98 and 2001 due to sparse overlap in data. During the 1997 and 1998 field seasons, several large storms occurred, allowing Hayes et al. (2002) to measure suspended load at much higher discharges than occurred in August and September 2001. In the range where measurements do overlap, between 1 and 5 m^3/s, the average concentration was higher in 1997–98 than in 2001 (24 kg/m^3 versus 15 kg/m^3), although this is somewhat misleading due to the skew in the samples. In 1997–98 only 6 of 20 samples were collected at discharges from 1 to 3 m^3/s, while in 2001, 16 out of 22 were collected over this range. Even during the storms in 1997 and 1998, concentrations did not reach hyperconcentrated flow levels, with a maximum sediment concentration by weight of less than 30%. Hyperconcentrated flows occur with sediment concentrations of greater than 40% by weight (Beverage and Culbertson, 1964). Hyperconcentrated flow probably did occur during the 1997 Typhoon Ibiang lahar on the Pasig-Potrero River.

In winter 2001, the flow condensed into a single armored channel incised into valley bottom sediments in the upper basin, 5.5 km upstream of Delta 5. Incision greater than 3 m had occurred in some reaches before an armored, stable bed developed (Fig. 10). The channel bed appeared much less mobile, and there were lower suspended sediment concentrations. Unfortunately, no direct measurements were made. Repeat observations were made in June of 2003, near the beginning of the rainy season. Even after one typhoon, river consolidation and incision were still present starting 6.9 km upstream of Delta 5. Flow in the single-thread channel was measured along two cross sections. The average unit discharge was 1.3 m^2/s, which is actually higher than any measurement made from active braids during the rainy season of 2001. Even though discharge was so high, sediment mobility was visibly lower than during the rainy season.

During the dry season in 2001, small clear-water channels also developed at the fan head. These channels were armored, much less mobile than main braids, groundwater fed, and able to support algae growth. We have seen no

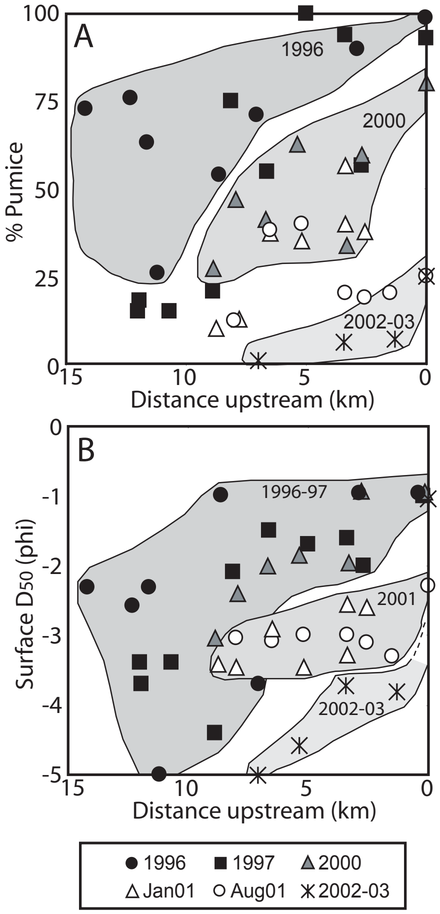

Figure 8. Bed surface surveys of (A) pumice content and (B) median grain size along the Pasig-Potrero River. Data plotted as −1ϕ are ≥ −1ϕ. Pumice content decreased and median grain size increased through time. The changes occur first in the upstream portion of the basin, setting up longitudinal gradients.

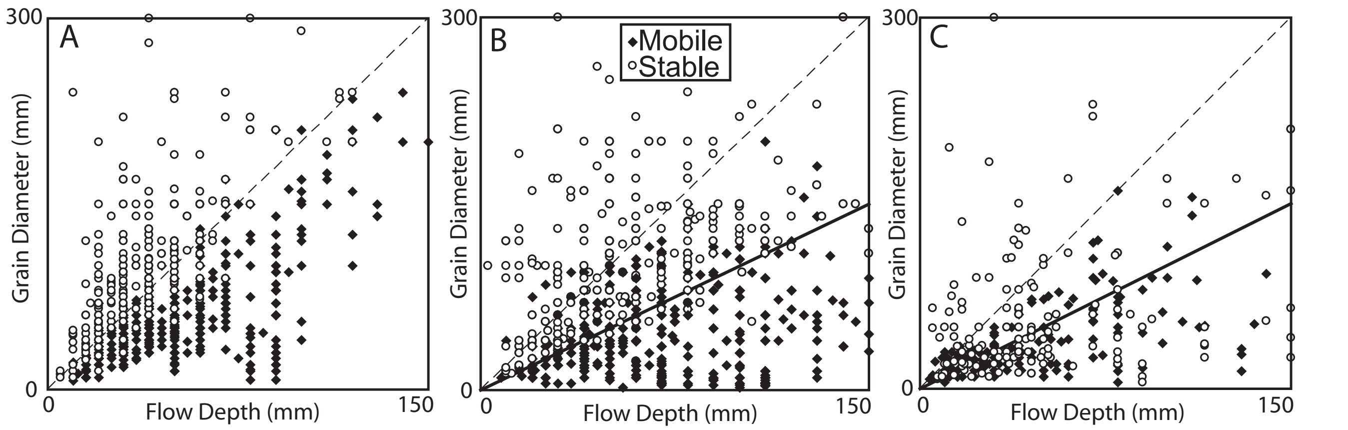

Figure 9. Grain mobility plots from 1997 and 2000 on the Pasig-Potrero River. (A) In 1997, there was a distinct break between mobility and stability at just below a 1:2 ratio of flow depth: grain diameter (Montgomery et al., 1999). (B) By 2000, a definite transition zone was present between the 1:2 ratio line and a 1:1 ratio over which grains could be either mobile or stable. (C) In braids running across low bar tops with concentrations of gravel clasts, grain interactions were more common. The mobility zone was the same as in the unarmored channels, but clasts could remain stable at any depth. Dashed lines are at a 1:2 ratio, and solid lines are at a 1:1 ratio.

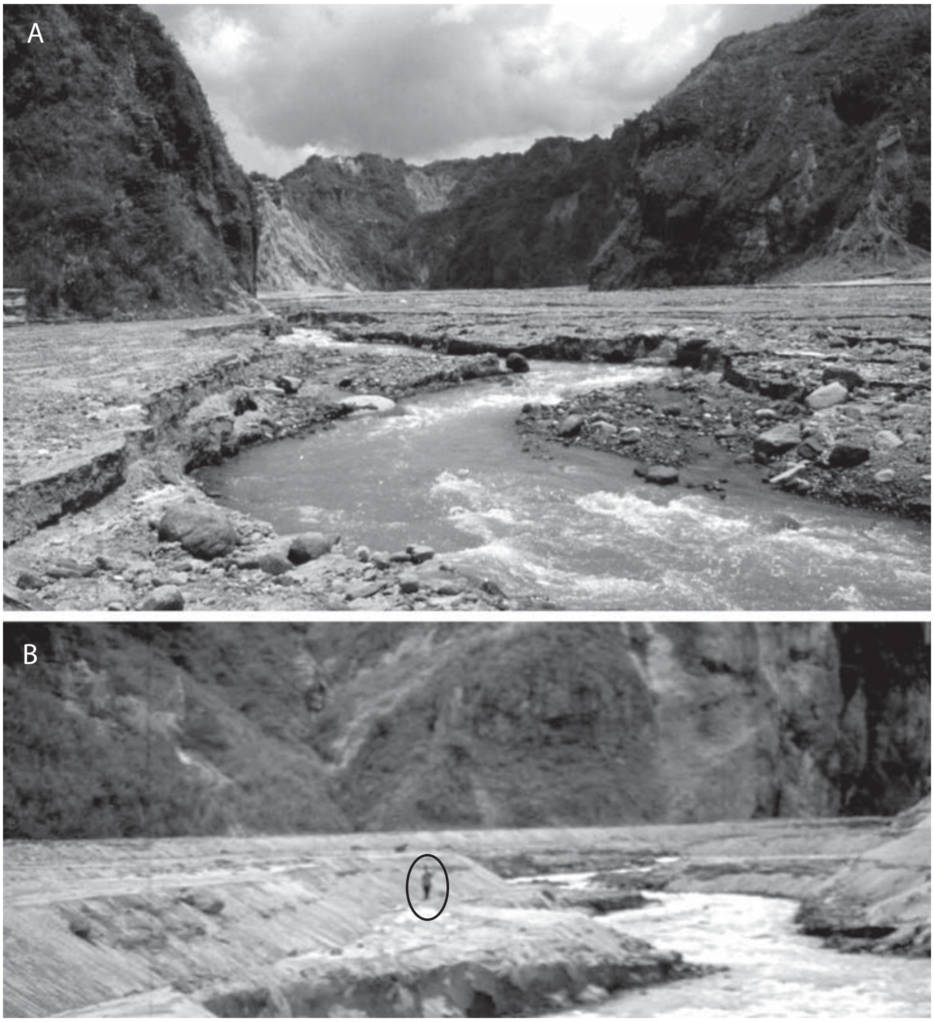

Figure 10. Photos of stream incision on the Pasig-Potrero River. During the dry season, upper reaches of the Pasig-Potrero River incise into the valley bottom sediments, armoring in the process. These photos show the upper Pasig-Potrero River during (A) the very beginning of the rainy season in 2003 and (B) in the middle of the dry season in 2001. Incision during the dry season in 2001 exceeded 3 m in some places (circled person for scale).

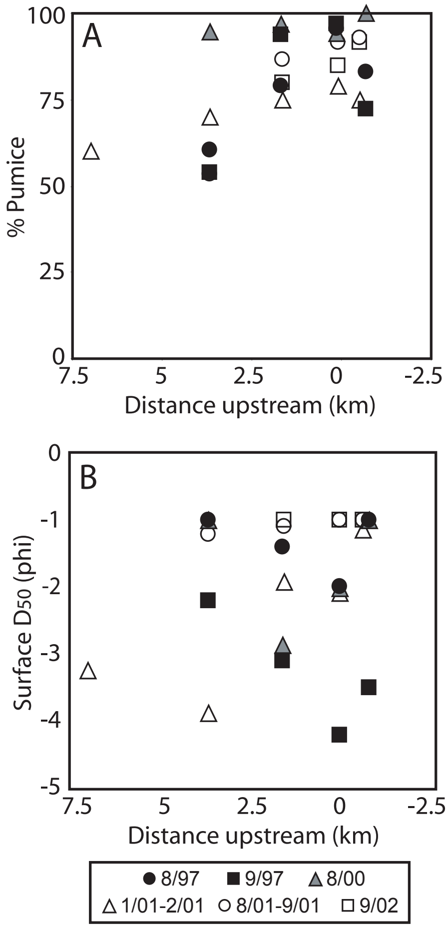

Figure 11. Bed surface surveys of (A) pumice content and (B) median grain size along the Sacobia River. Data plotted as –1ϕ are ≥ –1ϕ. There were no noticeable patterns either longitudinally or through time in either pumice content or surface grain size during the rainy seasons. During the dry season in 2001, a slight downstream fining gradient developed.

other evidence of aquatic life in the lower Pasig-Potrero River through 2002.

Sacobia River

The Sacobia River had 29% of its basin inundated with pyroclastic-flow deposits (Major et al., 1996). Numerous lahars occurred following the eruption, which lessened when the channel was beheaded in 1993. However, a lahar that left deposits greater than 2 m thick at the alluvial fan head occurred as recently as July 2002. The Sacobia River remains fully braided, wide, and shallow, with high sediment transport rates.

There are fewer pebble clusters visible than on the Pasig-Potrero River. Patches of armor appear on low bar surfaces, but the "armor" is generally composed of small pumice clasts that offer little resistance to movement as shown by clast mobility surveys. Mobility surveys had similar results to the Pasig-Potrero in 1997 and 1998 (Fig. 9). By 2000, clasts were slightly more stable in channels on bar tops than in main channels, but the difference was not as evident as on the Pasig-Potrero River. Surveys in winter 2001, summer 2001, and summer 2002 found little difference between channels and bar tops in terms of clast mobility. There were differences between lithic and pumice clasts in winter and summer 2001, with lithic clasts stabilizing at greater depths than pumice clasts. These lithologic variations were not evident in summer 2002 surveys.

We see no significant changes in surface grain size or pumice content from 1997 through 2002 (Fig. 11). There is some evidence of a downstream decrease in grain size and pumice content during the dry season of 2001, but there are no temporal trends. Despite the lack of measurable grain size adjustments, roughness values have increased from 1997 through 2002 (Table 2, Fig. 12). No seasonal incision was observed in winter 2001 like that on the Pasig-Potrero and O'Donnell Rivers. In 2000, the channel upstream of the alluvial fan head was essentially a ramp with a slope just over 2% (Fig. 13). By 2001, this ramp area developed a distinct concavity. Sparse grassy vegetation was starting to grow in rill fields and on high terraces by 2001, but we saw no evidence of vegetation or aquatic life in the active braidplain.

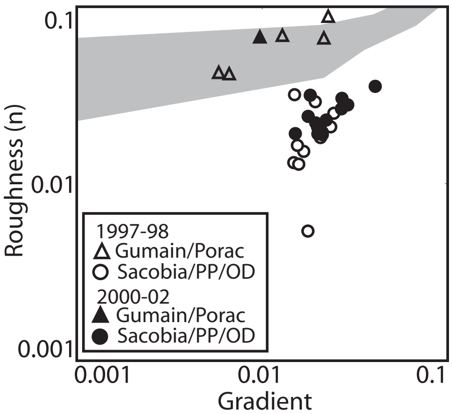

Figure 12. Manning's n roughness values. Roughness was back-calculated from hydrologic surveys from 1997 through 2002. Roughness increased through time on heavily impacted basins (circles), approaching values seen in the lesser impacted basins (triangles) and in mountain rivers worldwide (shaded area) (Barnes, 1967; Marcus et al., 1992).

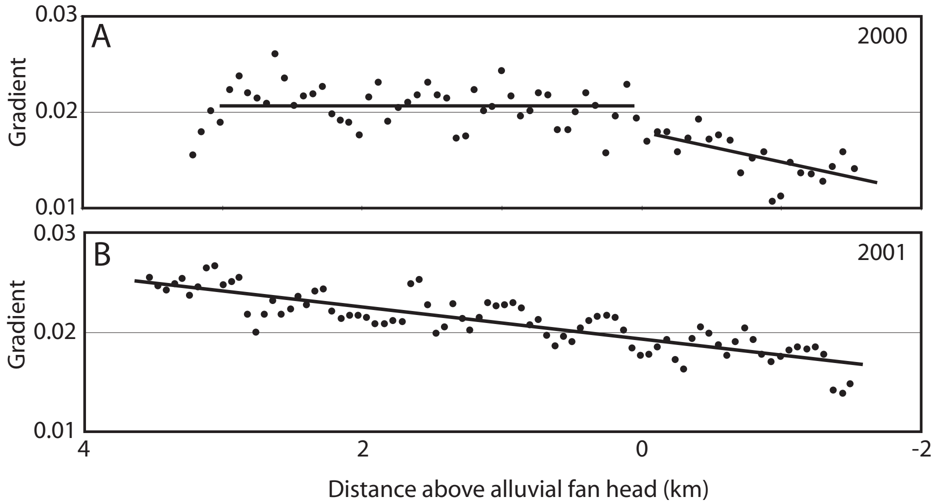

Figure 13. Longitudinal bed gradients on the Sacobia River. Stream gradient was calculated every 75–100 m along the accessible length of the Sacobia River. Plotted here are three-point moving averages for each of those gradient values. (A) In 2000, most of the river upstream of the alluvial fan head had no concavity, remaining at a slope just over 2% for almost 4 km before developing concavity downstream of the alluvial fan head. (B) By 2001, this reach had developed uniform concavity, with gradients steadily rising upstream.

DISCUSSION

Because of the magnitude of sediment loading at Pinatubo, stream recovery has been prolonged, allowing us to observe adjustments to the fluvial system over a number of years. Initially, lahars occurred in all basins, lasting just one rainy season in low-impact basins, while continuing for more than a decade in some high-impact basins. Following the lahar phase, sediment inputs to the system have declined as upland sources are depleted or stabilized. A simplistic way to envision this fluvial recovery phase is as a large flume with steadily decreasing sediment feed rate. As sediment inputs decline, channel and valley bottom adjustments occur that lower sediment storage volume and reduce the effective shear stress available to transport sediment. Given the difficulty in predicting the timing and sequencing of these adjustments from first principles in field situations, we made observations and measurements in basins with a range of initial sediment loading conditions to document adjustments during fluvial recovery. We focus first on changes over half a decade in the heavily impacted Pasig-Potrero River and then expand our view to include four other basins. Finally, we synthesize our observations to formulate a general conceptual model for channel recovery following basin-wide sediment loading. Differences in the style and rate of fluvial recovery between basins illustrate the importance of local sediment budget context on the pace of recovery.

Fluvial Recovery on the Pasig-Potrero River

Measurements of sediment yield at Pinatubo in the first few years after the eruption show an exponential decline (Fig. 2) (Umbal, 1997), although further studies on the Pasig-Potrero River show that a nonlinear power function decay may be more appropriate (Tuñgol, 2002). It is unclear whether sediment yields will continue declining nonlinearly, or if they will stabilize at a higher level. Climatic shifts or high magnitude precipitation events could act to reset recovery rates, producing and possibly maintaining sediment yields above predicted rates (Major et al. 2000; Major 2004).

We infer that sediment inputs to the fluvial system are still declining on the Pasig-Potrero River based on changes in bed surface composition. The 1991 pyroclastic-flow material is sandier (70%–85% by weight) and more pumice-rich than the original channel bed material (Scott et al., 1996b). A steady decline in pumice content on the Pasig-Potrero River indicates hillslope inputs to the river valley are not keeping pace with sediment evacuation. We interpret these observations to mean sediment inputs to the river valley are still declining. It is possible that the decrease in the percentage of pumice on the bed is related not to a removal of pumice, but rather to an increase of lithics as channels in the upper basin incise and expand into pre-eruption valley fill. However, the amount of incision into the pre-eruption bed would have to be far greater and more widespread than observed to compare with the volume of continuing inputs from recent eruptive material.

Sources of replenishment for sediment in the channel include mass wasting from high lahar and pyroclastic-flow terraces, runoff from gullied terraces (referred to as "rill fields"), and mining of the valley floor (Fig. 14). The high terraces are a finite source that becomes less accessible as the valley widens and the channel comes into contact less frequently with valley walls. The rill fields are starting to revegetate, which may slow inputs from them, although many still have no vegetation and remain an active sediment source. During high precipitation events, debris torrents pour from the rill fields, forming fans in the valley bottom that are then removed during high flows. The valley bottom represents the most accessible source of storage in the system. It still has abundant sediment, but channel incision is required to access the sediment, and this incision can be self-limiting due to bed surface armoring and stabilization.

As sediment inputs decline, the bed is coarsening and developing more pebble clusters and armor patches (Fig. 15). Clast structures create more form drag, directly increasing roughness. Clast structures like pebble clusters have been shown to increase bed stability, increasing the critical shear stress required to move individual particles within the cluster (Brayshaw et al., 1983). Field observations elsewhere show that particles in cluster bedforms can remain stable

Figure 14. Primary sediment sources at Mount Pinatubo. There are three main sediment sources for rivers draining Mount Pinatubo: rill fields, high terraces, and the valley bottom. The "rill fields" are gullied out terraces. They supply sediment to the channel during high precipitation events and potentially can be stabilized by vegetation. The high terraces can form shear cliffs. They erode through mass wasting, forming talus cones at the base of cliffs, which are then removed during high discharge events. They cannot be stabilized by vegetation, but as valleys widen, they become less accessible. The valley bottom represents a vast reservoir of sediment, but erosion of the valley bottom is self-limiting since the channel armors and stabilizes during incision.

longer and under higher-velocity conditions than isolated particles when subjected to rising flow conditions (Brayshaw et al., 1983; Brayshaw, 1985). Clast structures like clusters and stone lines can provide enough stability in some gravel-bed channels to reduce sediment transport rates by orders of magnitude (Church et al., 1998).

The increase in cluster bedforms is coincident with decreasing clast mobility on the Pasig-Potrero River. Mobility studies from braids with and without large densities of pebble clusters clearly show that in areas with more grain interactions, gravel clasts can remain stable under greater flow conditions. This reduction in clast mobility appears to be increasing the critical shear stress necessary to mobilize clasts that could reduce overall low-flow sediment transport. Critical shear stress is still quite low, however, and the bulk of the overall sediment yield is moved during high flows, well above the critical shear stress. Thus, the current bed configuration may not be affecting overall sediment yields during the rainy season. These high flows are capable of mobilizing all grain sizes and may destroy any cluster bedforms or armor patches present at low flow.

During the dry season, more dramatic changes were seen, with reaches in the upper basin consolidating into one main channel, incising, and armoring. Both suspended and bedload transport rates appeared much smaller. Even though there is still sediment available to

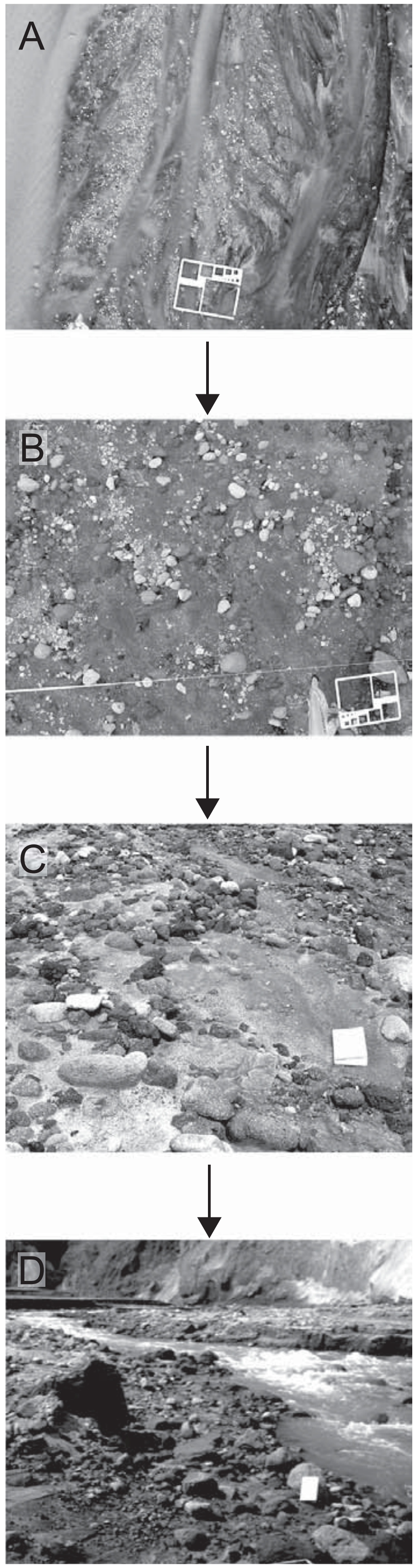

Figure 15. Development of bed armor in Pinatubo channels from (A) unarmored through (B) development of pebble clusters to (C) partial armor layer covering active channel surface as pebble clusters begin to interact to (D) fairly complete armor layer following incision during the dry season. Gravelometer for scale in (A) and (B) is 340 × 280 mm. Field book for scale in (C) and (D) is 120 × 195 mm.

these incised channels from the banks and bed, the process of incision and armoring appears to be self-limiting. As the channel incises, finer grains are winnowed away, leading to the development of a surface armor. This armor layer makes it more difficult for the bed to mobilize, essentially shutting down sediment transport in the upper basin during the dry season. Even though low dry season transport rates may not profoundly affect annual sediment yields, dry season behavior may be a preview of future year-round behavior as rainy season sediment sources are stabilized or depleted.

Neighboring Basins

Even though we have an 8 yr record on the Pasig-Potrero River, it still offers a limited view into the full spectrum of channel recovery following volcanic eruptions. We use other basins at Pinatubo to expand the model in time, including three (Porac, Gumain, and O'Donnell) that had less sediment loading and are therefore farther along in the recovery process, and one basin (Sacobia) that is progressing slower due to a substantial loss of transport capacity. It is important to keep in mind that although the Porac and Gumain Rivers received a far lesser impact than the Pasig-Potrero River and we doubt ever reached the wide, shallow, braided state that the Pasig-Potrero River is in currently, we believe they represent reasonable end members for channel recovery.

The Porac and Gumain Rivers evacuated pyroclastic-flow material early, with most or all of it moving through lahars to the alluvial fan in the first year. Both rivers are now gravel bedded and incised, with relatively stable beds year-round. The Porac River, which had the least impact, recovered the fastest. By 1997, it withstood a 100 yr precipitation event without substantial bank scour. By 2000, aquatic algae, macroinvertebrates, and fish had returned to the river. The Gumain River was subjected to slightly more sediment loading. It appears to have reached relative stability in terms of local bed elevation, but some reaches are still quite mobile laterally. The bed has become stable enough to support an aquatic ecosystem that includes fish as of 2001. In the Gumain, base-level stability and the initiation of ecosystem recovery have preceded a substantial decrease in lateral mobility rates.

By 2001, the O'Donnell River was gravel bedded and armored in the headwaters year-round with a redeveloping aquatic ecosystem as evidenced by the presence of aquatic plants, insects, and amphibians. Farther downstream, the river is wide, shallow, and braided all the way to the alluvial fan head during the rainy season. Because the upper few km of the basin remains gravel bedded and armored throughout the entire year, the lower basin must be receiving sediment primarily from local sources including adjacent rill fields and high terraces or the valley bottom. During the dry season, sediment production from rill fields and high terraces shuts down due to a lack of high precipitation and high flow events necessary to mobilize sediment into the valley bottom. Some reaches consolidate and incise into the valley bottom sediments. Other reaches actually cut down to bedrock.

We believe the O'Donnell best represents the state the Pasig-Potrero River is evolving toward within the next five to ten years. The area that is seasonally incised and armored should shift downstream through time. The reaches that remain armored year-round also should expand downstream as more rill fields and high terraces are stabilized or depleted. In the lower basin, inputs from unvegetated rill fields will continue to be a significant sediment source as long as base level continues to fluctuate and incision on the mainstem propagates up into the rill fields.

The Sacobia River characterizes the opposite end of the spectrum from the Porac and Gumain Rivers. Although it is similar to the Pasig-Potrero in many respects, being wide, shallow, braided, and sediment laden, many features indicate that it has not progressed as far toward recovery as the Pasig-Potrero River. The Sacobia still has a pumice-rich granule to fine pebble bed, with no temporal or longitudinal trends in surface grain size or pumice content. The only exception to this is a downstream gradient in grain size during the dry season in 2001. Pumice "armor" develops on bars, but this armor provides little resistance to motion. Clast mobility surveys on bar tops and channels show little difference between the two environments, in contrast with conditions on the Pasig-Potrero River.

It could be that channel recovery will get no further on the Sacobia. Due to low transport capacity, the channel may not flush excess sediment from the system, leaving it sediment-choked for many years. This could be seen as a form of recovery to a new equilibrium state. However, because the eruptive sediment sources are finite and still not stabilized, we believe the Sacobia will continue to evolve, but over a longer time scale than the Pasig-Potrero River. The Sacobia may appear stable over a time frame of 2–3 yr, but that does not represent recovery. As of 2002, the basin was still subject to lahars during high precipitation events, and there were no signs of any aquatic plants or animals in the valley bottom. As sediment sources are depleted or as vegetation becomes more established, slowing sediment inputs from rill fields, we expect the Sacobia River to begin showing more of the signs of recovery now apparent on the Pasig-Potrero River.

Conceptual Model for Fluvial Recovery

Based on temporal monitoring on the Pasig-Potrero and a space-for-time substitution with four other basins on the east flank of Pinatubo, we propose a general conceptual model for recovery of fluvial systems following basin-wide volcanic sediment loading (Fig. 16). The first stage in recovery is characterized by instability laterally, vertically, and in bed surface form and composition. At Pinatubo, this phase involved widespread lahars. These flows mobilized vast amounts of sediment, contributing to record sediment yields. They also led to wild fluctuations in base level on the main stem, which in turn created instability on adjoining tributaries (Tuñgol, 2002). Only after major lahars end can the fluvial system begin to process and adjust to the excess sediment load without big disturbances to base level. It is this phase, termed the fluvial recovery phase, wherein the channel bed can begin to adjust to changing input conditions without every lahar completely resetting the bed.

Following cessation of widespread lahars, stabilization or removal of upland sediment sources eventually allows sediment evacuation through the channel network to exceed sediment inputs from hillslopes. Pumice clasts and sand are removed preferentially through selective transport, first in the upper basin and then expanding downstream. This coincides with the establishment of downstream fining and the development of long profile curvature.

Once enough sand has been removed that gravel clasts begin to interact with one another, clast structures like pebble clusters and armor patches begin to form (Fig. 15). They are found initially on low-amplitude bars and the edges of primary braids. These structures, coupled with increasing surface grain size, act to increase form roughness, lowering the effective shear stress available for transporting sediment. In addition, the critical shear stress increases from an overall increase in grain size and development of cluster bedforms. These clusters create hiding effects, making it more difficult to mobilize sediment.

From our observations, clast structure development appears to be a precursor to full surface armor. Looking from one rainy season to the next, we see an increased density of clast structures and armor patches. During the dry season, low sediment inputs lead to winnowing through selective transport, substantially increasing gravel interactions, and leading to the development of a surface armor layer in the active channel. Sediment transport in the incised, armored dry season

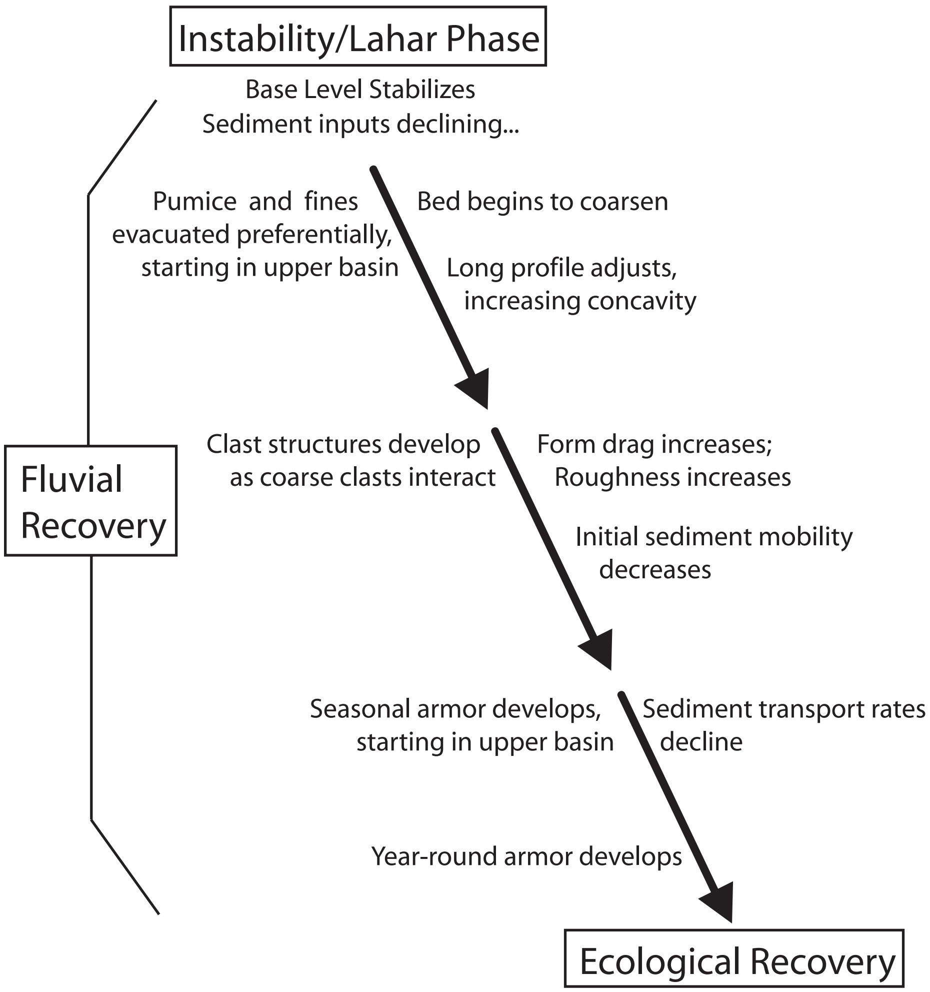

Figure 16. A general time line for channel recovery following extreme sediment loading. There are three basic phases: the initial instability phase, the fluvial recovery phase, and the ecological recovery phase. The initial instability phase at Pinatubo was characterized by numerous lahars leading to fluctuating base levels. The channel bed was smooth and unarmored, fine-grained, and highly mobile with high sediment transport rates. By the end of the fluvial recovery phase, the channel bed is coarse and armored, with much lower sediment transport rates and decreased channel mobility. These conditions allow ecological recovery to proceed.

channel is much lower than in braids with similar discharge during the rainy season. These incised reaches represent areas with decreasing sediment in storage, as the channel mines the valley bottom, flushing sediment from the upper basin into the lower basin and alluvial fan. This process may act to keep sediment yields high early in the dry season, as incision occurs, but after the channel has incised, sediment transport rates appear to be dramatically reduced from the highly mobile braided state seen in the lower basin and during the rainy season. We predict that this zone of incision will shift downstream through time, until all of the channel upstream of the alluvial fan is incised during the dry season. Eventually, as rainy season sediment sources are evacuated or stabilized, the channel may remain incised and armored year-round.

Ecological recovery does not appear to begin until some degree of bed stability exists. Thus the pace of ecological recovery is tied to the pace of channel recovery. Stable bed sediment helps maintain habitat for higher-order species like invertebrates (Townsend et al., 1997). Eventually the presence of clast structures like pebble clusters may help maintain ecological diversity in a stream by offering refugia to aquatic organisms during flood events (Biggs et al., 1997; Biggs et al., 2001). At Pinatubo, channels with more stable beds also have lower suspended sediment concentrations, aiding the return of photosynthetic organisms.

Even after base level stabilizes, the channel armors, ecological recovery begins, and the river has recovered, lateral migration rates may remain high, as observed on the Gumain River. This condition may continue as long as sediment transport rates remain high or lessen as riparian vegetation is established along river banks and bars as seen on the Porac River.

The pace of channel recovery is tied to the rate of sediment evacuation or stabilization. How and when upland sediment sources are evacuated or stabilized depends on the source and delivery processes. Although rill fields and valley bottom sediment may be stabilized by vegetation, high terraces are essentially immune to any stabilizing effects of vegetation. These high terraces can form shear cliffs tens of meters in height, well above the rooting depth of most plants. However, access to high terraces by active channels is reduced through valley widening. Valley bottom sediments are the most accessible source, but entrainment is self-limiting due to sediment transport feedbacks that result in bed armoring. In terms of seasonal variations, valley bottom sediments and some high terraces can be accessed year-round, but rill fields are only important sediment sources during high precipitation events, which are limited to the rainy season. This seasonal difference in sediment supply leads to the observed seasonal recovery patterns, as sediment contributions from the rill fields are essentially shut off during the dry season.

The time scale over which adjustments occur depends fundamentally on the nature and volume of local sediment sources, and this can vary not only between eruptions, but between individual river basins for a single eruption. Following the 1980 Mount St. Helens eruption, for example, hillslope sediment sources shut down rapidly and were relatively insignificant after only a few years (Collins et al., 1983; Lehre et al., 1983; Collins and Dunne, 1986). Revegetation was not a significant factor in reducing sediment yields. At Mount Pinatubo, however, sediment production from rill fields remains an important sediment source, and it probably will take revegetation of these deposits before they are stabilized. Local context must be considered when assessing the lingering effects of volcanic sediment loading. Figure 16 offers a conceptual framework for the sequencing of events in channel recovery following widespread sediment loading, but posteruption valley bottom context is important for interpreting recovery time scales.

CONCLUSIONS

Using observations from a suite of basins with variable sediment loading from the 1991

Mount Pinatubo eruption, we propose a conceptual model for channel recovery following extreme basin-wide sediment loading. After an initial period of widespread instability (characterized at Mount Pinatubo by lahars and base level fluctuations), the fluvial recovery phase begins. Upland sediment inputs decrease as sediment sources stabilize or are evacuated. In channels, sediment is mobilized preferentially through selective transport, starting in the upper basin and leading to downstream fining. Once the bed is coarse enough for gravel-size clasts to interact, clast structures develop, first on low bar tops and edges of channels and finally within the main flow. These clast structures act to increase form roughness and critical shear stress. Both of these effects lead to a decrease in initial clast mobility, which can result in bed armoring. Eventually, sediment inputs from hillslopes can no longer keep pace with transport capacity, and the channel can incise into valley bottom sediments. During incision, armoring through selective transport acts to limit overall incision and eventually stabilize the channel. After base level within the channel has stabilized, high lateral mobility rates can continue until banks are stabilized.

This conceptual model can apply to basin-wide sediment loading from numerous mechanisms, from single large landslides or regional episodes of extensive landsliding to volcanic eruptions. The time scale of recovery and details of specific stages are dependent on the climate and nature of sediment sources. At Pinatubo, for example, sediment sources are strongly seasonal, so incision and armoring are occurring first as a dry season phenomenon. In locations with different climates and sediment sources, incision and armoring may occur following the clustering stage without the initial seasonal component. While some sediment sources may decrease according to the classic exponential decline in sediment yield following an eruption, active sediment production from others may linger for years to decades while still supplying the fluvial system with excess sediment.

In many cases, the desired goal of river recovery is the reestablishment of an aquatic ecosystem of predisturbance complexity. Although the model above does not include the additional process of ecosystem recovery, channel bed recovery is an important precursor to the return of aquatic species. While widespread fluctuations in base level remain, or while the channel still maintains high suspended load concentrations and a highly mobile bed, it will be difficult for anything to live in the river. Thus, the time scale for ecological recovery is fundamentally dependent on the pace of physical channel recovery.

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