Cartographic modelling of erosion in pyroclastic flow deposits of Mount Pinatubo, Philippines

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ABSTRACT

The eruption of Mount Pinatubo on 15 June 1991 deposited approximately 5 to 7 km^3 of pyroclastic flow materials. The accumulated thickness of the pyroclastic flows varied, depending on proximity to the crater and the pre-eruption morphology, and reached more than 200 m along deep pre-eruption valleys. These deposits effected eight major watersheds around the slopes of the volcano and radically altered the hydrologic regimes, leading to unprecedented amounts of erosion and sediment delivery in the form of destructive lahars. One of the eight watersheds, the Sacobia catchment on the eastern slope of the volcano, was studied in detail, including its rapidly changing geomorphology before and during the eruption and for three consecutive years afterward. Emphasis was given to the importance of stream capture as a result of erosion and secondary explosions. To quantify the volumes of pyroclastic flow material and annual erosion, five digital elevation models (DEMs) were prepared and analyzed using a GIS. A total volume of 1.78 km^3 of pyroclastic flows deposited in 1991 in the Sacobia catchment covered an area of 24 km^2 and reached 15 km downstream from the crater. Erosion rates were calculated to be between 136 and 219 million m^3 per year.

Mount Pinatubo is situated on the island of Luzon, about 80 km northeast of Manila, the capital of the Philippines. The volcano, with K-Ar datings of approximately 1.1 million years and the youngest ^{14}C dating of ±400 year BP, is the youngest volcano in the Zambales range and the western Luzon volcanic arc [4, 5]. Figure 1, which provides an overview of the region, was prepared from an extensive DEM derived from 16 1:50,000-scale topomaps.

The Pinatubo deposits are subdivided in two general groups on the basis of lithology and age of emplacement: the "ancestral" and the "modern" [6]. The "ancestral" Pinatubo (±1 Ma to ±35,000 years) is an andesite-dacite stratovolcano of mostly lava flows and breccia deposits of laharic origin. The dome of Pinatubo consists of porphyritic hornblende andesite, with a microcrystalline to cryptocrystalline groundmass composed of feldspars, clay and magnetite [3]. On its slopes are numerous elongated to sub-rounded hills made up of breccia, created mostly by the "ancestral" lahars.

The "modern" Pinatubo (±35,000 years to present) is a dacite-andesite stratovolcano that shows signs of repeated, very explosive, eruptions which have produced large volumes of pumiceous pyroclastic flows [6]. Pyroclastic flows—also known as "nuées ardentes", ignimbrites or glowing avalanches—are extremely hot (±1,000°C), often incandescent, highly fluid, gravity-driven density currents of gas and volcanic fragments that sweep downslope (hugging the ground) and travel at hurricane speed (±100 km per hour). Pyroclastic flows from plinian eruptions (*eg*, Pinatubo) are generated when the rising tephra column fails to maintain the column density below that of the surrounding atmosphere; then gravitational column collapse occurs, with lateral movement dispersing down the flanks of the volcano.

THE 1991 PYROCLASTIC FLOW DEPOSITS

Mt Pinatubo is in a densely populated area, with major nearby cities (such as San Fernando and Angeles) and two large former military bases (Clark air base and Subic Bay naval base). The volcano began spewing ash on 3 June 1991 at 0730 h [8] and continued for three months until the end of August 1991. It peaked during the plinian eruption of 15 June, propelling ash up to 30 km above the vent. An overview of the area surrounding Mt Pinatubo, the deposits resulting from the 1991 eruption and the lahar deposits from 1991 to 1994, are shown in Figure 2.

The ashfall of 15 June covered extensive areas of Luzon and the South China Sea. The ashfall was thicker towards the southwest because of the prevailing northeasterly winds at higher altitude and the effect of typhoon Yunya which passed the Philippines in a westerly direction at the time of the eruption. Ashfall thicknesses in the vicinity of the volcano reached 50 cm near the slopes and about 5 cm 20 km east of the crater.

The 1991 eruption deposited approximately 6.83 km^3 of pyroclastic flows into the various watersheds, namely O'Donell (0.6 km^3), Sacobia (1.78 km^3), Porac-Gumain (0.05 km^3), Marella-Sto Thomas (1.3 km^3) and Balin-Baquero (3.1 km^3). The Sacobia watershed analyzed here starts at the eastern crater rim of the volcano (see Figure 2) and extends downslope to the lowland Candaba swamp (50 km east) and Manila bay (60 km southeast).

Most of these deposits were emplaced during the 15 June plinian eruption. Depositional temperatures measured in the Pinatubo area ranged from 300 to 390°C [10]. The observed in situ deposits are non-welded, dry, very friable and very loose. Grain size analysis of five pyroclastic flow deposits (both pre-historic and 1991 deposits) showed no large difference in the grain size (the median grain size of both is in the coarse sand size: 0.5 mm).

The rapid erosion/removal of the 1991 pyroclastic flow deposits has been a major social and scientific concern because it generates life-threatening and destructive lahars of enormous magnitude. The lahars have resulted in the loss of many lives and damage to property in areas surrounding the volcano. Some 50,000 persons

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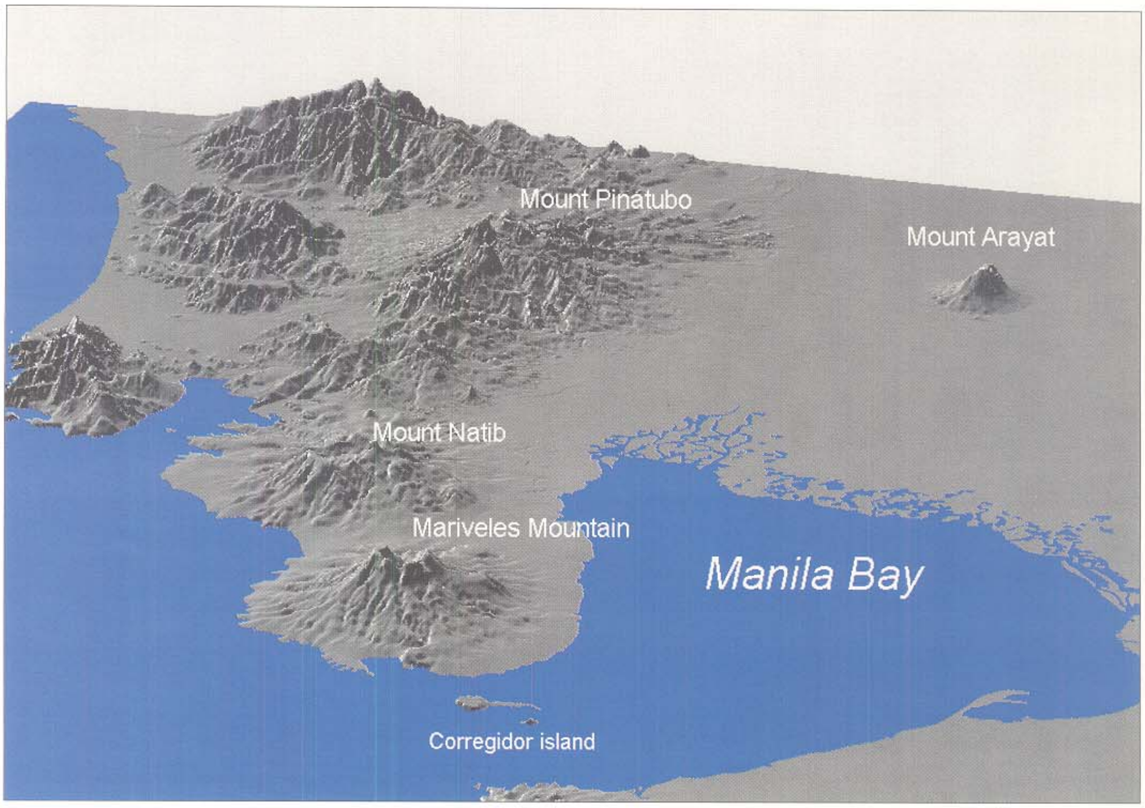


FIGURE 1 Overview of the region between Mount Pinatubo and Manila (lower right corner). This figure was made by overlaying a hill-shading image on a digital elevation model

were left homeless and the indirect impacts such as flooding and isolation have effected more than 1.3 million people in 39 towns and four large cities. Moreover, approximately 1,000 km^2 of prime agricultural land is at risk [1]. Lahars occur predominantly during the rainy season in the southwest monsoon period, which lasts from June to November. The average annual rainfall varies from 1,946 mm east of Pinatubo to 3,900 mm in the west. Long-duration and high-intensity rainfall, which is responsible for the production of large-magnitude destructive lahars, is usually associated with the occurrence of strong typhoons.

METHOD

The main objective of this study was to evaluate the geomorphic changes in the upper Sacobia catchment where pyroclastic flows have been deposited. The main components of this investigation included:

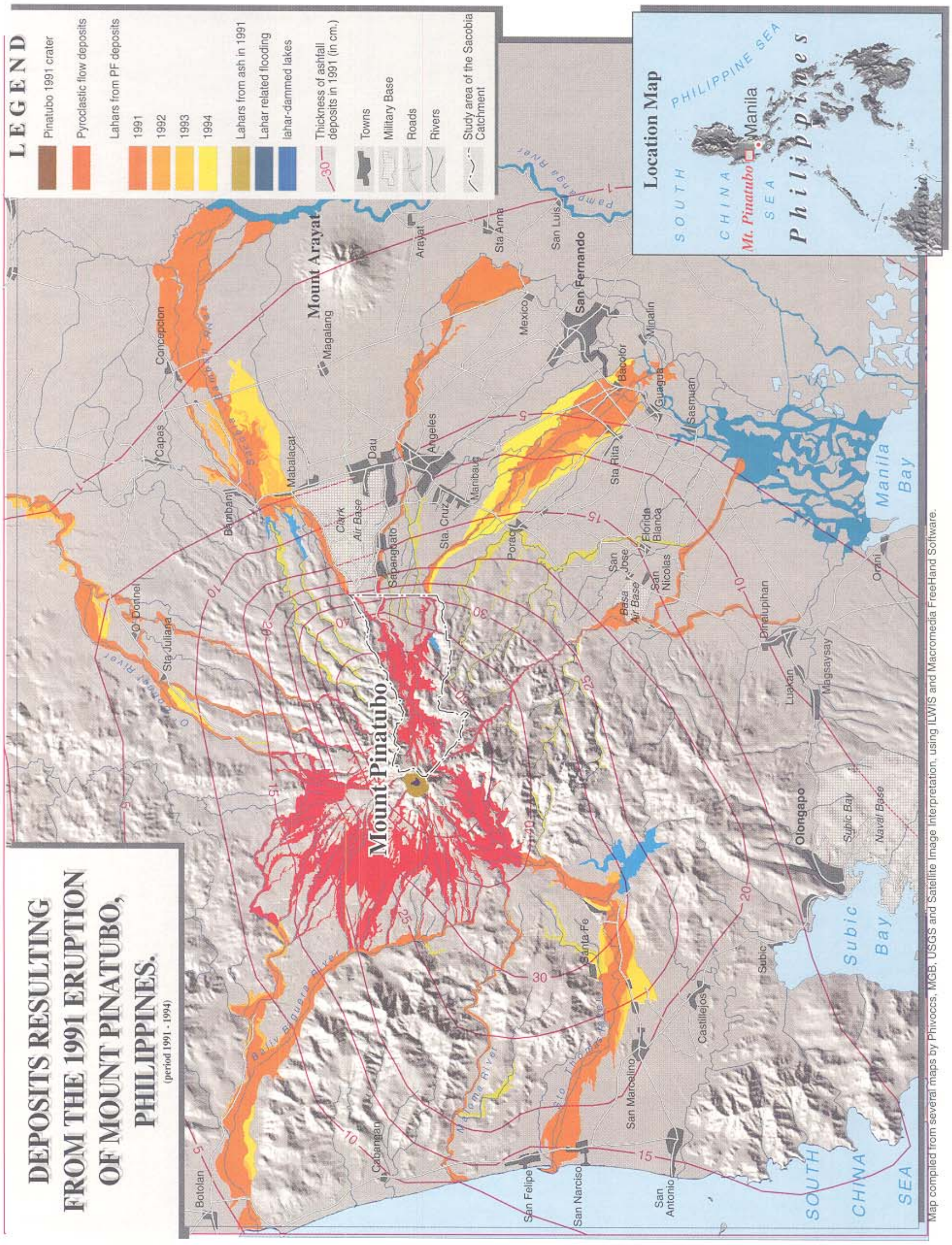
(1) elaboration of geomorphologic maps for the pre- and post-eruption situations, up to 1993, to evaluate the changes in catchment areas and their importance in producing lahars

(2) creation of digital elevation models for each year, from which the thickness of pyroclastic flows and the yearly eroded volumes can be calculated.

The method is illustrated schematically in Figure 3.

The study of geomorphologic changes was based on the interpretation of both vertical and hand-held oblique aerial photos, video tapes and satellite images acquired at different times. The pre-eruption geomorphology of Sacobia watershed was interpreted from 1:12,000 scale black-and-white aerial photographs from 1968. A photographic mission several weeks after the eruption presented various difficulties because of the continuous ash ejections from the main crater and the persistent bad and cloudy weather conditions. Vertical photographs were obtained in July 1991, but the photos were badly tilted and surface areas were largely obscured by clouds, making interpretation difficult. The post-eruption depositional surfaces of pyroclastic flows were analyzed using these photos and a Spot satellite image from 1991, together with information from existing maps. Post-eruption major gully developments and other geomorphic features on the 1991 pyroclastic flow deposits were analyzed using vertical aerial photos taken in 1991 and 1992 and hand-held oblique photos from April 1994, before the start of the rainy season, thus illustrating the situation at the end of the annual "lahar season" in 1993.

To calculate the volume of the 1991 pyroclastic flow deposits and the annual eroded sediment volumes, a DEM overlaying technique using GIS was used. This required constructing DEMs of several periods: *eg*, the pre-eruption DEM, the post-plinian eruption DEM (which shows the undisturbed deposits of the 1991 pyroclastic flows), and post-lahar DEMs for 1991, 1992 and 1993.



Map compiled from several maps by Phivocs, MGB, USGS and Satellite Image Interpretation, using ILWIS and Macromedia FreeHand Software.

FIGURE 2 Overview of the deposits from the 1991 eruption of Mt Pinatubo. The extent of the pyroclastic flow deposits is indicated, as well as the lahars deposited from 1991 to 1994

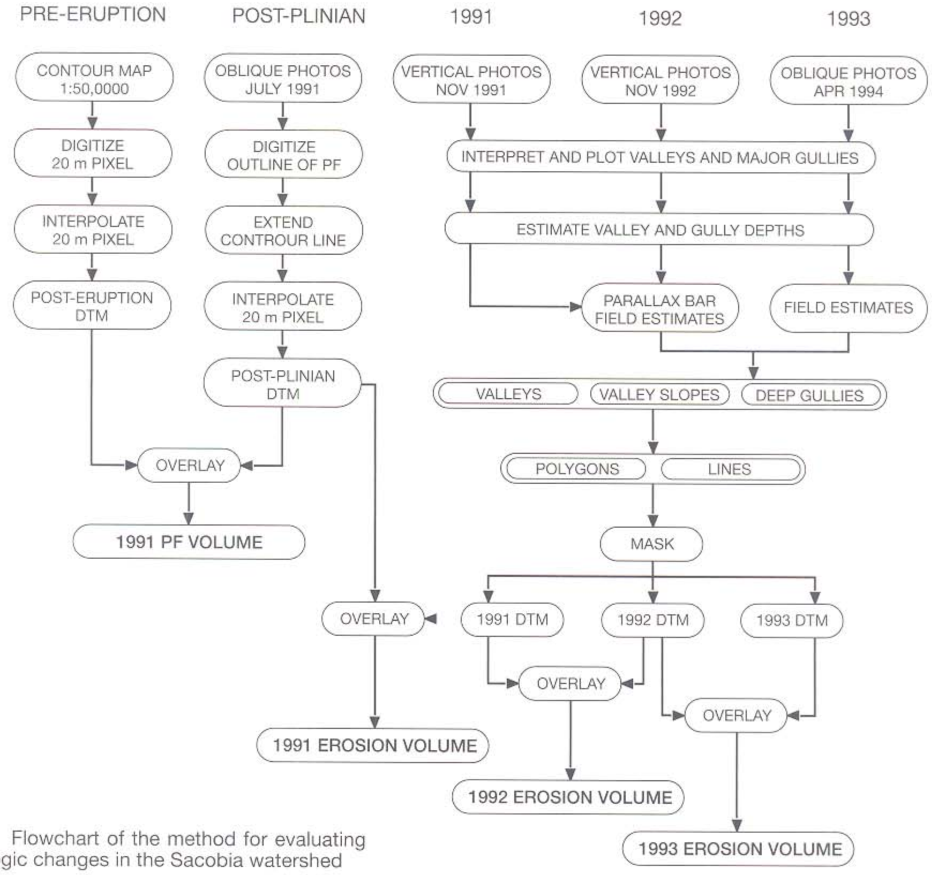


FIGURE 3 Flowchart of the method for evaluating morphologic changes in the Sacobia watershed

The pre-eruption DEM was generated by digitizing the contour lines (20 m interval) from the 1986 topographic base map prepared by the U.S. Defense Mapping Agency. The DEM was rasterized using a pixel size of 20 m.

To calculate the volume of the 1991 pyroclastic flow deposit, a post-plinian eruption DEM was constructed to show the features of the original and undisturbed 1991 deposits. In constructing the post-eruption DEM, oblique stereo photographs from July 1991 were used, since they showed the original levels of the new deposits. Contacts of the pyroclastic flows with the surrounding topography were plotted on the enlarged topographic base map. Additional isolines were digitized across the deposit. The elevations of the new pyroclastic flow levels were then masked into the pre-eruption DEM to fully reconstruct the post-1991 plinian DEM.

To be able to calculate the volume of erosion of the three annual post-lahar seasons, a DEM was prepared for each year. The temporal erosion was estimated by calculating the volumes of the valleys and large gullies generated after each lahar season. These features were interpreted from the post-rainy season photographs. The vertical incision depth of valleys and gullies was estimated in the field for a limited number of sites. The depths at other inaccessible sites were measured with a parallax bar. Unfortunately, analytical photogrammetric work could not be conducted because of the absence of precise ground-control points in the study area, the inaccessibility of the terrain and the fact that a precise GPS was not available. Because of the use of simple parallax measurements, the minimum mappable depth of gullies in this study was approximately 5 to 10 m. A very large number of points were measured with the parallax bar to minimize the error, but some measurement errors remained because of tilting of the photographs and the poor tonal contrast when measuring the tops and bottoms of gullies.

The boundaries of gullies were plotted over the 1991 pyroclastic flow deposits in a GIS. The depth measurements made with the parallax reading were subtracted from the elevations of the 1991 pyroclastic flow levels to obtain the elevations along stream lines; the elevations of the remaining gully slopes were interpolated. Larger valleys were represented as polygons. The areas of the polygons (together with the measured valley depths) were subtracted from the elevations of the post-eruption DEM. The sloping valley walls were masked separately, and their DEM values were calculated by interpolating the elevation values of the tops and bottoms of the valleys.

The same procedure was followed for the situations after the 1992 and 1993 rainy seasons, each time subtracting the newly eroded areas from the DEM of the preceding year.

PRE-ERUPTION GEOMORPHOLOGY

The geomorphologic map of the pre-eruption situation is represented in Figure 4, superimposed on a shaded relief map derived from the DEM for this period. The pre-eruption river system in the study area consisted of two major rivers, the Sacobia and the Pasig. The largest watershed is the Sacobia, which is divided into the northern upper (9.97 km^2), southern upper (11.73 km^2) and the lower (18.12 km^2) sub-catchments. The second-largest watershed is Pasig, which contains the following sub-catchments: Bucbuc (5.95 km^2), Yangca (4.55 km^2), Papatak (6.46 km^2) and Timbu (4.94 km^2). Other, small, catchments in the study area are Abacan (2.54 km^2), Taug (6.60 km^2) and Sapangbato (5.29 km^2). These sub-catchments are located in the distal part of the study area, about 12 km from the crater.

Newhall *et al* [6] identified at least six major eruptive episodes throughout the modern history of Mt Pinatubo, with repose periods of several centuries or millennia. The youngest eruption, before the 1991 event, was dated 400 ± 70 BP. The strongest eruption was dated in the period betweeen 30,390 (± 890) and 35,000 years BP. A very large caldera rim, in which the pre-1991 Pinatubo peak was seated, was inferred to have dimensions of 3.5 by 4.5 km [3]. This calderagenic eruption produced the extensive pyroclastic flows on the eastern side of the volcano which occupy an area five times larger than the 1991 deposits. These deposits resemble broad coalescing fans, reaching to about 20 km east of the volcano. In some parts, the deposits are welded and exhibit columnar jointing, which suggests a high temperature during deposition. The welded deposits are very resistant to erosion, and the surficial non-welded layers were subjected to a high degree of erosion, as indicated by the intricate patterns of deeply dissected gullies in the lower Sapangbato, Taug and Timbu catchments. These resistant pyroclastic flow deposits serve as partial watershed divides of the Abacan, Sacobia and Pasig rivers.

The original pre-1991 pyroclastic flow levels were intensely eroded in the upstream sections, leaving deep valleys of about 200 m. At elevations between 500 to 200 m asl between the Pasig and Sacobia rivers, this pyroclastic flow level can still be recognized, forming a large broad fan in the upper Sapangbato catchment. The broad and extensive lahar deposits built the large alluvial fan landscape around the volcano, which mantles the intensely built-up areas and formed fertile agricultural areas.

POST-ERUPTION GEOMORPHOLOGY

The geomorphologic map of the situation shortly after the 1991 eruption is shown in Figure 5. It shows the extent of the 1991 pyroclastic flow deposits, superimposed on a shaded relief map derived from the DEM for that period.

The new pyroclastic flow deposits covered approximately 24 km^2 and obliterated three major water divides, leaving only the high hills that form distinct "islands" in the middle of new and featureless flat pyroclastic flow deposits. The pre-eruption pyroclastic fan in the catchments of Sapangbato and Taug, which was not covered, acted as a wedge dividing the pyroclastic flow into two directions: north into the lower catchment of the Abacan and Sacobia rivers and south into the Pasig river.

One of the most important effects of the deposition of the extensive pyroclastic flow deposits was the change in the hydrologic situation. Since the pre-eruption river valleys were completely filled up, new streams developed on top of the pyroclastic flow level, following partially different courses. The most striking example of this resulted from the burial of the drainage divide between the Sacobia and Abacan rivers. Pyroclastic flow deposits overtopped this drainage divide by about 20 m and were deposited in the upper reaches of the Abacan catchment. During and directly after the eruption, lahars resulting from the passing of typhoon Yunya were therefore not following the pre-eruption river valley of Sacobia, but were drained through the Abacan river valley, causing destruction in the city of Angeles. The upper Sapangbato catchment was also diverted towards the Abacan catchment.

Another important change in the hydrologic situation took place in the Pasig river, where a 2.47 km^2 section of the pre-eruption southern upper Sacobia catchment was captured, thus extending the pre-eruption catchment of the Pasig river over the water divide, which was covered by 80 m of pyroclastic flow deposits. Further downstream stream piracy took place in the headwaters of Timbu creek, which captured the main Pasig river. An overview of the change in catchment sizes before and after the eruption is shown in Table 1.

GEOMORPHOLOGY AFTER THE FIRST RAINY SEASON

Figure 6 shows the geomorphologic situation between the end of the first rainy season at the end of 1991 and the beginning of the second rainy season in 1992. The geomorphology of the Sacobia catchment changed dramatically during the first rainy season after the 1991 eruption. Because of the heavy rainfall, the original pyroclastic flow surface was eroded, resulting in a series of terrace levels with a high gully density, separated by deep valleys. Four terrace levels were differentiated (PF terrace levels 1 to 4), with increasing rates of erosion. PF terrace levels 1 and 2 still represent the original depositional surface, with more erosion in level 2. Terrace levels 3 and 4 resulted from severe erosion, and are below the level of the original depositional surface. Within just a few months after the eruption, the main rivers had eroded impressive gorges to depths of approximately 35 m. Deposition of the pyroclastic flow and lahar materials blocked the Yangca creek, which is a tributary of the Pasig river, and a dammed lake began to develop.

Another important geomorphologic feature that can be observed from Figure 6 is the presence of secondary craters. Secondary craters are created by phreatic explosions occurring in the pyroclastic flow deposits. These are produced when water comes into sudden contact with the hot in-situ pyroclastic flow deposits, producing expanding steam. The mechanisms for generating secondary explosions are not fully understood, but they are often contemporaneous with heavy rains, although in some instances they can occur when there is little or no rainfall (these occurrences may be related to groundwater flow within the pyroclastic flow material). More frequent moderate to minor explosions are caused by the collapse of large valley-sides of the newly exposed hot pyroclastic flow deposits produced during the passage of erosive lahars. Most secondary explosions in the Sacobia

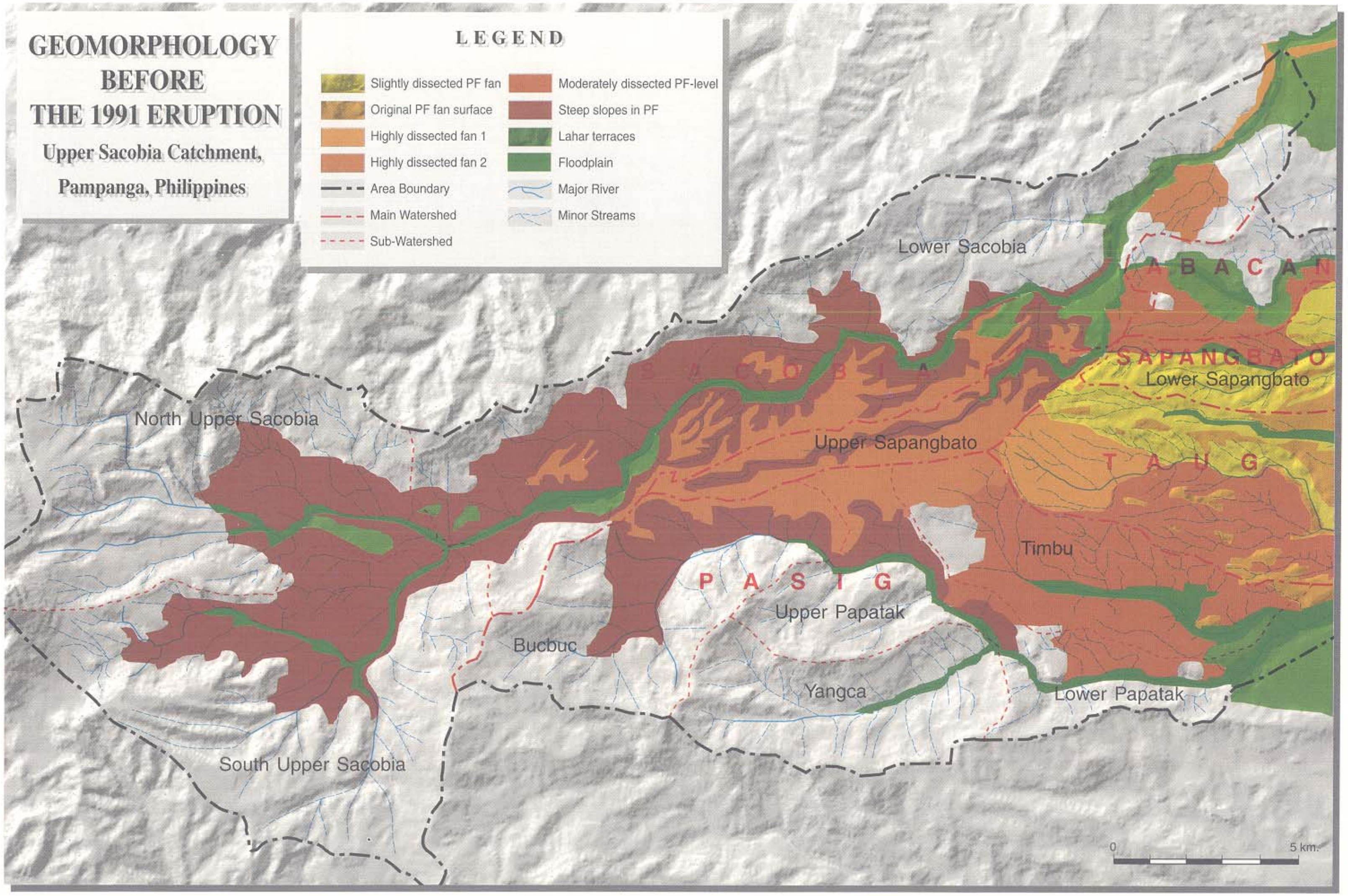


FIGURE 4 Pre-eruption geomorphologic map superimposed on a shaded relief map made from the pre-eruption DEM. The catchment areas and major streams are also indicated

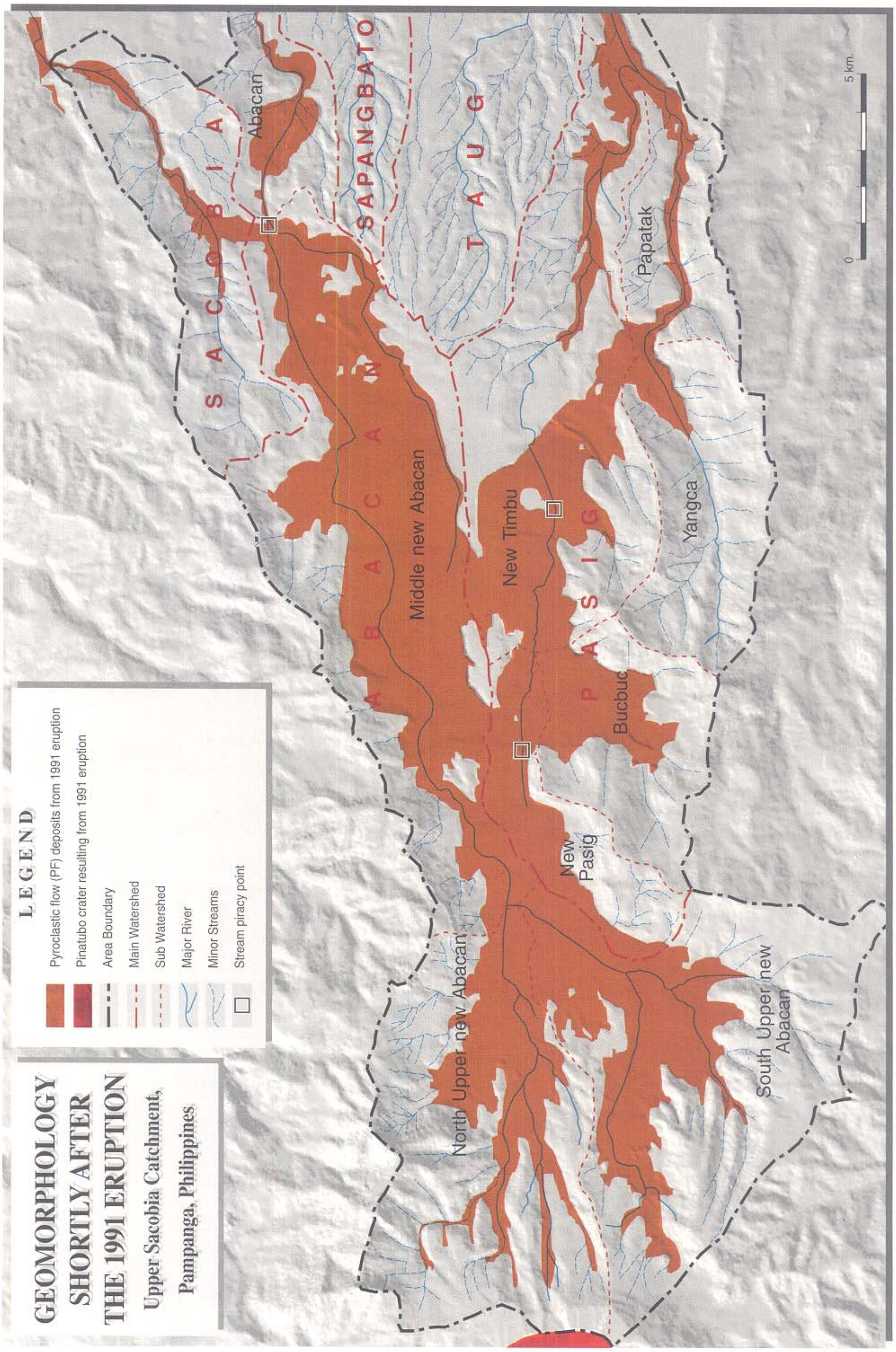


FIGURE 5 Post-eruption geomorphologic map superimposed on a shaded relief map made from the post-eruption DEM. The catchment areas and major streams are also indicated

watershed result in deep semi-circular to oblate craters or crown features with a relatively flat base. The depth of secondary craters ranges from 20 to about 80 m. One of the effects of secondary explosions may be the triggering of secondary pyroclastic flows, which can remobilize volumes of considerable thickness over large distances.

The most important secondary explosion after the rainy season of 1991 occurred on 4 April 1992, at the waterdivide between Sacobia and Abacan (indicated in Figure 6 as "piracy point"). The secondary explosions at the so-called "Abacan gap" produced 2 to 3 km of channel-confined secondary pyroclastic flow deposits and resulted in the recapture of the upper catchment by the Sacobia river, causing large destructive lahars in the downstream section, which buried several villages and destroyed hundreds of hectares of agricultural land. The secondary pyroclastic flows completely buried the recently constructed lahar-retaining structures along the Sacobia river. Only a small area of the pyroclastic flow-covered zone still drained towards the Abacan, but this section also was captured later by the Sacobia. Because of the loss of connection with the pyroclastic flow deposits, the Abacan river ceased to cause any serious lahar threats to the city of Angeles. The lahars then followed along the main courses of the Sacobia and Pasig rivers, with the former being the most important because it had the largest catchment area within the pyroclastic flow deposits. Another important stream capture took place when the Pasig river recaptured its old course, reducing the lahar activity via the Timbu river. An overview of the changes in catchment sizes during the first rainy season is given in Table 2.

GEOMORPHOLOGY AFTER THE SECOND RAINY SEASON

Figure 7 shows the geomorphologic situation after the second rainy season, at the end of 1992, and the beginning of the third rainy season in 1993. After the second rainy season, the valleys in the study area were widened and deepened considerably in comparison with the year before. Most valleys established their courses following the former deep pre-eruption valley axis where new pyroclastic flow deposits were thick. This may have been caused by the resistant pre-eruption pyroclastic flow terraces which were mantled by less than 30 m of new pyroclastic flows. Some of the gullies at Sacobia partially incised the pre-eruption deposits.

The areas of the terraces were rapidly diminishing as a result of valley widening at their bases, gully widening and secondary explosions. The upper terrace level (PF terrace level 1) in the southern confluence of the upper northern and upper southern Sacobia nearly vanished. The other isolated patches of this type of terrace were also completely eroded, especially in the southern portion of upper Sacobia subcatchment. Isolated terraces were beginning to form as a result of erosion along several sides. In 1992, large secondary explosions occurred in both the Sacobia and Pasig catchments. The main explosion along the Sacobia river had an area of 0.3 km^3 and a depth of 30 m; it was in an area which was a circular low depression in the pre-eruption morphology, and which was probably a site of prehistoric secondary explosions. Several minor explosions from side-wall collapse had occurred as a result of lateral erosion. The secondary explosion crater at the confluence of Bucbuc and Pasig and the large crater at the Sacobia river were not active in 1992, and their features are gradually diminishing as a result of gully-side erosion.

The lake at the confluence of Yangca creek and Pasig river had again generated large lake-breakout related lahars. At the same time, the lake was being filled by lahars that spread out from the Pasig river.

During the second rainy season, only minor changes in drainage areas took place, resulting from stream captures. The Sacobia river captured the last 0.3 km^2 from the Abacan river in direct contact with pyroclastic flow deposits.

GEOMORPHOLOGY AFTER THE THIRD RAINY SEASON

Figure 8 illustrates the geomorphologic situation between the end of the third rainy season, at the end of 1993, and beginning of the fourth rainy season in 1994. Valleys had grown rapidly in the upper portion of the catchment near the confluence of the two large valleys. This massive erosion was triggered by a large secondary explosion which occurred on 6 October 1993, and, as a result, a large secondary pyroclastic flow was directed towards the Pasig river. This event caused the capture of the entire upper Sacobia catchment by the Pasig river, and caused a major shift in lahar delivery from the Sacobia to the Pasig. Aerial reconnaissance indicated that the secondary pyroclastic flows covered the major gullies in both Sacobia and Pasig catchments with at least 20 m of hot secondary flow deposits. The event did not produce clear secondary craters because of the subsequent severe erosion—leaving only broad flat valleys. The capture occurred during typhoon Kadiang and

TABLE 1 Changes in catchment areas before and after the eruption (all values are in km^2) note: 0.208 km^2 of the Sacobia catchment was incorporated in the newly formed crater

				After 1991 eruption				
		Sacobia	*Pasig*	*Abacan*	*Taug*	*Sapangbato*		*Total*
Before 1991 eruption	Sacobia	5.421	2.474	31.719	0	0		39.822
	Pasig	0	21.894	0	0	0		21.894
	Abacan	0	0	2.539	0	0		2.539
	Taug	0	0	0	6.602	0		6.602
	Sapangbato	0	0.332	2.291	0	2.666		5.289
	Total	5.421	24.790	36.549	6.602	2.666	Before After	76.146 76.028

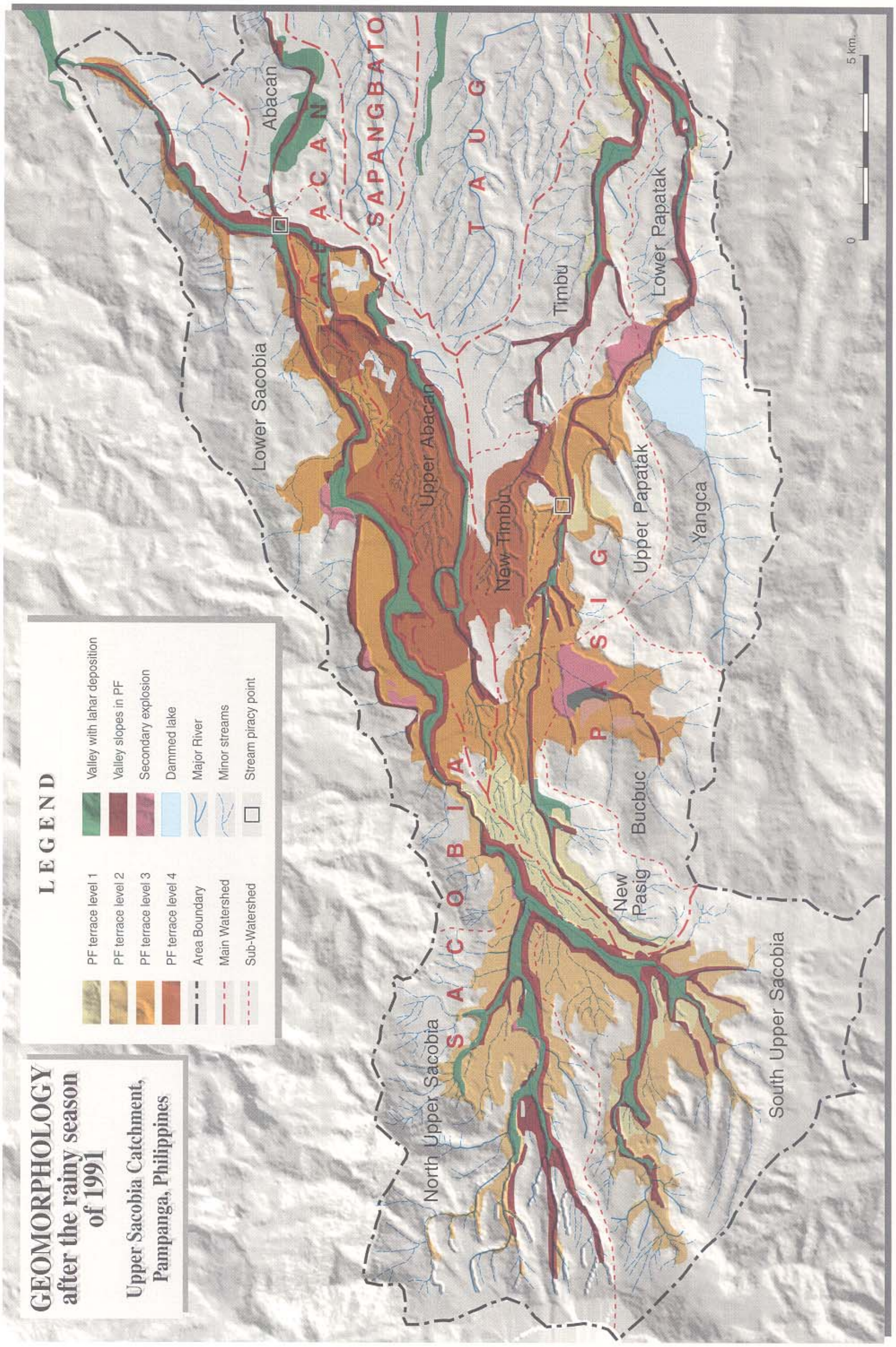


FIGURE 6 The situation after the first rainy season in 1991 superimposed on a shaded relief map made from the DEM for that period

TABLE 2 Changes in catchment areas during the first rainy season (all values are in km^2)

		After first rainy season (1991)					
		Sacobia	*Pasig*	*Abacan*	*Taug*	*Sapangbato*	*Total*
After 1991 eruption	Sacobia	5.421	0	0	0	0	5.421
	Pasig	0.001	24.789	0	0	0	24.790
	Abacan	28.791	0	7.758	0	0	36.549
	Taug	0	0	0	6.602	0	6.602
	Sapangbato	0	0	0	0	2.666	2.666
	Total	34.213	24.789	7.758	6.602	2.666	76.028

the relative timing of capture can be reconstructed by the change of lahar magnitude of both channels as measured by acoustic sensors in the lahar monitoring stations. An overview of the changes in catchment area is shown in Table 3.

As a result of the capture of the upper section of the Sacobia catchment, erosion in the Pasig river increased dramatically. The rapid vertical and lateral erosion in the pyroclastic flow deposits, which were still hot, resulted in numerous secondary explosions along the Pasig river. At the lower part of Sacobia, the valleys were considerably incised into the pre-eruption deposits, attaining a vertical valley wall of some 50 to 80 m.

The upper pyroclastic flow level was by then completely eroded, and the second level persisted only in the eastern part of the catchment. In the lower terrace levels, erosion reached the underlying pre-1991 pyroclastic flow deposits in several places.

The capacity of the temporary lake to retain water had decreased considerably as a result of deposition of lahars into the Yangca creek. No large lake-failure related lahars occurred during this period, since the lahar dam at Yangca creek was much higher than the active channel. The next year, however, the lahar dam failed, resulting in a major lahar in the dowstream Pasig catchment.

VOLUME CALCULATIONS

On the basis of the five DEMs, the volume of pyroclastic flows and the subsequent erosion during three years were calculated for each catchment. The results are given in Table 4.

Several authors have estimated the 1991 volume of the Sacobia pyroclastic flows. Estimates ranged from 0.65 to 1.6 km^3 [9, 2, 5, 12, 10]. After overlaying the pre-eruption and post-plinian eruption DEMs, we calculated a total volume of 1.278 km^3 of new (since 1991) pyroclastic flow deposits. Thicknesses of the new deposits on the deep pre-eruption valleys reached as much as 218 m. A total of 854 million m^3 (mcm) was deposited on the pre-eruption Sacobia, and about 400 million m^3 in the Pasig catchment. The Abacan catchment received 3.5 and the upper section of Sapangbato 23.3 million m^3.

The deposition of the pyroclastic flow deposits dramatically changed the new catchment areas. The Sacobia river had lost most of its catchment area to the Abacan river, and contained only 8.3 million m^3 in a catchment area of 5.24 km^2. Most of the pyroclastic flow material (740 million m^3) was then located in the Abacan catchment.

The volume of the eroded deposits during the rainy season of 1991 was calculated by overlaying the DEMs of pre-eruption and post-lahar 1991. The total eroded volume was 219 million m^3, of which 156 million m^3 was derived from the 1991 deposits and the rest from earlier deposits. More erosion occurred along the Sacobia watershed (108 million m^3) than in the Abacan river (26.761 million m^3), which by that time had lost most of its initial catchment area as a result of stream piracy. The estimated volume of lahar deposits at the Abacan channel is 60 million m^3 [8] and a large portion of the lahar deposit was derived from the eroded prehistoric lahars along the Abacan river (downstream of the study area).

After the second rainy season (end 1992), a total remaining volume of pyroclastic flows of 1.039 million m^3 was calculated. A total volume of 137 million m^3 was eroded, of which 82.7 million m^3 consisted of 1991 deposits. The largest erosion volume occurred in the Sacobia watershed (80 million m^3), which had the largest area (34 km^2). The four sub-catchments *ie*, Abacan, Taug, Sapangbato and Timbu (part of Pasig) did not contribute much to the large erosion volume that year. In the Yanga catchment, deposition instead of erosion took place, caused by the encroaching lahars of Yangca creek.

The situation changed dramatically after the third rainy season (end 1993) because of the capture of the upper Sacobia catchment by the Pasig river. The remaining volume of pyroclastic flow material was estimated as 959 million m^3 and the yearly erosion as 142 million m^3, of which 80 million m^3 was derived from 1991 deposits and the rest from earlier or secondary deposits. The river capture, resulting from a large secondary explosion, resulted in strong erosion in the Pasig catchment, partly in the pre-eruption sediments to depths of approximately 20 to 50 m. Some profiles shown in Figure 9 illustrate the erosion activity.

DISCUSSION

The results obtained in this study were compared with those obtained by other authors who used different methods. From relative general estimations, based on the use of approximate drawing of cross sections [2, 9], total pyroclastic flow volumes of 1.60 and 1.05 km^3 were obtained. A more precise method, using photogrammet-

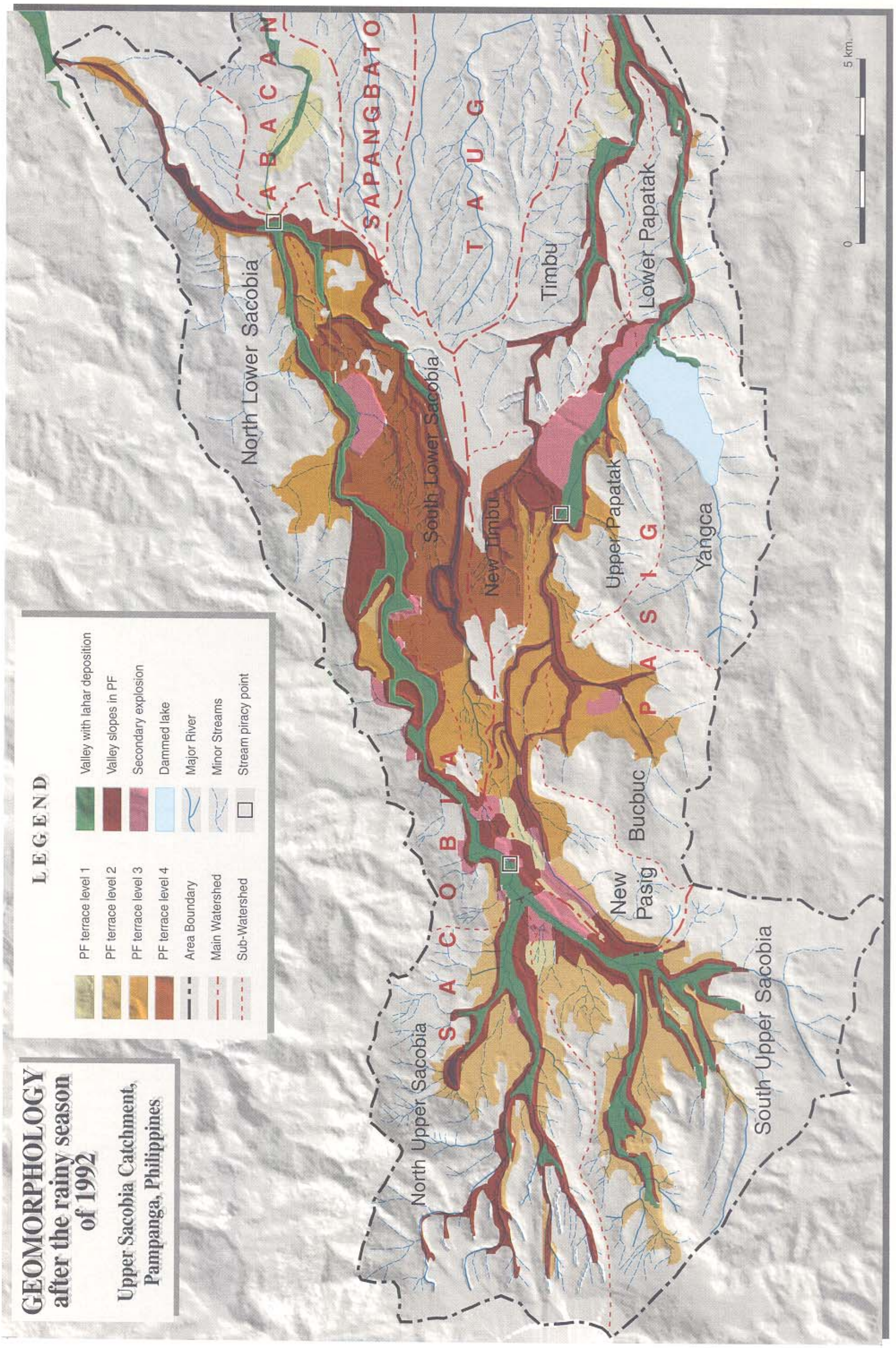


FIGURE 7 The situation after the second rainy season (in 1992) superimposed on a shaded relief map made from the DEM for that period

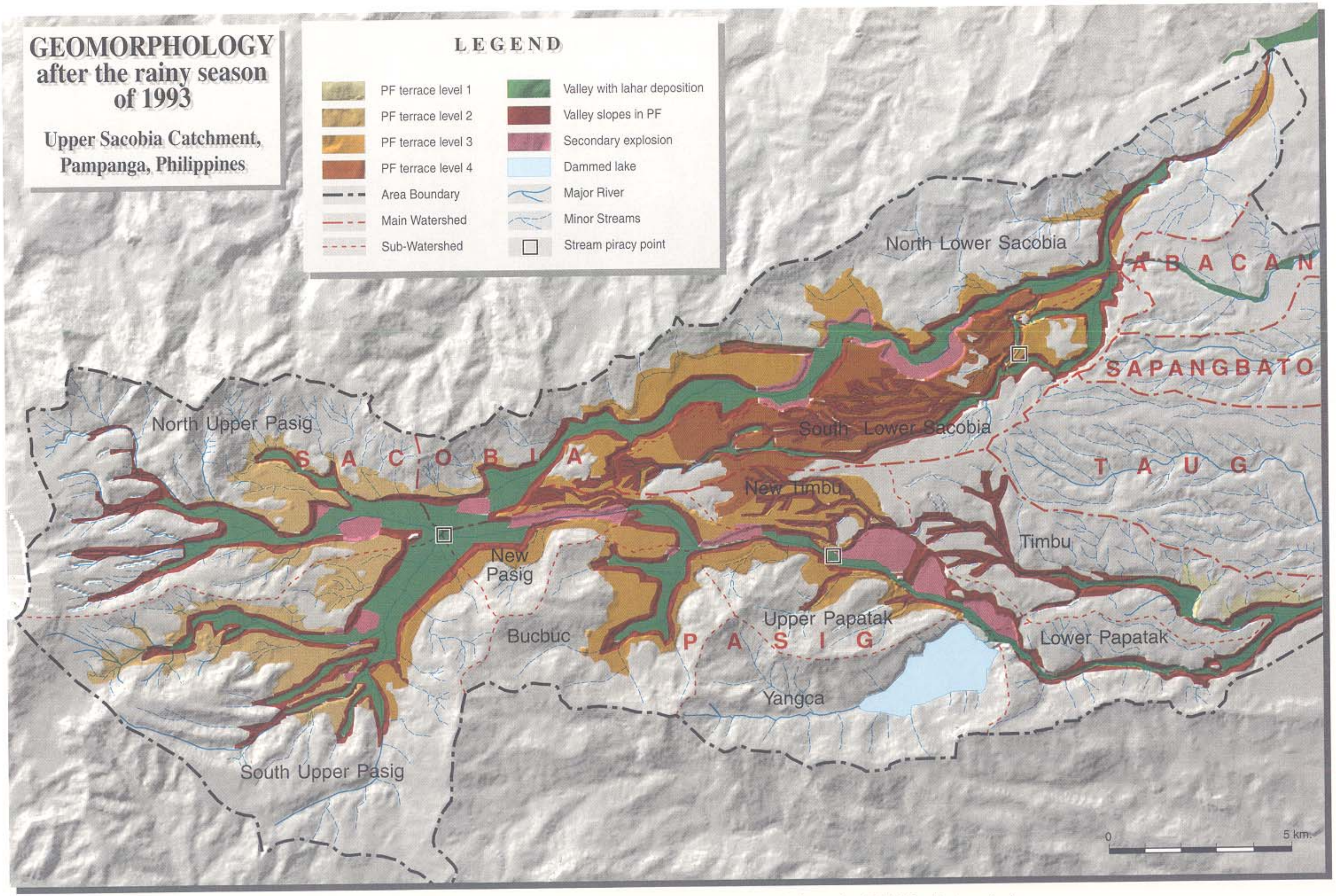


FIGURE 8 The situation after the third rainy season (in 1993), superimposed on a shaded relief map made from the DEM for that period

TABLE 3 Changes in catchment areas during the third rainy season (all values are in km^2)

		After third rainy season (1993)					
		Sacobia	*Pasig*	*Abacan*	*Taug*	*Sapangbato*	*Total*
After second rainy season	Sacobia	14.095	20.273	0	0	0	34.368
	Pasig	0.013	24.918	0	0	0	24.931
	Abacan	4.938	0	2.523	0	0	7.461
	Taug	0	0	0	6.602	0	6.602
	Sapangbato	0	0	0	0	2.666	2.666
	Total	19.046	45.191	2.523	6.602	2.666	76.028

TABLE 4 Catchment areas, volumes of pyroclastic flow deposits, and eroded volumes of pyroclastic flow deposits during three The first two columns indicate the pyroclastic flow volumes in the pre-eruption catchments

	Before eruption		*After eruption*		*After first rainy season (1991)*			*After second rainy season (1992)*		
Catchment	*Catchment area (km^2)*	*Volume of PF (10^{6}m^3)*	*Catchment area (km^2)*	*Volume of PF (10^{6}m^3)*	*Catchment area (km^2)*	*Volume of PF (10^{6}m^3)*	*Eroded volume (10^{6}m^3)*	*Catchment area (km^2)*	*Volume of PF (10^{6}m^3)*	*Eroded volume (10^{6}m^3)*
Sacobia	39.822	854.400	5.421	8.298	34.213	542.010	108.242	34.368	471.349	80.274
Pasig	21.894	398.354	24.790	529.698	24.789	470.795	84.005	24.931	469.724	53.047
Abacan	2.539	3.547	36.549	740.036	7.758	108.448	26.761	73.461	97.458	3.594
Taug	6.602	0	6.602	0	6.602	0	0	6.602	0	0
Sapangbato	2.666	23.3	2.666	0	2.666	0	0	2.666	0	0
Total	76.146	1278.032	76.028	1258.071	76.028	1121.253	219.008	76.028	1038.531	136.915

Erosion of 1991 PF deposits:156.8
Erosion of other deposits:62.3
Sedimentation within catchment:0.1

PF erosion during second season:82.7
Erosion of other deposits:54.2
Sedimentation within the area:44.0

ric techniques on cross sections [12], resulted in a value of 0.902 km^3. Compared with these values, our estimate of 1.278 km^3 is rather high, but this may be caused by the fact that the volume was based not on cross sections but over the entire area, using a DEM overlaying technique.

Erosion volume calculations based on direct measurements of the pyroclastic flow deposits have not been published to date. Annual rates of erosion have been obtained indirectly by others estimating the volumes of the delivered lahars [8]. Their results are shown in Table 5. When these values are compared with the ones obtained in this study (see Table 4), it is clear that the erosion volumes calculated by comparing DEMs are slightly larger than the volumes of the lahars. This could be caused by redeposition within the area and the fact that not all materials were transported to the areas surrounding the volcano—on which the lahar estimates are based. When the resedimentation volumes are subtracted from the total erosion (see Table 4), the values match rather well. Another reason for the difference may be that the finest fractions of the eroded sediments were transported farther away by rivers during lahar events, towards the lowland Candaba swamp (50 km east) and Manila bay.

To study and monitor erosion and the occurrences of lahars at Pinatubo, rain gauges and acoustic flow sensors with digital real-time data acquisition were set up by PHIVOLCS on the slopes of the volcano. From the measured rainfall at the Sacobia watershed, rainfall in three years did not vary considerably (2200 to 2400 mm). However, annual erosion of pyroclastic flow deposits drastically dropped to about 60 percent of the first year (219 million m^3), compared with the second

TABLE 5 Lahar volume estimates for the Sacobia catchment (from [8])

Catchment	*Volume of PF*	*Volume of erodible PF*	*Erodible pre-eruption sediments*	*Potential lahar sediments*	*1991 lahar sediments*	*1992 lahar sediments*	*1993 lahar sediments*
Sacobia	900	360	36	398	100	70	45
Pasig	500	200	20	220	50	40	55
Abacan	200	80	8	88	60	0	0
Total	1600	640	64	704	210	110	100

(137 million m³) and third years (142 million m³). Since the measurements were made for only three years, it is difficult to make valid assumptions for a longer period.

Several authors [7, 11] stated that in general the long-term erosion forecast would likely behave according to an exponential decay curve function. Such predictions were based on comparisons of the erosion rates of two volcanoes, *ie*, Mt St Helens in the United States and Galunggung in Indonesia. If the erosion values for the three years are compared, it is clear that there was a large decrease in volume from 1991 to 1992, also expressed by a decrease in lahar volumes. The next year (1993), however, does not fit into this exponential decay curve, since it had an erosion rate higher than the preceding year. This was caused mainly by the occurrence of the secondary explosions, as a result of which the upper Sacobia catchment was captured by the Pasig and the erosion rates in the Pasig increased dramatically.

Secondary explosions can still occur within the area for a number of years, until the pyroclastic material has sufficiently cooled. Another factor which may prevent the exponential decay of erosion and lahar volumes is the break-out of lahar-dammed lakes. In 1994, the break-out of the lake in the Yangca catchment caused a lahar in the lower Pasig area, which covered an area larger than in the preceding years (see Figure 2). The lahars will therefore continue to be an important hazard in the foot-slopes for a number of years. The most critical factor in predicting the future behaviour of lahars is the estimation of the potential erodible pyroclastic flow deposits still present in the area. To fully understand this, analytical photogrammetric techniques should be used, which will provide more detailed and reliable results.

rainy seasons after the 1991 eruption.

After third rainy season (1993)		
Catchment area (km^2)	*Volume of PF (10^6m^3)*	*Eroded volume (10^6m^3)*
19.046	296.648	56.146
45.191	659.474	86.073
2.523	3.194	0.223
6.602	0	0
2.666	0	0
76.028	959.316	142.442

PF erosion during third season:79.2
Erosion of other deposits: 63.2
Sedimentation within the area: 41.5

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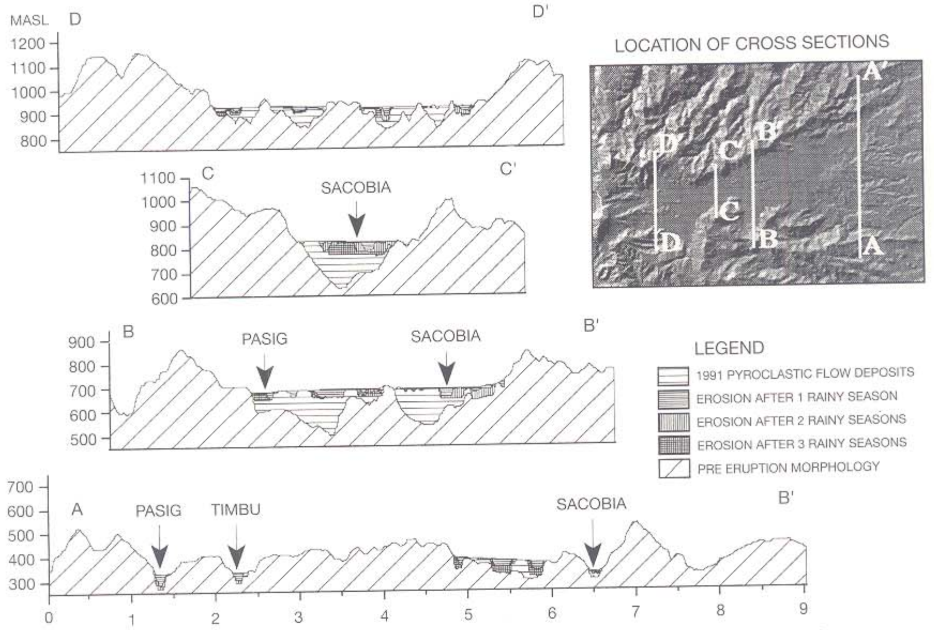

FIGURE 9 Cross sections showing elevations of the 1991 pyroclastic flow deposits within the pre-eruption valleys, and the erosion levels after three rainy seasons

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RESUME

L'éruption du Mont Pinatubo a déposé, le 15 juin 1991, environ 5 à 7 km^3 de matériaux d'écoulement pyroclastique. L'épaisseur accumulée de ces écoulements pyroclastiques a varié, suivant la proximité du cratère et la morphologie antérieure à l'éruption, elle a atteint plus de 200 mètres le long des profondes vallées pré-éruptives. Ces dépôts ont affecté huit bassins versants principaux autour des pentes du volcan et ont altéré les régimes hydrologique d'une façon radicale, ce qui a mené à une érosion sans précédent et laissé des sédiments sous forme de lahars destructifs. L'un des huit bassins versants, le captage de Sacobia sur la pente est du volcan, a été étudié en détails, y compris sa géomorphologie qui a changé rapidement, avant et pendant l'éruption et ensuite pendant trois années consécutives. On a mis l'accent sur l'importance de la capture du courant résultant de l'érosion et des explosions secondaires. Afin de quantifier le volume de matériaux de flot pyroclastique et l'érosion annuelle, on a préparé et analysé cinq modèles numériques de terrain (DEMs) à l'aide d'un GIS. Un volume total de 1.78 km^3 de flot pyroclastique déposé en 1991, dans le captage de Sacobia a couvert une zone de 24 km^2 et a atteint 15 km, en aval du cratère. Les taux d'érosion ont été calculés comme étant entre 136 et 219 millions m^3 par an.

RESUMEN

La erupción del Monte Pinatubo el 15 de junio de 1991 depositó approximadamente 5 a 7 km3 de materiales de flujo piroclásticos. El espesor acumulado de los flujos piroclásticos varió de acuerdo a la proximidad al cráter y la morfología pre-eruptiva, y alcanzó más de 200 m a lo largo de valles profundos pre-eruptivos. Estos depósitos afectaron a ocho cuencas hidrográficas principales en las vertientes del volcán y alteraron radicalmente a los regímenes hidrológicos, causando erosión y extraordinarias descargas de sedimentos en forma de lahares destructivos. Se estudió en detalle una de las ocho cuencas, la de Sacobia ubicada en la vertiente oriental del volcán, incluyendo los rápidos cambios de la geomorfología antes y durante la erupción y por tres años consecutivos después de la erupción. Se resaltó la importancia de las capturas fluviales que resultaron de la erosión y de explosiones secundarias. Para cuantificar los volúmenes del material de flujo piroclástico y de la erosión anual, se elaboraron y analizaron cinco modelos digitales de elevación (DEM) usando un SIG. Un volumen total de 1.78 km^3 de flujos piroclásticos se depositó en 1991 en la cuenca de Sacobia, cubriendo un área de 24 km^2 y llegando hasta 15 km aguas abajo del cráter. Las tasas de erosión se estimaron entre 136 y 219 millones de m^3 por año.