FIGURE 8.33 Mt. Kelut: Sand pocket on the Konto River. It is used as a paddy-field in the dry season. Location: East Java, Indonesia. *Photo: I. Suryo*

is now 1.5 m above the level of the surrounding paddy-fields.

To minimize the volume of loose volcanic material entering into the Brantas River, a series of check dams and sand pockets with a total storage capacity of 40 million m^3 has been constructed (Suryo and Clark, 1985). The lahar deposit area created by the 1966 eruption is bounded by dykes whose purpose is to trap the material transported by secondary lahars. The resulting deposits are used for agricultural purposes during the dry season (*Fig 8 33*).

The distance travelled by a primary lahar depends on the volume of water in the crater lake. The experience of the three successive eruptions has shown that no destructive primary lahar will be generated if the volume of water in the crater lake is kept below one million m^3. The drainage tunnel completed in 1967 has since kept the volume of the lake satisfactorily low (see *Fig. 8.31*).

Responsibility for issuing a lahar warning now lies with the Kelut Volcanic Debris Control Project. Observation posts have been established to keep a watch on the rivers, to monitor the risk and, if necessary, to strike the tong-tong used to give warning of a lahar (see *Fig. 8.8*).

8.3.3. Mt. St. Helens, USA (1980)

Mt St. Helens is 2,975 m high and is situated at the northern end of a series of volcanoes in the Cascade mountain range in the State of Washington, USA.

Many minor earthquakes and hundreds of steam-blast explosions had occurred in the area for almost two months before May 1980 Subsequently, the United States Geological Survey (USGS) set up seismometers to identify the epicentres and to monitor the volcanic activity. Many groups of university students as well as ham radio operators and ordinary citizens cooperated with the USGS in monitoring, and information transmission and exchange.

Soon after the mild eruption of 27 March 1980, the Washington State Department of Emergency Services published a pamphlet pointing out the difficulties of predicting a volcanic eruption. The pamphlet gave detailed advice to people entering the high-hazard area on how to respond to emergencies (see Appendix C). An evacuation order was also issued. The authorities resisted the growing public pressure to allow residents, timber workers and tourists to re-enter the area.

The Federal Emergency Management Agency (FEMA) set up a liaison office in Vancouver and issued bulletins informing the public of the most appropriate action to take in case an emergency situation developed. The bulletins covered such varied matters as health care to cope with volcanic ash, the contamination of city water due to soluble components of ash, and the effects of ash on the air filter of a tractor. The timely intervention of the public authorities was effective in preventing any danger of panic, and enabled researchers to devote themselves to the tasks of monitoring and analysis.

The eruptive activity had become sporadic by late April and early May, but both the seismicity and the rate of displacement of the bulging north flank of the mountain remained high. Most scientists anticipated the possibility of more vigorous volcanic activity, although none could, of course, be certain of its ultimate character.

On 18 May 1980, the main anticipated eruption took place. It was not the usual vertical eruption but an unexpected lateral blast. Its destructive power, in terms of released energy, was almost as much as that of a 10 megaton atomic bomb. Although the number of people killed was 74, it is estimated that had there been free access to the area and had the destructive event not occurred on a Sunday when few timber workers were on the job, there might have been more than a thousand fatalities.

The eruption had a major impact on the 600 km^2 catchment area of the Toutle River around the mountain (*Fig. 8.34*). The explosion triggered a gigantic rock avalanche and released hot gases as well as pumice, ash and mudflows. The northward-propelled lateral blast destroyed or overturned all vegetation in a 550 km^2 area north of the mountain. Especially in the periphery of the blast-affected area, the shock wave caused by the blast and the hot gases released were channelled away from the general direction of the blast down major valleys that lead west, north, and east. The blast deposited debris of from 0.025 m to more than 1 m on hill slopes throughout the devastated area.

Two very large, high-velocity debris avalanches were triggered by a pyroclastic surge during the first few minutes of the eruption. The transition from a gas-supported debris avalanche to a water-supported debris flow appears to have occurred at the base of the volcanic cone, approximately 10 km downslope from the crater rim.

Much of the material displaced by the eruption exploded or slid in a north-by-north-westerly direction, primarily into the North Fork Toutle River and the South Fork Toutle River. From there, debris from huge mudflows then swept down the Toutle River itself and into the Cowlitz River. Eyewitnesses described the front of the mudflow as a high wall rushing down the river. One hundred and twenty-three houses and many bridges were destroyed. The eruption significantly altered the landscape of the Toutle-Cowlitz Valley (*Fig. 8.35*)

The US Geological Survey had prepared a hazard map based on past experience of lava flows, pyroclastic flows (nuées ardentes) and mudflows, and had designated the danger area. The huge amount of material, the unexpected nature of the blast and the associated mudflow, however, ravaged a vast area far beyond the limits of the designated hazard area

Blast deposits reduced the infiltration of subsequent rainfall and thus appreciably increased runoff. Furthermore, the destruction of vegetation reduced water interception and evapo-transpiration, and may have increased runoff within the affected area by as much as 50 cm during the summer growing season following the erup-

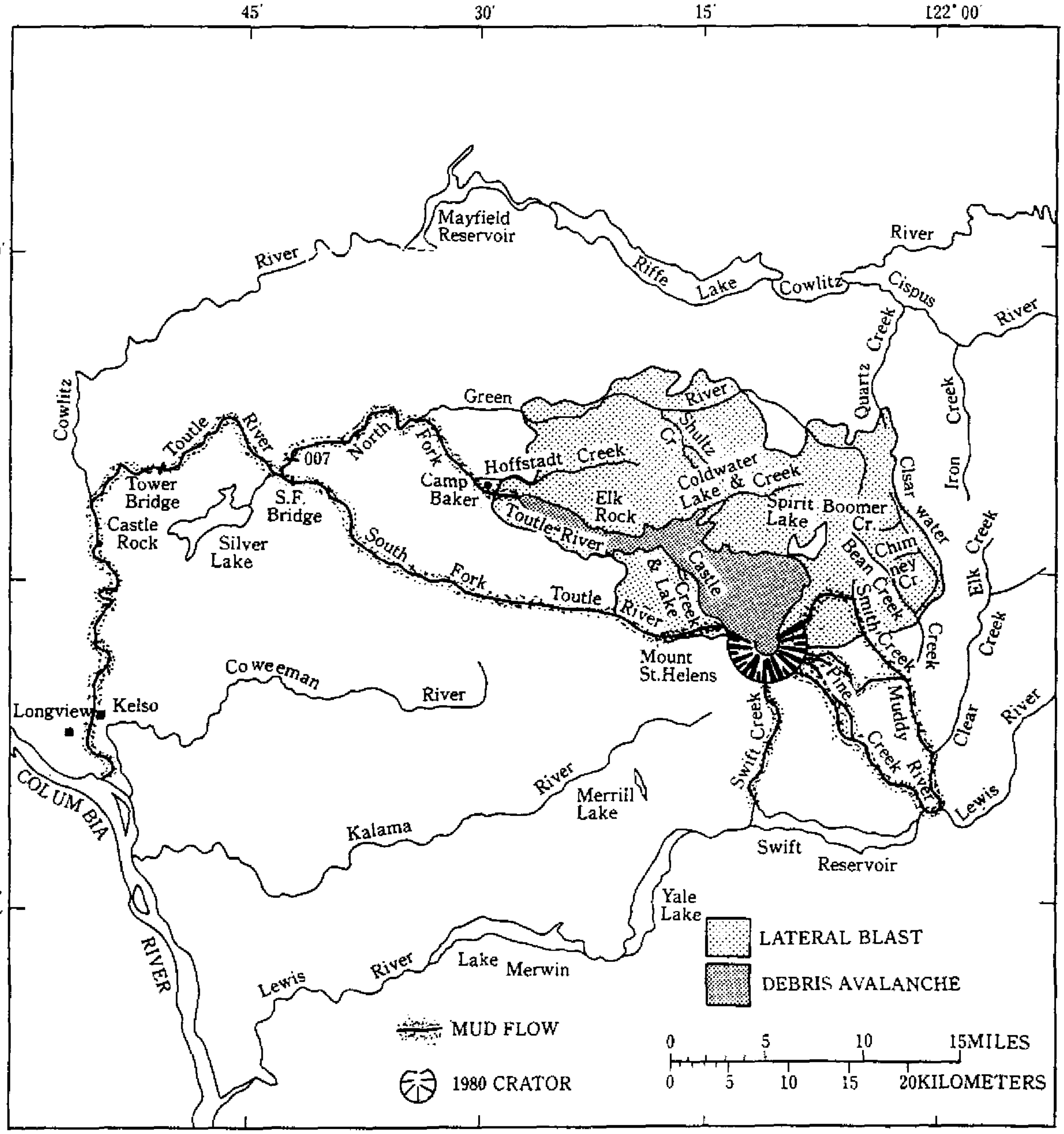

FIGURE 8.34 Map showing the distribution of debris around Mt. St. Helens after the 1980 eruption and resulting mudflow.

FIGURE 8.35 Significantly altered landscape resulting from the 1980 eruption of Mt. St. Helens. (Courtesy: US Geological Survey, Photo Library, Denver, CO).

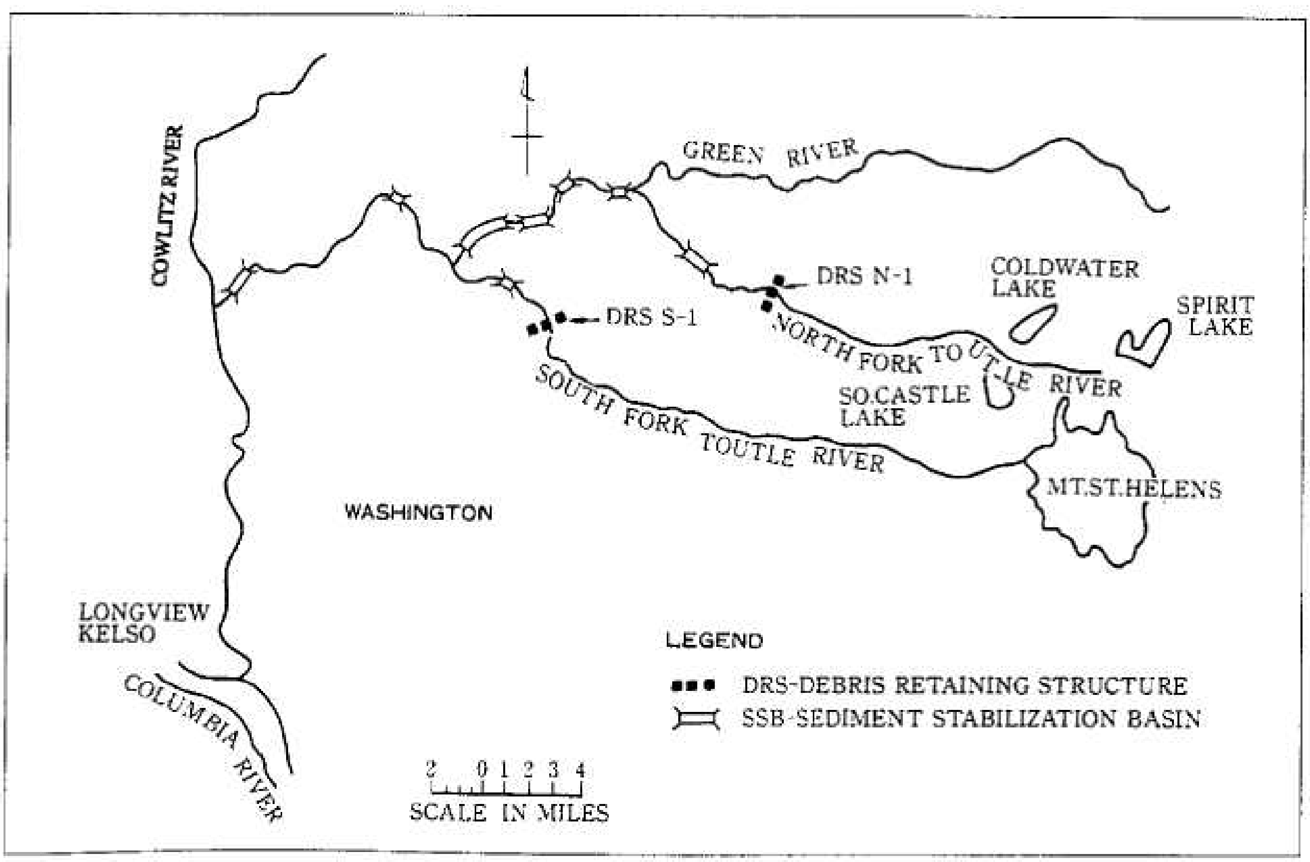

FIGURE 8.36 Mt. St. Helens: Locations of sediment-control structures.

tion. This augmented runoff accelerates erosion and causes secondary mudflows.

Structural measures to control the mudflows and stabilize the sediments were established along the South Fork and North Fork Toutle Rivers and on the Green River (*Fig. 8.36*). The site plan of some debris-retaining structures is shown in *Figure 8.37*.

8.3.4. Nevado del Ruiz, Colombia (1985)

Los Nevados Natural Park in Colombia is named after the large number of high mountain peaks covered by perpetual snow. Many of these peaks are volcanoes which have been extinct for millions of years. However, the Nevado del Ruiz volcano (5,400 m high) is an exception, and has shown signs of being active on several occasions. Mudflows originating from this volcano have occurred in the past (*Fig. 8.38*) and, in fact, the city of Armero is actually built on ancient mudflow deposits.

The volcano had remained quiescent for a considerable period prior to November 1984, when local earthquakes of low intensity began. This was followed by a small steam eruption on 22 December 1984, and by a large steam blast on 11 September 1985.

The signs of volcanic activity from November 1984 onwards had caused concern to the Colombian authorities. After a large explosion in September 1985, which generated ashfall and a mudflow which travelled 27 km, half-way to the town of Armero, preparation of a volcanic hazard map was begun and was completed by October 1985.

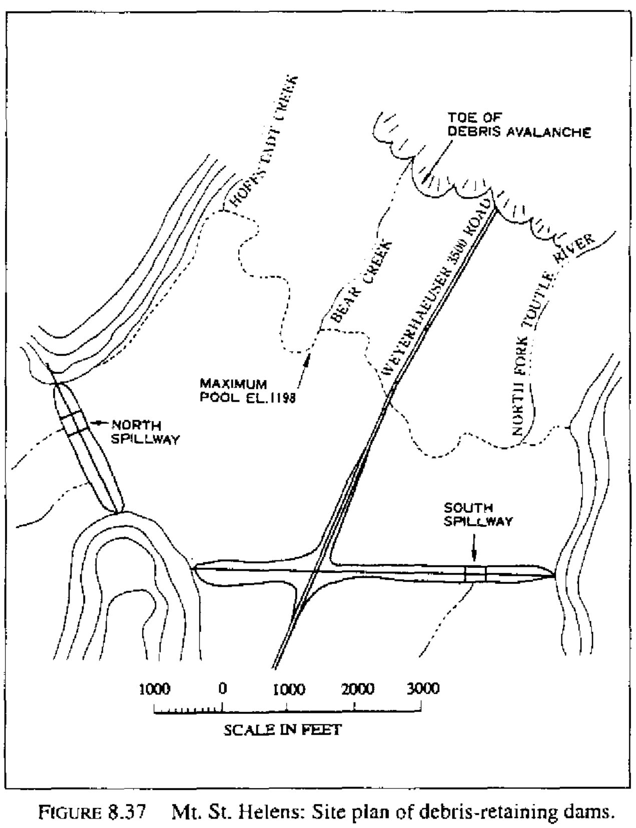

FIGURE 8.37 Mt. St. Helens: Site plan of debris-retaining dams.

During the four weeks preceding the disaster of 13 November 1985, efforts were made by the civil defence organization and other services to increase public awareness and develop emergency procedures in the high-risk areas, but in the absence of new activity from the volcano, their task was not an easy one. The great distance between the summit of the volcano and the populated areas concerned gave a false sense of security. The state of public awareness of volcanic hazard in Colombia was, in general, rather low. For instance, one senior official in Bogota, who claimed to know Nevado del Ruiz very well, insisted at first that it was not a volcano and that, in any case, it was not hazardous because it was ice-capped.

The first explosions at 1506 hours on 13 November 1985, which were similar to those of 11 September, triggered an alert and partial evacuation. Two hours later, complete evacuation appeared unnecessary, and in any event would have been hampered by heavy rain and nightfall. Consequently, a report of new explosions at 2108 hours which were not announced as being significantly larger, met with scepticism from both the local authorities and the population with regard to the need to evacuate. Furthermore, alerts to prepare for mudflows, which had been issued at 1700 hours by the Colombian Red Cross, were not disseminated properly. Two loud explosions occurred at 2108 hours, followed by pyroclast flows and surges which caused the melting of an estimated 5 per cent-8 per cent of the ice-cap. A large mass of water, rocks, mud and fallen trees flowed down the eastern flank of the volcano, roaring along the Lagunillas River, and on the western side along the Chinchina River.

A violent mudflow hit Armero at 2335 hours and continued to engulf the area for two hours. The mudflow, which had a speed of as much as 72 km/h and which was up to 12 m deep, destroyed all the buildings in its path. Both the course and the area inundated by the mudflow coincided with those shown on the hazard map (*Fig. 8.39*). The mud and debris covering Armero amounted to a volume of 15.8 million m^3 spread over 30.6 km^2 (*Fig. 8.40*).

According to eyewitnesses in Armero, the mudflow came in two surges: the first one was cold, while the second was hot. The next morning, the temperature of the mud deposit was still as high as 40° C. It is assumed that the first surge came from the Lagunillas valley, taking the shortest course, while the second one, which was mixed with hot pyroclastic material, came from the Azufrado valley.

Mudflows also occurred in the valleys of Guali and Chinchina. However, Chinchina city survived the mudflow because of its location on a higher river terrace.

After the mudflow disaster, most of the town of Armero (population 29,170) and some neighbourhoods of Chinchina (population 61,909) lay buried under up to 15 m of mud. The Nevado del Ruiz mudflow disaster has been the largest of the twentieth century thus far, in terms of the number of dead (24,740).

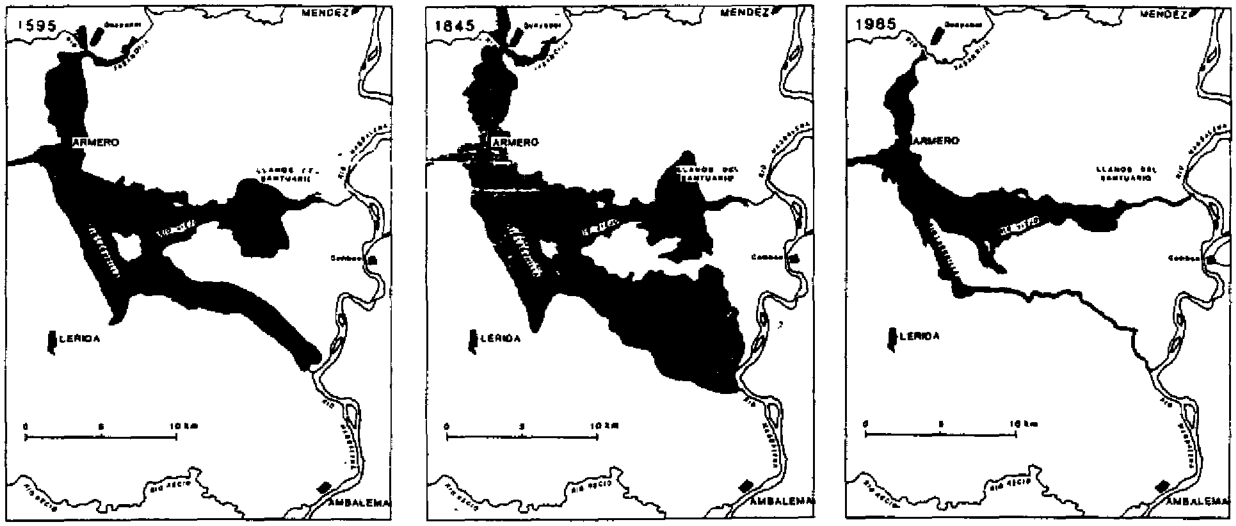

FIGURE 8.38 Mudflow deposits of 13 November 1985, near the city of Armero, compared with those reconstructed for the events of 1595 and 1845.

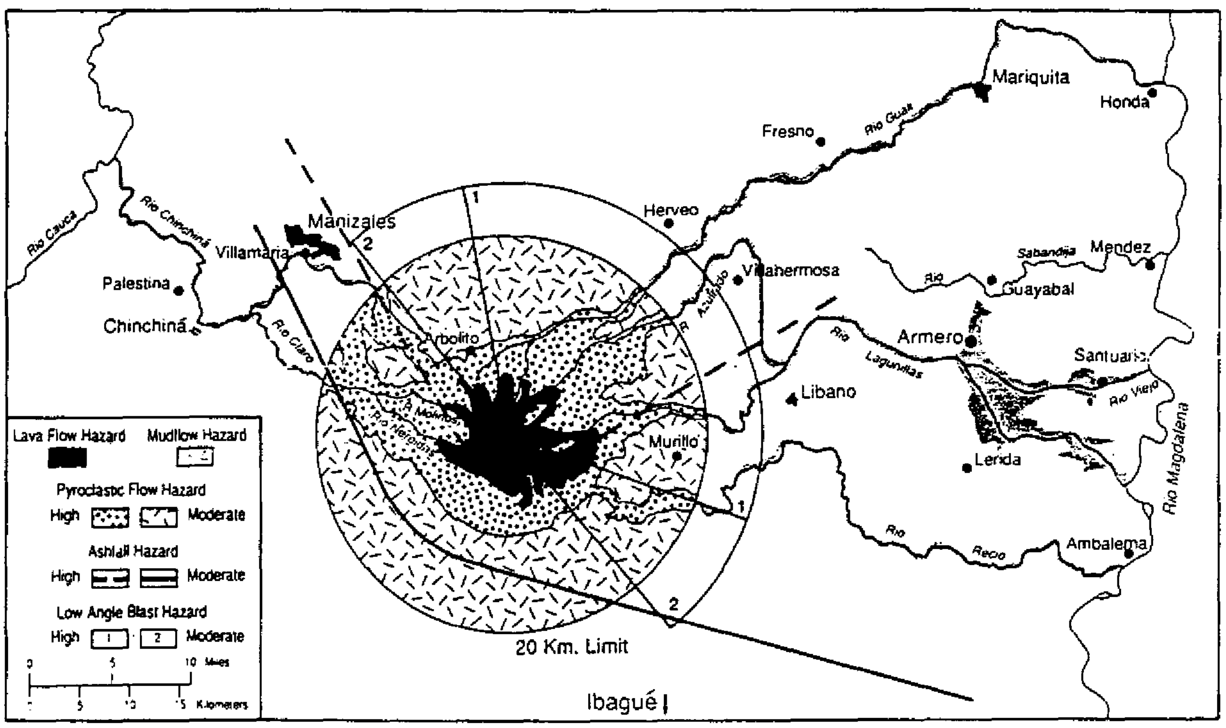

FIGURE 8.39 Volcanic hazard map of Nevado del Ruiz, Colombia.

FIGURE 8.40 Armero, Colombia, after the 1985 mudflow (Courtesy: Steven L. Raymer, National Geographic Society). *Photo: National Geographic.*

FIGURE 8.41 Powerful eruption of Mt. Pinatubo, July 1991. (Courtesy: C. G. Newhall, NOAA, National Geophysical Data Center, Boulder, Colorado, USA).

8.3.5. Mt. Pinatubo, Philippines (1991)

Mt. Pinatubo on the island of Luzon, Philippines, belongs to the Western Belt of the Philippine Quaternary volcanoes and has been dormant for about 500 years. Geological investigations, however, revealed that the peak is surrounded by extensive alluvial fans formed by pyroclastic flows and lahar deposits between 600 and 8,000 years in age. It has been estimated that the volcano has been active for about 1.1 million years.

The 1991 eruptive phase started on 2 April with a series of small phreatic explosions which emitted steam and small quantities of ash from a zone of vents. The first powerful explosion occurred on 12 June, followed by the most intense phase on 15 June (*Fig. 8.41*). These explosions produced heavy ashfall and pyroclastic flows. The latter swept over an area of more than 100 km^2 and extended as far as 15 to 16 km from the vent, with travel speed estimated at about 80 km/h. In some canyons, the thickness of these pyroclastic flows reached 200 m. Ashfall (tephra) reached a thickness of about 50 cm near the vent of the volcano and decreased to about 20 cm at 40 km distance (*Fig. 8.42*). The situation was aggravated by typhoon rains. The water added substantial weight to the loose ash and caused a large number of roofs to collapse. The volumes of airfall tephra (ash) and pyroclastic flow deposits have been estimated to be at least 0.5 km^3 and 7 km^3, respectively.

After 16 June, eruptions decreased in both magnitude and frequency. Ash emission continued until late August, while the last eruption occurred on 4 September. As a result of this eruptive phase, a new crater had formed. The elevation of the volcano's summit had decreased by almost 300 m. Heavy rainfall and decreasing temperatures in the caldera floor led to the formation of a shallow crater lake.

Lahars

There are eight major river systems draining Mt. Pinatubo (see *Fig. 8.42*), three on the west side and five on the east side. Each of these river systems is fed by numerous tributaries. The volcanic eruptions produced an enormous amount of pyroclastic material (7 km^3) filling the rills and valleys at higher elevations (*Fig. 8.43*). A typical river profile, shown in ***Figure 8.44***, illustrates the initially rapid change in gradient and shows that the pyroclastic deposits are perched on very steep slopes, which are inherently unstable.

The pyroclastic material is cohesionless and very susceptible to water erosion (*Fig. 8.45*). A rainfall intensity of as little as 10 mm can trigger a lahar on Mt. Pinatubo within 30 minutes. Secondary lahar flows in the valleys descending from the volcano started immediately with the onset of the monsoon rains (*Fig. 8.46*). About 80 per cent of the annual rainfall in Luzon occurs during the four-month period from June to September.

The lahars of Mt. Pinatubo have been roughly classified into two types. The first type contain from about 20 to 60 per cent of sediment by volume and behave like turbulent muddy rivers, except that they carry much more sediment than even the muddiest of normal rivers. The second type contain even more sediment (up to 80 per cent) and resemble fast, smooth-flowing slurries of freshly mixed concrete. These slurries are so dense (more than twice the density of water) that large boulders, rock-filled gabions, vehicles, concrete buildings, and even bridges are sometimes lifted up and floated away.

The 1991 eruption of Mt. Pinatubo with its accompanying ashfalls and lahars, caused loss of lives and inflicted extensive damage to the public infrastructure and private property. Lahars and accompanying floods destroyed a large number of bridges and roads, and damaged flood control facilities (*Fig. 8.47*). The latter included silted rivers, breached levees, clogged drains and destroyed dykes. The total length of river channels affected by pyroclastic flows and first-year lahars was over 30 km (*Fig. 8.48*). The direct damage amounted to approximately US$ 400 million at the end of 1991. More damage occurred in the following years during the typhoon season. Damage is expected to continue to occur, because during a single season only a fraction of the erodible pyroclastic deposits is being delivered to the lowlands. Preliminary sediment-delivery forecasts up to

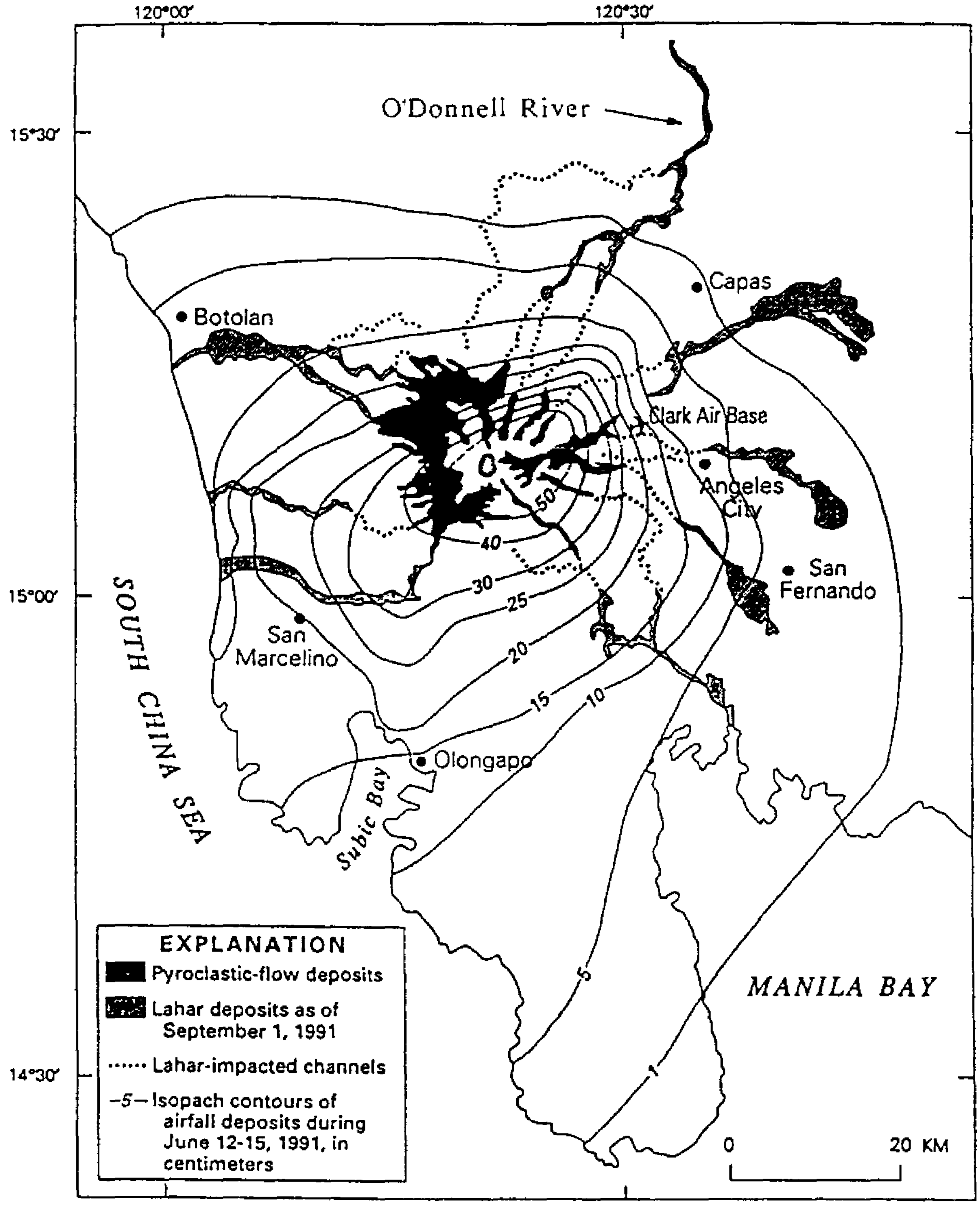

FIGURE 8 42 Pyroclastic-flow deposits in the headwaters of the rivers around Mt Pinatubo, and the location of the O'Donnell River (Map taken from *Earthquakes and Volcanoes*, vol. 23/1, 1992, USGS).

FIGURE 8.43 Mt. Pinatubo. Pyroclastic deposits (primary lahars) in the watersheds of the Pasig, Abacan and Sacobia Rivers *Photo. M Watanabe. 1991.*

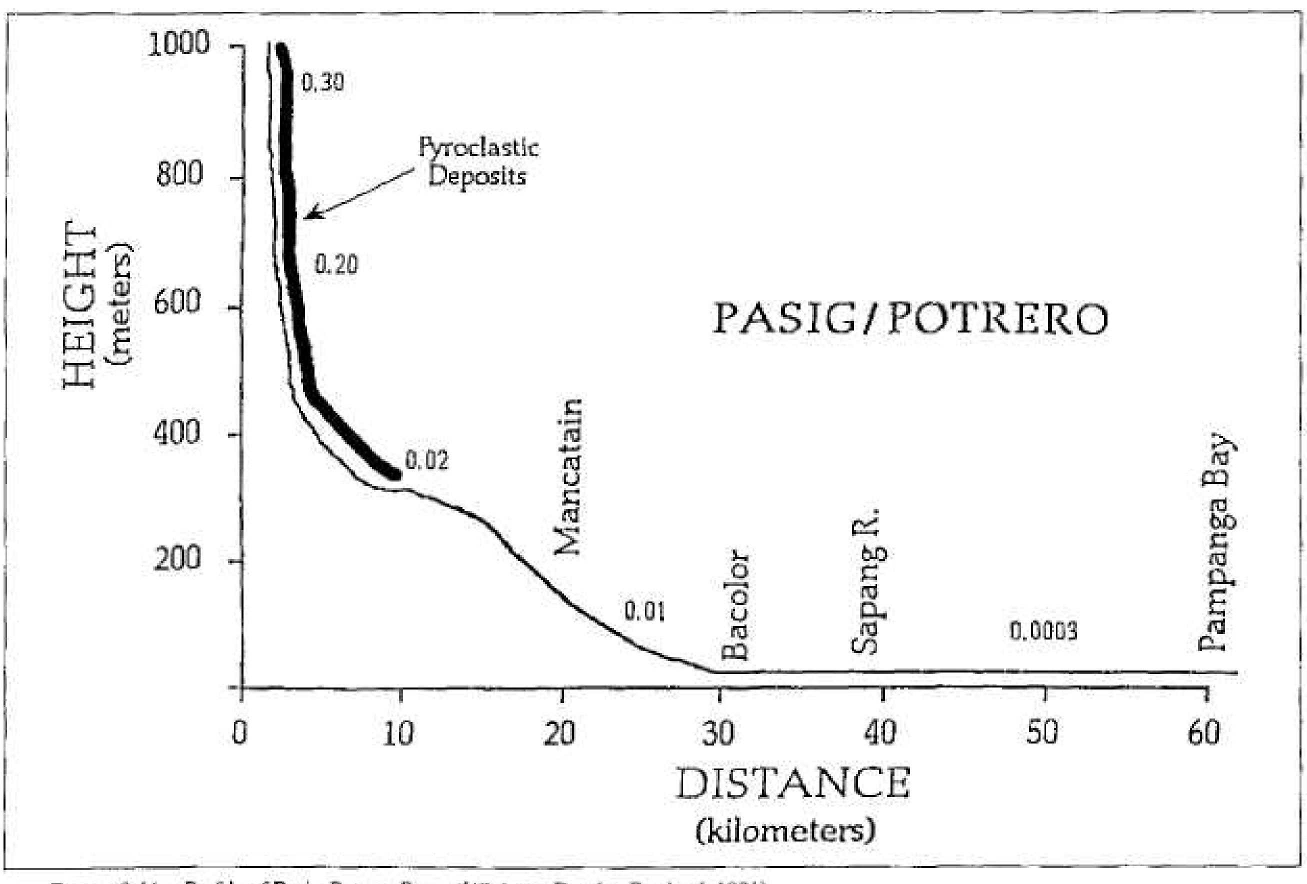

FIGURE 8 44 Profile of Pasig-Potrero River (US Army District, Portland, 1991)