

# COMPARATIVE PREPAREDNESS IN NEW ZEALAND AND THE PHILIPPINES FOR RESPONSE TO, AND RECOVERY FROM, VOLCANIC ERUPTIONS: CASE STUDIES FROM THE 1991 PINATUBO ERUPTION AND THE 1995-6 ERUPTIONS OF RUAPEHU

V. Manville<sup>1</sup>, D. Johnston<sup>1</sup>, S. Stammers<sup>2</sup> and B. Scott<sup>1</sup>

## ABSTRACT

New Zealand and the Philippines are two of the most tectonically and volcanically active regions in the world, due to their setting as large island chains on the convergent margin of the Pacific Plate. The Philippines has experienced numerous volcanic disasters over the past 400 years with the loss of over 7000 lives and considerable damage to infrastructure. The 1991 eruption of Mount Pinatubo, after 500 years of dormancy, was the largest volcanic eruption globally in the last 50 years, with serious socio-economic consequences for the Philippines. The 1995-6 eruptions of New Zealand's Mount Ruapehu, were the most serious volcanic activity experienced in the country over the last 50 years, but occurred at a frequently active volcano for which monitoring, hazard assessment, and response systems were already in place. Although the eruptions differ in size by two orders of magnitude, they illustrate how volcanic activity impacts infrastructure and society at different levels of economic development and vulnerability. Two of New Zealand's volcanic centres, Taupo and Okataina, have the potential to generate eruptions of a similar, or even greater, scale than Pinatubo. Therefore, lessons learnt from the Philippine experience will be of vital importance in planning for the mitigation of future volcanic disasters in New Zealand.

## INTRODUCTION

New Zealand stretches 1600 km from north to south between latitudes 35 and 47° S, on the western margin of the Pacific Ocean, separated from Australia by the Tasman Sea (Fig. 1). The two main land masses of the North and South Islands cover 115 000 km<sup>2</sup> and 151 000 km<sup>2</sup> respectively. The population of 3.5 million predominantly resides in the North Island, which contains the largest city, Auckland (1 079 000) and the capital Wellington (623 500). The climate is maritime temperate, with numerous areas of microclimatic conditions due to the geographic diversity of the country. A significant portion of the original native forest has been cleared for agriculture since Maori settlement c. 600 years ago and European colonisation in the early 19th century. The country faces high risks from a variety of natural hazards due to its geologic and geomorphic setting, spanning a tectonic collision zone and with a high axial mountain range stretching across oceanic weather patterns. The region is subject to frequent earthquakes and volcanic eruptions, and is vulnerable to tsunamis generated within the confines of the Pacific Ocean. Landslides are common throughout New Zealand, and floods caused by cyclones are also frequent.

The Philippine Archipelago consists of 7107 islands with a total area of 300 000 km<sup>2</sup> spread across 15 degrees of latitude and 10 degrees of longitude on the western rim of the Pacific Ocean (Fig. 2). Only about 2000 islands are inhabited and only 500 are larger than 1 km<sup>2</sup>. Luzon and Mindanao form the two largest islands in the group and cover two-thirds of the total land area, much of which is mountainous. The population is around 60 million (increasing at 2.3% per annum), of which 40 % is urban. Over 10 million people live in the largest city of Metro Manila in southern Luzon. The Philippines have a humid tropical climate with an average temperature range of 24-35°C, peaking at >38°C in mid-summer during May. Humidity is high and rainfall ranges from 2000 to 4000 mm/yr depending on the region. The climate is monsoonal, with a dry season from January to June and a wet season from July to December. The original vegetation cover, comprised dominantly of three-storied rainforest, has largely been stripped from the lowlands.

## VOLCANISM IN NEW ZEALAND

The New Zealand region is characterised by a high density of active volcanoes (Fig. 1), and a high frequency of eruptions.

<sup>1</sup> *Institute of Geological & Nuclear Sciences, Wairakei Research Centre, Taupo, NZ.*

<sup>2</sup> *Department of Geological Sciences, University of Canterbury, Christchurch, NZ.*

Volcanic activity over the last 10 000 years has been concentrated in the North Island of New Zealand, in four main areas: the Taupo Volcanic Zone (TVZ); its offshore continuation along the Tonga-Kermadec subduction zone; the Auckland-Northland volcanic field; and Taranaki (Egmont). The locations of these volcanic regions, and the compositions of the magmas erupted can be related to the large-scale convergence of tectonic plates in the New Zealand region.

The 300 km long Taupo Volcanic Zone (TVZ) is an area of intense Quaternary silicic volcanism associated with rapid extension and thinning of continental crust in the central North Island of New Zealand [2]. The TVZ is characterized by relatively small, but very frequent, caldera-forming eruptions. More than 34 such ignimbrite-emplacing events have occurred since 1.6 Ma from 8 relatively short-lived, nested, and/or overlapping volcanic centres aligned along a north-east striking structural trend [2, 3, 4]. In terms of life span, erupted volumes, and area the TVZ is comparable to the North American Yellowstone system [4, 5]. The southern end of the TVZ comprises two frequently active andesitic stratovolcanoes, Tongariro/Ngauruhoe and Ruapehu, which together make up the Tongariro Volcanic Centre. The central portion contains two of the world's most productive rhyolite caldera volcanoes, Taupo and Okataina. A third rhyolitic centre, at Maroa, is declining in activity but is still considered to be potentially active. The northern TVZ includes the highly active, largely submerged, andesite stratovolcano of White Island, and the rhyolite caldera complex of Mayor Island in the Bay of Plenty. The offshore extension of the TVZ along the New Zealand-Tonga-Kermadec subduction zone includes a number of submarine volcanoes (the Rumbles), and a cluster in the Kermadec Islands including Raoul and Macauley Islands.

The Auckland-Northland region contains three intraplate volcanic fields, characterized by small individual eruptions, at intervals of a few hundreds to a few thousands of years. The Auckland field is the best known, containing ~ 50 small volcanoes: Rangitoto at c. 600 years old is the youngest [6]. The magma is basaltic in composition, and eruptions tend to be small (typically 0.01 - 0.1 km<sup>3</sup>). Consequently, the areas affected are at most a few tens of km<sup>2</sup>, and the hazards are localised [7]. However, the growth of New Zealand's biggest commercial centre on top of the field has led to much greater awareness of the risks posed by a potential renewal of activity in this area. The other fields are centred on the Kaikohe-Bay of Islands and the Whangarei areas.

The Taranaki region contains a single active stratovolcano, the andesite cone of Mt Egmont (Taranaki). Although inactive since 1755 AD, the geological record of past ash falls indicates a return period for relatively large eruptions (> 10<sup>7</sup> m<sup>3</sup>) of < 330 years for the last 28ka.

#### **Classification and status**

New Zealand's volcanoes span a wide range of types, representing a cross-section of eruptive styles and magnitudes. Classification according to the chemistry of the erupted magma is one basic geological technique. In New Zealand, there is a spectrum of magma types from basalt through andesite and dacite to rhyolite, the chemistry changing from silica-poor (basalt) to silica-rich (rhyolite) through this range. As the silica content rises, the viscosity of the magma and its volatile content increases, leading to an escalation in the

explosiveness and violence of eruptions. Rhyolite volcanoes include Okataina, Taupo, Maroa, and Mayor Island, whose eruptions have typically been extremely violent, producing 10 - 100 km<sup>3</sup> of ash and pumice that devastated huge areas with pyroclastic flows. Extrusion of degassed viscous rhyolite lavas formed lava domes and fringing aprons of block and ash flows. Magma withdrawal during large-scale eruptions causes structural collapse of large areas, forming calderas up to 30 km across. Andesite volcanoes are intermediate in composition, and include Taranaki (Egmont), Ruapehu, Tongariro/Ngauruhoe, and White Island. Very frequent, but relatively small-scale explosive eruptions and lava flows build up a composite cone-shaped volcanic edifice with a summit crater. Basalt volcanoes are most common in the Northland-Auckland region, and as minor vents within the Taupo and Okataina Volcanic Centres. Small eruptions, often from monogenetic vents, construct small scoria domes, basaltic lava flows, maars, and tuff rings. Examples include Rangitoto and Mt Eden in Auckland.

For management purposes the National Civil Defence plan subdivides New Zealand's potentially active volcanoes into two classes: **frequently active** and **re-awakening** volcanoes (Table I). Frequently active volcanoes (White Island, Tongariro-Ngauruhoe, and Ruapehu) are characterised by numerous, often-prolonged eruption episodes over the last 150 years, i.e. the period of mainstream European settlement in New Zealand. Re-awakening volcanoes have been less active in historical times but have had numerous eruptions in the last 15 000 years. Re-awakening volcanoes include the Auckland field, Mayor Island, Mt Edgecumbe, Rotorua, Taranaki (Egmont), Maroa, and the rhyolite calderas of Okataina and Taupo.

#### **VOLCANISM IN THE PHILIPPINES**

The Philippines archipelago consists of a volcanic island arc developed in the complex convergence zone between the Eurasian and Philippine tectonic plates (Fig. 2). The Philippines is an area of intense volcanism and seismicity [8, 9], containing 21 designated *active* volcanoes, i.e. those that have erupted in the last 600 years [10]. Of these, six are monitored by the Philippine Institute of Volcanology and Seismology (PHIVOLCS): Mayon, Bulusan, Taal, Hibok-Hibok, Canlaon, and now Pinatubo. However, over 200 volcanoes are recognised as *potentially active* [11]. Much difficulty arises from the minimal data available on many of the Holocene (< 10 000 years BP) volcanoes, while a large proportion of the remainder are undated. Volcanism in the main island of Luzon is concentrated along relatively well-defined volcanic fronts associated with the subduction zones, and also along the Macolod Corridor which runs NE-SW across the southern part of the island. This area alone contains three large stratovolcanoes (including Mt Banahao, last active in 1730-1749), two large caldera complexes (Lake Taal and Laguna de Bay), and more than a hundred small monogenetic eruption centres concentrated in the Laguna Volcanic Field [12]. The subaerial composite cone of Mount Pinatubo in southwest Luzon became the Philippines most famous volcano, when it erupted in 1991 after six centuries of dormancy, and produced one of the largest volcanic events experienced world-wide this century [13]. Volcano Island in Lake Taal and Mayon in southeastern Luzon however have the distinction of being the archipelago's most frequently active volcanoes. Historical volcanic activity in the Philippines is summarised in Table II.

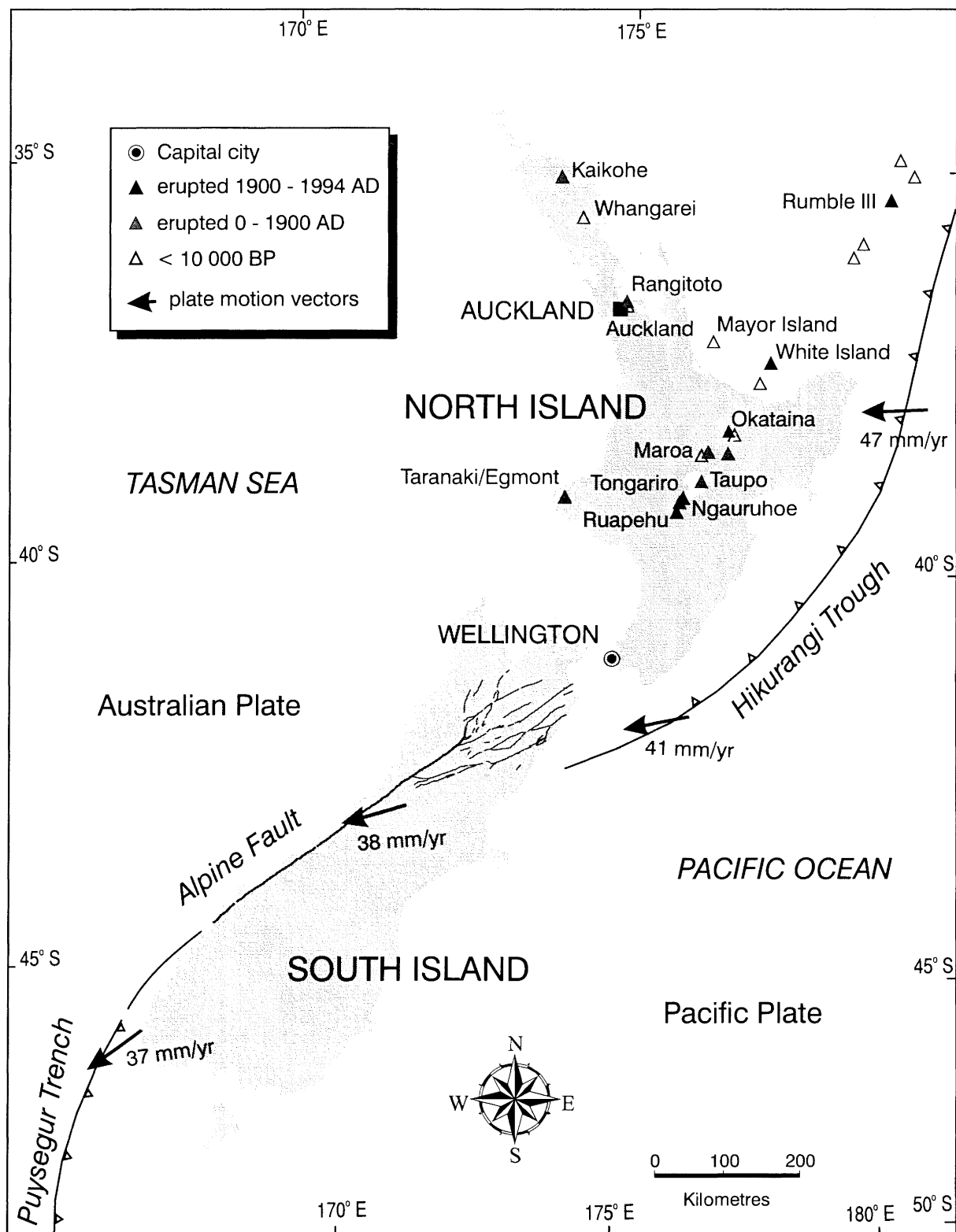


Figure 1: Volcanic map of New Zealand (after Simkin and Siebert 1994 [1]).

## CASE STUDY 1: THE 1991 ERUPTIONS OF MOUNT PINATUBO, PHILIPPINES

Mount Pinatubo is located within a chain of calc-alkaline composite volcanoes (Fig. 3) that make up the Luzon volcanic arc (Bataan Lineament). This line of Quaternary volcanoes reflects eastward subduction of the South China Sea plate beneath Luzon along the Manila trench to the west [8]. Its former summit (1 745 m) may have formed during lava dome emplacement during the most recent pre-historic eruptive episode c. 500 years ago [13]. The eruptive history of Mount Pinatubo is divided into two parts, an ancestral Pinatubo (~ 1 Ma to 35 ka), and a modern Pinatubo (~ 35 ka to the present). Modern Mount Pinatubo is a dacite-andesite dome complex and stratovolcano surrounded by a large gently sloping ring-plain of interbedded pyroclastic-flow and lahar deposits emplaced during large, episodic explosive eruptions [13]. Repose periods between eruptive activity, range from several centuries to millennia. Prior to the 1991 eruption more than 30 000 people lived on the flanks of Mount Pinatubo in small villages, with another c. 500 000 inhabiting cities and villages on the broad, gently sloping ring-plain surrounding the volcano. American military bases were sited 25 km east of the mountain at Clark Air Base and 40 km southwest at Subic Bay Naval Station.

### Eruption chronology

One of the features of the 1991 eruption of Mount Pinatubo is the realisation that very little was known about the volcano's potential for activity until shortly before the climactic phase of the eruption. The last known eruption from Pinatubo was c. 500 years ago, before the period of Spanish colonisation and the beginning of written historical records. In early 1991, few people suspected that the mountain hosted an active magmatic system, although preliminary studies on the geothermal potential of the area had been conducted [14].

### Pre-eruption events and early hazard assessments

The first indication of a re-awakening of Mount Pinatubo took the form of locally felt earthquakes in March 1991 (Table III), followed by small steam explosions along a line of vents on the upper flank of the mountain in early April [15]. In response, scientists from the Philippine Volcanic Survey (PHIVOLCS) installed portable seismometers on the flanks of the mountain where they began to record hundreds of small, high frequency earthquakes daily. This data led PHIVOLCS to recommend precautionary evacuation of 5000 people from within a 10 km radius of the summit.

In late April, a team from the United States Geological Survey (USGS) arrived to assist, and the joint team installed a network of seven seismometers with telemetry links to an office established at Clark Air Force Base, which became the Pinatubo Volcanic Observatory (PVO). Simultaneously, rapid geological mapping of the area to determine the size and style of previous eruptions was carried out to serve as the basis for a volcano-hazard map. This study showed that areas within 20 km of the summit were vulnerable to pyroclastic flows. Prehistoric lahar deposits derived by erosion and remobilisation of these flows extended down all major drainages to well beyond the proximal hazard zone (Fig. 3). The new hazard map, highlighting evacuation radii from the summit of Mount Pinatubo and predicted lahar paths, data

from the newly installed monitoring network, and a videotape illustrating volcanic hazards were used to explain the dangers of a potential eruption to civil-defence officials and military commanders. The evolving state of the volcano was communicated using a system of hazard alert levels [16].

### Increasing activity and the climactic eruption

Over the next month, seismic precursors and emissions of volcanic gases such as SO<sub>2</sub> and CO<sub>2</sub> increased [18, 19], indicating the upward migration of a body of magma beneath the volcano. In early June, shallow rock-fracturing earthquakes suggested that the rising magma was forcing a conduit through towards the surface, whilst a decline in gas emissions indicated the blocking of passages, increasing the likelihood of an explosive eruption. A small ash-producing eruption on June 3 presaged a period of increasing volcanic unrest accompanied by ash emission, increased seismicity, harmonic tremor, and outward deformation of the mountain. These events prompted PHIVOLCS to issue a level-3 alert on June 5, indicating the possibility of a major pyroclastic eruption within two weeks.

Accelerated outward tilting of the east flank of Pinatubo on 6 – 7 June indicated the movement of magma into the edifice itself. In response the alert level was raised to 4 (i.e. eruption possible within 24 hours), and recommendations for further evacuations were made by PHIVOLCS. On June 8 – 12, magma reached the surface to form a small lava dome and associated pyroclastic flows northwest of the summit in the upper Maraunot River canyon. Increased ash emission, shallow earthquake swarms, and emplacement of local pyroclastic flows led PHIVOLCS to raise the alert level to 5 (eruption in progress) on 9 June. The radius of evacuation was extended to 20 km, with over 25 000 people affected. On June 10, 14 500 military personnel were evacuated from Clark Air Base, leaving a skeleton staff of 1500. The PVO office moved to the eastern end of the base, 25 km from the summit.

The first major eruptive activity began on 12 June following a period of intense seismic tremor. An initial eruption column rose to 20 km and a pyroclastic flow moved down the Maraunot Valley. A further 600 staff were evacuated from Clark Air Base, the general evacuation radius was extended to 30 km, and the total number of evacuees rose to > 58 000. Explosive eruptions and the emplacement of pyroclastic flows continued over 12 – 13 June, with a change to long period seismicity. After a 28 hour lull in activity on 14 June, explosive eruptions recommenced with increasing frequency and generated numerous pyroclastic surges and flows from the collapse of a relatively low (12 km) eruption column. The change in eruptive style suggested that a climactic eruption was imminent and Clark Air Base was briefly completely evacuated, before PVO staff and a small military group returned. Increasing eruption frequency culminated in the onset of climactic activity at 1342 on 15 June that lasted for 9 hours. Continuous high-amplitude tremor saturated all seismometers that were not destroyed by voluminous pyroclastic flows, and pumice lapilli up to 40 mm in diameter fell on Clark Air Base which was finally evacuated. Numerous felt earthquakes indicated collapse of a 2.5 km diameter summit caldera during this phase of the eruption. Satellite images show the umbrella-cloud associated with the eruption spreading to 400 km in diameter within 2 hours at

Table I – Potentially active volcanoes of New Zealand.

Volcano	Type	Last eruption	Notes
Auckland	volcanic field	c. 1500	Eruption from Rangitoto basaltic shield, multiple monogenetic vents in field including scoria cones, tuff rings, and maars.
Taranaki/Egmont	stratovolcano	1755	Single stratovolcano
Ruapehu	composite stratovolcano	1996	Frequently active, 40 eruptions this century
Ngauruhoe	parasitic vent cone	1975	Young vent on south flank of Tongariro massif
Tongariro	composite stratovolcano	1896	4 main craters and several minor ones
Taupo	polygenetic rhyolite caldera	c. 181	Last major eruption in 181 A.D. generated 100 km <sup>3</sup> of tephra
Okataina	polygenetic rhyolite caldera	1886	Resurgent domes and cones form multiple vents. Tarawera 1886, Edgecumbe 2500 BP.
White Island	stratovolcano	1998	Frequently active
Rumble I-V, Clark, Tangaroa	stratovolcanoes	1986	Submarine volcanoes
Raoul Island	basaltic-dacitic stratovolcano	1964	
Macauley Island	dacitic caldera	1887	Formed by ~100 km <sup>3</sup> caldera eruption in last few thousand years
Monowai Seamount		1977	Submarine cone volcano

altitudes of 25 – 43 km, including lateral spread upwind of approximately 200 km.

Typhoon Yunya (later upgraded to tropical storm status) passed over Luzon at the time of the climactic eruption, contributing to the distribution of ash fall around the mountain and compounding the ash-loading effect on roofs. Tephra deposits > 10 mm thick covered an area of 7 500 km<sup>2</sup> of southern Luzon (i.e. 0.7 km<sup>3</sup>), and deposits > 100 mm thick blanketed a densely settled area of 2 000 km<sup>2</sup> [20]. Clark Air Base experienced 300 – 400 mm deposited ash. Pyroclastic flows were emplaced to 14 km from vent down all sectors of the volcano and buried some 400 km<sup>2</sup> beneath up to 200 m of pyroclastic material [21]. Rain from Typhoon Yunya triggered lahars in all catchments around Pinatubo [22, 23, 24].

#### Post-climax phenomena

Clark Air Base was reoccupied by PVO staff on 16 June. Seismic activity declined exponentially after the climactic eruption. Re-establishment of local seismic networks took two weeks. Continuous ash emission continued until 1 August with intermittent activity until 1 September when monsoonal rains began to form a shallow caldera lake. By the end of October 1991, remobilisation of proximal pyroclastic fans had redistributed around 0.9 km<sup>3</sup> of material, burying 300 km<sup>2</sup> of lowlands, and covered down river distances of up to 50 km [25]. The 1992 monsoon season added a further 0.5 – 0.6 km<sup>3</sup> of material with lahars in the O'Donnell, Sacobia

and the Pasig-Potrero river systems reaching distances between 60 and 70 km from source. These lahars have caused the most serious economic and societal consequences of the eruption. Secondary pyroclastic flows and hot lahars were generated by the interaction of monsoon rains with still-hot pyroclastic flow deposits during 1991 and 1992. A small lava dome grew in the summit caldera during July – October 1992 marking the effective termination of eruptive activity.

#### Scale of the eruption

A total bulk volume of 8.4 – 10.4 km<sup>3</sup> of pyroclastic material was ejected during the 1991 eruption of Mount Pinatubo [15], comprising 6 km<sup>3</sup> of pyroclastic flow deposits [21] and the remainder as ash fall [20]. This represents 3.7 to 5.3 km<sup>3</sup> of erupted magma. As such, the 1991 eruption of Mount Pinatubo is the largest in the world for 50 years and one of the 20<sup>th</sup> century's four largest.

#### Eruption hazard assessments and warnings

Despite the lack of knowledge of volcanic hazards at Mount Pinatubo prior to April 1991, an urgent program of monitoring and interpretation led to accurate warnings of one of the largest global eruptions this century. Without the warnings the death toll from the eruption could have been more than 20 000, rather than the 932 that actually died (total includes lahar and roof collapse victims and those who died from starvation and disease [68]). The accuracy and utility of these warnings were underpinned by three key elements:

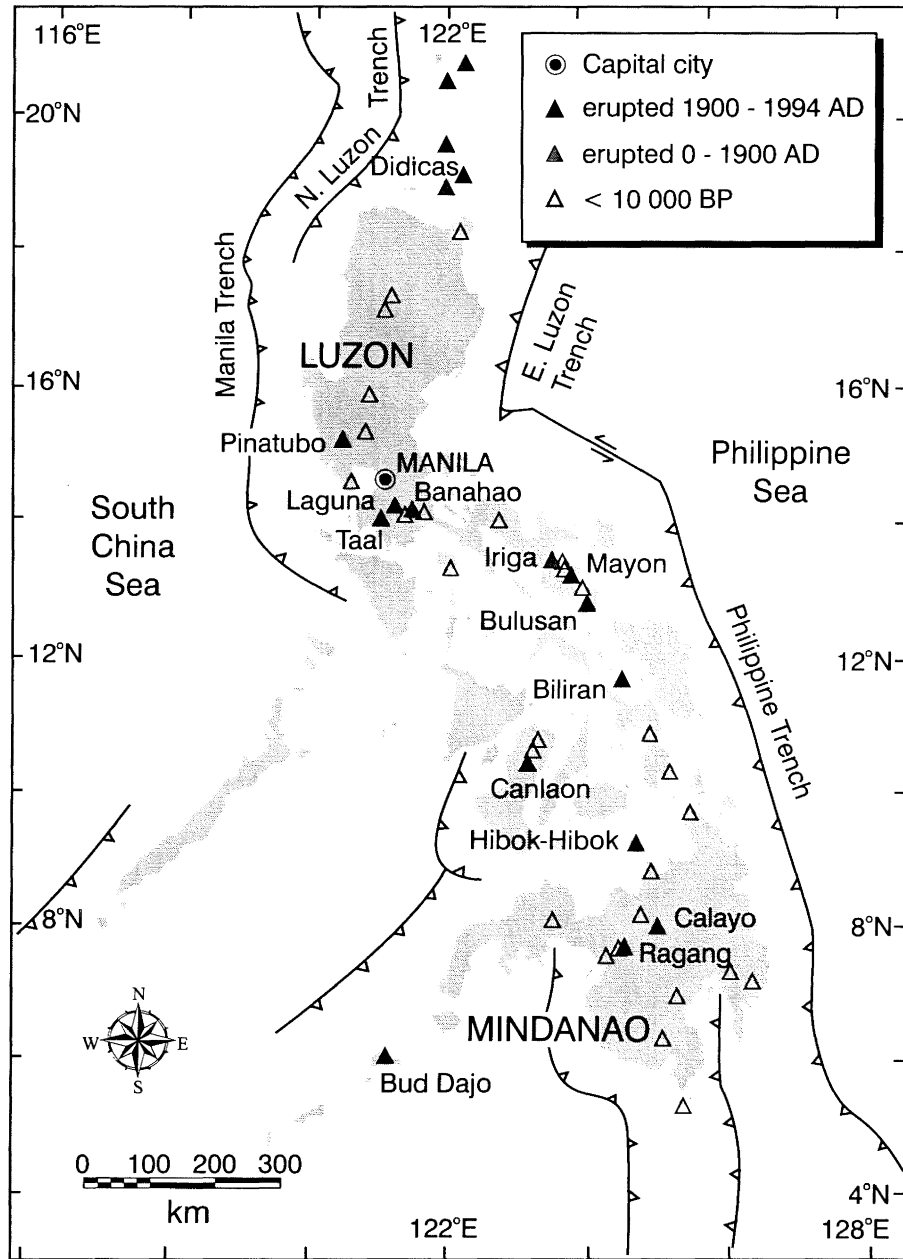


Figure 2: Active volcanoes of the Philippines archipelago (after Simkin and Siebert 1994 [1]).

**Table II: Historical volcanism in the Philippines archipelago. (after Simkin and Siebert 1994 [1])**

Volcano	Type	Last eruption	Notes
Bud Dajo	Pyroclastic cone	1641 & 1897	-
Ragang	Stratovolcano	1915	9 eruptions dating back to 1765
Calayo	Tuff cone	1886	-
Hibok-Hibok	Stratovolcano	1948	4 eruptions dating back to 1827
Canlaon	Stratovolcano	1993	Frequently active, 19 events since 1866
Biliran	Compound volcano	1939	-
Bulusan	Stratovolcano	1988	13 eruptions since 1852
Mayon	Stratovolcano	1998	Almost continuous activity
Iriga	Stratovolcano	1628?	-
Laguna volcanic field	Scoria cones and maars	c. 1350	Monogenetic volcanic field
Taal	Intra-caldera stratovolcano	1977	Almost continuous activity dating back to period of Spanish colonisation in 1572.
Pinatubo	Stratovolcano	1991	Largest eruption in Philippines this century, VEI 6, c. 7 km <sup>3</sup> of tephra as fall and pyroclastic flows.
Camiguin de Babuyan	Stratovolcano	1857	-
Didicas	Compound volcano	1978	6 eruptions since 1773
Babuyan Claro	Stratovolcano complex	1924	9 eruptions since 1652
Unnamed	Submarine	1854	North of Luzon
Iraya	Stratovolcano	1464	-

**Table III - Chronology of the 1991 volcanic activity and associated responses at Mount Pinatubo. (after Rantucci 1994; Punongbayan et al. 1996; Tayag et al. 1996). Sedimentary events are indicated *in italics*.**

Date	Event	Response
16 July 1990	Luzon earthquake, M 7.8, 100 km northeast of Pinatubo, other earthquakes in Pinatubo region.	
August 1990	Ground-cracking and enhanced steam activity.	PHIVOLCS response team visits the area and identifies eruptions as hydrothermal in origin
15 March 1991	Onset of felt earthquakes.	
April 1991	Weak steam and ash eruptions, seismic activity beneath crater.	PHIVOLCS response team repeats aerial survey. Portable seismometer installed. Volcano condition assessed as "unstable", precautionary 10 km radius danger zone centred on summit. 5000 Aetas evacuated. Seismic network upgraded. PHIVOLCS seeks aid of USGS and Volcano Crisis Assistance Team.
26 April – 13 May 1991		Pinatubo Volcano Observatory (PVO) established at Clark Air Base. Telemetered seismic network installed, COSPEC (SO <sub>2</sub> ) measurements begun. Warning scheme devised, profile of past eruptions compiled, hazard map preparation, public education and communication schemes begun.

Date	Event	Response
13 May	COSPEC measurement of 500t/d SO <sub>2</sub>	Alert level warning scheme introduced. Alert level 2, 10 km radius. Responding agencies prepare contingency plans.
23 May		Preliminary hazard map released. Government and local officials briefed over the next 2 weeks.
5 June	Increasing seismicity, fall in SO <sub>2</sub> emissions, rise in ash emission.	Alert level 3, 10 km radius. 10 000 people evacuated. PHIVOLCS team moves from 7 km to 22 km from summit on June 6. Contingency planning accelerated.
7 June 1991	Shallow tremor, ash and smoke, dome growth, rising SO <sub>2</sub> and CO <sub>2</sub> emissions.	Alert level 4, 20 km radius
9 June 1991	Moderate ash explosions, tephra fall 20 km from crater.	Alert level 5, 20 km radius. Total of 25 000 people evacuated.
9 – 11 June 1991	Escalating volcanic activity.	14 500 personnel evacuated from Clark Air Base. PVO office moves to eastern edge of Clark.
12 June 1991	Powerful explosion at 8:51 am creates a 20 km high eruption plume, extensive ash fall downwind, numerous felt earthquakes and volcanic tremor, dome growth resumes, further explosions.	Volcano acts as its own warning system. Warnings issued to aviation community, including effect of approaching typhoon.
13 June 1991	Continued explosions and ash fall, pyroclastic flows emplaced along valleys draining the mountain.	
14 June 1991	5 explosions recorded, hot lahars descended the slopes, aided by heavy rain from Typhoon Yunya.	Alert level 5, 30 km radius. ~ 50 000 people now in evacuation camps.
15 June 1991	Climatic eruption lasting 9 hours with 16 explosions, seismic activity peaks, eruption column to 40 km, extensive emplacement of pyroclastic flow fans around the mountain, the summit area collapses to form a 2 x 3 km caldera.	Alert level 5, 40 km radius (encompassing 17 towns). PVO moves to Pampanga Agricultural College, 38 km east of Pinatubo. Telephone and radio services interrupted.
18 June 1991	Manila receives 0.5 cm of ash 110 km away, darkening the sky. An extensive area of 10 000 km <sup>2</sup> around Mount Pinatubo is thickly blanketed by ash fall. Numerous M 3 to 5.7 aftershocks.	Alert level 5, danger zone radius revised downwards to 20 km.
30 June 1991	<b>Major lahars in Porac River bury six villages</b>	
23 July 1991	<i>Tropical storm Herming triggers lahars in ten catchments.</i>	
July – September 1991	Continued small ash eruptions, volcanic and seismic activity dies away.	4 September, Alert level revised down to 3, 10 km radius.
	<i>Mass remobilization of proximal pyroclastic flow fans triggers widespread lahar activity and secondary pyroclastic flows.</i>	
9 July 1992	Lava dome grows within the caldera.	Alert level 3, 10 km radius
14 July 1992		Alert level 5, 10 km radius
9 December 1992		Alert level 2, 10 km radius
1992 – 1999	<i>Continued lahar activity during rainy season.</i>	

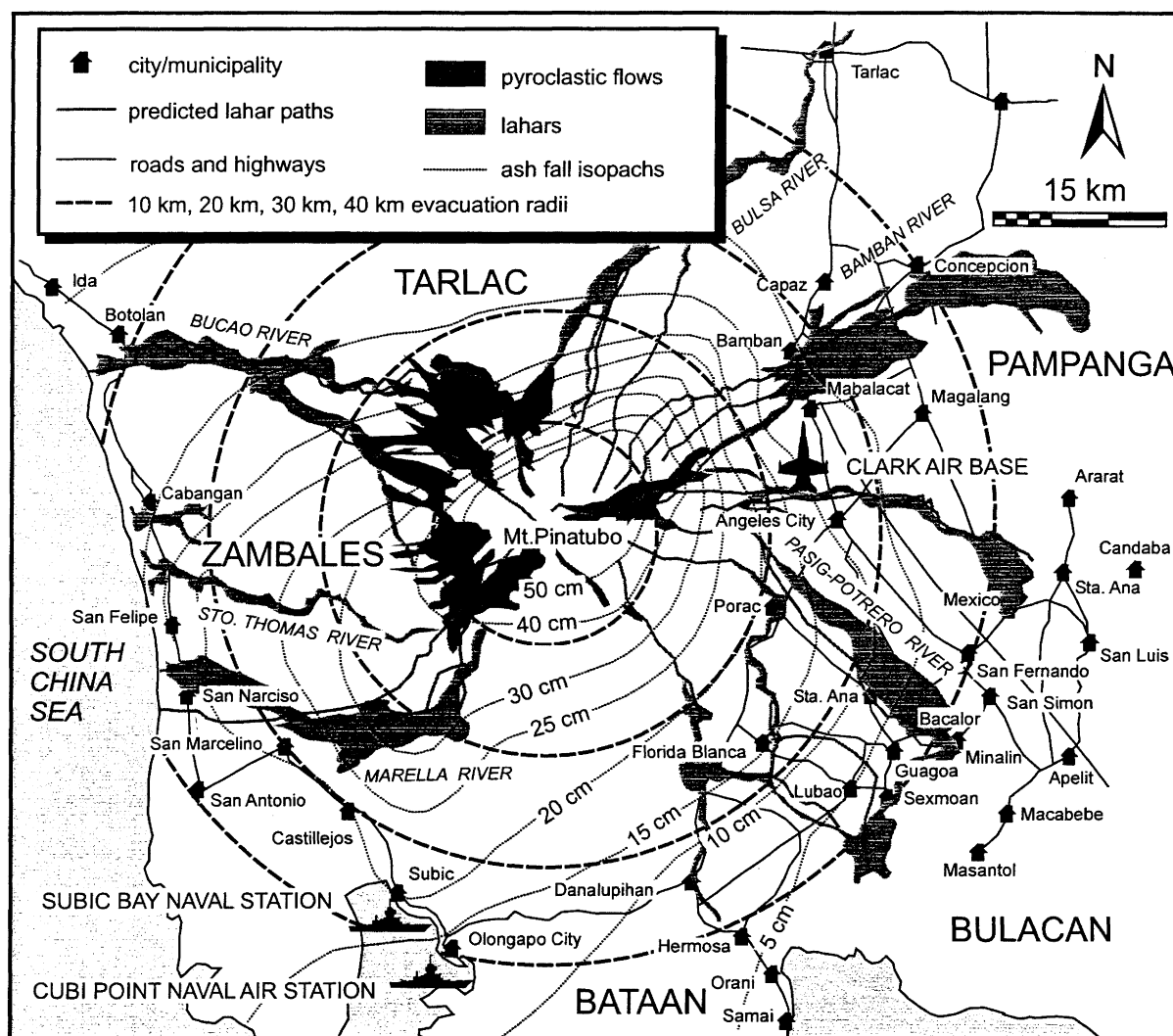


Figure 3: Regional map of Mount Pinatubo. Pre-eruption declared hazard zones are predicted lahar paths are shown in addition to actual pyroclastic flow deposits, ash fall isopachs, and post-eruptive lahars up to and including the 1993 monsoon season.

- Interpretation of the origins of the volcanic unrest
- A simple five level warning scheme and a hazard map based on composite 'worst-case' scenarios from previous eruptions
- An intensive educational campaign to ensure that warnings were both received and understood, of which the video "Understanding Volcanic Hazards" by Maurice Krafft was highly successful

Disaster management in the Philippines is dealt with by the National Disaster Co-ordinating Council (NDCC), an umbrella body headed by the Department of National Defence (DND) and the Office of Civil Defence (OCD). It is made up of member agencies and organisations responsible for disaster warning, rescue, relief, and reconstruction. PHIVOLCS joined the NDCC in 1990 with responsibility for earthquake and volcanic eruptions. Parallel bodies exist at

regional, municipal, city, and barangay (village) levels (Figure 4).

The situation at Pinatubo in 1991 was complicated by the socio-political setting, involving three provinces and their respective governors and provincial staff. In addition, warnings had to be communicated in a number of dialects and languages to three large cities, dozens of towns, hundreds of barangays, and several United States and Philippine military bases. Impending mayoral elections, the run-up to the 1992 general election, and discussions over the future of the U.S. bases added to the politically sensitive cauldron. Consequently, although warnings entered an established, simple, civil-defence communication and decision-making network, they were slowed by political, economic, and social interests [16].

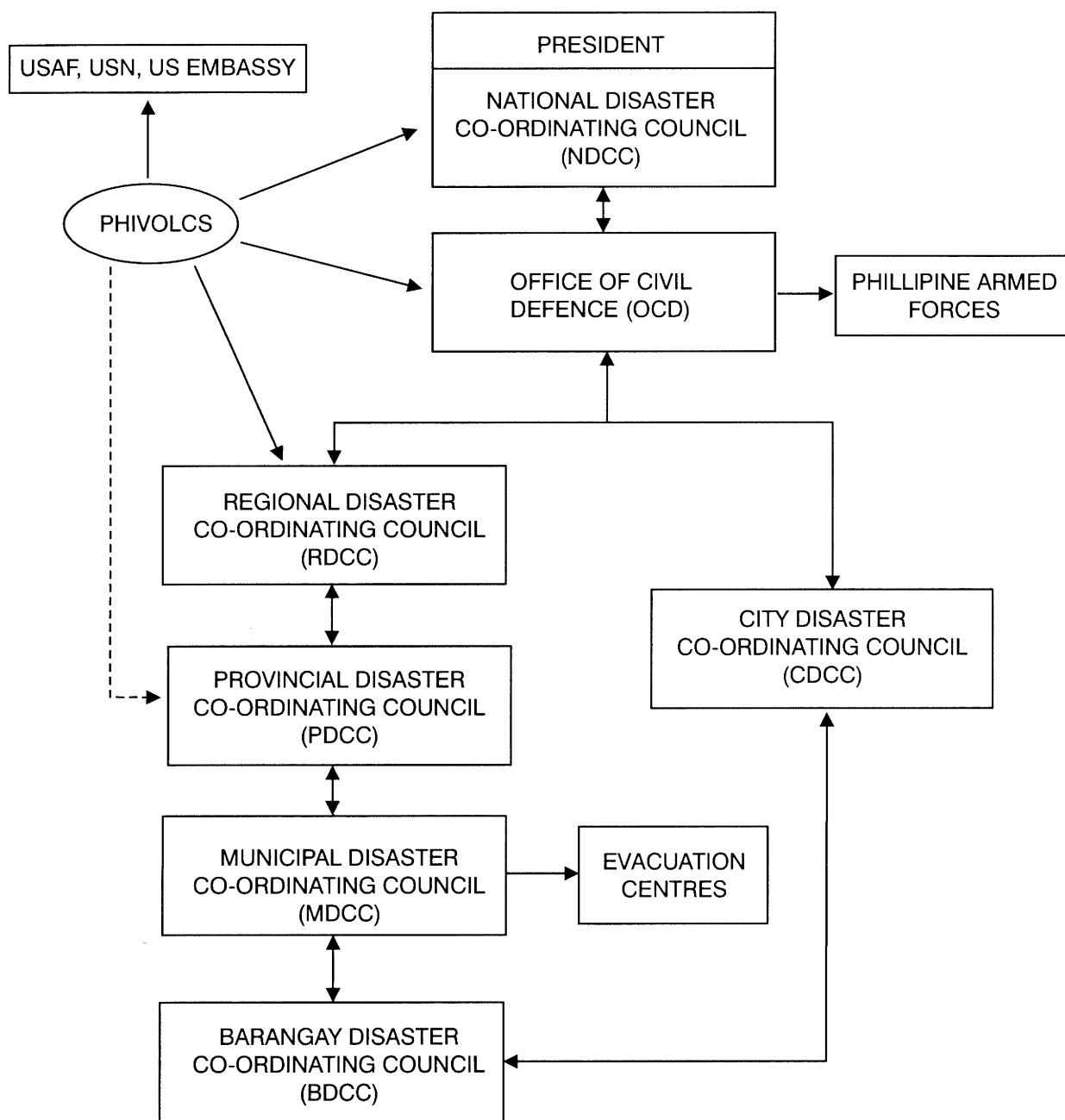


Figure 4: Philippine disaster management: organisational flowchart.

On 13 May 1991, a simple five-level warning scheme was adopted for Mount Pinatubo (Table IV). This was modified from similar schemes used at Rabaul, Redoubt and Long Valley, and generalised in UNDRO-UNESCO [66]. This scheme did not make predictions but noted increasing levels of unrest and an assessment of the likely timeframe within which an eruption could occur. Subsequently, this scheme was modified in December 1992 to take account of a number of issues arose from it, these are best illustrated by a series of key points or lessons learnt:

- “might happen” is commonly misreported/misread as “will happen” by mass-media and the general public

- the scheme should be simple, and understandable by people with no geological background
- only one person or consultative group should set the alert level
- it is easier to use a familiar system of hazard zonation than to develop a new one
- differences in hazard maps confuse users
- hazard maps using concentric, radial danger zones are simple and easy to understand, radial danger zones can also be easily expanded
- alert levels are designed for *escalating* volcanic activity, not long periods of low-level activity or declining activity

**Table IV – Five level alert schemes for Mount Pinatubo: original scheme and post-eruption revised scheme (after Punongbayan et al. 1996). Principle changes were to be less specific about time-frames, and more specific about sizes and types of eruptions.**

13 May 1991		ALERT LEVEL	9 December 1992	
Criteria	Interpretation		Criteria	Interpretation
Background, quiet.	No eruption in foreseeable future.	No alert	Background, quiet.	No eruption in foreseeable future.
Low-level seismicity, other unrest.	Magmatic, tectonic, or hydrothermal disturbance; on eruption imminent.	1	Low-level seismicity, other unrest.	Magmatic, tectonic, or hydrothermal disturbance; an eruption imminent.
Moderate level of seismicity, other unrest with positive evidence for involvement of magma.	Possible magmatic intrusion; could eventually lead to an eruption.	2	Moderate level of seismicity or other unrest with positive evidence for involvement of magma.	Probable magmatic intrusion; could eventually lead to an eruption.
Relatively high and increasing unrest including numerous b-type earthquakes; accelerating ground deformation, increased vigour of fumaroles, gas emissions.	If trend of increasing unrest continues, eruption possible within 2 weeks.	3	Relatively high and increasing unrest including numerous b-type earthquakes; accelerating ground deformation, increased vigour of fumaroles, gas emissions.	New or renewed eruption possible, probably within days to weeks.
Intense unrest, including harmonic tremor and (or) many “long-period” (low-frequency) earthquakes.	Eruption possible within 24 hours.	4	Intense unrest, including harmonic tremor and (or) many “long-period” (low-frequency) earthquakes and (or) dome growth and (or) small explosions	Magma close to or at Earth’s surface. Large explosive eruption possible within hours to days.
Eruption in progress.	Eruption in progress.	5	Hazardous explosive eruption in progress, with pyroclastic flows and (or) eruption column rising at least 6 km above sea level.	Large explosive eruption in progress. Hazards in valleys and downwind.

Stand-down procedures: In order to protect against “lull before the storm” phenomena, alert levels will be maintained for the following periods after activity decreases to the next lower level. From Alert Level 4 to 3; wait 1 week. From Alert Level 3 to 2; wait 72 hours.

Stand-down procedures: In order to protect against “lull before the storm” phenomena, alert levels will be maintained for the following periods after activity decreases to the next lower level.

From Alert Level 5 to 4: wait 12 hours after Alert Level 5 activity stops.

From Alert Level 4 to 3 or 2: wait 2 weeks after activity drops below Alert Level 4.

From Alert Level 3 to 2: wait 2 weeks after activity drops below Alert Level 3.

Note: Ash fall will occur from secondary explosions for several years after the major 1991 eruption, whenever rainfall and lahars come into contact with still-hot 1991 pyroclastic flow deposits. These secondary explosions will occur regardless of alert level.

- this led to a revision of the scheme so that time windows became less specific (i.e. change 'two weeks' to "days to weeks", while eruption size and style became more specific (i.e. change "eruption" to "large explosive eruption")

Some of these points arose when ash fall hazard maps were issued as downwind lobes based on statistical wind directions and as radial zones. In hindsight, the radial pattern was better owing to the unpredictability of wind directions at the actual time of the eruption. Where necessary, an appended wind-rose could have supplied additional data. Lahar paths were indicated on the hazard maps by marking the most likely affected rivers, areas of inundation were not marked due to the uncertainty surrounding lahar volume and flow path on the gently sloping ring-plain.

Hazard maps drawn up before the onset of major activity, based on interpretation of the geological record of past volcanism at Pinatubo (Fig. 3) proved remarkably accurate in predicting the areas affected by the eruption. However, the seriousness of the ash fall hazard, especially when compounded by Typhoon Yunya saturating the ash, was underestimated. Some 360 lives were lost due to building and roof collapse by ash-loading, while only 50-100 were killed by primary lahars and pyroclastic flows.

Accurate and timely warnings are of no use unless they are received, understood, and acted upon. This was tragically demonstrated at Nevado del Ruiz, Colombia, in 1985 [26, 27, 28]. Major problems encountered at Pinatubo included a lack of local awareness that the mountain was actually a volcano, and the unfamiliarity of terms used by scientists when describing volcanic hazards. A very effective solution was the widespread showing of the video 'Understanding volcanic hazards' by Maurice Krafft. This film shows graphic examples of many different volcanic hazards and was shown to a broad spectrum of people, including the President, the Secretary of Defence, governors, regional district official, base commanders, local officials, students, teachers, religious leaders, and barangay (village) residents. Numerous copies were made and distributed, and perhaps it should also have been broadcast on television. Copies of technical reports on ash impacts were also widely disseminated. Local and national media were effective in the rapid delivery of volcanic information to large numbers of people, aided by interviews with PHIVOLCS staff, despite a tendency to sensationalise or inaccurately report material.

A major issue was the credibility of the source of warnings. Legitimate uncertainty from scientists (unknown to the people they were trying to reach) regarding unfamiliar volcanic hazards and concepts, was often mistaken for ignorance. Scientists were also accused of pursuing their own agendas for fame or funding, rather than having the public interest at heart. A serious risk was that false alarms would weaken the credibility of PHIVOLCS. In the event, the rapid escalation of activity enabled the volcano to be its own warning system. Assessment of the education campaign in the run-up to the climactic eruption leads to the following points:

- accurate hazard assessments and warnings saved thousands of lives

- co-operation between PHIVOLCS staff, civil defence, and local officials was essential
- rapid deployment of monitoring equipment with the aid and expertise of USGS/VCAT teams improved the quality of data that warnings were based on
- stronger warning should have been issued on the ash fall hazard, syn-eruptive earthquakes, and the effect of Typhoon Yunya on ash fall

### **Impacts of the 1991 Pinatubo eruption**

The Pinatubo eruption caused extensive damage to human life and property over a wide area. The physical damage occurred in three ways:

- Direct effect of volcanic ash. The weight of the ash caused the collapse of roofs and buildings. It also blocked roads, damaged infrastructure services, blocked both natural and artificial drainage systems, and impacted on agricultural land, destroying crops and interrupting farming. This was most serious in central Luzon, which was previously the richest farmland in the Philippines (due to the fertility and drainage characteristics of the volcanic soil).
- Lahars generated by the remobilisation of proximal pyroclastic flow deposits and distal redeposited pyroclastic flow deposits. Dozens of lahars were triggered during the 1991 – 1992 monsoons, travelling beyond the area primarily impacted by ash fall to bury farmland, roads, villages and cities beneath metres of sediment.
- Lahar-induced aggradation of riverbeds led to increased flooding in the southern part of central Luzon [10].

### **Damage to buildings and municipal services**

Most damage to buildings occurred by ash deposit loading of roofs (Fig. 5). Rodolfo [29] describes numerous roof collapses including warehouses and wide-span roofed buildings at the United States Subic Navy Base in the town of Olongapo in the Philippines that received 150 mm from the 1991 eruption of Pinatubo. A survey of building damage in the nearby town of Castillejos concluded that roofs failed because the ash load was greater than the vertical load-carrying capacity of their supporting structure [30]. Wide-span roofed buildings suffered more damage than short-span domestic scale construction. Over 110 000 houses were damaged and 40% of these were destroyed, including numerous buildings in Angeles City 25 km east of the mountain. In addition, 98 hospitals and health centres, 18 markets, 13 municipal buildings, and 70 other government buildings were destroyed [31]. This was partially a function of the design of buildings in the Philippines, which only have to support their own weight and provide protection from rain and sun and the occasional typhoon. Fortunately, prevailing winds during the climactic phase of the eruption caused most tephra to fall on the relatively unpopulated western side of Mount Pinatubo. Water supply and sewerage systems were also seriously damaged by ash fall and building collapse. Telephone and power services were also disrupted during the eruption, and repair work was hindered by thick ash deposits and damage to roads.



*Figure 5: Building damage by roof collapse due to ash-loading (after [30]).*

#### **Damage to roads and bridges**

Direct damage to the road network occurred by the deposition of ash, and the clogging of side drains which resulted in flooding during the 1991 rainy season. Destruction of bridges by lahars was a major problem. The lahars eroded bridge supports, pushed over piles, and overtopped bridge decks during catastrophic aggradation of river channels. Modification of riverbeds by the lahars often meant that replacement bridges had to be much longer than the originals or sited in different locations. Keeping the main trade routes into the provinces of Pampanga and Zambales became the number one project so that aid and rehabilitation work, and crop sales could continue. When bridges were washed away, replacement bridges were quickly erected.

#### **Damage to agriculture and related activities**

Central Luzon is one of the most productive agricultural areas in the Philippines, accounting for 60% of national production. Agriculture is responsible for 27% of the GDP, over 50% of total national employment, and over 25% of export earnings. The area received several metres of ash near the mountain and 50 - 150 mm at distances of 40 km, followed by destructive lahars during the rainy season that also affected areas which had escaped primary ash fall. Over 550 000 hectares were impacted by the end of 1991, including 385 000 hectares of agricultural land (326 000 hectares of forestry, 43 000 hectares of cropland, and 16 000 hectares of fish farms), causing US\$500 million of damage. Losses due to the destruction of agricultural facilities, irrigation systems, agriculture-based industry, and lost agricultural revenue also occurred. Predicted losses for the period 1991-96 were set at US\$890 million [65].

#### **Social impact**

Two main social groups reside in the vicinity of Mount Pinatubo: the Aetas, an indigenous hill tribe group living on the southwestern flank of the mountain; and the farming communities living on the ring plain and flatlands. Nearly two million people were affected in some way by the eruption and its aftermath [32]. Around 200 000 people were evacuated from areas close to the volcano, with 300 evacuation centres being established by the government. A state of calamity was declared in 58 municipalities. The eruption also caused the displacement of 678 000 workers, doubling the number of unemployed in the region.

Twenty-five resettlement areas were built, of which three of these are outside the areas affected and are considered as off-site resettlements. The combined population of the resettlement areas as of 1999 is in excess of 142 812 individuals or 46 232 families (refer to figure 6).

Disruption of Clark Air Base and Subic Naval Base contributed to the withdrawal of the United States Armed Forces from the Philippines with economic consequences for local commerce. Lowland farmers lost their living environment, property, and livelihoods due to primary ashfall and lahar activity, disrupting agriculture, commerce, production, and social life. The Aetas suffered more than the lowland farming communities since Mt Pinatubo was also incorporated into their religion. Some 12 000 Aetas were evacuated and relocated in distant areas, which destroyed their traditional way of life and exposed them to malnutrition and disease in the evacuation camps. The Aetas however, quickly became entrepreneurs as an example in Barangay

Villar, Loob Bunga resettlement area illustrated [67]. Here the Aeta elders set up a cooperative to grow bananas on a 300 hectare section. They acquired a loan of P176 000 with a one year repayment deferment to allow the crops to grow. Root crops were planted between the banana trees to maximise productive potential.

#### Damage to the economy of the Philippines

The economy of the Philippines was vulnerable in the late 1980's due to a variety of internal and external factors. These included decreased investment, exports, and industrial growth, a drought in 1989, a strong earthquake in Luzon in July 1990, and the 1990-91 Gulf crisis that increased oil prices and worsened the country's balance of payments. GNP

was growing at 3.7 percent per annum, compared with the target of 6.5%. The 1991 eruption of Pinatubo proved catastrophic (Table V), largely due to the severe losses experienced by the agricultural sector, the mainstay of the Philippine economy.

As a result, the GNP growth rate dropped from 3.7% in 1990 to 1.1% in 1991. Recovery efforts were hampered by the already weakened state of the economy, compounded by the previous natural disasters of the 1990 Luzon earthquake and the typhoons that caused several hundred million US\$ damage during 1987-1991. These losses amounted to nearly US\$4 billion, of which Pinatubo contributed some US\$0.7 billion. In 1992, one US dollar was worth twenty peso, now (year 2000) one US dollar buys P41.



*Figure 6: Rapid erosion and remobilisation of primary pyroclastic flow deposits on the slopes of Mount Pinatubo, 4 years after the eruption.*

#### The lahars of Mount Pinatubo

The most serious long-term hazard at Pinatubo was the ongoing remobilisation of the primary pyroclastic flow deposits on the mountain, and the destructive lahars that were generated with every rainfall. The lahar hazard was a function of the delicate interplay between the sediment yield from the slopes (Fig. 6), and the sediment storage capacity of the lowlands [33]. Erosion and lahars in post-eruption Mount Pinatubo watersheds have filled lowland channels at rates unprecedented in the history of volcanic hazards mitigation or sediment control. Early predictions were that a total of 3 km<sup>3</sup> of material would be remobilized, two-thirds by the end of 1993, with the problem taking longer to develop and being longer-lasting on the west side of Pinatubo. By the end of 1993, lahars had made 50,000 people homeless and impacted on 1.35 million, with 1000 km<sup>2</sup> of land affected or at risk. Effective warnings helped restrict lahar deaths to ~100. The lahars delayed economic recovery in the region, discouraged

reinvestment, and caused tensions between political/social/economic interests and scientific reality. Lahars that have occurred between 1993 and 1999 have so far remained within the areas covered by the 1991-2 deposits. Even still, several barangays have been damaged or destroyed by the more recent lahars. Bacolor Municipality was buried under 5 – 6 m of lahar material during the 1995-6 monsoon season.

Response to the lahar problem at Pinatubo was predicated around three main issues:

- Long-range forecasts in the form of hazard maps, briefings, and a programme of public education
- Short-range forecasts in the form of immediate warnings of approaching lahars
- Measures intended for the mitigation of the problem

**Table V. Economic impacts of the 1991 eruption of Mount Pinatubo on the Philippine economy (after Rantucci 1994). Figures are in US\$ millions.**

<b>Agriculture</b>		<b>424.5</b>
production		229.7
crops (rice, vegetables, fruit trees, sugarcane)	44.7	
livestock	2.4	
poultry	2.4	
fishery	2.3	
forestry	177.9	
lost revenue		179.6
damage to Department of Agriculture facilities		4.6
damage to irrigation facilities		10.6
<b>Industry</b>		<b>15.3</b>
agri-based industry	6.9	
others	8.4	
<b>Infrastructure</b>		<b>66.6</b>
roads, highways, and bridges	25.6	
water distribution network	4.5	
schools	34.8	
hospitals	1.6	
<b>Private property</b>		<b>205.1</b>
	<b>Total</b>	<b>711.4</b>

Assessments of lahar hazards began within days of the start of the main Pinatubo eruptions, due in part to Philippine experience of lahars at Mayon. The Pinatubo Lahar Hazard Taskforce (PLHT) made up of members from PHIVOLCS, USGS, the Philippine Mines and Geoscience Bureau, and the Universities of Chicago and Manila, established manned watchpoints along rivers draining the mountain. Further assessments were made by PHIVOLCS, the Philippine Bureau of Soils and Water Management, and the US Army Corps of Engineers. In 1992, the PLHT was superseded by the Zambales Lahar Scientific Monitoring Group (ZLSMG). This proliferation of involved agencies led to tensions between parties. PHIVOLCS and the PLHT embarked on a campaign of education of both officials and the general public. Early on, the Krafft video on volcanic hazards was used, supplemented by impact scenarios for representative storms, domestic videos, information booklets and television documentaries. In future, public education and warnings will benefit from more visual representations of hazards, clearer warnings (despite uncertainties), scientific consensus on public statements, and a system for periods of declining, as well as increasing, lahar risk [34].

#### Long-range warnings

Long-range warnings of lahar hazards, based on maps of which areas were likely to be affected were influential in the

relocation of towns, engineering counter-measures, emergency planning, and the removal of at-risk property. Due to the evolving nature of the problem, lahar hazard maps were periodically updated and revised (Table VI). In the future, long-term forecasts will benefit from: more detailed/accurate sediment budgets; high resolution topographic maps of lowland areas; resurveying of channels and lahar deposits to locate avulsion sites; and the more extensive use of GIS.

#### Short-term warnings

Immediate warnings of potential or actual, approaching, lahar threats were used to supplement the long-term warnings. Initially these were based on meteorological conditions (typhoons, rain), upstream observations at manned watchpoints staffed by the Philippines National Police and the Armed Forces (Table VI). A three-stage system of warning was established:

- Lahar Alert Level 1 – rainfall on the mountain – get ready
- Lahar Alert Level 2 – continued rainfall, possible lahar – get set
- Lahar Alert Level 3 – lahar confirmed – go to high ground

**Table VI – Responses to evolving lahar hazards at Mount Pinatubo (after Janda et al. 1996).**

Date	Event
12 May 1991	Initial warnings of syn-eruptive lahars issued
15 May 1991	Hot syn-eruptive lahars cause loss of life and property
23 May 1991	PHIVOLCS issues volcanic hazard map, lahar paths are indicated only as lines along river valleys, inundation zones not marked because of uncertainty
July 1991	10 manned watchpoints established high on the mountain, 3-tier Lahar Alert Level system introduced.
Aug-Oct 1991	PHIVOLCS and PLHT issue a revised hazard map including expanded lahar hazard zones, zonation is effectively a ranking of risk. Lahar Alerts are issued for individual rivers. Additional watchpoints established in populated areas. PHIVOLCS-PHLT liase with weather forecasters at Clark Air Base and Cubi Point Naval Air Station.
August 1991	Acoustic flow monitors installed – instrumental detectors. Department of Public Works and Highways install tripwires and rainfall gauges.
September 1991	USGS, PHIVOLCS and PLHT produce estimates of lahar volumes for the next decade. Sediment yield rates are $0.5 - 1.0 \times 10^9 \text{ m}^3/\text{yr}$ from $540 \text{ km}^2$ source, an order of magnitude greater than anything previously experienced world-wide. Estimated that 40-50 % of primary pyroclastics would be remobilised within a decade (i.e. $2.5 - 3.6 \text{ km}^3$ of material).
1991-92	Department of Public Works and Highways begins engineering counter-measures.
4 April 1992	Sacobia River captures the headwaters of the Acaban River.
June 1992	Field monitoring of lahars begins, calibration of acoustic flow monitors.
July 1992	Greatest lahar impact near fan heads. 1:50 000 scale hazard maps issued.
August 1992	National Economic Development Authority (NEDA) and PHIVOLCS prepare a GIS mapset, allowing for rapid alteration and multiple data layers. A warning issued by PHIVOLCS based on instrumental detectors is ignored by regional authorities resulting in 8 deaths.
December 1992	NEDA-PHIVOLCS maps updated
1992	Research begins on lahar generating mechanisms, critical lahar-causing rainfall thresholds etc.
1993	Remobilisation begins to decline in terms of both number and sizes of lahars. Revegetation accelerating in source areas. Rain gauges and acoustic flow monitors upgraded.
July 1993	ZLSMG releases revised 1:50 000 hazard map

Difficulties arose due to too many false alarms, especially general alerts before valley-specific alarms began to be issued in September 1991. The rotation of experienced staff also tended to dilute practical lahar knowledge. Initially, instrumental lahar detectors were distrusted, but the improving technology and calibration of the acoustic flow monitors and rainfall gauges rapidly gained the confidence of responding agencies. Short-range warnings proved more effective than long-term forecasts in saving lives, despite being compromised by false alarms [34]. In the future, they will benefit from better weather forecasting; upgrades to rain gauges and acoustic flow monitors, and better communication systems with regional and local authorities [34].

### Response to warnings

General evacuation of the population during the volcanic crisis had the added benefit of protecting them from the effects of syn-eruptive lahars. Subsequently, evacuations were ordered at Lahar Alert Level 3, initially generally, and then by specific river. During dry spells, the number of people in the ~300 evacuation camps fell to 25 000, rising to 150 000 during wet weather. In the long-term, 10 semi-permanent and permanent resettlement sites were established by the government, but the people moving to these were replaced in the evacuation camps by those newly impacted by the encroaching lahar hazard. By 1996, 22 permanent, resettlement sites had been built within the worst affected provinces of Pampanga, Zambales and Tarlac. Three additional resettlement sites were also built off-site, or in the province of Nueva Ecija, which was only mildly affected by lahars and flooding.

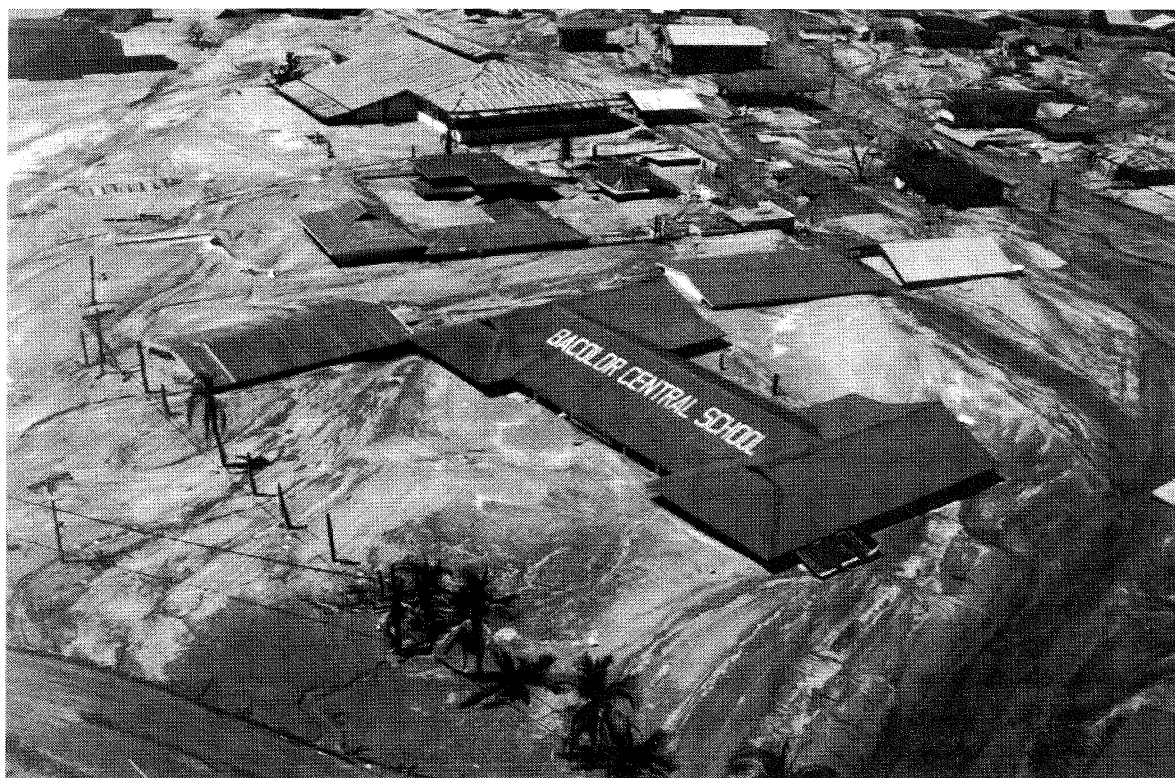
### Engineering solutions

Politician's and resident's reluctance to sacrifice land to burial by lahars, coupled with the engineering philosophy of problem-solving through intervention led to huge efforts to mitigate the lahar hazard through dike construction. Despite the huge sums of money spent on building dikes, sediment traps, and channel dredging, most efforts were futile in the face of the sheer scale of the problem (Fig. 7).

The worst problem was encountered on the unconfined fans draining the mountain, where the volume of sediment involved was enormous. The only practical solution, the sacrifice of large areas of land, pending resettlement in future decades (proposed by PHIVOLCS), proved just about universally unpopular. During 1991-92 numerous dikes were built by engineers from the Philippines, US, Switzerland, New Zealand and Japan at a cost of US\$154 million (compared with US\$93 million spent on evacuation camps) [35]. However, all were breached at the lowest/weakest points, rendering their downstream sections useless [36]. The primary problem is the impossibility of containing millions of cubic metres of sediment in long narrow channels. Engineers unfamiliar with lahars and other sediment-laden flows also underestimated their erosive power and magnitude. In June 1992, plans to build dikes only around towns while sacrificing the intervening areas were rejected. At this time, the debate between proponents of engineering solutions

versus resettlement became increasingly polarised. During 1993, lahars destroyed most of the measures that had been built in the previous year. A successful engineering intervention was the stabilisation of Mapanuepe Lake, impounded by lahar aggradation along the Marella River; this lake was later drained due to fears of it bursting after successive lahars increased the hydrostatic loading pressure.

The largest engineering undertaking to date was constructed on the Pasig-Potrero River system. The Megadike, otherwise known as the Pasig-Potrero Diking System, is located immediately upstream from Bacolor Municipality, Pampanga. It consists of a West Lateral Dike (6.58 km long), an East Lateral Dike (11.9 km long), a raised dike/Gapan San Fernando-Olongapo highway (GSO) immediately upstream of Bacolor township and a 3.16 km long Transverse Dike that joins the lateral dikes 3.2 km upstream of the GSO highway. Shields [37] describes problems encountered with the Megadike, where little geotechnical work was carried out prior to design and construction and design specifications were not strictly adhered to. Consequently, the structure failed in a number of locations, most significantly on 3 August 1996 when a 67 m breach of the east spillway formed along the Transverse Dike while the west spillway sustained substantial cracking. This damage effectively rendered the Transverse Dike useless.



*Figure 7: Bacolor township, one of 26 barangays buried by 2-5 m of lahar deposits by late 1995.*

## CASE STUDY 2: THE 1995-6 ERUPTIONS OF RUAPEHU, NEW ZEALAND.

The composite stratovolcano Ruapehu is New Zealand's largest cone volcano, with a long and complex history [38]. The oldest dated lavas are 230 000 years old, but there has probably been a "Ruapehu volcano" for at least 0.5 million years. The edifice appears to have been constructed in short bursts spread over a long period, interspersed with longer intervals of quiescence accompanied by glacial erosion and cone collapse. Ruapehu has dominantly erupted andesite, with only minor quantities of basalt and dacite. A variety of deposits, including lavas, tephra, pyroclastic flows, lahars, and debris avalanches have been produced by historic and recent-prehistoric eruptions. Three summit craters have been active during the last 10 000 years, including South Crater, the locus of current activity and home to a crater lake. The presence of Crater Lake has greatly modified eruptive behaviour over at least the last 1800 years. Even small eruptions are accompanied by potentially dangerous mudflows or lahars generated by expulsion of the lake water, which constitutes the most significant hazard associated with future activity. Breaching of a tephra barrier at the lake outlet, following refilling of Crater Lake after the 1945 eruption triggered a lahar in 1953 that destroyed a railway bridge, claiming 151 lives. Ruapehu is mainland New Zealand's most frequently active volcano, with a return period for small phreatomagmatic eruptions of 3 years, while significant eruptions occur every 30 – 50 years. Consequently, the volcano is extensively monitored by seismograph, deformation surveys, and crater lake temperature and chemistry analysis. The record of past historical and pre-historic activity is known in detail and serves to constrain predictions of future eruption style and magnitude.

### Eruption chronology

The 1995-96 eruptions of Ruapehu were the largest in New Zealand for 50 years [39], and followed a period of crater lake heating and small phreatomagmatic explosions (Table VII). A period of intense volcanic tremor in late June 1995 was followed by a phreatomagmatic explosion that destroyed lake-side monitoring equipment [40].

The eruption sequence began in earnest on 18 September with an explosion that deposited ash on the summit and generated a lahar in the Whangaehu valley. The largest single explosion of the 1995 sequence occurred on 23 September (Fig. 8), producing Surtseyan-type jets of ejected crater lake water. These triggered lahars in three catchments, including two flows that traversed the Whakapapa skifield an hour after the facility had closed for the day.

Continuous explosive activity on 25 September sustained a 10 km high eruption column and a continuous lahar down the Whangaehu Valley. These early eruptions through the crater lake generated primary lahars down 4 rivers, with over 90% of the volume of the lahar material ( $c.10 \times 10^6 \text{m}^3$ ) flowing down the Whangaehu River in 26 lahars [41]. Eruptive activity declined during late September, with small ash emissions.

Increasing tremor levels corresponded to significant peaks of activity 7, 11 and 14 October 1995. As the crater lake disappeared, the eruptions became drier and more sustained

and deposited ash up to 250 km from the volcano. During this period, the largest single ash-producing eruptions in New Zealand since 1945 occurred ( $0.01 \text{km}^3$ ). During late October and November high discharges of sulphur dioxide produced volcanic smog ("vog") over much of the central and southern North Island. Much of the ejected pyroclastic material was deposited on the flanks of the volcano and was subject to remobilization during heavy rain. An estimated 19 rainfall-induced lahars were produced between October 1995 and May 1996, in 5 catchments [42].

Strong volcanic tremor ended on 18 October 1995, and activity declined to degassing and low-level ash emission. Water began to collect on the crater floor in mid-November. On 15 June 1996 seismic tremor resumed, and a second sequence of phreatomagmatic eruptions commenced on 17 June, displacing the reforming crater lake. Subplinian eruptions on 17-18 June distributed ash over a wide sector north and west of Ruapehu. Smaller eruptions continued through July and the first week of August, again spreading ash over much of the North Island. The last eruptive activity occurred on the evening of 1 September 1996, producing a minor ash fall on the cone. Since then, the crater lake has begun to refill.

### Hazard assessments and warnings

Ruapehu is one of the world's most frequently active andesite volcanoes. Intensive study of past activity [43, 44] and the record of historical eruptions [45, 46 & 47] had outlined the probable style and magnitude of future activity at the mountain. A number of volcanic hazard assessments [48] based on repetition of past eruption scenarios were developed from these studies (Fig. 9).

The Institute of Geological and Nuclear Sciences (GNS) operates its volcanology section from the Wairakei Research Centre, Taupo, 80 km north of Ruapehu. GNS operates an effective minimum level of surveillance at all of New Zealand's volcanoes, and carries out background volcanological research: these two complementary activities allow eruption forecasts to be made. GNS assigns a scientific alert level (Table VIII) to each volcano, according to the National Civil Defence Plan. These are forecasts of how close a volcano is to erupting, not to the size of the eruption.

In addition, GNS produces regular Science Alert Bulletins that provide up-to-date information about ongoing activity (not predictive), hazard maps, ashfall predictions, media releases, and more detailed information for critical organisations such as the Civil Aviation Authority, Ministry of Agriculture and Fisheries, Transpower, the Department of Conservation, and regional and local authorities and iwi. Figure 10 shows the agencies involved with Ruapehu.

The response to the 1995-1996 eruptions at Ruapehu volcano, New Zealand, involved some 42 organisations and provided an opportunity to review certain operational aspects of response and their implications for the integrated emergency management of volcanic hazards. Analysis of the response [49], highlighted that the unpredictable, rapidly changing, diverse and geographically-dispersed nature of the consequences of volcanic eruptions creates a management environment characterised by uncertainty and which transcends the expertise and/or jurisdiction of any one

agency. The unprecedented, and complex, nature of the organisational response environment, and limited prior

networking between these agencies, resulted in a lack of co-ordination being a prominent response problem [50].

**Table VII - Chronology of the 1995-96 volcanic activity at Ruapehu volcano. (Ruapehu surveillance group - Institute of Geological and Nuclear Sciences). Sedimentary events are indicated *in italics*.**

Date	Event	Response
October 1994	Heating cycle begins.	Alert level raised to 1 in June 1994
January 1995	Weak steam explosions, heating cycle in Crater Lake from 15 to 51 °C, followed by a further cooling/heating cycle to August	Alert level raised to 2 in January, reduced to 1 in April, raised to 2 in May. Restrictions to lake access at level 2.
29 June 1995	Volcanic tremor, small phreatic explosion destroys monitoring equipment.	Alert level 2.
12 September 1995	Cooling cycle and declining seismic activity.	Alert level reduced to 1.
18 and 20 September 1995	Single moderate-sized phreatic explosions <i>and lahars in Whangaehu</i> , small inflation of crater area, rise in Mg and SO <sub>4</sub> levels in lake, low frequency, high amplitude tremor.	Two IGNS scientific parties visit the summit area. Alert level raised to 2, warnings issued to climbers. Crater rim deformation survey.
23 September 1995	Single explosion, blocks thrown 1.5 km, <i>lahars generated in Whangaehu, Whakapapaiti, and Mangaturuturu catchments.</i>	Alert level raised to 3. Self-evacuation of residents and visitors from within 40 km radius of summit begins.
25 September 1995	Multiple explosions, 10 km high plume, <i>near-continuous lahar in Whangaehu catchment.</i>	Alert level raised to 4. Desert Road closed as a precaution. Skifields closed and evacuated. Families of 25 army personnel evacuated from 22 km from summit. Ministry of Civil Defence issues 100 km general alert radius.
26 September 1995	COSPEC reading of 2600 t/d SO <sub>2</sub>	Deformation networks established on lower slopes. Several airports closed.
27 and 29 September 1995	Explosive eruptions generate <i>lahars in Whangaehu catchment.</i>	
2 October 1995		Ruapehu hazard map released.
3 October 1995	Declining seismic activity, minor ash emission, COSPEC ~ 200 t/d SO <sub>2</sub> .	Alert level lowered to 3. Secondary lahar warnings issued.
7 October 1995	Sustained 15 minute explosion, eruption column to 8 km height.	Alert level remains at 3, rapid escalation to 4 could occur with little warning.
11-12 October 1995	Sustained 8 hour explosive eruption removes the residual Crater Lake and distributes c. 2 x 10 <sup>7</sup> m <sup>3</sup> of tephra along a north-easterly-directed dispersal axis to 250 km downwind.	Alert level remains at 3.
13 October 1995	COSPEC reading of > 10 000 t/d SO <sub>2</sub>	
14 October 1995	Sustained explosive eruption disperses c. 1 x 10 <sup>7</sup> m <sup>3</sup> of tephra along a south-easterly directed dispersal axis. Aircraft report ash encounters.	Desert Road closed by 10 mm of ash. Alert level remains at 3, subject to hourly review.
15-29 October 1995	Strong gas emissions, COSPEC reading of > 10 000 t/d SO <sub>2</sub> , declining tephra output.	Alert level remains at 3. Gas hazard warning issued for upper mountain.
28 October - 1 November 1995	COSPEC readings decline to ~ 2000 t/d SO <sub>2</sub> <i>Rainfall remobilizes tephra deposits on the volcano forming large lahars.</i>	

2 - 15 November 1995	Volcanic activity ceases, <i>Crater Lake begins to reform</i> .	Revised hazard map for Ruapehu issued, includes zones of secondary hazards.
29 November 1995		Alert level reduced to 2. Revised hazard map issued for this alert level.
15 June 1996	Resumption of seismic tremor activity.	
17-18 June 1996	Continuous explosive eruptions remove incipient Crater Lake and sustain a 20 km high eruption column. Ash fall along a northerly directed dispersal axis for > 200 km. <i>Lahar 8 km long in Whangaehu Valley</i> .	
27 June 1996	Eruptions generate plume to 6 km.	
6-8, 10 and 11 July 1996	Moderate eruptions, plumes to 6 km, local ash fall.	
20 July 1996	Plume to 10 km, ballistics to 1.4 km, minor ash fall in Taupo. Last notable eruptive activity.	



*Figure 8: Surtseyan eruptions through Ruapehu crater lake, 23 September 1995.*

Issues arising from the management of the 1995 eruption were raised at a debriefing workshop in April 1996 [51]:

- misperception by responding agencies and the media that Alert Levels corresponded to the size of an eruption, rather than to how close the volcano was to erupting
- secondary hazards such as ash-induced avalanches and rain-triggered lahars were a previously unrecognised hazard at Ruapehu
- crater rim stability and the refilling crater lake
- development of an evacuation plan for Whakapapa skifield village
- upgrade of Eruption Detection System (seismometer and air-wave detector)

- lowering of alert levels was more difficult than raising them
- responding agencies rapidly exceeded their budgets
- distortion of information by overseas media (sensationalism)

#### **Impacts of the 1995 Ruapehu eruption**

The Ruapehu eruption caused extensive disruptions over wide area but in most cases only minor damage. The most damaging hazards related to the Ruapehu eruptions were:

- direct effect of volcanic ash. In October 1995 and in June-July 1996 ash fall was the most significant hazard at Ruapehu and had the most widespread impact. Ash was distributed over much of the North Island. The thickest ash falls resulted from the eruptions of 11-12 & 14 October 1995 and 16-18 June 1996, covered more than 30 000 km<sup>2</sup> and affected more than 20 communities, large areas of agricultural land and unpopulated forest land. It also blocked roads, damaged infrastructure services, blocked both natural and artificial drainage systems, and impacted on agricultural land, destroyed crops, interrupted farming and disrupted air-travel.
- primary lahars generated by the explosive displacement of crater lake water, numerous such events were generated in up to three catchments during the early stages of the 1995 eruption.
- remobilization of proximal pyroclastic fall deposits during spring and summer triggered multiple secondary, or rain-triggered lahars, during the 6 to 18 months after the eruption. Some of these occurred in areas not previously considered at risk from an eruption of this size, necessitating revision of hazard maps (Fig. 9). Down stream impacts on the Rangipo Power Station were severe.

The 1995-1996 Ruapehu eruptions had a wide range of impacts on a variety of sectors [51, 55], including river systems [52, 53], agriculture [54], fisheries [56], electricity generation [58], and New Zealand society [57, 59].

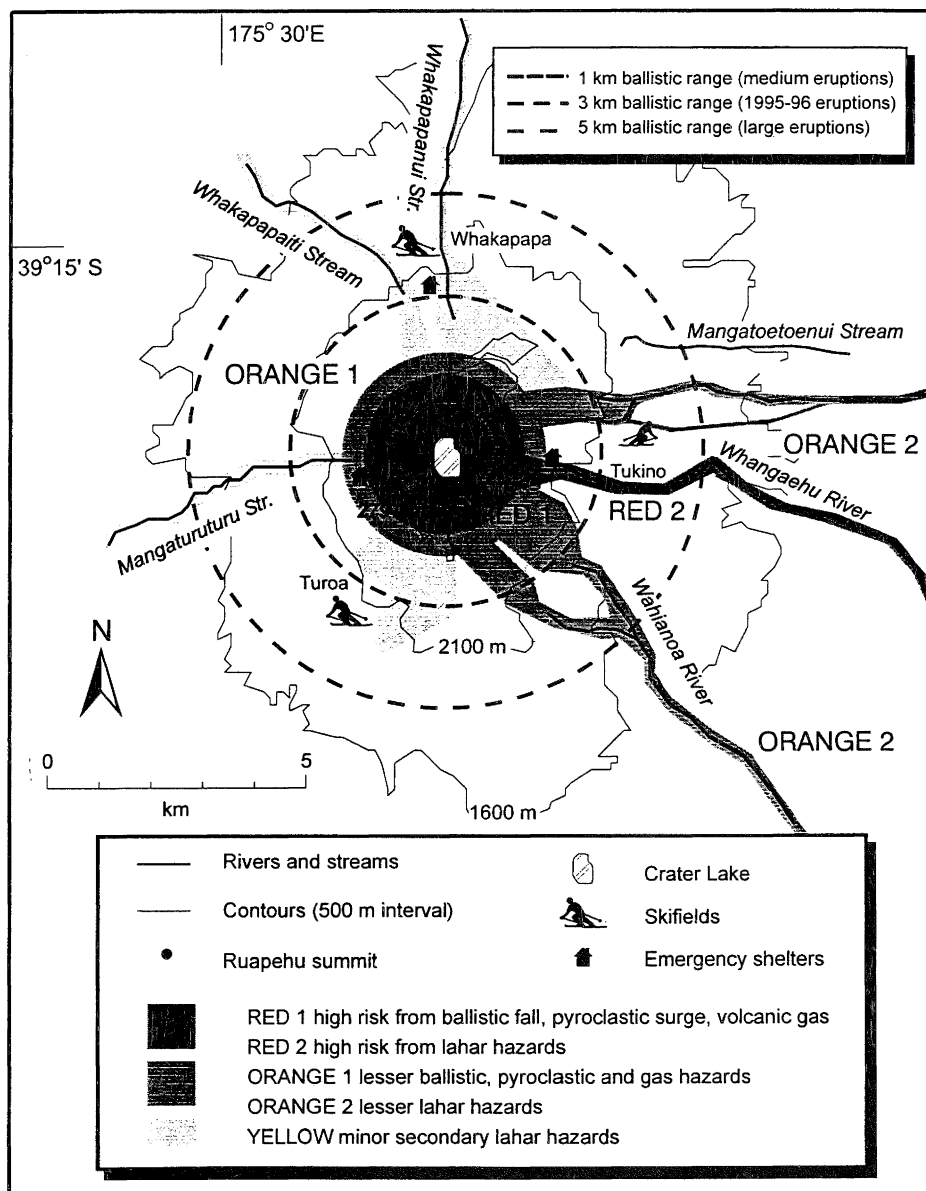


Figure 9: Regional map of Mount Ruapehu. Pre 1995-96 hazard zones are based on estimated ranges of ballistic projectiles and predicted lahar [48]. Shaded areas indicate updated hazard map issued by GNS on 15 November 1995.

Table VIII – Scientific alert levels for New Zealand volcanoes. These alert levels were revised during the September 1995 eruptions of Ruapehu because the existing version of the alert levels (1-5) had some limitations. Therefore, a new level zero was introduced, and a distinction made between active volcanoes and reawakening volcanoes.

<b>Frequently active cone volcanoes</b> (White Island, Tongariro-Ngauruhoe, Ruapehu)		<b>SCIENTIFIC ALERT LEVEL</b>	<b>Reawakening volcanoes</b> (Kermadecs, Northland, Auckland, Mayor Island, Rotorua, Okataina, Taupo, Taranaki/Egmont)	
<b>Volcano status</b>	<b>Indicative phenomena</b>		<b>Indicative phenomena</b>	<b>Volcano status</b>
Usual dormant, or quiescent state.	Typical background surface activity; seismicity, deformation and heat flow at low levels.	<b>0</b>	Typical background surface activity; seismicity, deformation and heat flow at low levels.	Usual dormant, or quiescent state.
Signs of volcano unrest.	Departure from typical background surface activity.	<b>1</b>	Apparent seismic, geodetic, thermal or other indicators of unrest.	Initial signs of possible volcano unrest. No eruption threat.
Minor eruptive activity.	Onset of eruptive activity, accompanied by changes to monitored indicators.	<b>2</b>	Increase in number or intensity of unrest indicators (seismicity, deformation, heat flow etc.).	Confirmation of volcano unrest. Eruption threat.
Significant local eruption in progress.	Increased vigour of ongoing activity and monitored indicators. Significant effects on volcano, possible effects beyond.	<b>3</b>	Minor steam eruptions. High increasing trends of unrest indicators, significant effects on volcano, possible beyond.	Minor eruptions commenced. Real possibility of hazardous eruptions.
Hazardous local eruption in progress.	Significant change to ongoing activity and monitoring indicators. Effects beyond volcano.	<b>4</b>	Eruption of new magma. Sustained high levels of unrest indicators, significant effects beyond volcano.	Hazardous local eruption in progress. Large scale eruption now possible.
Large hazardous eruption in progress.	Destruction with major damage beyond volcano. Significant risk over wider areas.	<b>5</b>	Destruction with major damage beyond active volcano. Significant risk over wider areas.	Large hazardous volcanic eruption in progress.

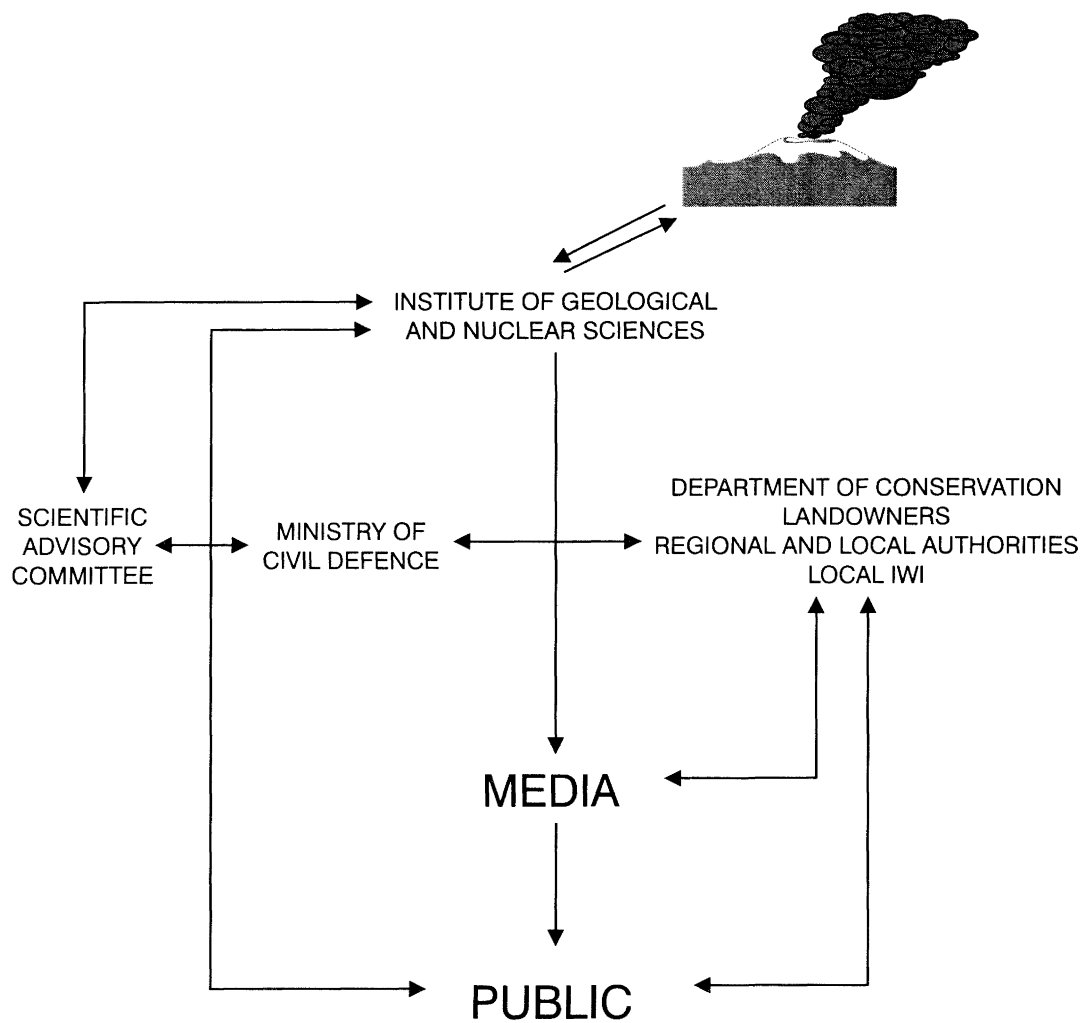


Figure 10: Agencies involved with Ruapehu.

### Social impacts

Small-scale events are often disruptive rather than destructive and so their social/ psychological impacts are often overlooked. High levels of anxiety were present in some individuals during the initial phase of the 1995 eruption but such concerns are traditionally downplayed. This observation is supported by an empirical study of childhood psychological functioning in three communities adjacent to Ruapehu [60, 61]. The early termination of several hundred jobs in the ski industry and related services also had a social and financial impact on all affected [62].

### Economic consequences

The economic impact of the Ruapehu eruption is extremely difficult to determine since such events are rare and there are no systems in place for measuring the economic costs. A number of organisations have reported direct losses, additional unbudgeted expenditure, and additional staff time used in response to the eruption but only a few have calculated an actual dollar cost of the eruption to their organisation (Table IX). The economic cost to the local tourism industry have been estimated at c. \$NZ 100 million (*written comm.* Ruapehu District Council). A few businesses capitalised on the eruption with a range of volcanic products

and the promotion of their communities as a safe place to "volcano watch".

The second largest economic cost (~\$NZ 21 million) was reported by the Electricity Corporation of New Zealand, resulting from damage to a hydroelectric power station and loss of production. Aviation industry costs were in excess of \$NZ 2.5 million (Table IX), but this figure only represents an estimate of lost revenue due to cancelled flights, and does not include costs due to disruption. Reported costs to responding government agencies included ~\$NZ 5.4 million from central government (including \$NZ 700 000 for additional monitoring by the Institute of Geological & Nuclear Sciences), ~\$NZ 454 000 from district councils and ~\$NZ 205 000 from regional councils. Some organisations included staff time and direct expenditure in their estimates whereas others reported only direct costs.

The total cost of ~\$NZ 130 million represents loss of economic production and services, damage to equipment, and expenditure on mitigation and response activities. This estimate is not the total cost, and can only represent a minimum value.

Table IX - Reported economic costs from the 1995-1996 Ruapehu eruptions

Sector	1995-1996	Reporting organisations (written communications)
Tourism	\$ 99 200 000	Ruapehu Alpine Lifts, Turoa Ski Field, Ruapehu District Council
Electricity generation	\$ 21 500 000	ECNZ
Central Government	\$ 5 645 700	Metservice, EQC, DOC, MCD, MAF, CAA, GNS, Airways Corp.
Aviation	\$ 2 401 200	Air NZ, Ansett, 4 airports
District Councils	\$ 588 500	Ruapehu, Taupo, Rotorua
Agriculture	\$ 382 500	MAF
Regional Councils	\$ 205 500	Manawatu-Wanganui, Waikato, Taranaki
<b>Total</b>	<b>NZ\$ 129 923 400</b>	

ECNZ = Electricity Corporation of New Zealand; EQC = Earthquake Commission; DOC = Department of Conservation; MCD = Ministry of Civil Defence; MAF = Ministry of Agriculture and Fisheries; CAA = Civil Aviation Authority; GNS = Institute of Geological and Nuclear Sciences. Figures in \$NZ.

### Disaster preparedness in New Zealand

Emergency management in New Zealand operates under the Civil Defence Act (1983), its subsequent amendments and the National Civil Defence Plan. In addition, other legislation has implications for natural hazard management. These regulations bind the Crown, local government and state-owned organisations. Regional councils and territorial authorities have responsibilities to perform a number of functions, as outlined in the National Civil Defence Plan, including preparation of civil defence plans. The Ministry for Emergency Management (formerly Civil Defence) is responsible for preparing the National Civil Defence Plan, overseeing its implementation and coordinating national strategies. Currently, emergency management in New Zealand is under review, with new legislation being drafted and a new approach based on the following concepts being developed (Ministry for Emergency Management 1998):

- assessing the risks of an emergency happening;
- reducing those risks and minimising the impact of emergencies should they occur;
- improving coordination of response to routine incidents;
- operating an effective network that copes with emergencies when they happen: and
- helping communities recover as quickly as possible.

The current National Civil Defence Plan outlines the following responsibilities for regional councils and territorial authorities with respect to volcanic hazards.

In addition to government legislation, considerable research is conducted into both the nature of hazards, i.e. basic geological studies, and societal vulnerability, i.e. the lifelines projects. The latter aim to review and reduce the vulnerability of key services including electricity, gas, water, and telecommunications. A national system of geophysical monitoring has been established by GNS, based primarily on telemetered seismometers transmitting data to two

independent base stations. Other seismic nets are used to monitor the status of all active or re-awakening volcanoes, i.e. the Tongariro Volcanic Centre, Taupo, Okataina, Taranaki/Egmont, and the Auckland Volcanic Field, supplemented by geodetic earth deformation networks and monitoring of surface geothermal features. However, surveillance is maintained at a minimum effective level due to funding constraints. At the time of the 1995-96 Ruapehu eruptions, funding was initially provided only for monitoring the eruption, not for responding to it: the entire annual GNS volcanology budget was spent in 3 weeks during the initial response phase. Funding of scientific activities related to adequate monitoring of and response to a prolonged volcanic crisis remains an issue.

### Disaster preparedness in the Philippines

Organisation for disaster response in the Philippines largely grew out of the experience of the Second World War. The Philippines government has established a number of different agencies at levels from national to local levels to plan for and respond to disasters (Table X).

#### The National Disaster Co-ordinating Council (NDCC)

The national government is responsible for planning, implementing, and allocating resources for disaster management, with the main body in charge of such duties being the National Disaster Co-ordinating Council. Under the provisions of the Calamities and Disasters Preparedness Plan (CDPP), the Secretary of Defence convenes the Council, whose members represent 14 government departments, the Office of the President, the Armed Forces, and the Philippine National Red Cross. The executive officer is the Administrator of the Office of Civil Defence (OCD), which is the operations centre and secretariat of the Council, in the Department of National Defence. The mandate of the NDCC is:

Table X – Philippine government initiatives relevant to natural hazard management (after Brown et al. 1991 [63]).

Initiative	Effect
1952 Commission on Volcanology (Comvol)	Government research and monitoring of active volcanoes in the Philippines.
1954 National Civil Defence Administration (NDSA)	Formal government organisation for civil defence during times of war. Services include rescue, evacuation, and emergency welfare.
1967 Committee on Warning Systems (COWS)	Provides warnings on impending disasters (no longer active).
1967 Department of Public Works and Communications	Establishes rules on public broadcasts during emergencies.
1968 Committee on Disaster Operations (CDO)	Required all government agencies to organise disaster control groups. CDO designated to co-ordinate their activities.
1970 Inter-departmental planning group established by Office of the President.	Main task to prepare the Natural Disasters and Calamities Plan.
1970 Natural Disasters and Calamities Plan	Establishes lines of control and command from regional to local levels. States the roles and responsibilities of government departments, agencies, and organisations involved in disaster mitigation. Requires setting up of action teams by these groups. A set of Standard Operating Procedures issued.
1972 Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)	Mandated to implement government policy for protection against natural hazards. Responsibility for environmental monitoring and research into natural hazards.
1973 Office of Civil Defence (OCD)	Takes over role of NCDA. Main co-ordinating body for all disaster-related activities of the government and private sector.
1978 National Disaster Co-ordinating Council (NDCC)	Strengthen disaster control capability and establish the national programme on community disaster preparedness.
1982 Philippine Institute of Volcanology	Restructured from Comvol, responsible for research and monitoring of active volcanoes.
1984 Philippine Institute of Volcanology and Seismology (PHIVOLCS)	Seismic responsibility transferred from PAGASA.
1988 National Committees for the International Decade for Natural Disaster Reduction	Four committees established in response to the United Nations declaration of the 1990's as the IDNDR.
1988 Calamities and Disaster Preparedness Plan (CDPP)	Amended and re-issued 1970 Natural Disasters and Calamities Plan.

- The preparation of a National Disaster and Calamities Preparedness Plan.
- The organisation of disaster co-ordinating councils down to the municipal level.
- The development of self-reliance among local government units in the management of disasters.
- To advise the President on the status of the preparedness programme, disaster operations and rehabilitation efforts of the government and private sector.

To help achieve these aims, Disaster Co-ordinating Councils (DCC's) have been established at the regional, provincial, city and barangay (village) levels, in order to provide services pre-, syn-, and post-disaster. These services include communications and warnings, emergency transportation, evacuation, rescue and engineering, health, fire, police, relief and rehabilitation, and public information. The NDCC is hampered by two problems: lack of funding – there is no operational budget; and lack of executive powers – it is primarily an advisory body.

#### **The Calamities and Disaster Preparedness Plan (CDPP)**

Drafted in 1970 and amended since, the Plan's objective is *"to save lives, to prevent needless suffering, to protect property and to minimize damages during disaster and calamities."* Under the Plan, the NDCC exercises control, through the OCD, over all emergency operations from regional down to local levels. It also states the roles and responsibilities of responding agencies at all levels, assigns specific tasks, and requires the formation of reaction teams.

#### **Office of Civil Defence (OCD)**

The primary function of the Office of Civil Defence is *"to co-ordinate, on the national level, the functions and activities of various government agencies and private institutions devoted to public welfare...to protect civilian populace and property in times of war and other national emergencies."* It has a key role in natural disaster management and the implementation of the CDPP. Since its formation, the OCD has become the main co-ordinating body for all disaster-related activities of the government and private sector. Initial activities focussed on direct relief assistance, with disaster preparedness and mitigation developing later. The OCD mandate is officially defined as:

- Pre-disaster (community preparedness): organisation of Disaster Co-ordinating Councils (DCC's) from regional to local levels; formation of Disaster Control Groups (DCG's) in schools, businesses, and non-governmental organisations; training of DCC and DCG members on disaster management; conduct of drills and exercises; public information and education; research and survey; and contingency planning.
- During disaster: management of the Civil Defence Operations Centre; co-ordinating activities (i.e. supervision of regional operations centres); and civil assistance.
- Post-disaster: restoration and rehabilitation.

Lack of funding is the major constraint on the OCD. From 1973 to 1988, only 50% of the actual budget was released by central government, and there is no appropriation for equipment. Consequently the OCD lacks transport and

communication facilities, making the dissemination of potentially life-saving warnings difficult. Field operations are limited to the 13 regional civil defence. DCG's have been slow to establish in the private sector due to the lack of external funding.

The OCD is the primary source of public education on a range of natural hazards, and using a variety of publications and media. Examples include the Manual on Family Readiness, which is produced in English, Pilipino, and a number of local dialects. The OCD also runs the National Disaster Consciousness Week, in July each year.

#### **Philippine Institute of Volcanology and Seismology (PHIVOLCS)**

This institute, under the Department of Science and Technology, operates the seismological and volcanological networks of the country. It is responsible for:

- Mitigating volcanic hazards through appropriate detection, forecast and warning systems.
- Formulating appropriate disaster preparedness plans.
- Predicting the occurrence of volcanic eruptions and earthquakes, and their geotectonic phenomena.
- Determining how eruptions and earthquakes will occur and areas likely to be affected.
- Generating sufficient data for forecasting volcanic eruptions and earthquakes.
- Exploiting the positive aspects of volcanoes and volcanic terrain to enhance the socio-economic developmental efforts of government.

#### **Financial measures and compensation**

During disasters the Department of Social Welfare and Development (DSWD) provides emergency relief assistance and social services to victims and organises their rehabilitation. Specific guidelines have been established for the implementation of appropriate measures. The Bureau of Emergency Assistance controls policies and standards for relief and rehabilitation activities, conducts pilot projects to test new methods, and makes policy change recommendations. Disaster relief is paid for out of the Calamity Fund, administered by the Office of the President, following requests by the NDCC. Local governments also reserve 2% of their annual budgets for disaster response. In the aftermath of the Pinatubo eruption, the Mt Pinatubo Commission was established. The role of this agency is to organise rehabilitation and recovery of the people and area impacted by the eruption. This includes provision of housing, health, infrastructure and employment, and also extends to construction of lahar retention structures.

#### **Overview**

Three key problems exist with the current state of disaster preparedness in the Philippines: lack of funding; lack of personnel; lack of data. These are discussed in more detail below:

- Scientific information and databases relating to natural hazards are largely incomplete or inadequate. There is a lack of systematic hazard mapping, particularly on a scale and extent useful for risk assessment and natural

disaster mitigation [63]. Existing hazard mapping is largely based on the record of occurrence and is of uneven coverage and quality. Use of aerial mapping, remote sensing, and GIS for hazard mapping purposes is in its infancy.

- While the National Calamities Preparedness Plan provides a sound basis, its effectiveness is reduced due to insufficient financial and human resources. In addition, following a disaster, few lessons are drawn from the problems that arose to ensure that they are not repeated in future.
- The Plan and the organisation and procedures associated with it do not address disaster mitigation. This shortfall exists in development planning at national, regional, municipal, and local levels.
- Severe training gaps exist, particularly at lower levels. The effectiveness of training is undermined by the frequent turnover of elected or appointed officials.
- The NDCC is primarily an advisory body, without executive powers. Consequently, compliance/co-operation with policy is difficult to enforce.

## DISCUSSION

The 1991 Pinatubo eruption provides many lessons in the prediction and management of large scale damaging volcanic events, and in their social, economic, and environmental consequences, whereas the 1995-96 Ruapehu eruptions give an insight into the effect of small-scale activity in a local context. The lessons from Pinatubo are relevant to the active and potentially active volcanic regions of New Zealand, where substantial population centres and infrastructures have developed next to volcanic centres. Each volcanically threatened region has its own hazard properties and the effects of these on population, industry, and commerce will differ from one to another. For example, while Taupo and Okataina have the potential for eruptions of a similar, or even considerably larger, magnitude than Pinatubo 1991, resumption of activity in the Auckland Volcanic Field would be on a much smaller scale.

Overall, four key areas can be identified in the context of preparedness for volcanic emergencies: forewarning, mitigation, response, and recovery. The first two relate to the pre-event phase, the third to the actual volcanic crisis or syn-event phase, and the fourth to the long-term consequences of the eruption, i.e. the recovery phase. A great deal of preparatory planning for each phase can be conducted in advance.

### 1. Forewarning – volcanoes kill more people by surprise than by size

Most of the world's largest eruptions this century have occurred in remote and sparsely populated areas causing little loss of life, while many of the deadliest have been relatively small but have occurred in densely populated areas. The greatest hazard is posed by a large, unexpected eruption from a long-dormant volcano in a densely populated area. Therefore, there are three factors in the improvement of forewarnings.

- identification of the threat, i.e. basic geological research and mapping of volcanic regions
- monitoring and surveillance of active and potentially active volcanoes

- establishment of warning systems and public education programmes to produce a volcano-aware populace.

At Pinatubo, few local people were aware that the mountain was a volcano, it was not monitored by PHIVOLCS, and almost nothing was known of its previous eruptive history. In contrast, levels of public awareness about Ruapehu volcano in New Zealand were very high, it is constantly monitored by GNS, and its historic and pre-historic eruptive history is well documented. However, awareness and understanding of volcanic hazards in communities near other volcanic centres may not be as high, especially those that have not erupted in historic times (e.g. Auckland, Northland, or Taranaki) [69, 70]. Funding levels for basic geological research in New Zealand are in decline and monitoring is carried out at a minimum effective level due to financial constraints. Improving New Zealand's scientific capability in the event of a major volcanic crisis requires a substantial investment in both staff and equipment.

### 2. Mitigation – forward planning

Unless a volcanic emergency is prepared for in advance, responses are likely to be ad hoc and chaotic, with confusion and friction occurring between responding agencies during the response and recovery phases of the crisis. Therefore, detailed contingency plans are required, specifying policies for preparation, response and recovery during the pre-, syn- and post-event phases. The responsibilities of local and central government and other responding agencies in planning and implementation of those policies should be identified and allocated in advance. Areas for special consideration include the evacuation, rehabilitation and possibly resettlement of perhaps thousands of people, financial support, and the role of the insurance industry. Since each volcanic region is unique, the plans relating to each should contain:

- a clear description of the possible extent, nature, and magnitude of the threat
- clearly defined warning protocols linking scientific assessments of the threat to the responding agency and public information systems
- a public warning system
- establishment of liaisons between scientific advisors, emergency management and media, including protocols regarding the dissemination of information
- identification and allocation of organisational responsibilities, and the establishment of policies at both local and central levels, including government
- the roles of emergency response managers and all emergency staff need to be identified and defined, with plans for staff rotation and relief
- identification of logistic support requirements and responsibilities, medical and health issues, maintenance of law and order
- evacuation plans: transport, shelter, food etc. for displaced people in large numbers, plus medical, hygiene, and counselling needs
- procedures for the relocation of emergency control centres need to be established and practised where necessary
- response exercises should be conducted and the plans refined accordingly

- commercial organisations should be encouraged to develop contingency plans
- key services, i.e. hospitals, communications centres etc. should be located away from high risk areas and constructed to withstand volcanic hazards (e.g. ash loading)
- past experience should be drawn on

### **3. Response – the event phase**

During the actual volcanic eruption, contingency plans prepared in advance by the various responding agencies are put into effect. A number of key issues relevant to this phase are:

- throughout the crisis, a single controlling system operated by a unified management structure is applied
- contingency plans developed in advance are put into effect, with evacuations occurring as and when necessary, alternative evacuation routes may be required
- timely and factual public information is critical to the ability of the population to respond appropriately, highlighting the importance of public education and the relationship between the media, scientific advisors, and response managers
- local and central government should be clear with regard to their respective roles
- scientific agencies should be appropriately funded at a level sufficient to provide first class advice to emergency managers

An additional issue is the role of overseas agencies. At Pinatubo, a rapid response team from the USGS arrived early in the eruption sequence to provide technical assistance and improved instrumentation. The much smaller scale of the Ruapehu events enabled the situation to be handled by local personnel. A future larger or more protracted eruption would likely require aid from overseas scientific agencies.

### **4. Recovery phase – eruption aftermath**

Post-eruption effects can continue for a long time and lead to social and other effects worse than the original eruption. These need to be taken into account in recovery planning. This paper and others [29, 64] describe the ongoing lahar problems following the 1991 Pinatubo eruption and note that in the recovery process, solutions that were scientifically and technically sound were not necessarily politically and socially acceptable. Like response contingency plans, recovery plans should also be prepared well in advance of an actual eruption. These should include:

- identification of an agency responsible for recovery planning and implementation
- consideration of relief supplies, and the agencies responsible for procuring and delivering them
- procedures for co-ordinating aid
- essential services and other key parts of the infrastructure should be restored as soon as possible to reduce damage and facilitate more rapid recovery in other areas, i.e. roads, communications, power etc.

The social and economic impacts of volcanic eruptions are determined not only by direct physical consequences but also by the interaction of social, cultural and institutional processes. Community resilience is important in determining the level of

government and agency support required. The recovery from small eruptions mostly involves a simple restoration of damaged "lifelines", industries and communities, whereas large-scale events may involve total rehabilitation of the severely affected areas. The cost of recovery goes beyond the cost of physical repairs and includes the cost of the provision of long-term community support. The recovery process for a large eruption will be expensive and time-consuming, and should be carefully co-ordinated in order to maximise the use of limited resources to meet a range of social and economic circumstances. Crucial areas include the resettlement of displaced populations, and the creation of employment to avoid welfare dependency.

### **Benefits of a study mission to the Philippines**

For many years the New Zealand National Society for Earthquake Engineering has operated a reconnaissance scheme to send teams to foreign earthquake events in order to gain valuable lessons, covering a range of issues including: the behaviour of buildings, damage to lifelines and the emergency management response to the event. A strong case can be made for extending such a scheme to include volcanic eruptions, preferably covering as many of the different styles of eruption that New Zealand is likely to encounter as possible. Potential countries for visits could include the Philippines (Pinatubo, Mayon, Taal), the United States (Mount St. Helens, Rainier), and Japan (Unzen). As the impacts of volcanic hazards manifest themselves in differing ways over different timeframes several time periods following an event should be considered as useful. Immediately after an event, observations and quantification of the factors that lead to damage and failure of buildings and infrastructure would be extremely useful. In the longer term, as the recovery process proceeds, valuable lessons can be learnt in areas such as ash-removal and disposal, long-term corrosion and abrasion damage, stabilisation of lahar deposits, and the rehabilitation of inundated land: as well as in the social and management issues related to the recovery process itself.

A study mission to Pinatubo to investigate engineering, contingency planning and emergency management issues should include individuals from central and local emergency management agencies, appropriate government departments, and scientists/engineers. Team members should visit areas of interest to their respective disciplines and interview key people involved in the management of the volcanic crisis and its aftermath. The 1995-96 eruption of Ruapehu demonstrated New Zealand's ability to cope with a small-scale eruption in a remote area with a low population density and limited infrastructure. The most important lessons to be gained from a visit to the Philippines would be those applicable to a resumption of activity at one of New Zealand's potentially active caldera volcanoes, Taupo and Okataina, or an eruption in the Auckland Volcanic Field. In either scenario, the most important issues would relate to the evacuation of a large population and the long-term recovery phase, areas in which New Zealand has little experience. Areas of investigation could include:

- long term damage and recovery of engineering "lifelines"
- the success of otherwise of remedial engineering works designed to mitigate the effects of lahars and large-scale sediment remobilisations and their cost-effectiveness

- the steps involved in the successful evacuation of a large population, including the process by which evacuation decisions were made
- the difficulties involved in providing adequate shelter, food and basic utilities to a large displaced population
- the role of the Mt Pinatubo Commission (MPC), an agency whose role is to mobilise rehabilitation and recovery of the people and area affected by the eruption (i.e. housing, health, infrastructure, employment, engineering works etc.)
- the effectiveness of public information and warning systems and public education programmes

### CONCLUSIONS

The 1991 eruption of the Pinatubo was the largest eruption world-wide, in the last 80 years. It erupted over 70 times more volcanic material than the 1995-1996 Ruapehu eruption and had a major and ongoing physical, social and economic impact on the Philippines. However, the 1995-1996 Ruapehu eruption highlighted the vulnerability of New Zealand to even small eruptions, and demonstrated that these impacts would be amplified and expanded should New Zealand experience a larger eruptive event in the future. Despite the widespread damage reported there were very few quantitative measurements of the impacts of a range of volcanic hazards on communities and their engineering lifelines from both the 1991 Pinatubo and 1995-1996 Ruapehu eruptions. This is also unfortunately the case from most recent eruptions. New Zealand has two volcanoes, Taupo and Okataina, capable of generating an eruption of similar or even larger magnitude than the 1991 Pinatubo eruption. At present, it seems unlikely that New Zealand would be able to respond to a large-scale volcanic eruption with regional impacts and consequences, largely due to the absence of contingency planning for a volcanic emergency at this scale. Although New Zealand is well in advance of the Philippines in terms of scientific understanding and surveillance (albeit at a minimum effective level) of its active and potentially active volcanoes, the absence of regional/national-scale natural (including volcanic) disasters in the last fifty to one hundred years means that the country has little experience in responding to and recovering from such events. However, the ongoing recovery process in the Philippines affords the opportunity to improve our understanding of the implications a large-scale eruption would have for New Zealand. Lessons learnt now and applied to the New Zealand situation will save lives and money in the future.

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### REFERENCES

1. Simkin, T., Siebert, L., (1994) "Volcanoes of the world". *GeoScience Press*, Tucson, Arizona, 349 p.
2. Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M., (1995) "Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review". *Journal of Volcanology and Geothermal Research*, Vol. 68, pp. 1-28.
3. Wilson C.J.N., Rogan A.M., Smith I.E.M., Northey D.J., Nairn I.A., Houghton B.F., (1984) "Caldera volcanoes of the Taupo Volcanic Zone, New Zealand". *Journal of Geophysical Research*, Vol. 89 (B10), pp. 8463-8484.
4. Houghton B.F., Wilson C.J.N., McWilliams M.O., Lanphere M.A., Weaver S.D., Briggs R.M., Pringle M.S., (1995) "Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand". *Geology*, Vol. 23, pp. 13-16.
5. Wilson, C.J.N., (1993) "Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand". *Philosophical Transactions of the Royal Society*, London, Vol. A.343, pp. 205-306.
6. Allen, S.R., Smith, I.E.M., (1994) "Eruption styles and volcanic hazard in Auckland Volcanic Field, New Zealand". *Geoscience Reports of Shizuoka University*, Vol. 20, pp. 5-14.
7. Johnston, D.M., Nairn, I.A., Thordarson, T., Daly, M., (1997) "Volcanic Impacts Assessment for the Auckland Volcanic Field". *ARC Environment Division*, Technical Publication 79, 208 p.
8. Defant, M.J., Jacques, D., Maury, R.C., De Boer, J.Z., Joron, J.-L., (1989) "Geochemistry and tectonic setting of the Luzon arc, Philippines". *Geological Society of America Bulletin*, Vol. 101, pp. 663-672.
9. Knittel, U., Oles, D., (1995) "Basaltic volcanism associated with extensional tectonics in the Taiwan-Luzon island arc: evidence for non-depleted sources and subduction zone enrichment". In: Smellie, J.L. (ed.) *Volcanism associated with extension at consuming plate margins*. *Geological Society Special Publication* No. 81, pp. 77-93.
10. Rantucci, G., (1994) "Geological disasters in the Philippines: The July 1990 earthquake and the June 1991 eruption of Mount Pinatubo". *Italian Ministry of Foreign Affairs – Directorate General for Development Cooperation*, 156 p.
11. Torres, R.C., Self, S., and Punongbayan, R.S., (1995) "Attention focuses on Taal: Decade Volcano of the Philippines". *EOS, Transactions AGU*, Vol. 76 (24)
12. Wolfe, J.A., Self, S., (1983) "Structural lineaments and Neogene volcanism in southwestern Luzon". In: Hayes, D.E. (Ed.) *The tectonic and geological evolution of the southeast Asian seas and islands*, part 2, *AGU Geophys. Monogr. Ser.*, 27, pp 157-172, Washington, DC.
13. Newhall, C.G., Punongbayan, R.S., (1996) (eds.), "Fire and mud: Eruptions and lahars of Mount Pinatubo, Philippines", *University of Washington Press*, 1126 pp.

14. Delfin, F.G., jr., Villarososa, H.G., Laguyan, D.B., Clemente, V.C., Candelaria, M.R., Ruaya, J.R. (1996) "Geothermal exploration of the pre-1991 Mount Pinatubo hydrothermal system". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 197-214.
15. Wolfe, E.D., Hoblitt, R.P., (1996) "Overview of the eruptions". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 3-20.
16. Punongbayan, R.S., Newhall, C.G., Bautista, Ma.L.P., Garcia, D., Harlow, D.H., Hoblitt, R.P., Sabit, J.P., Solidum, R.U., (1996) "Eruption hazard assessments and warnings". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 67-86.
17. Tayag, J., Insauriga, S., Ringor, A., Belo, M., (1996) "People's response to eruption warning: The Pinatubo experience, 1991-92". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 87-99.
18. Harlow, D.W., Power, J.A., Laguerta, E.P., Ambubuyog, G., White, R.A., Hoblitt, R.P., (1996) "Precursory seismicity and forecasting of the June 15, 1991, eruption of Mount Pinatubo". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 285-306.
19. Daag, A.S., Tubianosa, B.S., Newhall, C.G., Tuñgol, N.M., Javier, D., Dolan, M.T., Delos Reyes, P.J., Arboleda, R.A., Martinez, Ma.M.L., Regalado, Ma.T.M., (1996) "Monitoring sulfur dioxide emission at Mount Pinatubo". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 409-414.
20. Paladio-Melosantos, Ma.L.O., Solidum, R.U., Scott, W.E., Quiambao, R.B., Umbal, J.V., Rodolfo, K.S., Tubianosa, B.S., Delos Reyes, P.J., Alonso, R.A., Ruelo, H.R., (1996) "Tephra falls of the 1991 eruptions of Mount Pinatubo". In: Newhall, C.G., Punongbayan, R.S. (eds.), Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 513-536.
21. Scott, W.E., Hoblitt, R.P., Torres, R.C., Self, S., Martinez, M.L., Nillos, T., jr. (1996) "Pyroclastic flows of the June 15, 1991, climactic eruption of Mount Pinatubo". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 545-570.
22. Pierson, T.C., Janda, R.J., Umbal, J.V., Daag, A.S., (1992) "Immediate and long-term hazards from lahars and excess sedimentation in rivers draining Mt. Pinatubo, Philippines". U.S. *Geological Survey Water-Resources Investigations Report* 92-4039, pp. 183-203.
23. Rodolfo, K.S., Umbal, J.V., Alonso, R.A., Remotigue, C.T., Paladio-Melosantos, Ma.L., Salvador, J.H.G., Evangelista, D., Miller, Y., (1996) "Two years of lahars on the western flank of Mount Pinatubo: Initiation, flow processes, deposits, and attendant geomorphic and hydraulic changes". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 989-1014.
24. Major, J.J., Janda, R.J., Daag, A.S., (1996) "Watershed disturbance and lahars on the east side of Mount Pinatubo during the mid-June 1991 eruptions". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 895-920.
25. Pierson, T.C., Daag, A.S., Delos Reyes, P.J., Regalado, Ma.T.M., Solidum, R.U., Tubianosa, B.S., (1996) "Flow and deposition of post-eruption hot lahars on the east side of Mount Pinatubo, July - October 1991". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 921-950.
26. Lowe, D.R., Williams, S.N., Leigh, H., Connor, C.B., Gemmill, J.B., Stoiber, R.E., (1986) "Lahars initiated by the 13 November 1985 eruption of Nevado del Ruiz, Colombia". *Nature*, Vol. 324, pp. 51-52.
27. Hall, M.L., (1990) "Chronology of the principal scientific and governmental actions leading up to the November 13, 1985 eruptions of Nevado del Ruiz, Colombia". *Journal of Volcanology and Geothermal Research*, Vol. 42, pp. 101-115.
28. Voight, B., (1990) "The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection". *Journal of Volcanology and Geothermal Research*, Vol. 44, pp. 349-386.
29. Rodolfo, K.S., (1995) "Pinatubo and the politics of lahar". *University of the Philippines Press*, Manila, 341p.
30. Spence, J.S., Pomonis, A., Baxter, P.J., Coburn, A.W., White, M., Dayrit, M., Field Epidemiology Training Program Team, (1996) "Building damage caused by

- Mount Pinatubo eruption of June 15, 1991". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 1055-1061.
31. Bautista, C.B., (1996) "The Mount Pinatubo disaster and the people of Central Luzon". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 151-161.
  32. DPWH, (1991) "Assessment of damage to infrastructure caused by the June 1991 eruption of Mount Pinatubo (September 1991)". *Department of Public Works and Highways, Philippines*, unpublished.
  33. Janda, R.J., Daag, A.S., Delos Reyes, P.J., Newhall, C.G., Pierson, T.C., Punongbayan, R.S., Rodolfo, K.S., Solidum, R.U., Umbal, J.V., (1996) "Assessment and response to lahar hazard around Mount Pinatubo, 1991 to 1993". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 107-140.
  34. Cola, R.M., (1996) "Responses of Pampanga households to lahar warnings: lessons from two villages in the Pasig-Potrero River watershed". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 141-149.
  35. Mercado, R.A., Lacsamana, J.B.T., Pineda, G.L., (1996) "Socioeconomic impacts of the Mount Pinatubo eruption". In: Newhall, C.G., Punongbayan, R.S. (eds.) 1996, Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines. *Philippine Institute of Volcanology and Seismology and University of Washington Press*, pp. 1063-1070.
  36. Rodolfo, K.S., Umbal, J.V., Alonso, R.A., (1993) "A rational analysis of the Santo-Tomas-Pamatawan Plain and lahar system of southwestern Mount Pinatubo, Zamabales Province, Philippines". *Zambales Lahar Scientific Monitoring Group*, unpublished report, 16 p.
  37. Shields, H., (1998) "Engineering Geology of the Megadyke Lahar Protection Measures in the Pasig-Potrero River System, Mount Pinatubo, Philippines". Unpublished M.Sc. thesis, University of Canterbury.
  38. Hackett, W.R., Houghton, B.F., (1989) "A facies model for a Quaternary andesitic composite volcano: Ruapehu New Zealand". *Bulletin of Volcanology*, Vol. 51, pp. 51-68.
  39. Bryan, C., Christenson, B.W., Hodgson, K.A., Houghton, B.F., Johnston, D.M., Jurado-Chichay, Z., Lindsay, J., Manville, V., Nakagawa, M., Nairn, I.A., Otway, P.M., Sherburn, S., Scott, B.J., Thordarson, T., Wood, C.P., Wilson, C.J.N.W., (1996) "Volcanic eruption at a New Zealand ski resort prompts re-evaluation of hazards". *EOS, Trans. AGU*. Vol. 77, no. 20, pp. 189-191.
  40. Nairn, I.A., (1996) "The 1995 Ruapehu eruptions". In: Keys, J.R.(H.), Williams, K.L. (eds.), Ruapehu eruption debriefing. *Department of Conservation, Tongariro-Taupo Conservancy*, 68 p.
  41. Cronin, S.J., Neall, V.E., Lecointre, J.A., Palmer, A.S., (1997) "Changes in Whangaehu river lahar characteristics during the 1995 eruption sequence, Ruapehu volcano, New Zealand". *Journal of Volcanology and Geothermal Research*, Vol. 76, pp. 47-61.
  42. Hodgson, K.A., Manville, V., (1999) "Sedimentology and flow behaviour of a rain-triggered lahar, Mangatoetoe Stream, Ruapehu volcano, New Zealand". *Geological Society of America Bulletin*, Vol. 111, pp. 743-754.
  43. Palmer, B.A., Purves, A.M., Donoghue, S.L., (1993) "Controls on accumulation of a volcanoclastic fan, Ruapehu composite volcano, New Zealand". *Bulletin of Volcanology*, Vol. 55, pp. 176-189.
  44. Donoghue, S.L., Neall, V.E., Palmer, A.S., Stewart, R.B., (1997) "The volcanic history of Ruapehu during the past 2 millennia based on the record of Tufa trig tephra". *Bulletin of Volcanology*, Vol. 59, pp. 136-146.
  45. Beck, A.C., (1950) "Volcanic activity at Mount Ruapehu from August to December 1945". *Journal of Science and Technology*, Vol. B31, pp. 1-13.
  46. Healy, J., Lloyd, E.F., Rishworth, D.E.H., Wood, C.P., Glover, R.B., Dibble, R.R., (1978) "The eruption of Ruapehu, New Zealand, on 22 June 1969". *New Zealand Department of Scientific and Industrial Research Bulletin* 224, 80 p.
  47. Nairn, I.A., Wood, C.P., Hewson, C.A.Y., (1979) "Phreatic eruptions of Ruapehu: April 1975". *New Zealand Journal of Geology and Geophysics*, Vol. 22, pp. 155-173.
  48. Houghton, B.F., Latter, J.H., Hackett, W.R., (1987) "Volcanic hazard assessment for Ruapehu composite volcano, Taupo Volcanic Zone, New Zealand". *Bulletin of Volcanology*, Vol.49, pp. 737-751.
  49. Paton, D., Johnston, D., Houghton, B., Smith, L., (1998) "Managing the effects of a volcanic eruption: Psychological perspectives on integrated emergency management". *Journal of the American Society of Professional Emergency Planners*, Vol. 5, pp. 59-69.
  50. Johnston, D.M., Paton, D., Houghton, B.F., (1999) "Volcanic Hazard Management: Promoting integration and communication". In: Ingleton, J. (ed.), Natural Disaster Management, *Tudor Rose*, Leicester, England, pp. 243-245.

51. Keys, J.R.(H)., Williams, K., (1996) "Ruapehu eruption debriefing". *Department of Conservation, Tongariro-Taupo Conservancy*, 68 p.
52. Cronin, S., Hedley, M., Smith, G., Turner, M., (1996) "Impacts on soil and pasture chemical composition". In: Impacts of October 1995 Ruapehu ash fall on soil fertility. *Department of Soil Science and Fertiliser and Lime Research Centre*, Massey University, 33 p.
53. Cronin, S.J., Hedley, M.J., Neall, V.E., Smith, G., (1998) "Agronomic impact of tephra fallout from 1995 and 1996 Ruapehu volcano eruptions, New Zealand". *Environmental Geology*, Vol. 34(1), pp. 21-30.
54. Gregory, N.G., Neall, V.E., (1996) "Volcanic hazards for livestock". *Outlook on Agriculture*, Vol. 25, pp. 123-129.
55. Keys, J.R.(H)., (1996) "The effects of Ruapehu eruption". *Tongariro - The Annual Journal of the Tongariro Taupo Conservancy*, Vol. 5, pp. 38-40.
56. Maxwell, I., (1996) "Mount Ruapehu eruption 1995 - effects on the Taupo fishery". *Tongariro - The Annual Journal of the Tongariro Taupo Conservancy*, Vol. 5, pp. 46-48.
57. Johnston, D.M., (1997) "The physical and social impacts of past and future volcanic eruptions in New Zealand". Unpublished Ph.D. thesis, Massey University, New Zealand.
58. Malcolm, L., van Rossen, A., (1997) "Ashes to ashes? Rangipo rebuild". *International Water Power & Dam Construction*. (February), pp. 22-24.
59. Johnston, D.M., Houghton, B.F., Neall, V.E., Ronan, K.R., Paton, D., (in press) "Impacts of the 1945 and 1995 - 1996 Ruapehu eruptions, New Zealand: an example of increasing societal vulnerability". *Geological Society of America Bulletin*.
60. Ronan, K.R., (1997a) "The effects of a series of volcanic eruptions on emotional and behavioural functioning in children with asthma". *New Zealand Medical Journal*, Vol.110, pp. 11-13.
61. Ronan, K.R., (1997b) "The effects of a "benign" disaster: symptoms of post-traumatic stress in children following a series of volcanic eruptions". *Australasian Journal of Disaster and Trauma Studies* 1, (<http://www.massey.ac.nz/~trauma/>).
62. Miller, M., Paton, D., Johnston, D.M., (1999) "Community vulnerability to volcanic hazard consequences". *Disaster Prevention and Management*, Vol. 8, pp. 255-260.
63. Brown, N., Amadore, L.A., Torrent, E.C., (1991) "Philippines country study". In: Disaster Mitigation in Asia and the Pacific. *Asian Development Bank*, ADB Manila, pp. 193-254.
64. de Jesus, J.P., (1995) "The Philippines after the 1990 quake and the Pinatubo eruptions". In: Wellington After the Quake: the challenge of rebuilding cities, proceedings of a conference held in Wellington, New Zealand, 27-29 March 1995, pp. 209-216.
65. ADB, (1991) "Report of the Task Force on the damage caused by the eruption of Mt. Pinatubo and proposed rehabilitation/restoration measures, August 1991". *Agriculture Department, Asian Development Bank*, (ADB), Manila.
66. UNDRO/UNESCO, (1985) "Volcanic emergency management". Geneva, *UNDRO/UNESCO*, 86 p.
67. Department of Social Works and Development. (1996) "From the Victims to Victors. The Mt Pinatubo Experience: Relief and Rehabilitation". *DSWD*, 180p.
68. Bautista, M.C.R.B., (1993), "Lahar and Flood: The Bane of Mount Pinatubo's Lowland Victims". In: Bautista M.C.R.B. (ed.) In the Shadow of the Lingerin Mt Pinatubo Disaster. *CSSP Publications*, Philippines, pp. 17-38.
69. Ballantyne, M., Paton, D., Johnston, D.M., Kozuch, M., Daly, M., (2000) "Information on volcanic and earthquake hazards: the impact on awareness and preparation". *Institute of Geological and Nuclear Sciences Limited Science Report 2000/2*.
70. Johnston, D.M., Benton, K., (1998) "Volcanic hazard perceptions in Inglewood, New Zealand". *The Australasian Journal of Disaster and Trauma Studies*, Vol. 2, pp. 1-8.