# Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure

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## ABSTRACT

This report presents first-hand observations of the impacts of the 2006 eruptions of Merapi volcano, in central Java, on agriculture and infrastructure of the Yogyakarta region. A field team visited the region during the period 22 June – 5 July 2006, representing the University of Canterbury's Natural Hazards Research Centre, GNS Science, the New Zealand Earthquake Commission and the New Zealand Ministry of Civil Defence and Emergency Management. In addition to coverage of agricultural and infrastructural impacts, this report also includes a description of the volcanology of the 2006 eruptions, and a discussion of the Indonesian response to the volcanic crisis including evacuation and crisis management.

Agriculture received the most damage of any economic sector, mostly due to the close proximity of a significant number of farms to Merapi volcano. Impacts on crops varied with ash thickness, as well as by crop type and plant maturity. Up to 100% of crops were lost in some locations. Significant weight loss in cows was observed, due to animals eating tephra-covered fodder.

Overall, impacts to infrastructure were slight. Lifeline utilities and other infrastructure exhibited a higher degree of resilience than expected, probably due to the absence of rain as the eruption occurred during the dry season. Deposits left from the eruption on the upper, south-facing slopes of Merapi still pose a severe lahar threat to the floodplains below in times of heavy rain.

Despite their relatively small size, the 2006 eruptions of Merapi caused two deaths, the destruction of most of the village of Bebeng/Kaliadem, the displacement of tens of thousands of people, and significant impacts on the agriculture of the region. We conclude this report by attempting to draw lessons for New Zealand from our findings.

## KEYWORDS

Merapi volcano
Indonesia
2006 eruption
Agricultural impacts
Infrastructural impacts

# 1. INTRODUCTION

Indonesia (Figure 1) experiences an average of one significant volcanic eruption every year (Witham, 2005) because of intense volcanic activity along the Sumatra and Java subduction zones which comprise one of the longest, most prolific convergent margins on Earth. Merapi volcano, located approximately 25 km north of the city of Yogyakarta in central Java (Figure 2), is widely recognized as one of the most frequently active volcanoes on Earth (Witham, 2005). In early April 2006, Merapi began to show signs of volcanic unrest as volcano-tectonic and volcanic earthquakes increased daily (WHO, 2006). Seismic activity continued throughout May, and extrusive activity, in the form of lava flows from the summit, was first observed on 4 May, marking the beginning of the eruption.

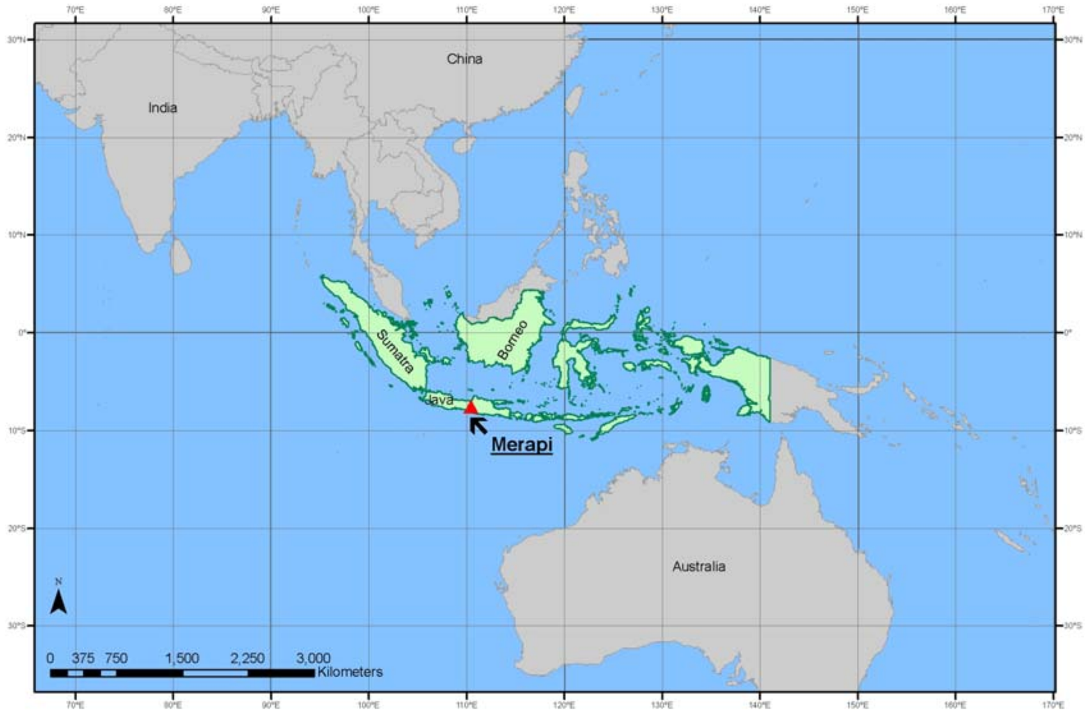


**Figure 1** Map of Indonesia, with Merapi indicated by red triangle

Proximal hazards during the eruption were due largely to block and ash (pyroclastic) flows resulting from periodic partial collapse of the growing lava dome on the summit of Merapi. Distal hazards were due to tephra falls originating from convecting plumes of hot gas accompanying both larger block and ash flows and the fracturing summit lava dome. Variable winds dispersed tephra widely around Merapi volcano.

This report presents a summary of observations of impacts of this eruption on agriculture and infrastructure in the Yogyakarta region of central Java, collected during a field visit


**Figure 2** Map of Yogyakarta region, south central Java. Merapi is located at top centre

to the region between 22 June and 5 July 2006. Other aspects covered include the chronology of the 2006 eruption, evacuation prior to and during the eruption, the local response and crisis management, and future hazards from the eruption.

## 1.1 Rationale for field visit

The New Zealand Earthquake Commission (EQC) funded the field visit for two of the authors (T. Wilson and G. Kaye) to collect observational data on the direct impacts of the 2006 eruption of Merapi on agriculture and infrastructure around the volcano. An important application of this work is to apply the findings in New Zealand, to further our predictive capabilities for the impacts of future eruptions in New Zealand. Although many projects are currently underway in New Zealand to improve understanding of the impacts of volcanic eruptions and other natural hazards on communities, lifelines, agriculture and infrastructure (e.g. King et al., 2004; Kaye et al., 2006; Wilson and Kaye, 2007), there is little direct observational data because of the small number of eruptions in recent times in New Zealand.

The eruption of Merapi also provided an opportunity to advance volcanic hazard risk assessment. The Regional Riskscape Project (or Riskscape) is reliant on the concept of ‘fragility functions’. These are numerical relationships between hazard intensity and damage, which need to be validated with existing observations and data. Thus, the 2006 Merapi eruption provided field observations that will be used to refine fragility functions for Riskscape.

## 2. METHODS

### 2.1 Field stops and observations

The team spent five days (23, 25-27 June, 4 July 2006) in the field at Merapi, and circumnavigated the volcano. Taking care to visit all sectors of the volcano, 213 field stops were made. At each field stop, a GPS waypoint was recorded (Figure 3 and Appendix 1). Information recorded in the field included observations of ashfall conditions and evidence of physical impacts (Appendix 1). Where appropriate, ash, soil and rock samples were collected and brought back to New Zealand for analysis. Photographs and video footage were also collected at every location, and matched with GPS points in order to facilitate a more detailed review back in New Zealand.

### 2.2 Interviews with farmers and local residents

While circumnavigating Merapi, the team interviewed 35 farmers and a further 15 local residents with the help of an interpreter. Efforts were made to obtain a spatially diverse sample, although this was hampered by logistical and time constraints. Farmers and residents were approached when they were observed working in the fields, in evacuation centres, or in villages or hamlets. A set of questions was put to them, covering the amount of ashfall they had experienced, any physical damage sustained, damage to crops or animals, any economic losses sustained, and the performance of infrastructure during the eruption. Occasionally, due to the language barrier, information was received on the impacts of past eruptions rather than the current eruption; a distinction was made where possible.

### 2.3 Interviews with agricultural and soil science experts

In Yogyakarta, discussions were held with local agriculture and soil science experts at the Institute of Science and Technology (ISTA) and the University of Gadjah Mada (UGM), on 28-29 June 2006. Discussions covered the impacts of ashfall on crops and other farming practices, physical damage, economic losses and the performance of infrastructure. These experts provided invaluable information about the technical nature of farms, crops, seasonality, and agricultural practices around Merapi.

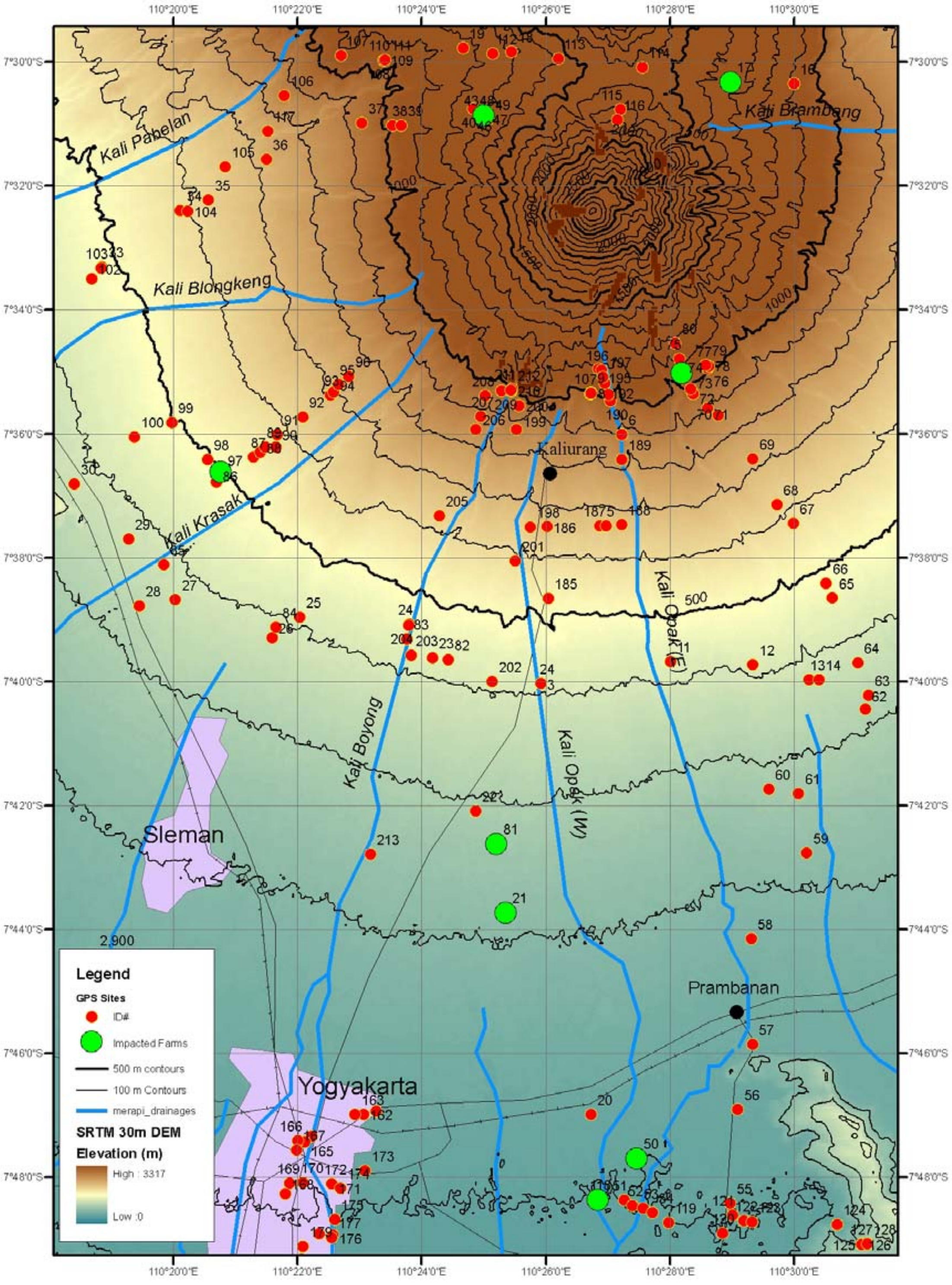


**Figure 3** Field stops around Merapi showing GPS waypoint numbers

# 3. ERUPTIVE HISTORY AND GEOLOGIC BACKGROUND

Merapi has a long, active, and varied history. The volcano has been extensively studied, and is intensively monitored. Previous studies (e.g. Newhall et al., 2000; Camus et al. 2000; Voight et al., 2000; Andreastuti et al., 2000) have constrained the historic and prehistoric eruption record at Merapi from stratigraphic mapping and age-dating investigations. These studies, coupled with observations and monitoring data from the last two centuries, suggest that Merapi's recent behaviour differs from its prehistoric activity.

## 3.1 Prehistoric eruptions

Stratigraphy and radiocarbon dating of pyroclastic deposits at Merapi volcano have been summarised by Newhall et al. (2000), and reveal 10,000 years of explosive eruptions. The Holocene record suggests that the mean recurrence period for Volcanic Explosivity Index (VEI) 4 events is approximately 100–200 years, and for VEI 5 is approximately 1000 years. These recurrence periods may be overestimates, as not all tephras or pyroclastic flow deposits for events of this size have been recognized (Andreastuti et al., 2000).

## 3.2 Historic eruptions

### 3.2.1 19$^{th}$ century eruptions

Tephrostratigraphic evidence (Andreastuti et al. 2000, Voight et al. 2000, Newhall et al. 2000) suggests that eruptions of Merapi during the 19$^{th}$ century were larger than those of the 20$^{th}$ century. Four eruptions of VEI 3 or greater occurred during the 19$^{th}$ century; the largest was a VEI 4 event in 1872 which produced a large crater and generated a pyroclastic flow (from column-collapse) that travelled over 20 km from Merapi's summit. Three VEI 3 events occurred in 1822 (possibly 1832), 1846 and 1849. It is possible that the 1822 eruption may have been a similar size to the 1872 VEI 4 event. In contrast, only two VEI 3 eruptions occurred during the 20$^{th}$ century.

### 3.2.2 20$^{th}$ century eruptions

Since the beginning of the 20$^{th}$ century, Merapi volcano has been intensively studied and monitored, and detailed records of its eruptive history throughout the 20$^{th}$ century are available (Figure 4). As well as showing the distance from the summit and direction of observed 20$^{th}$ century pyroclastic flows, this diagram also shows the extent of mapped prehistoric flows. It is clear that the pyroclastic flows depicted in Figure 4 are all considerably smaller than the flow generated by the 1872 VEI 4 event, which travelled 20 km. Also, there is a predominance of flows to the westerly quadrant.

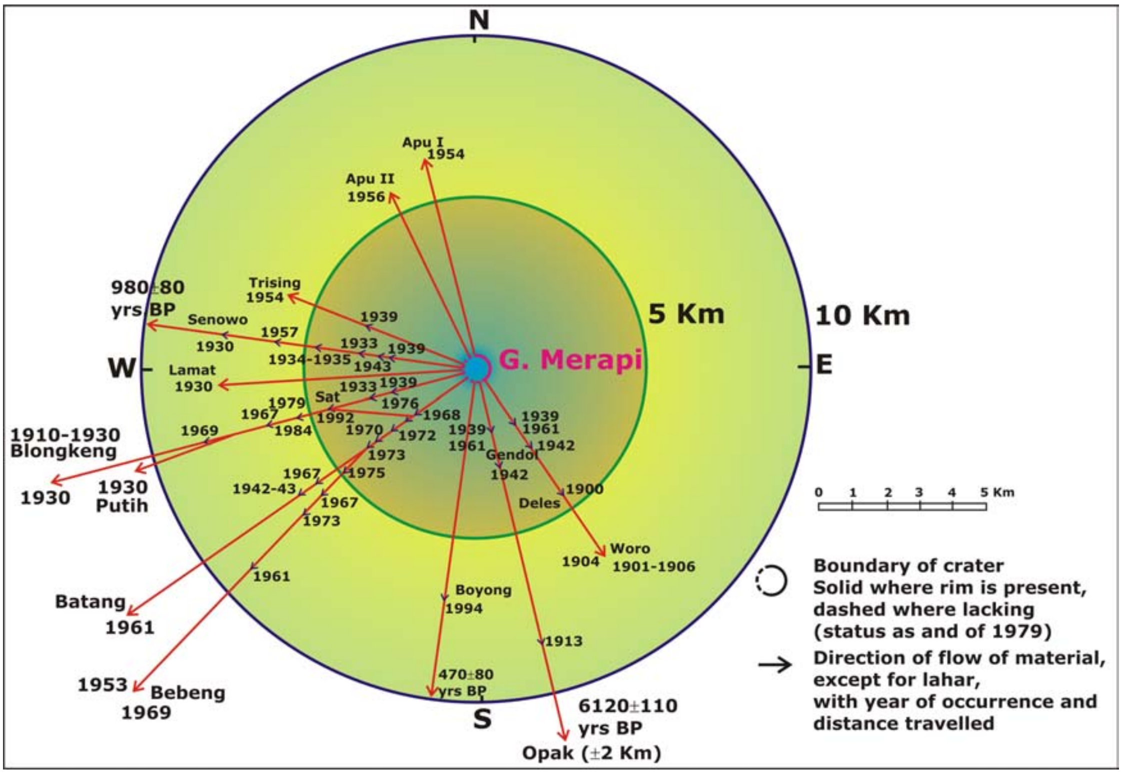


**Figure 4** Prehistoric and 20th century pyroclastic flows from Merapi (adapted from Thouret et al, 2000)

Notable eruptions during the 20th century were the 1930 VEI 3 event, which generated a pyroclastic flow that travelled 12 km, caused 1,369 deaths and made approximately 13,000 people homeless (Table 1). Another VEI 3 event occurred in 1961. It also generated a 12 km pyroclastic flow, but was less hazardous, with six people killed and approximately 6,000 made homeless. Smaller eruptions have also had devastating impacts on local people. For instance, in 1994, a VEI 2 eruption produced 7 km pyroclastic flows along the Boyong River, which killed sixty people in the village of Turgo. A further 6,026 people were made homeless by or evacuated from this event.

During the 20th century, eruptive activity from Merapi has been characterised predominantly by the repeated expulsion of viscous, highly crystalline lavas to form bulbous lava domes and thick, stubby lava flows. The gravitational instability and collapse of these extrusions tends to generate violent, although modestly-sized, pyroclastic flows commonly defined as 'Merapi-type' (Voight et al., 2000).

### 3.2.3 Impacts on human populations

Since the mid-1500s there have been approximately 7,000 deaths caused by volcanic activity at Merapi (Thouret et al., 2000; Witham, 2005), with one of the most lethal eruptive episodes in 1930 with 1,369 deaths. On average, a volcanic disaster has occurred approximately once every three years (Witham, 2005). Hundreds of villages have been destroyed along with thousands of hectares of farmland and forests over the past 300 years (Voight et al., 2000). The effects of eruptions have become increasingly more devastating because of the increasing population density around Merapi. Impacts on populations around Merapi are illustrated in Table 1 for selected eruptions.

**Table 1** Human impact of selected eruptions of Merapi volcano (from Witham, 2005)

| Date of eruption | VEI of eruption | Number killed | Number injured | Number evacuated or made homeless |
|---|---|---|---|---|
| 1930 | 3 | 1,369 | - | 13,000 |
| 1961 | 3 | 6 | 6 | 8,000 |
| 1994 | 2 | 64 | 500 | 6,026 |
| 1998 | Effusive | - | 314 | 6,000 |
| **Total (20$^{th}$ century)** | | **1,590** | **932** | **32,275** |
| | | | | |
| 2006 | Effusive | 2 | - | 12,000 |

## 3.3 Hazard management at Merapi

There is continued speculation about whether the relatively small eruptions of Merapi that have occurred throughout the 20$^{th}$ century and now into the early 21$^{st}$ century herald a new era of eruptive style at Merapi. Alternatively, the past century's activity may be low-level background activity that could be interrupted at short notice by much larger explosive eruptions (Newhall et al., 2000). Considering Merapi's 10,000-year record of explosive activity (Newhall et al., 2000, Voight et al. 2000), many scientists favour the latter hypothesis and have expressed concern that a large eruption will occur in the future with only modest or inadequately appreciated precursors.

This debate has important implications for hazard evaluation and management at Merapi, particularly in view of the fact that an estimated 440,000 people live in high-risk areas around Merapi vulnerable to pyroclastic flows, surges and lahars (Thouret et al., 2000). A further complication is that it is typical for eruption locations to change, putting different sectors, with populations in varying states of preparedness, at risk. During the last 100 years most pyroclastic flows have been to the western quadrant, and to a lesser extent, to the north and south of the summit, but the collapse of current or historic domes can dramatically change the direction of pyroclastic flows. This was observed during the current (2006) eruption, and is discussed further in Section 4.4 below.

# 4. THE 2006 ERUPTION OF MERAPI

## 4.1 Chronology

A chronology of the 2006 eruption of Merapi is provided in Table 2. Locations referred to in the table are shown in Figures 6 and 14.

**Table 2** Chronology of 2006 eruption of Merapi

| Date | Time | Event |
|---|---|---|
| 25 April | - | Merapi Volcano Observatory (BPPTK) reports 198 multi-phase (MPT) earthquakes, 4 shallow volcanic tremors (SVT), and one tectonic quake (TT) |
| 26 April | - | BPPTK reports 57 MPTs, one SVT |
| 3 May | - | BPPTK reports 84 MPTs, one SVT, and 4 discharges |
| 4 May | 02:00 | Lava erupted from summit |
| 7 May | - | 133 MPTs, 88 TT, and one SVT |
| 8 May | 0:00-06:00 | One SVT, 34 MPTs, 29 TTs |
| 9 May | - | 6 VTs, 142 MPTs, 152 RFTs. |
| 10 May | 0:00-06:00 | One SVT, 123 MPTs, 88 rock fall tremors (RFT), and 4 TTs. Evidence of new growing lava dome at summit reported |
| 12 May | - | 90 MPTs, 214 RFTs, 4 TTs, 11 pyroclastic flows (PF) max. 1.6 km down upper Krasak and Boyong Rivers, lava flows (LF) down same drainages to 1,500m from summit |
| 13 May | 0:00 and 06:00 | 27 MPTs, 24 RFTs, and 14 PFs of uncertain distance. BPPTK recommends communities within 8 km of the crater on the south-southeast sector evacuate, along with those within 10 km of the crater on the southwest-west side and those within 8 km on the western flank. |
| 14 May | 0:00 to 06:00 | 23 ash/steam clouds erupted once every 15 minutes |
| 4/5 June | unknown | Geger Boyo collapses |
| 13 June | - | Alert level lowered from 4 (caution) to 3 (alert) |
| 14 June | ~12:00 | Small dome collapse flow causes renewed evacuation of Kaliadem and surrounds |
| 14 June | ~15:00 | Dome collapse, block and ash flow down Woro valley onto Kaliadem village. Two men were killed in a bunker where they tried to escape the flow. Water pipes were severed, cutting off water to 12,000 people. The alert level was raised to 4 (caution) |
| 22 June to 5 July | - | Small dome-collapse block and ash flows continue, but decrease in intensity and frequency |
| 12 July | - | Alert level lowered from 4 (caution) to 3 (alert). |
| 12 July to 25th August | - | Continued decrease in eruption activity |
| By October 1 | | Return to baseline Alert Level |

## 4.2 Primary physical behaviour and general impacts

The 2006 Merapi eruption was typical of previous small effusive eruptions from this volcano. Fresh, highly-degassed andesitic magma was extruded at the summit into a lava dome, which occasionally shed material from its collapsing lower edges down onto the upper edifice due to gravitational instability. These collapse events created block and ash flows, of which the largest was on 14 June. A block and ash flow travelled approximately 4 km down the Woro Valley and devastated the towns of Kaliadem and Bebeng. Two men, who tried to escape the flow by sheltering in a bunker, were killed.

As a result of both the magma extrusion and the collapse-induced flows, fresh juvenile lava was fractured at the summit dome and ash was mobilised skyward in convective currents from the hot flows, and carried by prevailing winds to fall on communities around the volcano. A gas and ash plume trailing to the west-southwest is shown in Figure 5.

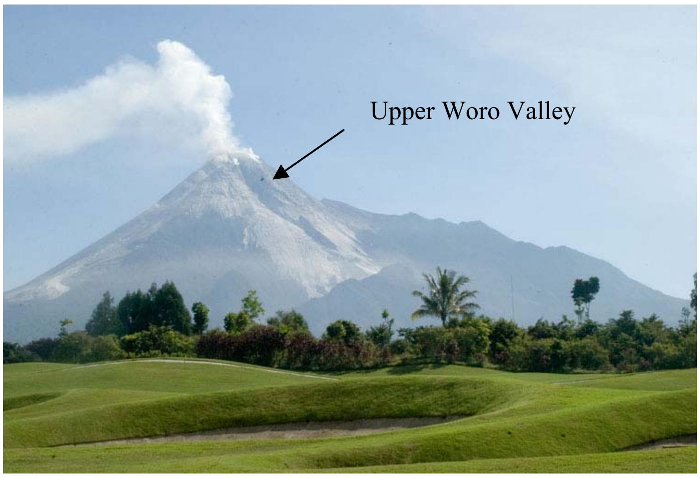


**Figure 5** W-SW ash plume from Merapi, viewed from Merapi golf course ~12 km south of the summit on 22 June 2006

## 4.3 Ash deposition (isopach map)

A range of ash and tephra thicknesses were deposited around Merapi, with greater depths found around the valleys on the western, southwestern and southeastern flanks of the mountain, where the large block and ash flows travelled. Tephra depths were recorded during field visits, and are listed in Appendix 1. Approximate isopach lines have been constructed from this data, and are shown in Figure 6. Prevailing winds from the west and south also distributed tephra over the eastern and northern sides of the mountain. However, most of the surrounding areas experienced only traces of ashfall.

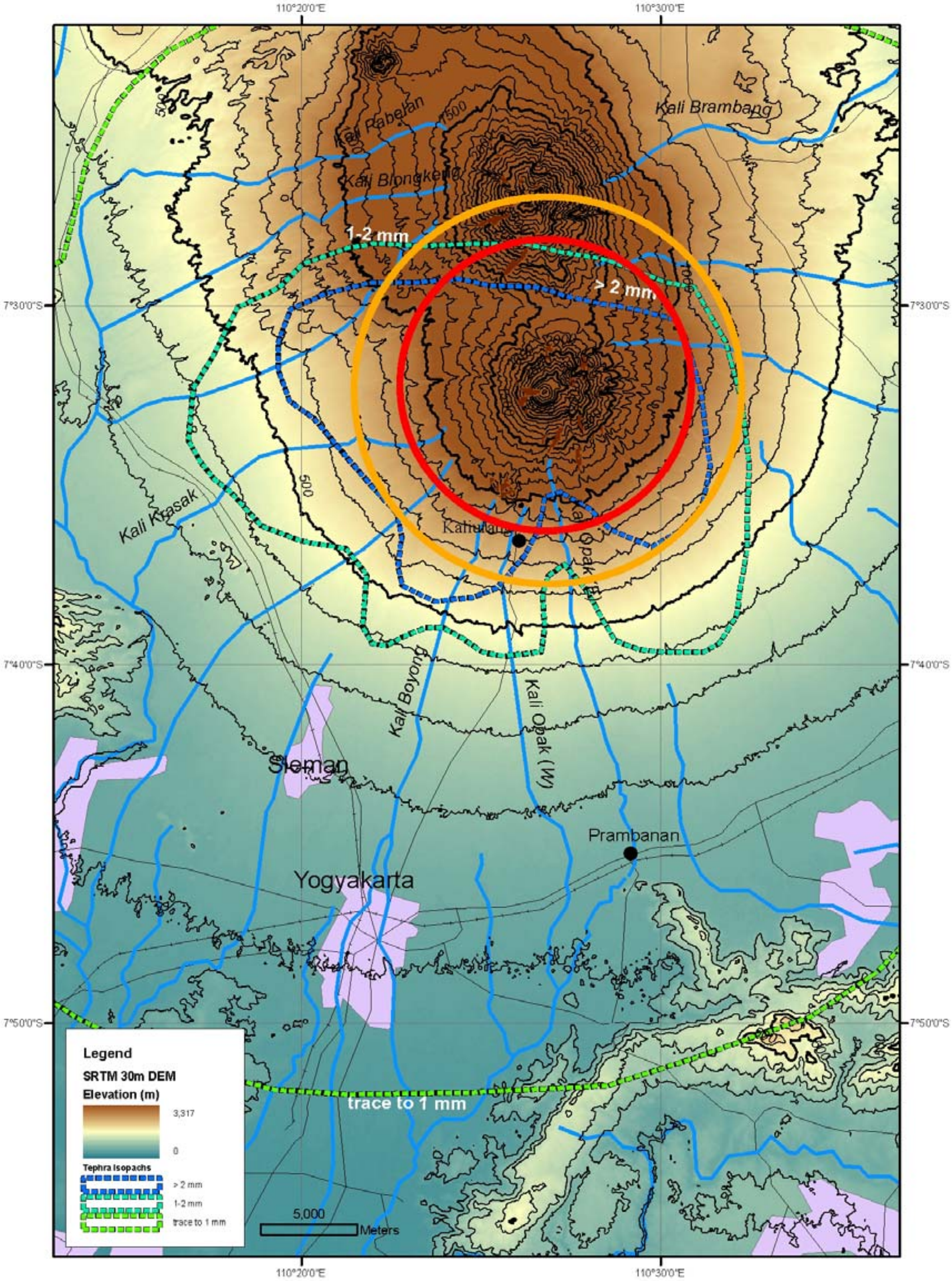


**Figure 6** Isopach lines for the 2006 Merapi eruptions and inner (8 km radius) and outer (10 km) exclusion zones

## 4.4 The collapse of the Geger Boyo

The 1931 lava domes on the southwest flank of Merapi were named 'Geger Boyo' (crocodile back) by local residents and volcanologists, due to the domes' resemblance to the spine of a crocodile (Figure 7). They were a prominent feature on the upper southwest ridge of the volcano, and acted as a protective barrier for communities on the southeast side of Merapi by deflecting flows towards the west and southwest. Because of the protection offered by the Geger Boyo, communities on the southeast side of Merapi had not been subjected to any significant pyroclastic flows since 1930.

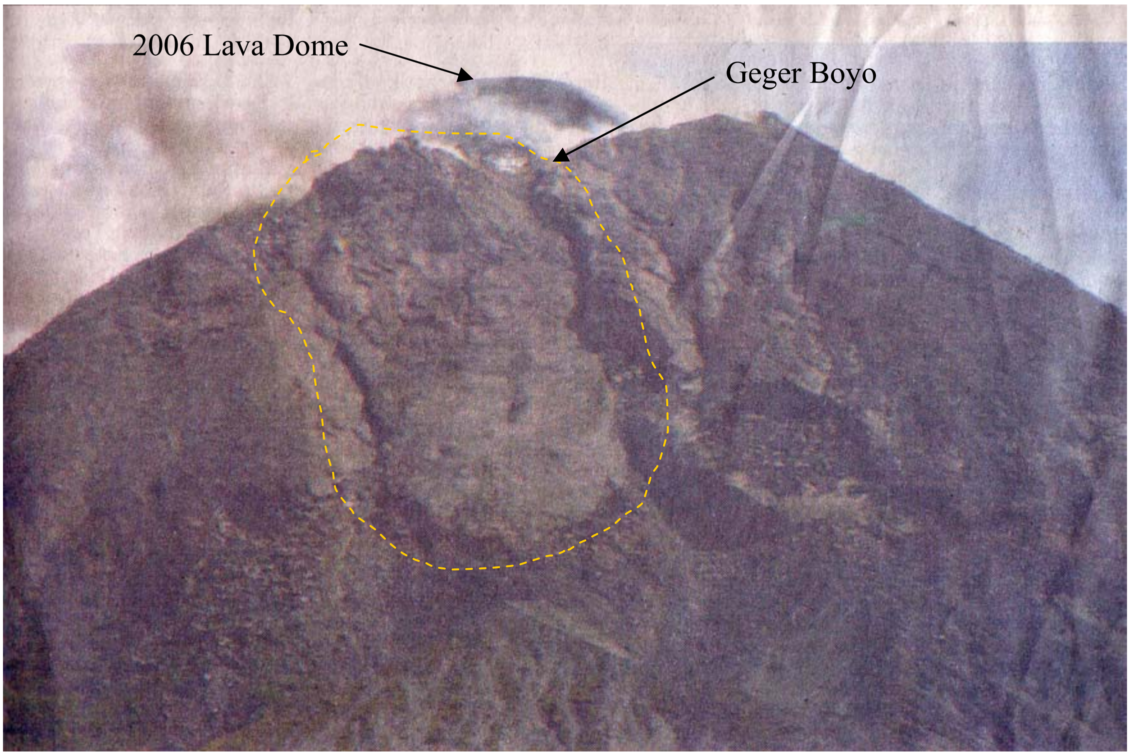


**Figure 7** View of the Geger Boyo (outlined) on 11 May 2006 (Dr. S. Bronto, pers. comm.)

The Geger Boyo collapsed between 4 and 5 June 2006, cascaded down the Woro valley and opened up the southeastern flanks of Merapi to the unstable and growing lava dome at the south summit of the volcano (Figures 8-9). This shift in hazard location was immediately publicised by the Merapi Volcano Observatory (known locally as the BPPTK), and featured prominently in the local newspapers (Dr. S. Bronto, pers. comm.).

**Figure 8** Southeast flank of Merapi on 5 June 2006, showing the Upper Woro valley, the collapsed Geger Boyo and the growing lava dome at the summit (Dr. S. Bronto, pers. comm.)

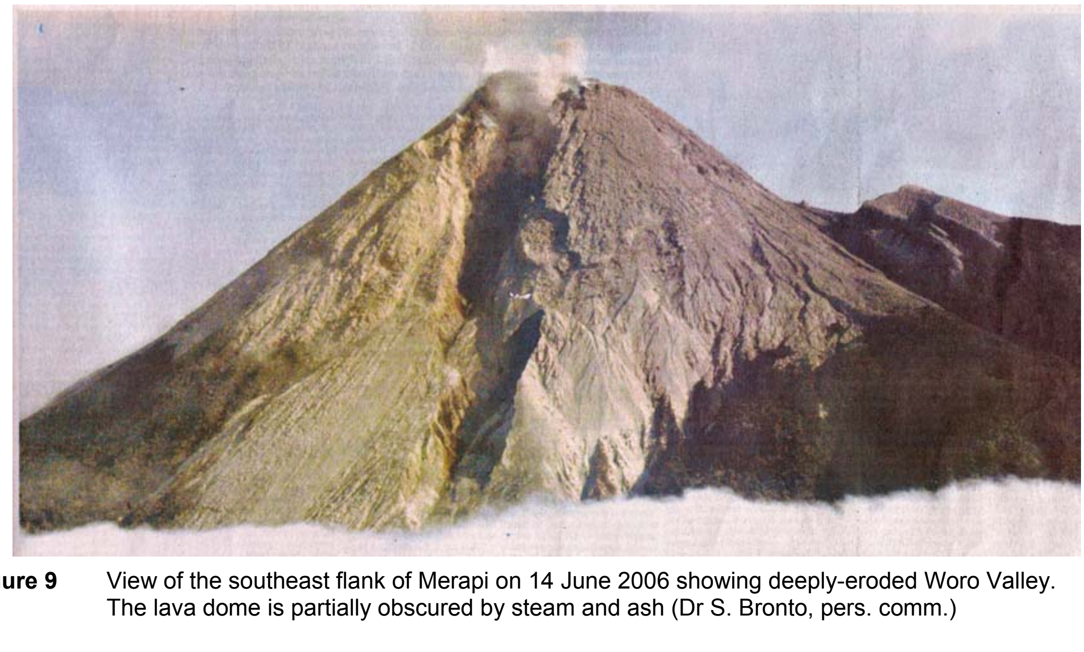

**Figure 9** View of the southeast flank of Merapi on 14 June 2006 showing deeply-eroded Woro Valley. The lava dome is partially obscured by steam and ash (Dr S. Bronto, pers. comm.)

## 4.5 Block and ash flows on 14 June

At approximately midday on 14 June 2006, a small block and ash flow came down the upper Opak/Gendol River valley (Figures 10 and 11), causing BPPTK to order an immediate evacuation of Kaliadem (Bebeng) village, and forcing the remaining residents to flee down the mountain. The overall damage to Kaliadem village is shown in Figure 12, which is taken from a similar vantage point to Figure 11.

Two volunteers remained behind to assist with evacuations, and retreated to a concrete bunker specifically designed to withstand a pyroclastic flow, with heavy doors, running water and an oxygen supply. However, a second, and much larger, block and ash flow occurred at approximately 3 pm. The bunker was damaged (Figure 13) and the two men were killed.

The approximate path of the large pyroclastic flow on 14 June is shown in Figure 14. It travelled approximately 4 km from the summit, and divided into two lobes on either side of Kaliadem village.

**Figure 10** 14th June block and ash flow viewed from Merapi golf course (permission of S. Bronto)

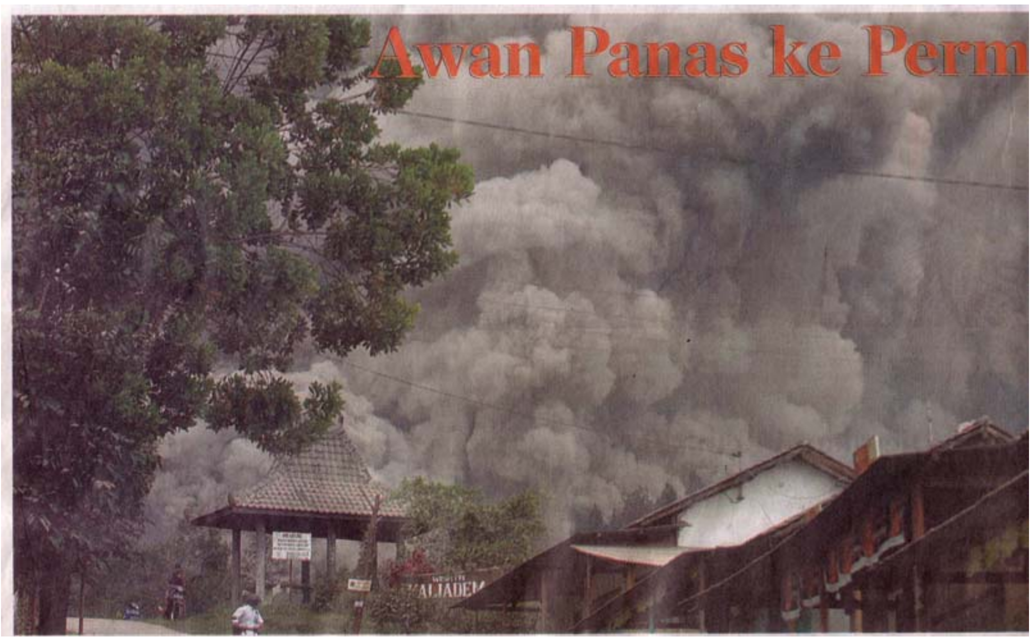


**Figure 11** Advancing front of the 12 pm 14 June block and ash flow from Kaliadem village

**Figure 12** Kaliadem village after the 14 June block and ash flow (note partial burial of shrine)


**Figure 13** Bunker in Kaliadem village where two men lost their lives

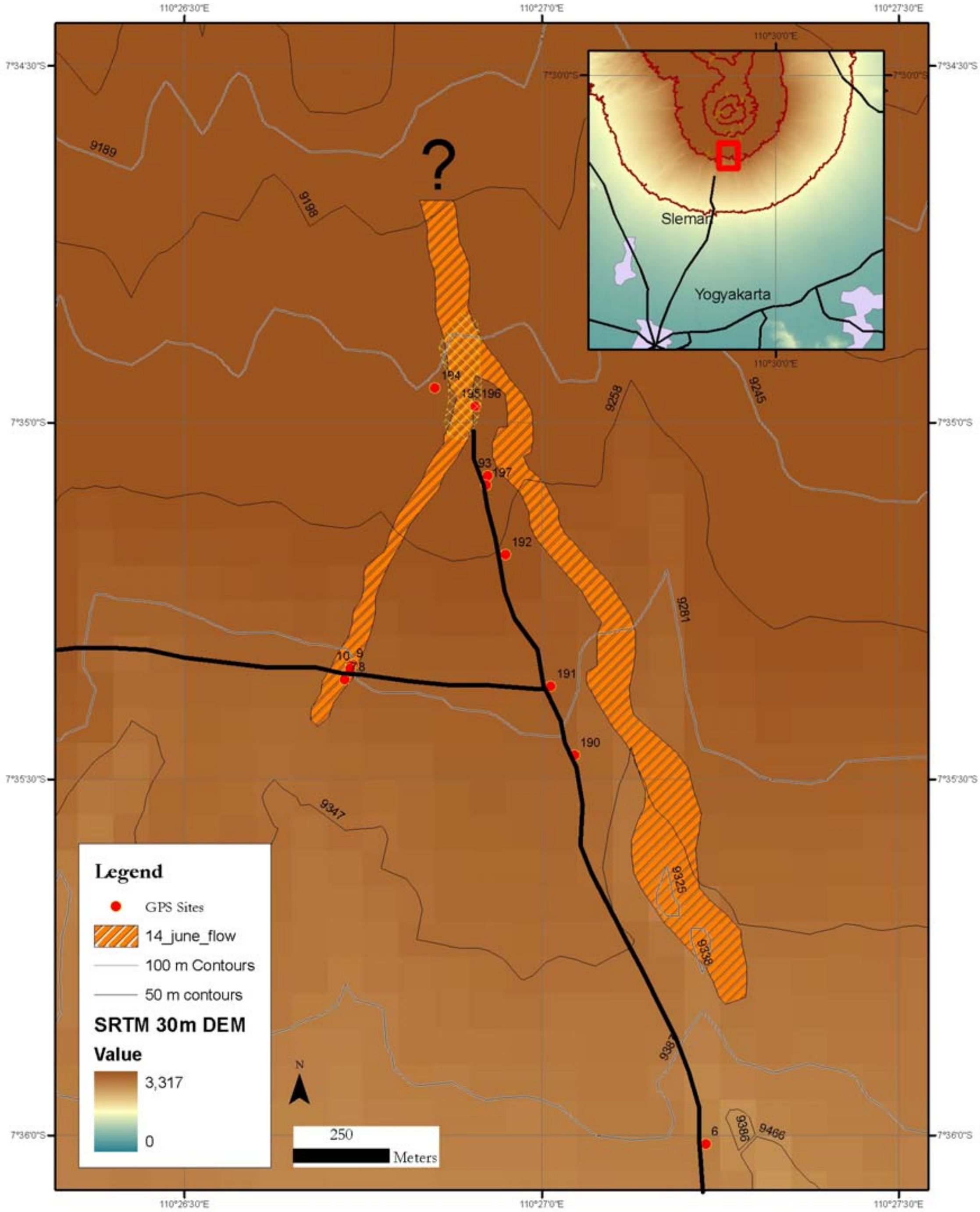


**Figure 14** Sketch map of Kaliadem / Bebeng village showing 14 June pyroclastic flows. Yellow hatched area denotes approximate location of village destroyed by flow

### 4.5.1 Damage to buildings in Kaliadem village

In addition to taking two lives, the larger block and ash flow on 14 June 2006 caused considerable damage to many buildings in Kaliadem/Bebeng as it over-rode the earlier flow. Houses were buried by several metres of flow material, and some roofs were crushed by falling debris. The blocks from the lava dome were extremely degassed and highly crystalline (Newhall, pers. comm.). Consequently, the flow material was not as hot as might have been expected for freshly erupted juvenile material, and most buildings damaged by the flow were impacted by the blocks, but not burned (Figures 15 and 16). Some buildings were slightly scorched on their exteriors by smouldering woody debris entrained within the flow (Figure 16). Approximately ten metres from the lower extent of the flow in Kaliadem, plastic sheeting that had been wrapped around a house to prevent ash from entering the building was not melted by the 14 June flows (Figure 17). The margins of the flow were sharp both in Kaliadem village and to the west, where a lobe of the flow destroyed a road slightly below the village (Figure 18). The western lobe of the flow in the upper Opak River had very abrupt damage margins. Foliage was not even singed only a few meters from the edge of the flow (Figure 18).

**Figure 15** House destroyed by impact of blocks during 14 June 2006 block and ash flows

**Figure 16** Partially-buried and scorched house in Kaliadem

**Figure 17** House in Kaliadem wrapped in plastic to exclude ash

**Figure 18** Road close to Kaliadem partially covered by debris from 14 June flows (note sharp boundaries)

# 5. AGRICULTURAL IMPACTS

## 5.1 Overview of agricultural practices around Merapi

The land use around Merapi can be described as high-intensity, low-technology, subsistence tropical agriculture (Figure 19). Farm sizes are typically between one and two hectares, and may support families ranging from an elderly couple to a large extended family of up to ten people. The Yogyakarta region has a year-round tropical growing season that is typically divided into a wet season (October to March) and a dry season (April to September).

**Figure 19** Typical paddy-type agriculture on the south flank of Merapi

There are few inputs into farms. Fertiliser inputs are low, and usually consist of manure from farm animals such as cows, goats or sheep. The team found no evidence of the use of mineral fertilisers. New high-yield varieties of rice have been introduced over the past ten years, with considerable success. As in New Zealand, there are no subsidies or government assistance for farmers (D. Indradewa, pers. comm.). Some use of pesticide sprays, from a knapsack-type dispenser, was observed.

### 5.1.1 Farm types

Paddy-grown rice is the preferred crop for farmers. It is a traditional favourite, well-suited to the centuries-old paddy-style farming. While the economic returns are less than for other cash crops, farmers perceive rice to be a low-risk crop due to its resilience to pests, and the low labour demands once it is established (D. Indradewa, pers. comm.).

Secondary cash crops are part of the rotational practices used by all farmers, and include tobacco, corn, maize, chilli peppers, tomatoes, watermelons, taro, carrots, bananas, cabbages and peanuts. Successful harvests of cash crops offer good economic returns for farmers but are more susceptible to disease, pests and climatic variations.

Livestock are mainly kept to produce meat for domestic consumption. Typical farm animals include cows, oxen, sheep, goats, chickens, and ducks. There appears to be limited milking of animals in the region, and that which occurs is centred mainly on Kaliadem.

### 5.1.2 Lowland/upland division and influence on seasonality

The topography of the Merapi region has a significant influence on agricultural practices. There is a clear division between lowland areas, which have a secure water supply allowing irrigation throughout the year, and upland areas which do not have a secure water supply in the dry season.

In lowland areas, the constant water supply allows preferred crops (mainly rice, which is water-dependent) to be grown year-round, with three to four harvests per year possible. Productivity is high on lowland farms, with rice yielding up to seven tonnes per hectare.

Upland areas are able to grow preferred crops during the wet season, but during the dry season, when the reliable water supply is lost, must fall back on secondary cash crops. As a result, only two to three harvests per year are typically possible, and the productivity is also lower and usually around 1.5 tonnes per hectare (D. Indradewa, pers. comm.).

The team visited the Merapi region during the dry season in 2006. Irrigated lowland soils were moist, but the upland soils were dry and dusty, particularly on the upper slopes of the volcano. Rice crops were rarely observed in upland farms. When rice crops were seen, they were at a mature stage of development with developed seed-heads, ready for harvest. We observed a wide variety of cash crops in upland regions, with nearly all the crops listed in Section 5.1.1 present at various stages of growth. Less diversity was observed in lowland farms, with only rice, tobacco, chili peppers and corn observed.

## 5.2 Observed impacts of volcanic activity on crops

The main volcanic hazard affecting agriculture was tephra fall, derived from convecting plumes rising off the block and ash flows from dome collapse events. While block and ash flows were limited to the western and southern flanks, the prevailing winds distributed ashfalls more widely around all sectors of the volcano (Figure 6). Farms in the direct path of block and ash flows were destroyed (for example, at Petung and Kaliadem). Local authorities estimated that by late July 2006, up to 3,000 hectares of agricultural land had been destroyed by the eruption. The sharp nature of the margins of block and ash debris flows was noted in Section 4.5.1. Vegetation within a metre or two of flows was typically scorched by the flow debris, but the team noted signs of regrowth and recovery of the vegetation within ten days or so of the initial damage.

### 5.2.1 Crop vulnerability

Crop vulnerability was very dependent on crop type. Root and low-growing vegetables, such as carrots, potatoes, onions and cabbages, were consistently observed to be the most resilient to ashfall. A likely explanation is that these vegetables tend to be shielded by taller plants (such as chilli peppers, tomatoes, tobacco or peanuts) which provided a tephra-shadow effect. Plants with shiny leaves, such as cabbages, also appear to be able to shed ash readily, which decreases their vulnerability. However, plants with large, hairy leaves, such as tobacco, are efficient traps for ash and are very vulnerable.

The maturity of a plant was also observed to be an important factor in determining the degree of physical damage. However, there was no general relationship between stage of development and damage, and different crops appeared to be vulnerable to ashfall at different stages of their development. For example, rice was vulnerable during mature stages, with damage apparent to the seed-head, but was resilient during initial stages of development. In comparison, corn was vulnerable during early to mid-stage development but quite resilient when mature.

Our field observations on the relative vulnerabilities of crops grown in the Merapi region are presented in Table 3. For each crop we have described the vulnerable parts and stages of development, and combined these with our field observations to assign a relative vulnerability to each one, using a four-point scale of 'high', 'moderate', 'some' and 'low'.

### 5.2.2 Local adaptations

Agricultural experts expected there to be some adjustment to planting strategies, with farmers moving towards planting more resilient plants in the short term (D. Indradewa, pers. comm.). We observed that in many areas, local farmers had started to plant more resilient crops such as carrots, potatoes, onions and cabbage. Most farmers appear to have adopted a wait-and-see attitude in response to the ashfall, and were following normal crop rotation practices rather than abandoning crops and ploughing them under to start again.

### 5.2.3 Influence of seasonality on crop impacts

On the basis of previous experience at Merapi, farmers and agricultural experts we consulted indicated that impacts of eruptions on agriculture are less severe during the wet season. Daily monsoonal rains wash ash and aerosol deposits from plants rapidly, and are also thought to integrate the ash into the soil more rapidly.

### 5.2.4 Observed impacts of ashfall on crops

Our field observations on the impacts of volcanic ash on local crops are also summarised in Table 3. Three main categories of damage were recorded in the field, and these are discussed further below. It is important to note that these field observations have not been followed up by further laboratory-based studies.

#### *5.2.4.1 Acid damage*

Surface coatings on fresh volcanic ash are highly acidic due to the presence in the plume of aerosols composed of the strong mineral acids $H_2SO_4$, HCl and HF (Witham et al., 2005; Stewart et al., 2006). Fresh volcanic ash therefore has the potential to cause acid damage when it is deposited on vegetation. In addition to tephra fall, plants may also be exposed to acidic volcanic gases such as $SO_2$, $H_2S$, HCl and HF, which can also interact with moisture in the atmosphere to form vog (volcanic fog) and acid rain.

In general, acid deposition onto vegetation (natural and crops) can cause the following impacts (Environment Canada, 2007):

- it can alter the protective waxy surface of leaves, lowering disease resistance (plants can usually replace leached cations, even when treated to a low pH rain, but exceptional damage and leaching can occur when the cell membrane has been damaged);
- it may inhibit plant germination and reproduction;
- it accelerates soil weathering and removal of nutrients;
- it makes some toxic elements, such as aluminium, more soluble (high aluminium concentrations in soil can prevent the uptake and use of nutrients by plants).

See Appendix 2 for further information on acid deposition damage to vegetation, and a brief review of the impacts of historic eruptions on vegetation.

Acid damage to vegetation can occur as a result of tephra fall, but can also occur when there is little or no tephra deposition on plants, as the acidity may arise from volcanic gases, vog or precipitation. Thus, signs of damage to plants in the absence of tephra fall, or where only traces of tephra have fallen, are likely to be primarily due to effects of acidification, rather than additional effects such as physical smothering and inhibition of photosynthesis (discussed further in Section 5.2.4.2).

In areas which received light tephra falls (<2 mm), typical signs of acid damage were plants with dry, yellowish and curling leaves. This damage was unlikely to be due to moisture stress alone, as it was observed in lowland areas with a plentiful water supply.

In areas that received tephra falls of at least 3 mm, signs of damage were more severe and included plants with yellowed and blackened leaves. As the thickness of deposited tephra increased, more extreme cases of acid damage were observed, including plants with burnt, shrivelled leaves that had died and were being shed by the plant (Figure 20). Fruit would often be burnt in appearance (Figure 20). In Petung, which received 20 mm tephra fall, the damage to chilli peppers was so severe that the entire crop was lost in this district.

Acidification effects may be exacerbated by tephra fall occurring during the dry season. In the rainy season any deposited tephra is likely to be quickly washed off plants, but in the dry season, the small amount of condensation that gathers in the mornings on the plants may provide enough moisture to leach acidity from the tephra onto the plants, but not enough to wash the ash off.

**Table 3** Summary of observed impacts of ashfall on crops

| Crop | Vulnerability rank | Vulnerable parts of plant | Vulnerable stages of development | Ash thickness versus damage (selected examples) | Attempted mitigation methods and their success |
|---|---|---|---|---|---|
| Rice | Low | Seed-head (development of grains inhibited) | During final stages of seed-head development (mature rice) | 1. Traces of ash (<1 mm) appear to cause no damage and are regarded by many farmers as beneficial<br>2. Damage to seed-head with 5 mm ash (waypoint 38)<br>3. Waypoint 117 with 15 mm ash:<br>- mature rice = 50% loss (Rp1.5 million damage)<br>- juvenile rice = 25 % loss<br>- baby rice = no expected loss | Washing of juvenile rice in paddy with irrigation water. Natural cleaning by condensation in morning is highly effective. |
| Tobacco | High | Broad, hairy leaves trap ash and will die eventually if not cleaned<br>Flowers are very sensitive | Tobacco is vulnerable throughout its life cycle due to the tendency of its leaves to trap ash, and is particularly vulnerable during flowering. Smothering of mature plants occurs at 20 mm ashfall. | 1. Damage to leaves begins at 1-2 mm ash<br>2. The crop was written off with repeated 2-3 mm ashfalls over 4 weeks (waypoint 17)<br>3. At waypoint 49, the leaves on a mature plant were falling off with 20 mm ash | Shaking the crop is only partially successful but is commonly used.<br>Cleaning leaves by hand causes abrasion to leaves and has limited success.<br>Damaged broad leaves at base are often pulled off. |
| Tomatoes | High | Leaves, flowers and fruit are all very vulnerable. | Nearly all stages are vulnerable, but mature plants are particularly vulnerable. | 1. Damage to leaves begin at 1-2 mm ash<br>2. With repeated 5-10 mm ashfalls over a month, the crop was written off and the fruit rotted on the vine (waypoint 47) | Shaking is only partially successful.<br>Hand cleaning causes abrasion to leaves and has limited success. |
| Carrots | Low | None encountered as leaves tend to shed ash | None encountered | 1. Mature carrots were unaffected with 10mm ashfall (waypoint 48) | Inter-row planting between taller plants was effective, though probably not intentional. |
| Onions | Some | Tips of leaves are vulnerable; the length of the dead leaf tip was longer in ashfall-affected areas and leaves were drier. | Juvenile onions are vulnerable but are expected to recover well. | 1. Damage to leaf tips wtih 2-3 mm ash (waypoint 17).<br>2. Damage to leaf tips with 15-20 mm ash (waypoint 80). | Some isolated cases of shaking, which has limited success. |
| Cabbage | Moderate | Outer leaves discolour and rot.<br>In extreme cases, inner leaves would also rot. | Mature plants most vulnerable | 1. Young cabbages were unaffected by 10 mm ash (waypoint 48)<br>2. 90% loss of a cabbage plot with 20mm (waypoint 80) | Washed in small irrigation channels immediately after harvest to remove ash; this was highly successful. |
| Chilli peppers | High | Flowers are highly vulnerable, and all leaves are vulnerable to acid damage, particularly when young.<br>The fruit also is vulnerable. | Both mature (3-4 month old) and juvenile plants are vulnerable, but there is greater economic loss when plants are mature as fruit are lost.<br>The flowering stage is highly vulnerable. | 1. Some leaf and fruit damage with 0.5 mm ash (waypoint 6)<br>2. All flowers damaged and some leafs damaged with 2-3 mm (waypoint 17)<br>3. 60% of crop near maturity lost with 2.5 mm ash (waypoint 96)<br>3. 95% loss of crop at all stages of development at chilli pepper farm with 15-20 mm ashfall (waypoint 73), with severe damage to fruit and leaves.<br>4. 100% loss of crop with 20 mm ash (wp 80). | Shaking was attempted, but with limited success. |

**Table 3 continued**

| Crop | Vulnerability rank | Vulnerable parts of plant | Vulnerable stages of development | Ash thickness versus damage (selected examples) | Attempted mitigation methods and their success |
|---|---|---|---|---|---|
| Peanuts | Some | Leaves are efficient at shedding tephra | None encountered | - | Shaking |
| Oranges | Moderate | Skin (if not cleaned, skin would grow around ash which would form nodules ~1mm in size. Leaves showed some limited damage. | - | 1. Some leaf and fruit damage with 15-20mm ash (waypoint 73) | None encountered – uneconomic to clean each piece of fruit |
| Cauliflower | Moderate | Seed-head and leaves vulnerable to acid damage. | Mature plants most vulnerable with an open seed-head | 1. Seed-head and leaves damaged (plants written off) with 15-20mm (waypoint 73) | None encountered |
| Cucumbers | Insufficient Observations | - | - | - | None encountered |
| Corn/maize | High | Leaves are vulnerable. The cob is usually well protected from tephra infiltration. | Juvenile corn is most vulnerable.<br>Mature corn would die earlier than expected, but cobs would ripen (some seed-heads wouldn't fill) and could often be harvested. | 1. Corn crop written off 4 weeks from harvest with 5-7mm ash (waypoint 19)<br>2. 60% harvest of a mature crop with 20 mm ash (waypoint 80)<br>3. Mature crop (2.5 m high) abandoned despite cobs appearing unaffected, with 25 mm ash (waypoint 48) | None encountered |
| Potatoes/Taro | Some | Leaves are vulnerable but root crop is usually unaffected. | Young plants vulnerable. | 1. Leaves damaged by tephra fall, 100% loss expected with 4-5 mm ash (waypoint 17) | None encountered |
| Bananas | Insufficient Observations | Leaves are very effective collectors of ash; the fruit appeared to be unaffected. | - | - | None encountered |
| Lemons | Moderate | Leaves vulnerable.<br>Fruit could be expected to suffer from same problems as oranges. | - | 1. Acid damage to leaves with 2-3 mm ash (waypoint 17) | None encountered |
| Other trees | Low | Leaves on trees within or at margins of block and ash flows were scorched, but many showed signs of recovery after 10 days. Acid and abrasion damage to leaves and flowers. | Young and small trees most vulnerable to block and ash flows. | 1. Trees with trunks greater than 25 cm survived block and ash flow in Woro river<br>2. Acid damage to leaves with > 1 mm ash (widespread isolated cases)<br>3. Flowers damaged by acid and abrasion – 15-20mm: possible tephra surge (waypoint 80) | None encountered |
| Watermelons | Insufficient Observations | *Not grown in any tephra fall areas* | | | |

#### *5.2.4.2 Smothering of plants*

In addition to causing acid damage to plants, tephra falls can also physically smother plants and inhibit photosynthesis. This effect is unlikely to be important in areas of light tephra fall, but will become more pronounced as the thickness of deposited tephra increases. Our observations suggested that light tephra falls would often be restricted to the upper parts of plants, whereas heavier tephra falls would also affect the lower leaves and thus cover the entire plant. A tobacco crop smothered by approximately 35 mm tephra fall is shown in Figure 22. Plants that had been covered by tephra for several weeks showed signs of both acid damage and photosynthetic inhibition (Figure 21). Longer exposure periods are thought to result in stunting of plant growth.

Some plants were able to adapt to tephra smothering by sprouting new leaves. For example, clean new sprouts were observed on lemon trees that had been covered (approximately 60-80% of plant) by ash for over four weeks.

With heavier ashfalls (>30 mm), in addition to the effects on photosynthesis noted above, leaves become weighed down and eventually stems will break. Smothering was a particular problem for plants with large, broad and hairy leaves that trap ash readily, such as tobacco (Figure 22). Damage observed included stunted growth and withering of the leaves. Crops growing near roads would often suffer the greatest impacts because of ash remobilised by vehicles.

An additional problem with ashfall contamination of tobacco was that harvested leaves were rejected by processing plants because of the strong associated sulphurous smell, and concerns about the presence of cristobalite in the ash, which has the potential to cause silicosis.

#### *5.2.4.3 Ashfall damage to fruit and vegetable skins*

In areas that had received tephra falls for a number of weeks, such as Petung, Magelang and Selo, fruit and vegetable skins that had not been cleaned were beginning show signs of damage. Unwashed skin appeared to have incorporated the tephra by growing around it and creating small (approximately 1 mm diameter) nodules within the skin (Figure 23). These nodules could not be washed off and were difficult to pick out. Although the fruit within was undamaged and edible, traders rejected this fruit because it was ‘ashy’.

**Figure 20** Left photo: presumed acid aerosol damage to chilli-pepper plants in Petung. Right photo: presumed acid damage to tomato plants in Magelang

**Figure 21** Wilted tobacco leaf in Selo. This plant had been cleaned after being covered by tephra for 3 weeks

**Figure 22** Tobacco crop smothered by ~35mm of tephra fall in Magelang

**Figure 23** Tephra inclusion on the skin of an orange from Petung

### 5.2.5 Attempts to mitigate ashfall impacts on crops

The team observed several different approaches being used to attempt to mitigate the impacts of ashfall on crops. The most effective method was washing crops in water immediately after harvest. This worked very well for cabbages when washed in irrigation channels immediately after harvest. However, in general, it is very difficult to clean ash from leaves, and it becomes more difficult as more time elapses from deposition of the ash. Rinsing with water is the best way to remove ash, but frequently is not possible because of water shortages. Shaking crops to remove ash was a common practice, but is time-consuming and does not completely remove ash. One farmer interviewed by the team estimated that it took him two hours to shake a corn crop of 10 m by 20 m in area. Our observation of this crop, six hours later, indicated that most leaves still had a residual coating of ash. Wiping the ash from the surface of leaves does not remove all ash, and also causes abrasional damage.

Some farmers attempted to remove ash from vulnerable crops such as chilli peppers, but in general, mitigation methods appear to be uneconomic for most crops.

## 5.3 Observed impacts of volcanic activity on livestock

Most animals were housed within feedlots, which despite being quite rudimentary structures appeared to offer good protection from ashfall (Figure 24). Perhaps as a result, incidences of health problems commonly associated with volcanic eruptions (such as respiratory tract and eye irritation) were generally low.

The main observed impact on livestock was weight loss from eating ash-covered fodder. Animals are fed primarily from manually-cut fodder obtained from the abundant growth on and around farmlands. Thus, grazing animals usually do not feed directly on ash-covered pasture. However, following ashfalls, farmers found it difficult to get access to clean water or clean fodder. During the cutting and transport of the fodder, much of the ash was shaken off. However, fine ash was retained on the fodder, and was subsequently ingested by livestock (Figure 24).

**Figure 24** Livestock feeding on ash-covered fodder in Petung

The weight loss of cows on the southern flank of Merapi, particularly at Kaliadem and Petung, resulted in many animals dropping in value from a pre-eruption value of Rp 7-8 million (NZ$ 1,200-1,400) to Rp 2-6 million (NZ$350-1,100) per animal as many farmers were forced to sell off stock before they died. There was no information available about whether the cows recovered following relocation and an ash-free diet.

Farmers in the village of Kaliadem, many of whom earn their living raising cattle, were unable to gather fodder following the ash falls associated with 14 June block and ash flows. This area had also lost water supplies following the 14 June flows, and the Umbul Lanang spring dried up creating significant water shortages in the area. This created major problems in obtaining water for farm animals, as relief water supplies were only for human consumption. As a result this was one of the worst-affected regions the team visited, and has been used here as a case study.

The *Jakarta Post* reported that on 20 June, there were 450 dairy cows in the Kaliadem area, each producing an average of 15 litres of milk per day, to be sold at Rp 1,500 per litre. No dairy cows were observed during our visit to the village as they were located several hundred metres further up the flank and safety reasons prohibited movement into this area. However, a number of villagers reported that milk production had significantly dropped, probably because of complications related to both the water shortages and the contamination of fodder with ash. Many of the farmers decided to sell the cows for what they could, rather than risk the cattle dying. The cows were sold for between Rp 5.5 million and Rp 6 million (NZ$ 1000-1100). They normally sell for between Rp 7 and 8 million (Jakarta Post, 20/06/06). Due to the limited extent of the damage however, traders specifically travelled to Kaliadem to buy cattle at marked down prices. Most farmers were simply glad to be able to sell their cattle and there were no feelings of exploitation.

There were some reports of animals being put off their food due to tephra contamination, as was reported after the 1995/96 Ruapehu eruptions (Neild et al., 1998). This may account for the weight loss, but it is also possible the tephra in the gut caused metabolic problems. There is also the possibility of chemical poisoning of the animals by aerosols attached to the tephra, but without autopsies of affected animals, the exact nature of the weight loss remains speculative.

## 5.4 Potential impacts of volcanic activity on soil fertility

Tephra deposition usually results in long-term benefits to soil fertility (Blong, 1984; Lansing et al., 2001), such as increased sulphur, selenium, and halogen availability (Cronin et al., 1998; 2003). However it was unclear what impact the deposition of ash from the 2006 eruption would have on soils on farmland situated on and surrounding the volcanic edifice. Many of the farmers spoken to by the team acknowledged the likely long term benefits. However, the nature of these benefits and the time scales of the processes involved were not well established and were under discussion among local soil scientists. Among those we spoke to, there was a common belief, based on previous experience at Merapi, that improved soil fertility would take approximately three to four years to manifest itself (Figure 25; D. Indradewa, pers. comm.). However, soil fertility may be negatively affected in the short term, because the mineral components of the ash may not be available for plant uptake (Cronin et al., 2003). Experts we consulted suggested that manure fertilisation may be required to maintain soil fertility. It is not known whether ash leachate analysis was conducted following the eruption to predict what impact the deposited ash would have on soils.

Tephra and soil samples were brought back to New Zealand for laboratory testing to determine their chemical composition. Results, and a discussion of implications for soil fertility, will be presented in a subsequent report.

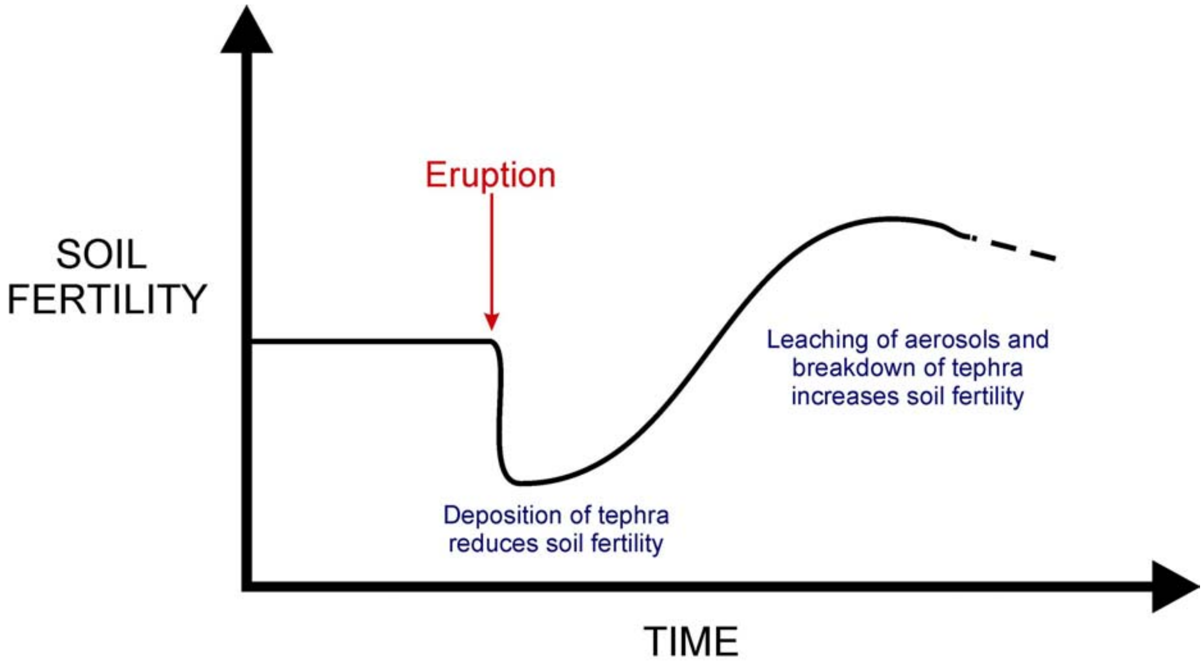


**Figure 25** Sketch of estimated soil fertility response by Indonesian soil scientists (D. Indradewa, pers. comm.)

## 5.5 Production losses

At 13 of the farms visited, farmers were asked to describe the damage to their crops, and estimate their production losses (Table 4). These farms were located in agricultural areas, such as Kaliurang, Klaten, and Magelang which had experienced between ~2 and 25mm of tephra fall. There was no systematic selection of farms; rather farmers working in their fields were approached in areas that had suffered tephra damage to production crops. Losses appear to be due primarily to the reduced quality of crops fetching lower prices, and there were no reports of commodity prices for crops increasing due to shortages (D. Indradewa, pers. comm.).

In many cases, the farmers were expecting severe losses to their crops (i.e. 80-100% loss). This represents significant economic disruption and potential hardship for the farmers and their dependents. The small farms (numbers 4,7 and 9) appear to be particularly vulnerable, which may compound the difficulties they already experience in producing sufficient crops to survive from small plots of land. These losses may be partially mitigated by the opportunity for further crops later in the year, compared to the usual single crop per year in New Zealand.

**Table 4** Estimated production losses for individual farms[1]

| Farm number | Farm size (ha) | GPS waypoint | Tephra thickness (mm) | Farmer estimates of damage | | |
|---|---|---|---|---|---|---|
| | | | | Crops(s) | % loss | Monetary loss (Rp) |
| 1 | 1.5 | 17 | 2-3 | Tobacco | 80 | 2,500,000 (combined total) |
| | | | | Chilli-peppers | 90 | |
| | | | | Onions | 20 | |
| | | | | Cabbages | 30 | |
| 2 | 1.0 | 20 | 5 | Rice (mature) | 50 | 1,500,000 |
| 3 | 1.0 | 47 | 20 | Rice and Onions | 60 | 550,000 |
| 4 | 0.5 | 47 | 20 | Tobacco | 100 | 700,000 (combined total) |
| | | | | Tomatoes | 100 | |
| | | | | Rice | 80 | |
| 5 | 0.5 | 49 | 25 | Tobacco | 70 | 3,000,000 |
| 6 | 2.0 | 49 | 25 | Tobacco | 75 | 2,000,000 |
| | | | | Peanuts | 30 | 400,000 |
| 7 | 0.8 | 73 | 15-20 | Chilli-peppers | 95 | 1,500,000 |
| 8 | 3.0 | 80 | 20-25 | Corn | 90 | 2,300,000 (combined total) |
| | | | | Chilli-peppers | 90 | |
| | | | | Potatoes | 20 | |
| 9 | 0.4 | 80 | 20-25 | Tobacco | 90 | 1,500,000 |
| | | | | Chilli-peppers | 100 | |
| 10 | 0.5 | 80 | 20-25 | Corn | 40 | *unknown* |
| 11 | 3.0 | 80 | 20-25 | Cabbage | 80 | *unknown* |
| | | | | Oranges – skin damage | 90 | |
| 12 | 2.05 | 96 | 2-3 | Chilli-peppers | 50 | 3,000,000 |
| | | | | Tomatoes | 50 | 3,000,000 |
| 13 | | 117 | 15 | Rice (mature – 3 months) | 50 | 1,500,000 |
| | | | | Rice (juvenile – 2 months) | 25 | 500,000 |
| | | | | Rice (young – 2 weeks) | 0 | 0 |

[1] The approximate annual farm income for the region was in the range of Rp 5-50 million (D. Indradewa pers comm., 2006)

## 5.6 Resilience of agricultural systems

Many farms, particularly those high on the southern and western flanks of Merapi, are expected to lose up to 100% of damaged crops during the current rotation. However, because of the warm climate, fertile soils and good access to water (on the lowlands and during the wet season), the farms are anticipated to recover rapidly following cessation of tephra falls, with many farmers predicting 2-3 harvests within the next 12 months. Thus, the year-round growing season contributes substantially to resilience within this agricultural system, particularly for lowland farms. Lowland farmers are therefore able to choose preferred crops, such as rice, that will maximise returns.

Upland farms are somewhat more vulnerable during the dry season, but farmers are still able to replant immediately if required. Our observations suggested that upland farmers add greater diversity to their selection of cash crops, to build more resilience into their farming systems, due to the unreliable water supply in upland regions. But the increased resilience also helps reduce the impact of volcanic activity. The attitude that 'if one crop fails then others will survive' was frequently encountered by the team, with respect to crop selection practices. Our observations supported the effectiveness of this approach, with some farms affected by heavy ashfalls showing severe damage to some crops and virtually no damage to others. For instance, chilli pepper plants would be severely affected while other crops planted between them, such as carrots, would be almost unaffected.

The naturally-high resilience of agricultural systems in the Merapi area is to some extent offset by the inability of most farmers to absorb financial losses. Farming in the area is only slightly above a subsistence level and many farmers spoken to by the team considered themselves unable to absorb the loss of even one crop rotation. This level of hardship was probably a motivating cause of farmers returning to the exclusion zone after being evacuated (discussed further in Chapter 7). Many farmers reported that they had few other options, and felt that they must 'ride out' the eruption (particularly those in the upland regions) and wait for the rains to wash crops and help integrate the tephra into the soil. Some farmers stated that if they were required to relocate, they would need government assistance to do so. However there was a low level of belief in the likelihood of government assistance following heavy expenditure in response to the magnitude 5.9 earthquake that occurred on 27 May 2006 in Yogyakarta province, causing over 4900 deaths.

In New Zealand, the innate resilience of agricultural systems to volcanic ashfall is likely to be lower due to the temperate climate and confined growing season in most places. Typically only one or two crop rotations are possible during the growing season, and crops may be particularly vulnerable during spring with high photosynthesis and rainfall requirements potentially being disrupted by smothering ash fall and ash leachate impacting soil and water chemistry.

## 5.7 Summary

The agricultural sector was very vulnerable to the impacts of the 2006 Merapi eruption, although this vulnerability was not uniform across the sector and indeed in some instances a high degree of resilience was observed on many farms (especially those growing rice). Access to a reliable water supply appeared to be a key factor in overall farm resilience, although a diverse selection of crops grown on each farm also increased resilience.

## 6. INFRASTRUCTURE IMPACTS

### 6.1 Overview of infrastructure in the Merapi region

Java, with a population of 124 million, is the world's most densely-populated island, and the Merapi region is no exception. The southern flanks of Merapi volcano have an approximate density of 1400 people/km$^2$ (Thouret *et al.,* 2000).

The general quality of life in Java is relatively high for a developing country, largely due to the influence of income from tourism. The GDP (per capita) was reported to be US $3,800 (CIA Factbook, 2006). Homes are permanent and solidly-constructed although masonry is generally unreinforced and therefore highly vulnerable to damage in earthquakes (J. Cousins, pers. comm.). Houses are typically constructed from cemented lava blocks with roof construction from bamboo and clay tiles (Figure 26). Almost without exception, homes have electricity, running water, and underground sewage disposal systems (either via sewer lines or pit toilets).

**Figure 26** Interior of typical house in Merapi region showing lava block masonry and bamboo and clay tile roof

Rural roads are mostly paved asphalt and are typically one to one-and-a-half lanes, or three metres, wide (Figure 18). Most people appear to own or have access to a vehicle, ranging from late model imported cars and 4WD vehicles, to small motorcycles such as mopeds or scooters. The city of Yogyakarta (population approximately 0.5 million) does not have a multilane highway system, but has a network of paved roads which are frequently heavily congested.

Water is drawn either from wells or established drainage systems, large and small, on the flanks of the volcano. In some locations higher up on Merapi, wells draw water from underground aquifers into enclosed pumphouses, from which the water is distributed downhill through a system of pipes and irrigation canals to houses and farms.

Indonesians make extensive use of cellular telephones, with over 10% of the national population, or approximately 25 million people, owning at least one (AOEMA, 2003). Cellular towers (Figure 27) dot the landscape, both high and low on the volcano.

**Figure 27** Cellular repeater antenna near Kaliadem

Two major international airports service the Yogyakarta region of central Java: Yogyakarta airport, and Surakarta (Solo) airport. Several tens of flights per day pass through each of these.

## 6.2 Impacts on infrastructure

### 6.2.1 Roofs

Impacts of tephra on roofs were minimal to non-existent despite tephra depths of several centimetres being recorded in some places. The team did not observe any tephra damage to roofs, or any mitigative or cleanup actions being practised, although some people described doing hand-powered ash removal (e.g. sweeping) from their roofs.

In the village of Petung, at approximately 1100 m elevation on Merapi's south flank, a damaged clay tile roof was observed (Figure 28). However, it was unclear whether the damage to the roof was the result of the 2-3 cm accumulation of tephra on it, or whether it had been damaged by the magnitude 5.8 earthquake of 27 May 2006. The hole in the roof is unlikely to have been caused by a block falling, as the bamboo supports underneath appear to be intact.

According to Johnston (1997) and Spence et al. (2005), dry tephra loading in the range experienced during the 2006 eruption of Merapi is not expected to cause damage to roofs because it causes loadings of <1 kPa. This is consistent with our observations. However, if the tephra had been wet rather than dry, increased damage to roofs would have been expected. The only confirmed damage to roofs attributable to the eruption was in Bebeng, where airborne blocks from the 3 p.m. 14 June block and ash flow demolished roofs (Figure 14).

**Figure 28** Damaged roof in Petung

### 6.2.2 Building structures

The only major damage to buildings sustained during the 2006 eruption of Merapi was caused by the large block and ash flow that occurred at 3 p.m. on 14 June. Buildings in the path of the flow were completely destroyed. Houses were buried up to roof level, roofs and windows were smashed and debris entered the interiors (Figures 15 and 16).

### 6.2.3 Transportation

Despite widespread deposition of tephra on roads, no disruptions to transportation were reported other than the road that was destroyed by the 14 June block and ash flow below Kaliadem (Figures 18 and 29). Several metres depth of debris were deposited on this road, and heavy equipment will be required to re-open it.

None of the vehicle-owning villagers we spoke with reported problems caused by tephra to their vehicles, such as to air intakes. The field driver for our team reported that there was no need for additional maintenance to the vehicle despite five days in the field in conditions of tephra resuspension on roads. Tephra was washed from the vehicle and engine with household water at the end of every field day, which is reportedly common practice among vehicle owners in Indonesia.

### 6.2.4 Water and wastewater

The damage to water installations and spring wells in Bebeng village caused by the 14 June block and ash flows resulted in thousands of people losing their water supply. Newspapers reported that 12,000 people were without water (e.g. Malaysia Sun, 14 June 2006). This greatly increased the demand on emergency water tankers, with the Sleman district local government distributing 14,000 litres of clean water daily. The International Federation of Red Cross and Red Crescent Societies (IFRC) also provided water relief to villages (Figure 30). From 19 to 25 June alone, the Red Cross distributed a total of 1,017,000 litres of water (IFRC staff, pers. comm.). Apart from these incidences, no other major damage or disruption to water and wastewater services was reported. Some villagers spoken to by the team reported that they obtained water from relief organisations, or had to switch their supply from surface water to well water, because of tephra contamination.

**Figure 29** View into Kaliadem on 5 July 2006, showing the mantle of debris from the 14 June block and ash flow


**Figure 30** Water distribution facility at Red Cross evacuation camp at Merapi Golf, 5 July 2006

**Figure 31** Snapped electricity pole in Kaliadem

### 6.2.5 Electricity

The only report of disrupted electricity service during the 2006 eruption came from the village of Kaliadem, where power poles and lines were snapped by the block and ash flows of 14 June (Figure 31). The destroyed buildings suffered permanent electricity loss, but the areas adjacent to the flows, which lost power initially, regained it within several hours.

### 6.2.6 Telecommunications

As with electricity, Kaliadem was the only site of loss of telecommunications during the 2006 eruption. Immediately after the larger block and ash flow on 14 June, cellular telephone service in the village suffered in quality. Whether this resulted from over-usage, physical destruction of communications infrastructure, or the presence of ash in the air obscuring signals is not clear.

### 6.2.7 Air travel

The two major airports in the region were relatively unaffected by the 2006 eruption. However, some flights to and from Surakarta (Solo), Semarang, and Yogyakarta were diverted occasionally due to ash from Merapi (WHO, 2006). Other than these diversions, there were no reports of ground damage to aircraft or aeronautical facilities and operations.

# 7. SOCIAL IMPACTS AND EVACUATION

## 7.1 Population growth on the flanks of Merapi

As noted in Section 6.1, the population density in the vicinity of Merapi volcano is extremely high, with an estimated 1.1 million people living on its slopes in 2000 (Thouret et al., 2000), in approximately 300 villages above 200 metres in elevation. Of these, some 440,000 people live in high-risk areas subject to pyroclastic flows, surges and lahars (Thouret et al., 2000). Population density on the Merapi edifice is >1400 people/km$^2$ on the western and southern flanks of the volcano and the growth rate of the population was calculated as up to 3% annually in the mid-1990s (Thouret et al., 2000). This rate of growth is not limited to the Merapi region but is a general feature of Java, where it is reported that the population increased tenfold during the 20$^{th}$ century (Voight et al., 2000). This rapidly increasing population has put significant stress on the natural resources of Java, leading to marginal and hazardous regions such as the flanks of Merapi, being inhabited.

Increasing population growth on the slopes of Merapi has led to a substantial increase in risk to human life over the past century (S. Bronto, pers. comm.., Thouret et al., 2000; Voight et al., 2000). The impacts of eruptions throughout the twentieth century have become increasingly devastating, despite their generally low explosivity. Lack of land-use planning is also likely to be a factor contributing to the increased vulnerability of the population.

A 1978 hazard zone map of Merapi (Pardyanto et al., 1978) defines three areas termed 'forbidden zone', 'first danger zone' and 'second danger zone', based on declining levels of hazard. These classifications are now regarded as outdated (Thouret et al., 2000), but the zones are still used in publications and by emergency management personnel and on signage. Thouret et al. (2000) estimate that the number of people living or working in the forbidden zone increased approximately twofold from 40,000 to 80,000 people between 1976 and 1995, and is probably significantly greater now.

In summary, all available information, including our observations, point to a steadily increasing volcanic risk around Merapi, driven by population growth and lack of land-use planning.

## 7.2 Overview of the 2006 evacuation

A key part of the social disruption caused by the 2006 eruption of Merapi was the evacuation of at-risk communities, mainly on the western and southern flanks of the volcano. Based on local and foreign media reports, non-governmental organisation (NGO) reports (e.g. UN and Red Cross), and discussions with Indonesian colleagues, the evacuation can be divided into five phases: 1) the initial evacuation; 2) the first return in mid-May; 3) the 27 May earthquake; 4) alert-level raising and lowering surrounding the 14$^{th}$ June block and ash flow; and 5) the final return.

The evacuation of vulnerable communities from the flanks of Merapi was for the most part an efficient and effective mitigation measure. However, aspects of the evacuation provide valuable lessons for future eruptions of Merapi and elsewhere.

### 7.2.1 Phase 1: the initial evacuation

In early April 2006, the Indonesian government began logistical preparations for a volcanic crisis as volcano-seismic activity at Merapi began to increase. The evacuation of the most at-risk communities began on 3 May, in advance of the alert level system reaching its highest level on 13 May. On 3 May, several hundred pregnant women and elderly people were evacuated at 10 a.m., and in the second phase, children were evacuated at 4 p.m.

By 13 May, medical teams had been placed in strategic locations, and evacuation routes had been established (WHO Emergency Situation Report, 13/05/06). The Merapi Volcano Observatory (known locally as BPPTK) encouraged evacuation of communities on the western sector of the volcano within 8 km of the summit; on the southwest-west sector within 10 km, and on the south-southeast sector within 8 km of the summit (S. Bronto, pers comm.).

Large-scale evacuation took place following the announcement, and the Indonesian Red Cross reported that by 13 May, 6942 people had been evacuated. By 19 May, the Indonesian Red Cross (www.redcross.org.sg) reported that a total of 20,080 people were housed in emergency shelters as follows: 907 in Boyolali District, 8866 in Magelang, 6163 in Sleman, and 4144 in Klaten.

Evacuations were followed up with searches by volunteers, soldiers, and police to locate those forgotten or refusing to evacuate. These efforts were scaled down once people began to return to the exclusion zone.

There was a high degree of self-evacuation. In Sleman district, 4,000 of the 9,500 residents self-evacuated before emergency workers arrived (WHO Emergency Situation Report, 13/05/06). Emergency workers noted that many men chose to stay behind to watch over their farms and homes, whilst other evacuees remained with extended families at locations outside the evacuation zone (often causing overcrowding in the small houses) or in evacuation camps. We observed three evacuation camps during the day that contained only women and children, all the men reported to have been in the exclusion zone tending to their farms. Authorities seemed to allow farmers to return to their farms during the day, although it was unclear whether this was a formal policy. Evacuees often travelled between camps and villages without prior notice, which made determining actual needs and planning response efforts more difficult (WHO Emergency Situation Report, 13/05/06).

### 7.2.2 Phase 2: first return in mid-May

Within days of the first evacuations, volcanic activity at Merapi continued intermittently but the expected large eruption did not occur. This uncertainty created difficulties for the authorities as the lack of an explosive eruption or a dome collapse led evacuees to believe that the evacuation may have been unnecessary or an over-reaction to the situation. However, according to the authorities, there was still significant potential for a larger eruption to occur as $SO_2$ emissions continued to increase, and dome growth continued at several hundred thousand $m^3$ per day. As a result this return of people occurred with no lowering of the alert level and despite daily warnings from the BPPTK of the continuing danger (Dr. Sutikno Bronto pers. comm.).

A major concern for evacuees was the looting of temporarily-abandoned homes and farms. Financial pressures, such as un-tendered crops and livestock, were also a factor in motivating evacuees to return to their farms. On 18 May, up to 1800 people are believed to have returned to their home villages from evacuation camps (WHO Emergency Situation Report, 22/05/06). This trend continued as eruptive activity decreased further on 20 May, with many more farmers returning to their farms to tend damaged crops and feed livestock. It was unclear from emergency management reports and from local interviews whether people decided to return on an individual basis or whether there was some peer pressure influence. A characteristic feature of this phase of the evacuation was that evacuees would travel to their farms during the day and return to the evacuation camps at night (as discussed above).

### 7.2.3 Phase 3: 27 May earthquake and increased eruptive activity

On the 27$^{th}$ of May a M 5.9 earthquake, with an epicentre ~30 km to the south-southwest of Merapi, struck the region killing over 5,800 people, injuring over 20,000, and destroying 150,000 homes in the Yogyakarta and Central Java provinces. This earthquake resulted in a large international response, coordinated by the United Nations. Many of the emergency supplies pre-positioned for a large eruption from Merapi were diverted to the earthquake response. The earthquake resulted in the closure of Yogyakarta airport, which hampered relief operations, downed telephone lines, caused power blackouts, disrupted transportation networks, and resulted in significant confusion and panic. Logistical problems impeded the flow of aid, which caused some concern, particularly for emergency workers and volcanologists who were greatly concerned the earthquake may cause an increase in eruptive activity from Merapi volcano.

The earthquake rapidly escalated the scale of emergency in Yogyakarta province from a largely internal Indonesian affair to a large scale multi-national disaster response. The volcanic eruption crisis and evacuation was eclipsed and overwhelmed by the earthquake response.

Eruptive activity steadily increased during the weeks following the earthquake, leading to BPPTK releasing new evacuation recommendations for communities in hazardous areas. However, no large explosive eruption occurred as was feared by some emergency personnel. Following the earthquake, good hazard awareness was shown by villagers on the flanks of Merapi as waves of villagers returned to evacuation camps in Klaten and Sleman (WHO, 2006). Both villagers and scientists feared that the earthquake could have destabilised the lava dome, thus increasing the risk of triggering a significant eruption. Many villagers interviewed expressed feelings of being ‘geologically spooked’ and indicated that their personal hazard perceptions had been significantly raised. This may explain the widespread self-evacuations that followed the earthquake.

The earthquake did not cause catastrophic damage to villages on the Merapi edifice, but there was moderate damage to many villages. Evacuation camps already struggling with the evacuation from Merapi faced shortages of supplies as relief efforts shifted orientation toward the badly damaged area south of Yogyakarta. There were some reports of worsening sanitation problems and a general shortage of relief supplies in the ten-day period following the earthquake (OCHA Report 8, 3/06/06). Commodities reported to be in short supply were:

masks for respiratory protection, infant supplies, sanitary supplies and water (OCHA Report 15, 22/06/06). A key requirement of many farmers was plastic sheeting to cover water tanks. According to local media reports, affected communities in Klaten complained about uneven aid distribution.

### 7.2.4 Phase 4: confusion caused by lowering of alert level

During early to mid-June, villagers had again begun to return home. On 13 June, after several days of low eruptive activity, BPPTK lowered the alert level from Level 4 (caution) to Level 3 (alert). The BPPTK reported through media releases to local media that its scientists believed the cracking of the lava dome on 8 June provided some release of pressure, resulting in reduced eruptive activity; although there is some contention about this analysis.

This lowering of the alert level occurred despite the collapse of the Geger Boyo (a section of an old lava dome) on the 4$^{th}$ and 5$^{th}$ of June. The Geger Boyo structure had previously restricted larger pyroclastic flows to the west and southwest sectors of the mountain, shielding the southeast flank of the volcano (Section 4.4). By exposing the southern flank, a region with no recent history of such hazards suddenly had to come to terms with a greatly increased risk to possible pyroclastic flows from dome collapse events. It appears this was not considered enough by the BPPTK to delay lowering the alert level.

Following the lowered alert level, evacuees were trucked home to their villages, with several thousand returning on 13 June and more returning on 14 June. Despite the lowering of the alert level, villagers were advised to be on alert, and evacuation trucks remained on standby.

On 14 June, there was a sudden increase in eruptive activity when a small block and ash flow came down the upper Opak/Gendol river valley around midday following a dome collapse. The BPPTK ordered an immediate evacuation of Kaliadem village by asking local people to activate the warning siren around 12 p.m., and approximately 15,000 people were evacuated (OCHA Report 17, 7 July). A much larger block and ash flow came down the valley at around 3 p.m., and buried part of Kaliadem village (Section 4.5). Fortunately most people had evacuated, but two volunteers perished within a bunker designed to protect villagers against such flows, suggesting that the future construction of such bunkers should be reviewed.

Appeals were immediately made for masks, sunglasses, medicine for respiratory illnesses, eye drops, and oxygen in the Sleman District. There were some isolated cases of requests for clean water, medicine and food following the14 June flows (in Umbulharjo, Kepuharjo and Glagarharjo hamlets; OCHA Report 14, 15/06/06).

After the 14 June flows, the evacuation areas were redefined to include areas within a radius of 8 km from the crater, and within 300 metres on either side of the Krasak, Bebeng, Bedog, Boyong and Gendol rivers (S. Bronto, pers. comm.). The Indonesian government agency controlling the evacuation (SATLAK PB) reported that 531 people were evacuated in Magelang, 4,559 people in Sleman and nearly 4,000 people in Klaten. No-one was evacuated in Boyolali District but four sub-districts (Selo, Musuk, Cepogo and Ampel, with a total population of 57,000) were affected by the ash fall and sulphuric fumes (OCHA Report 15, 22/06/06).

The premature lowering of the alert level on 13 June caused significant confusion and mistrust to develop between people living in at-risk locations, and the BPPTK. This lowering of the alert level and provision of trucks to transport farmers home implied authorities believed it was safe for people to return home, although they were told to remain on alert. Several farmers interview from the Kaliadem region said they did not trust the government anymore following the 14 June collapse event. Scientists from the BPPTK were aware of this mistrust and the negative effect it may have on future warnings and advice.

### 7.2.5 Phase 5: final return

Throughout our field visit to the Merapi region (22 June – 5 July 2006), most evacuation camps appeared to be progressively emptying. On 22 June, the evacuation centre in Magelang was empty, though roughly 3,760 people remained at sites in Sleman and another 2,455 people at sites in Klaten (OCHA Report 15, 22/06/06). There were still a large number of people travelling back and forth from the camps to their farms on a daily basis. By 10 July, the alert level was lowered to Level 1, apart from a 6 km exclusion zone on the southern slope. By late July the International Red Cross reported most evacuees had returned home.

## 7.3 Evacuation camps

### 7.3.1 Overview of the camps

At the evacuation camps (Figure 31), evacuees were provided with three meals a day, access to clean water, emergency health services, and shelter (usually in the form of a tent). Our inspection of three camps in the Klaten district showed them to be well-managed, clean and tidy. There was no sign of reported hygiene problems, as reported by the Red Cross (Red Cross website). Camps were well-advertised with large signs above them and on roads leading to them. However, evacuees spoken to by our team reported high levels of boredom, but also stressed and anxious about the uncertainty for their livelihoods the eruption had created. Many were fearful of the impact the eruption was having on their crops and livestock. With many homes evacuated, there was also a fear of looting occurring in the evacuation zone.

**Figure 32** Talking to evacuees at the Kaliadem evacuation shelter

### 7.3.2 Movement between evacuation camps and farms

A key aspect of the evacuation was the movement of many evacuees back to farms in the exclusion zone during the day to tend farms and check homes. They would then return at night to evacuation camps. An evacuation camp in Klaten close to Merapi Golf Course held approximately 50 to 60 people during the day, but occupants said it swelled dramatically at night. One farmer in Petung told of his fears of Merapi erupting again, especially at night; however he was extremely concerned about looters so would return daily to look after his farm and repair his home, damaged by the 14 June flows. Typically it was males and young women who would return to the zone. During our three visits to evacuation camps no males above the age of 15 were observed, and the camp population mostly comprised elderly women, young mothers and children.

## 7.4 Exclusion control

The Indonesian government initially allocated approximately Rp 20 billion ($US 2.3 million) to fund the evacuation in May, which subsequently increased following the 27 May earthquake (WHO Emergency Situation Report 9, 15/6/06). Roadblocks were set up below the evacuated towns and villages to create an exclusion zone. Evacuation routes were well-marked (Figure 33). Road closures were marked with a standard circular symbol with a red band through centre (Figure 34). This signage was consistently used in all areas visited by the field team. Bamboo barriers (Figure 34) were also used in places, particularly during the initial phase of our field visit.

Initially this zone was closed to all but emergency authorities and journalists. However, over the course of our visit, we observed changes in the control of traffic into the exclusion zone. In the last week of June, we observed highly organised road closure checkpoints, staffed by up to six people equipped with fluorescent vests, masks and radios (Figure 34). This was true of most roads leading into the exclusion zone around all sectors of the volcano. By the first week of July there appeared to be much less control over entry into the exclusion zone, and we were able to drive in past unattended checkpoints (for instance, past the Kaliadem checkpoint shown in Figure 34, which was unattended by the first week of July). While we do not want to speculate on official policy, this apparent reluctance to enforce the exclusion zone may have been a strategy to limit the economic losses to farmers.

## 7.5 The social landscape and factors influencing risk perceptions and evacuation behaviour

### 7.5.1 Economic pressures

The tendency for people to stay in evacuation camps overnight and return to their farms was mentioned previously in Section 7.3.2. The main reasons for this are believed to be both economic and cultural. Economic factors were previously mentioned in the discussion of impacts on the eruption on local farms (Section 5). Subsistence farmers were very reluctant to leave their farms which are in general their only source of financial security, and our team spoke to several farmers who considered themselves unable to absorb any financial losses. There also appeared to be a collective belief that the government would be unlikely to provide any compensation for crop losses, particularly as the 27 May earthquake also imposed high demands on relief funds.

### 7.5.2 The role of traditional beliefs

Indonesia is the world's most populous Muslim-majority nation, with 86% of Indonesians declaring themselves Muslim in the 2000 Census. In Java, as in other parts of Indonesia, Islam has reportedly blended with other belief systems. In particular, the influence of Hinduism and classical India beliefs are defining traits in Indonesian culture, and the Indian concept of the god-king shapes Indonesian concepts of leadership. While Indonesian Muslims are typically devout, local customs and beliefs are generally favoured over Islamic law, so that, for instance, there are greater levels of freedom and social status for women compared to countries adhering to Sharia law more closely. Javanese Muslims reportedly occupy a broad continuum between *abangan* (a form of Islam influenced by pre-Islamic animistic and Hindu concepts) and *santri* (a more orthodox form of Islam).

Pre-Islamic Javanese traditions have encouraged Islam in a mystical direction, and supernatural beliefs abound for many phenomena, including volcanism. While language barriers may have prevented us from fully understanding the range of traditional beliefs about Merapi, our conversations with local people suggested the following picture.

Communities living in the Merapi region believe there is a spiritual link between the volcano and the Indian Ocean to the south. The increased activity of the volcano following the 27 May earthquake, centred around 25 km SSW of Yogyakarta, served to strengthen perceptions of this belief for many people. Another important belief is that there is a spiritual kingdom at the mountain's summit and that an eruption is a 'party' of the mountain king, or an expression of his displeasure at receiving insufficient offerings, or perhaps more generally at the disrespect shown by people living on the slopes of the mountain. Another version of this belief was that the eruption was a punishment or warning that people had become too worldly and materialistic (Taipei Times, 30/05/06).


**Figure 33** Evacuation route sign just below Kaliadem

**Figure 34** Staff manning the roadblock below Kaliadem, 22 June 2006

These beliefs were carried through into actions. We heard of ceremonies being held, usually organised by community elders or leaders, to ask the mountain king for mercy and to make offerings such as burying coins.

A further element of the belief system concerned the existence of omens. On the western and southern sides of the mountain in particular, we encountered the belief that the mountain would only erupt after certain omens or portents, some of which may appear in dreams. A commonly-mentioned omen was the sight of animals, particularly white animals, moving downhill.

The belief in omens in particular is an obvious source of conflict between traditional beliefs, and messages from emergency management authorities. While in general evacuations during the 2006 eruptions of Merapi were regarded as effective and efficient, there were instances where conflicts arose when local residents were reluctant to evacuate because they had not observed any omens and did not believe official warnings.

An important character in the social landscape of Merapi is Mbah Marijan, the ceremonial guardian of the volcano appointed by the Sultan Hamengkubuwono X of Yogyakarta. The guardian's role is to be Merapi's safe keeper, and Marijan oversees ceremonies and offerings to the volcano intended to placate the mountain king. During the 2006 eruptions of Merapi, Marijan did not see any signs of an impending eruption and encouraged villagers to remain in their homes (Red Cross, 16 May; Dr. S. Bronto, pers comm.).

Marijan is regarded by local people as 'understanding the volcano', and is also considered an unofficial leader for his local community (the villages of Kinahrejo and Umbulharjo) and more generally for the Sleman subdistrict. His influence led many people to decide not to evacuate despite recommendations from the authorities to do so. Confusion created by the premature lowering of the alert level and decision to allow people to return home prior to the major block-and-ash flows of 14 June is likely to have increased the level of distrust in the BPPTK and the emergency management authorities in general, and led to people putting more faith in the predictions of Mbah Marijan.

These traditional beliefs are well-understood by local academic staff and government volcanologists. However there appeared to be a reluctance to explain how they address such issues when a direct conflict occurs, such as that descrived with Mbah Marijan. A pragmatic approach is evident in this quote from President Yudhoyono:

> *I understand that in Yogyakarta there are still traditional beliefs among people. We respect these beliefs, but when it comes to saving people, we have to do our job well.* (Red Cross, 16 May).

### 7.5.3 The role of a stratified community in facilitating evacuations

The stratified social structure and clearly-defined leadership of the communities around Merapi was an essential part of the efficiency of the evacuations. Information was able to be quickly distributed by the head of the village or village elders. These leaders were also able to mobilise the whole village for full evacuation if necessary. This approach ensured that few were left behind, and in general highlighted the benefits of a unified and cohesive community during an emergency such as an evacuation.

### 7.5.4 Individual risk perceptions and preparedness

Local residents interviewed by the team showed a very high level of awareness of Merapi's volcanic hazards, and also a high level of awareness of what to do during an eruption. Nearly all the twelve people we interviewed within 15 kilometres of the volcano had established an evacuation plan, either as part of their village evacuation plan or an individual family plan. These plans included meeting points for family members if they were separated.

Most Indonesians we met, even those with university-level education, expressed reluctance to use paper maps for direction-finding or relating directions to us. However, perhaps in compensation, most also had very well-developed mental maps of their surroundings. This is likely to have important implications for local hazard education initiatives.

The overall high levels of hazard awareness and strategies for coping with an eruption are not surprising considering that most local residents have lived in the region for their entire lives and are likely to have experienced multiple eruptions. However, there can be dangers in over-familiarity. For example, many evacuees we spoke to stated that that they 'knew' Merapi as they had lived in the region for their whole lives. Local newspapers had reports of people believing Merapi would 'spare them' (Jakarta Post, 10/06/06). We found a commonly-held expectation among upland farmers that Merapi would eventually stop erupting as it had done in the past. The extrapolation from experiences in the recent past may contribute to the perception that the volcano is likely to produce small, low-explosivity eruptions in the future, a perception that is regarded by some scientists as being dangerously inaccurate (see Section 3.3).

### 7.5.5 Risk communication

Risk communication appeared to have been consistent for the most part, with the media usually presenting accurate information from the BPPTK. The Indonesian president delivered the same message to evacuation camps, asking people to stay calm and remain in the evacuation camps until the eruption was over. Nearly all people we spoke to had a good awareness of current hazard information, although it appears economic concerns caused many people to accept a greater degree of risk by returning to the evacuation zone.

A range of risk communication initiatives had been undertaken on the western and southern flanks as recently as 2005. Many villages also had hazard maps and evacuation details on posted boards at key points in the village.

# 8. OTHER HAZARDS AT MERAPI

## 8.1 Lahars

The Indonesian word *lahar* means 'volcanic mudflow'. Lahars have occurred frequently at Merapi in the past. Lahars can occur as an immediate consequence of explosive eruptions, or for some time afterwards. This is because unconsolidated volcaniclastic debris deposited on the upper slopes of the volcano can be mobilised by heavy rainfall (for instance, when the monsoon season begins in September), sending lahars down the drainage system. Lahars can cause damage much further afield than areas affected by pyroclastic flows, and can threaten villages that may consider themselves safely removed from the hazard zone for Merapi.

Lahars are a considerable problem from a management point of view because they can occur when the mountain is not erupting. Despite the small size of the 2006 eruptions of Merapi, a significant lahar hazard now exists as a result of the eruptive products deposited on the western and southern slopes. Lavigne et al. (2000) noted that the lahar-prone drainage systems on the south flank of Merapi support a high population density and vital resources for the region.

Several mitigation measures have been put in place to lessen the impact of lahars at Merapi. These include Sabo dams, which cull large clasts from lahar flows (Figure 35), and check dams, or lateral stop-banks, which confine lahar flows within channels (Figure 36). Unfortunately these dams are all located on the west and southwest flanks of Merapi. The south side, which is now vulnerable to pyroclastic flows and lahars following the collapse of the Geger Boyo, is currently unprotected.

**Figure 35** Sabo dam in Indonesia

**Figure 36** Check dam on Merapi south flank river

## 8.2 Sector collapse

The threat of a sector collapse at Merapi is substantiated by deposits suggesting that a similar event may have taken place in the past (Newhall et al., 2000). The hills immediately above the popular tourist destination of Kaliurang are interpreted as slump blocks that are remnants of sector collapse of prehistoric Merapi (Newhall et al., 2000). A sector collapse would likely be catastrophic, putting tens or perhaps even hundreds of thousands of lives at risk.

## 8.3 Future eruptions at Merapi

Merapi is one of the most active volcanoes in the world (Witham, 2005) and the threat of small eruptions is constant. As covered in Chapter 2, effusive eruptions from Merapi are frequent and can last for decades. In particular, eruptions involving lava dome growth generate hazards in the form of dome collapses causing block and ash flows and tephra fall. Larger explosive eruptions (VEI 3+) have longer return periods, but are much greater hazards and would threaten much larger areas.

# 9. SUMMARY AND CONCLUSIONS

## 9.1 Impacts on agriculture

The agricultural sector was very vulnerable to the impacts of the 2006 Merapi eruption, although this vulnerability was not uniform across the sector and indeed in some instances a high degree of resilience was observed on many farms (such as those with rice crops). The sector received the most damage of any economic sector, mostly due to the close proximity of a significant number of farms to Merapi. Impacts varied with ash thickness, as well as by crop type and plant maturity. Up to 100% of crops were lost in some locations. Significant weight loss in cows was observed due to animals eating tephra-covered fodder. Access to a reliable water supply appeared to be a key factor in overall farm resilience, although a diverse selection of crops grown on each farm also increased resilience.

Tropical agricultural systems are thought to have quite a high degree of resilience due to the favourable climate and fertile soils allowing a year-round growing season. It also appears that farmers in the Merapi region have adapted their farming practices to build in more resilience by having a diverse range of cash crops in addition to the staple rice crop. However, individual farmers generally considered themselves unable to absorb financial losses such as the loss of one crop rotation. This economic pressure probably led to the adoption of risky behaviour during the eruption, with farmers staying in evacuation camps overnight but returning to the exclusion zone by day to tend their farms.

## 9.2 Impacts on infrastructure

Impacts on the local infrastructure of the Merapi region from the 2006 eruption varied with location and hazard. Generally, the infrastructure showed considerable resilience to tephra falls. Tephra thicknesses less than 0.5 mm did not cause any damage other than nuisance value. Tephra thicknesses up to several centimetres did not produce any reported damage to buildings, utilities, vehicles, or telecommunications equipment.

Areas in the path of pyroclastic flows were completely destroyed, but the damage dwindled to background levels within several metres of the flow boundaries.

The degree of resilience observed was higher than that expected, based on other models for ash impacts (Spence et al., 2005; Baxter et al. 2005). However, there may be a delayed lahar hazard as a result of the 14 June 2006 block and ash flows, which deposited unconsolidated debris on the upper slopes of the south side of Merapi. Any lahars generated may cause further impacts on infrastructure, such as bridges and roads, downstream.

## 9.3 Social impacts of the 2006 eruptions

Two people lost their lives in the 2006 eruptions of Merapi. They were sheltering in an emergency bunker designed to provide protection from pyroclastic flows, but this structure was overwhelmed by the 3 p.m. pyroclastic flow on 14 June. This failure should prompt a review of the construction of these bunkers. Part of Kaliadem village was destroyed by this event.

Large-scale evacuation of people living in high-risk villages on the slopes of Merapi was carried out, and is generally thought to have been an effective response to the eruptions, efficiently carried out. During the first phase of the evacuations, some 20,000 people were housed in evacuation camps, which were generally well-resourced and well-managed. However, the disruption, stress of abandoning farms, and uncertainty took their toll on many people we spoke to. Other problems with the evacuation are discussed further in Section 9.4.

## 9.4 An emergency management framework

Considering the '4Rs' of emergency management, the *response* to the 2006 eruptions of Merapi have been covered at length in this report and summarised briefly above. Our field visit was made during the latter stages of the eruption, and we can only comment to a limited extent on *recovery* in this region. As far as the other two components of *reduction* and *readiness* are concerned we can offer the following observations.

Risk reduction is a difficult prospect in the Merapi region. The volcano is one of the most active in the world. During the 20$^{th}$ century, eruptions of Merapi caused 1600 deaths, and tens of thousands more were injured, evacuated or made homeless. The impacts of eruptions have become increasingly more devastating because of the rapidly-growing population. An estimated 1.1 million people live on the slopes of Merapi, and the population growth rate was calculated as 3% annually in the mid-1990s. Java has one of the highest population densities in the world, imposing significant stress on its natural resources and leading to marginal and dangerous regions (such as the slopes of Merapi) being inhabited. Approximately 440,000 people live in high-risk areas subject to pyroclastic flows, surges and lahars from Merapi. The situation is exacerbated by the general lack of land-use planning. In summary, all available information points towards an increasing volcanic risk in the Merapi region.

Fortunately, risk readiness among vulnerable communities in the Merapi region was found to be very good. At an individual level, people had a good understanding of volcanic hazards, and were well-prepared for evacuations. Nearly all the people we spoke with had established an evacuation plan, either as part of their village evacuation plan or as an individual family plan. These plans included meeting points for family members if they were separated. When evacuations occurred, they were carried out efficiently. As an example, around 15,000 people were evacuated from Kaliadem village after the first block and ash flow at noon on 14 June, within a three-hour timeframe. The well-established social structure and clearly-defined leadership roles in rural communities were undoubtedly important in facilitating evacuations.

However, there are some problem areas. Economic pressures caused farmers to return to their farms in the exclusion zone during the daytime, and may also have caused other residents to refuse to evacuate altogether. The fact that supernatural beliefs about the volcano hold sway in this region may also contribute to this trend; people may put more faith in traditional beliefs (such as omens of an impending eruption) rather than scientifically-based warnings. The emergency management authorities may have also suffered setbacks to their credibility by lowering the alert level in advance of a major eruptive event (14 June block and ash flows); people returned to their homes but then had to be re-evacuated. The continuing uncertainty was a difficult situation for both the authorities and the local residents.

## 9.5 Lessons for New Zealand

### 9.5.1 Agriculture

During our field visit, we collected data on crop damage in relation to tephra thickness, crop type and maturity. It is apparent that some types of crop are highly susceptible to ash fall hazards and will likely suffer severe loss or abandonment of the crop, even from thin ash falls. The large range of crops and impacts to crops and livestock observed will provide a useful basis for predicting impacts of an eruption in New Zealand on the horticultural sector. The information will also be used in fragility functions for the Riskscape model.

An important lesson for New Zealand is that during an eruption it is likely large areas of agricultural land will be evacuated, even if not impacted, due to the uncertainty of volcanic eruptions. The Ministry of Civil Defence and Emergency Management, Ministry of Agriculture and Forestry, Regional Councils and other authorities likely to be involved in the response to a volcanic eruption should be aware that farmers will be reluctant to evacuate their lands, and will want to return once evacuated to check on their farm whether it has been impacted by hazards or not.

### 9.5.2 Infrastructure

Observations made at Merapi during the 2006 eruptions suggest that existing models of infrastructure impacts due to tephra fall may be inaccurate, with damage to infrastructure generally less than expected. Our findings will be used to refine these models to include, for example, the presence of absence of rainfall.

A lesson from our observations of pyroclastic flow damage was that modelling needs to take into account the physical characteristics of the erupted material. At Merapi, the block-and-ash flow material was highly degassed, and the resulting pattern of damage had very sharp margins as a result of the cohesiveness of the flow. However, differing flow characteristics are likely to generate different patterns of damage.

### 9.5.3 Social impacts

The evacuation systems and procedures, together with education initiatives increasing individual awareness of hazards, are clearly well-organised at Merapi and should provide some useful lessons for New Zealand.

## 10. SUGGESTIONS FOR FURTHER WORK

The following suggestions for future projects build on the findings of this report:

- Detailed studies of damaged houses in Kaliadem / Bebeng village to determine the damage in relation to the building construction;
- Discussion with the national authorities in Jakarta on the final economic impacts of the 2006 eruption;
- Discussion with public health and disaster relief agencies (such as the Red Cross/ Red Crescent in Yogyakarta) of the final numbers of people affected by the 2006 eruption;
- Analysis of the recovery dynamics of agricultural systems, including aspects such as changes in soil fertility and production yields of crops;
- Investigation of lahar hazards as a result of the 2006 eruption;
- A social science project looking at where villagers get their information from, who they trust, levels of knowledge and preparedness, general world views and so on;
- At the onset of further activity from Merapi, a return to the volcano would provide an opportunity to collect information on impacts in order to compare them to the 2006 eruption.

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# APPENDIX 1

**Table A1** Field stops around Merapi, 22 June – 5 July 2006

| ID | ALT | LAT | LONG | ASH | STOP_NUM | NOTES |
|---|---|---|---|---|---|---|
| 2 | 486.8 | -7.667116 | 110.432070 | 0.1 | | trace to less than 1 mm |
| 3 | 480.3 | -7.667157 | 110.432107 | 0.0 | | |
| 4 | 478.9 | -7.667152 | 110.432100 | 0.0 | | |
| 5 | 677.6 | -7.624893 | 110.447960 | 0.0 | | |
| 6 | 916.5 | -7.600205 | 110.453837 | 0.0 | | |
| 7 | 1029.9 | -7.589340 | 110.445404 | 0.0 | | Opak River below Kaliadem |
| 8 | 989.3 | -7.588996 | 110.445601 | 0.0 | | |
| 9 | 1004.0 | -7.589021 | 110.445550 | 0.0 | | |
| 10 | 1004.5 | -7.589082 | 110.445531 | 0.0 | | |
| 11 | 1004.9 | -7.661272 | 110.466841 | 0.5 | 1.90 | flow not here, less than 0.5 mm ash |
| 12 | 430.6 | -7.662139 | 110.488987 | 0.0 | | evac centre? |
| 13 | 402.0 | -7.666142 | 110.504014 | 1.0 | 1.10 | buried temple - beside woro river |
| 14 | 400.0 | -7.666258 | 110.506790 | 0.1 | 1.11 | sand mining, trace ash |
| 15 | 400.0 | -7.623153 | 110.549022 | 0.1 | 1.12 | trace |
| 16 | 464.0 | -7.505895 | 110.499983 | 3.0 | 1.13 | |
| 17 | 1382.3 | -7.505434 | 110.482974 | 2.0 | 1.14 | Up Selo Pass |
| 18 | 1366.1 | -7.497389 | 110.424226 | 3.0 | 1.16 | |
| 19 | 1168.8 | -7.496228 | 110.411126 | 4.0 | | |
| 20 | 149.4 | -7.783062 | 110.445544 | 0.0 | | |
| 21 | 247.2 | -7.728737 | 110.422602 | 0.0 | | Sutikno's House |
| 22 | 303.2 | -7.701582 | 110.414584 | 0.0 | | No ash |
| 23 | 305.1 | -7.660238 | 110.402960 | 0.1 | 4.10 | trace |
| 24 | 461.1 | -7.651302 | 110.396709 | 0.1 | 4.20 | trace |
| 25 | 434.4 | -7.649399 | 110.367230 | 0.0 | 4.30 | evac centre (same as stop number 1.5) |
| 26 | 433.9 | -7.654893 | 110.359899 | 0.5 | 4.40 | <0.5 mm |
| 27 | 433.0 | -7.644662 | 110.333889 | 0.1 | 4.50 | trace |
| 28 | 427.9 | -7.646292 | 110.324267 | 2.0 | 4.60 | |
| 29 | 392.1 | -7.628284 | 110.321386 | 0.0 | 4.70 | |
| 30 | 398.1 | -7.613477 | 110.306780 | 0.0 | | |
| 31 | 386.8 | -7.593300 | 110.293038 | 0.1 | 4.80 | trace |
| 32 | 381.8 | -7.578713 | 110.292615 | 1.0 | 4.90 | stopped to film |
| 33 | 491.8 | -7.555095 | 110.314184 | 1.5 | 4.10 | |
| 34 | 610.3 | -7.540021 | 110.335247 | 1.5 | 4.11 | |
| 35 | 637.0 | -7.537097 | 110.342801 | 2.0 | 4.12 | |
| 36 | 640.6 | -7.526184 | 110.358369 | 2.0 | 4.14 | |
| 37 | 949.9 | -7.516535 | 110.384042 | 3.0 | 4.15 | |
| 38 | 1046.5 | -7.517148 | 110.392231 | 5.0 | 4.17 | conv. With farmer |
| 39 | 1072.2 | -7.517091 | 110.394595 | 20.0 | 4.18 | mosque |
| 40 | 1248.6 | -7.512649 | 110.413955 | 0.0 | | |
| 41 | 1302.0 | -7.514438 | 110.416874 | 15.0 | 4.19 | |
| 42 | 1322.9 | -7.514284 | 110.416837 | 0.0 | | |
| 43 | 1320.0 | -7.514238 | 110.416840 | 0.0 | | |
| 44 | 1321.0 | -7.513865 | 110.417188 | 0.0 | | |
| 45 | 1319.3 | -7.513563 | 110.417628 | 0.0 | | |
| 46 | 1319.5 | -7.513604 | 110.417730 | 0.0 | | |

| ID | ALT | LAT | LONG | ASH | STOP_NUM | NOTES |
|---|---|---|---|---|---|---|
| 47 | 1320.5 | -7.513813 | 110.417327 | 0.0 | | |
| 48 | 1320.5 | -7.514240 | 110.416807 | 0.0 | | |
| 49 | 1321.2 | -7.515405 | 110.417976 | 20.0 | 4.23 | |
| 50 | 117.6 | -7.794861 | 110.457885 | 0.0 | 5.00 | |
| 51 | 114.3 | -7.806159 | 110.454497 | 0.0 | | |
| 52 | 123.2 | -7.807637 | 110.456649 | 0.0 | | |
| 53 | 100.3 | -7.808277 | 110.459428 | 0.1 | 5.10 | Opak River Bridge (pillow lavas), trace |
| 54 | 104.4 | -7.809532 | 110.461993 | 0.0 | | Blue EQ tents |
| 55 | 122.7 | -7.807060 | 110.482921 | 0.0 | | Road - TW Vidoe damage |
| 56 | 133.7 | -7.781793 | 110.484923 | 0.0 | 5.20 | |
| 57 | 164.8 | -7.764278 | 110.488881 | 0.0 | 5.30 | |
| 58 | 187.8 | -7.735908 | 110.488573 | 0.0 | | Road above highway |
| 59 | 187.1 | -7.712768 | 110.503436 | 0.0 | 5.40 | |
| 60 | 288.0 | -7.695559 | 110.493289 | 0.0 | 5.50 | Road |
| 61 | 286.8 | -7.696812 | 110.501251 | 0.0 | 5.60 | |
| 62 | 317.1 | -7.674177 | 110.519136 | 0.1 | 5.70 | Trace to <1 mm |
| 63 | 334.4 | -7.670395 | 110.520037 | 0.1 | 5.80 | trace, talked to farmer with 72 ducks |
| 64 | 369.0 | -7.661629 | 110.517156 | 0.8 | 5.90 | 0.5 to 1 mm |
| 65 | 441.6 | -7.644227 | 110.510346 | 1.0 | 5.10 | |
| 66 | 448.6 | -7.640216 | 110.508670 | 1.0 | 5.11 | evac camp |
| 67 | 590.9 | -7.624061 | 110.499856 | 0.1 | 5.12 | trace |
| 68 | 594.9 | -7.619163 | 110.495488 | 0.1 | 5.13 | trace |
| 69 | 598.5 | -7.606772 | 110.488953 | 1.0 | 5.14 | |
| 70 | 874.0 | -7.595085 | 110.479720 | 2.0 | 5.15 | road block |
| 71 | 880.7 | -7.593128 | 110.476787 | 0.0 | | |
| 72 | 1001.8 | -7.589301 | 110.472964 | 0.0 | | |
| 73 | 1020.3 | -7.587984 | 110.472334 | 4.0 | 5.16 | |
| 74 | 1086.4 | -7.583661 | 110.469887 | 5.0 | 5.17 | Photo 2243 |
| 75 | 1138.1 | -7.579820 | 110.469222 | 10.0 | 5.18 | |
| 76 | 1036.4 | -7.582343 | 110.476833 | 0.0 | 5.19 | |
| 77 | 1029.2 | -7.581965 | 110.477086 | 0.0 | | Ash is very thick here - about as thick as we've seen, rain crust on ashy roofs |
| 78 | 1032.6 | -7.581913 | 110.477099 | 15.0 | | |
| 79 | 1046.5 | -7.581532 | 110.476297 | 0.0 | | Vegetable Patch |
| 80 | 1235.2 | -7.575753 | 110.468136 | 35.0 | | Cows, taped them eating |
| 81 | 190.7 | -7.710330 | 110.420149 | 0.1 | 6.20 | Sri's House, trace |
| 82 | 440.9 | -7.660881 | 110.407144 | 0.0 | | |
| 83 | 442.1 | -7.655215 | 110.396121 | 0.1 | | trace |
| 84 | 400.8 | -7.652070 | 110.360838 | 2.0 | | |
| 85 | 394.0 | -7.635182 | 110.330809 | 0.1 | | trace |
| 86 | 489.7 | -7.613010 | 110.344931 | 2.0 | 6.30 | |
| 87 | 534.1 | -7.606254 | 110.354826 | 0.0 | | |
| 88 | 541.8 | -7.604936 | 110.356644 | 0.0 | | |
| 89 | 549.5 | -7.603622 | 110.357987 | 0.0 | 6.40 | |
| 90 | 551.0 | -7.603687 | 110.360863 | 0.1 | 6.50 | trace |
| 91 | 613.7 | -7.600196 | 110.361276 | 0.0 | | |
| 92 | 613.0 | -7.595532 | 110.368077 | 0.1 | 6.60 | trace to 1mm |
| 93 | 703.8 | -7.589610 | 110.375501 | 1.0 | 6.70 | |
| 94 | 702.6 | -7.588804 | 110.376401 | 2.5 | 6.80 | |
| 95 | 709.3 | -7.586846 | 110.377740 | 0.0 | | |
| 96 | 726.6 | -7.584569 | 110.380481 | 3.0 | 6.90 | Chili Peppers |

| ID | ALT | LAT | LONG | ASH | STOP_NUM | NOTES |
|---|---|---|---|---|---|---|
| 97 | 499.3 | -7.610122 | 110.346174 | 0.0 | | |
| 98 | 504.1 | -7.607041 | 110.342496 | 0.0 | | |
| 99 | 488.0 | -7.597096 | 110.332980 | 1.0 | 6.10 | |
| 100 | 491.4 | -7.600944 | 110.322967 | 1.0 | 6.11 | |
| 101 | 371.0 | -7.593098 | 110.292844 | 0.0 | | |
| 102 | 368.8 | -7.558353 | 110.311453 | 0.1 | | trace |
| 103 | 377.7 | -7.555560 | 110.314014 | 1.0 | | |
| 104 | 604.1 | -7.540153 | 110.337199 | 0.0 | | river |
| 105 | 663.9 | -7.528322 | 110.347335 | 8.0 | | |
| 106 | 849.7 | -7.509086 | 110.363110 | 15.0 | 6.12 | Selo Road (different than when we came down?), Tobacco |
| 107 | 1071.3 | -7.498309 | 110.378354 | 12.0 | 6.13 | |
| 108 | 1092.4 | -7.499714 | 110.389860 | 8.0 | 6.14 | Wonolelo |
| 109 | 1091.9 | -7.499668 | 110.389918 | 0.0 | | Wonolelo |
| 110 | 1098.9 | -7.499412 | 110.390122 | 6.0 | 6.15 | |
| 111 | 1098.9 | -7.499412 | 110.390122 | 5.0 | 6.16 | |
| 112 | 1255.1 | -7.497857 | 110.419135 | 4.0 | 6.17 | |
| 113 | 1418.1 | -7.499119 | 110.436701 | 3.0 | 6.19 | |
| 114 | 1580.5 | -7.501473 | 110.459345 | 0.0 | 0.00 | |
| 115 | 1737.5 | -7.512834 | 110.453495 | 2.0 | 6.20 | |
| 116 | 1721.6 | -7.515635 | 110.452555 | 5.0 | 6.21 | Said there was 50mm up the slope (1km from summit) |
| 117 | 758.1 | -7.518674 | 110.358698 | 0.0 | 6.22 | 15 mm since may |
| 118 | 766.1 | -7.805921 | 110.447454 | 0.0 | | |
| 119 | 118.6 | -7.812281 | 110.466446 | 0.0 | | |
| 120 | 114.5 | -7.814974 | 110.480772 | 0.0 | | |
| 121 | 116.0 | -7.810124 | 110.483531 | 0.0 | | |
| 122 | 126.5 | -7.811631 | 110.486516 | 0.0 | | |
| 123 | 119.3 | -7.811988 | 110.488719 | 0.0 | 9.20 | House being demolished by airforce |
| 124 | 116.4 | -7.812624 | 110.511572 | 0.0 | | Heavy EQ Damage |
| 125 | 214.7 | -7.817855 | 110.518339 | 0.0 | 9.30 | |
| 126 | 216.2 | -7.818094 | 110.518259 | 0.0 | | Stream Bed |
| 127 | 209.9 | -7.817878 | 110.519926 | 0.0 | | Weird volccaniclastic |
| 128 | 206.3 | -7.817898 | 110.519671 | 0.0 | | |
| 129 | 103.9 | -7.837346 | 110.474208 | 0.0 | | |
| 130 | 106.1 | -7.837390 | 110.471860 | 0.0 | | |
| 131 | 101.3 | -7.842040 | 110.470323 | 0.0 | | |
| 132 | 99.9 | -7.848897 | 110.464875 | 0.0 | | |
| 133 | 113.8 | -7.849689 | 110.457359 | 0.0 | | |
| 134 | 219.1 | -7.852829 | 110.453709 | 0.0 | | |
| 135 | 261.6 | -7.854697 | 110.453800 | 0.0 | | |
| 136 | 263.8 | -7.858413 | 110.453768 | 0.0 | | |
| 137 | 251.0 | -7.862898 | 110.457337 | 0.0 | | |
| 138 | 232.3 | -7.867117 | 110.454876 | 0.0 | | |
| 139 | 229.4 | -7.872318 | 110.449933 | 0.0 | | |
| 140 | 228.7 | -7.874139 | 110.448536 | 0.0 | | |
| 141 | 215.5 | -7.881813 | 110.440098 | 0.0 | | |
| 142 | 105.1 | -7.883186 | 110.438824 | 0.0 | | |
| 143 | 113.3 | -7.882901 | 110.432842 | 0.0 | | |
| 144 | 72.7 | -7.883008 | 110.432801 | 0.0 | | Hill we climbed down to get sample |
| 145 | 60.7 | -7.827738 | 110.443223 | 0.0 | | Lunch |
| 146 | 339.0 | -7.569572 | 110.259657 | 0.0 | | |
| 147 | 338.7 | -7.570709 | 110.256160 | 0.1 | 10.10 | trace |

| ID | ALT | LAT | LONG | ASH | STOP_NUM | NOTES |
|---|---|---|---|---|---|---|
| 148 | 338.7 | -7.572871 | 110.254402 | 0.1 | | trace |
| 149 | 338.7 | -7.577308 | 110.250753 | 0.1 | | trace |
| 150 | 326.5 | -7.587574 | 110.242163 | 0.0 | | |
| 151 | 278.4 | -7.591523 | 110.238421 | 0.0 | | |
| 152 | 274.6 | -7.596697 | 110.234886 | 0.0 | | |
| 153 | 261.4 | -7.604883 | 110.230057 | 0.5 | 10.20 | |
| 154 | 263.0 | -7.602850 | 110.225164 | 0.0 | | |
| 155 | 260.4 | -7.602128 | 110.222254 | 0.0 | | |
| 156 | 258.7 | -7.605010 | 110.219041 | 0.0 | | |
| 157 | 258.7 | -7.605784 | 110.209534 | 0.1 | | trace |
| 158 | 267.4 | -7.605984 | 110.208888 | 0.0 | | |
| 159 | 267.4 | -7.605984 | 110.208888 | 0.0 | | |
| 160 | 263.3 | -7.603198 | 110.215544 | 0.1 | 10.30 | trace |
| 161 | 142.9 | -7.782264 | 110.387887 | 0.0 | | |
| 162 | 140.0 | -7.783051 | 110.384441 | 0.0 | | |
| 163 | 138.1 | -7.783026 | 110.382136 | 0.0 | | |
| 164 | 100.1 | -7.788942 | 110.370456 | 0.0 | | |
| 165 | 107.8 | -7.790581 | 110.368577 | 0.0 | | |
| 166 | 128.9 | -7.790158 | 110.366724 | 0.0 | | |
| 167 | 140.0 | -7.792727 | 110.366402 | 0.0 | | |
| 168 | 140.7 | -7.804480 | 110.363379 | 0.0 | | |
| 169 | 121.5 | -7.801679 | 110.364676 | 0.0 | | |
| 170 | 124.6 | -7.801493 | 110.368071 | 0.0 | | |
| 171 | 134.0 | -7.801816 | 110.375887 | 0.0 | | |
| 172 | 134.0 | -7.801816 | 110.375887 | 0.0 | | |
| 173 | 127.3 | -7.798198 | 110.384837 | 0.0 | | |
| 174 | 130.9 | -7.802874 | 110.378272 | 0.0 | | |
| 175 | 130.6 | -7.811420 | 110.376696 | 0.0 | | |
| 176 | 112.1 | -7.815578 | 110.376179 | 0.0 | | |
| 177 | 114.0 | -7.816215 | 110.375884 | 0.0 | | |
| 178 | 113.8 | -7.815261 | 110.372545 | 0.0 | | |
| 179 | 109.7 | -7.818541 | 110.368168 | 0.0 | | |
| 180 | 109.2 | -7.821947 | 110.367843 | 0.0 | | |
| 181 | 106.4 | -7.824285 | 110.367600 | 0.0 | | |
| 182 | 97.7 | -7.827564 | 110.367527 | 0.0 | | |
| 183 | 102.0 | -7.833420 | 110.366812 | 0.0 | | |
| 184 | 95.1 | -7.834379 | 110.385006 | 0.0 | | |
| 185 | 513.7 | -7.644282 | 110.434040 | 0.0 | | |
| 186 | 659.6 | -7.625038 | 110.433679 | 0.0 | | |
| 187 | 678.3 | -7.624807 | 110.449483 | 0.0 | | Red Cross Water Station (?) |
| 188 | 687.5 | -7.624495 | 110.453727 | 0.0 | | |
| 189 | 675.7 | -7.606937 | 110.453800 | 0.0 | | |
| 190 | 1011.4 | -7.591118 | 110.450767 | 0.0 | | |
| 191 | 1016.7 | -7.589501 | 110.450213 | 0.0 | | |
| 192 | 1020.3 | -7.586426 | 110.449162 | 0.0 | | |
| 193 | 1021.3 | -7.584580 | 110.448747 | 0.0 | | |
| 194 | 1120.3 | -7.582529 | 110.447512 | 0.0 | | |
| 195 | 1119.6 | -7.582957 | 110.448460 | 0.0 | | |
| 196 | 1116.9 | -7.582955 | 110.448457 | 0.0 | | |
| 197 | 1092.9 | -7.584802 | 110.448706 | 0.0 | | |
| 198 | 675.2 | -7.625081 | 110.429218 | 0.0 | | |

| ID | ALT | LAT | LONG | ASH | STOP_NUM | NOTES |
|---|---|---|---|---|---|---|
| 199 | 835.0 | -7.598959 | 110.425553 | 3.0 | 13.10 | |
| 200 | 836.9 | -7.592497 | 110.426234 | 0.0 | | road block |
| 201 | 609.4 | -7.634183 | 110.425200 | 0.0 | | |
| 202 | 444.3 | -7.666763 | 110.418995 | 2.0 | | |
| 203 | 441.1 | -7.659648 | 110.397174 | 0.0 | | |
| 204 | 451.9 | -7.651591 | 110.396574 | 0.0 | | |
| 205 | 600.0 | -7.622150 | 110.404771 | 4.0 | | |
| 206 | 787.7 | -7.598908 | 110.414575 | 3.0 | | |
| 207 | 903.5 | -7.595376 | 110.415998 | 0.0 | | evac camp |
| 208 | 928.8 | -7.589783 | 110.417097 | 3.0 | | road block |
| 209 | 982.6 | -7.588463 | 110.421539 | 3.0 | | |
| 210 | 986.4 | -7.588411 | 110.424079 | 4.0 | | road block |
| 211 | 1006.4 | -7.587958 | 110.424301 | 1.0 | | area destroyed by 1994 flows |
| 212 | 1022.7 | -7.588269 | 110.424004 | 1.0 | | 600mm of ash deposited in 1994 |
| 213 | 890.3 | -7.713088 | 110.386244 | 0.0 | | |

# APPENDIX 2

There has been limited published research on acid damage to vegetation from volcanic ash. It is well known ash falls can lead to elevated acidity and sulphur levels in soil (e.g. Cronin et al., 1998). These changes in soil composition can reduce the availability of phosphate and other essential minerals and alter soil characteristics to such an extent that arable crops and pasture plants will not survive (Cronin et al., 1998; 2003). There is less information on impacts on vegetation, although there have been several instances where acid rain or soluble ash-leachates following an eruption have caused detrimental effects to vegetation (Peterson and Tilling, 2000; Jacobson, 1984; Blong, 1984).

Recent studies on the historical eruption of Laki volcano, in Iceland in 1783-84, have suggested that a 'dry mist', produced by the massive release of volcanic aerosols into the atmosphere during the eruption, may have caused impacts on soils and vegetation right across Western Europe (e.g. Grattan and Pyatt, 1994; Thordarson and Self, 1993). A wide range of critical plant processes were reported to have been affected by the volcanic mist, included photosynthesis, leaf formation, leaf reduction, fruiting, flowering and seeding. Observed impacts included premature yellowing of green leaves, trees prematurely losing leaves, and crops appearing weathered, shrivelled or dried despite abundant moisture, and with particular damage to leaf tips (Grattan and Pyatt, 1994). Despite damage to outer leaves and husks, the grains of cereal crops were reportedly unaffected, and some crops, such as rye, even appeared mildewed. Some plant varieties were relatively unaffected by the 'dry fog'; these included wheat, mulberry bushes, fig trees and vines. Many of the above symptoms are considered typical acid damage (Grattan and Pyatt, 1994; Lang et al., 1980).

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