The Atlas of Merapi volcano, Indonesia

Franck Lavigne, Julie Morin, Dr Surono

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F. Lavigne, J. Morin, Surono (eds.)

First Edition, 2015

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PREFACE

Scientific context

This atlas of Merapi volcano is a result of a collaborative research from two successive scientific projects:

(i) The MIA VITA Project (Mitigate and assess risk from volcanic impact on terrain and human activities - 2008-2013) was financed by the European Commission under the 7th Framework Programme for Research and Technological Development, Area "Environment", Activity 6.1 "Climate Change, Pollution and Risks". It was led by the French Bureau de Recherches Géologiques et Minières (BRGM - Grant agreement no. 211393). The objective of this 48-month project was to develop integrated tools and cost effective methodologies to mitigate risks from various volcanic hazards (vulnerability and resilience assessment, prevention and crisis management) on four active volcanoes: Merapi (Indonesia), Kanlaon (the Philippines), Fogo (Cape Verde), and Mount Cameroon (Cameroon).

(ii) The SEDIMER Project (Sediment-related Disasters following the 2010 centennial eruption of Merapi Volcano, Java, Indonesia), is funded by the AXA Research Fund (2011-2015), and is led by the Laboratoire de Géographie Physique (CNRS). This ongoing project aims at building a database on lahar occurrence and related disasters, to identify the sediment sources for lahar generation, study the lahar dynamics and geomorphic impacts with implications for risk prevention.
Both projects are collaborative studies that gather international and Indonesian experienced experts and young scientists in geography, geomorphology, hydrogeology, sedimentology, volcanology, geophysics, sismology, petrology, modeling, GIS, statistics, etc.

The first atlas on an active volcano

In the past, comprehensive reference works summarising the current state of knowledge of some active volcanoes were gathered into an atlas, e.g. the Volcanic Hazard Atlas of the Lesser Antilles (Lindsay et al., 2005). Individual island-specific entries include sections that summarise all previous work, the geological history of the islands, and the monitoring network of the volcanoes. Each potentially active volcano on the island is then discussed in turn, with emphasis on past eruptive activity, geothermal activity and seismicity.
Unlike this approach, the atlas of Merapi is the first atlas focusing entirely on a single active volcano. Another significant difference is that it does not focus exclusively on the geology, or the volcanic hazards and the monitoring of the volcano. Yet it covers a much wider spectrum in order to assess the actual volcanic risk. Therefore, it encompasses original sections on resources, vulnerabilities, and capacities in addition to the more conventional sections dedicated to Earth Science.
The maps of this atlas are mainly based on field data compiled during a 2-years long census campaign (2009 -2010) in the framework of the MIA VITA project. More than 550 questionnaires have been filled out at the scale of the village (*dusun*). In Indonesia, the lowest official administrative unit is the municipality (*desa*), therefore the village's borders were not available at the beginning of this study. Finally they were drawn using participatory mapping based on local traditional knowledge.

A digital atlas in free access

In addition to the hard copy version of the atlas dedicated to the local stakeholders, a digital version is available online in pdf format.

New eruptions at Merapi will probably require frequent updating of this atlas. For this reason, it must be stressed that the plates of the Atlas should not be viewed as fixed. The online version will be updated as new information comes to light, or in case of a new eruption. In addition, existing plates will be enhanced, and new plates will be progressively added, e.g. plates on the main historical eruptions, plate on volcanic tourism at Merapi, etc. In the long term, the atlas will become the comprehensive reference work on the physical and human geography of Merapi.

SUMMARY

Merapi volcano is one of the most active volcanoes worldwide. Approximately 1.3 million people live within a radius of 20 km from the summit. In the framework of both, the FP7 MIA VITA Project, and the SEDIMER Project funded by AXA Research Fund, we have built a database at the village scale, which includes the elements at risk and the local resources. This unique geospatial database was used to build a series of maps at the scale of the volcano, providing the core of the Merapi atlas. Designed by the French Laboratory of Physical Geography in Meudon (France) and the Center of Volcanology and Geological Hazards Mitigation in Bandung (Indonesia), this atlas provides a state of the art synthesis of knowledge on Merapi, from the reconstruction of past eruptions and assessment of volcanic hazards to the quantification of vulnerability and capacities. It is pertinent to a broad audience ranging from volcanologists to the Indonesian population interested to learn about their sacred volcano. The primary goal of this atlas is to provide an essential blueprint for planners and public officials involved in long-term development as well as risk and crisis management.

The first edition of the atlas contains 58 color plates gathered in 8 chapters: the first chapter introduces the broad tectonic and geologic context as well as the environmental and human context of Merapi volcano. The second chapter pertains to the geology, the past activity, and the volcanic hazards at Merapi. The third chapter is dedicated to the resources offered by the volcano, including agriculture, livestock, and sand mining activities. The fourth chapter focuses on vulnerability and capacities. The fifth chapter details the 2010 VEI 4 eruption of Merapi and its environmental consequences. The sixth chapter summarises the socio-economical impact of the eruption, including mapping of casualties, evacuation, building damage, and an assessment of air traffic disturbance. The seventh chapter focuses on rain-triggered lahar activity following the 2010 eruption, and the associated impact at the local scale. In the concluding chapter, we show how the 2010 eruption of Merapi improved volcanic risk management, through an updated volcanic hazard map, the establishment of a new high-tech monitoring system, as well as the increase of risk awereness.

Extensive use of colour in maps at various scales, graphics, and photos, provides a visually appealing synthesis of the hazards and risks at Merapi volcano, one of the most dangerous in the world.

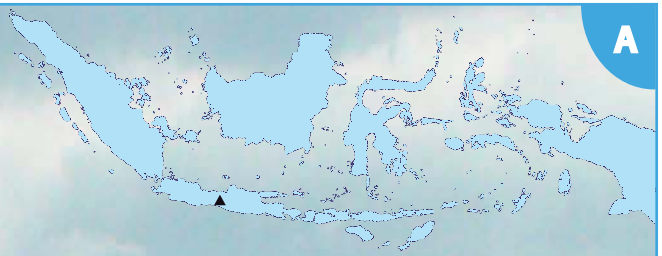
RINGKASAN

Gunungapi Merapi merupakan salah satu gunungapi yang paling aktif di dunia. Lebih kurang 1.300.000 penduduk tinggal di radius 20 km dari puncak Gunungapi Merapi. Melalui proyek FP7 MIA VITA dan SEDIMER yang di danai oleh AXA, kami telah membuat database dalam skala desa yang mencakup unsur-unsur risiko dan sumberdaya lokal. Database geospasial digunakan untuk membuat seri peta pada skala gunungapi yang tersaji dalam Atlas Merapi. Atlas Merapi disusun oleh "French Laboratory" Geografi Fisik di Meudon (Perancis) dan Pusat Vulkanologi dan Mitigasi Bahaya Geologi di Bandung (Indonesia), atlas ini menyajikan perpaduan antara seni dan pengetahuan tentang Merapi dari rekonstruksi letusan masa lalu dan penilaian bahaya vulkanik dengan perhitungan kerentanan dan kapasitas (daya tampung). Atlas Merapi berkaitan dengan khalayak luas, mulai dari ahli gunungapi sampai penduduk Indonesia yang tertarik untuk belajar tentang gunungapi. Tujuan utama pembuatan Atlas ini adalah memberikan gambaran penting bagi perencana dan pejabat publik yang terlibat dalam pembangunan jangka panjang seperti risiko dan krisis manajemen.

Atlas ini terdiri dari puluhan halaman yang tersusun dalam 8 bab, yakni pendahuluan tentang rangkuman konteks geologi meliputi konteks lingkungan dan manusia di sekitar Gunungapi Merapi. Bab kedua berkaitan dengan geologi, aktivitas masa lalu, dan bahaya vulkanik di Gunungapi Merapi. Bab ketiga membahas tentang sumberdaya yang disediakan oleh gunungapi Merapi, termasuk pertanian, peternakan, dan kegiatan penambangan pasir. Bab keempat fokus pada kerentanan dan kapasitas (daya tampung). Bab kelima menyajikan tentang rekonstruksi VEI 4 pada letusan Merapi tahun 2010 dan konsekuensi lingkungannya. Bab keenam merupakan rangkuman dampak sosial-ekonomi dari letusan Gunungapi Merapi, termasuk pemetaan korban, evakuasi, kerusakan bangunan, dan penilaian gangguan lalu lintas udara. Bab ketujuh fokus membahas aktivitas lahar yang dipicu oleh hujan setelah letusan Gunungapi Merapi pada tahun 2010, dan dampak yang terjadi dalam skala lokal. Dalam penutup bab, kami menunjukkan bagaimana manajemen risiko letusan Gunungapi Merapi pada tahun 2010 semakin baik, melalui peta bahaya vulkanik yang telah diperbarui, pembuatan sistem pemantauan berteknologi tinggi, serta peningkatan kesadaran risiko. Penyajian peta menggunakan warna di berbagai skala, grafis, dan foto ditujukan agar pembaca mudah memahami bahaya dan risiko di Gunungapi Merapi, salah satu gunungapi yang paling berbahaya di dunia.

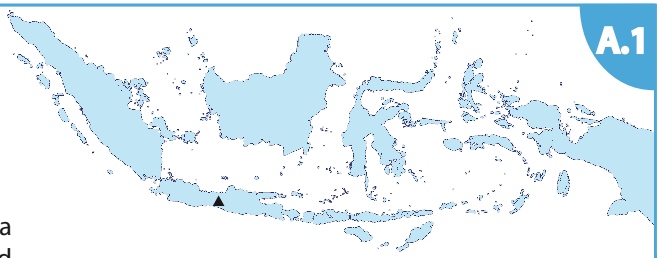
CONTENT

Introduction



Merapi volcano from rice fields © F. Lavigne, 2012

Tectonics of Indonesia



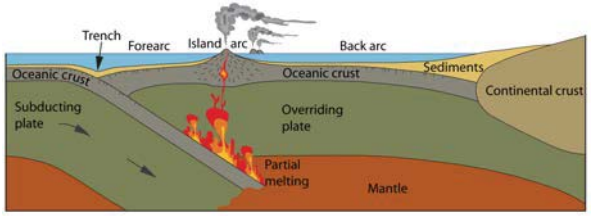
The Indonesian archipelago is the result of complex tectonic plate collision involving four different plates. Subduction of the continental Indo-Australian plate beneath the Eurasian plate formed the main Sunda-Banda volcanic arc stretching from Sumatra to the West, through Java, Bali, Nusa Tengara Islands till Banda to the East. To the East, subduction of the oceanic Pacific and Philippine Sea plates beneath the Eurasian plate has generated the Maluku and Sulawesi volcanic and tectonic provinces. The process of rapid subduction leads to the genesis of mountain chains, a high rate of volcanic activity, and tremendous stresses in the Earth's crust that cause its rupture along active faults. This makes this region one of the most seismically active of the World.

From historical and seismic records, we know that very strong earthquakes with magnitude > 8 have occurred in the past almost everywhere in Indonesia, except in Borneo Island. Major earthquakes occur along the Sumatran Fault about once or twice every decade. Earthquakes of magnitude > 8 have been directly responsible for thousands of fatalities on this island (e.g. in 1833 or 1861). On 26 December 2004 (i.e. Boxing Day), a 9.1-magnitude earthquake triggered a tsunami in the Indian Ocean that killed 230,000 people, nearly three-quarters of whom were in Aceh (Lavigne et al., 2009). In October 2010, ten villages on the Mentawai islands were swept away by a 3-meters tsunami generated by a 7.7 magnitude quake. Deadly earthquakes triggering potential tsunami are also frequent in Java; in 2006, 5,700 people were killed by the 27 May earthquake and more than 800 by the 17 July tsunami. Deadly tsunamigenic earthquakes may also occur off the Lesser Sunda Islands (e.g. Flores in 1992 or Sumba in 1977) or off Papua (1996).

Houses damaged by the 9.1 quake in Banda Aceh (26.04.2004)

© F. Lavigne, 2005

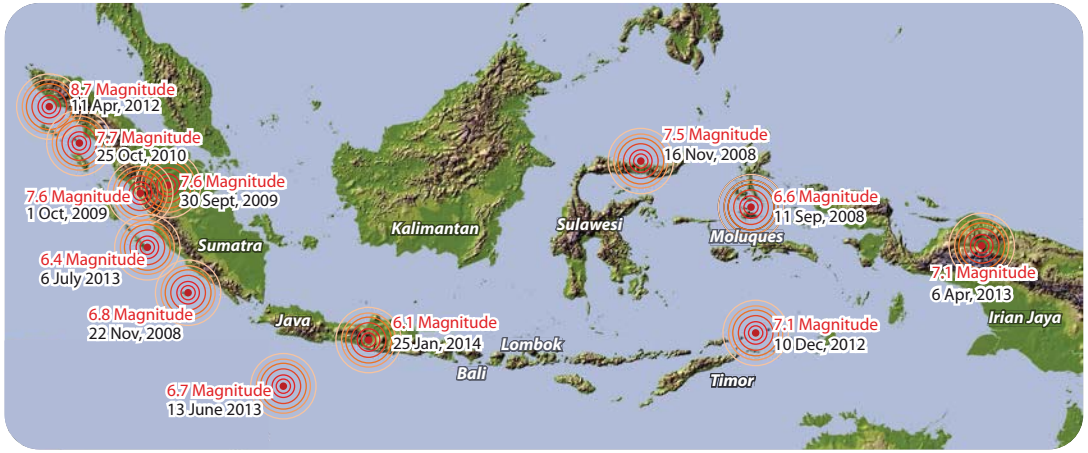
Subduction process and island arc



Source: Trista L. Thornberry-Ehrlich, Colorado State University, http://www.nature.nps.gov/.

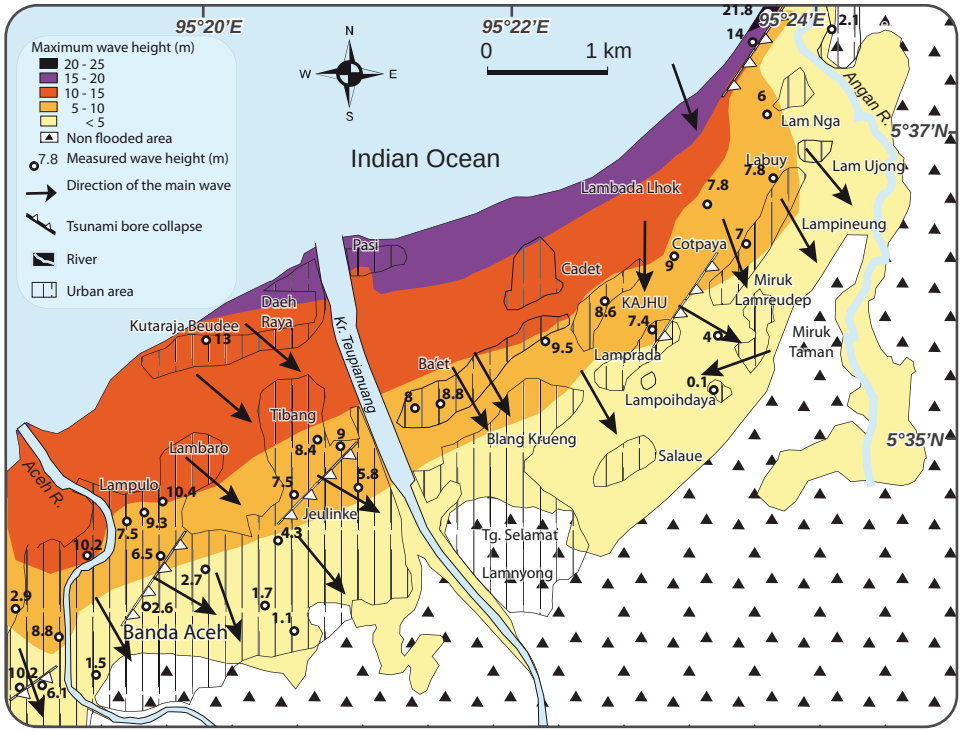
An island-arc setting includes a chain of offshore, island volcanoes above a subducting plate. The back-arc is located opposite the trench and subducting plate, behind the chain of volcanoes called an "island arc".

Distribution of recent Large earthquakes in Indonesia (2008-2014)



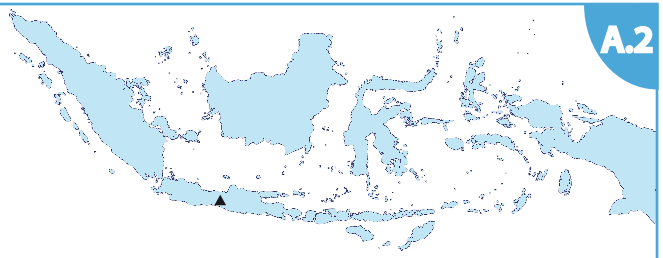
Source: Modified after mapsofworld.com and www.treehouse-maps.com.

Tsunami propagation across Banda Aceh on 26.12.2004



Source: Lavigne et al., 2009

Volcanoes of Indonesia

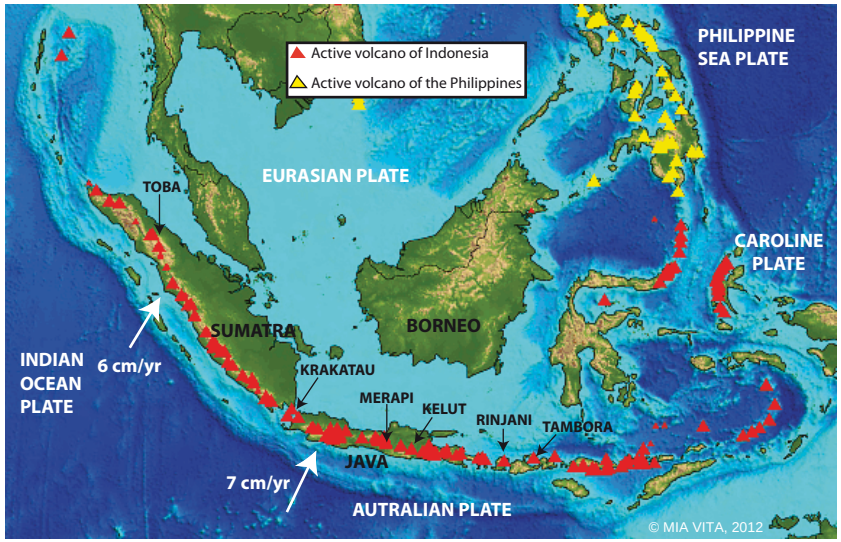


Volcanoes in Indonesia are part of the Pacific Ring of Fire. The Indonesian archipelago contains about 130 active volcanoes, which is more than any other country. About 76 of them have erupted in historical times. It contains some of the world's most famous volcanoes like Toba, Krakatau, Tambora, and Merapi.

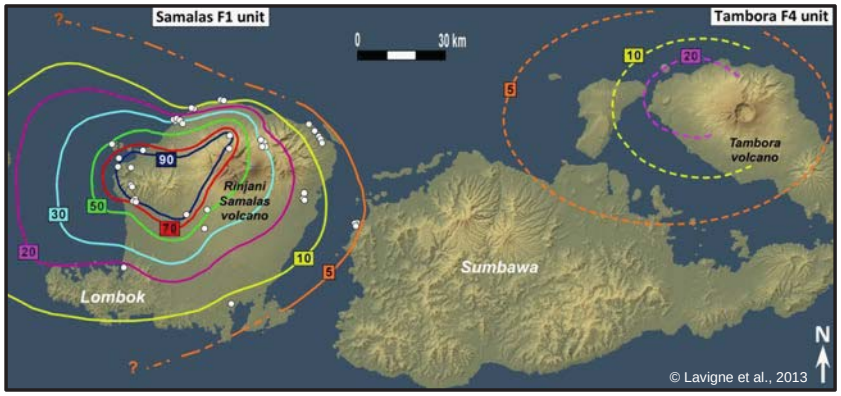
The most active volcanoes of the country after Merapi are Semeru and Kelut, both on East Java. Semeru (3676 m) has erupted continuously since 1967, generating daily vulcanian explosions, pyroclastic flows every 1 to 7 years, and lava flows twice a century on average.

Since AD 1000, Kelut has erupted more than 30 times, of which the largest eruption was at scale 5 on the Volcanic Explosivity Index (VEI, defined by Newhall & Self, 1982). It has been responsible for thousands of deaths on Java island, mainly due to the sudden draining of its crater lake and subsequent lahars. Its last major eruption on 13 February 2014 sent a column of ash 25 km high, killed 2 people and forced 200,000 people to evacuate.

Distribution of active volcanoes



Thickness of the main Plinian fall deposits of Samalas AD 1257 and Tambora AD 1815

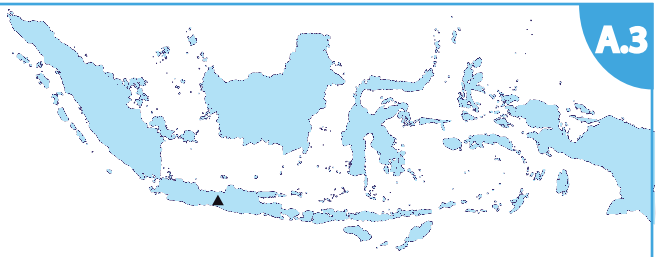


Indonesian volcanoes are best known for their catastrophic eruptions with worldwide climatic impacts. Mount Tambora was notable for the most violent eruption in recorded history in April 1815. The explosion was heard on Sumatra island more than 2000 km away. Volcanic ash falls were observed almost everywhere in Indonesia. Most deaths from the eruption were from starvation and disease, as the ashfall ruined agricultural productivity in Sumbawa and Lombok. The death toll was at least 71,000 people.

A recent study demonstrated that a similar –an even larger- catastrophic eruption occurred in AD 1257 in Lombok island (Lavigne et al., 2013). Like at Tambora, the summit of Mount Samalas, a former volcano part of the Rinjani volcanic complex, collapsed to form a 6-km wide caldera. Based on ice core records, this eruption yielded the largest volcanic sulfur release to the stratosphere in the past 7000 years. The huge amount of ash (in excess of 30 km^3) blasted into the upper atmosphere by the 1257 and 1815 eruptions of Samalas and Tambora contributed to an abnormal and highly destructive worldwide weather event the following year. Both 1258 and 1816 became a *year without a summer* in Europe and Northern America. Widespread crop failures caused hunger and even famine in some places.

Further back in time, the Toba super-eruption that occurred about 73,000±4000 years Before Present (BP) might have expelled ~ 2800 km^3 of volcanic material, and made a sizable contribution to the present 100×30 km caldera complex.

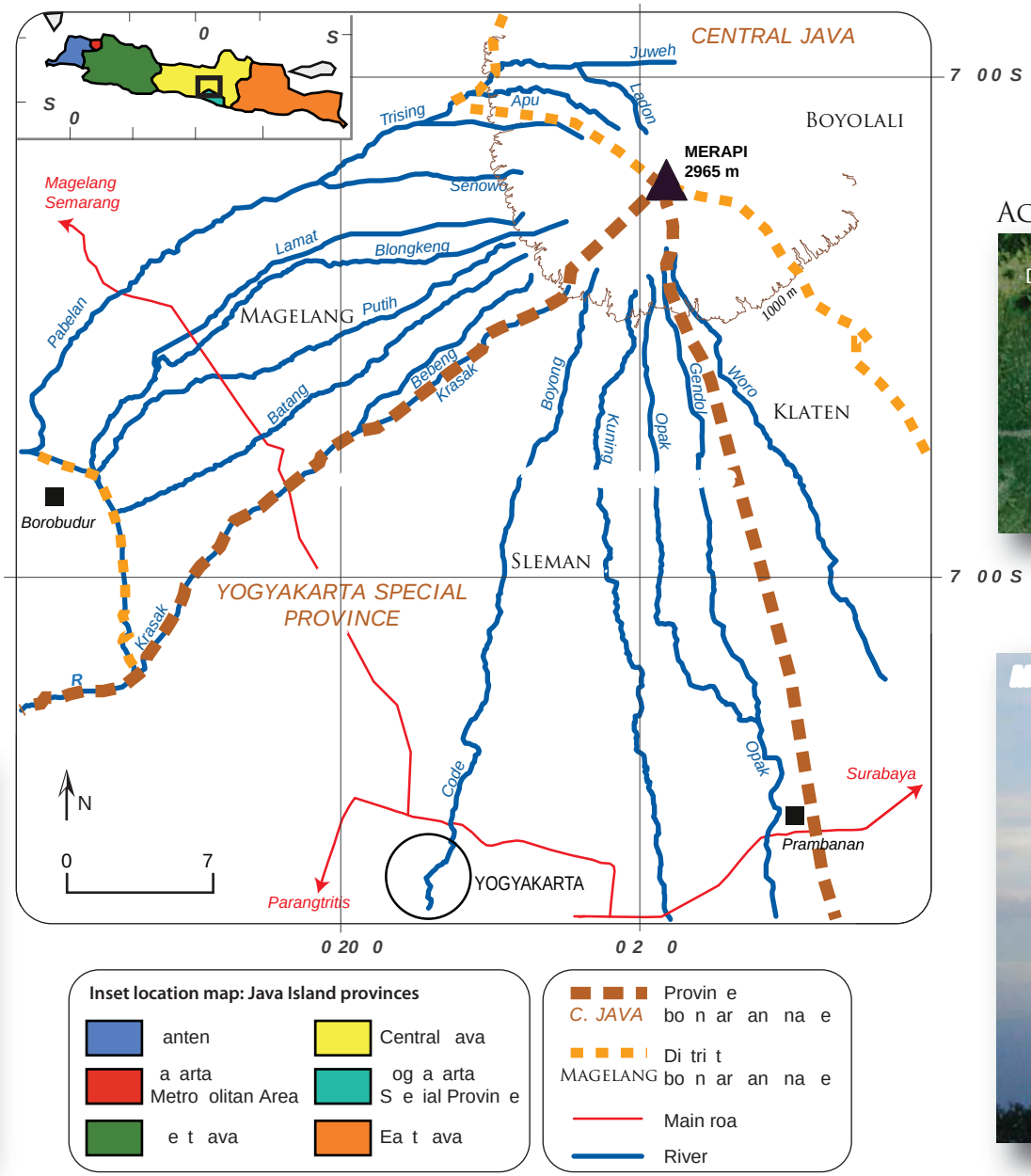
Location of Merapi volcano



Merapi stratovolcano (2965 m) is located in Java, Indonesia, 30 km north of the city of Yogyakarta. This region is famous for its pre Islamic temples, especially Borobudur and Prambanan temples.

Merapi is the last edifice of a WNW-ESE trending chain of volcanoes in Central Java. It includes Mt. Sumbing (3371 m. a.s.l.) and Mt. Sindoro (3151 m a.s.l.), which are active volcanoes although their activity has been very limited over the past centuries (e.g. Sumbing has had only one historic eruption in 1730). On the other end of the chain, Dieng Volcanic Complex is expressed topographically as a highland plateau (~2000 m a.s.l.), with an extensive assemblage of spatially, temporally, and genetically related major and minor volcanic centers.
Merapi belongs to a second group of four stratovolcanoes oriented N-S that includes Ungaran, Telomoyo and Merbabu volcanoes.

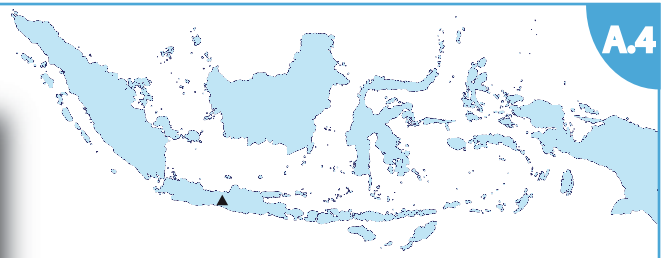
Location of Merapi volcano



Administratively, it is located on the border four districts or *kabupaten*: Sleman in the Special Region of Yogyakarta, and Magelang, Boyolali and Klaten in the Central Java Province.

Active volcanoes around Merapi

Climatic context



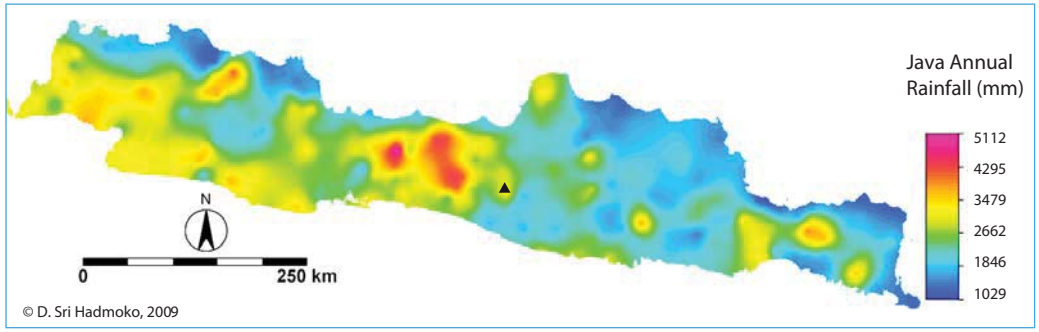
Java experiences a tropical monsoon climate, with average daytime temperature ranging from 19°C to 30°C, and two distinct seasons: the rainy season running from October to April, and the dry season running from May to September. Most rainfall occurs between 12 and 19 h, with the tendency more prominent in the rainy season, which accounts for as much as 80% of the annual rainfall.

Due to the wind direction during the rainy season and to topographic effects, the rainfall is more intense on Merapi's western flank. The 15-year average annual rainfall between 1976 and 1990 was 3253 mm at Plawangan (1275 m elevation, south slope) and 2,416 mm at Babadan). However, the actual yearly amount ranges at various stations from 2000 mm to 4500 mm.

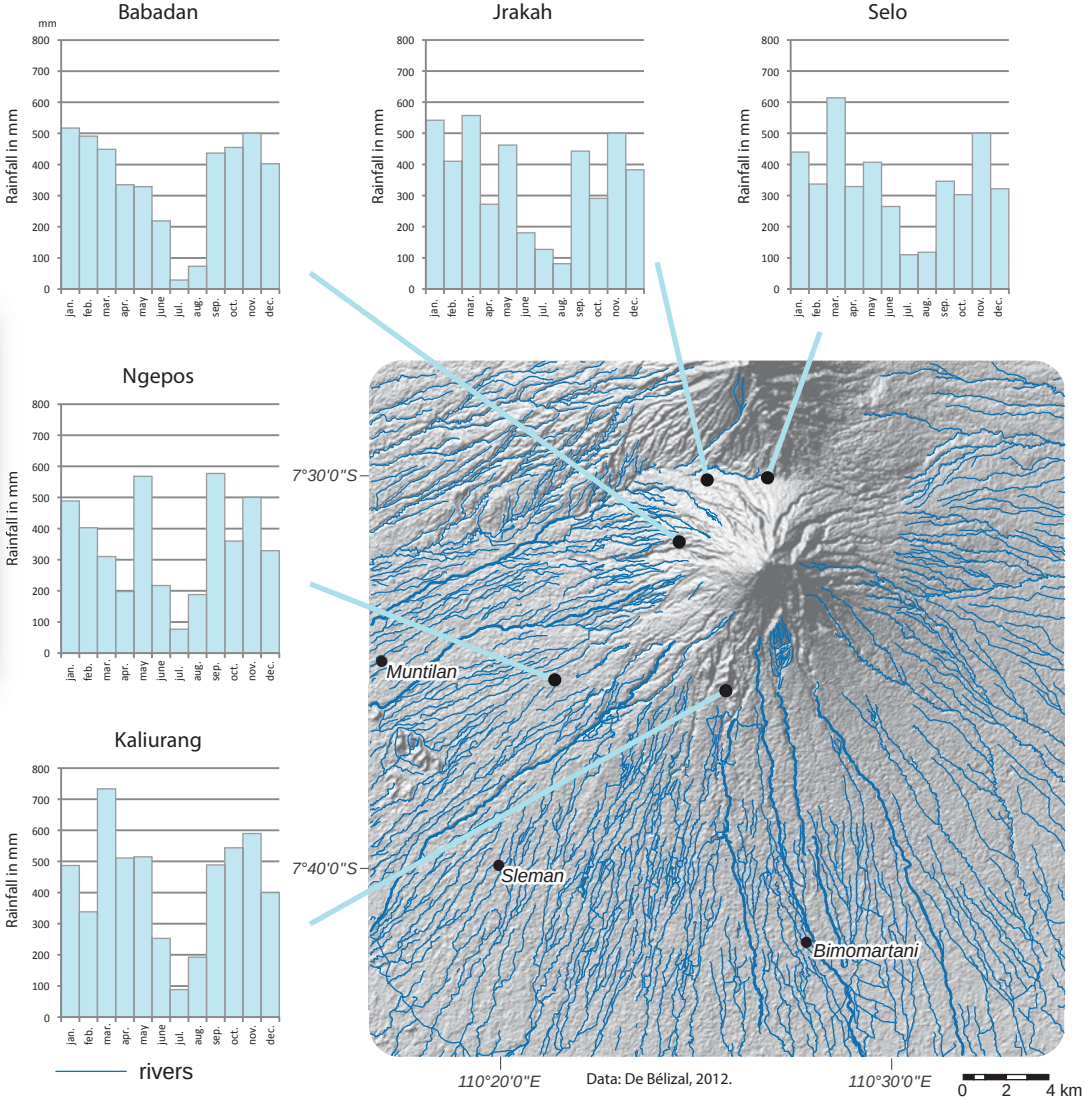
Although typhoons do not strike Indonesia, the heaviest rains occur during high-intensity tropical storms. Exceptional rainfall can be as much as 466 mm/day recorded at Ngepos station on 25 November 1979. Between 1980 and 2000, rainfall exceeded 100 mm/h at least seven times on the slopes of Merapi (Lavigne et al., 2000). The role of rainfall is crucial, as it remobilizes volcanic material, triggering lahars (volcanic debris flows). At Merapi, the time of lahar generation coincides with strong rainfall intensity.

Two types of triggering rainfalls are commonly distinguished, local rainfall (also termed stationary, orographic, or updraft rainfall), confined to slopes above 1200 m in elevation, and regional (or migratory) rainfall, that is transported from the NW or the SW (Lavigne et al., 2000).

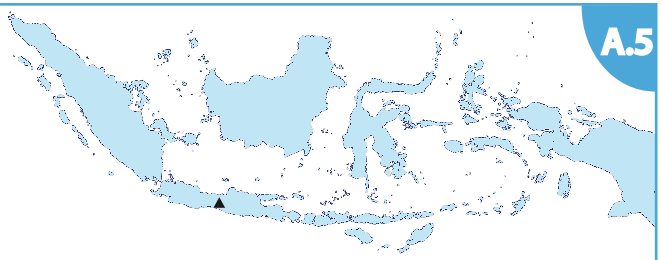
Rainfall distribution in Java



Rainfall around Merapi in 2010



A Highly Populated Volcano



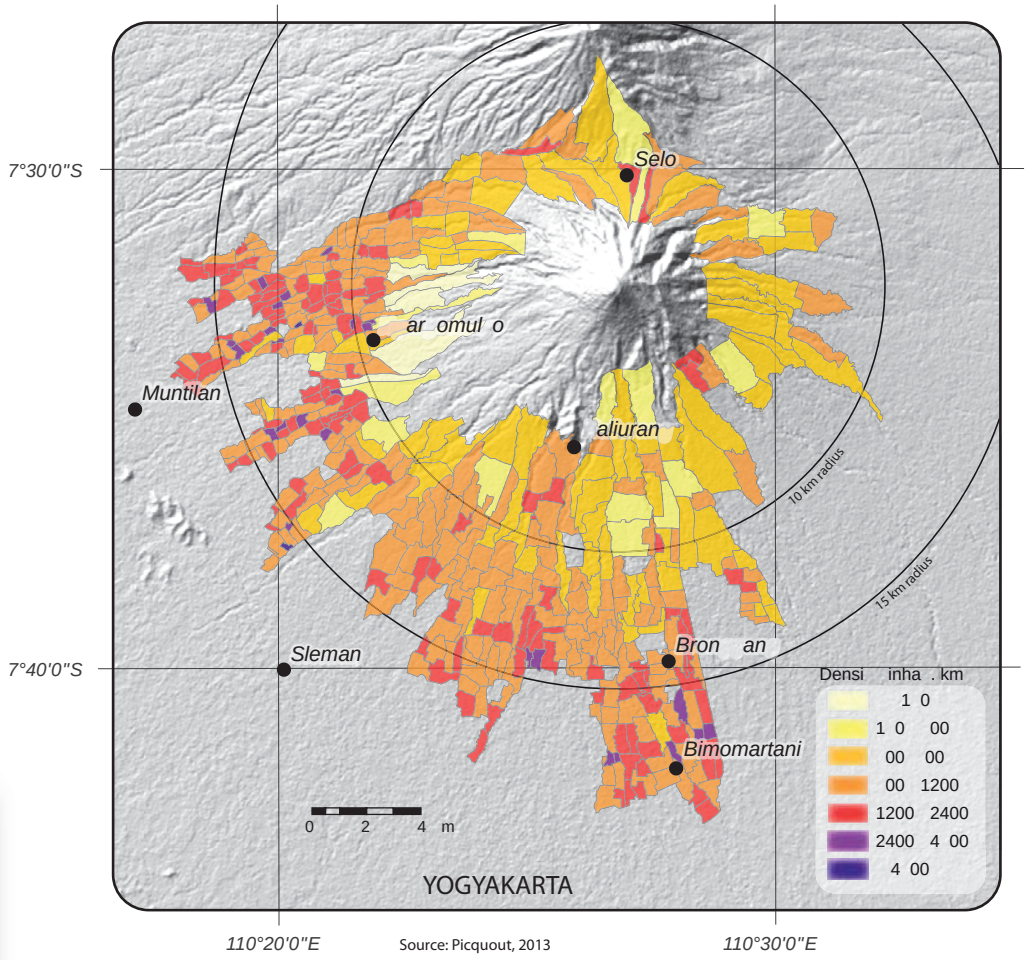
Out of the 1.1 million people living on the flanks of the active Merapi volcano, more than half are at high risk in areas prone to pyroclastic flows, surges, and lahars. People accept the risk because of the rich volcanic soil. Over time, volcanic deposits can develop into some of the richest agricultural lands on Earth.

Mapping human population density around Merapi reveals an increase in density from the summit to the base of the volcano's flanks. Within a 10 km radius of the summit, the most hazardous area, population densities are of an average 764 inhabitants per square kilometer. Some highly populated villages (> 1500 inhab./km^2) settled within a 5 km radius area are very exposed to the volcanic hazards.Their vulnerability is increased because the local people must use steep, damaged roads to flee. On the southern flank, the villages climb the volcano slopes up to 1150 m a.s.l. around the Gendol and the Woro rivers. Further south, population densities increase considerably between 200 and 400 m high, due to the attractive proximity of Yogyakarta city. Yogyakarta urban area is located on a highly populated, fluvio-volcanic plain. The city is the political, economic, social and cultural center of the special Province of Yogyakarta. For 50 years, this city of over 1 million inhabitants has attracted people from the surrounding overcrowded rural areas. In order to preserve the productive tilled lands and irrigation networks around the city, the government has attempted to control the urban growth. The guidelines in the master plan have restricted the extension of the city. However for the last 30 years, thousands of migrants have settled within areas prone to floods and lahars along the Code river.

In 1995, about 13,000 people were already living at risk in the suburbs of Yogyakarta along the Code River with the population density exceeding 5600 inhabitants per km^2.

Villages located on Merapi's western flank are densely populated due to the importance of rice cultivation. A very high population density is required, as this type of farming is very labour intensive since all work is done by hand. As this activity can develop along steep slopes, high population density is noted up to Ngargomulyo's altitude, within the 10 km radius around the summit.

Population Density



Source: Picquout, 2013

© : 2014 satellite image from CNES (Google Earth)

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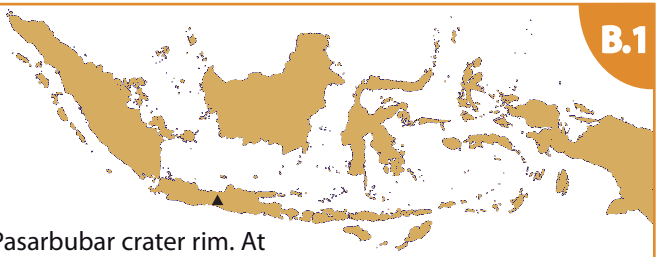
The Geology of Merapi and Its Volcanic Hazards

Growing dome in Merapi crater © J. Morin, February 2013

Geology of Merapi Volcano



Several periods of growth and destruction of the Merapi stratocone have preceded the present volcano. Three edifices have been distinguished by Newhall et al. (2000): the Proto-Merapi (>5000 BC), the Old Merapi (5000 BC- 0 AD), and the New Merapi (since 0 AD). Plawangan and Turgo hills on the Southern flank of the volcano, as well as Bibi hill on the Eastern flank, are considered remnants of old lava flows (>100,000 years) from the Proto-Merapi.

The Eastern flank of the present edifice is also covered by more recent lava flows (purple on the map), dated from 30,000 to 5,000 years (Gertisser et al., 2012). The arcuate faults on this flank are thought to parallel the scars of at least two flank failures whose ages are still debated. The main collapse which may have occurred between 1600 and 1100 year BP (Newhall et al., 2000) left a somma rim high on Merapi's eastern slope that may parallel the Pasarbubar crater rim. At a radial distance of a few kilometers from the Merapi cone, the volcanic deposits that are now exposed (from pyroclastic flows and surges, ash fall and lahars) are essentially Holocene in age.

Merapi - Volcano-stratigraphic units

New Merapi

- 8 — Lava domes of the recent episode [1888 AD - Present (direct observation and historical accounts)]
- 7 — Recent and mostly historical pyroclastic-flow and lahar deposits [? ≤ c. 1550 AD - Present (historical accounts and ^{14}C dating)]

Old Merapi

- 6 — Young (post-Somma-Merapi) lava flows [1.7 ± 1.7 ka (K-Ar)]
- HPS*
  - 5 — Pyroclastic-fall deposits [< 11,792 ± 90 ^{14}C y BP (^{14}C)]
  - 4 — Pyroclastic-flow and lahar deposits [< 11,792 ± 90 ^{14}C y BP (^{14}C)]
- 3 — Lava flows of the Somma-Merapi [30.3 ± 1.0 ka; 29.4 ± 1.0 ka; 24.2 ± 0.8 ka; 10.7 ± 0.8 ka; 8.6 ± 1.4 ka; 4.8 ± 1.5 ka (K-Ar)]

Proto-Merapi

- 2 — Lava flows of Gunung Turgo and Gunung Plawangan [138 ± 3 ka; 135 ± 3 ka (K-Ar)]
- 1 — Lava flows of Gunung Bibi [109 ± 60 ka (Ar-Ar)]

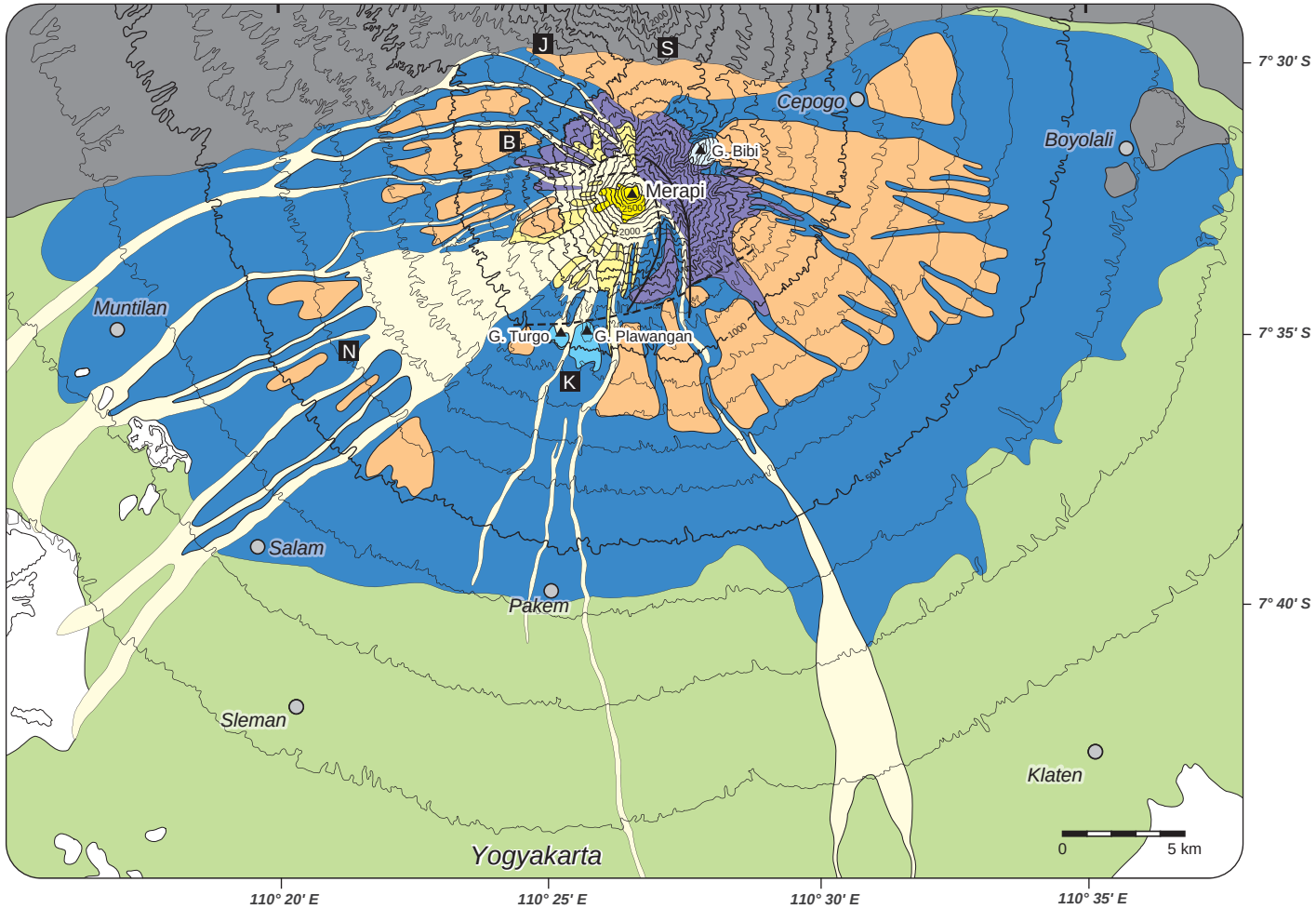
* HPS = Holocene Pyroclastic Series

Other units and symbols

- Surficial deposits
- Rocks of Merbabu volcano
- Cenozoic rocks of the Menoreh and Southern Mountains
- Faults

Volcanological Posts

- B Babadan
- J Jrakah
- K Kaliurang
- N Ngepos
- S Selo



Source: data and map from Gertisser et al. 2012.

Eruptive History and Hazards

Over the last two centuries, Merapi's activity has regularly alternated between long periods of viscous lava dome extrusion and brief explosive episodes at 5-8 year intervals, which generated dome-collapse pyroclastic flows and destroyed part of the pre-existing domes.
Violent explosive episodes recurring every 26-54 years on average have generated pyroclastic flows, surges, tephra-falls, and subsequent lahars.

One of the most dangerous hazards at Merapi is the dome-collapsed pyroclastic flow, also called "*Merapi-type nuée ardente*". Although its travel distance is usually less than 8 km, this type of pyroclastic density currents (PDCs) occurs without any natural (e.g. seismic) warning. On 22 November 1994, 64 people were killed by such events in the Turgo village.
The 61 reported eruptions since the mid-1500s have killed approximately 7000 people (Voight et al., 2000).

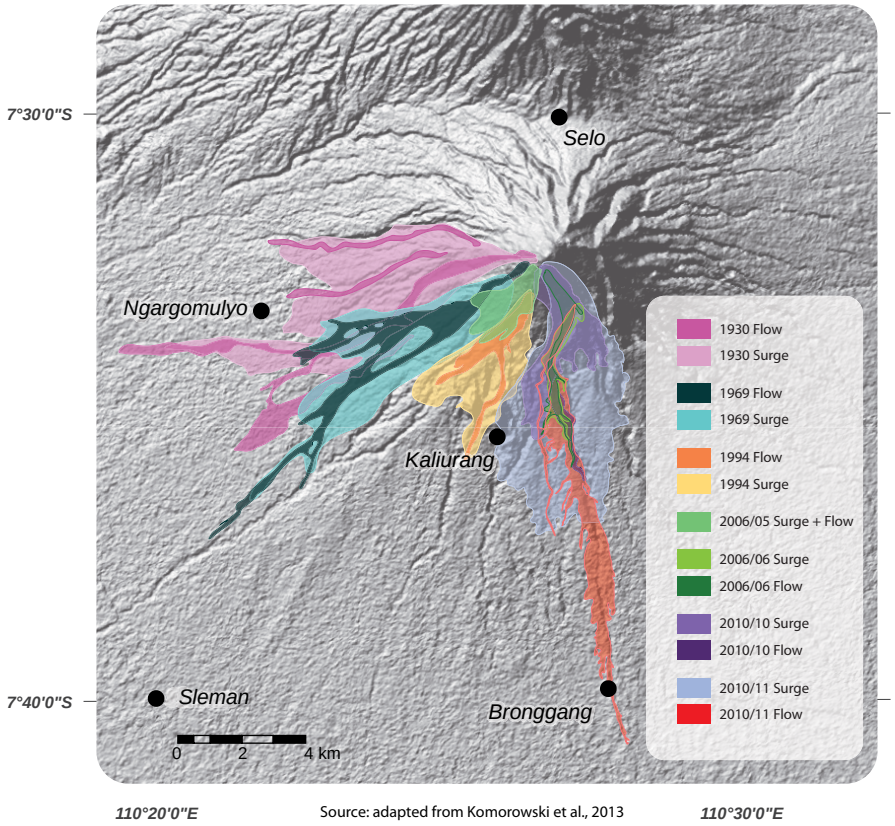
Major Merapi eruptions since 1872

Date of eruption	VEI	Volume ejected (million m^3)	Victims	Injured	Evacuated or made homeless
1872	4		200		
1904	2		16	45	3 000
1920	2	5	35		1 000
1930	3	26	1 369		13,000
1954	2	20	64	57	3 000
1961	3	29.4	6	6	8 000
1994	2	3.5	64	500	6 026
1998	2			314	6 000
2006	1	13.3	2		22,253
2010	***4***	***150***	***341***	***368***	***1 300,000***

VEI= Volcanic Explosivity Index

Sources: Thouret et al. 2010; Mei and Lavigne 2012

Main Pyroclastic deposits since 1930



Source: adapted from Komorowski et al., 2013

Main hazards

Pyroclastic Density Currents

Pyroclastic Density Currents (PDCs) are a combination of superheated gases and rocks (tephra, between 200 and 1000°C) rushing down the flanks of volcanoes at velocities reaching up to 194 m/s (700 km/h). They raze and burn everything to the ground on their way. There are two main types of PDCs: (1) concentrated pyroclastic flows controlled by topography, and (2) dilute turbulent high energy currents (pyroclastic surges).

Ash

Volcanic ash is composed of small fragments (<2 mm) of pulverized rock, minerals and volcanic glass. It is ejected into the air by volcanic eruptions and spreads widely. Ash can generate health problems for people and livestock, disrupt air traffic, transportation, and damage electric power supply systems, as well as communications, water and waste-water networks. Ash also impacts buildings (e.g. roof collapse).

Lahars

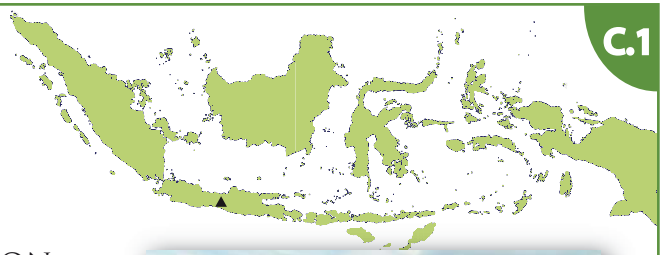
Lahars are debris flows or hyperconcentrated flows composed of volcanic material transported by water. At Merapi, their occurrence is due to intense precipitation that re-mobilizes unstable materials left by previous eruptions. Their surface velocity is between 2 and 8 m/s (7 to 29 km/h), and their discharge reaches hundreds of cubic meters per second (peaks can reach 1800 m^3/s or more at Merapi).

Main Resources on Merapi

© F. Lavigne

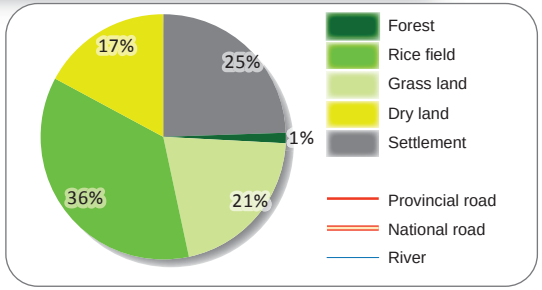
Rice fields at the foot of Merapi © Noer Cholik, BPPTKG

Land use and agriculture

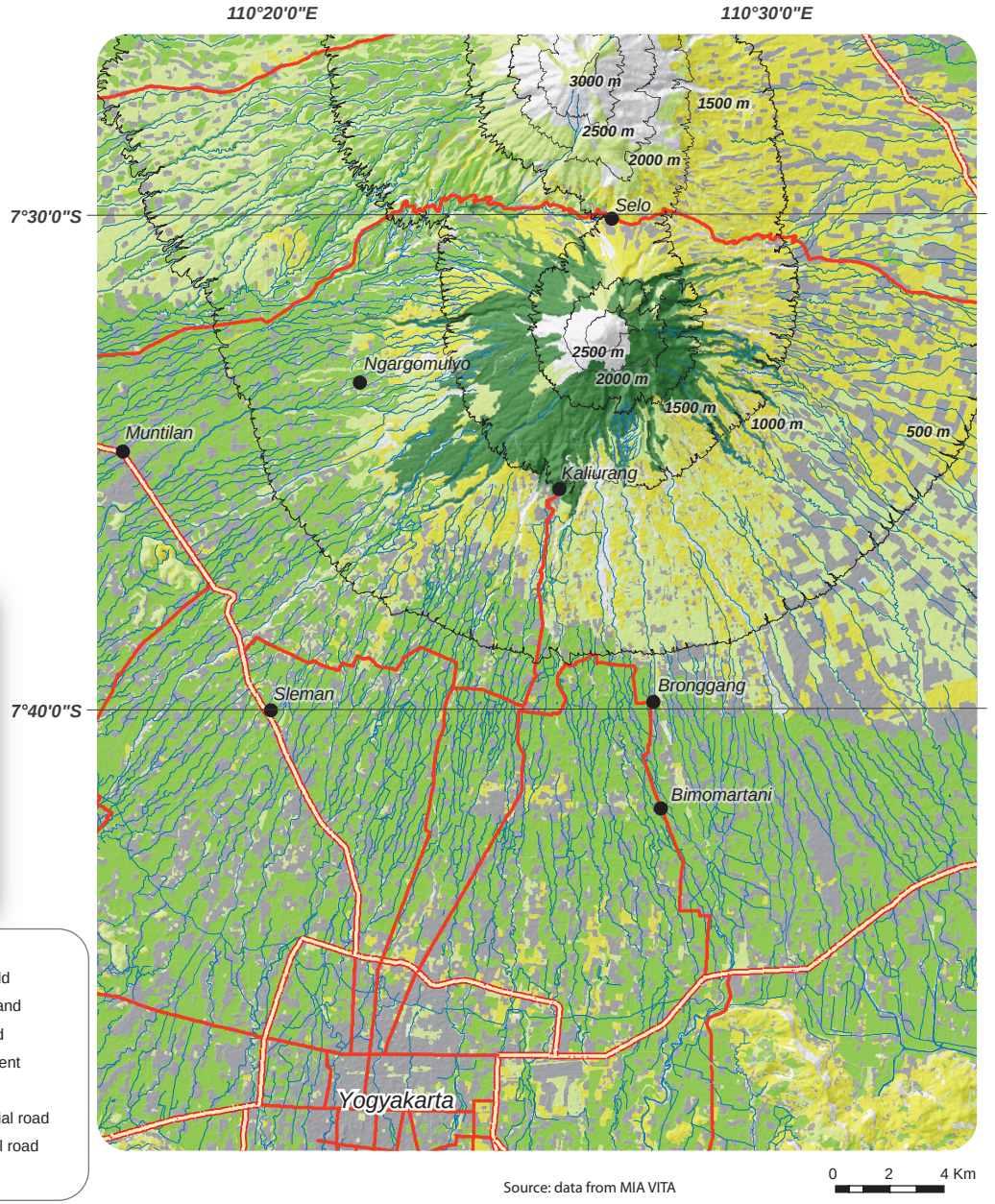


Merapi's surroundings are essentially rural. Rice fields represent the main land cover (36%), followed by settlements, grasslands and dry lands. All the land is exploited, except Merapi's steepest slopes, which are covered by forests. Settlements also take up an important share of land use (25%), especially close to Yogyakarta. There is a contrast between Merapi's western flank, where rice fields are dominant, and its northern and eastern flanks, where dry lands are located.

Unquestionably, there is more rainfall on Merapi's western flank, providing the necessary conditions for rice production. Most farmers concentrate on small fields, modeling the landscape with terrace cultivation. Irrigation systems, widely developed in this area (41% of the cultivated area), contribute to the high productivity of rice fields.



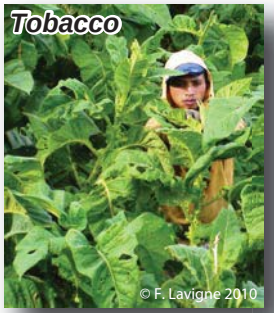
Land use around Merapi Before the 2010 Eruption



Source: data from MIA VITA

Dry lands represent 23% of the cultivated area around Merapi. Most of them belong to the Tegalan type, i.e. dry fields that do not involve fire to enable cultivation on slopes as for the Ladang type. Food crops are dominant (e.g. peanuts, cassava), but commercial crops are also planted such as tobacco, chili, or fruits like salak.

Cultivation practices also include home gardens created within villages, providing families with extra food and income. The cultivation system is stratified and complex: cooking herbs, sweet potatoes, tomatoes and chili lay on the ground. Cassava plants provide roots and leaves that can both be eaten. Vines that produce beans, squash or edible berries are often cultivated on bamboo trellises around the edge, along with bananas. A few tall fruit trees provide protection or shade for the smaller plants.



Livestock

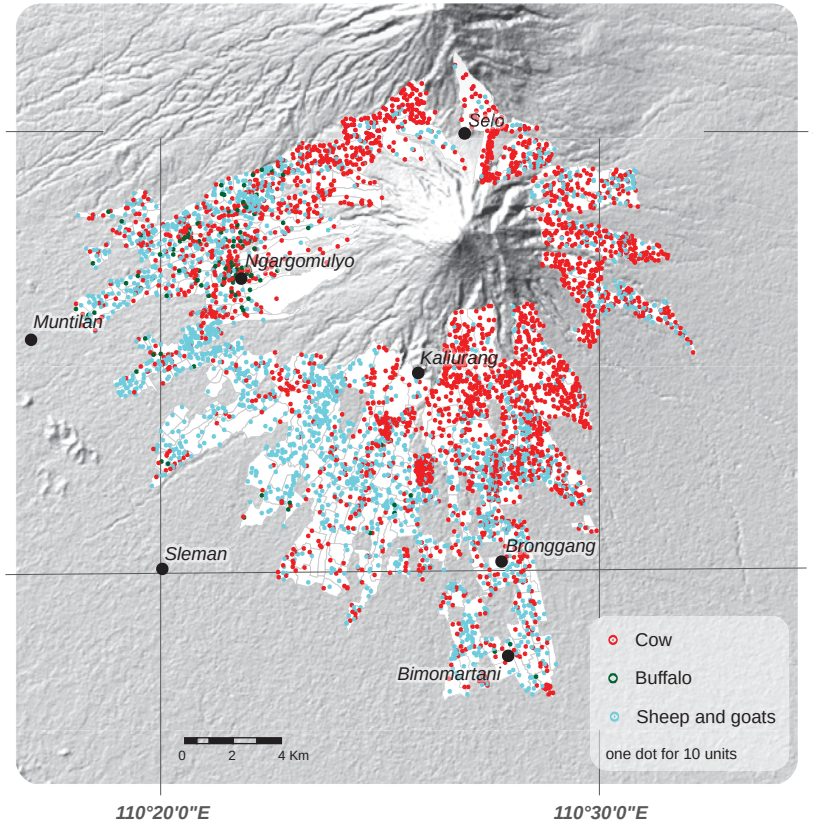
Livestock is considered more as a food livelihood than an economical resource, as it represents important food stocks for local communities on Merapi slopes.

Cows represent the main livelihood through milk production and sale. Cow stocks are mostly spread out along the slopes where they can graze freely (Natural Reserve, Dove 2008), while sheep and goat stocks can be found everywhere. Most buffalos can be found on the western side of the volcano and are used as workforce in rice fields. Pigs stocks are not considered as they are very limited in the Merapi area.

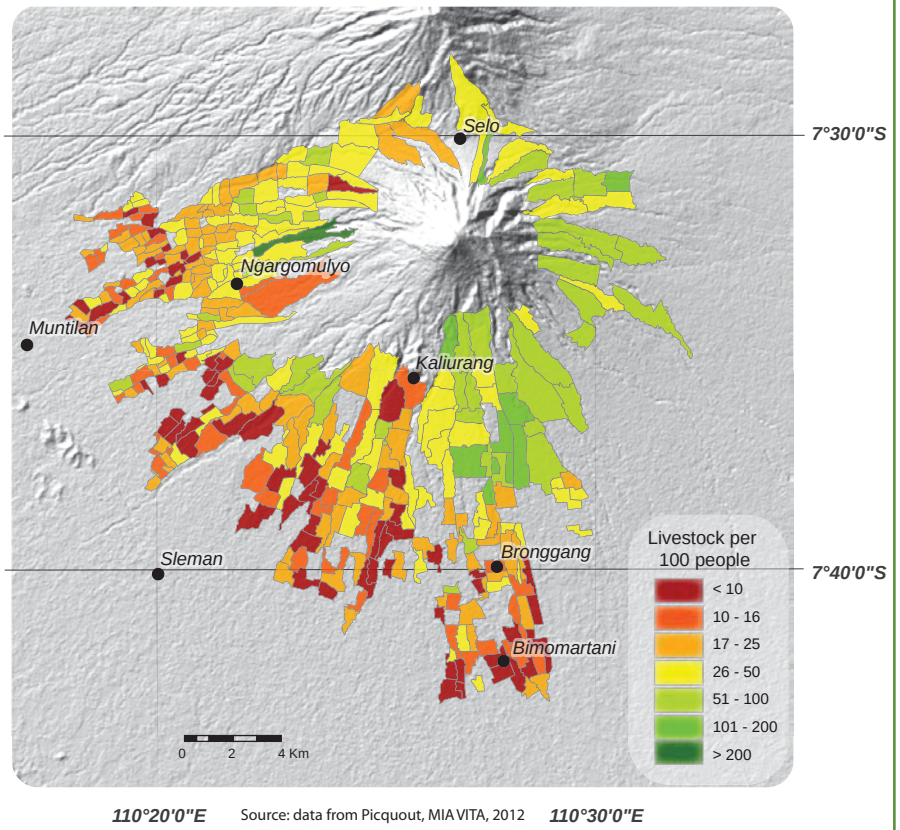
Livestock is not proportional to the amount of people living in each village. Merapi's eastern slopes show a high ratio of livestock per inhabitant, whereas the southern and south-western sides have a poor ratio of livestock per inhabitant.

Saving livestock during volcanic crisis is a major concern for the inhabitants. Apart from the risk of immediate death, e.g. in pyroclastic flows, it is sometimes difficult to find clean grass and water for the cattle after ash fall events.
Residents sometimes try to evacuate their animals when they evacuate themselves. If needed they are ready to face personal danger to continue feeding their animals in evacuated zones.

Livestock in 2010

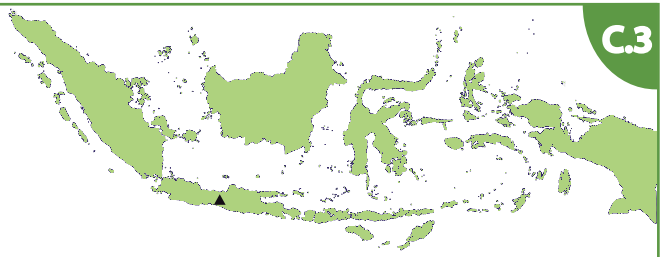


Livestock availability



Source: data from Picquout, MIA VITA, 2012

Block and Sand Mining

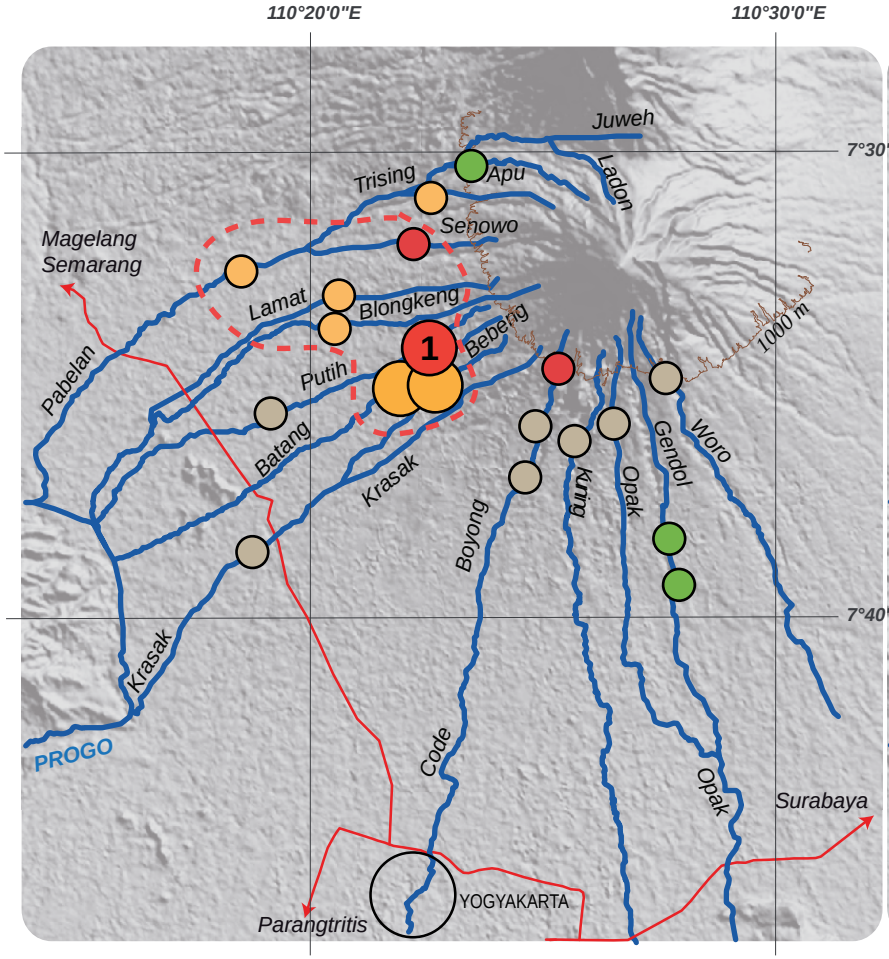


Block and sand mining is a widespread activity in the Merapi volcano valleys. Thousands people depend on these activities for income. The sand is used as building material, while blocks are sold as raw material for sculpture workshops and building.

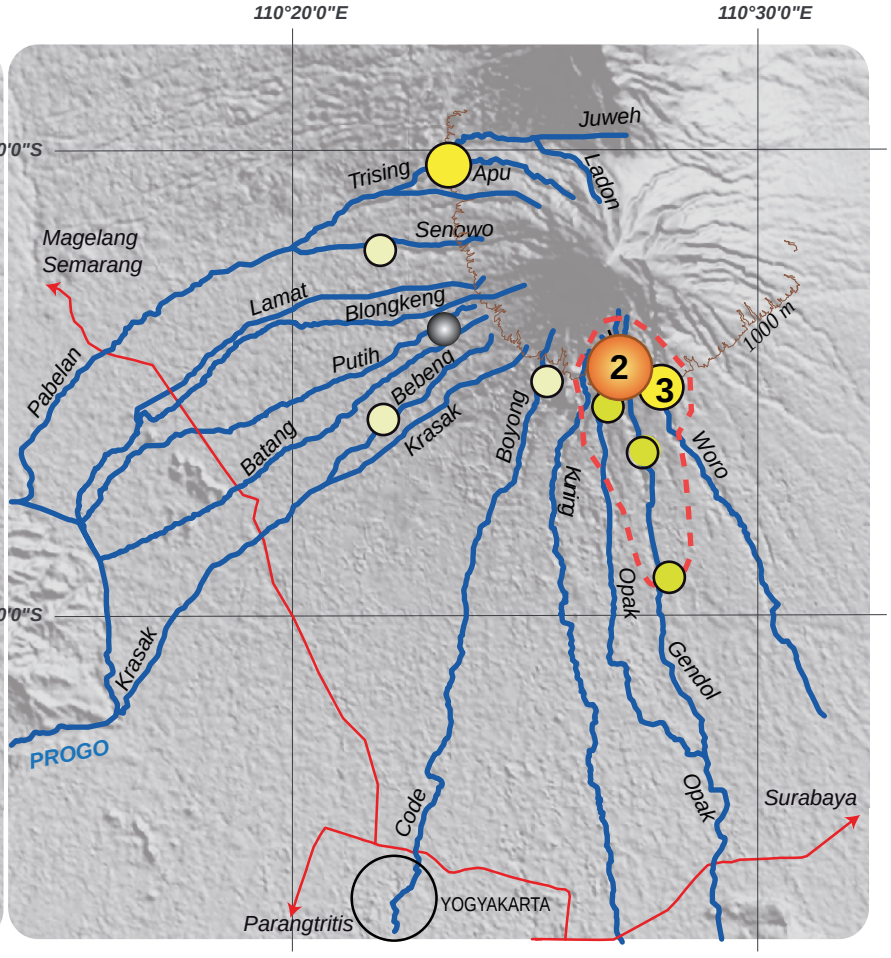
The most accessible areas for extraction are the beds of the main rivers, which are regularly fed by PDCs and lahars coming from the upper slopes of Merapi. While sand and blocks were mostly extracted along the Putih in the early 2000s, after the 2006 eruption and consecutive lahars, the extraction activity migrated to the Gendol, on southern flank. Therefore quarries change location according to the materials deposited by eruptions.

Kopeng quarry, Gendol river

Quarries in the early 2000's



Quarries in the late 2000's



Evolution \ Exploitation	> 2000 m³/day	< 2000 m³/day	Unknown volume
Decline early 2000s	●	●	
Decline mid 2000s	●	●	
Intensification mid 2000s		●	
Unknown evolution			●

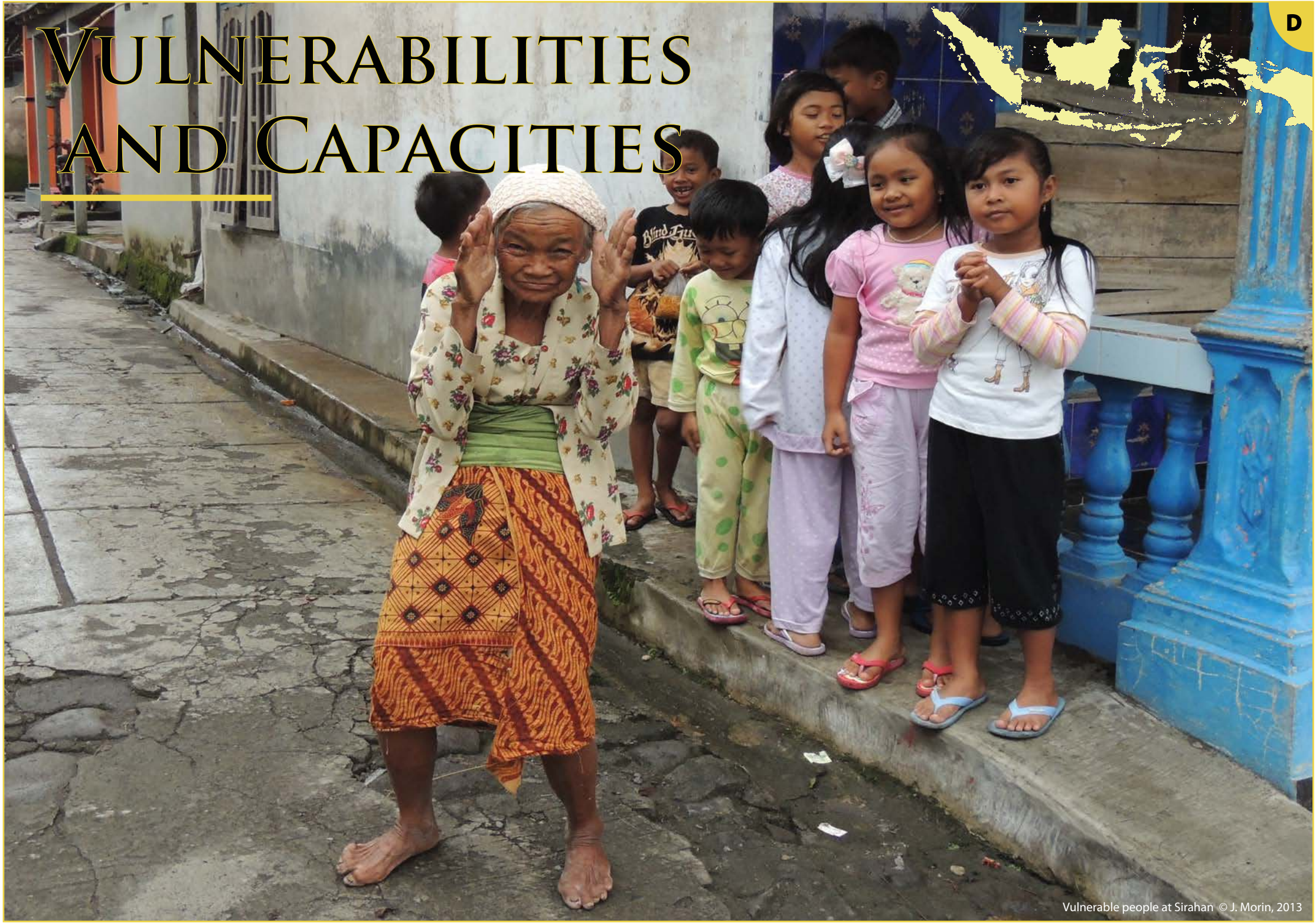
Main extraction basin
Main road
River
0 2 4 8 Km

1 Jurangjero
2 Jambu-Kaliadem
3 Balerante

Source: De Bélizal, 2012.

Main site (> 4000 m³/day)
Secondary site (800 to 1000 m³/day)
Peripheral site (< 800 m³/day)
Minor site (< 800 m³/day)
Closed site

Vulnerabilities and Capacities



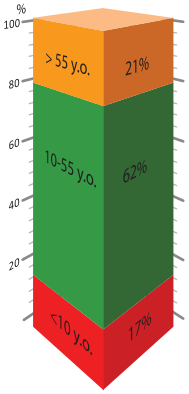
Vulnerable people at Sirahan © J. Morin, 2013

Vulnerable People

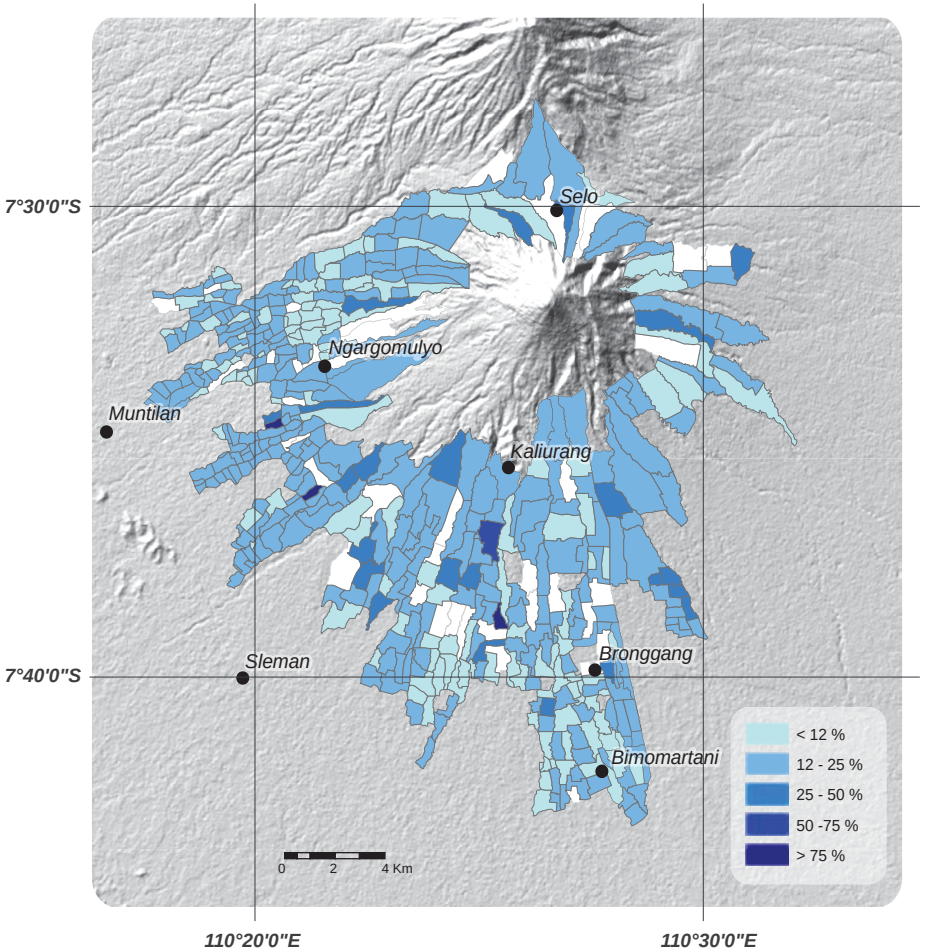
People over 55 are considered seniors in Indonesia (life expectancy at birth is 71.6 years). Elders, as well as children under 10 are particularly vulnerable. They represent 38% of the population around Merapi.

Elders, disabled people, and children require particular attention during evacuation: medical care and assistance for the elderly and adult supervision for the young. While schools can manage children's evacuation during school time, elders are less grouped and therefore harder to deal with. Both vulnerable groups need to be taken care of as quickly as possible when a threat is confirmed.
Mentally and physically disabled people represent a significant part of the population on Merapi's western flank.

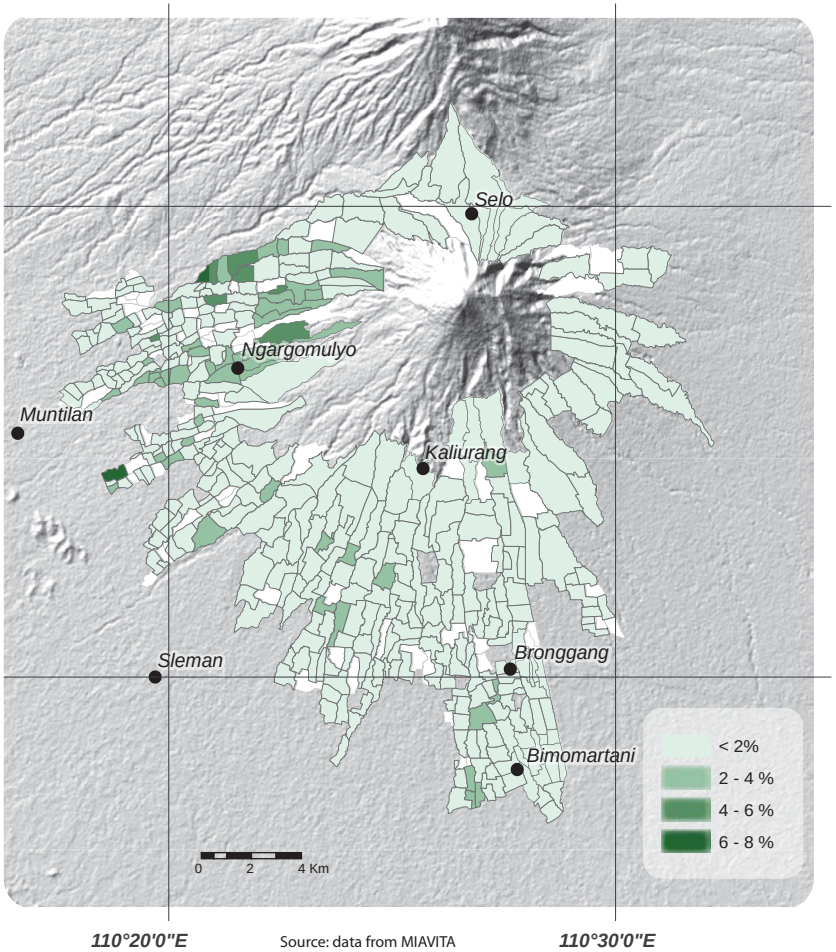
Age distribution of people around Merapi



Children (0 to 10 years) per Dusun in 2010

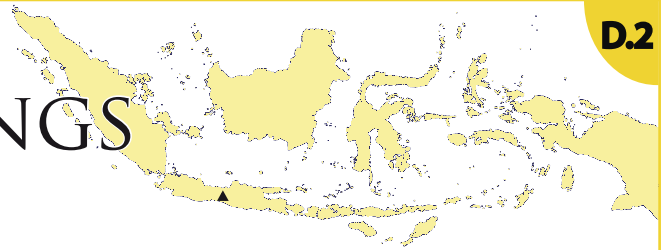


Disabled people per Dusun in 2010



Source: data from MIAVITA

Physical Vulnerability of Buildings



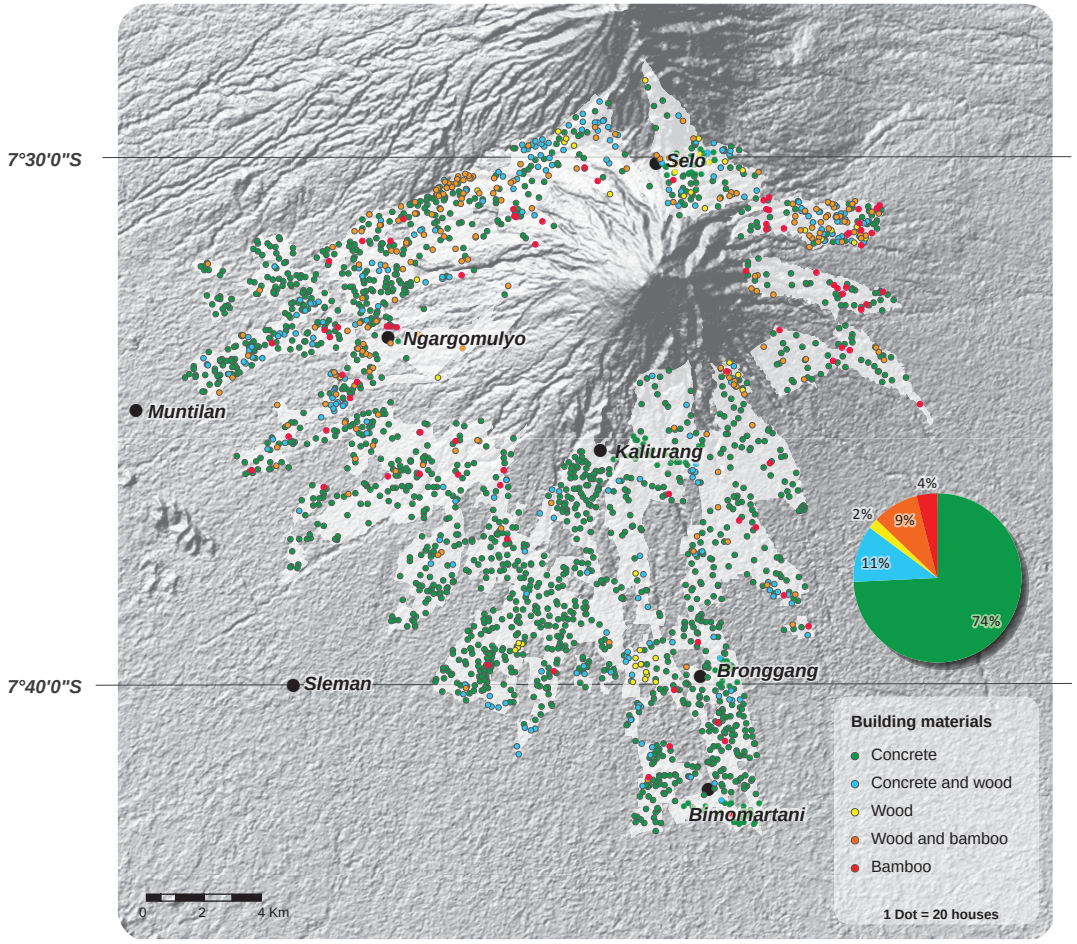
Around Merapi, built-up areas represent 16% of the land cover (45 km^2). On Merapi's western flanks where rice cultivation is the most important, houses are grouped, with densities of more than 200 houses per ha. On the eastern flank, mostly occupied by dry land cultures, settlement is more diffuse and houses are bigger.

Almost 3 out of 4 houses around Merapi are built with concrete. All new houses are built this way, whereas traditional Javanese houses have wooden walls, even if people tend to upgrade them with concrete.

A building's vulnerability depends on the material it is composed of, but also on the type of hazard that may strike it. During an eruption, pyroclastic flows destroy everything, whatever the construction material. However, pyroclastic surges do not impact all buildings in the same way: concrete buildings are more resistant. Architectural details of the structure also affect the way buildings resist destruction. For example, openings can let the flow go through, reducing its dynamic pressure on the building; however, the temperature of the surge and material carried within it may ignite any flammable material inside and cause fires.

Accumulation of ash on roofs can trigger collapse of buildings, especially if the ash is saturated by rain (up to 2000 kg/m^3: volcanoes.usgs.gov/ash/build/index.php). Main characteristics which affect the resistance to ash load are: the roof slope (flat roofs are more vulnerable), the roof span (bigger roof are more vulnerable), and the roof and building construction material.

Types of buildings around Merapi



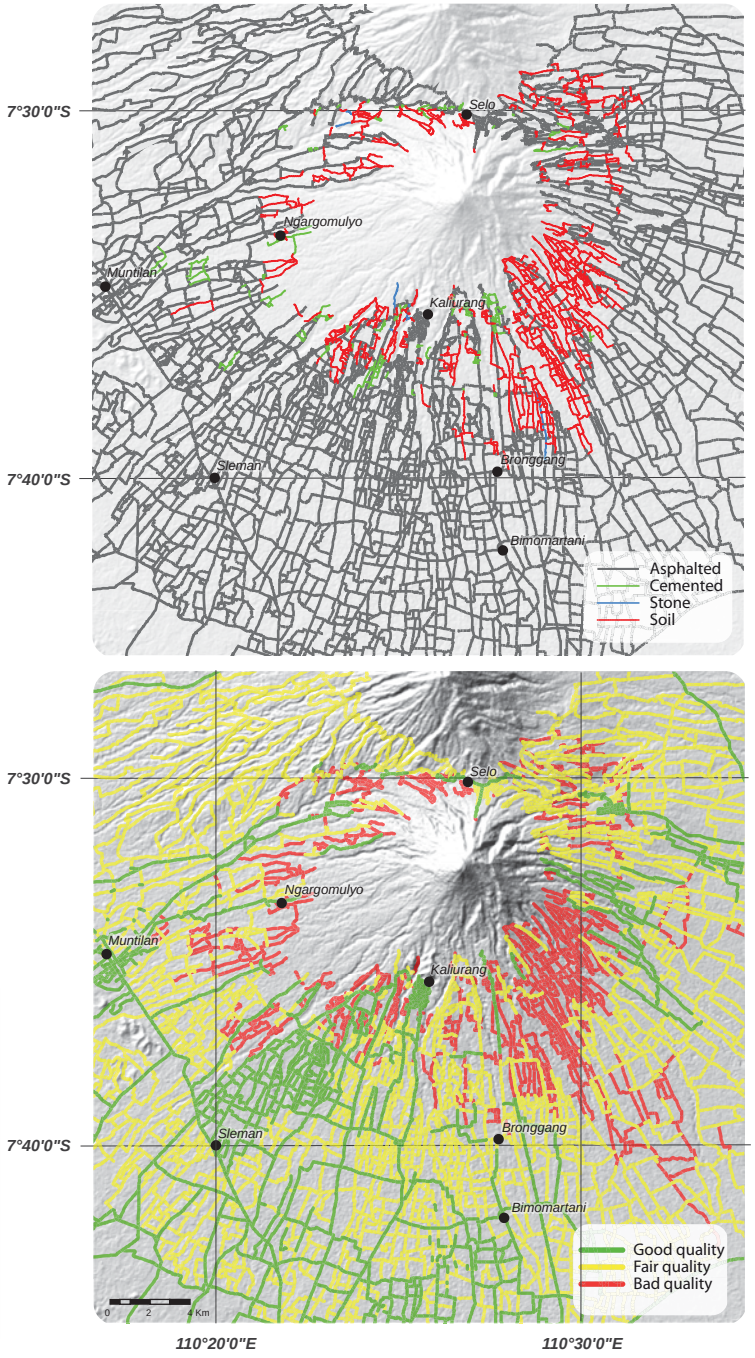
Source: data from MIAVITA

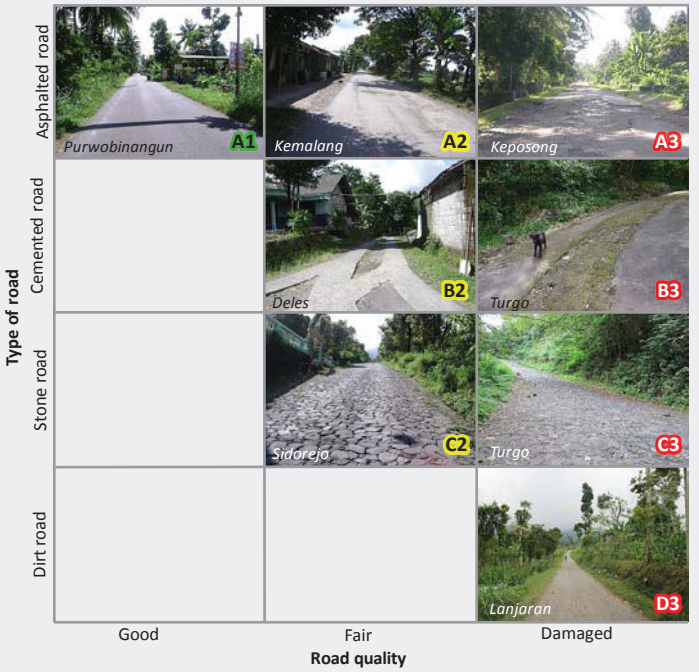
Road Network

Road material and quality

The road network is quite dense around Merapi. Main roads go straight up the volcano while secondary roads follow the volcano's contours and connect the main roads.
Provincial and district road conditions are relatively good. Local roads linking each municipality are mostly asphalt and the roads in the southwestern part of the volcano are in the best condition. In most villages, road conditions are inversely proportional to the altitude: the higher they are, the lower their quality (Mei et al., 2013).

The tropical downpours contribute to fast degradation of the network, especially on unpaved roads. In addition, roads covered by ash are very slippy. As a result, the velocity of evacuation with vehicles is very limited.
The maintenance of evacuation roads became a major issue for post-crisis management following the 2006 Merapi eruption (Mei & Lavigne, 2012). In response, local governments worked to enhance the quality of roads by paving them with asphalt. However, the condition of the roads degrades with time, especially because of trucks hauling volcanic materials (De Belizal et al., 2011).





Types of road material and quality:

A1: asphalt road with no surface deformation, cracking or potholes.

A2: asphalt road with light cracking or surface deformation, potholes already repaired.

A3: asphalt road with severe cracking, surface deformation and potholes.

B2: cement road in good surface condition.

B3: cement road with cracking and potholes due to humidity.

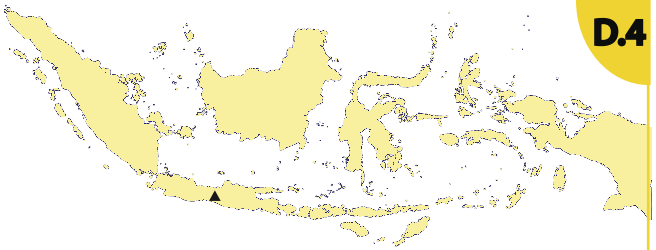
C2: stone road in good surface condition.

C3: stone road in poor surface condition.

D3: unpaved road or dirt road.

Source: data and pictures from Mei, MIA VITA

Transportation Capacity

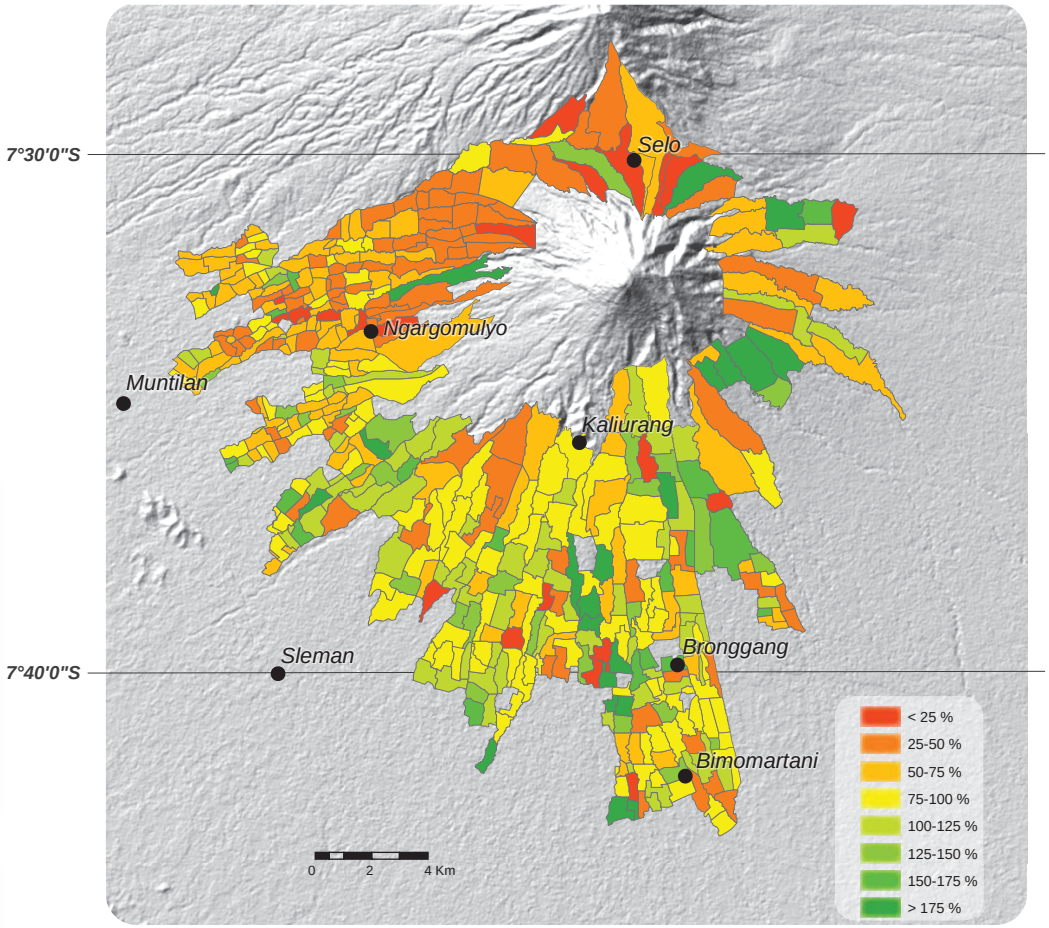


In Indonesia, the most commonly used means of transport is the motorcycle, because of its low cost. On volcanoes, this phenomenon is accentuated because the population is poorer. Cars are mainly used in big cities, essentially by the middle and upper classes. The census conducted within the MIAVITA Project on the available means of local transport, recorded an average of one car for 43 inhabitants and one motorcycle for 5 inhabitants. This census led to the evaluation of each village's transportation capacities, measuring the ratio of inhabitants that could be evacuated with local means of transportation.


Motorcycles in a village at Merapi
© M. Gherardi, 2013


Cars on a main road near Merapi
© F. Leone, 2013

Transportation capacity balance



Source: data from Picquout, MIA VITA

Buses and trucks are considered as being able to transport 30 people a minibus or and pick-up 10, a horse-drawn buggy 8, a car 6, and a motorcycle 3. The total transportation capacity is compared to the number of inhabitants to map the balance in transportation capacity.

Villages where the transportation capacity balance is 50% could only transport half of the local population. For villages with a balance of more than 100%, their transportation capacity would potentially enable the evacuation of the village's entire population.

The mapping of the transportation capacity balance displays a contrast between Merapi's northern and northwestern flanks and its southern flank. The population living on the northern flank is known to be more sedentary. Most inhabitants work in agriculture and sell their crops at markets close to their villages after having transported them by pickup. Accordingly, these modest income families do not invest much in means of transportation. Moreover, public transport networks (bus, taxi) are very poorly developed.

Villages located along the southern and southeastern flanks have more means of transport, due to their proximity to larger towns (Yogyakarta and Surakarta), which generate employment and attract students. Vehicle dealers from the cities regularly visit the closest villages offering motorcycles on credit.

Contrasts in access to means of transportation represent a major obstacle for the success of large-scale evacuation.


Typical pickup at Merapi
© A. Picquout, 2010

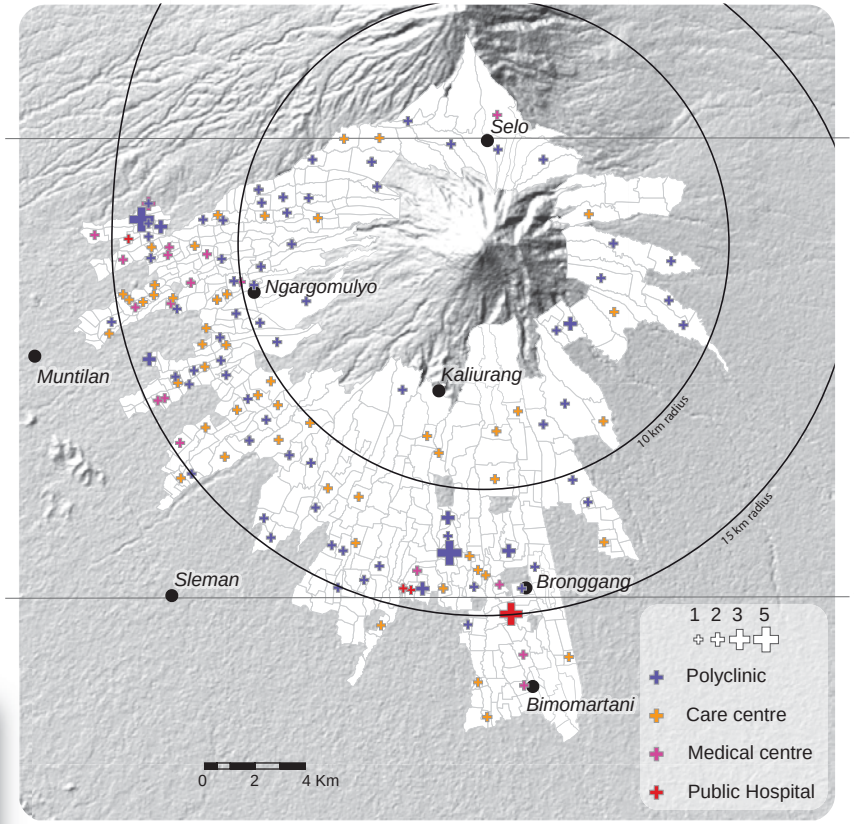
Health Resources

Volcanic eruptions can result in a wide range of health impacts, arguably more varied than in any other kind of natural disaster. Medical services can expect an increase in the number of patients with respiratory symptoms, eye or skin irritation during and after an ashfall event. In the worst cases, exposure to volcanic ash may result in acute respiratory morbidity, especially in those with pre-existing respiratory disease. People can also be directly burnt by pyroclastic density currents or hit by lahars. In addition, the temporary disablement of municipal sanitation systems may lead to increased disease in affected areas.

Around Merapi, more than 2 million people are exposed to ashfall hazard. Healthcare workers responding to the needs of volcanic risk management might therefore find themselves involved in scenarios as varied as disaster planning, epidemiological surveillance, treating the injured, or advising on the health hazards (Hansell et al., 2006). Practicalities of risk management plans need to be thought in advance, and plans need to encompass medical care.

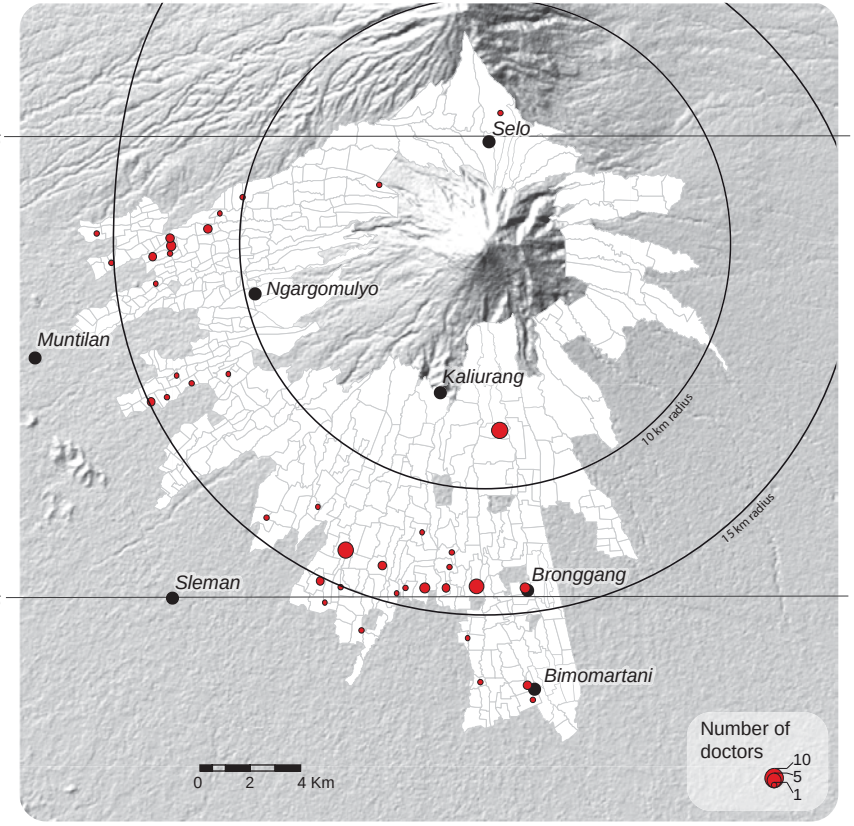
Mapping local healthcare structures (e.g. public hospitals or medical centres locally called PUSKESMAS) and heath personal is therefore an issue of great importance.

Healthcare structures



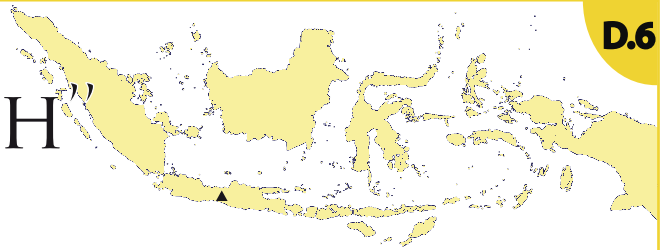
The location of health structures shows an irregular distribution around Merapi. Public hospitals are essentially located on the southern flank, close to main cities. Care centers and polyclinics are available in most dusuns.

Doctors



There are only a few doctors along the slopes of Merapi. Most of them are located more than 12 km away from the dome, leaving the highest dusuns a doctor-free zone.

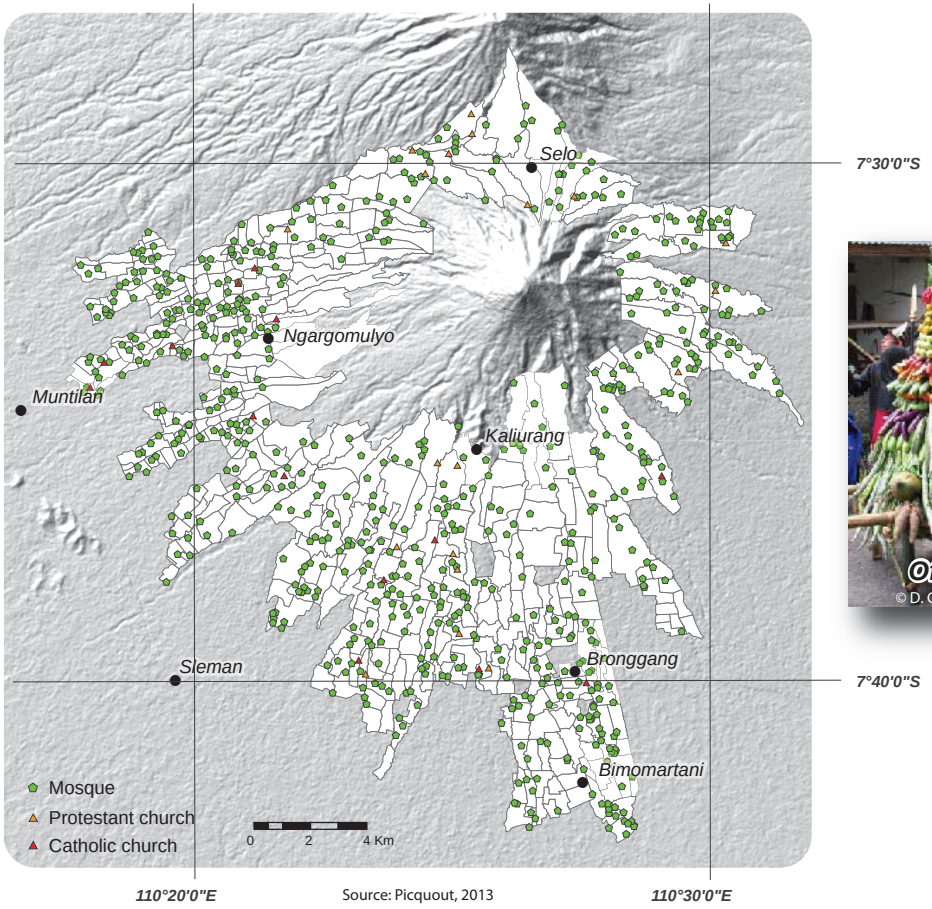
Source: data from Picquout, MIA VITA



A VOLCANO UNDER "SPIRITUAL WATCH"

The role of cultural factors in shaping people's behavior in the face of volcanic hazards has been emphasized by anthropologists. The danger is filtered by an individual's perception of the world, which varies, -among other factors-, according to religious beliefs and community traditions.
Around Merapi volcano, religious beliefs have animist, Hindu, Buddhist, Christian, and Muslim influences. The influence of religion is evident in the large proportion of people who think that actual and potential loss associated with volcanic eruptions are under the control of divine forces. Around Merapi, most places of worship are mosques. Christians are a minority. On the northern and eastern flanks, Christians are essentially Protestant, while they are mostly Catholic on its western flank.
In the shadow of the main monotheist religions, spirit cults, ancestor worship, spirit healing and shamanistic forms ('dukunisme'), and mythical traditions enjoy much popular support. An eruption is often understood as an admonition from the supernatural world. As a result many people living on the Merapi flanks are not fearful. The permanent activity of the volcano has been totally integrated in people's daily life. Mount Merapi is personified: "*Mbah Merapi*" - *Mbah* means grandparent - belongs to the human world.

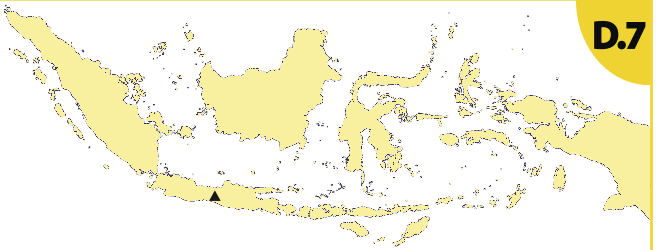
PLACES OF WORSHIP



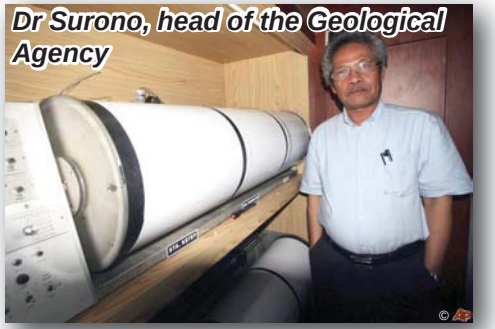
There are two cultural leaders in the traditional Javanese religion (*Kejawen*): the sultan of Yogyakarta and the *Juru Kunci*. The *Juru Kunci* is the key holder of the volcano. He communicates with the spirits who look after the mountain. On the slopes of Mt Merapi, local people put their trust in the local mystic *Juru Kunci*, Mbah Marijan, until he died in 2010. He was appointed by the sultan to carry out annual offerings to the volcano during the *Labuhan* ceremony.
Many people attend the ceremonies, wishing to get a blessing from the Creator of the world. The distance between the village and the *Juru Kunci*'s house at Kinahrejo influences the risk perception. Certainly, people living close to Kinahrejo trust the *Juru Kunci* above all else and feel protected, whereas people living further away from him, but at the same distance from the crater have less confidence in his supernatural power. The presence of the *Juru Kunci*'s house at Kinahrejo partly explains the refusal of the inhabitants to evacuate before the 2006 eruption of Merapi, although the evacuation had been ordered by the authorities (Lavigne et al., 2008).

However, the influence of the cultural factors on risk perception and on people's behaviour has progressively decreased since the 1990's (Schlehe, 1996).
The sultan of Yogyakarta, who represents the link between the traditional and modernity, may have played a key role in this change. He has actively participated in the success of the evacuations in 2006, because he explained the necessity to evacuate the local people against the advice of the *Juru Kunci*. The death of the *Juru Kunci* during the 2010 eruption will certainly enhance this process.

Volcanic Risk Management



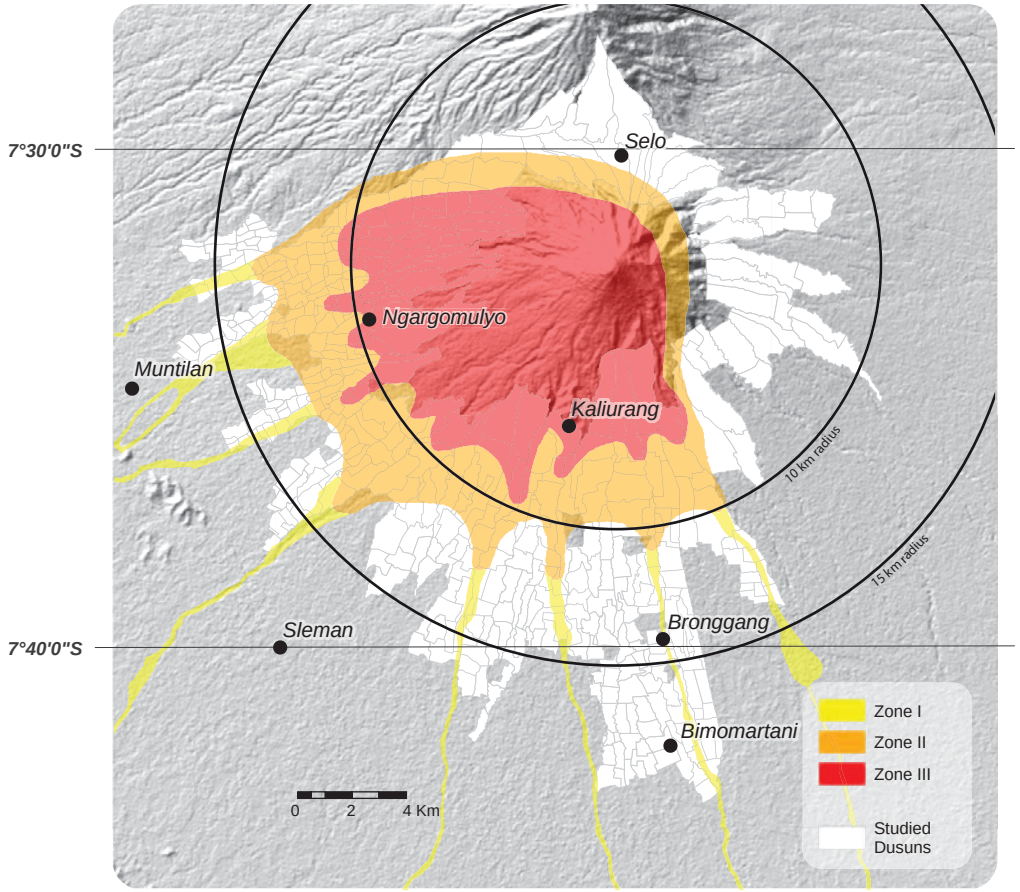
The Ministry of Energy and Mineral Resources, through the Geological Agency and the Center for Volcanology and Disaster Mitigation (CVGHM), is in charge of providing information services to the communities to reduce people's exposure to natural hazards, e.g. hazard maps.


Dr Surono, head of the Geological Agency

The first hazard map (1/100,000) was published in 1978 by the Volcanological Survey of Indonesia. It was based on the lateral extent of the pyroclastic and lahar deposits from the 1930 and 1969 eruptions. This map has been updated and made available online by the Volcanology and Geological Hazard Mitigation (CVGHM) in 2002. It displays three danger zones (KRB) ranked from I (low) to III (high).

Zone I : potentially affected by lahar or stream flow (flood) and possibly affected by overflowing or pyroclastic flows.
Zone II : potentially affected by pyroclastic flows, toxic gasses, glowing rock falls and lahar.
Zone III : frequently affected by pyroclastic flows, lava flows, rock falls, toxic gasses and glowing ejected rock fragments (in a 2 km radius).

Volcanic Hazard Map before the 2010 eruption



Source: adapted from Hadisantono et al., 2002

After the 2006 eruption of Merapi, the hazard map was updated again intended for situations that had not been considered before (e.g. eruption in the central part of the summit, vertical ash column). This updated hazard map was used by local authorities as an input for contingency planning that took place in 2009 in each district surrounding the volcano.

Besides the scientific risk maps and zoning, the basic elements required for municipalities planning are information documents (at regional and local scale) gathering all the knowledge on hazard, elements at stake, prevention and emergency measures, urban master plans or simplified hazard zonation.

The most important information to be disseminated relates to the activity condition of the volcano. There are five observatory posts at Merapi: Kaliurang, Babadan, Ngepos, Jrakah and Selo. The condition and the morphology of the summit is reported from each post to CVGHM's Volcano Investigation and Technology Development Office (Balai Penyelidikan dan Pengembangan Teknologi Kegunungapian, or BPPTK) and to the Merapi Volcano Obsevatory (MVO, a section of BPPTK) in Yogyakarta, and then transmitted to CVGHM. The same information is also reported to local governments.
Both CVGHM and BPPTK provide real-time observations of the volcanic activity, as well as closed-circuit video feeds on their website (http://vsi.esdm.go.id/).


Monitoring room BPPTK

Community-based disaster risk management

Socialization and CBDRM

At Merapi, most of the information is provided during *socialization* phase, a period of time, corresponding to the pre-alarm phase, during which a great effort is put into informing people about the volcano and its activity.

This *socialization* is achieved in the frame of a Community-Based Disaster Risk Management (CBDRM), which empowers communities with self-developed and culturally acceptable ways of coping with crises due to natural hazards. At Merapi the Obligatory Training for Volcano Eruption Disaster Countermeasure (OTVEDC or *Wajib latih*) for the community in KRB III is planned, prepared, and implemented by the community with the scientists and the government. It gathers together, among others, the PASAG Merapi (a 20-year old community organization on disaster preparedness) and Merapi Forum (a government representation on disaster management around Merapi).


Wajib latih in Muntilan district
© J. Morin, 2013


Focus Group Discussion (FGD)
© E. Mei, 2010

The series of activities consists of workshops on module making, module trial, and facilitator training. Community meetings (Focus group discussions, or FGDs) are used to share experiences of past eruptions, identify problems during the crisis period, ensure that everybody knows the emergency plan, evacuation procedure, location of meeting points, etc. This activity generates three things: disaster risk mapping, standard operating procedure, and contingency plans at the village level.

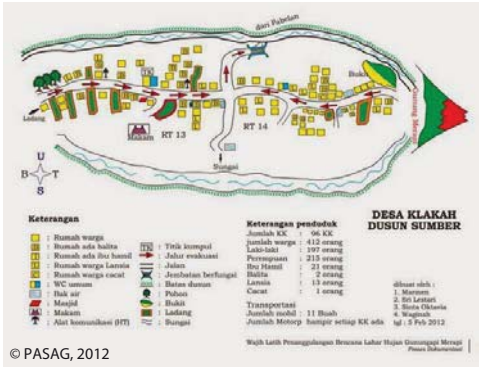
JALIN Merapi is a community-based information network around Merapi. It integrates various media to quickly spread useful information on the volcano. At least four community radios (e.g. Radio Lintas Merapi at Deles, Klaten) are actively reporting information to their community, especially during volcanic crisis. JALIN MERAPI website has interactive features such as online messenger, discussion forum, maps and databases. Field updates are delivered by handy radio and SMS messages from mobile phone. Social media also play a key-role in disseminating information during volcanic crisis, especially Twitter.

Participatory 2D and 3D mapping

A series of participatory 2D sketch maps have been drawn by the local communities living on the Merapi flanks since the 2000's., under the umbrella of the NGO PASAG Merapi.

Participatory 3D Models (P3DM) basically consist of the building of stand-alone scaled relief models over which thematic layers of geographical information are overlapped. These 3-dimensional models raise local awareness of territories, provide stakeholders with powerfull mediums for land-use management and serve as effective community- organizing tools.
In the frame of the MIA VITA project and in collaboration with the French NGO *CCFD-Terre Solidaire*, a P3DM has been built in 2011 in Ngargomulyo municipality on the western flank of Merapi. It contributed, first to precisely locate the damages during the 2010 eruption; second to delineate the trails and roads that have been used to evacuate.

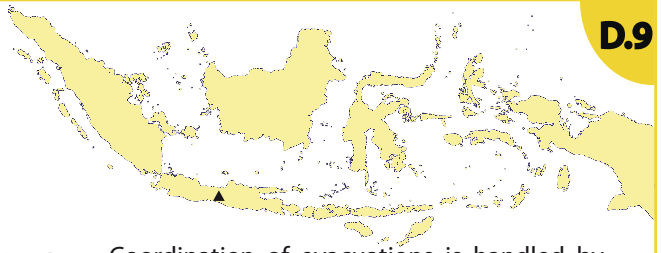
Participatory 2D sketch map (Sumber, Klakah, Boyolali)



© PASAG, 2012


Participatory 3D Mapping at Ngargomulyo, Magelang
LEGENDA
© F. Lavigne, 2010

Crisis Management



Crisis management in Indonesia is based on a top-down hierarchical organization. The National Disaster Management Agency (BAKORNAS/BNPB: Indonesian National Coordinating Agency for Disaster Management / Indonesian National Board for Disaster Management), founded in 1966, is a non-departmental body; its membership comprises up to 10 ministers and related governors. This agency's functions are to formulate, stipulate, and co-ordinate disaster management and its activities, pre-disaster, emergency response and post-disaster activities. To implement disaster management duties in Province and District/City regions, Regional Disaster Management Agencies (Satkorlak-Satlak/BPBD) have been established.

In the frame of the contingency plan approved in 2009, a scenario for Merapi's eruption was prepared for each district, and the roles of each institution involved were defined. The volcanic crisis management is based on the recommendations of the CVGHM, the institution in charge of assessing and monitoring volcanic activity in Indonesia. CVGHM provides four warning levels of volcanic activity. For each warning level recommendations are given for what people living on the volcano slopes are supposed to do (e.g. no need for concern, stand by for technical direction issued by CVGHM, prepare to evacuate, evacuate).

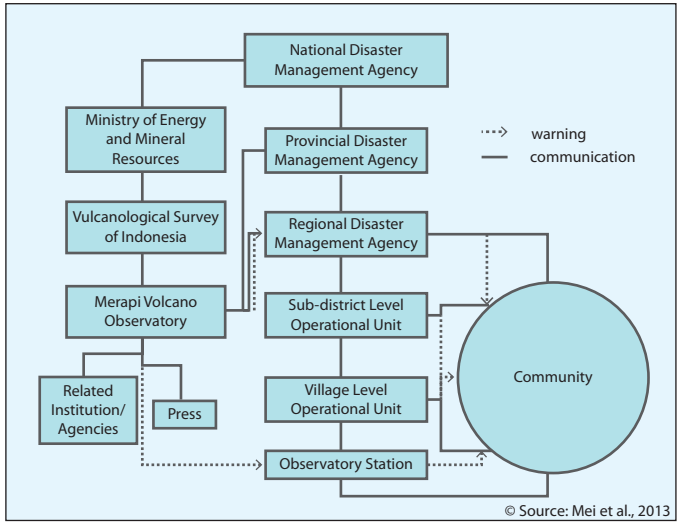
The BNPB and the BPBD are in charge of disseminating the alert level to the public following the established communication protocol. Evacuation orders are also given by BNPB and local governments at district level. However, if the danger is imminent, the BPPTK can use sirens to inform people directly to evacuate.

Warning levels for volcanic eruptions in Indonesia

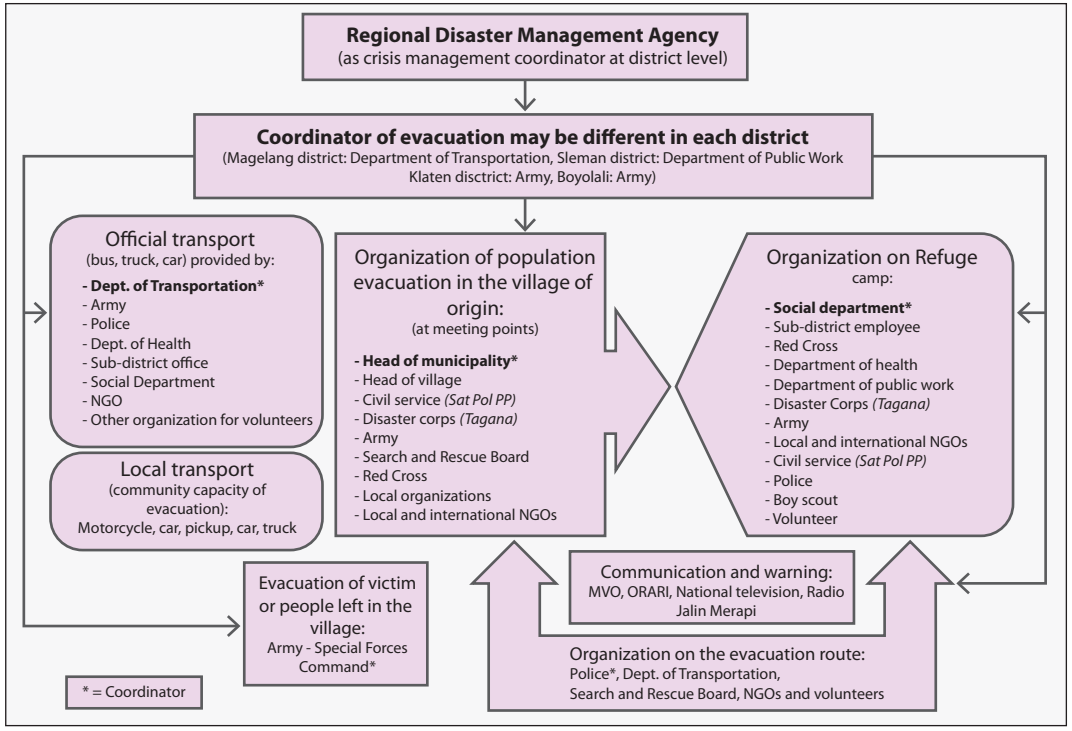
	Volcanic activity level	Meaning
I	AKTIF NORMAL	Normal (or Base) level, non-eruptive state
II	WASPADA	Attention (or Advisory) level, "starting unrest"
III	SIAGA	Pre-alarm (or Watch) level, rapid increase of precursors and on increased potentiality of eruption
IV	AWAS	Alarm (or Warning) level, the eruption is imminent or happening

Coordination of evacuations is handled by one or more institutions: the Indonesian Department of Transportation, the Departement of Public Works, and the Army. Official transport such as busses, trucks or cars are provided by the Indonesian Department of Transportation, Department of Health, Social Department, Army, Police, by the Sub-district Government, and/or by Non-Government Organizations (NGOs) and by a number of other organizations and volunteers. In addition, private vehicles are used.

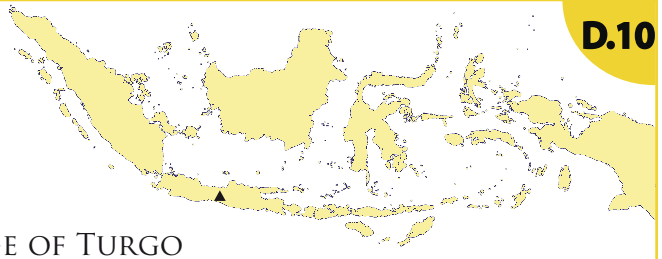
Early warning system diagram in Indonesia



Organization of public authorities during volcanic crisis

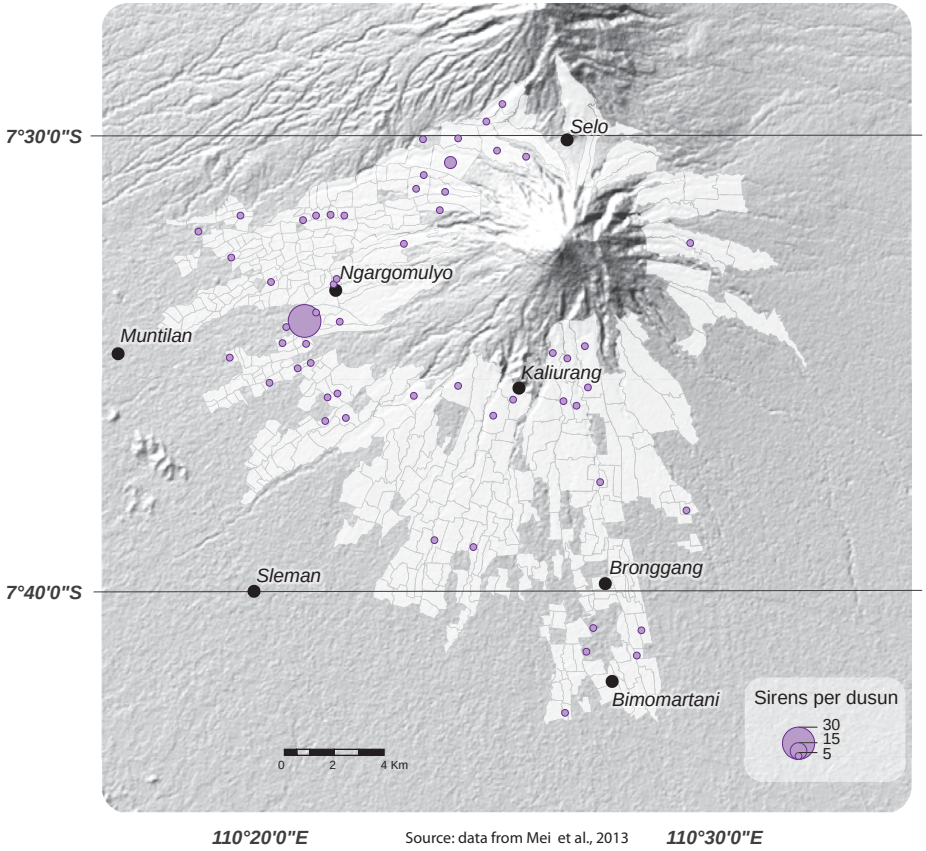


Early Warning Systems



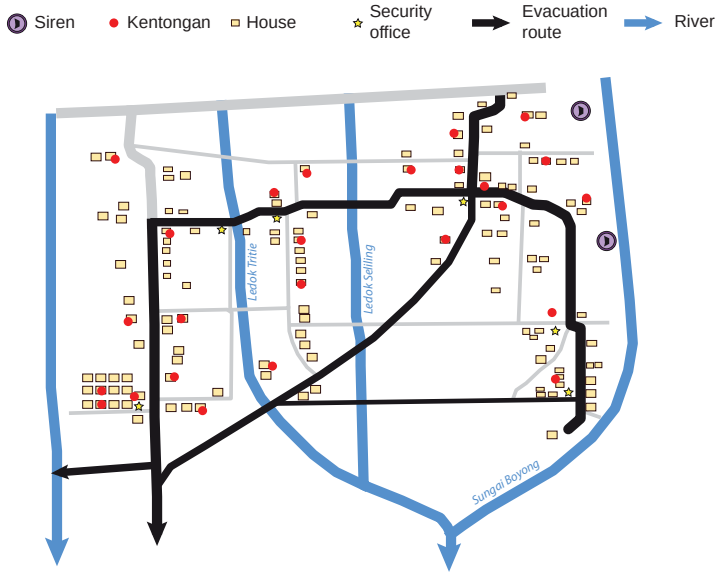
Warnings issued by volcano observatories are sent to the inhabitants through the local governments. Warnings are usually issued by the Merapi central observatory based at the BBPKMG in Yogyakarta.
Sirens are the main tool in use to alert communities in case of a threat. As sirens allow wide-ranging warning, their existence in a Dusun is a real asset to broadcast alerts. In case of an imminent threat, Civil Defense authorities can trigger them to launch evacuation processes.
Within communities, traditional means of alert are still available and used in case of a threat. The kentongan (traditional gong) is widely used for numerous purposes, including gathering local communities. When it is beaten continuously, people know a danger is imminent and following the authorities directives gather in a safe area.

Sirens around Merapi



Source: data from Mei et al., 2013

Kentongans in the village of Turgo



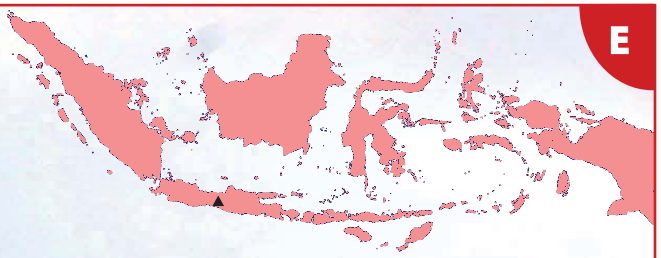
Adapted from Kadarisman, 2010

An early warning system network also provides a feeling of security. In 2002 at Merapi, over 70% of villagers thought that the traditional kentongan was an efficient system. However, only 46% of them were aware of the codes related to a volcanic eruption.

Kentongan communication code

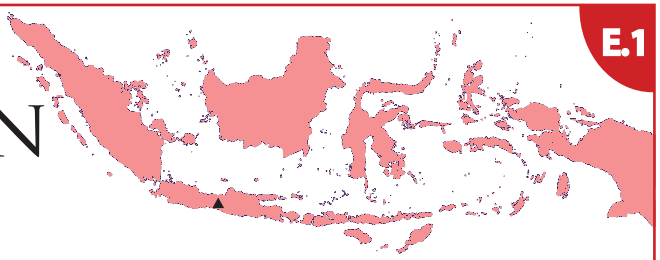
Aman	Normal, safe	O O O O O O ------ O O O O O O
Siap	Ready	O O ----- O O ----- O O
Kejadian Khusus	Special event	O O O ---- O O O ---- O O O
Kejadian Besar	Major event	O O O O O O O O --- O --- O O O O O O O O
Bencana Alam	Disaster	O O O O O O O O O O O O O O O O O O O O O O
Kematian	Death	O O O – O O O O O O – O O O (repeated twice)

The 2010 Eruption



Pyroclastic Density Current on 10 November 2010 © Noer Cholik, BPPTKG, 2010

Chronology of the 2010 eruption

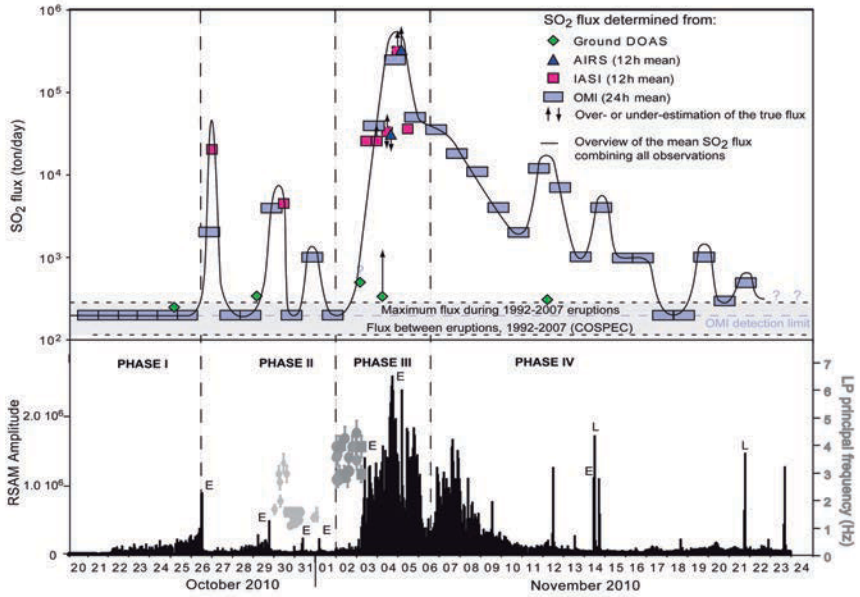


The earliest signs of Merapi summit's inflation following the 2006 eruption began in November 2009. Early indications of increased seismic activity included swarms of volcano-tectonic (VT) earthquakes.

The period from 20 September until the initial explosive eruption on 26 October was marked by a dramatic increase in all monitored parameters. Prior to the 26 October eruption, the seismicity rate increased and SO_2 fluxes reached levels comparable to the highest rates observed during past eruptions (from 1992 to 2007). Compared to previous eruptions, the greater frequency of earthquakes, the amplitude of released seismic energy, the rapid and large deformation (from EDM), and significant gas emissions were evidence that a larger volume of magma was involved.

On 21 October CVGHM raised the alert from level II to III. On 25 October at 06:00 local time, after seismicity and deformation increased to unprecedented levels, the alert was raised to its highest level IV and CVGHM warned that there was a high probability of a large explosive eruption, greater in magnitude than those of recent history.

Comparison between SO2 fluxes and RSAM data



Top: Overview of SO2 degassing during the 2010 Merapi volcano eruption (UTC time)
Bottom: seismic data (RSAM) computed for the Plawangan station (6km from the summit). Source: Surono et al., 2012

2010 Eruption chronology

① 26 to 29 October
Initial phreatomagmatic vent-clearing phase in which 38 people who refused to evacuate were killed and more than 150 buildings damaged across an area of approximately 7.5km²

② 29 October to 4 November
An escalating phase of rapid dome growth and collapse with PDCs of increasing runout reaching to 12km

③ 5 November - 00:01 to 00:11
Explosion of the dome and upper sealed conduit with associated laterally directed turbulent PDC that felled trees and damaged more than 1,300 buildings within a 22km² sector of the south flank and produced block-rich valley-confined PDCs that travelled more than 15km from the crater

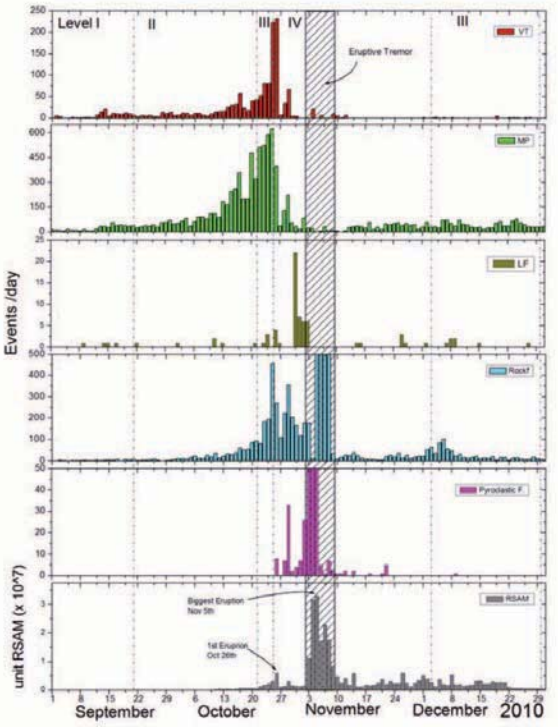
④ 5 November - 00:11 to ~02:30
Retrogressive collapse of the remaining dome and upper edifice producing PDCs that travelled more than 16km (15.5km radius) into the Gendol river channel, with flow overspill and dilute surges extending up to 200m from the parent flow and killing more than 120 people

⑤ 5 November - 00:11 to ~03:00
Fountain and subplinian convective column collapse that produced concentrated scoria- and pumice-rich confined PDCs to 13km and 16km in the Gendol channel, respectively

⑥ 6 to 23 November
Rapid renewed short-lived dome growth associated with continuous degassing and ash emission with a decline to eruption end

Source: Jenkins et al., 2013

Daily count of seismicity recorded prior of and during 2010 eruption



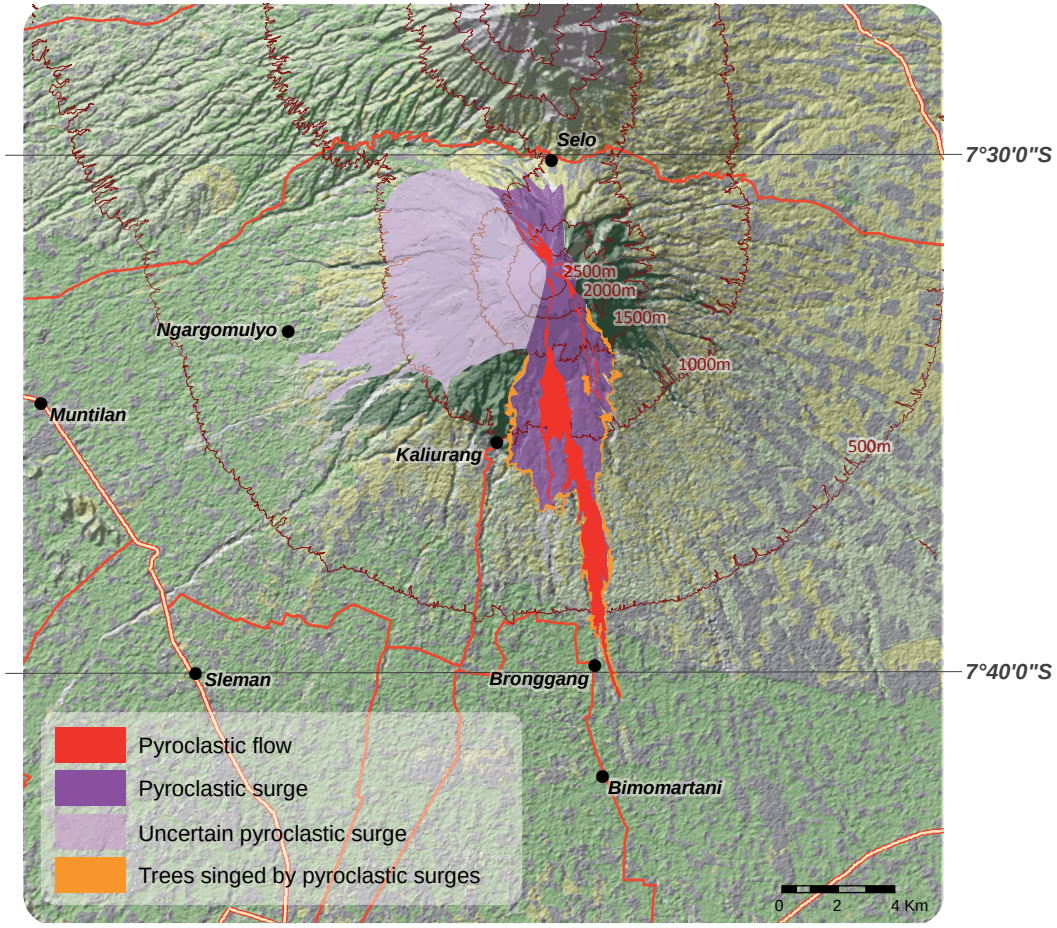
VT = Volcano-tectonic; MP = Multiphase (=Hybrid earthquake);
LF = low-frequency; Rockf = Rockfall earthquakes; Pyroclastic F = Pyroclastic flows;
RSAM = Real-time Seismic Amplitude Measurement (Source: Surono et al., 2012)

Distribution of volcanic Deposits

The Merapi 2010 eruption highlights that explosive and gravitational disintegration of a series of rapidly growing domes can generate a great diversity of eruptive processes and products. They are responsible for extensive and major impacts of contrasting nature and extent on the population, infrastructures and the environment. The 2010 eruption of Merapi was the most dramatic and intense eruptive episode since 1872. This multistage eruption produced an escalating sequence of distinct deposits from five main volcanic processes: ashfall, dome explosion, dome collapse, explosive eruption with column collapse, and debris flows (lahars, *see plates G*). Pyroclastic density currents (PDCs) were produced in all phases of this complex eruption.

Five main types of primary PDCs were produced during the 2010 Merapi eruption that are characterised by marked differences in distribution, dynamic characteristics, deposits, and impact. They are: 1) unconfined high-energy turbulent stratified PDCs (thereafter called high-energy PDC) formed from the explosion of rapidly growing lava domes; they caused the greatest and most extensive devastation and affected a broadly rectangular area about 3-4 km wide over a distance of 8.4 km; 2) valley-confined block-rich concentrated PDCs formed from gravitational collapse of the growing domes; they were responsible for many fatalities during the eruption and reached far up to 15.5 km in the Gendol valley and about 8.5 km in the Opak River; 3) overbank PDC lobes from the valley-confined block-rich concentrated PDCs that overspilled into other valleys; and 4) dilute PDCs that detached from the main valley-confined block-rich concentrated PDCs and propagated 50-400 m laterally from them in distal areas; and 5) valley-confined pumice-rich concentrated PDCs that formed from the collapse of explosive pumice-rich pyroclastic fountains and reached up to 15.5 km in the Gendol valley.

Deposits of the 2010 pyroclastic Density Currents



© Source: Solikhin et al., 2015, additional data from Komorowski et al., 2013

FOCUS ON PDCs

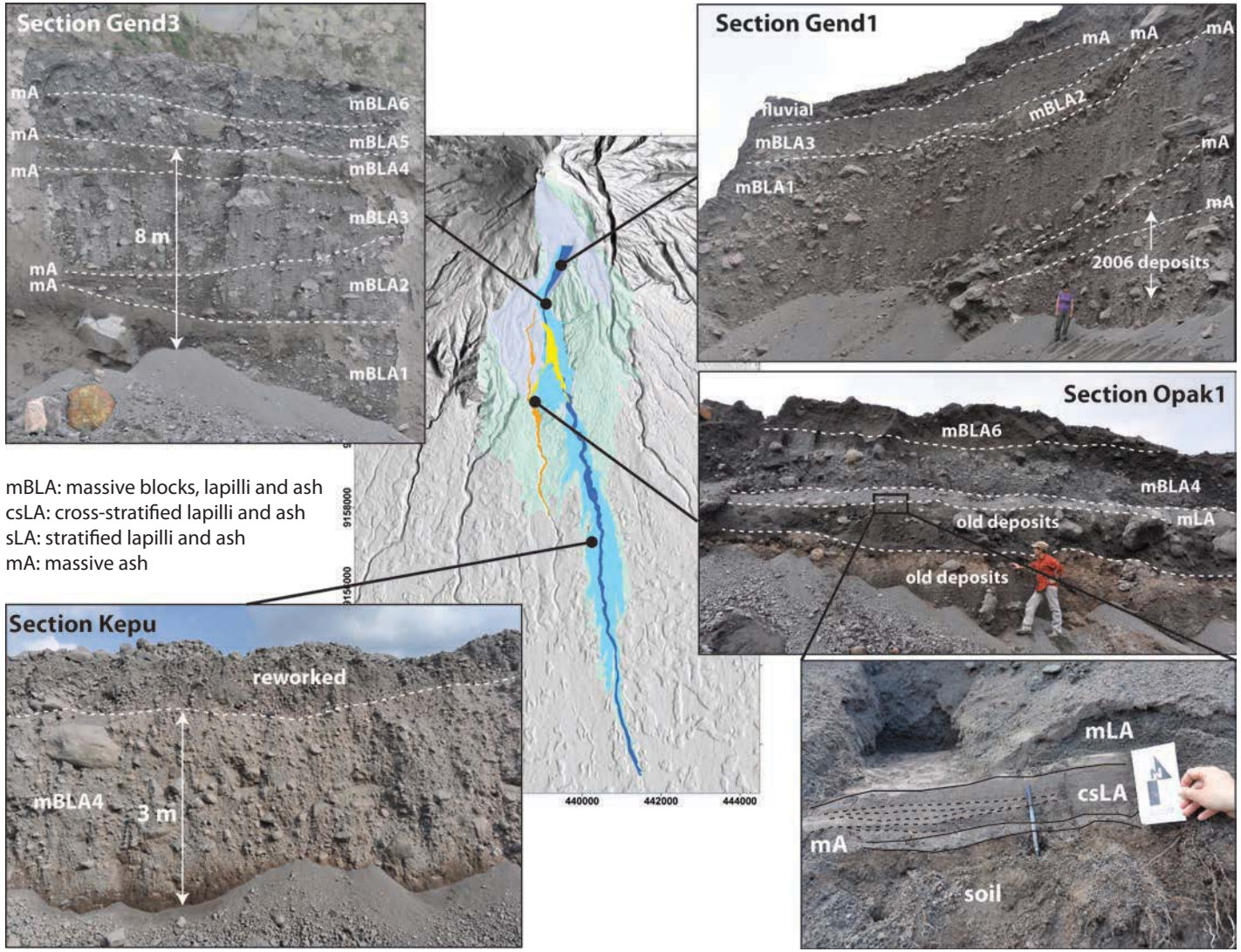
Pyroclastic density currents (PDCs) are variably hot mixtures of volcanic particles, gas, and ambient air that originate from eruption columns or dome collapses and flow mostly as a result of gravitational forces. In some cases, sudden decompression of a pressurized lava dome or shallow-depth intrusion can generate a vertically or laterally expanding hot mixture of volcanic particles, gas, and ambient air that will form a high-energy dilute density current (high-energy pyroclastic surge) near the source before it transforms into a more concentrated PDC controlled by gravitational forces. Although there can be a continuum, there are two main types of PDCs: 1) dilute turbulent to non-turbulent PDCs that are less controlled by topography; and 2) concentrated less turbulent PDCs that interact differently with topography to behave either as valley-confined flows or overbank flows and that often generate on their margins and flow fronts, detached or decoupled dilute turbulent PDCs. The diversity of PDC deposits reflects the different PDC source processes as well as the complex and evolving processes of transport and deposition of the solid particles along their path.

Valley-Confined Pyroclastic Flows

A total of 23 pyroclastic flows events were identified within the Gendol valley. Their total estimated deposit volume is ~36×10^6 m^3.
The first eruptive phase occurred on October 26th, depositing 16.6% of the total volume.
Phase 2 (Oct 30th - Nov 3rd) deposited 11.5% of the total. Phase 3 (Nov 4th - 5th), which corresponds to the peak activity of the 2010 eruption, deposited more than 70% of the total volume. Late pyroclastic flows occurred during phase 4 (Nov 6th - 23rd), depositing only 0.9% of the total volume. Complex, local-scale variations in flow dynamics and deposit architectures are apparent. The main factors that control the propagation of major flows and their potential hazards for overbanking were driven by:
(1) the rapid occurrence of several voluminous pyroclastic flows , associated with a steady filling of the landscape after the first two phases of the eruption;
(2) longitudinal changes in channel capacity following an increased sinuosity in the valley and decreased containment area;
(3) the effects of various triggering mechanisms (gravitational dome collapse, vertical or lateral dome explosions and column-collapse) and source materials involved for each pyroclastic flow generating event.

Succession of deposits (stratigraphy) along Gendol valley:
- **mBLA1** : October 26th valley-filling deposits
- **mBLA2** and **mBLA3** : October 29th to November 3rd deposits
- **mBLA4** and **mBLA5** : November 4th - 5th deposits, the only two main pyroclastic flow units identified in the distal reaches of the Gendol channel.

Valley-confined pyroclastic flow deposits



Source: data and maps from Charbonnier et al., 2013 and Komorowski et al., 2013

High-energy Pyroclastic Density Currents

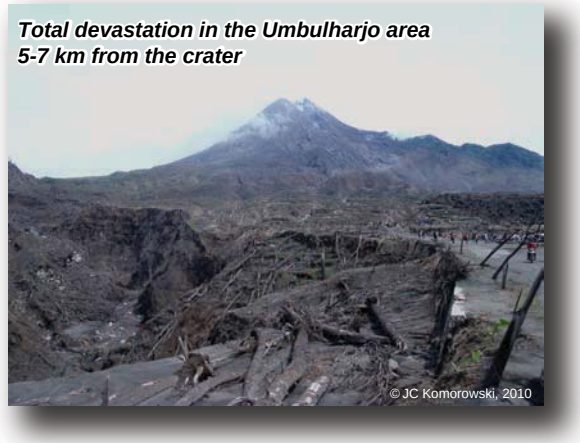
The greatest and most extensive devastation of the 2010 Merapi eruption was imparted to infrastructure and the environment by the emplacement, on several occasions throughout the eruption, of unconfined high-energy turbulent stratified pyroclastic density currents (also called high-energy pyroclastic surge). They affected a broadly rectangular area of about 22 km^2, about 3-4 km wide over a distance of 8.4 km to the south of the crater.

The excessive growth rate of lava domes during the eruption, as well as the presence of rapidly-ascending, volatile-rich magma in the conduit led to their recurrent pressurization and explosive fragmentation. Very powerful explosions were focussed and directed laterally to the south by the horseshoe-shape, large, summit crater and the deep Gendol Breach canyon on 26 October, and particularly during the paroxysmal phase of the eruption on 5 November.

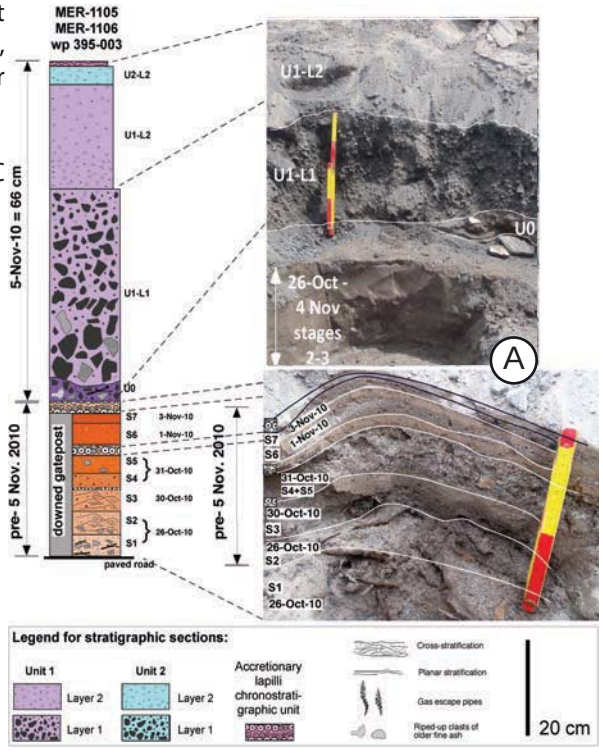
The expanding mass of hot volcanic fragments and gas was able to accelerate down the very steep slopes of Merapi's southern flank forming a stratified turbulent rapidly expanding hot current. In a previously unrecognized process for such small volumes of magma involved, the 2010 Merapi eruption underscores dramatically how major topographic features (the high transversal Kendil ridge, the deep Gendol
River canyon) were able to strongly focused the PDC mass towards a major constriction, thereby limiting the loss of kinetic energy. This favoured elevated PDC velocities and high particle concentration, promoted overspilling of highly mobile PDCs across high ridges into other river valleys, and generated significant dynamic pressures (≥ 15 kPa) to distances of 6 km that caused total destruction of buildings and the forest.

The 5 November blast-like deposits consists of three units (U0, U1, U2) that correlate to explosions of an 11-minute sequence. Both U1 and U2 show bi-partite layer stratigraphy with lower L1 and upper L2 layers. The erosive waxing flow head deposited L1 layer that is very coarse-grained, fines-poor, poorly-sorted and massive. The waning upper part and wake of the PDC deposited L2 layer that is much finer grained, fines-rich, moderately to well-sorted, with laminar to wavy stratification.

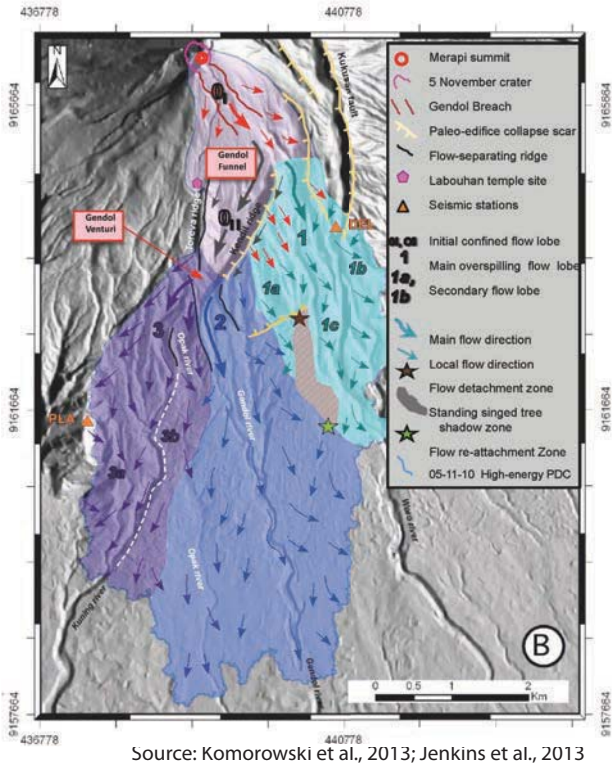
Field observations indicate that PDC height reached ~ 330 m with an internal velocity of ~ 100 m/s within 3 km from the source, comparable to observations at the most violent world historic volcanic blasts of the last 100 years such as Montagne Pelée (1902), Bezymianny (1956), Mount St. Helens (1980) and Soufrière Hills (1997). The Merapi 2010 eruption highlights that small-volume pressurized domes can generate devastating high-energy, high-velocity PDCs. This constitutes a credible high impact scenario for future eruptions at Merapi that pose particular monitoring, crisis response, and risk reduction challenges.



Sequence of deposits observed near Kinahrejo



Lobes of the 5 November high-energy PDC



Source: Komorowski et al., 2013; Jenkins et al., 2013

Environmental impacts of high energy PDCs

Examples of environmental impacts of high energy PDCs

A vast area, about 223 km^2, between the Kuning river and the Woro river, was affected by PDCs. Vegetation was totally destroyed to slightly singed. This extends to Merapi Golf course (8.4 km distance), and is the largest affected area since 1874.

A. Map showing the distribution of high-energy PDC deposits from 26 October and 5 November 2010 and the typology of environmental impact (ground surface, trees).

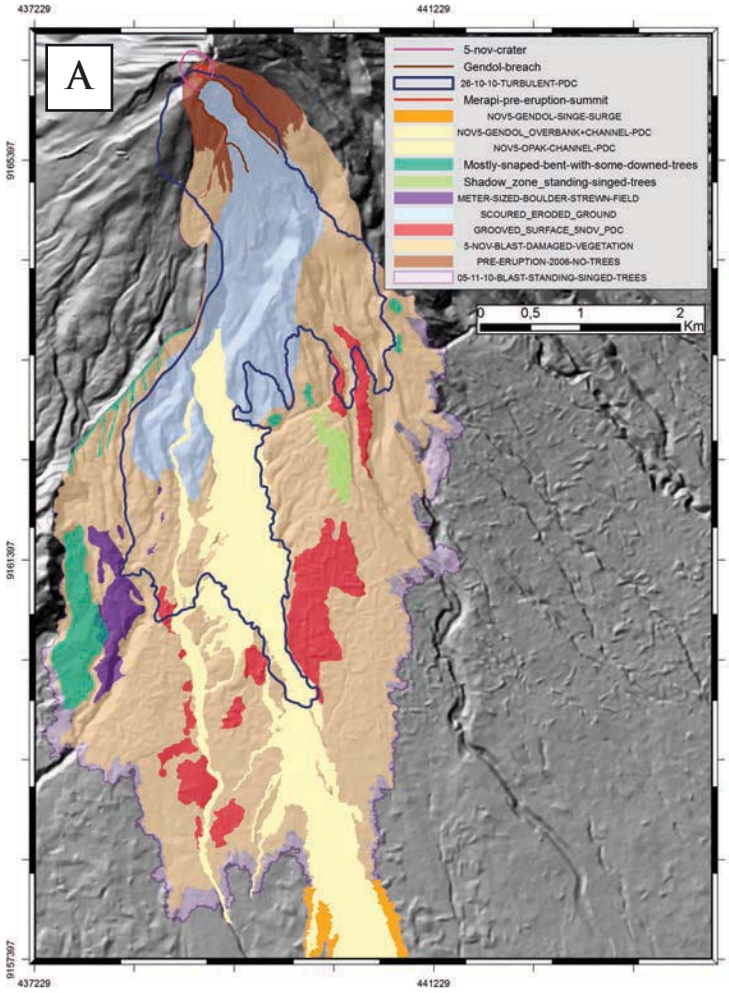
B. Overview of the impact on the forest of high-energy PDCs emplaced at 00:05 local time on 5 November 2010; Area of dense forest in the Kuning river as shown before the eruption on 11-09-2006 on high resolution GeoEye imagery (Google, 2012).

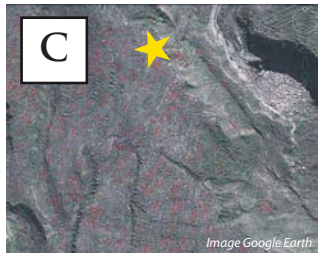
C. Same area after the eruption as shown on 11-06-2011 on high resolution GeoEye imagery (Google, 2012). Identifiable downed trees were traced in red to derive the flow orientation.

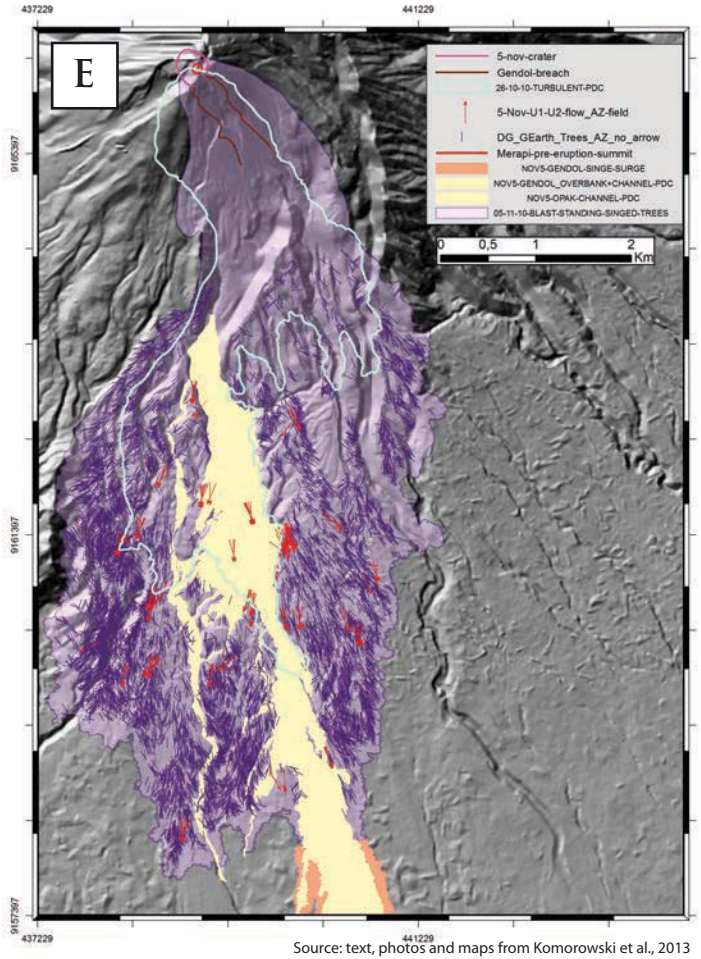
The edge of the area of singed trees presents a crenulate outline, due to the effect of slight topography such as gullies and small hills and also due to the shape and typology of individual large groups of trees and patches of vegetation, which likely had different heat resistance and moisture content.

D. Metre-sized fresh dense dome andesite and accidental boulders lifted and transported over some distance by the high-energy PDC and scattered on top of downed, abraded but uncharred trees at site with yellow star (Kuning River).

E. Map of the orientation of trees (n=10 201) downed and transported by the high-energy PDCs (U1 and U2) of 5 November 2010 as it interacted with topographic features as a result of complex flow paths. Red arrows are field measurements, purple lines measurements were derived from satellite imagery.



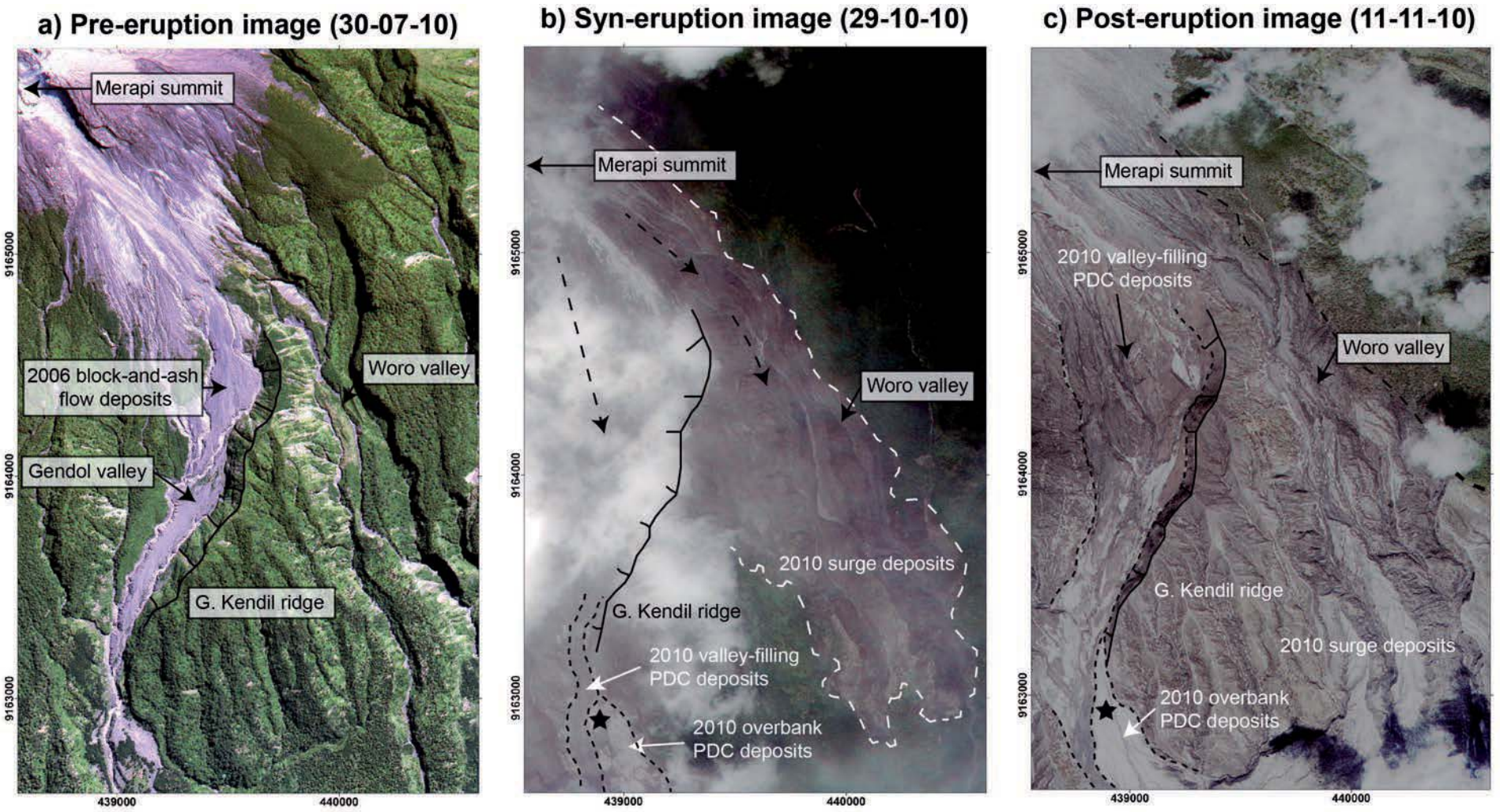




Source: text, photos and maps from Komorowski et al., 2013

Geomorphologic Impacts of the PDCs (1)

A temporal analysis of the 2010 event was conducted using datasets of WorldView-2 (Digital Globe) multispectral satellite imagery. It shows a section of Merapi's southern proximal area (from 1.8 to 4 km from the summit) at three different periods: before (a), during (b) and after (c) the main 2010 pyrosclastic flow events. Dashed arrows indicate the main flow direction, and black stars show the first overspill location on the eastern interfluves of the Gendol valley. The more diluted high-energy parts of the currents entered the Woro valley and spilled over either partially (b) or totally (c) the 200-m-high Kendil ridge, as pyroclastic surges swept a broader area toward the south-eastern flank. This proximal decoupling of the more energetic part of the 2010 pyroclastic flows at around 2 km from the summit occurred at a much larger scale during the activity peak of November 4th–5th, resulting in the complete stripping of Kendil hill's vegetation.

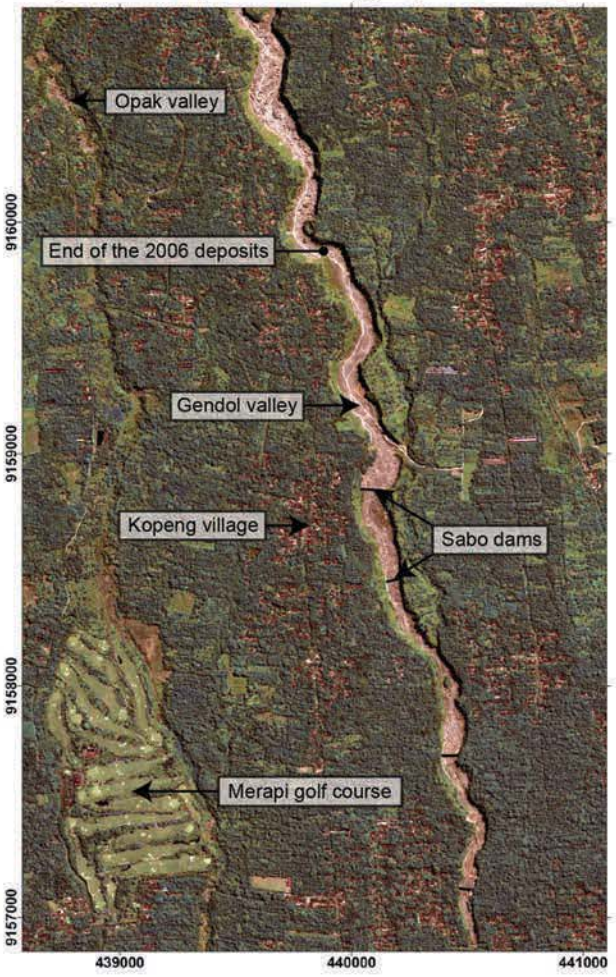


Source: text and maps from Charbonnier et al., 2013.

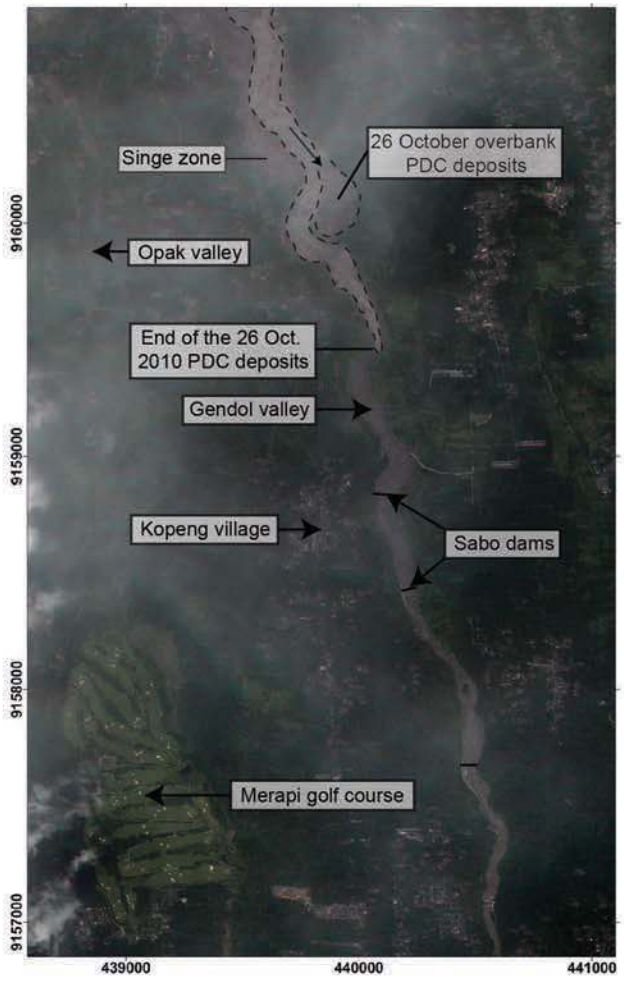
Geomorphologic Impacts of the PDCs (2)

The rapid emplacement of several voluminous pyroclastic flows in the medial area (5.5 to 10 km), associated with the steady filling of the landscape after the first two phases of the eruption, dramatically increased the hazard potential for overbanking (dashed black arrows) of the November 4-5th pyroclastic flows. Many of the anthropogenic barriers in the Gendol and Opak valleys, like Sabo dams and bridges, were either totally or partially buried by >10 m-thick deposits. Effects of the Sabo dams on overbanking processes can be observed at several locations along the Gendol channel, where deposits accumulated against the dam and spread sideways outside of the channel confines and across interfluvial areas. By far, the greatest damage to buildings and infrastructures was caused by the widespread inundation of pyroclastic surges, in areas between the Gendol and Opak valleys in the west, and the Gendol and Woro valleys in the east (c). Here, the surge deposits extended ~600 m laterally from the channels, devastating large populated areas, and damaging hundreds of houses and buildings.

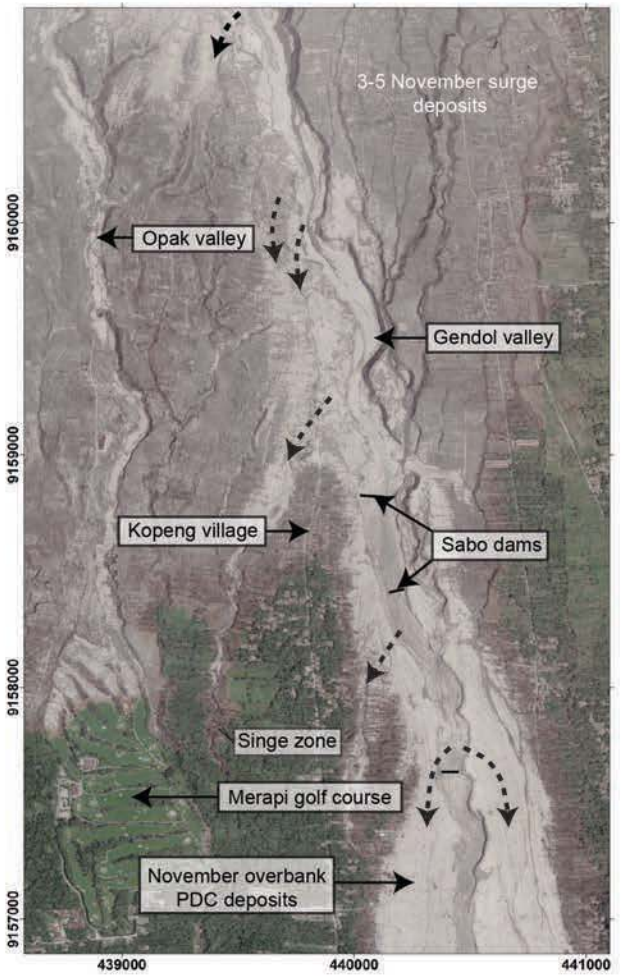
a) Pre-eruption image (30-07-10)



b) Syn-eruption image (29-10-10)



c) Post-eruption image (11-11-10)

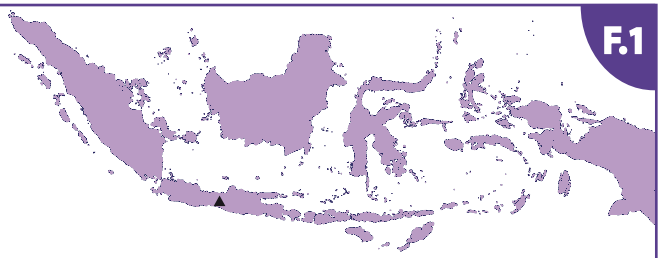


Source: text and maps from Charbonnier *et al.*, 2013.

SOCIAL AND ECONOMIC CONSEQUENCES DURING THE 2010 ERUPTION

Kaliadem, 27 October 2010. © Noer Cholik, BPPTKG, 2010

Casualties



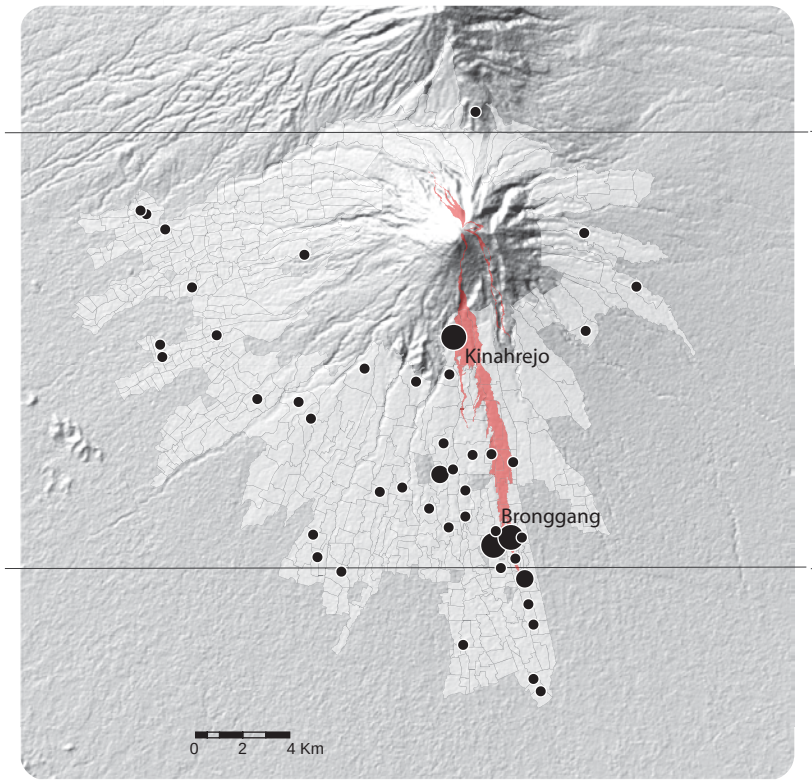
Based on BNPB (National Board for Disaster Management) data, 367 people were killed during the 2010 eruption, including 200 directly caused by Pyroclastic Density Currents (PDCs). Most fatalities were, therefore, located on Merapi's southern flank.

The initial explosive eruption of Merapi on 26 October 2010 killed 38 people at Kinahrejo village, including Mbah Marijan the spiritual key holder of Merapi.

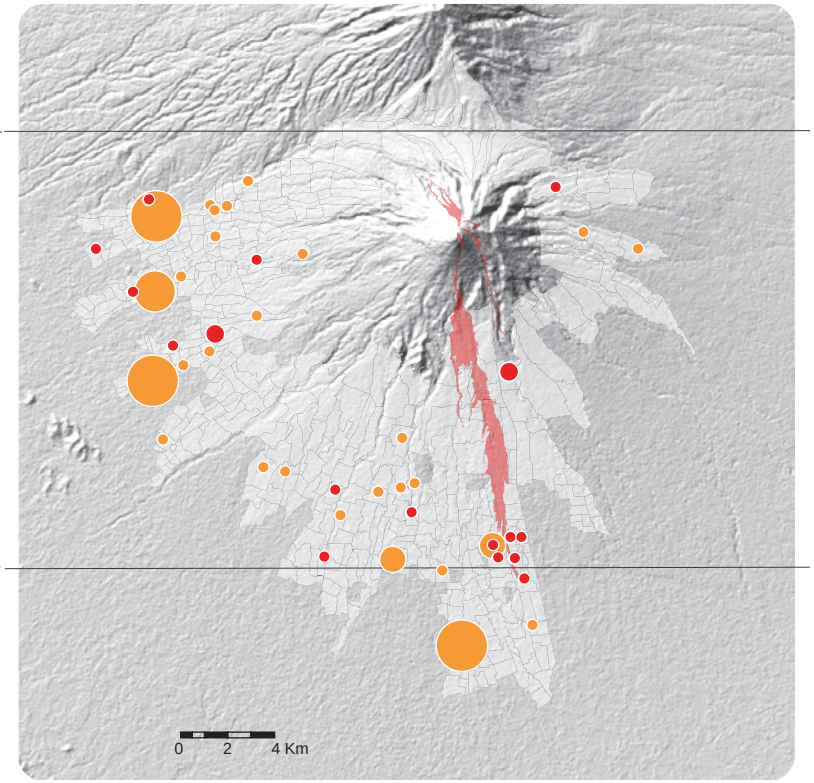
In the village of Bronggang, approximately 13.5 km to the south of Merapi, 54 people who were in the process of evacuating from the village a few hours before the 5 November paroxysm were killed when dilute pyroclastic surges entered the village. Casualties suffered severe burns and were coated in a layer of fine ash (Jenkins et al., 2013). Fatalities were rapid and accompanied by severe skin or inhalation thermal injuries sustained from pyroclastic surges, rather than the result of direct trauma. Some corpses showed evidence of being caught in fires, while others were suggestive of death from the heat of the PDCs only.

The near total lethality for victims caught in dilute turbulent surges suggests that despite the low structural damage, temperatures of 250-300°C are not survivable by residents caught outside or inside buildings because of the ease with which hot ash could infiltrate through ubiquitous ventilation openings (Jenkins et al., 2013).

Fatalities

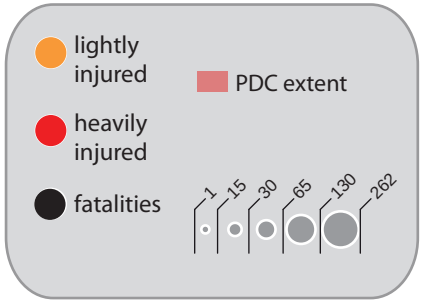


Injuries



Source: data from Picquout, MIA VITA

Based on BNPB data, a total of 277 people were directly or indirectly injured during the 2010 eruption. Most of them were located on the western and southern flanks of the volcano, where the hazard was most intense. Slightly injured people located on the western flank were affected by respiratory issues due to their exposure to volcanic ash, as the ash cloud migrated westward by the winds during the eruption.

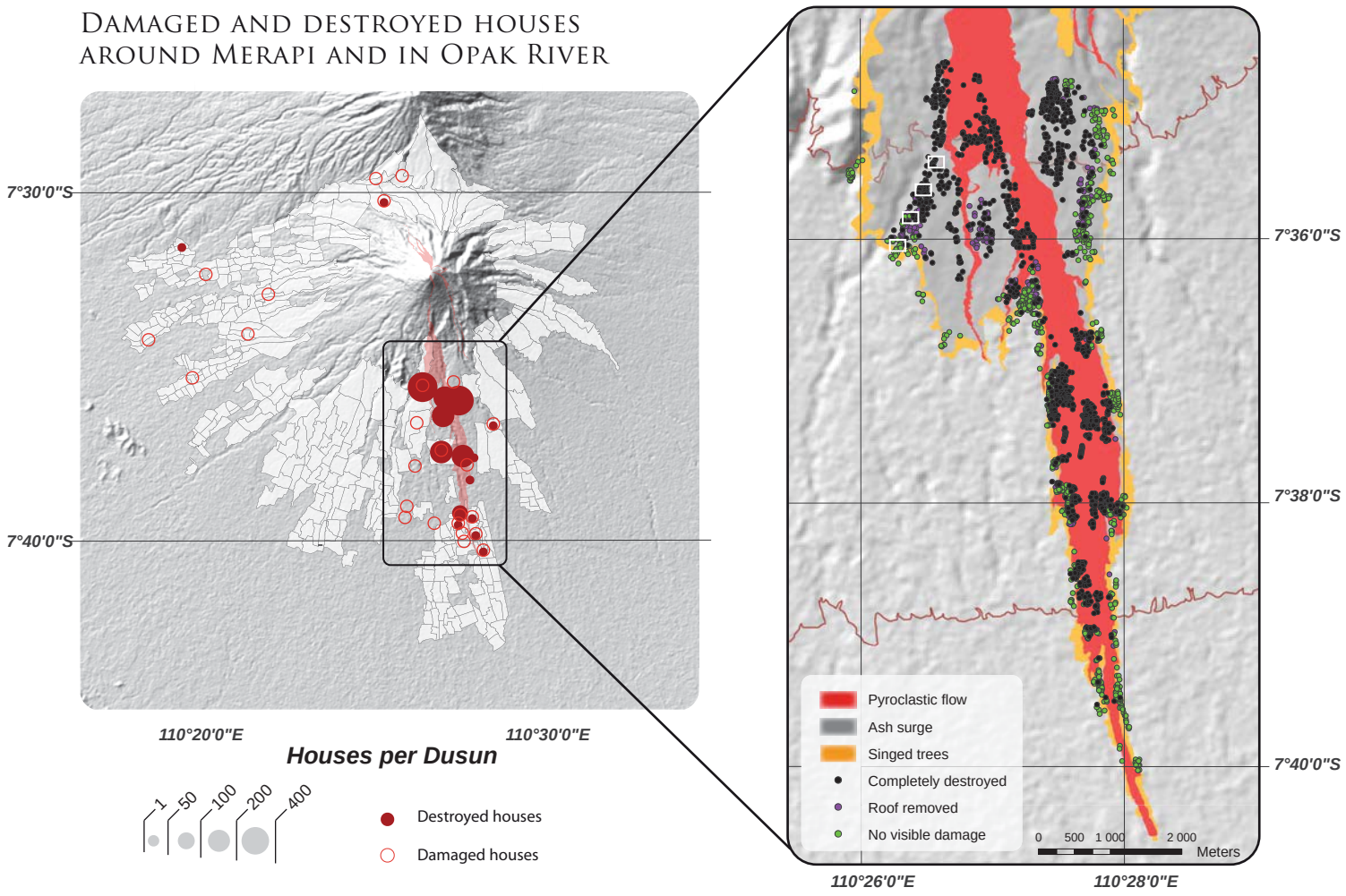


Impact of Pyroclastic flows on houses

More than 1200 destroyed buildings were recorded following the November 5th explosion and associated pyroclastic flows, with >60% of these buildings completely removed from their foundations. Thankfully, the PDCs effects were local as it was contained within a few valleys. Around the pyroclastic flow path, 245 houses lost their roofs in the blast. Within the affected area, only 628 houses were unscathed.

Damage to buildings decreased with distance from the summit, illustrating the reduction of pressure as the pyroclastic density current flowed down, as shown by those pictures, taken in the Opak channel.The first one (a) is located at a distance of 5.8 km from the Merapi. The pressure value due to PDC was superior to 10 kPa. The second one (b) was located at 6.10 km and suffered a dynamic pressure between 10 and 5 kPa. The third one (c) was situated at 6.5 km and was subjected to a dynamic pressure between 5 and 2 kPa. The last picture (d) was located at 7 km from the volcano and the pressure was less than 1 kPa.

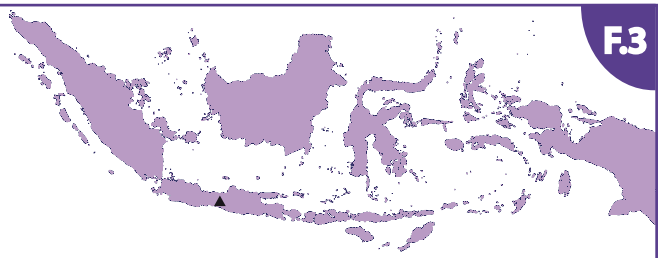
Damaged and destroyed houses around Merapi and in Opak River



Sources: data from Picquout, MIA VITA, at the Dusun level; Jenkins et al., 2013, at small scale ; all pictures S. Jenkins.

Damaged buildings

Evacuation zones

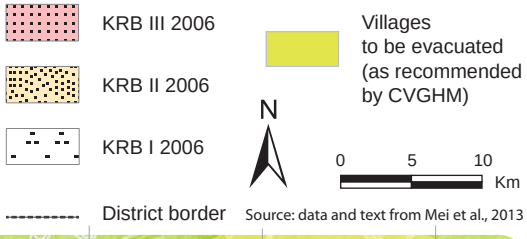


Volcanic crisis periods and change of alert level

The authorities have adapted the evacuation zones based on the evolution of volcanic activity:

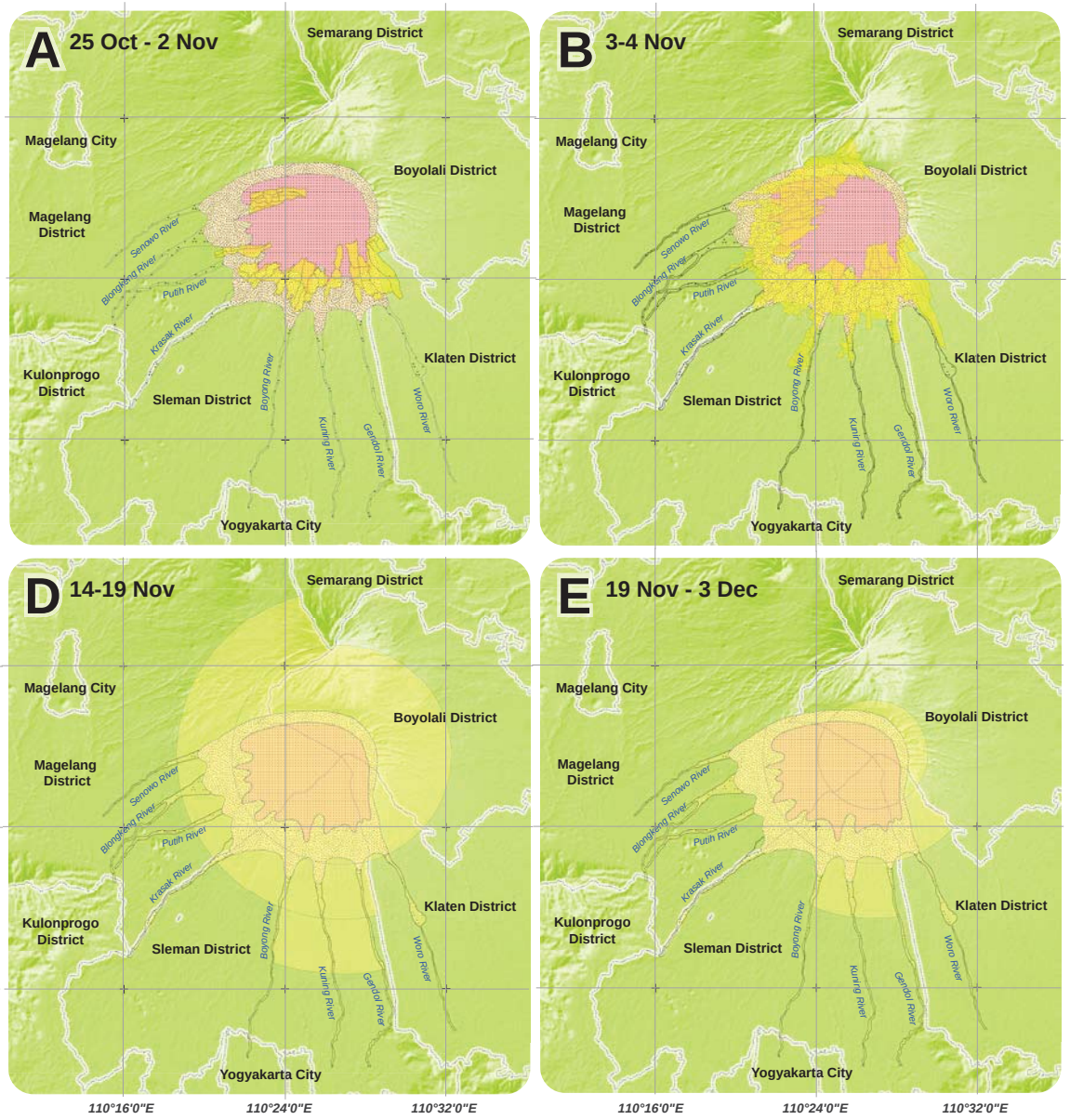
* Period A, 25 October–2 November. According to the 2009 hazard zone map, CVGHM recommended evacuation of 12 municipalities located in KRB III (Purwobinangun, Wonokerto, Girikerto, Hargobinangun, Umbulharjo, Kepuharjo, Glagaharjo, Balerante, Sidorejo, Tegalmulyo, Kemiren and Kaliurang).
* Period B, 3–4 November. CVGHM recommended evacuation of 32 municipalities in the KRB III, abandoning the 2009 map for the benefit of new evacuation plans updated according to the danger zone radius changes.
* Period C, 5–13 November. Several hours before the paroxysmal eruption, CVGHM extended the restricted zone to 20 km from the summit and recommended evacuation of people in this radius.
* Period D, 14–19 November. Radius of 20 km for the sector between the Boyong and Gendol rivers was maintained. The radius was reduced to 15 km for Magelang District and 10 km for Klaten District and Boyolali District.
* Period E, 19 November–3 December. The radius was reduced to 15 km for the sector between the Boyong and Gendol rivers, 10 km for the rest of Sleman District, 10 km for Magelang District and Klaten District and 5 km for Boyolali District.

The wider extent of restricted zones to the south is due to the morphological patterns of Merapi summit which is a horseshoe opened southward.



Source: data and text from Mei et al., 2013

Changes in restricted zones during the 2010 eruption

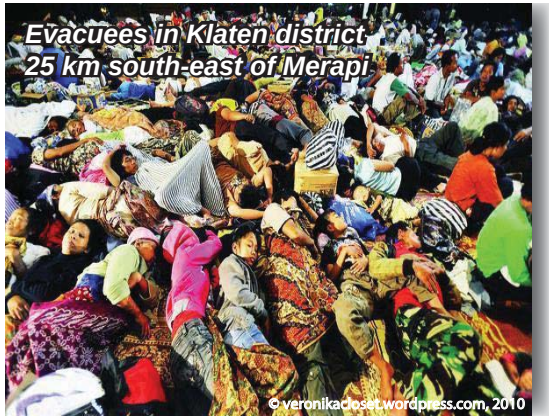


Shelter Types

Several types of evacuation shelters were set up or improvised during the 2010 crisis:
- Official shelters, such as schools or official buildings, were provided by the government. Local authorities recorded and registered the refugees.
- Community-based shelters were provided by individuals or communities from other regions (due to the large number of community-based shelters, local authorities often did not record the refugees). Support and help were provided by NGOs and communities from beyond the area affected by the eruption.
- Relative-based shelters were provided by relatives/families.

It is estimated that most of the population within the 20 km radius who did not evacuate to official shelters went to community-based, and/or relative-based shelters.

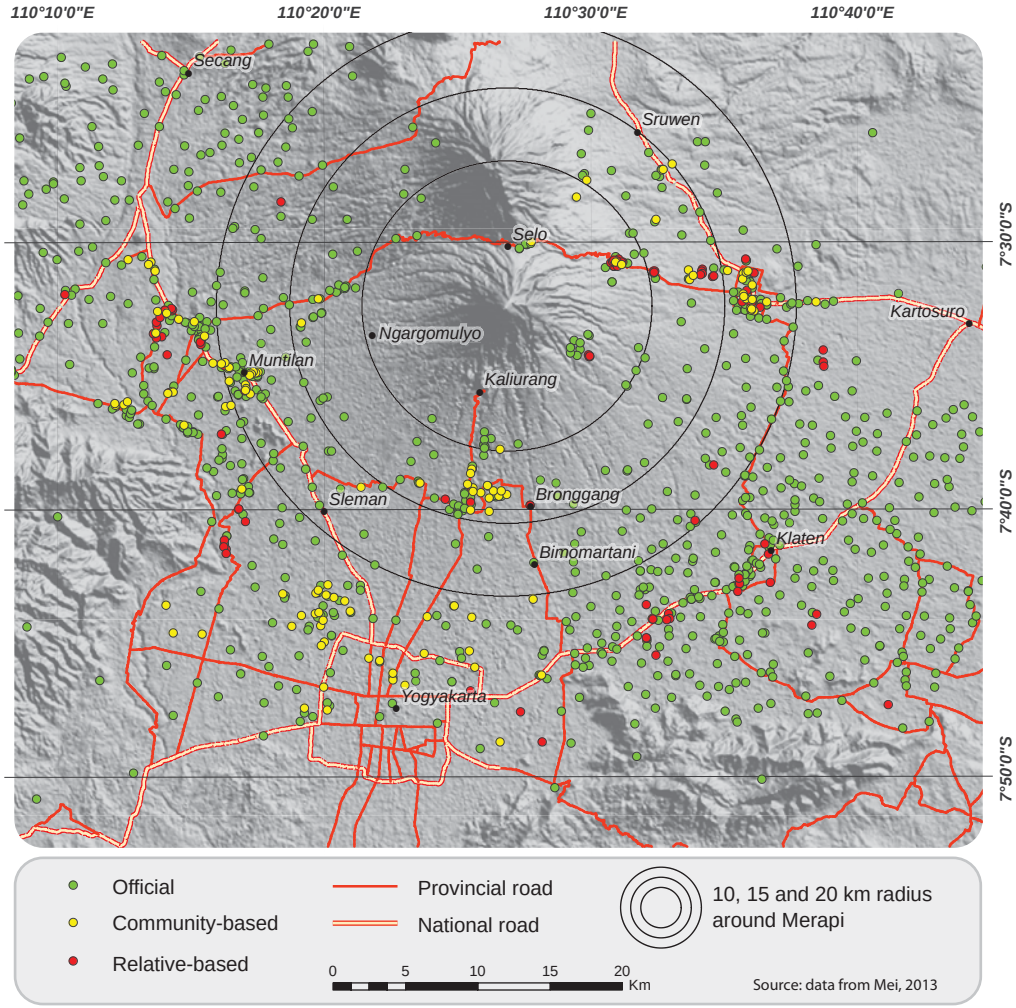
Because of the lack of space and comfort in shelters, people tended to stay at home during the day and come back to evacuation shelter in the evening (Mei and Lavigne, 2013).



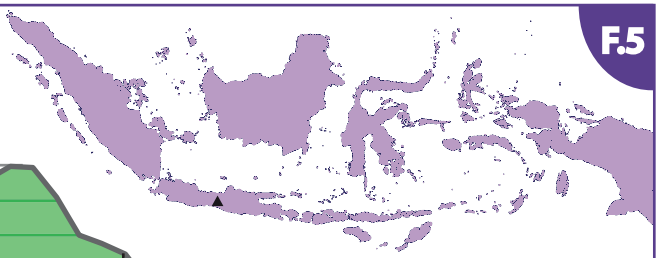
'The conditions of shelters were very unpleasant, but at the time, what was most important for us was our safety. We brought nothing except the clothes on our backs. We were lucky to be able to run away from danger.'

Sutirejo, a 78 year-old woman from Turgo, interviewed on 26 June 2010 by E.T.W. Mei

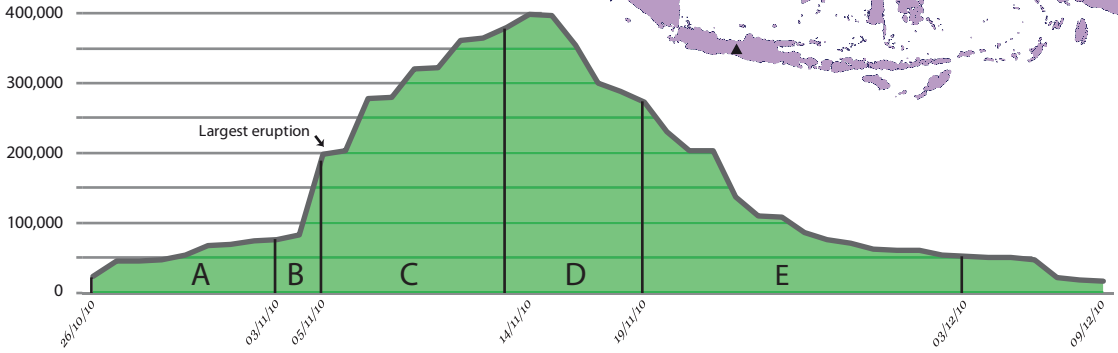
Shelter types around Merapi during the 2010 eruption



Shelter Attendance



Number of people displaced due to the 2010 eruption



At the beginning of the 2010 eruption, approximately twenty refugee camps were prepared to accommodate people living in KRB III municipalities as described in the 2009 contingency plan. These camps, located less than 20 km from the summit, welcomed the first wave of refugees (~22,000 people) on 26 October after the first volcanic explosion. The number of evacuees reached 53,048 on 30 October. The organization of refugee camps worked smoothly in the early period of displacement.

When the restricted zone was extended on 4-5 November, the number of refugees exponentially increased while no refugee camps had been prepared beyond 20 km. Therefore, most of the evacuees after the main explosion were settled in emergency in public buildings (schools, hospitals, stadiums, village halls, and universities) or even residents' houses or yards. On 13 November there were at least 600 camps registered by BNPB, scattered around Sleman, Magelang, Boyolali, Klaten and several other Districts in Central Java Province and Yogyakarta Special Region Province.

Despite the evacuation order to clear the 20 km radius 10 days earlier, the highest number of refugees way reached on 14 November (399,403), due to insufficient preparedness in handling the evacuation and refugees' movements from one camp to another (sometimes several times). The number of refugees then decreased significantly when the local authorities decreased the radius of the restricted zone to 10 km. People from villages that were still habitable went home for good. On 9 December less than 20,000 people were still recorded in the refugee camps.

Location and attendance of refugee camps during and after the 2010 eruption

October 26TH - 22 599 refugees

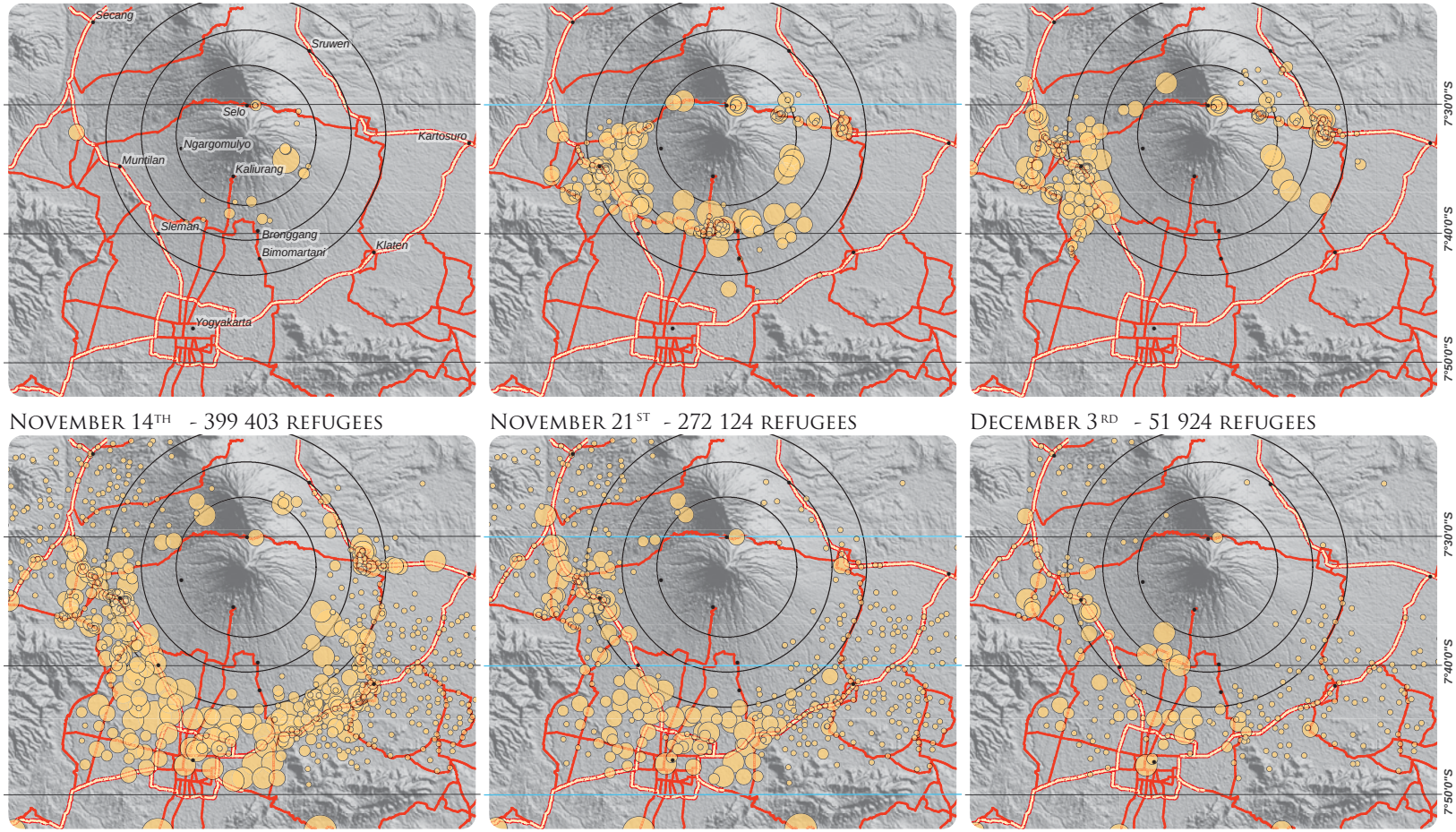
November 4TH - 82 701 refugees

November 5TH - 198 488 refugees

November 14TH - 399 403 refugees

November 21ST - 272 124 refugees

December 3RD - 51 924 refugees



Source: Mei and Lavigne, 2013; Mei et al., 2013

Population Behaviors During the Crisis

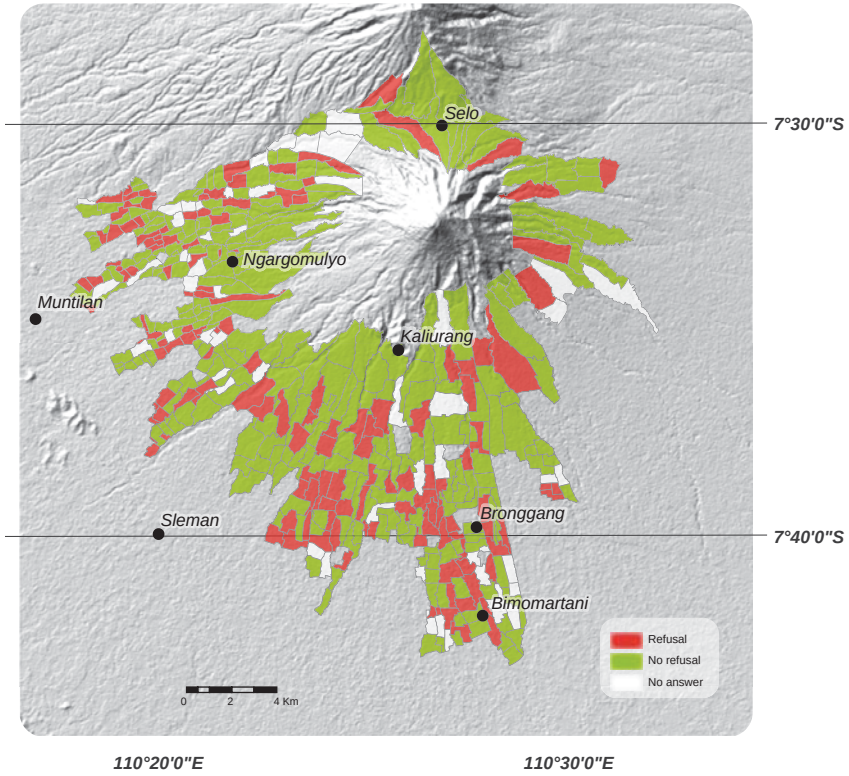
Most of inhabitants evacuated only when the first pyroclastic flows were reported on 26 October despite the evacuation order given earlier on 25 October. This evacuation may be classified as "evacuation when hazard is imminent" a phenomena that is common at Merapi. As in previous eruptions, people wait to evacuate until a pyroclastic flow or ash fall event has taken place, even though the government had previously informed them that the volcano was already at its highest warning level.

Despite evacuation orders and efforts of local authorities to evacuate people, some residents were reluctant to leave their villages. Refusal to evacuate was mostly due to people's perception of the volcano, cultural beliefs and socio-economic conditions. This refusal led to casualties, i.e. the evacuation refusal of Marijan (Merapi volcano's gatekeeper) and his followers led to the deaths of thirty-five people in the village of Kinahrejo (5 km from the summit). Along the southern flank of the volcano, evacuation refusals were mostly conditioned by trust in the gatekeeper and the feeling of being protected by his presence, even though Marijan suggested to people not to follow his decision to stay in the village. However, people living far away from the gatekeeper's village opted not to leave their house because of their poor understanding of volcanic processes. Others stayed in their village to look after their livestock.

During the paroxysmal eruption on the night of 4–5 November, people self evacuated. Without detailed instructions, people tried to escape by themselves, but many did not know exactly where to go.

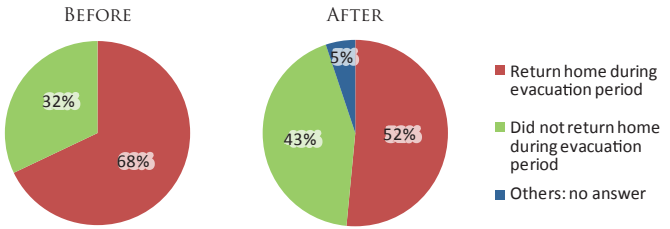
> 'When we had to evacuate, most residents did not know where they had to go to except to go away from Merapi.'
>
> *Sutaji, head of Bronggang-Suruh village, interviewed in December 2011*

Evacuation refusal

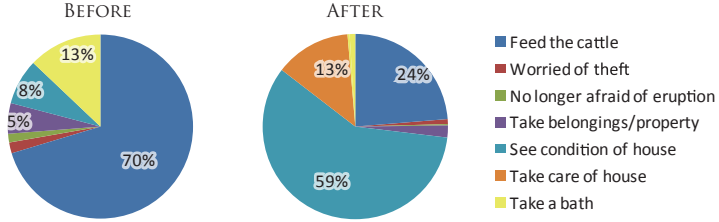


Beliefs and behaviours during the 2010 eruption

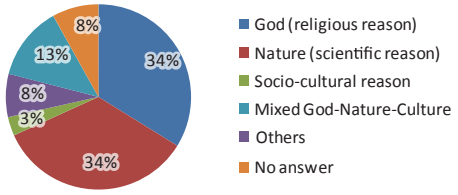
Return home during evacuation period



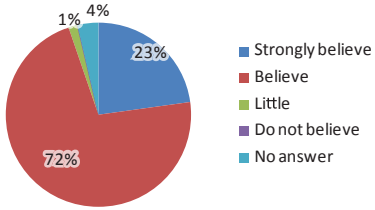
Reasons to return home during evacuation



People's perception of volcanic eruption



Trust in government and volcanologists



Source: data from Mei and Lavigne, 2012; Mei et al., 2013

Impacts of the eruption on air traffic

Volcanic eruptions that eject ash into the atmosphere represent a threat to the safety of air traffic. Tephra is very abrasive to the cabin, and ash accumulates in the engines generating engine failure. On June 24th, 1982, a British Airways Boeing 747-236B (Flight 9) flew through the ash cloud from the Mount Galunggung eruption (in West Java), resulting in the failure of all four engines. Since then, international rules restrict air traffic in case of a threat.

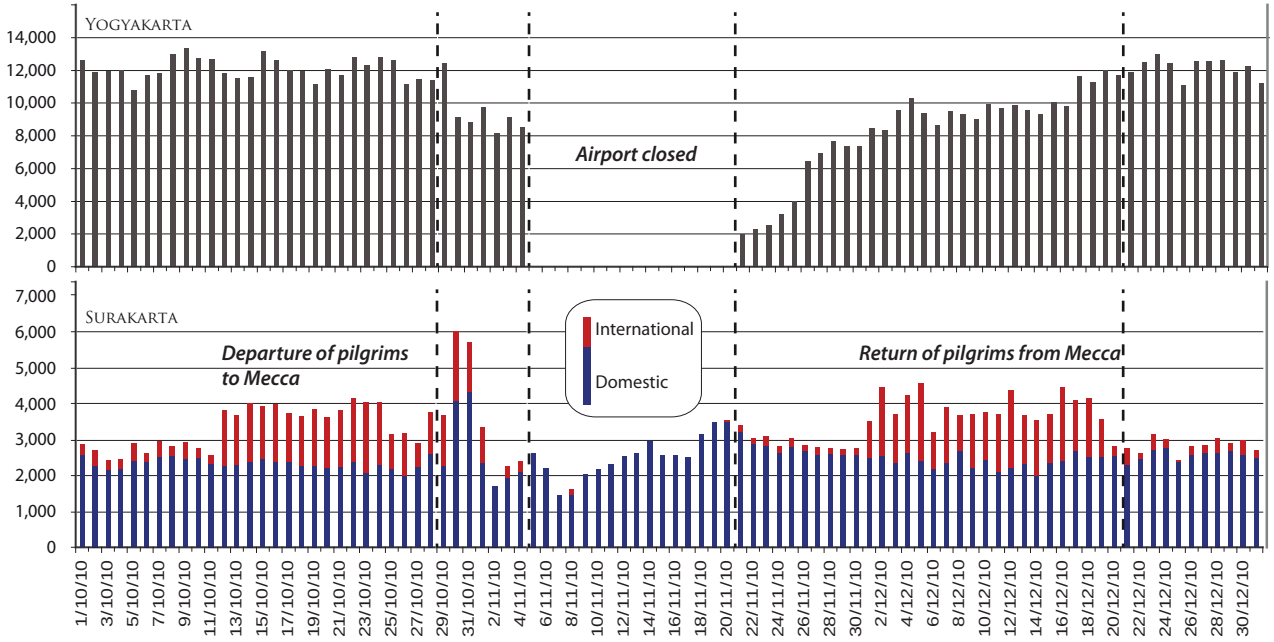
Under normal circumstances, 90 flights are programmed every day in Adisucipto Airport, with an average 11,500 passengers per day.
For the first time, Merapi eruptions resulted in major disruptions of air traffic in Yogyakarta, which has resulted in a paralysis of the city's activities. During the volcanic crisis, about 2,000 flights were canceled, comprising 1,350 flights during the closure of the airport for 15 days, and 600 flights due to a lack of a sufficient number of reservations after its reopening.

Some companies like Garuda Indonesia suspended or transferred their flights to other airports, whereas the low cost carriers like Lion Air continued to fly despite the risks involved.

Passengers per day in Yogyakarta and Surakarta Airports

Source: data from Picquout, 2013

Passengers per day in Yogyakarta and Surakarta Airports

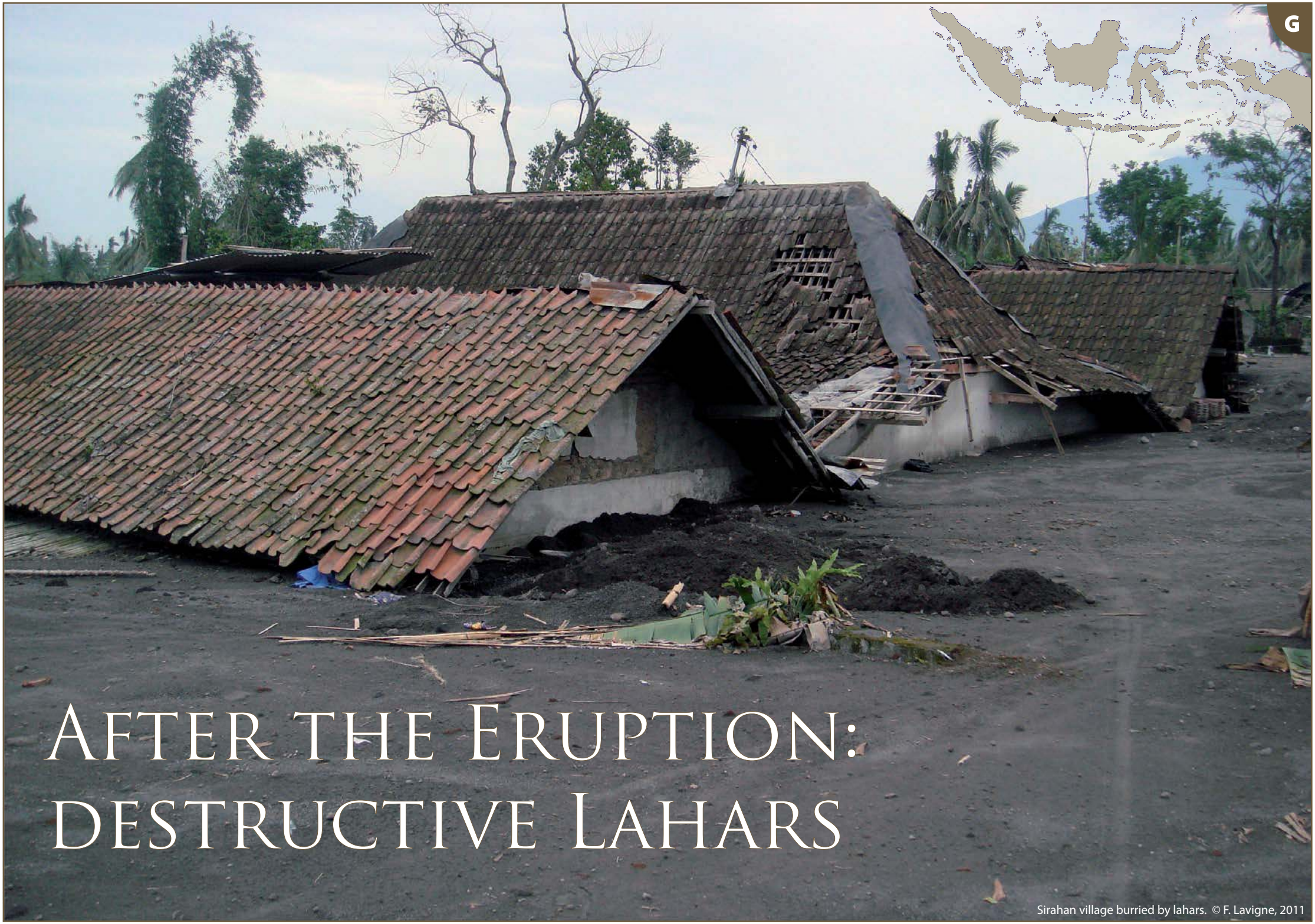


Source: data from Picquout, 2013

The eruption of Merapi was fatal to Mandala Airlines, which encountered financial problems since 2010 and declared bankruptcy on 13 January 2011.

The eruption disrupted the pilgrimage to Mecca for thousands of Muslims. Surakarta Airport is the starting point of the pilgrimage for the Central Java province. As it was also under volcanic ash threat, all international flights to and from Surakarta were suspended from November 5th to 19th. Nevertheless, the organizers were able to cope with the crisis by relocating the departure airport for the pilgrimage.

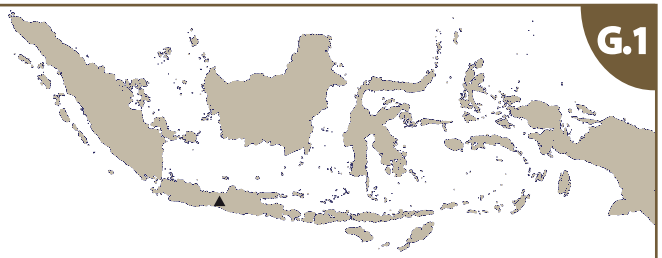
Globally, "only" 2,520 flights were cancelled in Java in 2010 against 110,000 flights in Europe due to the Eyjafjallajökull eruption.
Nonetheless, the disturbances lasted longer (~2 months); different strategies were adopted, e.g. decisions to clean the runway, to re-launch flight activities by bypassing the cloud or by flying aircrafts at a different altitude, etc. The precautionary principle ruled differently in Indonesia. Indonesian airlines are economically weak, leading some of them to fly at risk instead of cancelling their flights.



After the Eruption: Destructive Lahars

Sirahan village burried by lahars. © F. Lavigne, 2011

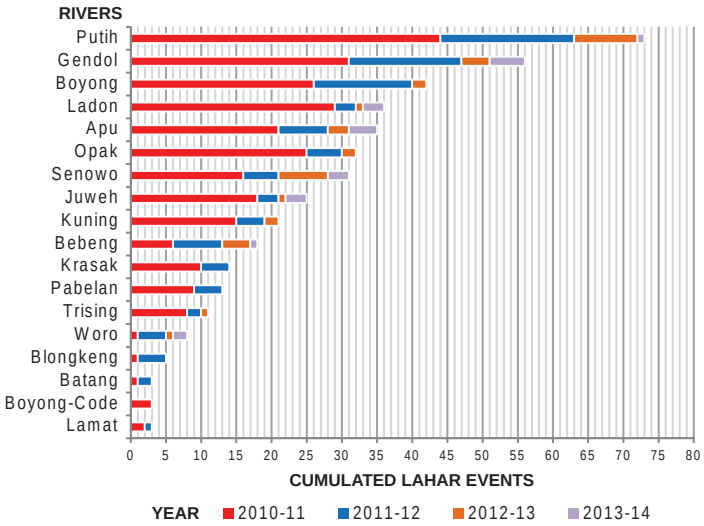
Lahar Occurrence



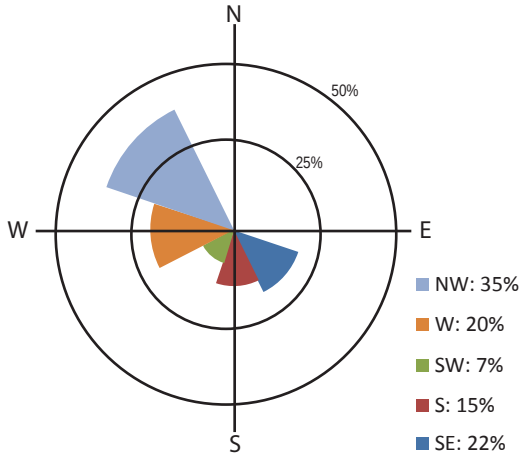
The first lahars associated with the 2010 Merapi crisis occurred during the eruption. Between October 27th and December 3rd, 2010, when the maximal alert level was lowered, 45 syneruptive lahars were recorded. Since the beginning of the eruption to March 2014, 429 lahars were reported. They occurred on 17 rivers, both on the western and southern slopes. Moreover, lahars reached the distal areas of Merapi volcano. Those generated in the Boyong River reached Yogyakarta City located 24 km south from the Merapi summit on November 29, 2010, March 19 and May 1, 2011. Many settlements, which had not been affected by lahars for decades, had suddenly to face frequent lahar onslaughts.

In the Putih River, 55 events occurred during the first hydrological year (October to April). Over the same period, rivers Boyong and Gendol in the southern flank, and Ladon and Apu in the northern flank experienced between 20 and 30 lahar events each. Less than 20 lahar events were recorded in the other rivers. At least four factors may explain why most of the first post-eruptive lahars were preferentially triggered in western rivers:

Lahar distribution by valley (Oct. 2010 - Apr. 2014)



Main directions of lahars (Oct. 2010 - Apr. 2014)



Refer to the map on plate A-3 to locate the rivers.

Source: E. De Bélizal, unpublished

(i) Rainfall amount from January to April is twice as high on the western flank of the volcano (>4000 mm at Babadan) than on the southern flank (2000 mm at Kaliurang);
(ii) The watershed of rivers Putih and Pabelan is larger than that of rivers in southern flank;
(iii) Fallout tephra up to 20 × 106 m^3 were mainly deposited on the western slope of Merapi, due to the dominant wind direction during the eruption.
(iv) Pyroclastic-flow deposits in rivers Gendol and Opak remained very hot for months (even years) after the eruption, thereby preventing the flow of rainwater that evaporated instantly on contact with the ground.

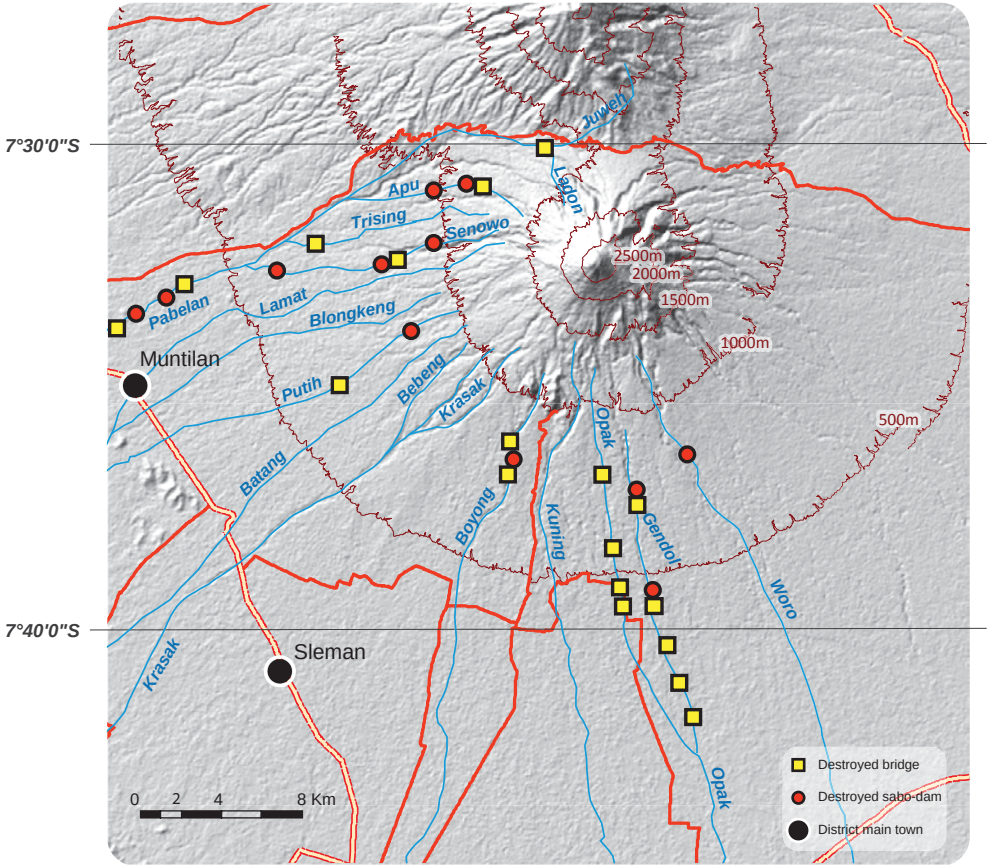
More than 3,000 people became homeless after the first rainy season following the 2010 eruption, as 860 houses were buried or partially destroyed by lahars, mainly on the rivers Putih, Opak and Gendol. Crops, rice fields, irrigation arroyos, and road networks were also strongly affected by lahars on both the western and southern slopes. The road network was strongly affected by the destruction of bridges and dams crossing the river.

DAMAGE TO BRIDGES AND DAMS

Sabo dams trap sediments until they are obstructed by the successive deposits. Sabo dams and bridges crossing the numerous rivers flowing down Merapi were quickly destroyed by lahars after the 2010 eruption. From December 2010 to April 2011, 14 sabo dams and 21 bridges were filled or swept away along the western and southern flanks of Merapi.
The example of the SE-RD5 sabo dam is quite representative. Its construction across the Senowo River ended in 2009. This state-of-the-art sabo dam shows larger outlets than usual and is not obstructed by a road. However, this sabo dam was not designed to sustain more than 4 to 5 lahars a year.
The Senowo River was affected by 13 lahars until March 2011, and so filled up quickly. Blocks from the first lahars got stuck and clogged up the sabo dam, preventing any flow from going through.

Built in 2010, upstream Apu river, this sabo dam only lasted a few months.

BRIDGES AND DAMS DAMAGED AFTER THE 2010 ERUPTION



Source: data from E. De Bélizal, MIAVITA 2012.

SE-RD5 SABO DAM AND ASSOCIATED BRIDGE, 800M DOWNSTREAM

One can notice the ~5m thick deposits accumulated upstream this sabo dam and bridge.

Lahars and their impacts at Tamanagung
Pabelan River

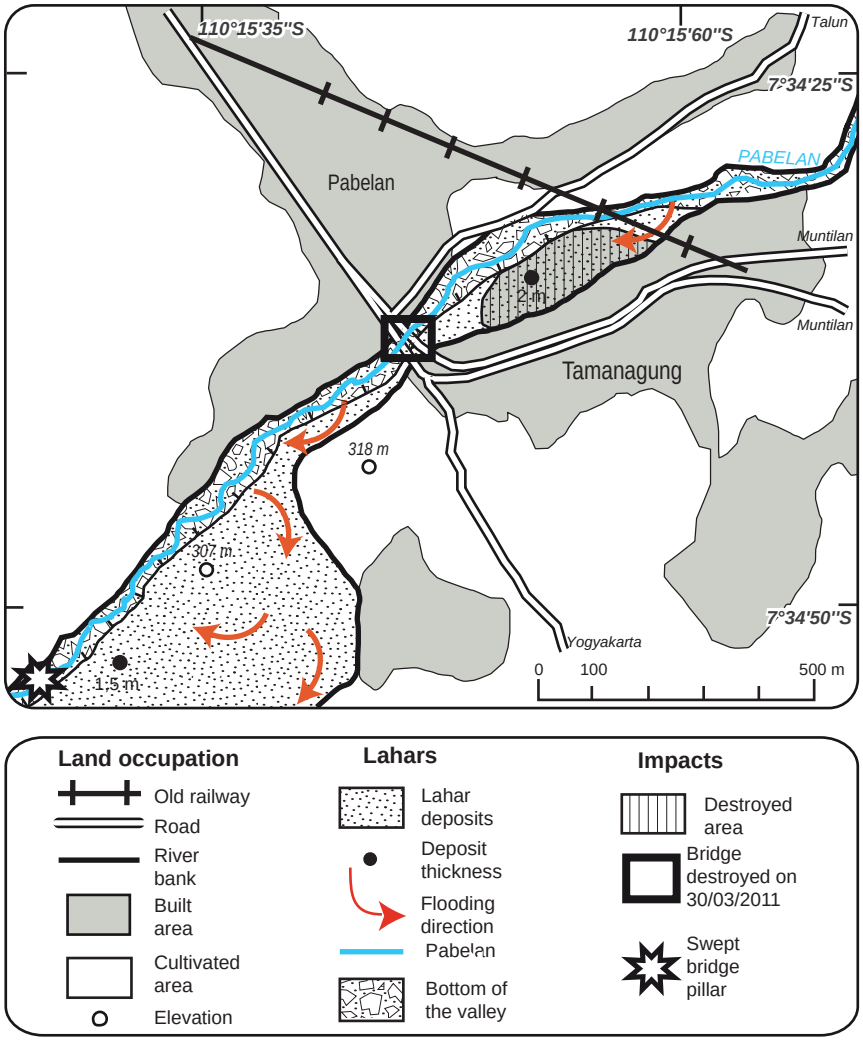
Tamanagung is a village located 20 km west of Merapi's crater, along the Pabelan River.

In Tamanagung, a dozen houses were built on an old terrace 5m above the Pabelan's 47 m wide and 21 m deep riverbed.

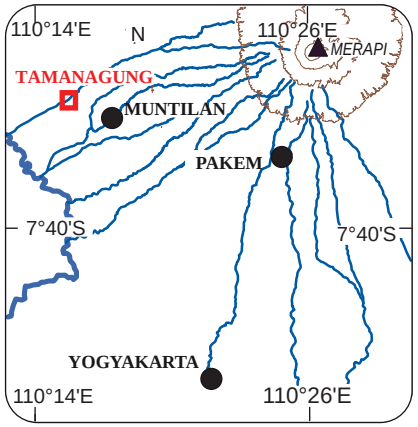
On March 30th, 2011, a series of lahars from the Pabelan's tributaries converged (Trising, Senowo, etc.) upstream of Tamanagung, forming a large single lahar flowing down the Pabelan. When it reached Tamanagung, constrained by the sinuosity of the riverbed, it overflowed the inhabited river terrace, burying houses under a 2 m high deposit, while the twin bridges of the Yogyakarta-Semarang highway collapsed.

The lahar debit was estimated at more than 1.800 m3/s at the twin bridges. At this precise location, the cross-section is about 490 m^2, and the velocity of the flow was estimated to be of 3.7 m/s.

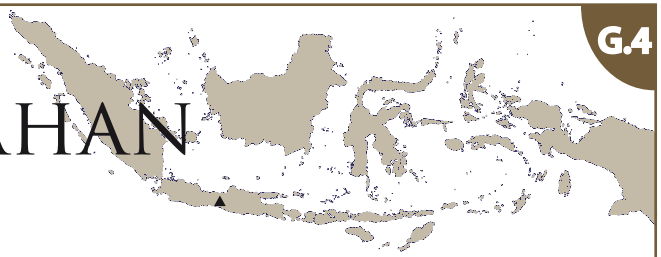
March 2011 lahars in Tamanagung



Source: data and map from De Bélizal et al. 2013



Lahars and their impacts at Sirahan
Putih River

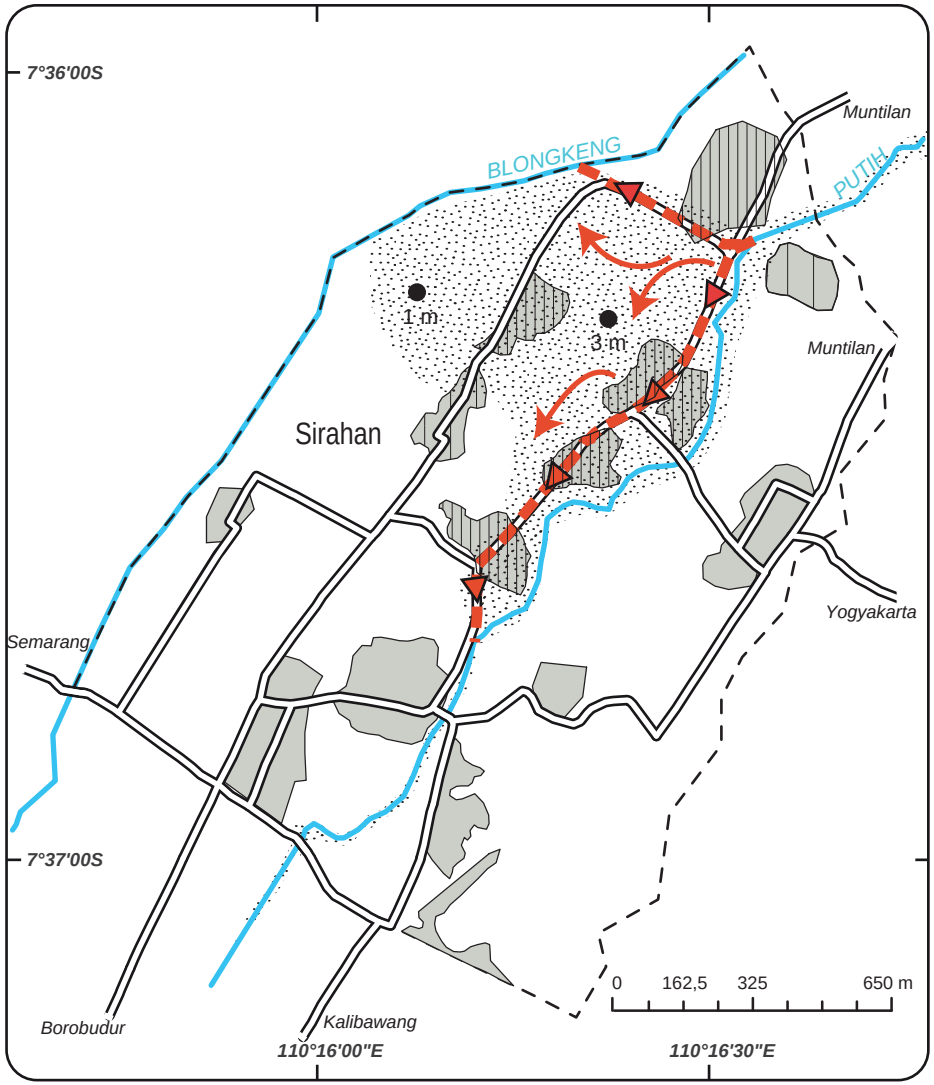


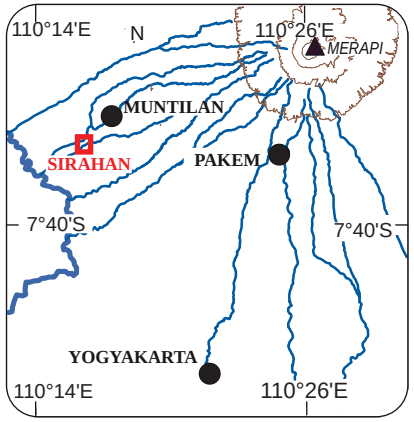
In the Putih River, lahars began during the November 5th, 2010 eruption. Eighteen lahars were recorded until January 3rd, 2011. Located 20 km southwest of the crater, Sirahan is a village on the banks of the Putih, whose riverbed does not exceed a 1.5 m depth for a 3 m width. From November to December 2010, lahars left over 5 m of deposits extending the riverbed to a 10 m width. Early January 2011, local communities built a dyke on the riverbed, leading to its elevation above the inhabited level by the quick accumulation of volcanic material transported by the river.

On January 9th, 2011, a powerful 4 m thick lahar overflowed the dyke flooding Sirahan. The river eroded a new channel of 3.5 m depth across the inhabited area and the rice fields, until it converged back to the Putih, hundreds of meters downstream. This change of riverbed occurred due to the 25 lahars that flowed down the Putih between January 2011 and the end of the rainy season, in late May 2011. By then, the riverbed was 30 m wide and 7 m higher than before the eruption.

These lahars generated important structural damage in Sirahan: 37 houses were destroyed, 217 damaged, 30 ha of arable land was buried under 3 m of lahar deposits.

Impacts in Sirahan





Land occupation
- River
- Road
- *Desa* limit
- Built area
- Cultivated area

Lahars
- Lahar deposits
- Deposit thickness
- Overflow
- Flooding direction

Impacts
- Destroyed area
- Damaged area

Source: data and map from De Bélizal et al. 2013

Lahars and their impacts at Ngerdi

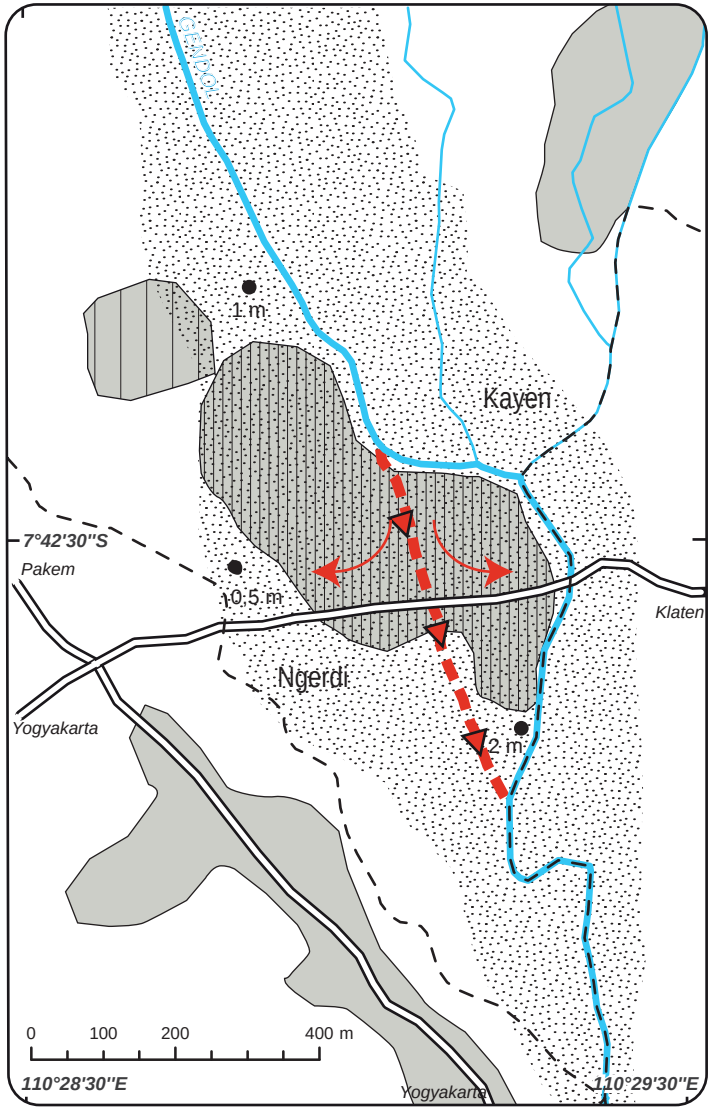
Gendol River

A phenomenon similar to the one that occurred in Sirahan took place in Ngerdi: lahars caused the river to change paths (defluviation).

Most houses destroyed by the May 1st, 2011 lahar were located close to Gendol's small riverbed (1.5 m deep by 3 m wide). This lahar did not meander around Ngerdi, but overflowed, crossing the village of Kayen, as well as its rice fields. Fifty one houses were damaged.

After leaving over 40,000 m^2 of deposits, the river eroded a 1.5 m deep channel in the village. One day after the lahar, the Gendol was divided into two flows: one following the original riverbed, the other crossing the village.

Impacts in Ngerdi



Source: E.De Bélizal et al. 2013

Land occupation

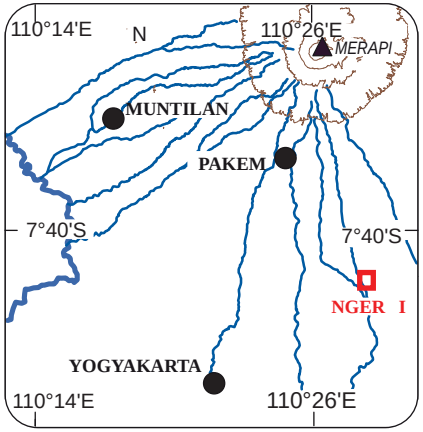
- River
- Road
- *Desa* limit
- Built area
- Cultivated area

Lahars

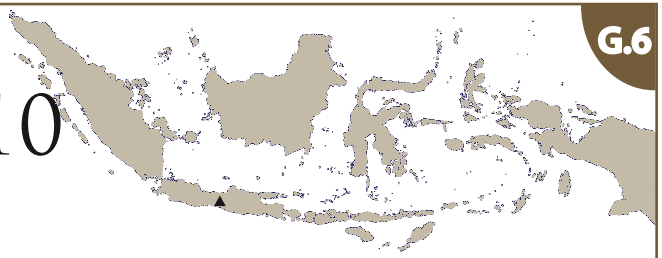
- Lahar deposits
- Deposit thickness
- Overflow
- Flooding direction

Impacts

- Destroyed area
- Damaged area



Block and Sand Mining After 2010



The significant amount of pyroclastic material combined with frequent lahars following the 2010 eruption completely changed the spatial organization of the extraction sites around Merapi.

New extraction sites opened while others closed. Globally, the volume of extracted material decreased after the eruption. But this was soon counterbalanced, with the reintroduction of large tipper trucks and the use of mechanical diggers, recently authorized by the government.

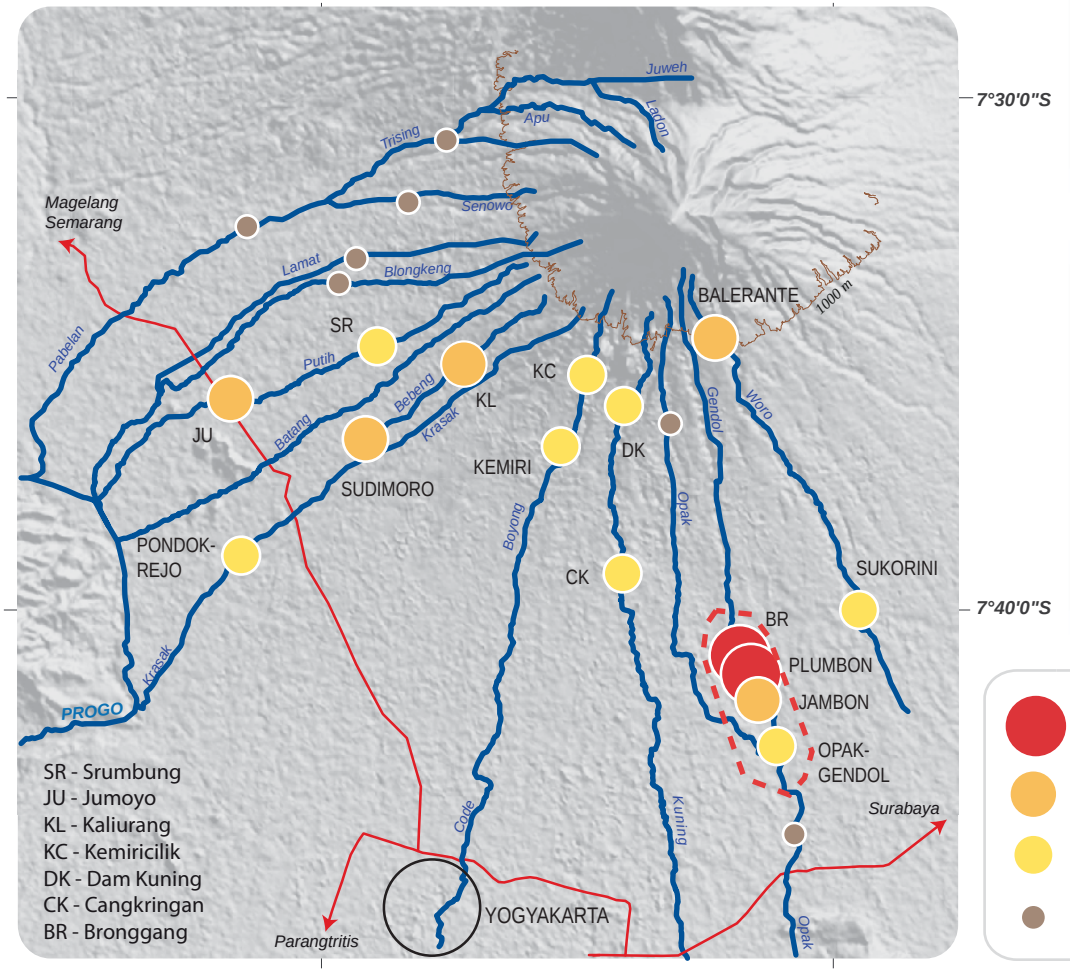
The hierarchical organization of extraction sites showed the emergence of a new extraction basin downstream of the Gendol River after 2010.

The activity in secondary sites remained, but is still far below that of the main sites. Daily extraction volumes per site never exceed 300 m^3, and the lowest limit is of 40 m^3. Secondary sites where at least 100 m^3 are extracted daily are located along a major axis (Jumoyo), or are old sites that were not too severely damaged by pyroclastic flows in 2010 (Kaliurang, Sudimoro, Balerante). In 2012, the activity was still low here, but could intensify along the Putih, where lahars regularly renew the resource. On the other hand, in Balerante or along the Bedeng, the activity is solely maintained by local inhabitants.

Minor sites are located along rivers from the Putih to the Woro, except along the Batang. These older sites were rehabilitated after the 2010 eruption (Srumbung in the Putih; Boyong, Dam Kuning and Pondokrejo in the Krasak). Sales are mainly local, as these sites are far from the main roads.

Irregular sites are not used every day. Rarely more than three to five trucks can be seen there. Their accessibility is poor, especially along the Pabelan River where most bridges were destroyed. People prefer exploiting sites along the Gendol, which is much more accessible.

Quarries in June 2011



Source: data and map from De Bélizal, MIAVITA 2012

Enhancing Risk Management

Volcano monitoring room at BPPTKG © J. Morin, 2013

Updated Hazard Maps

In 2010, the pyroclastic phenomenon generated by the explosive volcanic activity did not correspond at that time to the previous hazard zones map updated after the 2006 eruption. As the contingency plan was created in 2009 on the basis of this map, several areas affected by the 2010 eruption were not yet included as a danger zone, i.e. Bronggang village. Due to the lack of preparation to evacuate and education to disaster risk reduction, many people in this village became victims of the 4-5 November PDCs. After the 2010 eruption, the official hazard map has been updated. The danger zone III, i.e. the one threatened by rockfalls, toxic gasses, and pyroclastic density currents, has been extended up to 17 km along the Gendol River.

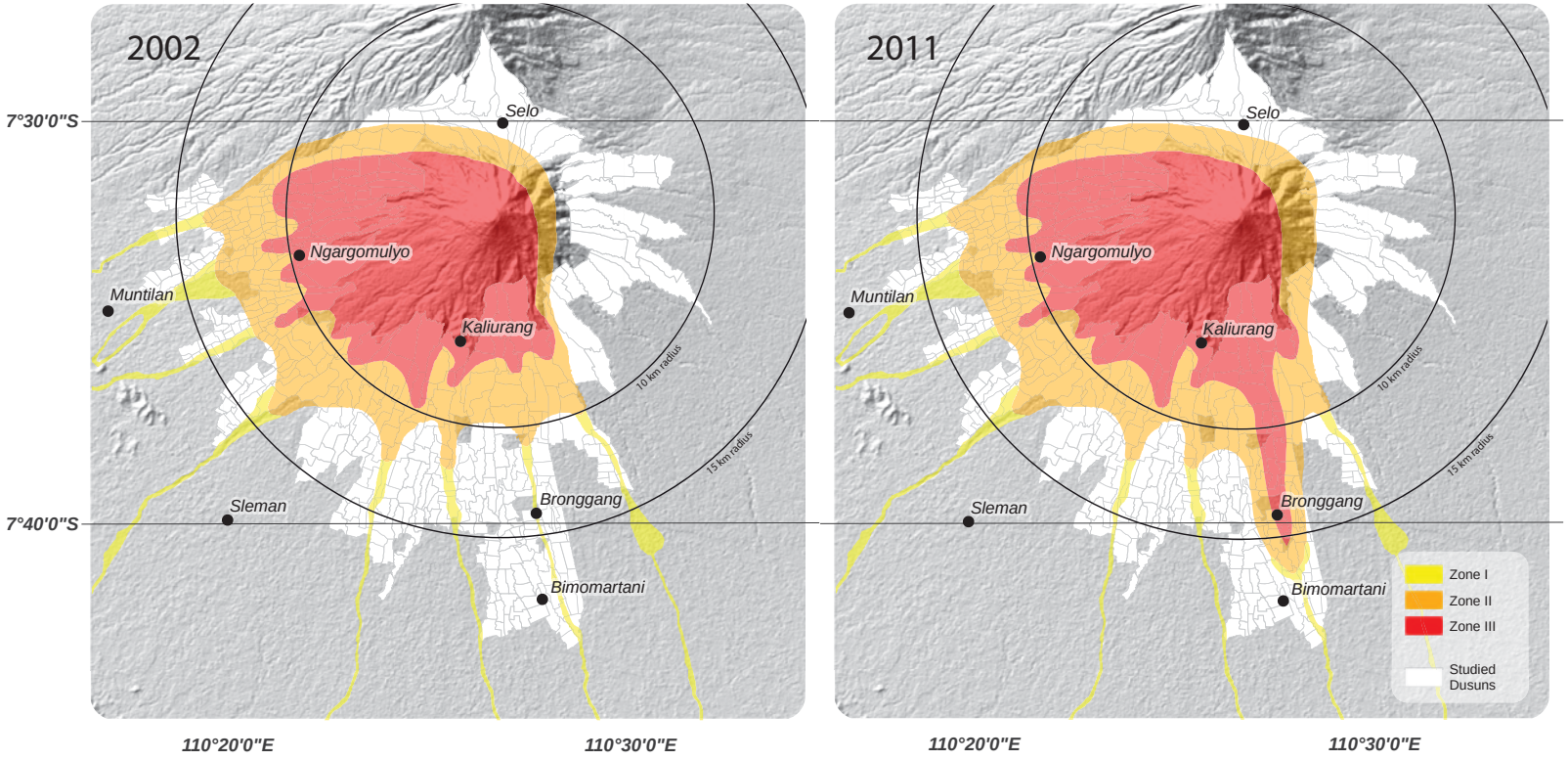
Even if this new volcanic hazard map includes a lahar zone, the previously termed 'second danger zone' (Pardyanto et al., 1978) then KRB I, it has 3 main flaws. First, although valleys most prone to lahars are identified, the scale of the map is not large enough to accurately delimit lahar inundation in specific channels. Second, valleys on the eastern and northern slopes of the volcano, which were not affected by historical lahars, are not included in the lahar hazard zone even though older lahar deposits commonly outcrop along the channels on these slopes. Third, the map does not account for the present morphology of the channels, or for the presence of the Sabo structures.

Therefore BPPTK developed a new hazard zonation for lahar since the 2010 eruption of Merapi, using lahar simulation models (LAHARZ and TITAN2D). These models use several factors, such as LIDAR-based Digital Elevation Models (DEM), and hydraulic parameters.

Map of lahar modelling Boyong-Code river

Source: BPPTKG

Evolution of the hazard map published by CVGHM



Zone I: potentially affected by lahar or stream flow and possibly affected by overflowing or pyroclastic flows.

Zone II: potentially affected by pyroclastic flows, toxic gasses, glowing rock falls and lahar.

Zone III: frequently affected by pyroclastic flows, lava flows, rock falls, toxic gasses and glowing ejected rock fragments (in a 2 km radius).

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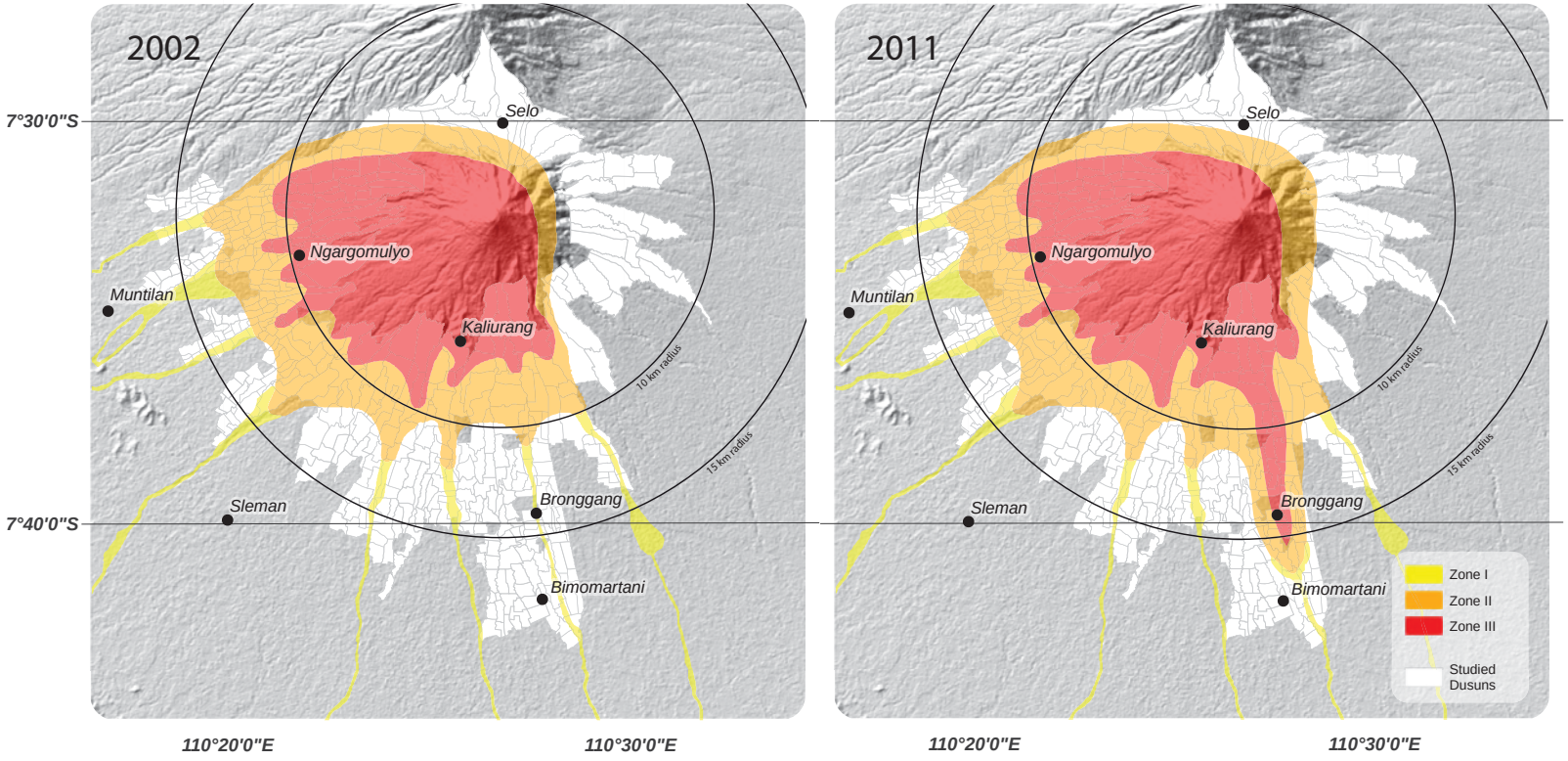

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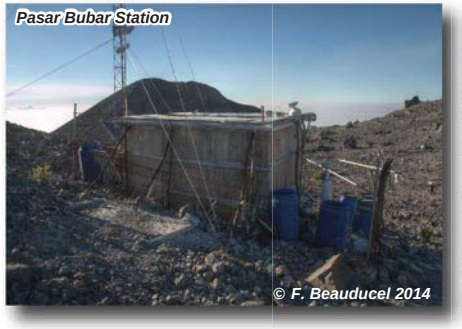
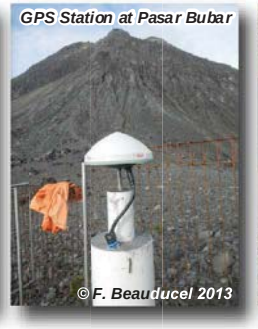
Monitoring The Volcanic Activity

Merapi monitoring system combines a variety of methods of various disciplines:
visual, geological, geophysical (seismic and deformation), and geochemical (gas analysis).





Visual Monitoring

In terms of visual monitoring, there are 5 observatory posts, with observers in charge of monitoring and managing the visual and meteorological data. Visual data includes morphological changes or events related to volcano activities such as rock avalanches, pyroclastic flows, and hotspots. Observatory posts are equipped with meteorological measuring devices such as rainfall, wind speed, humidity, and air temperature. Visual monitoring is also performed by using CCTV cameras installed on the top of several hills, Plawangan, Kaliurang, and Deles in the southeast of Merapi. DOMERAPI* project has also installed stereograph and thermal camera in Kalitengah Lor and Deles.

Geological Monitoring

Monitoring associated with geologic disciplines includes the quantification of the morphology evolution of the summit area, as well as observation of the process of rock alteration due to gas emissions and exposure to high temperatures. At the time of the eruption, observation involves determining the volume and distribution of erupted material, as well as the eruption chronology based on the stratigraphy of deposit material.

Seismic Monitoring

Seismic monitoring at Merapi is a combination of short-period (SP) and broadband seismic stations (BB). A total of 9 stations installed around Merapi consists of 4 SP stations and 5 BB stations. One station is installed about 65 km south of Merapi as a reference of regional seismic activity.

SP data are transmitted by using an analog VHF radio and are digitized at BPPTKG office. BB stations use CMG-40TD Guralp seismometers. Data is transmitted by using a digital system with a frequency of 5 GHz via TCP/IP protocol.

DOMERAPI project has also installed a small aperture seismic array (Antenna) in Pasar Bubar to locate seismic sources associated with magma intrusion.

Deformation Monitoring

EDM

EDM instruments (Electronic Distance Measurements) estimate the radial deformation through the measurement of the distance between a reference position on the slopes (observatory post) and a fixed target (reflector) at the summit. There are 10 units reflectors installed around the flank as measured from 6 positions which 4 positions in the observatory posts (Kaliurang, Babadan, Jrakah, and Selo), in Deles (Southeast sector), and in Mriyan (East sector).

TILTMETER

In the long and medium term, monitoring ground deformation by tiltmeter allows observation of subtle inflation-deflation processes associated with magmatic activity of the volcano. Tiltmeter sensors are AppliedGeomechanics 701-2A, which have a resolution of 0.1 µrad and a sampling speed of 1 sample per 5 minutes. Borehole tiltmeters were installed by DOMERAPI as elements of the Multiparameter stations. The sampling rate is 100 samples per second.

GPS + GLONASS

On volcanoes, accuracy of a few centimeters or less is necessary for detecting the build up of stress and pressure caused by magma rising toward the ground surface. To obtain this accuracy, realtime GPS is used in 9 permanent stations, 4 of them are installed by BPPTKG (in BPPTKG office as reference station, Deles, Grawah, and Klatakan), and 5 stations are installed by DOMERAPI project (in Selo, Babadan, Jrakah, Plawangan, and Pasar Bubar). Data is being transmitted and processed automatically at BPPTKG office.

Geochemical Monitoring

Geochemical monitoring is done by measuring regularly the gas composition of fumaroles in the crater area. The analysis is performed at BPPTKG by chromatography, spectrophotometry, and volumetry. Decrease in water vapor and increase in other volcanic gas content increase is an indication of magma supply. SO_2 plume flux is surveyed with Differential Optical Absorption UV Spectroscopy (DOAS) in scanning mode, using two automated stations.

*: https://sites.google.com/site/domerapi2/

Monitoring Network

The map of merapi monitoring network in 2014

LEGENDS

- Observatory Post
- Realtime GPS station
- Short Period seismic station
- Broadband seismic station
- Tiltmeter & thermometer station
- Seismic Antenna station
- DOAS station
- Stereography Camera station
- MP Multiparameter station (Seismic, Tiltmeter, & Self Potential)
- Red: Stations of BPPTKG
- Blue: Stations of DOMERAPI Project

Jrakah
Selo
Ketep Pass
Grawah
Babadan
Pasar Bubar
Klatakan
Lava 1902
MP
Pusung London
Ijo
Bandit
MP
Labuhan
Taman Nasional
Gunung Merapi
Deles
Kalitengah Lor
Plawangan
Ngepos
Kaliurang
Museum Ullen
Sentalu Yogyakarta
Babadan
Jurangjero
Srumbung
N
W
E
S
1 km
2 km
7°30'0" S
7°35'0" S
110°20'0" E
110°25'0" E
110°30'0" E

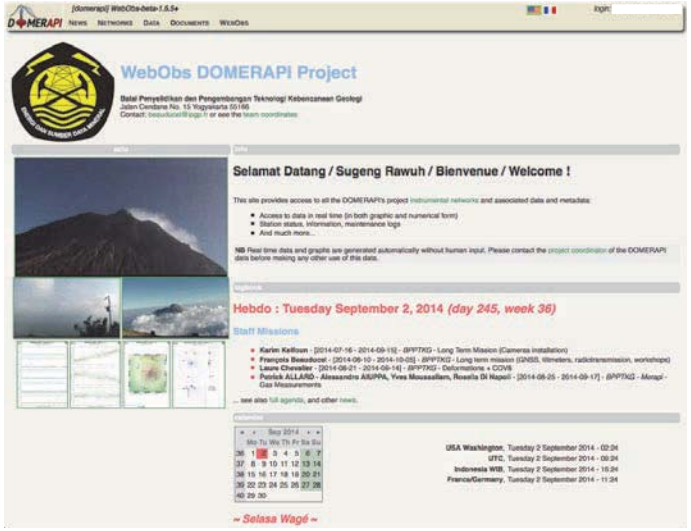
WebObs: An integrated web-based system for observatories (1)

Seismological and volcanological observatories have common needs and often common practical problems for multi disciplinary data monitoring applications. In fact, access to integrated data in real-time and estimation of measurements uncertainties are keys for an efficient interpretation and decision making. But instrument variety, data sampling, heterogeneity of acquisition systems lead to difficulties that may hinder crisis management. We faced this problem in the IPGP overseas observatories and since 2001, we developed an operational system that attempts to answer these questions in the context of a multi-instrumental observatory [Beauducel and Lafon, 2014].

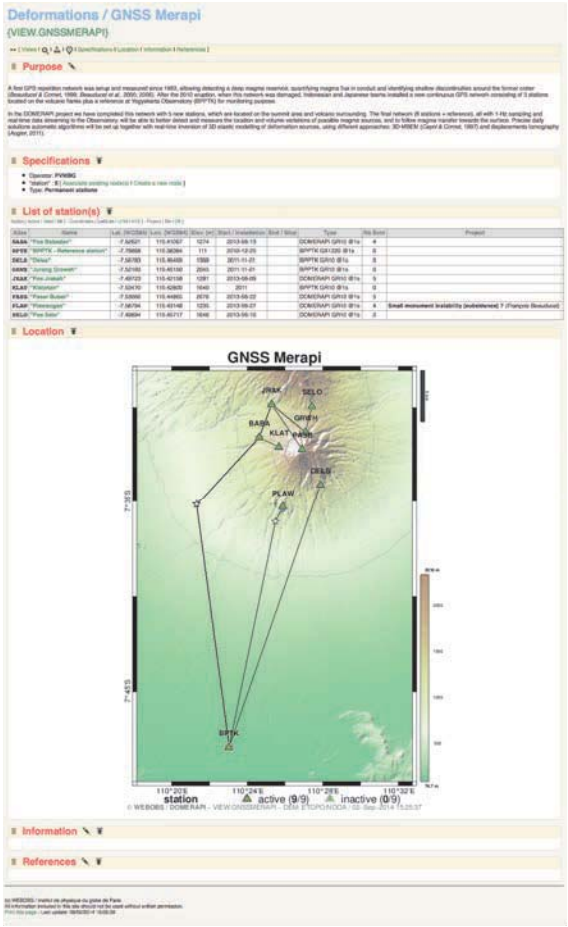
The WebObs system, based on open-source scripts, proposes:

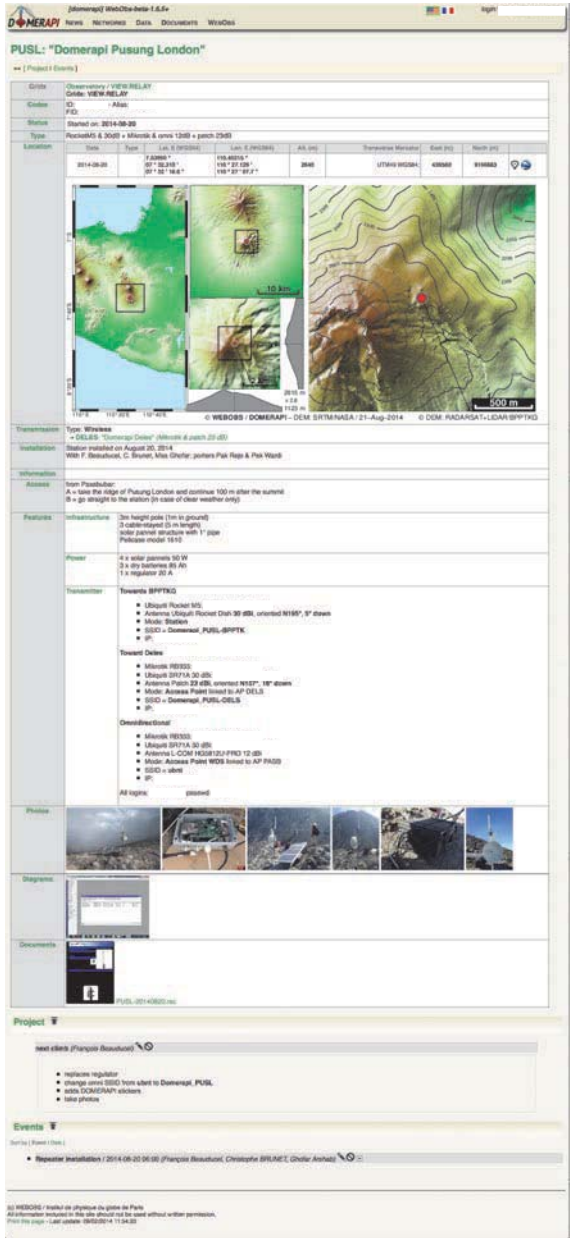
- an extended database for networks management, stations and sensors (maps, station file with log history, technical characteristics, meta-data, photos and associated documents);
- web-form interfaces for manual data input/editing and export (like seismic bulletin, geochemical analysis, repetition deformation measurements, ...);
  routine data processing with dedicated
- automatic scripts for each technique, production of validated data outputs, static graphs on preset moving time intervals, possible e-mail alarms;
  acquisition processes, stations and individual sensors status automatic
- check for technical control.

In 2013, the DOMERAPI project installed WebObs at BPPTKG. At the time of the printout, it includes GPS automatic process and plots, multi-parameter and transmission stations equipment logs.



Networks management





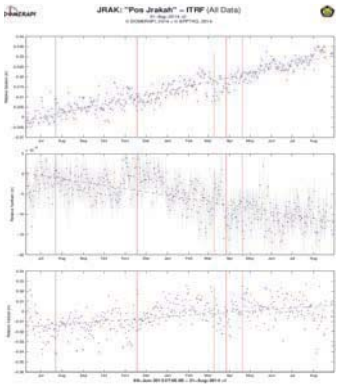
Source: Beauducel et al., WebObs/IPGP, 2014

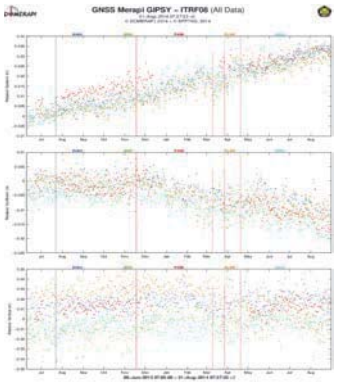
WebObs: An integrated web-based system for observatories (2)

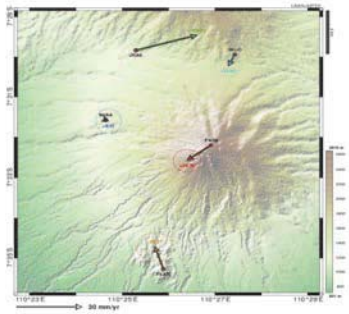
GPS data automatic processing

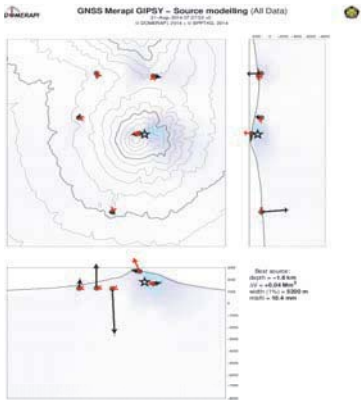
GPS stations record data at 1-Hz sampling and raw files are automatically transmitted to BPPTKG every hour. Precise positioning is performed using GIPSY-OASIS (JPL) software with the best available orbits precision and ITRF08 global referencing.

WebObs processing exports graphs at different time scales (2 months, 1 year, all data): time series, velocity vectors, and deformation source modeling from relative displacements inversion.

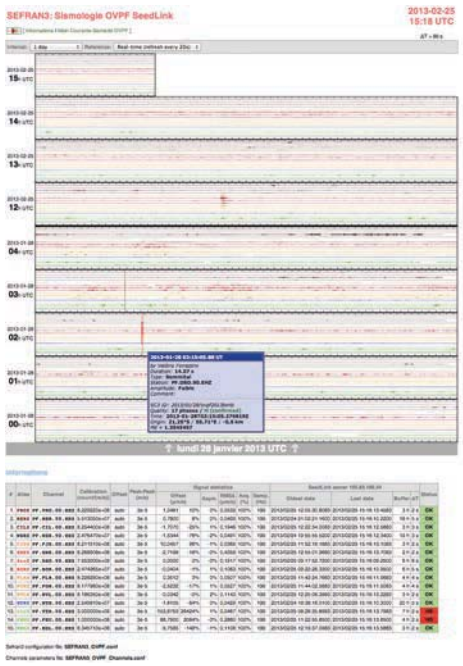








Seismic stripchart and bulletin

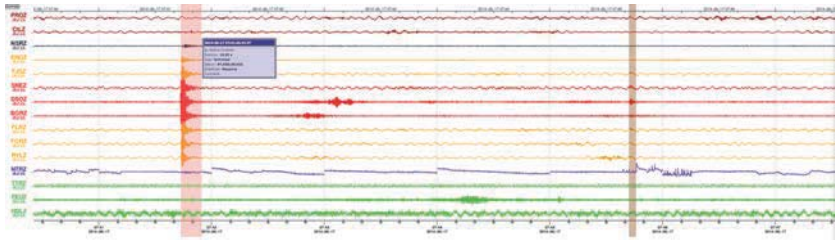


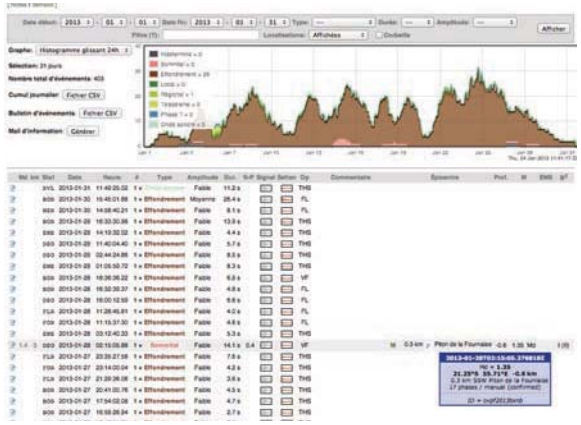
A digital stripchart is included in WebObs (SEFRAN): it uses Seedlink/Arclink data streams to produce multi-stations seismograms in real-time.

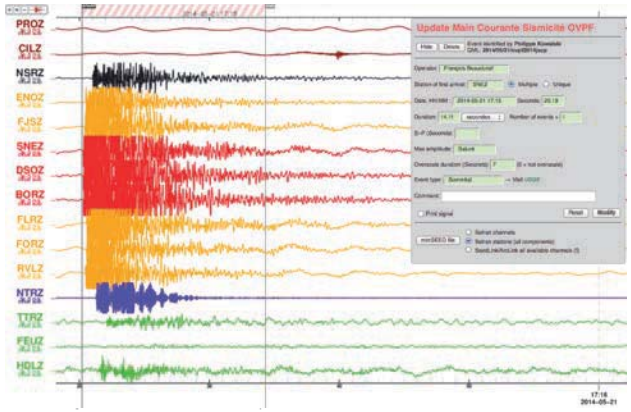
Manual picking and event identification allows to fill and edit a simple seismic bulletin with graph, search and filter facilities.

Access to original waveforms is made through miniseed files. Requests can also be made by web-service (a simple URL chain).

Combined with a SeisComP3 database and QuakeML export, it provides dynamic access to location and magnitude information of events, and also automatic triggering possibilities.







Source: Beauducel et al., WebObs/IPGP, 2014

A New High-Tech Monitoring System for lahar detection

The monitoring systems of BPPTK (Geological Agency) and Balai Sabo (Ministry of Public Works) were almost totally destroyed during the 2010 PDCs and subsequent lahars.

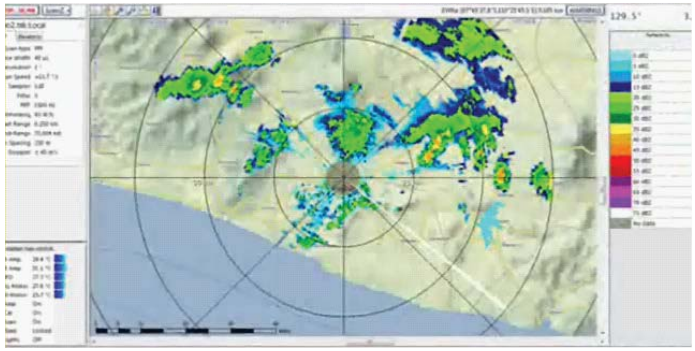
Since 2011, both institutions have installed a new high-tech system for rainfall monitoring, i.e. telemetered raingages and Doppler weather radar (Balai Sabo), which provide almost real-time data of rainfall intensities.

From 2010 to 2012, BPPTK established 24 lahar monitoring stations near the rivers on the southern and western slopes of Merapi. This monitoring system includes telemetered rainfall sensors, seismic sensors (five geophones in 2013), and video cameras. Data transmission from field stations to the central processing unit at BPPTK uses a combination of broadband digital radio and analog VHF radio.

Rainfall warning is given if the cumulative rain intensity exceeds 40 mm in 15 minutes. Threshold values for Real-time Seismic Amplitude Measurement (RSAM) vary from 3,000 to 7,000 units depending on background noise at each station.

Rainfall and seismic data is automatically distributed via SMS and emails to a list of recipients. Visual information can be accessed continuously via www.merapi.bgl.esdm.go.id.

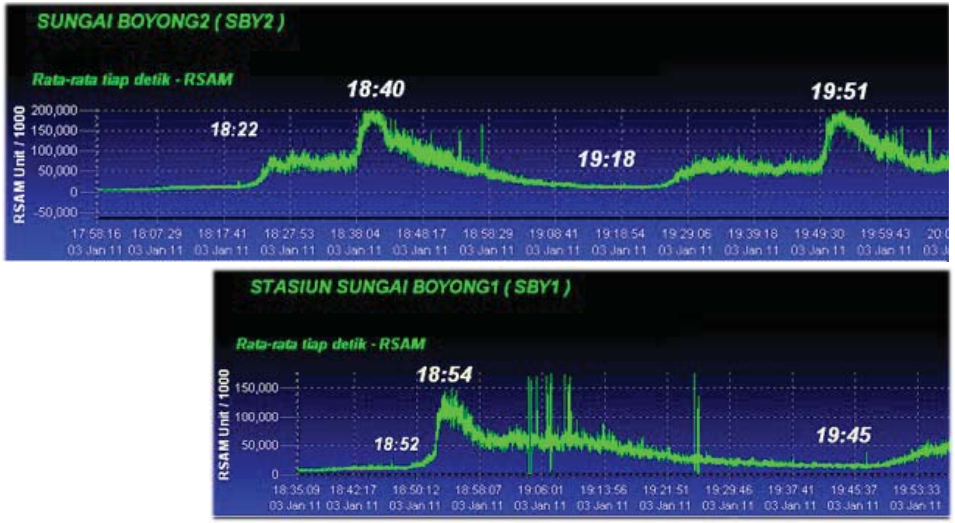
Doppler weather radar (Balai Sabo)



Source: B. Sukatja, Balai Sabo

Webcam monitoring system for lahar observation at BPPTKG and Balai Sabo

RSAM measurements during the 3 January 2011 lahar event

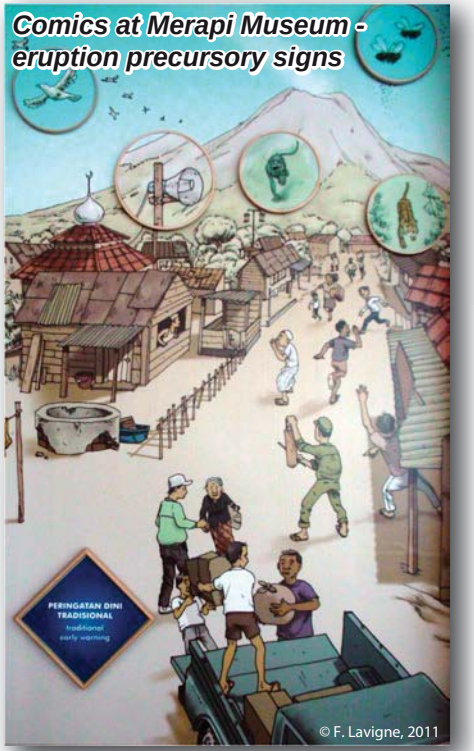


Source: BPPTK

Increasing Hazards Awareness

Before the 2010 eruption of Merapi, several tools were already used to develop hazard awareness of the local people. Community education on volcanic disasters (e.g., socialization, posters, pamphlets, signposts, evacuation drills, etc.) was conducted collectively by the members of BPPTK, local authorities, academic institutions and NGOs. However these activities were only conducted with communities from the villages located within the official hazard zone of KRB III and II.
To prevent future loss of life during unusually large eruptions, disaster risk education and preparation are presently conducted for all Merapi danger zones, including KRB I (lahar-prone zone).

Furthermore, additional hazard signs have been set up in all hazard zones, as well as evacuation guidance and indications of meeting points at the time of crisis. The new Merapi Museum also provides useful information to tourists, including comics on precursory signs of an eruption.



Comics at Merapi Museum - eruption precursory signs
© F. Lavigne, 2011

Poster from Satgas Mitigasi Bencana Merapi (SMBM) NGO: «Danger, cold lahars - Move away from the river!»

Source: SMBM

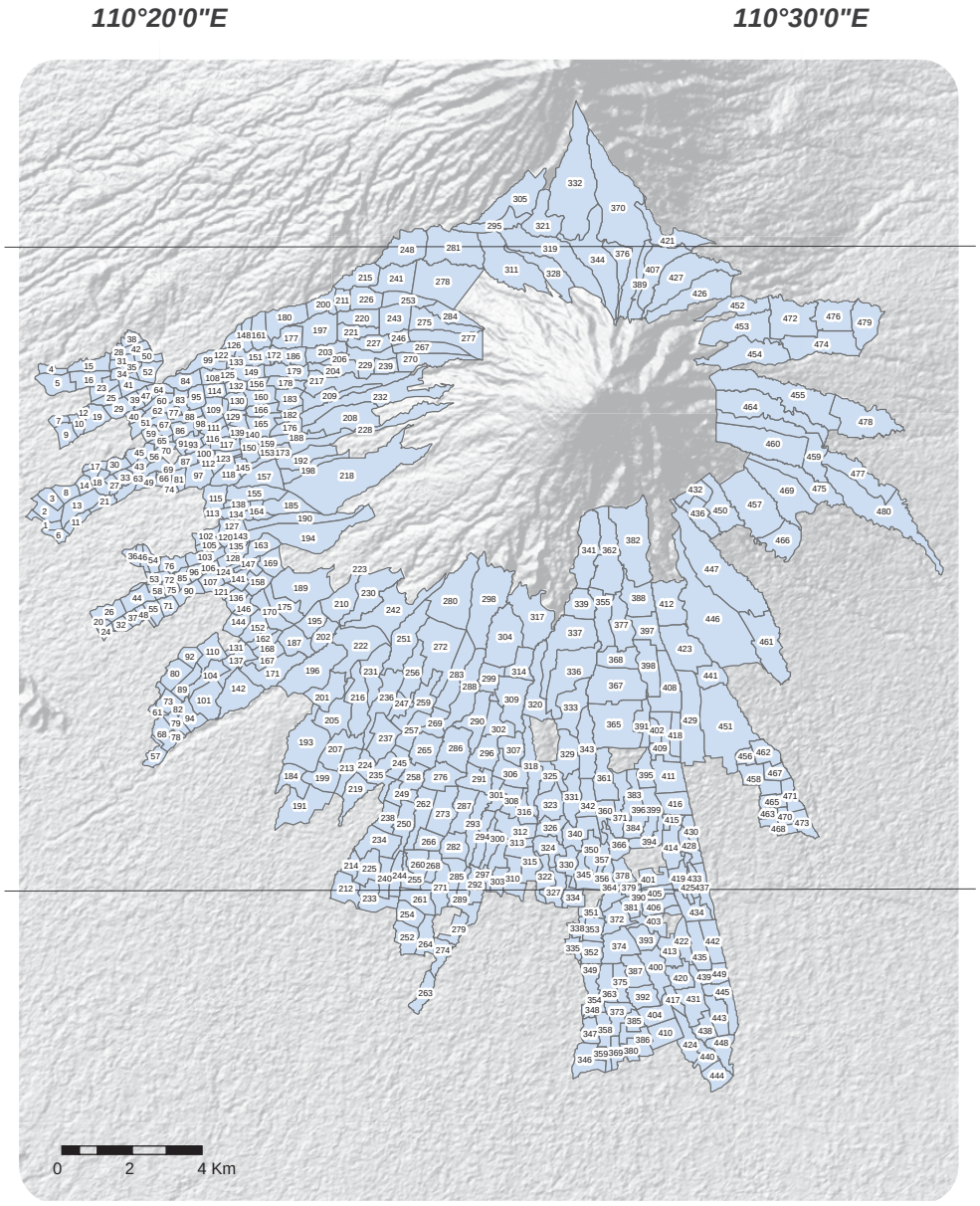
Hazard area signpost
© F. Lavigne, 2013

Hazard area signpost for pyroclastic flow and lahar
© F. Lavigne, 2011

Evacuation route signpost
© F. Lavigne, 2012

Evacuation route and meeting point signs
© F. Leone, 2013

Location of Villages



1 Kwilet II
2 Kwilet I
3 Gaten
4 Kebokuning
5 Margowangsan Bendan
6 Senggrikan
7 Selobentar
8 Sedan
9 Seloiring
10 Selomerah
11 Sabrang
12 Selobendo
13 Ketunggeng
14 Maguan
15 Semaren
16 Sawangan
17 Grawah
18 Ngadipuro III
19 Klatak
20 Ngelorojo
21 Keron
22 Ngadipuro II
23 Bakalan
24 Ngaglik
25 Tegalsari
26 Jamblangan
27 Ngadipuro I
28 Keron
29 Macanan
30 Candigelo
31 Sigug
32 Cawakan
33 Ngrajek
34 Ngaglik Bawah
35 Klangon
36 Kedungsari
37 Wates
38 Jebulan
39 Karang
40 Setran
41 Ngentak
42 Gondangan
43 Kembang
44 Sorobadan Kidul
45 Karanggondang
46 Mangunsari
47 Sorobadan
48 Dowakan
49 Balong
50 Kiyudan
51 Bajengan
52 Ngaglik Atas
53 Mranggensari
54 Sunggingsari
55 Krajan
56 Dukuh
57 Sempon
58 Sorobadan Lor
59 Dukun Satu
60 Talun Kidul
61 Cempan
62 Demo Kawadasan
63 Dukoh Joho
64 Talun Lor
65 Dukun
66 Sempon
67 Sigran
68 Kranggan Kidul
69 Junwono
70 Tegalsari
71 Kauman
72 Gondangsari
73 Timbelan
74 Wates
75 Pringsari
76 Barisan
77 Gejayan
78 Kranggan Lor
79 Banaran
80 Pandean
81 Wayoan Ngisor
82 Bersanan
83 Rejosari
84 Dukuh
85 Rejosari
86 Japunan
87 Selosari
88 Blanten
89 Wonosari
90 Pondok
91 Grogolan Bawah
92 Kresan
93 Musuk
94 Argopeni
95 Banggalan
96 Pagersari
97 Wayoan Dhuwur
98 Duren
99 Soka
100 Petung
101 Kemukus
102 Bendan
103 Sumbersari
104 Sudimoro
105 Warudoyong
106 Candisari
107 Cabe Kidul
108 Mangunsoko
109 Kemiriombo
110 Jerukagung
111 Grogolan Atas
112 Argosono
113 Lempong
114 Garung
115 Tulungrejo
116 Ngentak
117 Gedangan
118 Ngental
119 Candi
120 Krajan
121 Gedawung
122 Guwo
123 Cepek
124 Cabe Lor
125 Bendo
126 Candi pos
127 Gedangan
128 Grogolsari
129 Gawok
130 Sumber
131 Mangosono
132 Gejiwan
133 Wuni
134 Losari
135 Kalisari
136 Logandeng
137 Jombong
138 Ngelo
139 Dukun
140 Suruh
141 Purwosari
142 Tegalrejo
143 Ngargosoko Wetan
144 Tegalrejo
145 Gintung
146 Nepen
147 Ngepos
148 Candi tengah
149 Grogol
150 Kalibening Kulon
151 Sewukan I
152 Kamongan
153 Windusari
154 Srikaton
155 Tegalrandu
156 Tutup Ngisor
157 Demo
158 Ngablak
159 Kalibening Wetan
160 Diwak
161 Candi duwur
162 Tempuran
163 Salamsari
164 Jengkol
165 Berut
166 Ngentak
167 Nglumut I
168 Nganggrung
169 Jengglik
170 Kawungan Cilik
171 Nglumut II
172 Sewukan II
173 Sabrang
174 Batur Duwur
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186 Sewukan Tegal
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196 Sempu
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209 Banaran
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213 Gembang
214 Karanggeneng
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217 Gondangrejo
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219 Karanggawang
220 Gudang II
221 Gudang I
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224 Daleman
225 Gatep
226 Gowok Pos
227 Kepil
228 Gemer
229 Krinjing
230 Sumberejo
231 Manggungsari
232 Karanganyar
233 Sembung
234 Beneran
235 Surodadi
236 Babadan
237 Nangsri
238 Watuadeg
239 Tempel
240 Bunder
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245 Glagahombo
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251 Nganggring
252 Bulus I
253 Gowok Sabrang
254 Bulus II
255 Pakisaji
256 Kloposawit
257 Pancoh
258 Wringin
259 Sukareja
260 Baratan
261 Samberembe
262 Kumendung
263 Penen
264 Kembangan
265 Tawangrejo
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267 Pugeran
268 Pagerjurang
269 Ngelosari
270 Trono
271 Ngelo
272 Kemiri Kebo
273 Cemoroharjo
274 Turgogede
275 Babadan I
276 Kemput
277 Trayem
278 Tlogolele III
279 Kaliwanglu Wetan
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281 Klakah Duwur
282 Blembem Lor
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284 Babadan 2
285 Blembem Kidul
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287 Trojayan
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339 Pangukrejo
340 Kiyaran
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342 Plupuh
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463 Setran
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474 Rejosari
475 Sukorejo
476 Gunungmanik
477 Lanjaran
478 Banjar Rejo
479 Gedangan
480 Doyosari

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