GEM Foundation Program Report

Final report. Reporting Period: November 1st 2017 – October 30th 2019

Summary of Activities

Sector Name: Natural and Technological Risks
Sub-sector Name: Geological Hazards

Task 1: Harmonization of earthquake and volcano datasets, models and risk analysis tools

We performed a survey to identify:

- the tools most used by volcano modellers for performing volcanic hazard analyses;
- the type of analyses performed;
- the volcanoes considered and the possible risk studies conducted..

The results helped us to choose the most important typologies of volcano hazard analyses and the most relevant tools to be incorporated into our framework. Overall, 12 scientists from the three local organisations involved in the project (i.e. Colombian Geological Survey, Phivolcs, Rabaul Volcano Observatory) completed 13 surveys. Figure 1 shows an example of the feedback obtained.

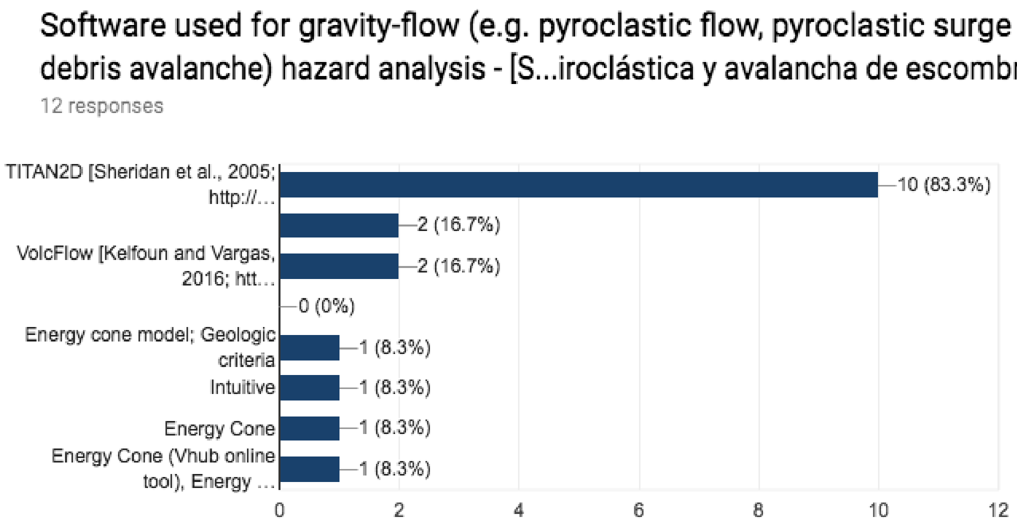

Figure 1. Example histogram summarising the feedback obtained with regard to the software used for gravity-flow analyses.

The Volcanoes for which we received information are:

- Azufral (Colombia)
- All PNG Volcanoes
- Cerro Bravo (Colombia)
- Cumbal Volcanic Complex (Colombia)
- Galeras (Colombia)
- Puracé (Colombia)
- Taal, Mayon, Bulusan, Kanlaon (Philippines)
- Nevado del Ruiz (Colombia)
- Sotará (Colombia)

It appears that the typologies of volcanic hazard analysis more frequently performed consider lahars and gravity flows (e.g. pyroclastic density currents). Lava flow and volcanic ash and/or tephra fall hazard analyses are also frequently performed. Additional but less frequent studies address phenomena like the volcanic tsunamis, shock waves and rubble avalanches.

The software most commonly used for tephra and ash-fall analyses are Tephra2 [Bonadonna et al., 2014] and Wind Reanalysis [Palma, 2013] both available on the Vhub repository [https://vhub.org/]. For ballistic hazard, the code Eject [https://vhub.org/resources/455] is the one most frequently adopted. TITAN2D [Sheridan et al., 2005], Q-LavHA [Mossoux et al., 2016] and LaharZ and LaharZ_py [Schilling, 1998] represent the de-facto standards for gravity-flow, lava flow and lahar hazard analyses, respectively. The ArcGIS extension Voris [Felpeto et al., 2007] is adopted for general volcano hazard analyses.

The hazard typologies and calculation software considered in this project are summarized in the following table.

Hazard	Software	Organization	Intensity
Ashfall	Ash3d	USGS (https://vsc-ash.wr.usgs.gov/ashgui/#/)	Ash thickness and load
Lava Flow	Q-LavHa	Vrije Universiteit Brussel (http://we.vub.ac.be/en/q-lavha)	Binary (1- affected, 0- not affected)
Pyroclastic Density Currents	Titan2d	Vhub and Buffalo University (http://www.gmfg.buffalo.edu/)	Binary (1- affected, 0- not affected)
Lahar	LaharZ	USGS (https://pubs.er.usgs.gov/publication/ofr98638)	Binary (1- affected, 0- not affected)

Table 1. Most relevant hazard perils, software's and organizations for the volcano community.

In the following sections we briefly describe the improvements added to GEM software tools (such as the OpenQuake Engine, the Input Preparation Tool (IPT), and the QGIS Plugin) to support volcano risk assessment. Many of the improvements were based on feedback from the local experts and participants of the regional workshops.

Extension of the OpenQuake Engine to volcanic risk assessment

The CRAVE project required the implementation of a new calculator in the OpenQuake Engine called 'multi_risk', which is able to manage at the same time different types of hazards, specifically ash fall, pyroclastic density currents flow, lava flow and lahar flow, passed as CSV files with headers 'lon', 'lat', 'intensity'. The calculator is also able to consider the difference between dry and wet ash by setting the `ash_wet_amplification_factor` parameter in the job.ini file. The output of the calculator is a CSV file with 'Exposure + Risk' fields. For convenience we also produced a 'Total Risk' output which is simply the sum over the assets of the values in the 'Exposure + Risk' output.
In order to support other formats used in the volcanic hazard community we prepared tools to convert hazard footprints into the format accepted by the OpenQuake-engine. These tools were included in the Input Preparation Toolkit (see details in the next section).

The cases considered are:

- An output file from the selected modelling codes (see table 1)
- A polygon shapefile from ESRI describing the hazard peril in a single field. For this particular case a .ZIP file containing at least the .shp, .shx, .dbf and .prj files must be provided.

These features were all included in the latest release of the OpenQuake engine which is available as open-source software from: https://github.com/gem/oq-engine.

Input Preparation Tool (IPT)

In order to perform risk calculations based on volcano hazard footprints produced by third party tools, it is necessary to import results into the engine. We extended the IPT to include a section for importing various types of volcanic hazard footprint to facilitate this operation.
To provide source files for the new 'multi_risk' calculator we extended our IPT web application to import hazard files of different types (csv, custom text and shapefile), converting them, if necessary, to openquake engine manageable files and collect all other files required to be processed by the openquake engine.
Currently supported phenomena are:

- ash fall - hazard input types: Ash3D output file, default CSV format or shapefile (ESRI)
- lahar - hazard input types: Q-LavaHa output file, default CSV format, shapefile (ESRI)
- lava flow - hazard input types: LaharZ output file, default CSV format, shapefile (ESRI)
- pyroclastic density currents - hazard input types: - Titan2 output file, default CSV format, shapefile (ESRI)

We improved the user interface for this section and also included support for converting evenly spaced grids of points (raster) to multi-polygon areas (vector) using WKT format strings. Vector layers using multi-polygons to describe regions can also be loaded and converted into WKT format. We added support to reproject input layers into WGS84 the projection used by the OpenQuake Engine. This allowed us to improve the handling of "binary" (affected vs not affected) hazards and determining which assets are inside / outside affected areas.
The IPT is available both as an integrated application in the OpenQuake platform, https://platform.openquake.org/ipt/ and is also included in "standalone" local installations provided via the OpenQuake Engine installers.

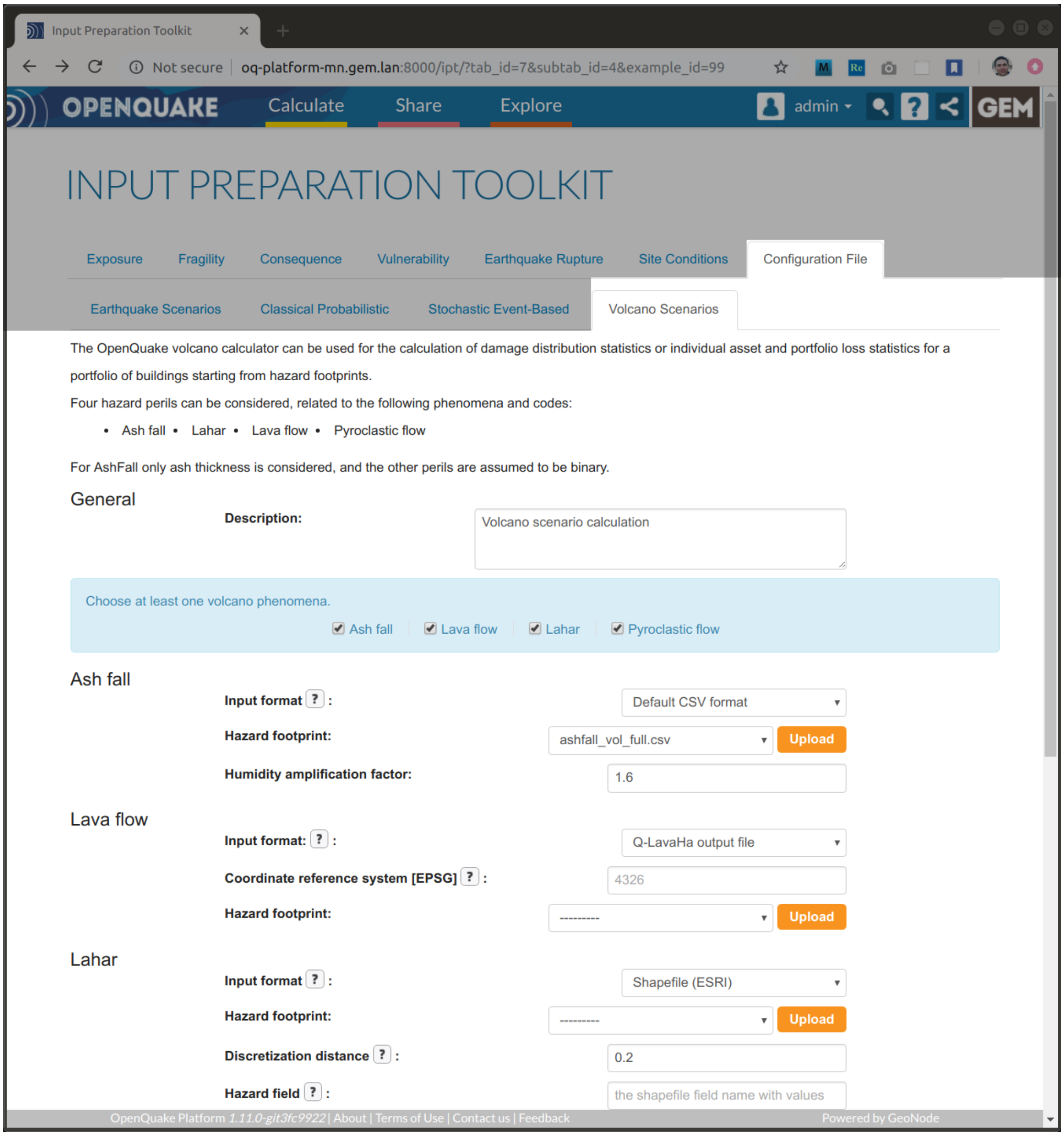

Figure 2. New "Volcano Scenario" section in Input Preparation Tool.

OpenQuake QGIS Plugin

In line with the changes applied to the OpenQuake Engine and IPT, we also improved the QGIS Plugin as part of the volcano risk assessment tools.

The new OpenQuake Engine outputs 'Exposure + Risk' and 'Total Risk' can be loaded by the plugin automatically as QGIS layers. These outputs represent the affected buildings, occupants and economic losses due to four volcano hazards: ash fall, lava flow, lahars and pyroclastic density currents. The 'Total Risk' is displayed as a table with a summary of the total affected buildings, population and replacement cost. For the 'Exposure + Risk' output it is possible to filter assets by taxonomy and by tag, and to aggregate the corresponding data by polygons (geographical regions) defined in a QGIS layer provided by the user. In case 'Risk' visualization is chosen, it is possible to select the kind of peril and the category of damage to display. Examples of the improved capabilities for the QGIS plugin are presented in the figure below.

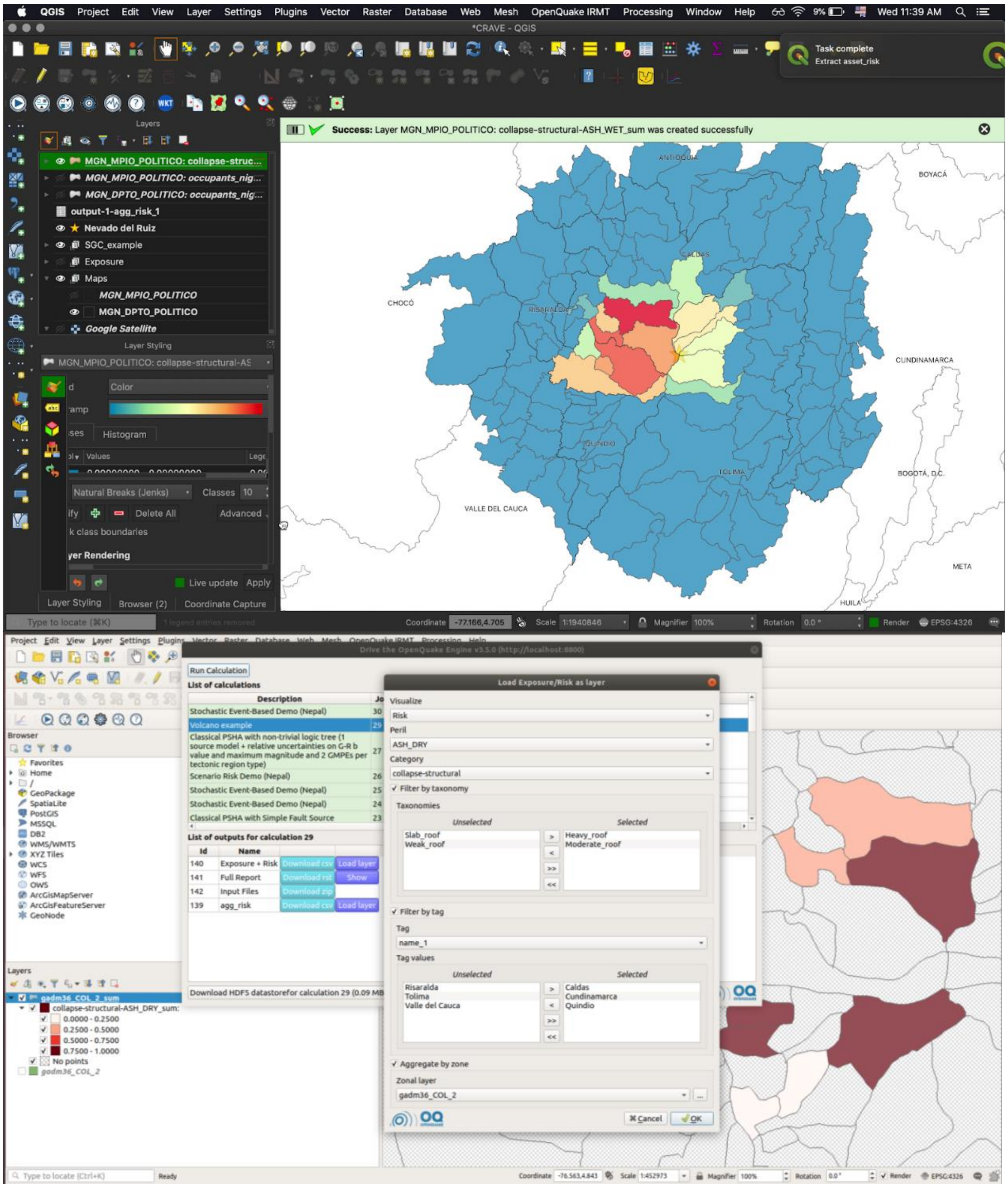

Figure 3. New Volcano support in QGIS Plugin

Tutorial Video

We also produced and published a tutorial video showing how the IPT, OpenQuake Engine and QGIS Plugin can be used to perform volcanic scenario calculations using the El Ruiz volcano as an example. The video has been shared with the project partners and collaborators (VDAP, SGC, BGS, among others) and it is available to the general public through the following link: https://www.youtube.com/watch?v=I2KEHUAZ-j8

Task 2: Assessment of earthquake and volcano risk in the Pacific countries

One of the common ingredients between seismic and volcanic risk assessment is the exposure dataset. By using the same input information, we can ensure that the differences between the risk due to these two perils is only due to the different vulnerabilities and hazard severities, and not because a different exposure dataset was used.

Since 2013 the GEM Foundation has been working collaboratively in the development of exposure models that describe the characteristics of the residential, industrial and commercial built environment. Information regarding main building characteristics that influence the response of the structure under seismic loads were considered and included in the models.

Despite of having such exposure models, the spatial resolution and building characteristics considered in the GEM exposure models are not sufficient for the assessment of volcanic risk. Volcanic eruptions have several simultaneous perils that affect population and infrastructure in different geographical scale. For example, lahars follow the topographic slopes, and concentrates its effects in the surroundings of rivers and streams. Lava flow, for instance, can affect some kilometres in the vicinity of the crater (usually less than 100 km), while global exposure models for earthquake hazard can have a much larger resolution. Finally, it is fundamental to include in the building inventory characteristics regarding the roof material and type, since the vulnerability under ash/tephra fall depend on this.

In this context, to improve the spatial detail of the building inventory, remote sensing data (nighttime lights, global human settlements layer) and crowd-sourcing datasets (e.g. OpenStreetMap data) were used on top of the global exposure dataset from the Global Earthquake Model. It should be noted that despite the fact that this dataset has a global coverage, their spatial resolution follows the smallest available administrative level for each country. This translates into *Municipios* in Colombia, *Barangays* in the Philippines and villages in Indonesia. Moreover, the procedure employed within CRAVE can be applicable to any country in the world, which facilitates the extension of the current project to other regions.

Two case studies were carried out in the context of the project in collaboration with the local partners: A scenario risk assessment for the Nevado del Ruiz volcano in Colombia, and a probabilistic tephra dispersal modelling for an eruption of the Pinatubo volcano in the Philippines.

Volcanic risk scenario for Nevado del Ruiz volcano, Colombia

The Colombian Geological Survey (SGC) provided information/data to construct a volcano test case for the well-known “Nevado del Ruiz” volcano, located in central Colombia (https://www2.sgc.gov.co/volcanes/index.html). Hazard footprints for ash fall (thickness and load), lava flow, pyroclastic density currents, lahar and avalanches were considered in the analyses (see figure below). The selected hazard footprints correspond to an eruption with similar characteristics as the ones indicated in the national hazard maps, that correspond to the worst-case scenario.

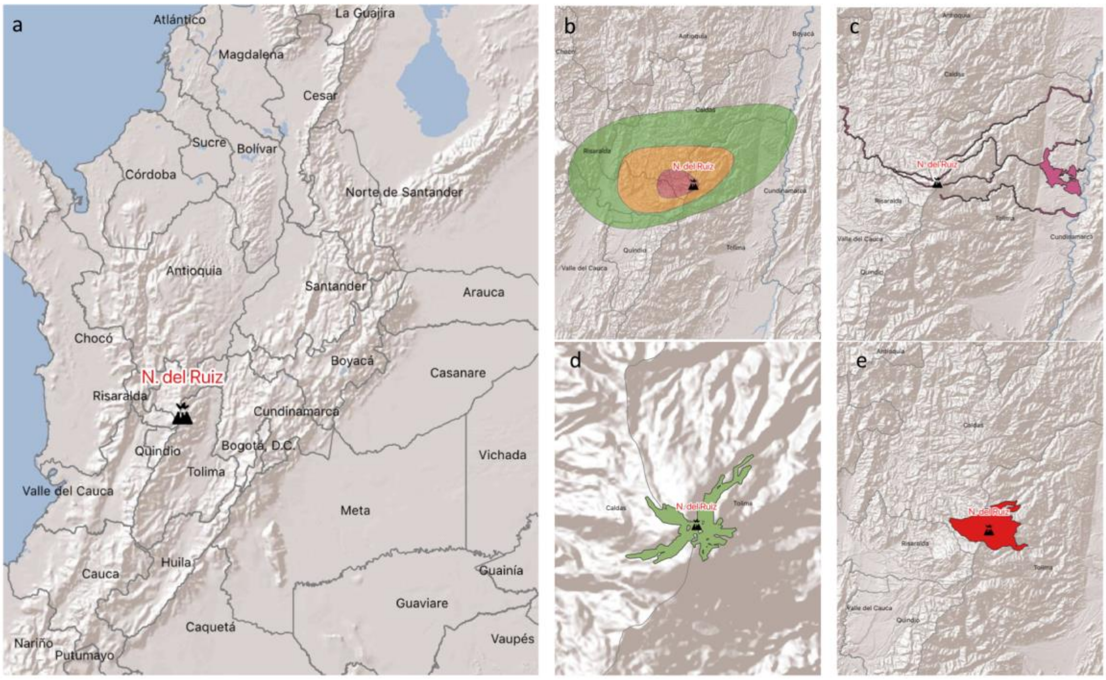

Figure 4. Colombian Nevado del Ruiz volcano test case: a) location; from b) to e) footprints for: b) ash fall deposit thickness, c) lahars, d) lava flow and e) pyroclastic density currents.

An updated and improved exposure model for Colombia was developed in collaboration with the Colombian Geological Survey (SGC). The model was based on the GEM Global Seismic Risk Model (GEM, 2018). Information regarding the roof type and material was incorporated in the model. The new model considers information from the national census survey (DANE, 2005) at the block level (instead of the previous model that had data at municipality level - i.e. second administrative division), but also takes into account national results from previous census surveys (from 1993).

Since the resolution of the model in the urban areas was suitable for volcanic risk assessment, only the spatial resolution for the rural buildings was improved using satellite imagery with rivers, lakes, roads, night time lights and population density. Moreover, the SGC collected detailed information with the exact location of the residential buildings in the surroundings of the volcano, covering around 36,000 housing units (all located in rural areas), which has been incorporated into the residential exposure model. The figure below presents the location of the buildings around the volcano.

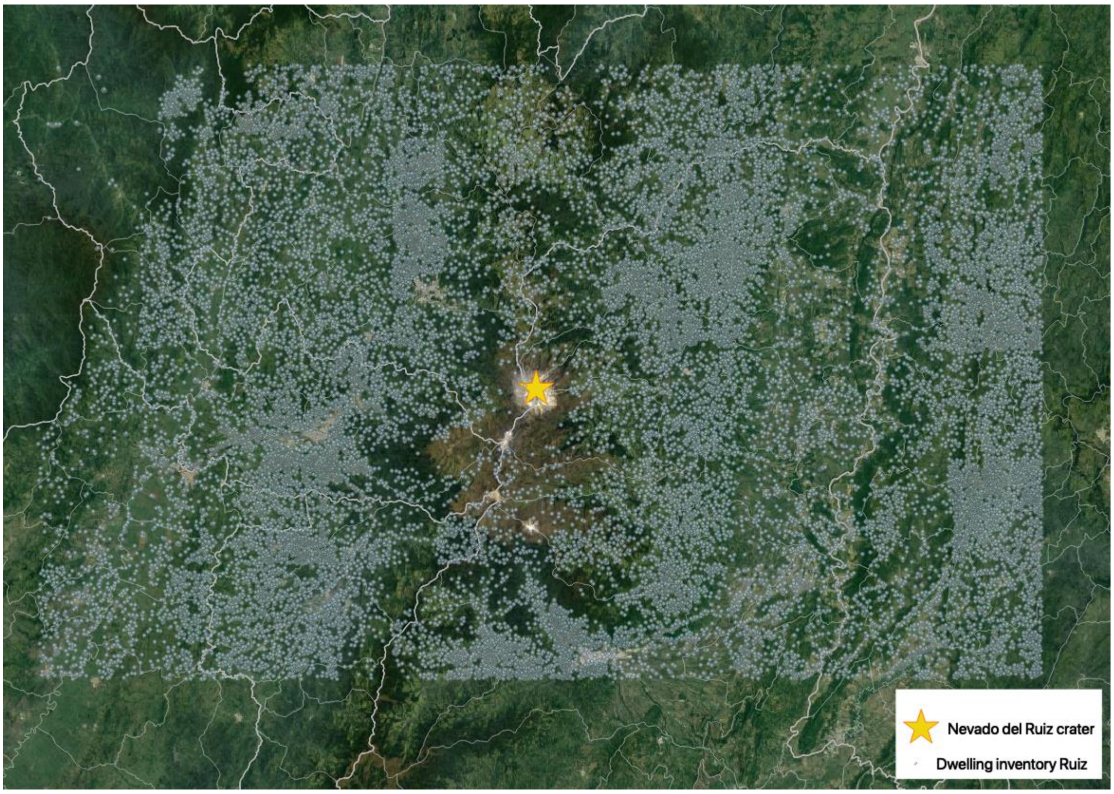

Figure 5. Nevado del Ruiz crater and location of nearby residential buildings

For the estimation of the ash load impact, it is necessary to provide fragility functions that represent the probability of roof damage given the ash load. A literature review for existing tephra and ash fragility functions was carried out, and the functions developed by Torres-Corredor *et al.* 2017[1], for Galeras volcano in Colombia were selected. The set of fragility functions account for roof collapse probability for four roof types: light roof, moderate roof, heavy roof, and reinforced concrete slab roof.

The figures below present examples of the maps and risk metrics generated for lahar and for ash fall in dry conditions.

[1] Torres-Corredor, R.A., Ponce-Villarreal, P., y Gómez-Martínez, D.M. 2017. Vulnerabilidad física de cubiertas de edificaciones de uso de ocupación normal ante caídas de ceniza en la zona de influencia del volcán Galeras. Boletín de Geología, 39(2): 67-82.

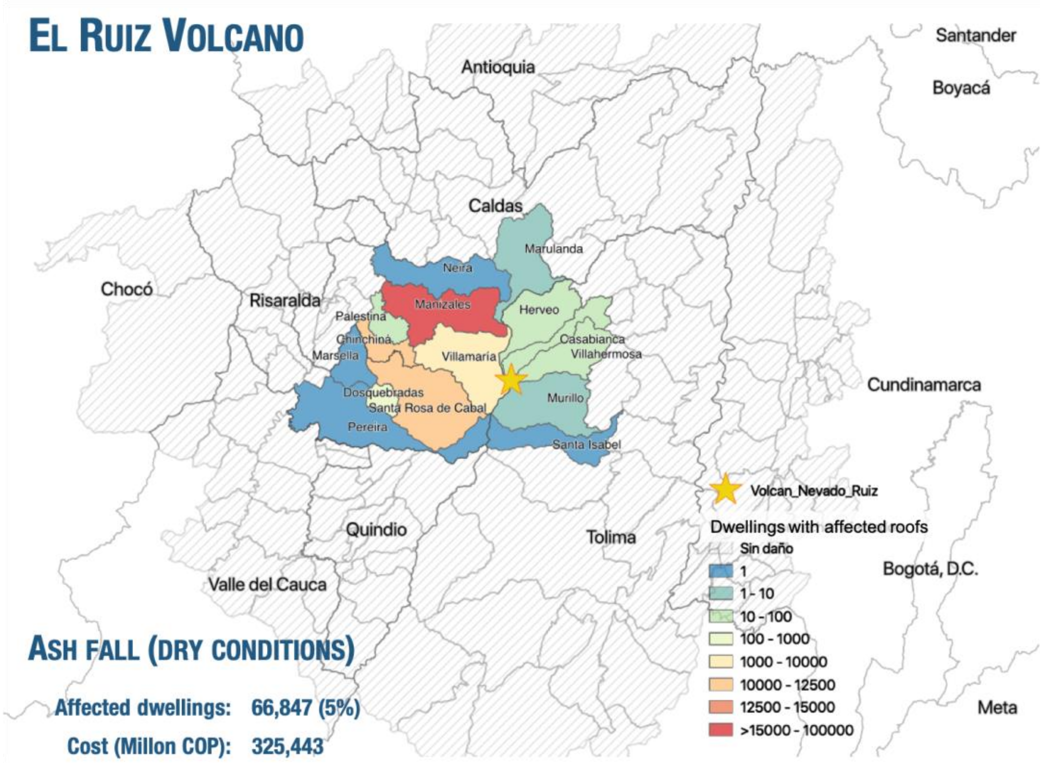

Figure 6. Risk estimates for Ash fall in dry conditions for El Ruiz volcano. The map depicts the number of dwellings with affected (collapsed) roofs at each municipality.

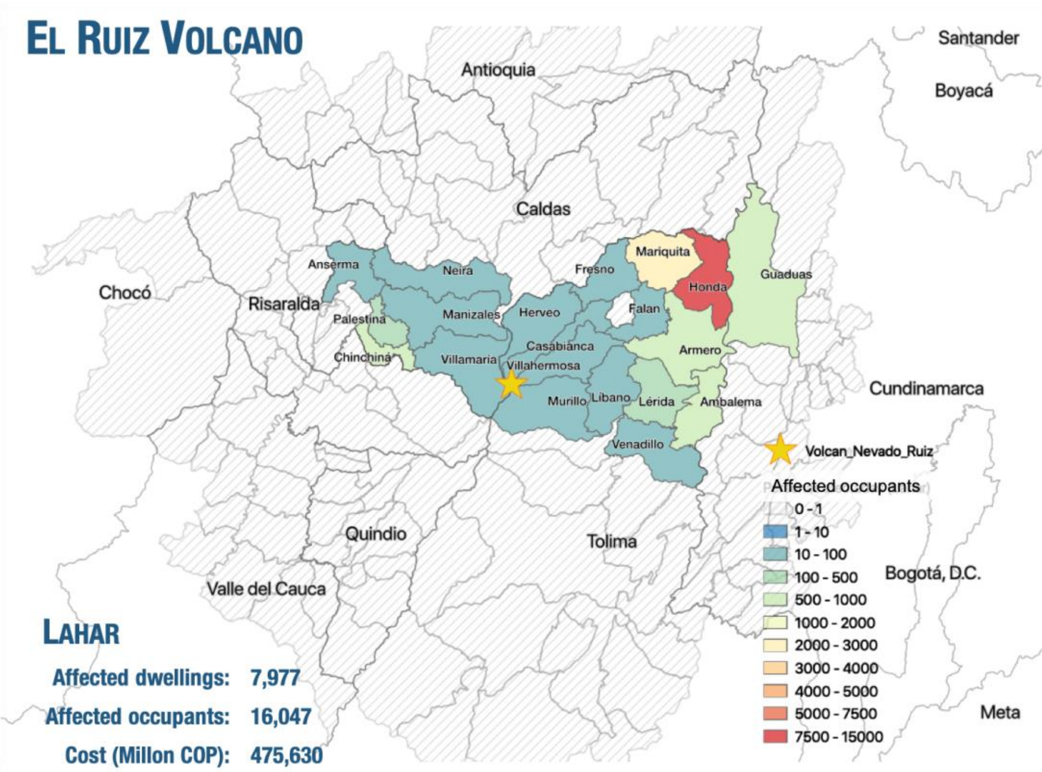

Figure 7. Risk estimates for Lahar in El Ruiz volcano. The map depicts the number of affected occupants (population) at each municipality.

Probabilistic tephra dispersal modelling for Pinatubo volcano, Philippines

In collaboration with colleagues from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and the British Geological Survey (BGS), the Earth Observatory of Singapore (EOS) led the development of a probabilistic tephra dispersal model.

There were a number of requirements for the probabilistic tephra dispersal modelling:

1. The use of an established hazard model that is open-access and can be implemented by local partners;
2. A focus on scenario-based probabilistic modelling for one volcano, rather than fully probabilistic or regional multi-volcanic assessment;
3. Outputs should be on a 500 m by 500 m grid to match exposure assessments and provide the annual probabilities for exceeding key tephra loading thresholds.

The Pinatubo volcano in northern Luzon was selected as a case study. The eruption of 1991 was simulated as a probabilistic scenario using the freely available and well-established Tephra2 model (Connor *et al.,* 2008). Tephra2 was run through the open-source probabilistic wrapper TephraProb (Biass et al., 2016) to provide an easy-to-use approach for simulating, processing and visualising large numbers of potential eruption outcomes.

Credible ranges for a VEI 6 eruption were established from a range of sources, with bounds provided by the VEI classification, the Pinatubo 1991 eruption and by the literature. 15,000 simulations were run for the established scenario at Pinatubo, accounting for seasonal effects and variation in source parameters, e.g. plume height, erupted mass, grain size distributions.

Analysing the results of the individual footprints shows that tephra is typically dispersed towards the west, but that the area affected is dependent upon the sampled source parameters and meteorological conditions. Three main outputs were produced: 1) Probability maps: the probability of exceeding a certain load threshold for each grid cell; 2) Isomass maps: the tephra load associated with certain probability percentiles for each grid cell; and 3) Hazard curves: that describe the probability of exceeding the range of tephra fall loads at individual locations. The figures below present examples of the generated results.

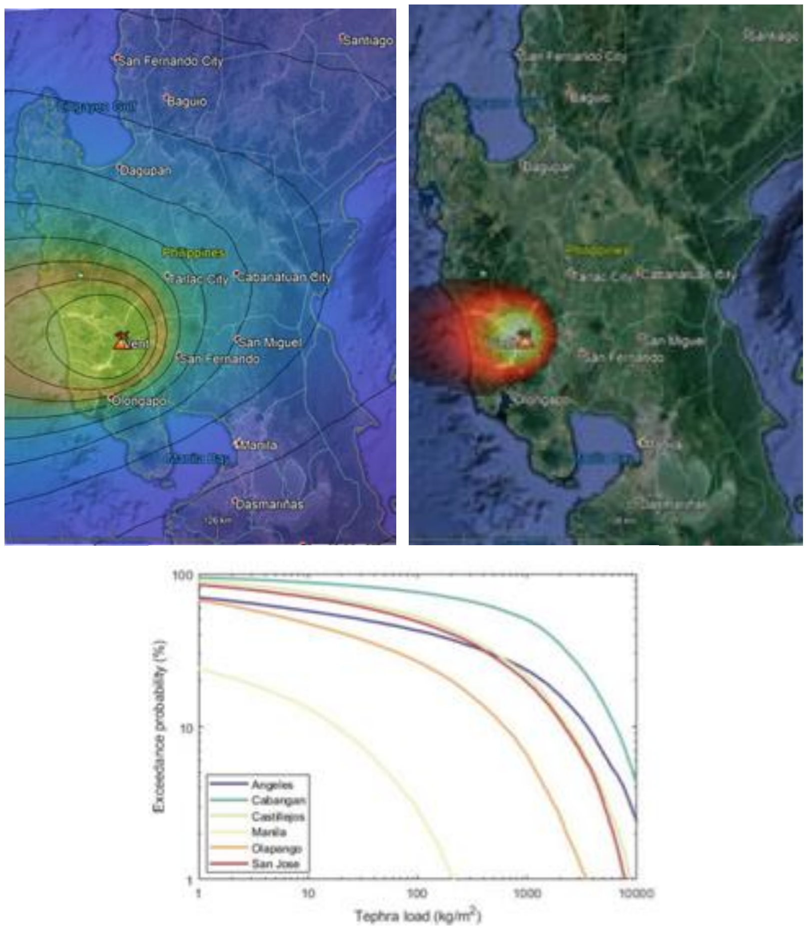

Figure 8. VEI 6 style eruption in Pinatubo scenario. (top-left) Probability maps to exceed ground tephra accumulations of 1 kg/m2; (top-right) Isomass map using fixed exceedance probabilities of 90%; (bottom) Hazard curves computed for a small number of selected cities, with no seasonality considered.

The exposure model for the Philippines was also improved using a similar approach as the one described for Colombia. Information from the 2015 Population and Housing Census at municipal level was retrieved for the residential case, which reported the number of dwellings by material of the walls and material of the roof. The available census data comprised information about the material of the roof classified into 8 categories. By combining the building classification for earthquake hazard with the material of the roof, the most likely roof class was assigned based on expert judgment.

The categories to classify the roof performance are closely related to the roof fragility models available in the region. In the case of the Philippines, the model proposed by Jenkins et al. (2014) was selected for the present risk assessment. This study provides information regarding the collapse roof probability of exceedance due to tephra load for five categories of roof, from A to E, being A the weakest roof type under ash load and E the strongest one.

At national level, it was found that the predominant roof classes are type D, A, and C representing 42%, 33%, and 22% of the buildings respectively. The categories B and E are not common and each one represents 1% of the total buildings. In contrast, if the fraction of roof classes is estimated based on the building replacement cost instead of the number of buildings, the fractions are instead 59%, 21%, and 15% for types D, A, and C respectively; while type E moves up to 5% and type B keeps the 1%. The Figure below shows the distribution of roof type across the affected area, where it can be observed that closer to the highly urbanized areas, like Manila, the roof class D is predominant (colour green in the pie charts), while toward the Nord and the East the predominant roofs are class A (colour red in the pie charts).

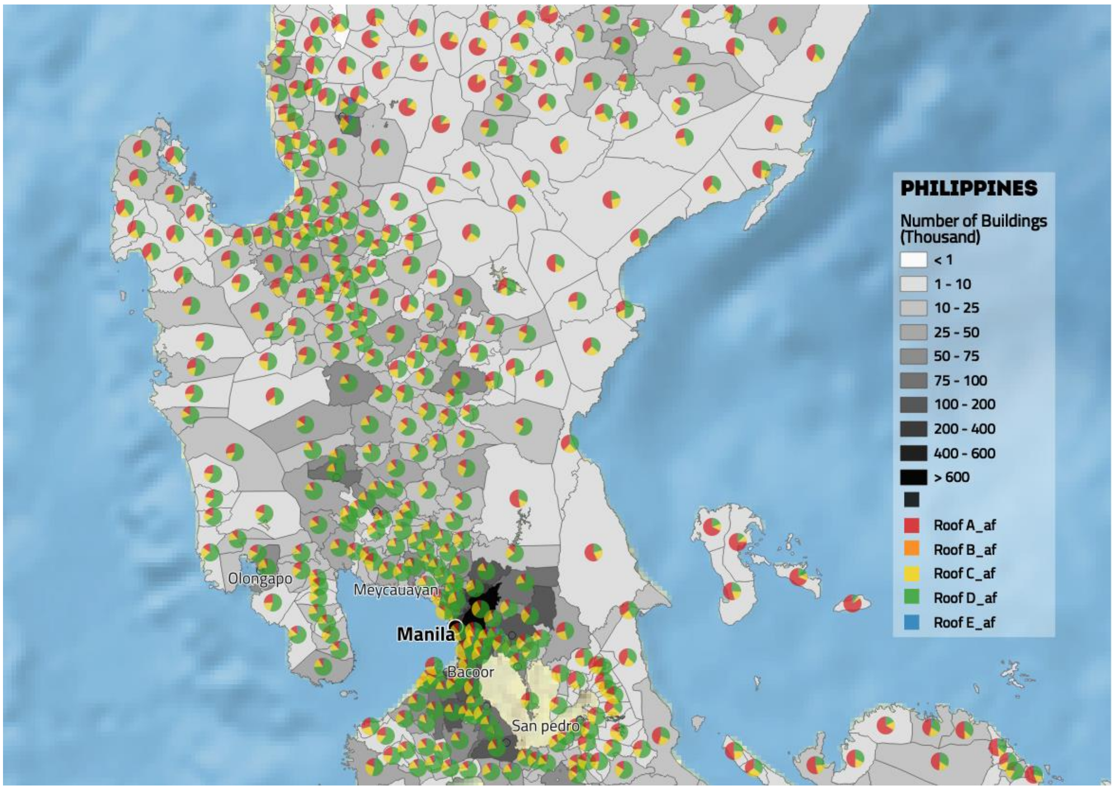

Figure 9. Distribution of roof classes in the surrounding area of the Pinatubo volcano.

Considering the probabilistic simulations for a VEI 6 eruption scenario from Pinatubo volcano, three possible weather conditions were contemplated:

- Possible eruption during the dry season (5000 simulations)
- Possible eruption during the rainy season (5000 simulations)
- Possible eruption for all seasons (5000 simulations)

Using the OpenQuake-engine, each of the ash load simulations is combined with the location of the buildings, and based on the building and roof class, the probability of having roof damage is computed along with the potential economic loss. Table 10 presents the summary of mean number of collapsed roofs and economic losses for the three considered weather conditions.

Season	Collapsed roofs [Thousand]	Economic loss [Million USD]
Dry	242	1,149
Rainy	384	1,812
All	324	1,529

Table 2. Summary of mean number of collapsed roofs and economic losses for the Pinatubo simulations.

The distribution of the number of collapsed roofs and the corresponding collapse ratio is presented in *Figure 10* for the three considered weather conditions. For economic loss, similar figures are presented in *Figure 11*. As expected by the volcanic eruption, larger collapse ratios are encountered closer to the volcano crater, given that the roof classes were generally similar in the affected area.

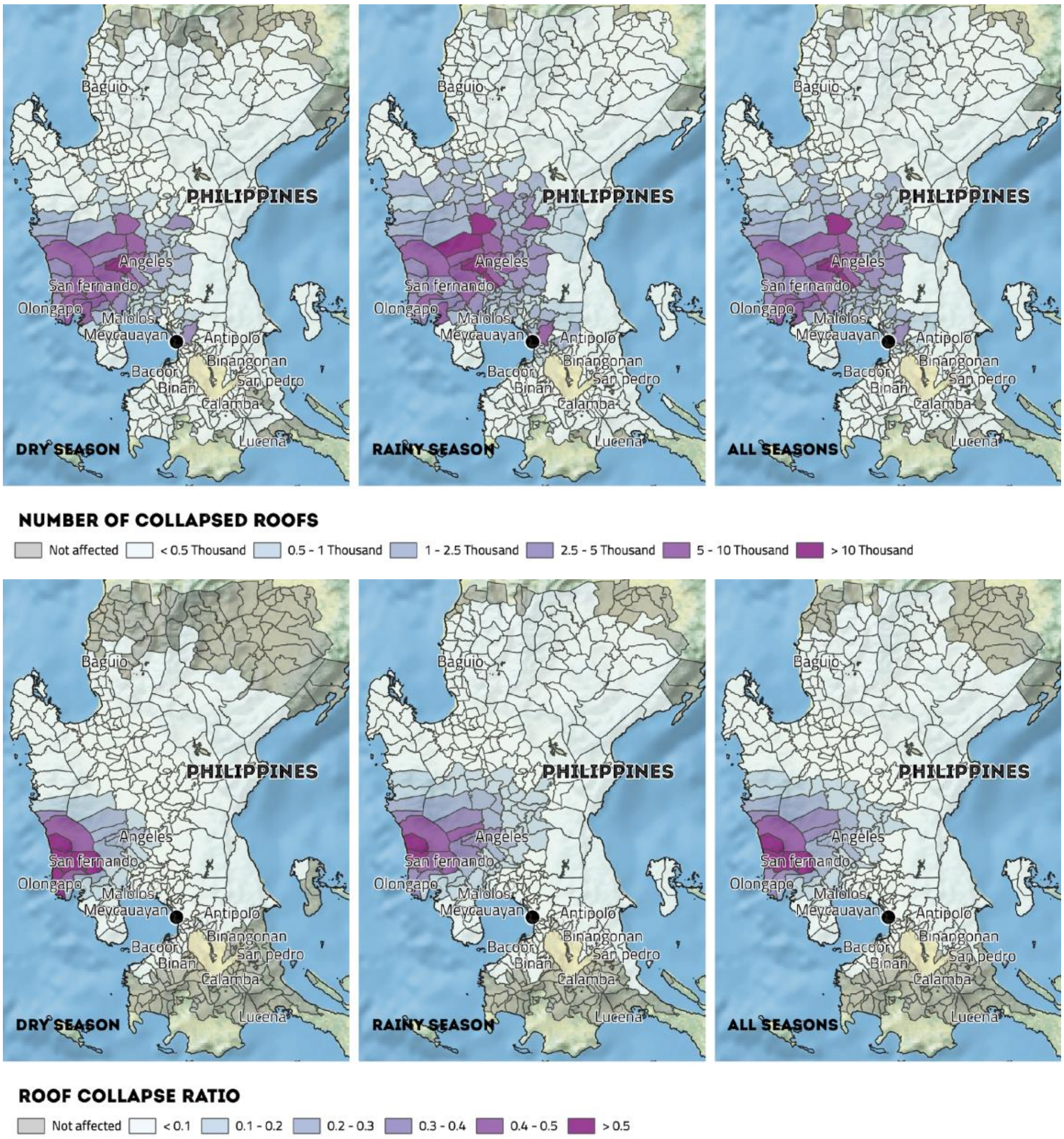

Figure 10. Distribution of collapsed roofs (top), and roof collapse ratios (bottom).

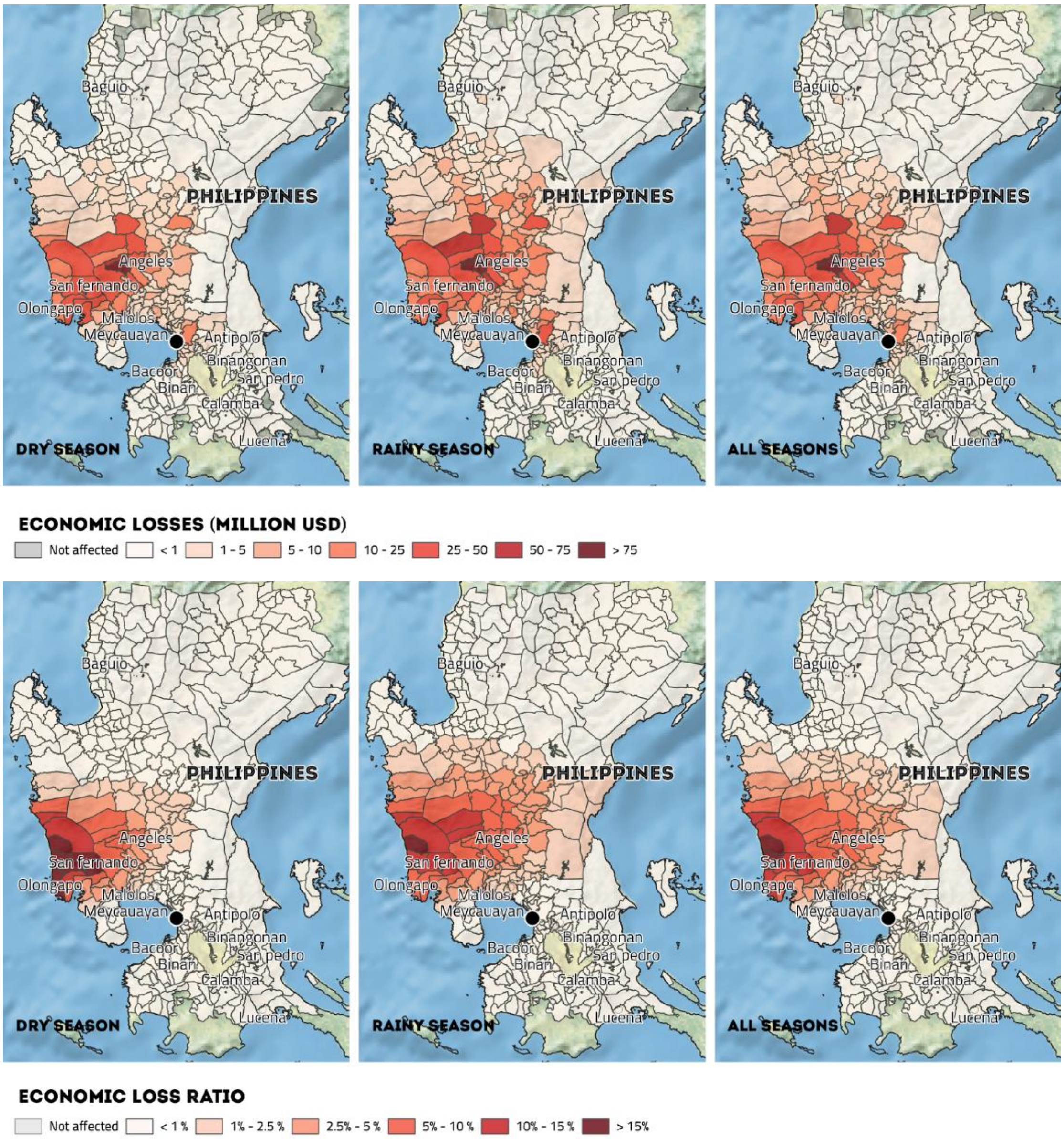

Figure 11. Distribution of economic loss (top), and loss ratio (bottom) due to roof collapse in buildings.

When comparing the number of collapsed roofs and economic losses across different building classes in all seasons, it is observed that reinforced and confined masonry construction is the most affected building class. The main reason is because is the predominant building construction practice in the country, representing 56% of the affected roofs and 71% of the direct economic losses.

Task 3: Training and dissemination of outcomes

The following workshops took place within the CRAVE project:

Kick-off meeting

The kick-off meeting took place in Bogota at the offices of the Colombian Geological Survey (SGC) on the 22nd of February 2018. During the meeting the goals of the CRAVE project were presented by GEM, as well as some concepts on seismic hazard, vulnerability and risk modelling. The British Geological Survey (BGS) presented general aspects of volcano hazard modelling and the mission of the Global Volcano Model, the SGC demonstrated how three volcanoes are currently being monitored and how seismic hazard maps have been developed in the past and the Rabaul Volcano Observatory (RVO) presented the current situation in terms of volcano hazard monitoring and assessment in Papua New Guinea.
During this event all partners also discussed the way forward, including the division of tasks, case studies, relevant risk outputs and the timeframe for the next workshops.

Final workshops in Colombia and Indonesia

The presentation of the tools and datasets from CRAVE took place in Bogota (Colombia) and Bandung (Indonesia). These events were organized by the Colombian Geological Survey and the Institute of Technology of Bandung. A brief summary of each event is presented below:

Bogota, Colombia (13-17 of May) - Geological Survey of Colombia

The first two days of the workshop were used to prepare input data for the demonstrations and discussions that took place in the following days.

- Day 1 – Working with experts from the Nevado del Ruiz
- Day 2 – Generating outputs from the volcanic hazard tools for OpenQuake (for the three volcanoes)
- Day 3 – Presentation to a general audience (UNGRD, IGAC, DANE, DNP, DPS, Comité de conocimiento del riesgo, IDIGER), and local modelers and engineers (30 participants expected).
- Day 4 – Exploring OpenQuake tools for the assessment of the impact from volcanoes and earthquakes. Discussion of results and how to expand the tools and results.
- Day 5 – Internal discussion with SGC on future collaborations.

Five days in Bogota provided a fruitful time to share and discuss the national volcanic hazard and risk assessment, as well as risk management challenges in the country. The workshop was divided into two main parts:

The first part focused on the technical aspects of volcanic hazard and risk assessment. Representatives from the three mains national volcanological observatories participated in the sessions (Manizales, Popayan and Pasto).
Hands on exercises where carried out using the OpenQuake tools for volcanic risk analysis, using El Ruiz Volcano as case study. Additional demonstrations and discussions of volcanic scenario modelling were held, considering other five volcanoes in the country: Galeras, Puracé, Azufral, Cumbal and Chiles.
For volcanic hazard, participants agreed that the hazard products to be developed must be adapted to the needs of risk assessment in order to arrive at a more realistic view of risk. It was also mentioned that more technical discussion is needed for the probabilistic modelling of other volcanic phenomena e.g. ash fall to establish realistic probabilities or rates of occurrence of such phenomena.

The second part of the workshop was conceived for a broader audience, involving stakeholders that contribute to the Disaster Risk Reduction strategy in the country. In a morning session the Colombian Geological Survey (SGC), the National Unit for Disaster Risk Reduction in Colombia (UNGRD) and the GEM Foundation presented the achievements and challenges that the country currently faces. Following the presentations, a rich discussion was held with the 40 participants representing seven governmental institutions (Ministry of Housing, Ministry of Finance, Ministry of Environment and Sustainable Development, Department of National Planning, National Administrative Department of Statistics, Institute for Risk Management and Climate Change of Bogota District (IDIGER), and the Red Cross), representatives from USAID/OFDA, and the technical representatives of the volcanological observatories already mentioned.

The discussion highlighted the importance of effective communication across national institutes that develop fundamental input and output information for earthquake and volcano risk assessment, as well as the importance of factoring in communication and social risk metrics such as damage to roads and airports and access to clean water, as they can significantly impact the modification/adjustment or formulation of risk management strategies.

Bandung, Indonesia (20-22 of May) – IT Bandung

The workshop in Indonesia saw participation from BNPB, PVMBG, ITB, PHIVOLCS, BGS and the Rabaul Volcano Observatory. It was organized by ITB and it had a 3-day duration.

- Day 1 – Presentation of the project and the experience from different experts to the technical communicate and some stakeholders (60 participants expected).
- Day 2 – Exploring OpenQuake tools for the assessment of the impact from volcanoes and earthquakes (limited to 20 participants).
- Day 3 – Discussion with local institutions about future collaborations.

A similar event as the one done in Bogota took place in Bandung (Indonesia) the following week. With support from the Institute of Technology of Bandung (ITB), the event featured a day of presentations and discussion with representatives from the Center for Volcanology and Geological Hazard Mitigation (CVGHM), the Indonesian Ministry of Public Works, the National Disaster Management Agency (Badan Nasional Penanggulangan Bencana - BNPB), the Meteorology, Climatology and Geophysics Agency (Badan Meteorologi, Klimatologi dan Geofisika - BMKG), the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and the British Geological Survey (BGS). This section of the workshop provided an opportunity to discuss and better understand the current gaps in volcano, earthquake and tsunami hazard and risk assessment in the region and beyond.

On the second day of the event, 40 participants employed OpenQuake for the estimation of economic losses and damage due to earthquake and volcano scenarios. The participants highlighted the need for open tools for risk assessment and to share data concerning exposure and disaster loss to improve or calibrate existing models. Data such as exposure and disaster loss are required for monitoring of the Sendai Framework for Disaster Risk Reduction.

Challenges and opportunities in the project

Whilst the collaboration was fruitful with partners in Colombia (both on the earthquake and volcano risk), the interaction with the partners in South-East Asia was more challenging. Despite the fact that organizations from the Philippines and Indonesia expressed interest in being involved in the project from the beginning, both countries were struck by several earthquakes and volcano eruptions during the development of this project, which kept the staff focused on emergency response for large periods of time. During the development of this project, there were also several changes in top positions in Indonesia, which delayed the advancement of activities that require a strong buy-in from the local experts (e.g. exposure modelling, collection of volcano hazard footprints).

The involvement of additional representatives from both countries (as part of the release of GEMs Global Earthquake Model in December 2018) renewed the enthusiasm about the project in the region, and hence the organization of the workshop in Bandung. To increase the trust amongst the local partners and pave the way for future collaborations, we designed the workshop with numerous interventions from local partners and time to discuss future activities. We also note that the reason for presenting the tools and datasets in May (and not closer to the end of the project - October) was to allow sufficient time to further improve the outcomes of CRAVE based on the feedback and needs of the local partners.

The activities of the CRAVE project have already proved useful as a basis for additional work beyond the original project scope. Training and dissemination of the tools have also been considered in the new TREQ project funded by USAID through two main events: VOBP (Volcano Observatories Best Practice) meeting that took place during November 2019 in Mexico City, and a workshop during the Cities On Volcanoes (CoV11) conference will be held on the 25th of May 2020. Moreover, the University of Geneva, Switzerland, has invited us to present the CRAVE project and the OpenQuake tools during a half day workshop that will take place as part of the CERG-C[2] programme on the 13th of May 2020.

Review of Indicators

The indicator status is as follows:

I. *Number of people benefiting from geological disaster-related activities, by sex: 140 direct beneficiaries, of which 61 women.*

II. *Number of geological policies or procedures modified as a result of the activities to increase the preparedness for geological events: 0*

III. *Number of people trained to reduce the impact of geological events, by sex: 140 direct beneficiaries, of which 61 women.*

[2] http://www.unige.ch/sciences/terre/CERG-C/