CHALLENGES IN ASSESSING EXPOSURE AND VULNERABILITY TO NATURAL HAZARDS IN LARGE CITIES: THE CASE STUDY OF AREQUIPA NEAR THE MISTI VOLCANO, SOUTH PERU

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Assessing risk of potential natural catastrophes in cities remains challenging, in particular as we need to elaborate quantitative criteria for exposure and vulnerability. Statistical and probabilistic methods have been applied to Arequipa, one of the most vulnerable Latin America cities. The second largest city of Peru is highly exposed to natural hazards: earthquakes, eruptions from the historically active El Misti volcano, rain-triggered flash floods and mass flows together with landslides from the Río Chili canyon walls. First, we propose a long-term probabilistic multi-hazard assessment for the Misti composite cone located 17 km from Arequipa. Second, we examine criteria for delineating areas prone to mass flow hazards and characterizing multiple sources of vulnerability for the city. Third, a statistical methodology to better estimate damage probability for buildings is proposed.

1. Probabilistic hazard maps based on the Bayesian Event Tree code

We apply the Bayesian Event Tree code for Volcanic Hazard (BET_VH) to produce probabilistic hazard maps for the predominant volcanic phenomena that may affect c. 900,000 people living around El Misti (Sandri et al., 2014). A long-term multi-hazard assessment based on the BET_VH tool allows the quantification of hazard estimate uncertainty due to the natural variability in eruption sizes and associated phenomena. A set of several maps shows the yearly probable extent of each of these volcanic threats, for which we consider variability in eruption size, style, vent location, seasonal distribution of winds and rainfall/snow, two categories of density for three sizes/styles of tephra fall, and three categories of lahars.

The hazard maps, which were produced with the same BET method, refer to a time window of one year. We treat probabilistically several model runs from Eject!, TEPHRA2 and TITAN2D for the main hazardous phenomena (lahars, pyroclastic density currents PDCs, tephra fall, and ballistic ejecta), and data from past eruptions at El Misti (tephra fall, PDCs, and lahars) and at other volcanoes (PDCs). These are suitable ingredients for a Bayesian multi-risk assessment that appears to be one of the best methods for comparing multiple sources of risk and to make rational decisions to protect the population. Whenever new data or new model results are available to the scientific community, they can be easily included in the proposed Bayesian procedure in order to update the hazard assessment.

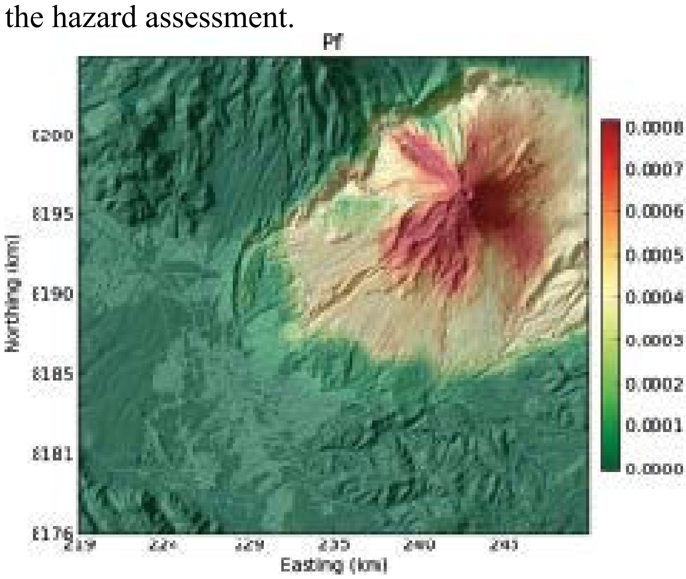

Fig. 1. The probability maps reveal that only the north and east suburbs of Arequipa are exposed to all volcanic threats except for ballistic ejecta, which are limited to the uninhabited but touristic summit cone. The probability for pyroclastic density currents (PDCs) reaching recently expanding urban areas and the city along ravines is around 0.05% per year, similar to the probability obtained for roof-critical tephra loading during the rainy season.

Among the multiple dangers looming over Arequipa, flash floods and lahars represent a latent threat (0.25% per year) because at least 50,000 people live in or around exposed valleys in precarious conditions. In these areas containing low-income neighbourhoods, outlining hazard zones and improving risk management is crucial to better protect the population. The city of Arequipa suffers from flash flood events following heavy rainfall every 3.5 years over the past 70 years. In addition, a network of four drainage channels can convey lahars approximately 20 km away from Misti across the entire city during heavy rain episodes, even without eruption.

The fundamental difference with the present hazard-zone map for El Misti (Mariño et al., 2007; Cobeñas et al., 2014), based on a deterministic approach from geology, stratigraphy and chronology, is that multi-hazard probability maps display, on a common year scale, the probability of different hazardous phenomena impacting different points around El Misti. While probabilistic maps cannot replace any hazard-zone map for emergency management in case of volcanic eruption, we hope that our study might assist any future improvement in risk evaluation and land-use planning.

2. Delineation of flash flood- and lahar-prone areas and multi criteria vulnerability assessment

The majority of vulnerability assessment methods address single hazards but there is a need to elaborate a multi-hazard approach to risk management in cities such as Arequipa, which are exposed to events that may occur simultaneously. The Río Chili Valley represents the major concern to city safety owing to the probable cascading effect of combined threats: PDCs and rockslides, dammed lake break-outs and subsequent lahars or floods. One of the major objectives of this study is therefore to embed available data from volcanic and hydrologic hazards into the GIS-database and enlarge the indicator system to account for the social and economic disparities in vulnerability.

This research offers a reliable tool to delineate areas at risk by taking into account three main parameters: lahar and flood hazards, the population's vulnerability (through the buildings conditions and living standards) and the population's exposure (Thouret et al., 2013).

Our risk-evaluation study is based on field surveys and interpretation of HSR satellite images to assess the quality and structural integrity of buildings, collect socio-economic parameters (educational and poverty level of the population, unemployment figures, population density), and additional information from interviews with risk management officials.
To fully evaluate the exposure, the access to, or relative isolation from, and distance to strategic resources such as safe areas located on the highest terraces, hospitals, fire stations and drinking water has been considered. The combination of these criteria emphasizes the contrasting vulnerabilities between the city centre and the outskirt areas, but city-block surveys reveal large spatial variations in vulnerability within the valleys (Fig. 2).

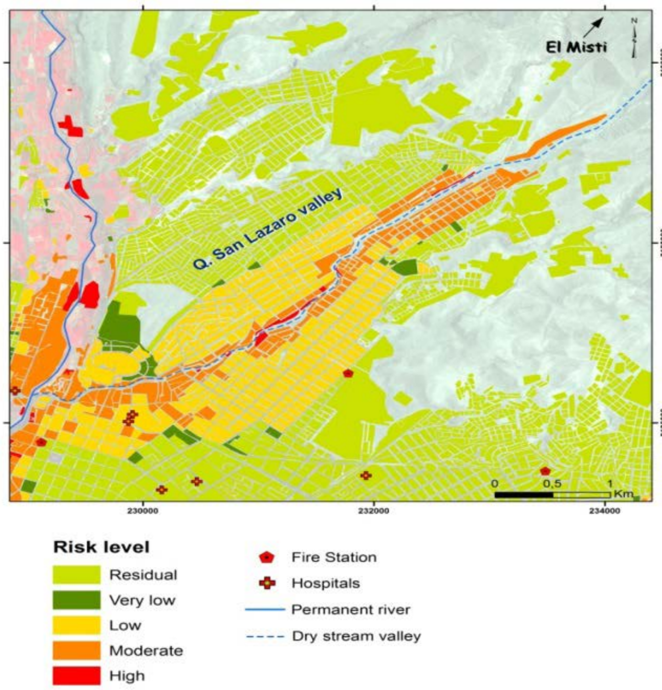

Fig. 2. Not surprisingly, detailed risk-zone maps at the city-block scale, covering the city of Arequipa and adjacent suburbs, show that the areas at high risk coincide with blocks or districts with populations at low socio-economic levels. Inhabitants at greatest risk are recent immigrants from rural areas who live in unauthorized settlements in the outskirts of the city in the upper parts of the valleys. Such settlements are highly exposed to natural hazards but have little access to vital resources. As a result, most areas at risk are directly located in the torrenteras and in the new 'illegal' settlements located on the flanks of El Misti (e.g. combined risk level as portrayed along the San Lazaro valley and at the confluence with the Río Chili valley).

The physical vulnerability of buildings and infrastructure to flash floods and lahars is an essential step in risk assessment in large cities. A survey of 46 city blocks from eight districts, different in age, construction material and land use, and the description of ~1000 edifices provided architectural, structural and historical characteristics for each of the pilot areas. The vulnerability assessment of 20 bridges across the three valleys has been based on three categories of structural, hydraulic and strategic parameters. The failure of, or overbank flow upon, eight low bridges would isolate strategic relief assets and the historic city from suburbs in case of a catastrophic event. Interpretation of High-Spatial Resolution (50 cm pixel) satellite images, which allows us to quickly identify as much as 69% of the structural types of buildings, can help to estimate the physical vulnerability in addition to traditional mapping based on field enquiries. Field survey is critical, however, to assess the structural building characteristics as 'hidden' housing in the core of city blocks may introduce a bias (Thouret et al., 2014).

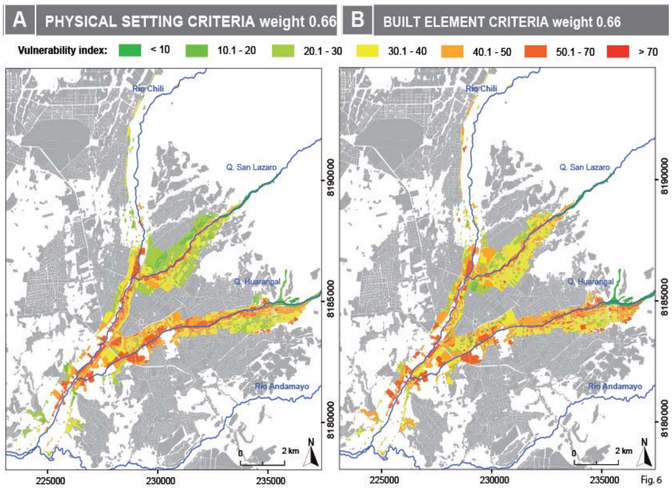

Fig. 3. Physical vulnerability is moderate to high in the city, but spatially variable throughout the study areas. The vulnerability index is higher if the built-up element criteria are considered alone, but more contrasted if the physical setting criteria are accounted for. The most vulnerable city blocks with housing of poor structural quality are located on the lowermost terraces near channel and perpendicular or oblique to the flow path, in particular in constricted reaches of the Rio Chili and near the tributary confluences.

The results of this study can provide guidance in vulnerability assessment of large cities in Latin America and, arguably, to all urban settlements in developing countries as follows:

1) The most vulnerable city blocks are located in the vicinity (within 50 m) of river channels, in the low floodplain down valley or nearby the confluence with its tributaries. Noteworthy is the highly vulnerable, narrow reach of Río Chili near the city centre, where two very vulnerable bridges jeopardize the access to both critical sides of the city.

2) PCA analysis conducted on 3015 city blocks aimed to determine the weight of nine criteria used for calculating the vulnerability index and mapping the distribution of physical vulnerability across the city. In addition to the location of city blocks on low, flood-prone terraces, the type and geometry of city block and building parameters play the principal role in enhancing or decreasing vulnerability. Although construction techniques and material have evolved since the city foundation, the quality of construction including architecture and structural planning weighs out all types of construction material.

3) Despite limitations of PCA and HSR methods, uncertainty in estimates of the physical vulnerability remains generally low. However, we must bear in mind that the spatial disparities in vulnerability are also tied to the socio-economic characteristics and urbanization growth stages across a city. Socio-economic vulnerability is low in the city centre while populations living along the tributaries and upstream of fans generally have a lower level of income and education than other districts and thus are more vulnerable.

3. Statistical methodology for estimating damage probability for buildings

A statistical methodology is developed that enables estimation of damage probability for buildings. The applied method uses observed inundation height as a hazard proxy in areas where more detailed hydrodynamic modeling data is not available. The aspects of building design and site specific environmental characteristics that render a building vulnerable are considered after the 8 February 2013 flash flood event that occurred along the Avenida Venezuela channel. On this day, 124.5 mm of rain fell within 3 hours triggering a flash flood that inundated at least 0.4 km2 of urban settlements along the channel, affecting more than 280 buildings, 23 of a total of 53 bridges, and led to the partial collapse of sections of the main road, paralyzing central parts of the city for more than one week (Ettinger et al., 2015).

The mathematical approach considers both physical vulnerability and hazard related parameters. It reduces uncertainty in the determination of descriptive parameters, parameter interdependency and their respective contributions to damage. This study aims to (1) enable the estimation of damage probability for a given hazard intensity, and (2) obtain data to visualize variations in damage susceptibility for buildings in flood-prone areas. Data collection is based on a post-flood event field survey and the analysis of HSR Pléaides images. An inventory of 30 city blocks was collated in a GIS database in order to estimate the physical vulnerability of buildings. As many as 1103 buildings were surveyed along the affected drainage and 898 buildings were included in the statistical analysis. Univariate and bivariate analyses were applied to better characterize each vulnerability parameter. Multiple corresponding analyses revealed strong relationships between the “Distance to channel or bridges”, “Structural building type”, “Building footprint” and the observed damage. Logistic regression enabled quantification of the contribution of each explanatory parameter to potential damage, and deTermination of the significant parameters that express the damage susceptibility of a building. The model was applied 200 times on different calibration and validation data sets in order to examine performance. Results show that 90% of these tests have a success rate of more than 67%. Probabilities (at building scale) of experiencing different damage levels during a future event similar to the 8 February 2013 flash flood are the major outcomes of this study (Fig. 4).

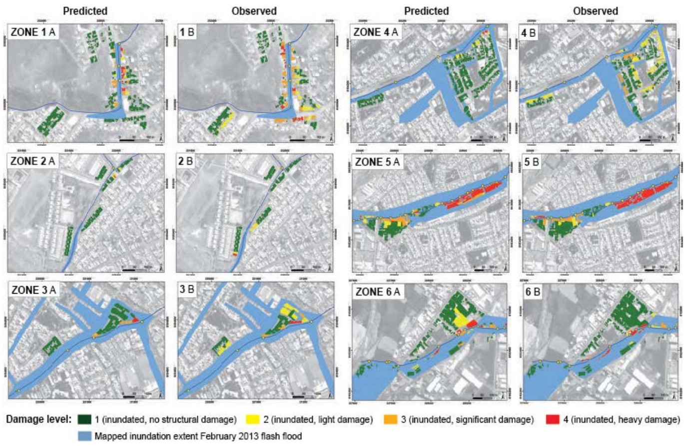

Fig. 4. Damage probabilities calculated for damage levels 1-4 (series A) and all observed damage levels (series B) using calibration and validation data sets (898 buildings) of the selected test scenario (Ettinger et al., 2015).

Observed damage intensities were overall low and only few buildings suffered serious damage. Results from the proposed statistical data analysis validate the method as an operational tool to calculate damage probabilities for a flash flood event of similar intensity. However, the lack of damage documentation, in particular for highest damage categories, is at present a constraint to further develop the model for a larger range of hazard types and magnitudes.

One of the major advantages of the method outlined is that damage probability can be estimated and mapped even for buildings that have not been sampled in the field as long as some of their characteristics are known or may be assessed from remote sensing data. Especially in a context where few damage data are available or where access to the field in the aftermath of an event is difficult, this technique helps to assess and project damage potential to non-sampled areas. This is useful for both loss estimation and risk prevention, by contributing to the planning of mitigation measures such as refitting or risk management, or by evacuation planning in the case of disaster.

4. Risk prevention and management: "una tarea para todos"!

Our study provides good rationale for the risk zoning of the city, which in turn may be used as an educational tool for better understanding the potential effects of natural hazards and the exposure of the population residing in and around Arequipa. Severe consequences of floods and lahars may be reduced with a timely evacuation and population having easy access to vital resources such as hospitals and dispensaries, water tanks and shelters. Awareness actions performed by Civil Protection teams can be targeted more efficiently. However, the people's actual behaviour in case of a crisis remains difficult to take into account. Therefore, significant specific actions such as the removal of houses located in the ravine bottoms and cleaning of the ravines of trash and rubbish would represent a strong signal for the strict implementation of risk-reduction plans adopted by the municipality and regional government of Arequipa.

This multidisciplinary approach will continue in the near future in order to: (1) define precisely the potential effects of volcanic flow and flash flood hazards and improve the delineation of the districts that need to be protected; (2) evaluate monetary loss of impacts in the case of lahar and floods; (3) collect additional and updated socio-economic parameters, which will improve the quality and usefulness of risk mapping; (4) evaluate consequences in terms of evacuation and access to resources, and; (5) conduct jointly more simulation exercises led by Civil Protection for lahar crises using more precise hazard- and risk-zone maps. We hope that our work will provide the impetus for risk-management authorities of the municipality and the regional government of Arequipa to enforce existing urban planning regulations in hazardous zones and to adopt an effective long-term strategy to reduce risks from natural hazards.

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