Journal of Hydrology 541 (2016) 563–581

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Building vulnerability to hydro-geomorphic hazards: Estimating damage probability from qualitative vulnerability assessment using logistic regression

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ARTICLE INFO

Article history:
Available online 20 April 2015

Keywords:
Flash flood
Vulnerability
Logistic regression
Damage probability
Risk
Arequipa

SUMMARY

The focus of this study is an analysis of building vulnerability through investigating impacts from the 8 February 2013 flash flood event along the Avenida Venezuela channel in the city of Arequipa, Peru. On this day, 124.5 mm of rain fell within 3 h (monthly mean: 29.3 mm) triggering a flash flood that inundated at least 0.4 km^2 of urban settlements along the channel, affecting more than 280 buildings, 23 of a total of 53 bridges (pedestrian, vehicle and railway), and leading to the partial collapse of sections of the main road, paralyzing central parts of the city for more than one week.

This study assesses the aspects of building design and site specific environmental characteristics that render a building vulnerable by considering the example of a flash flood event in February 2013. 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. Building design and site-specific environmental conditions determine the physical vulnerability. The mathematical approach considers both physical vulnerability and hazard related parameters and helps to reduce uncertainty in the determination of descriptive parameters, parameter interdependency and respective contributions to damage. This study aims to (1) enable the estimation of damage probability for a certain 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 high (sub-metric) spatial resolution images (Pléiades 2012, 2013). 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

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http://dx.doi.org/10.1016/j.jhydrol.2015.04.017

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.

1. Introduction

On February 8 2013, heavy rainfall (124.5 mm within 3 h versus a monthly mean of 29.3 mm) triggered a flash flood event along the Avenida Venezuela channel in the city of Arequipa, Peru. On this day, more than 280 buildings, 23 of a total of 53 bridges (pedestrian, vehicle and railway) were affected and the partial collapse of main road sections paralyzed central parts of the city for more than one week. Previous risk assessment studies in Arequipa did not include the Avenida Venezuela channel due to its smaller size and largely confined channel course. The high recurrence rate of hydro-geomorphic hazards (Martelli, 2011; Thouret et al., 2013, 2014) and apparent locally high vulnerability of buildings and critical infrastructure in Arequipa are major motivations for this study.

Risk in the context of disaster risk management is commonly defined as a potential loss for a given probability function (Crichton, 1999; Kaplan and Garrick, 1981). In the standard conceptual framework, risk is the product of hazard, vulnerability and exposure (Cardona, 2004; Carreno et al., 2006). While the hazard is generally described by its severity, e.g. inundation height for a given return return period, exposure relates to the number and value of elements potentially affected (Hiete and Merz, 2009). Many different definitions, concepts and methods to systemize vulnerability exist in the current literature (Birkmann, 2006; Cutter et al., 2003; Wisner et al., 2004; Thywissen, 2006; IPCC, 2007; Bründl et al., 2009). In this study we follow the definition for physical vulnerability proposed by Glade (2003) and Villagran de Leon (2006) as the predisposition of an element or system to be affected or susceptible to damage as the result of the natural hazard's impact. Vulnerability assessment for hydro-geomorphic hazards such as dilute floods, debris flows, hyperconcentrated flows etc. is inherently complex, mainly as a result of the following factors (Gaume et al., 2009): (i) lack of accurate or real-time observational data necessary for reliable hazard analysis; (ii) only substantial damage information is generally recorded and accurate information on failure characteristics is often missing (Fuchs et al., 2007b; Papathoma-Köhle et al., 2011); (iii) different time and geographical scales involved (Gruntfest, 2009; Marchi et al., 2010); (iv) natural adjustments of the environment to return to a state of equilibrium; (v) rapid intervention by technical services to restore functionality of urban infrastructure reduces the time frame for damage assessment in the field; (vi) site-specific triggering processes and upstream–downstream evolution of debris-flow phenomena (Di Baldassarre and Montanari, 2009). If field investigations are conducted to study and record structural damage following a hazard event, these data are then generally correlated to the process intensity, frequently derived from deposition height or inundation height, in order to develop empirical fragility curves (Fuchs et al., 2007a,b; Holub and Fuchs, 2008). These curves are then employed within risk assessments to estimate structural damage in future events. The lack of high-quality observational evidence and uniform, i.e. non site-specific, approaches to data collection, implies that the majority of fragility curves are still developed using expert judgment (Papathoma-Köhle et al., 2012; Totschnig and Fuchs, 2013). The compilation of field data for different sites in the European Alps, Taiwan etc. published in recent studies (Totschnig et al., 2011; Holub et al., 2012; Papathoma-Köhle et al., 2012; Totschnig and Fuchs, 2013) has helped to develop vulnerability functions applicable within the framework of risk management for specific regions (Totschnig and Fuchs, 2013). If the required input data are available, the method is transferable to other alpine regions. However, data availability remains a major constraint in many countries (e.g., Douglas, 2007; Jakob et al., 2012; Lo et al., 2012; Totschnig and Fuchs, 2013). For Latin America, very few case studies have been published with a focus on physical vulnerability analysis. In contrast to many sites monitored and equipped in the European Alps, areas prone to hydro-geomorphic hazards in the Andes are rarely monitored, and in the worst case, not even mapped. It therefore becomes difficult to apply methods derived from European experience in the same or a similar way. In addition there is a critical lack of observational data collected in the immediate aftermath of disasters. For the study presented here, data to apply existing vulnerability assessment methods were not available, although alternative information could be collected.

Flash floods are common in semi-arid areas, such as Arequipa, and can, despite their infrequent nature, have a devastating effect in both geomorphological and human terms (Gaume et al., 2009; Jonkman and Vrijling, 2008; Martínez Ibarra, 2012). The occurrence of flash floods is highly variable, both spatially and temporally, most occurring as the result of localized intense storms (Graf, 1988; Reid and Frostick, 1992; Hooke and Mant, 2000). Several important factors arise as a result of these characteristics. First, areas prone to flash floods need to be adequately prepared. Because events usually occur unexpectedly, warning and preparation are essential (Montz and Gruntfest, 2002; Collier, 2007; Borga et al., 2008; Gaume et al., 2009); however, because events are typically rare, the motivation to invest time and resources into such activities may be lower than for more frequent hazards (Gruntfest and Handmer, 2001). Flash floods usually affect relatively small areas and losses resulting from them do not always generate much long-term response, unless there is high loss of life. However, losses per unit (acre, square mile, or kilometer) of area affected tend to be high compared to other events such as riverine floods or hurricanes due to locally high intensity (Gaume et al., 2009; Martínez Ibarra, 2012).

Vulnerability indicators for flash flood hazard are at present too site-specific to render the use of vulnerability assessment broadly operational. Additionally, building structures differ regionally and nationally and channel settings vary locally. The general approach to assess structural vulnerability focuses on impact intensity and structural susceptibility of elements at risk, assigning probabilities to different damage thresholds, from no damage through to complete destruction. From this technical point of view, and as a general rule, vulnerability assessment is based on the evaluation of parameters and factors such as building type, construction materials and techniques, state of maintenance, and presence of protection structures (Fell et al., 2008). For this reason, vulnerability values describe the susceptibility of elements at risk, facing different process types, with various spatial and temporal distributions of hazard intensity (e.g. flow depth, accumulation height, flow velocity and/or pressure, Fuchs et al., 2007a,b; Holub and Fuchs, 2008).

Several recent studies (Martelli, 2011; Santoni, 2011; Ettinger et al., 2014, 2015; Thouret et al., 2013, 2014) examined the physical vulnerability of buildings and critical infrastructure in the city