Geomorphology 273 (2016) 150–167

Contents lists available at ScienceDirect

Geomorphology

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

Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps

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ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form 8 June 2016
Accepted 30 July 2016
Available online 2 August 2016

Keywords:
Multi-hazard
Hydro-meteorological hazards
Quantitative risk assessment
Vulnerability
Uncertainty
GIS
Italy

ABSTRACT

Extreme rainfall events are the main triggering causes for hydro-meteorological hazards in mountainous areas, where development is often constrained by the limited space suitable for construction. In these areas, hazard and risk assessments are fundamental for risk mitigation, especially for preventive planning, risk communication and emergency preparedness. Multi-hazard risk assessment in mountainous areas at local and regional scales remain a major challenge because of lack of data related to past events and causal factors, and the interactions between different types of hazards. The lack of data leads to a high level of uncertainty in the application of quantitative methods for hazard and risk assessment. Therefore, a systematic approach is required to combine these quantitative methods with expert-based assumptions and decisions. In this study, a quantitative multi-hazard risk assessment was carried out in the Fella River valley, prone to debris flows and flood in the north-eastern Italian Alps. The main steps include data collection and development of inventory maps, definition of hazard scenarios, hazard assessment in terms of temporal and spatial probability calculation and intensity modelling, elements-at-risk mapping, estimation of asset values and the number of people, physical vulnerability assessment, the generation of risk curves and annual risk calculation. To compare the risk for each type of hazard, risk curves were generated for debris flows, river floods and flash floods. Uncertainties were expressed as minimum, average and maximum values of temporal and spatial probability, replacement costs of assets, population numbers, and physical vulnerability. These result in minimum, average and maximum risk curves. To validate this approach, a back analysis was conducted using the extreme hydro-meteorological event that occurred in August 2003 in the Fella River valley. The results show a good performance when compared to the historical damage reports.

1. Introduction

Hydro-meteorological hazards are processes or phenomena of atmospheric, hydrological or oceanographic nature that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage (UNISDR, 2009). Shallow or deep-seated landslides, debris flows, rock falls, flash floods and river floods can be triggered simultaneously or consecutively in mountainous areas by extreme hydro-meteorological conditions.

Since more than one hazard types can occur in mountainous areas during the same hydro-meteorological event, it is important to assess the risk in a multi-hazard framework. Compared to single processes, standard approaches and methodological frameworks for multi-hazard risk assessment are less common in the literature. Kappes et al. (2012) indicated that this is due to the different characteristics of hazard types, which also require different methods for analysis. Multi-hazard risk assessment has received a lot of attention in research in the past decades, focusing on the analysis at different scales. For small scales, the World Bank approach (Dilley et al., 2005) or the EU ESPON project (Schmidt-Tomé et al., 2006) could be mentioned. Several EU research projects dealt with the problem of multi-hazard risk assessment at medium scales, such as the TIGRA (Del Monaco et al., 1999), ARMONIA (Del Monaco et al., 2007), MATRIX (Marzocchi et al., 2012; Nadim et al., 2013) and CLUVA (Garcia-Aristizabal et al., 2015). Initiatives for multi-hazard risk assessment at medium to large scales include the EU funded NASRAS (Marzocchi et al., 2009), RISK-NAT (Douglas, 2007) and MEDIGRID (Bovolo et al., 2009) projects; the German DFNK project on a comparative study of multi-hazard risk in Cologne (Grunthal et al., 2006); the Australian Cities project (Granger et al.,

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http://dx.doi.org/10.1016/j.geomorph.2016.07.041
0169-555X/

1999) and several other initiatives (e.g. Van Westen et al., 2002; Carpignano et al., 2009; Lari et al., 2009).

A number of software tools have been developed for multi-hazard risk assessment, for example HAZUS in the USA (Schneider and Schauer, 2006), RiskScape in New Zealand (Schmidt et al., 2011), CAPRA (Cardona et al., 2010), MATRIX (Garcia-Aristizabal and Marzocchi, 2013) and RISK-GIS in Australia (Granger et al., 1999). The common aspect of these tools is that they are used to analyse damages and replacement costs, casualties, disruption and the number of people affected by various hazards. They are also very data demanding. They differ in terms of the methods used for hazard assessment, asset exposure analysis, vulnerability assessment and risk calculation.

Relatively limited work has been carried out on integrated multi-hazard risk assessments for hydro-meteorological hazards in mountainous areas. This is related to the problem that mass movement hazard is particularly difficult to quantify in a medium-scale assessment, due to lack of historical data to correlate triggering events with the associated landslide density, the difficulty to express the intensity of mass movements, and the lack of vulnerability curves for many types of mass movements. Also the interaction between the different types of hazards is complicated, as they may influence each other (e.g. landslides damming streams may lead to flash floods), and they may have very different impacts on the elements-at-risk (Kappes et al., 2010, 2011; Hufschmidt and Glade, 2010; Papathoma-Köhle et al., 2011). There are still no software tools available for the combined analysis of flood and landslide processes (e.g. Gruber and Mergili, 2013). Bell and Glade (2004) developed a raster-based multi-hazard risk analysis approach for snow avalanches, debris flows and rock falls and applied it in an area in Iceland. The final risk to life and economy, expressed as total value at a community level, was obtained by summing the risks due to each single hazard. Marzocchi et al. (2012) carried out a multi-hazard risk assessment in a municipality in Italy, in which they ranked the risk of five types of hazards (volcanic, seismic, flood, landslide and industrial) using the value of annual risk. Van Westen et al. (2014) showed a procedure to quantify multi-hazard risk related to mass movements and flood at a medium scale for the Barcelonnette Basin, French Alps, in which the temporal probability of triggering events for different hazard types (shallow landslides, debris flows, rock falls, snow avalanches and floods) was considered, based on historical hazard events. For the quantification of multi-hazard probability and vulnerability, Ming et al. (2015) applied the copula theory and trend surface analysis to obtain the joint probability distribution in a case study area in the Yangtze River Delta region, China. Although the hazard types were limited and the same vulnerability model was used for different sample areas, the way to quantify the joint return period of different hazards was innovative. A quantitative probability model for evaluating multi-hazard risk was also proposed by Liu et al. (2014), in which hazard loss was not analysed but the interaction effect of different hazard types was evaluated.

Uncertainty is an inherent aspect of multi-hazard risk assessments, and the various components have a large degree of uncertainty, such as the temporal probability of hazard scenarios, the associated distribution and quantification of hazard intensity, the interaction of hazard events, the quantification of elements-at-risk, and the physical vulnerability expressed as a function of hazard intensity and degree of loss. Methodologically, uncertainty can be incorporated into risk assessment using probabilistic methods, such as the application of Monte Carlo simulation generating a large number of possible risk scenarios, resulting in the calculating of a loss exceedance curve (e.g. Grunthal et al., 2006; Mignan et al., 2014; Ming et al., 2015). However, application of such approaches in mountainous environments, involving mass movement hazards in combination with flash flood, is greatly hampered by the lack of data and appropriate models, and the extreme modelling time required.

Therefore, we propose a simpler approach for such environments using a risk curve which is generated using a limited number of scenarios. A risk curve graphically represents losses (economic and casualties) plotted against the annual probability of occurrence of triggering events (Schmidt et al., 2011; Van Westen et al., 2014). Our study aims to provide a methodological procedure for quantitatively assessing multi-hazard risks at a medium scale (1:25,000 to 1:50,000) in mountainous areas prone to hydro-meteorological hazards, such as debris flows, flash floods, and river floods. The method incorporates the deficiencies in available data, and proposes a combination of quantitative models combined with expert-based assumptions to quantify the risk as minimum, average or maximum risk curves. The risk associated with each hazard process is quantified based on its intensity and spatio-temporal probability, the exposed elements-at-risk (buildings and people inside buildings) and their physical vulnerability. The historical hazard events and damage data are used to derive a number of triggering events, with a range of temporal probabilities and with associated hazard maps. The hazard extent and intensity are modelled for these scenarios at medium scale using quantitative empirical and numerical models. Uncertainties in temporal probability, hazard intensity, the value of exposed elements-at-risk and physical vulnerability are determined and expressed as maximum and minimum values. These are used in the risk calculation resulting in three risk curves per hazard type, each representing the minimum, average or maximum risk. The method is schematically presented in Fig. 1.

2. Study area

The Fella River valley is located in the province of Udine, within the Friuli-Venezia Giulia (FVG) region, in the north-eastern part of the Italian Alps (Fig. 2). The Fella River is a major tributary of the Tagliamento River. The study area covers 247 km^2, and comprises four local administrative units: Dogna, Pontebba, Malburghetto-Valbruna, and Tarvisio. The Fella River valley ranges in elevation in this sector between 426 and 2753 m a.s.l. Land cover consists of predominately forested areas (75%), with approximately 10% bare surface and 8% grasslands, with the urban areas located along the valley bottoms and on alluvial fans (Malek et al., 2014). Geologically, the area is underlain mostly by Permian and Triassic formations, consisting of dolomite, limestone and calcareous-marls. Quaternary deposits are mostly represented by debris fans, and glacial and alluvial deposits (Tropeano et al., 2004; Calligaris et al., 2008). The area is also characterized by complex geological structures including folds, faults and fractures which contribute to the instability of slopes. Historically, the Fella River valley is affected mainly by floods and mass movements (Manca et al., 2007).

The catchment has an average annual precipitation of 1920 mm which can reach up to 3000 mm in the higher part of the study area, and extreme daily rainfall exceeding 50 mm has been recorded frequently in the area in a 20 to 30 year time span. Rainfall produced by a convective storm in August 2003 resulted in severe flood and debris flows throughout the Fella River valley. During this event, daily precipitation was between 350 and 450 mm, with most of the rain falling in a 12 h period and reaching peak intensities higher than 100 mm h^{-1} (Sangati and Borga, 2009). More than 100 debris flows were triggered, including an unusually large debris flow occurring in Rio Cucco Village (Malburghetto Commune), with a volume of approximately 78,000 m^3 (Marchi et al., 2009). This event caused loss of life and substantial disruption to the local economy, involving direct damage close to 1 billion euros (Tropeano et al., 2004).

3. Methodology

The methodology proposed in this study follows a number of steps: basic data collection, hazard assessment, generation of elements-at-risk maps, vulnerability assessment, loss estimation and multi-risk estimation (Fig. 3). Different types of data were collected, including environmental conditions, rainfall, historical hazard events and data on the elements-at-risk. Digital elevation data were available in the form of