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Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale

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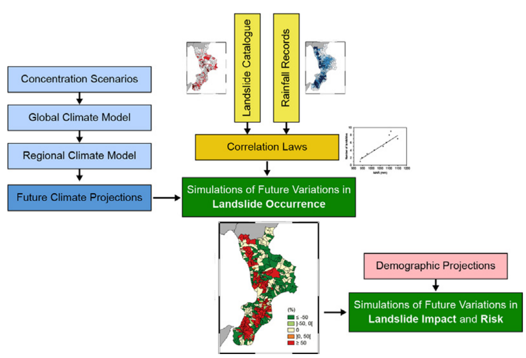
HIGHLIGHTS

- A method for assessing variations in landslides under the effect of climate changes is proposed.
- The method is applied in a Southern Italian region, and it is totally replicable.
- A historical landslide catalogue and climate projections for two scenarios are used.
- Changes in the population exposure to landslides are also evaluated.Frequency and impacts of landslides are expected to increase in the study area.

GRAPHICAL ABSTRACT



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ABSTRACT

According to the fifth report of the Intergovernmental Panel on Climate Change, an increase in the frequency and the intensity of extreme rainfall is expected in the Mediterranean area. Among different impacts, this increase might result in a variation in the frequency and the spatial distribution of rainfall-induced landslides, and in an increase in the size of the population exposed to landslide risk. We propose a method for the regional-scale evaluation of future variations in the occurrence of rainfall-induced landslides, in response to changes in rainfall regimes. We exploit information on the occurrence of 603 rainfall-induced landslides in Calabria, southern Italy, in the period 1981–2010, and daily rainfall data recorded in the same period in the region. Furthermore, we use high-resolution climate projections based on RCP4.5 and RCP8.5 scenarios. In particular, we consider the mean variations between a 30-year future period (2036–2065) and the reference period 1981–2010 in three variables assumed as proxy for landslide activity: annual rainfall, seasonal cumulated rainfall, and annual maxima of daily rainfall. Based on reliable correlations between landslide occurrence and weather variables estimated in the reference period, we assess future variations in rainfall-induced landslide occurrence for all the municipalities of Calabria. A +45.7% and +21.2% average regional variation in rainfall-induced landslide occurrence is expected in the region for the period 2036–2065, under the RCP4.5 and RCP8.5 scenario, respectively. We also investigate the future variations in the impact of rainfall-induced landslides on the population of Calabria. We find a +80.2% and +54.5% increase in the impact on the population for the period 2036–2065, under the RCP4.5 and RCP8.5 scenario, respectively. The proposed method is quantitative and reproducible, thus it can be applied in similar regions, where adequate landslide and rainfall information is available.

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1. Introduction

Rainfall is the primary trigger of landslides in many areas of the world. Given their triggering mechanisms and propagation characteristics, rainfall-induced landslides pose a serious threat to the population (Salvati et al., 2010; Petley, 2012). An increase in the frequency and the intensity of extreme rainfall events was observed in many regions, and recognized in the last report of the Intergovernmental Panel on Climate Change (IPCC–Intergovernmental Panel on Climate Change, 2014). Focusing on Europe, Madsen et al. (2014) published a review on trend analyses and climate change projections for extreme rainfall. The majority of the examined studies indicated a generalized, increasing trend in extreme precipitation (though the definition of "extreme" varies among the studies) in the observed data, and in future climate projections. Recently, analysing an ensemble of numerical climate simulations under climate change conditions, Scoccimarro et al. (2016) predicted, for the end of the 21st century, an increase in the intensity of heavy rainfall events in winter over Europe.

These variations in rainfall frequency and intensity affected, and may affect in the future, the spatial distribution and the frequency of rainfall-induced landslides (Crozier, 2010; Gariano and Guzzetti, 2016). The World Meteorological Organization (2013) estimated a 20% increase in the global number of fatalities due to disasters induced by extreme rainfall events in the decade 2001–2010 compared to the previous decade 1991–2000. Such increase was attributed to different causes, including variations in frequency and magnitude of extreme weather events, urbanization in hazardous areas, and variations of land use in susceptible areas. Considering that climate changes will increase the frequency of the intense rainfall events (IPCC–Intergovernmental Panel on Climate Change, 2014), and are expected to modify the areas subject to rapidly-moving, shallow, rainfall-induced landslides, the size of the population exposed to landslide risk is expected to increase (Gariano and Guzzetti, 2016). However, a quantitative evaluation of the effects of climate changes on landslides, and more generally on geo-hydrological hazards, remains challenging. Even more difficult is the quantitative assessment of future variations in the occurrence and the frequency of slope instabilities related to changes in climate, in particular in rainfall regimes and patterns.

In this work, we propose a method for the regional-scale evaluation of future spatial and temporal variations in the occurrence of rainfall-induced landslides. For the purpose, we exploit information on the occurrence of 603 rainfall-induced landslides in Calabria, southern Italy, in the period 1981–2010, daily rainfall data recorded in the same period in the region, and future climate projections based on two IPCC scenarios for the period 2036–2065. We present two maps showing the quantitative variations in rainfall-induced landslide occurrence in all the municipalities of Calabria, and we assess the expected changes in the impact of landslides on the population.

2. Background

In the scientific literature, the effects of climate and environmental changes on landslides are analysed adopting modelling or empirical approaches (Gariano and Guzzetti, 2016). The modelling approach investigates variations in the slope stability conditions related to future (synthetic) rainfall projections, downscaled from global climate models, and used as input to physically-based, statistical, or regional slope stability models (e.g., Jakob and Lambert, 2009; Chang and Chiang, 2011; Melchiorre and Frattini, 2012; Comegna et al., 2013; Rianna et al., 2014, Villani et al., 2015; Turkington et al., 2016, Ciabatta et al., 2016; Ciervo et al., 2016; Robinson et al., 2016). The empirical approach analyses jointly long records of landslide occurrences and climatic variables (usually rainfall or temperature), searching for geographical and temporal variations in the occurrence, frequency, or rate of activation of the landslides. The majority of the modelling approaches is local, and investigates a single slope, or a single landslide, with some exceptions. Some modelling approaches were applied to populations of landslides in homogeneous areas (e.g., Chang and Chiang, 2011; Melchiorre and Frattini, 2012). Conversely, the empirical approaches were applied at the regional scale, mostly – but not exclusively – in mountainous areas.

Depending on the covered period and the method used to reconstruct the landslide and climate records, two groups of empirical approaches can be singled out. A first empirical approach – hereafter referred to as "empirical historical approach" – compares catalogues of historical landslide occurrences with rainfall and temperature records, covering a few to many decades, typically in the last two centuries (e.g., Jomelli et al., 2004; Polemio and Petrucci, 2010; Polemio and Lonigro, 2015; Gariano et al., 2015). A second empirical approach exploits paleo-environmental data to reconstruct records of ancient landslides, and to analyse periods of increased/decreased landslide activity (e.g., Borgatti and Soldati, 2010; Stoffel and Beniston, 2006; Borgatti and Soldati, 2010; Sewell et al., 2015).

Works that adopt an empirical historical approach focus mostly on debris flows, shallow landslides, and rock falls occurred in a period ranging from mid-19th century to present, and consider rainfall and temperature (mainly at a monthly time scale) as the relevant weather variables. The studies revealed a wide range of impacts of climate variations on landslides, including contradictory, uncertain, and undetermined effects (Gariano and Guzzetti, 2016). As an example, Flageollet et al. (1999), studying different landslides in the Barcelonnette basin (South-East France) using monthly rainfall data in the 42-year period 1954–1995, did not find a significant relationship between climate variables and landslide activations, and concluded that the complexity of the landslide phenomena made it difficult to define "universal laws" linking landslides to climate variations. Yet, more recently, several authors found relationships between variations in climate variables (mainly rainfall) and changes in landslide activations or occurrence (e.g., Jomelli et al., 2004 and Stoffel et al., 2014, in the Italian and French Alps; Polemio and Petrucci, 2010 and Gariano et al., 2015, in Calabria, southern Italy; Lonigro et al., 2015, and Polemio and Lonigro, 2015 in Puglia, southern Italy).

The empirical historical approach adopted in this work is based on the use of catalogues of historical landslides triggered by rainfall. An ideal historical catalogue is not merely a list of landslides that have affected a given area at a selected moment, or period. Instead, a historical catalogue should represent the chronology of all (or almost all) the landslide activations that have occurred in the study area. The historical catalogues that are available in literature are chiefly lists of disaster-losses, which include other natural hazards as floods, droughts, extreme temperature, and storms (Chen et al., 2013; Papagiannaki et al., 2013). These catalogues are built using documentary data (Raška et al., 2014), including newspapers (Llasat et al., 2009; Garcia-Urquia and Axelsson, 2014; Pereira et al., 2014), that provide basic information on the date of occurrence and the impact of the damaging events (Petrucci, 2013; Damm and Klose, 2015), and have limitations that must be considered (Aceto et al., 2016). Recently, social media is becoming a new source of information on damaging events (Taylor et al., 2015). The diffusion of modern mobile communication devices fosters the dissemination of information through the Internet, with photographs and videos replacing the text descriptions typical of newspaper articles of the past century (Garcia-Urquia and Axelsson, 2014). Historical catalogues must be sufficiently long and complete to allow for significant statistical analyses. The completeness and quality of the landslide records varies with the analysed period (Petrucci and Pasqua, 2008), depending on the abundance and type of information sources, the skill of the investigators, and the resources available to compile the catalogues (Guzzetti et al., 2005). The characteristics of the catalogues depend on the scale of the survey, which restricts the information sources that can reasonably be analysed, and the length of the study period. Pereira et al. (2014), working in Portugal, showed that local newspapers were more effective than national newspapers in reporting damaging landslides. Generally, the larger the investigated area, the shorter is the analysed period, and the lower the data spatial density.