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Assessing the impact of climate-change scenarios on landslide occurrence in Umbria Region, Italy

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SUMMARY

Landslides are frequent and widespread geomorphological phenomena causing loss of human life and damage to property. The main tool for assessing landslide risk relies on rainfall thresholds and thus, many countries established early warning systems aimed to landslide hazard assessment. The Umbria Region Civil Protection Centre developed an operational early warning system for landslide risk assessment, named PRESSCA, based on the soil saturation conditions to identify rainfall thresholds. These thresholds, currently used by the Civil Protection operators for the day-by-day landslide hazard assessment, provided satisfactory results with more than 86% of the landslides events correctly identified during the period 1990–2013.

In this study, the PRESSCA system was employed for the assessment of climate change impact on landslide hazard in Central Italy. The outputs of five different Global Circulation Models (GCMs) were downscaled and weather generators were used for obtaining hourly rainfall and temperature time series from daily GCMs projection. Then, PRESSCA system was employed to estimate the number of landslide occurrence per year. By comparing results obtained for three different periods (1990–2013 (baseline), 2040–2069 and 2070–2099), for the Umbria territory a general increase in events occurrence was expected (up to more than 40%) in the future period, mainly during the winter season. The results also revealed that the effect of climate change on landslides was not straightforward to identify and the close interaction between rainfall magnitude/intensity, temperature and soil moisture should be analysed in depth. Overall, soil moisture was projected to decrease throughout the year but during the wet season the variations with respect to the present period were very small. Specifically, it was found that during the warm-dry season, due to the strong decrease of soil moisture, even for a sensible increase in rainfall intensity, the landslide occurrence was unchanged. Conversely, during the cold-wet season, the number of landslide events increased considerably if a positive variation in rainfall amount, more significant than rainfall intensity, was coupled with small negative variations in soil moisture.

1. Introduction

Rainfall-induced shallow landslides are one of the most common and dangerous natural hazards, mainly due to their high temporal frequency, that every year cause fatalities and high economic damage worldwide (Melchiorre and Frattini, 2012). In the last few years, the concern is growing because the effects of climate change could exacerbate landslides impact. As a result of the thermodynamic effect, a warming atmosphere translates into higher air moisture content, which in turn may increase the frequency and intensity of heavy precipitation events (Trenberth, 1999). Fischer and Knutti (2015) claim that for 2 °C of warming the fraction of precipitation extremes attributable to climate change on a global scale rises to about 40%. There is a high confidence that changes in heavy rainfall will affect landslides in some regions of the world (IPCC, 2012) but it is not quite clear how the local environments will react to these changes also in combination with higher air temperatures (Stoffel et al., 2013; Schmidt and Dehn, 2000).

Depending on the spatial and temporal resolution, various methodological approaches assessing the impact of climate change on landslide occurrences are available in literature, including the application of downscaled climate projections to physically based and statistical/empirical models (Coe and

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Godt, 2012). For instance, Collison et al. (2000) have used a GIS-based coupled hydrology/slope stability model that has been initialized by downscaled data from one Global Circulation Model (GCM) to investigate the impact of climate change on landslide frequency and amount at one site in South-East England. Specifically, GCM data have been used to force a simplified hydrological model in order to simulate the water table depth (through the estimation of the soil moisture conditions). This information has been used to evaluate the factor of safety for the analysed hillslope. Collison et al. (2000) have noticed that the expected increase in rainfall for the horizon 2080 is countered by the increase in temperature and, hence, the frequency of shallow landslides in the area located in SE England does not substantially change. Uncertainty and diverging conclusions on future landslide activity are raised by Melchiorre and Frattini (2012) who highlight the needs to properly take the error margins inherent in scenario-driven global climate projections into account (Crozier, 2010). Melchiorre and Frattini (2012) have used a coupled hydrological-stability model and GCM climate scenarios to evaluate changes in slope stability conditions due to climate change in Central-Southern Norway. The GCM data have been used to evaluate the soil saturation conditions and the pressure heads through the hydrological model, then an infinite slope stability module has been run to compute the factor of safety. Specifically, the authors have used 11 different scenarios of future daily precipitation and Monte Carlo simulations to model uncertainty arising both from GCM climate scenarios and from the epistemic uncertainty of hydrological and slope stability model parameters. Although slope stability conditions have shown a decreasing trend for the future scenario, an accurate quantification of changes in stability conditions due to the high level of uncertainty in climate modelling, antecedent precipitation conditions and soil parameters has not given. Kim et al. (2015) have used two different Representative Concentration Pathways (RCPs) to provide future landslide susceptibility maps in GIS environment in Korea. The outcomes have shown an increasing number of landslides by the end of the century with more than 20% of the landslide hazard area that affect urban sectors.

Conversely, Dixon and Brook (2007) have used a more simple approach to analyse the impact of climate change on deep landslide occurrence for a case study in the United Kingdom. By comparing projected 2080s rainfall derived from UKCIP 2002 with a 1 and a 6-month empirical rainfall threshold a reduction of the landslide return period by 2080s has been expected. However, Dixon and Brook (2007) have stressed the importance of temperature changes that might influence the response of landslide through increased evapotranspiration leading to a change in the triggering precipitation thresholds, and this counterbalances the impact of changes in precipitation. Also Jakob and Lambertb (2009) have used a simplified approach to analyse the effects of climate change on shallow landslides occurrence along the southwest coast of British Columbia, Canada. On the basis of observed data, the authors have identified empirical landslide thresholds relating 24-h storm and four week antecedent rainfall. Therefore, by analysing precipitation data from an ensemble of 19 GCMs, Jakob and Lambertb (2009) have found that the positive change in the antecedent precipitation has been predicted about 10% and the increase in the short-term precipitation around 6%. On this basis, and by using the empirical landslide thresholds, they have concluded that landslide frequency along the south coast of British Columbia should increase during the twenty-first century. The novel aspect of this study is that, although in a quite simple way, Jakob and Lambertb (2009) have tried to establish an empirical relationship between soil moisture conditions and critical rainfall intensity lending themselves to landslide activity. To assess landslide hazard several countries have developed early warning systems (e.g. Baum and Godt, 2010), generally based on the definition of empirical rainfall amounts needed for landslide triggering (Brunetti et al., 2010; Gariano et al., 2015, to cite a few). Although simple to implement in an operational framework, rainfall thresholds alone do not take soil saturation conditions into account, that play a key-role in the climate system (Seneviratne et al., 2010) and in particular in landslide triggering (Godt et al., 2006; Segoni et al., 2010; Ray et al., 2010, 2011; Bittelli et al., 2012; Brocca et al., 2012; Lepore et al., 2013; Capparelli and Versace, 2014; Bordoni et al., 2015). Indeed, infiltrating rainfall can significantly increase the soil pore pressure inducing slope movement. On this basis, the Civil Protection Centre of Umbria Region (CPC), Central Italy, has developed an early warning system for the shallow landslide hazard assessment, named PRESSCA, based on the relationship between rainfall and soil moisture conditions throughout the regional territory (Ponziani et al., 2012). The procedure for landslide warning is based on the combination of rainfall thresholds and estimates of soil moisture conditions derived from a soil water balance model calibrated and tested with local soil moisture observations (Brocca et al., 2013, 2014). PRESSCA uses real-time precipitation and temperature data in order to define the initial soil saturation conditions that are coupled with forecasted rainfall data and compared with the rainfall thresholds in order to evaluate the landslide hazard up to three days in the future.

The overall aim of this study is to analyse how shallow landslide occurrence may be affected by climate change for the area of Umbria Region. To this end, the PRESSCA early warning system performances are at first tested using a recently assembled landslide catalogue. Therefore, the reliability of downscaled hourly temperature and precipitation time series, obtained from different GCMs and used to initialize PRESSCA, is verified for the present period, 1990–2013. Finally, the impact of climate change on landslide occurrence is evaluated by forcing the PRESSCA system with downscaled GCMs data for two future periods, i.e. 2040–2069 and 2070–2099. The latter evaluation is performed by comparing the frequency of landslide events that exceed the rainfall-soil moisture thresholds in the future with respect to the present period.

2. Study area and datasets

The study area is the Umbria region located in Central Italy, with an area of approximately 8800 km^2; the landscape is mainly hilly with a mountainous area in the eastern sector and an alluvial plain that stretches along the north-south direction. Due to the physiography of the territory, the Umbria region is prone to landslides, and specifically to rainfall-induced landslides. Indeed, more than 500 shallow landslides triggered by rainfall events have been recorded and listed in a regional catalogue by the CPC during the period 1990–2013.

Meteorological (rainfall and temperature) data, obtained through the regional monitoring network and from 5 different GCMs, are used in this study. To evaluate the PRESSCA system, and to build a reference dataset to be used as benchmark, the 1990–2013 period is considered as baseline, whereas to evaluate the climate change impact on landslide, GCMs data for the future periods 2040–2069 and 2070–2099 are considered. All GCM data are interpolated over the centroid of the region using an Inverse Distance Weighted algorithm and the hourly time step is used, after downscaling, in order to obtain the 24, 36, 48 and 72 h rainfall amounts. More details about the employed dataset in the study are described in the following paragraphs.