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Hydro-geomorphological modelling of ash-fall pyroclastic soils for debris flow initiation and groundwater recharge in Campania (southern Italy)

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ABSTRACT

Carbonate mountain ranges surrounding volcanic centers in the Campania region of southern Italy are covered by discontinuous ash-fall pyroclastic deposits of variable thicknesses. The cover thickness and stratigraphy are relevant to hydrological controls on both rainfall-induced landslides and groundwater recharge. To improve understanding of the hydrologic regimes within the pyroclastic soil mantle, a hydrological monitoring station was installed upslope of a debris flow source area in the Sarno Mountains. Monitoring results demonstrate consistently unsaturated conditions, strong seasonal and inter-annual variations in pressure head, and delayed and damped dynamics at different depths related to rainfall and evapotranspiration patterns. Frequencies of recorded pressure head time series were analyzed to quantify the seasonal hydrological regime of the cover as a whole, as well as variations within individual soil horizons. For the whole ash-fall pyroclastic soil cover, variable seasonal frequencies of pressure head were recognized exceeding landslide alert and groundwater recharge threshold values. Analysis of frequencies for individual soil horizons showed a strongly delayed timing determining in winter and summer an opposite hydrological behavior between the shallowest and deepest soil horizons. A model that accounts for topographic variations in cover thickness and these hydrological regimes is proposed to quantify hydro-geomorphological controls on debris flows triggering and groundwater recharge. The model is based on the estimation of ash-fall pyroclastic soil thickness along slopes by the total thickness fallen in a given area and an inverse relationship with slope angle, allowing the assessment at the distributed scale over peri-volcanic mountainous areas. Moreover, it links the spatially variable thicknesses of ash-fall pyroclastic soils to the amount of soil water storage allowing the assessment of frequency of hydrological conditions leading to debris flow initiation and groundwater recharge.

1. Introduction

The carbonate mountainous areas that surround the Campanian Plain (Campania, southern Italy) are characterized by unusual surficial geological conditions due to the covering of ash-fall pyroclastic deposits, erupted in the last 39 k-yrs. mainly by the Somma-Vesuvius volcano and subordinately by the Phlegrean Fields volcanic center. In such a geomorphological framework, the ash-fall pyroclastic soil mantle exerts a very relevant hydrological behavior, depending on spatially variable deposition and heterogeneity of stratigraphic settings. Furthermore, the existence of a dense vegetation cover living on the pyroclastic mantle is another factor to be taken into account, depending on particular hydrological properties of pyroclastic soils and climatic features. The related principal issues are recurrent rainfall-induced shallow landslides, involving pyroclastic deposits and leading to deadly debris-flows, and groundwater recharge of underlying karst aquifers as well, which are very relevant for the feeding of regional aqueduct systems (Allocca et al., 2014).

The landslide hazard along the Avella, Sarno, Salerno and Lattari mountain ranges, which surround the Campania Plain (Fig. 1) and cover an area of about 650 km^2, is a well-known national issue due to the repeated debris flows events which have caused the loss of about 900 lives since 1900. A significant advance to understand mechanisms and processes leading to instability of ash-fall pyroclastic soil covers and estimate landslide hazard was given after the high magnitude debris flow event, which occurred on 5–6 May 1998 along the Sarno Mountains and caused the loss of 160 lives. The strong cause-effect relationship between occurrence of heavy rainfall and landslide triggering led firstly to estimate Intensity-Duration (I-D) rainfall thresholds (Caine, 1980) by an empirical approach (Calcaterra et al., 2000; De Vita and Piscopo, 2002). Subsequently, also deterministic approaches, based on a coupled modelling of hydrological conditions occurring within the ash-fall pyroclastic cover during heavy rainstorms and slope stability (Lu and Godt, 2013; Bordoni et al., 2015) were attempted (Crosta and

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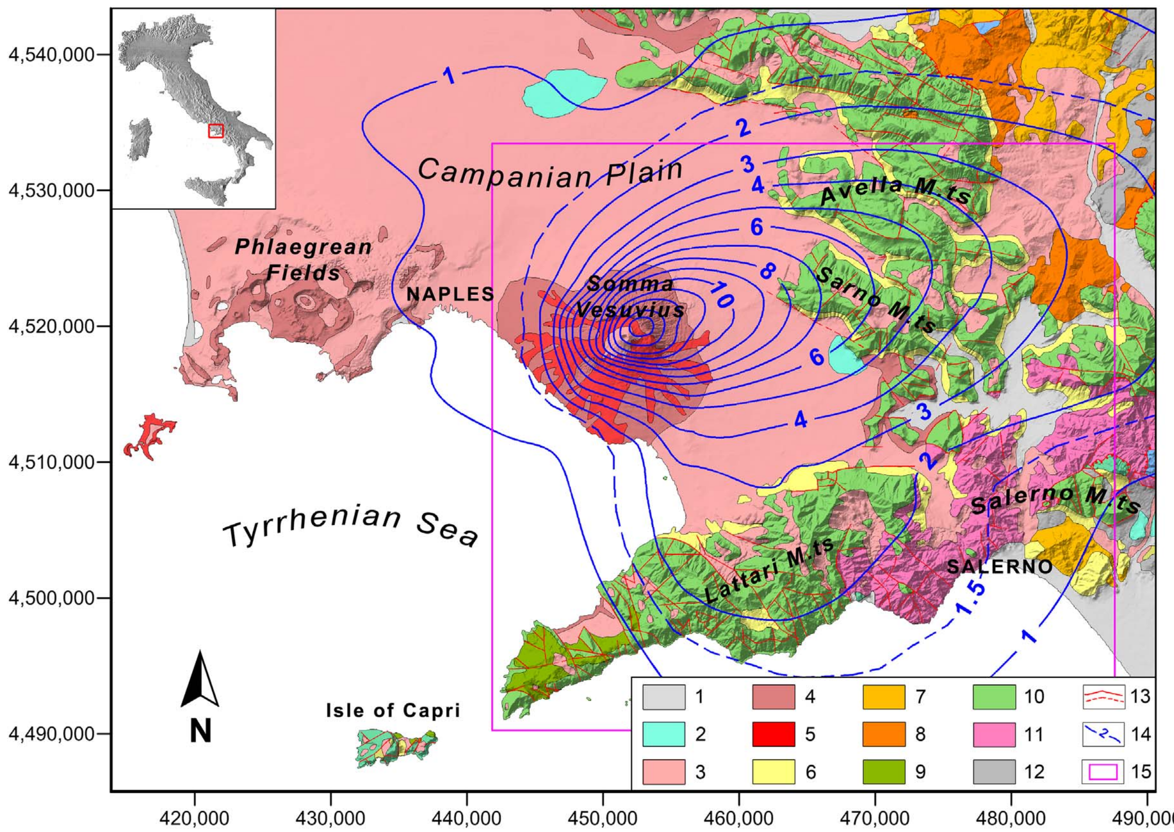

Fig. 1. Geological map of the area including mountain ranges surrounding the Somma-Vesuvius volcano: 1) alluvial deposits; 2) travertine deposits; 3) incoherent ash-fall deposits (Recent Pyroclastic Complex); 4) mainly coherent ash-flow deposits (Ancient Pyroclastic Complex); 5) lavas; 6) detritus and slope talus deposits; 7) tardo-orogenic terrigenous deposits; 8) syn-orogenic terrigenous deposits; 9) Miocene flysch; 10) Middle Jurassic-Upper Cretaceous limestone; 11) Lower Triassic-Middle Jurassic dolomites and calcareous limestone; 12) pre-orogenic basinal units; 13) outcropping and buried faults; 14) total isopachous line (meters) of ash-fall pyroclastic deposits erupted by the Plinian Somma-Vesuvius' eruptions (modified from: De Vita et al., 2006a, 2006b; De Vita and Nappi, 2013), representing z_0 value (Eq. (1)); 15) area represented in Fig. 4. Coordinates along map borders are in the UTM WGS84 system.

Dal Negro, 2003; De Vita et al., 2013; Pagano et al., 2010; Papa et al., 2013a). In these approaches, effects on slope resisting and driving forces of unsaturated (Lu and Likos, 2004) and saturated conditions (Terzaghi, 1943) were taken into account. These studies allowed both the comprehension of slope instability mechanisms, recognizing the role of stratigraphic and morphological settings on unsaturated/saturated throughflow, and the assessment of deterministic I-D rainfall thresholds. Moreover, other studies were focused on the hydrological monitoring of ash-fall pyroclastic soil mantles, which appeared an important achievement for the setting up of effective early warning systems (Damiano et al., 2012; De Vita et al., 2012; Fusco et al., 2013; Fusco and De Vita, 2015; Greco et al., 2013; Sorbino, 2005). These studies revealed a dominant unsaturated condition and a complex hydrological regime, from hourly to seasonal time scales. Given these findings another advance was carried out to assess the seasonal effect of hydrological conditions on I-D thresholds (Napolitano et al., 2016), allowing to estimate also uncertainties due to a variable antecedent hydrological status of the ash-fall pyroclastic soil mantle on rainfall conditions leading to slope instability.

In addition to the shallow landslide issue, the hydrological regime of ash-fall pyroclastic mantle plays an important role on groundwater recharge of underlying karst aquifers because determining the amounts of water losses toward the atmosphere through the evapotranspiration process and percolation down to the groundwater table. A recent study on groundwater recharge of karst aquifers of the Campania region covered by ash-fall pyroclastic soils (Allocca et al., 2015) confirmed the relevant role of these soil coverings, whose water storage determines the equivalence between actual evapotranspiration (AET) and the potential one (PET). Therefore, considering the strategic relevance of karst aquifers surrounding the Campanian Plain (Allocca et al., 2014), the understanding of hydrological behavior and regime of pyroclastic soil mantle appears another important advance for modelling groundwater recharge of these aquifers.

Considering both issues, the hydrological regime and processes taking place at different time scales within the ash-fall pyroclastic soil mantled slopes are crucial aspects to be assessed. To pursue this focus we carried out a study that can be understood in the hillslope hydrology branch (Kirkby, 1978; VV.AA., 1990, 1996). The expected results were supposed potentially fostering future assessments of both landslide hazard and groundwater recharge (Healy, 2010) of karst aquifers.

The hydrological role of the ash-fall pyroclastic soil mantle along mountain slopes surrounding the Campanian Plain is spatially variable, depending on thicknesses and stratigraphic settings. Therefore its distributed modelling is conceivable as a hydro-geomorphological model (Iida, 1999; Onda et al., 2004; Sidle and Onda, 2004), which couples the spatial distribution of ash-fall pyroclastic soil thickness and the hydrological behavior of pyroclastic soil coverings. In such a direction, results of preceding studies aimed at the spatial modelling of ash-fall pyroclastic soils thickness in the areas surrounding the volcanic centers of the Campania (De Vita et al., 2006a, 2006b; De Vita and Nappi, 2013) give the basis for the reconstruction of a hydro-geomorphological model of the ash-fall pyroclastic mantle.

In this paper we present a study on the temporal and spatial variability of the hydrological conditions of the ash-fall pyroclastic soil mantle, which are conceived as both preparatory factors for triggering landslides phenomena and controlling groundwater recharge of karst aquifers nearby the Campanian Plain. The experimental research started with the analysis of pressure head time series acquired within the whole thickness of the ash-fall pyroclastic soil mantle through a soil hydrological monitoring station, set in a representative slope area of the