Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X

doi: doi.org/10.53243/RootS2025-40

Monitoring water fluxes in ash-fall pyroclastic soils covering peri-volcanic slopes of Campania region (southern Italy) to assess hazard to shallow rainfall-induced landslides

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ABSTRACT: The ash-fall pyroclastic soils that mantle the mountains in the peri-volcanic sector of Campania region (southern Italy) represent a special environment where soil-root-water interactions act as predisposing factor for the triggering of deadly fast-moving shallow landslides occurring under rainfall events. Considering the intense development of the vegetation cover, the assessment of hydro-mechanical soil-vegetation coupling is a key factor in the estimation of landslide hazard. To this end, as part of the PNRR GeoSciences IR project, two multi-sensor stations were deployed in south-western and north-eastern slopes of the Sarno Mts. and one in northern slopes of Lattary Mts., in sites representative of geomorphological and stratigraphic conditions typical of the source landslide zones. Each station consists of multiple sensors detecting soil matric suction and soil volumetric water content, deployed at different depths, till the local bedrock. Moreover, each station is provided with sensors measuring meteorological parameters, dataloggers and data transmission devices powered by solar panels. Time series of the first year of monitoring activity show marked seasonal variations at different depths with delayed and damped response dynamics. These observations were preliminarly correlated to precipitation and air temperature time series to assess their effect on soil hydrological variables. The monitoring results are expected to enhance the analysis and forecasting of potential future landslide events, thereby improving hazard assessment.

Keywords: Rainfall-induced shallow landslides; hydrological monitoring

1 INTRODUCTION

Landslides are widespread phenomena triggered by various factors, including earthquakes, rainfall and volcanic activity. Among them, rainfall-induced fast-moving shallow landslides are particularly hazardous due to their sudden onset, long runout, and high velocity (Formetta & Capparelli, 2019). Given their severe impact on human life and infrastructure, they represent a significant societal risk, requiring adequate techniques to monitor and assess the related hazard. The ash-fall pyroclastic soils covering the peri-volcanic carbonate mountains around the Campanian Plain (southern Italy) constitute a complex geo-hydrological environment, prone to the occurrence of shallow rainfall-induced flow-like landslides, where the dense vegetation cover plays a key role in slope stability during rainfall events. In fact, the interaction between vegetation, soil water and soil shear strength, in variable saturation conditions, including also the mecahnical reinforcing effect of roots, provides a strong control on the complex mechanisms of slope stability. The Sarno and Lattari mountain ranges, bordering the Campanian Plain, are well known as hit by deadly rainfall-induced shallow landsliding since the 17th century, until the last catastrophic event of the 5th and 6th May 1998 which caused the loss of 160 lives (Guadagno and Revellino, 2005). After the last event, several studies have investigated slope instability mechanisms, emphasizing the influence of stratigraphic and morphological settings on hillslope hydrological processes and leading to the definition of deterministic I–D rainfall thresholds. Moreover, hydrological monitoring of ash-fall pyroclastic soils has provided essential knowledge for developing effective early warning systems (Fusco et al., 2017; Greco et al., 2021). Nevertheless, to fully address this type of rainfall-induced landslides, the coupled mechanical and hydrological control of vegetation on slope stability needs to be further analyzed. Accordingly, within the Work Package 3 of the PNRR GeoSciences IR project (https://geosciences-ir.it/), the construction of a research infrastructure for the analysis of predisposing and triggering hydrological conditions of rainfall-induced flow-like landslides in the mountain ranges surrounding the volcanic centers of the Campania region (southern Italy) was proposed. The monitoring systems, consisting in three soil-hydrological and meteorological stations, were installed in slope areas, representative of the highest proneness conditions to the initiation of rainfall-induced flow-like landslides.

2 LOCATION AND FEATURES OF MONITORING SITES

2.1 Geological features of the study area

The peri-volcanic mountain slopes surrounding the Phlegraean Fields and Somma-Vesuvius volcanic center in Campania region are historically prone to rainfall-induced flow-like landslides. These slopes are characterized by a Mesozoic carbonate bedrock mantled by ash-fall pyroclastic belonging to the “Ancient Pyroclastic Complex” (APC, 39 k-yrs B.P., mainly ash-flow deposits of “Campanian Ignimbrite”) and the “Recent Pyroclastic Complex” (RCP, 17 k-yrs B.P.) (Sparice et al., 2014) formed by the more recent deposits of the Somma-Vesuvius volcano eruptions. Depending on the orientation of dispersal axes of the major Plinian eruptions, the stratigraphic settings are spatially variable across the mountain ranges. Accordingly, the Sarno Mts. are covered by a reference stratigraphic setting (De Vita et al. 2013) formed by: 1) A horizon, consisting of prevailing humus (Pt); 2) B horizon, mainly characterized by highly pedogenised pumiceous pyroclasts (SM); 3) C horizon, formed by pumiceous pyroclasts, slightly weathered (GW or GP); 4) Bb horizon, corresponding to a B horizon buried by a successive depositional event and thus considered as a paleosol (SM); 5) Cb horizon, representative of a buried C horizon (GW or GP); 6) Bb-basal horizon, corresponding to a residual pyroclastic deposit, highly weathered by pedogenesis (SM); 7) R horizon, fractured carbonate bedrock with open joints, infilled by the overlying paleosol for the first few meters. Slope failures generally affect the upper 1.5 m of ash-fall pyroclastic deposits, mainly involving the B, C, and Bb horizons. According to several authors (Guadagno et al., 2005; Tufano et al., 2016; Fusco et al., 2021; Greco et al., 2021), the triggering of these landslides is mainly controlled by the geomorphological features of the slopes, the spatial variability of the stratigraphic setting, and the textural characteristics of the ash-fall pyroclastic soil cover. Source areas are typically located at slope knickpoints, at the top of natural rocky scarps, and along road cuts (Guadagno et al., 2005). Based on former studies relying on the soil hydrological monitoring and modeling (De Vita et al., 2013; Fusco et al., 2017), ash-fall pyroclastic soils are chiefly characterized by unsaturared conditions. Therefore, the infiltration process, leads to the reduction of the soil suction and shear strength (Lu & Lycos, 2004) favoring the triggering of initial soil slips or debris slides, typically involving limited volumes and evolving into debris avalanches and/or debris flows, depending on slope morphology and soil availability along the downslope path (Hungr et al., 2014).

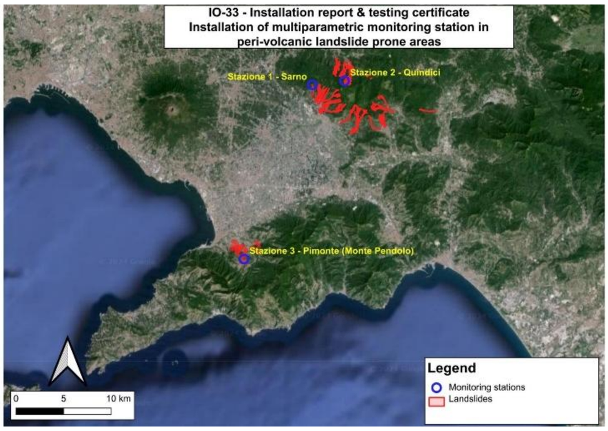

Figure 1. Location of the three monitoring stations in the framework of the peri-volcanic mountains ranges of Sarno and Lattari Mts

2.2 Site selection criteria, installation conditions and sensors distribution

The monitoring systems were designed on the basis of the results of previous researches carried out in the last two decades on the hydrological conditions leading to the triggering of this type of flow-like landslides (Calcaterra et al., 2000; Napolitano et al., 2016), which were based on the reconstruction of detailed engineering-geological models of the landslide source areas, characterization of geotechnical and hydrological properties of ash-fall pyroclastic soils, soil hydrological and slope stability modelling, field soil hydrological monitoring and estimation of rainfall thresholds by means of empirical and deterministic approaches. The monitoring sites were selected considering (i) the slope angle most frequently associated with landslide initiation (30°–40°) and (ii) proximity to small-scale geomorphological singularities such as upslope of pre-existing landslide crown zones and natural and anthropic morphological discontinuities. According to the abovementioned criteria, the monitoring sites were located upslope of the source area of historical flow-like landslides events, which hit the Sarno Mts., in May 1998, and Lattari Mts. (Pendolo Mt.), in February 1963. Accordingly, the three monitoring stations were installed in the territories of Sarno (province of Salerno), Quindici (province of Avellino) and Pimonte (province of Napoli) (Figure 1). The sensors were installed in the ash-fall pyroclastic cover, and their deployment was guided by the local stratigraphic conditions and the thickness of the soil mantle. The site characterization was obtained through on-purpose engineering geological investigations including test pits and dynamic penetrometric tests.

2.3 Features of the monitoring stations

The field soil hydrological and meteorological monitoring stations consist of multiple sensors and associated datalogging and data-transmission devices provided with the supply of a solar panel power system (Figure 2). Nine multisensor probes were installed to measure volumetric soil water content (SM θ, m^3/m^3), soil temperature (ST, °C), and soil electrical conductivity (SEC) (CAMPBELL SoilVue 10). In addition, 18 sensors and 9 tensiometers were installed to measure soil water potential (SWP, kPa, METER Teros 21; Teros 32), which we consider herafter as soil suction. Three systems for monitoring meteorological variables, including cumulative rainfall (CR, mm), rainfall intensity (RI, mm/h), relative humidity (RH, %), solar radiation (SR, W/m^2), air temperature (AT,°C), air pressure (AP, kPa), wind velocity (WV, m/s), and wind direction (WD, °) (METER ATMOS 41), were also deployed. The acquisition rate was set with one reading every 10 min for all sensors. In the current setting, data are uploaded, by GSM remote connection, to an online platform every 12 hours. The monitoring periods started on the April 30, 2024, May 15, 2024 and May 28, 2024 for the Sarno, Pimonte and Quindici stations, respectively.

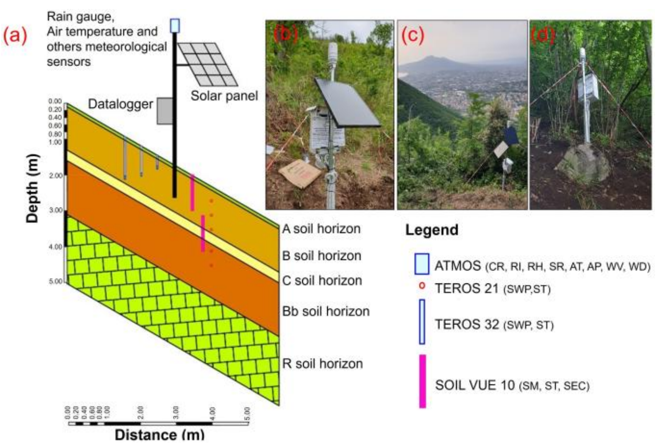

Figure 2. (a) Schematic representation of the monitoring stations. External appearance of the (b) Sarno, (c) Quindici and (d) Pimonte stations

3 PRELIMINARY RESULTS

Monitoring results obtained for over one year (Figure 3) showed consistently unsaturated conditions for all depths and soil horizons of the soil profiles, strongly controlled by rainfall and evapotranspiration regimes. Near-saturation conditions with soil suction of about 3 kPa occurred only after intense rainfall in shallow horizons (0.40 m - 0.60 m). During the rainy periods, lower soil suction values were observed as controlled by greater rainfall amounts and lower evapotranspiration rates. The shallower B soil horizon showed the greatest fluctuations and a temporal correlation with rainfall events, more direct than those found for the other deeper soil horizons (B_b and B_{bbasal}). At the beginning of the spring, a steady increasing trend of soil suction was identified for the Quindici and Pimonte monitoring stations due to the rarefaction of rainfall events and the strong evapotranspiration demand of the deciduous chestnut forest. In these periods, the soil suction values fluctuated between about 3 kPa and above 3000 kPa. In the dry periods, soil suction were measured up to the functioning limit of the sensors (3000 kPa). Then, starting from the beginning of autumn, a descending trend was determined by rainfall events, mostly rainstorms, and the end of the deciduous forest activity. This condition was initially observed in the shallower B soil horizon, where it appeared more pronounced, and later extended to the deeper B_b and $B_{b\text{-basal}}$. By the comparison of box plots of soil suction is possible to appreciate differences in the ranges at various depths which appear to be correlable with the type of vegetation cover (Figure 3). The widest range of soil suction was recognized for the Quindici monitoring station, down to the depth of 1.2 m, as being related to the occurrence of a very dense chestnut forest.

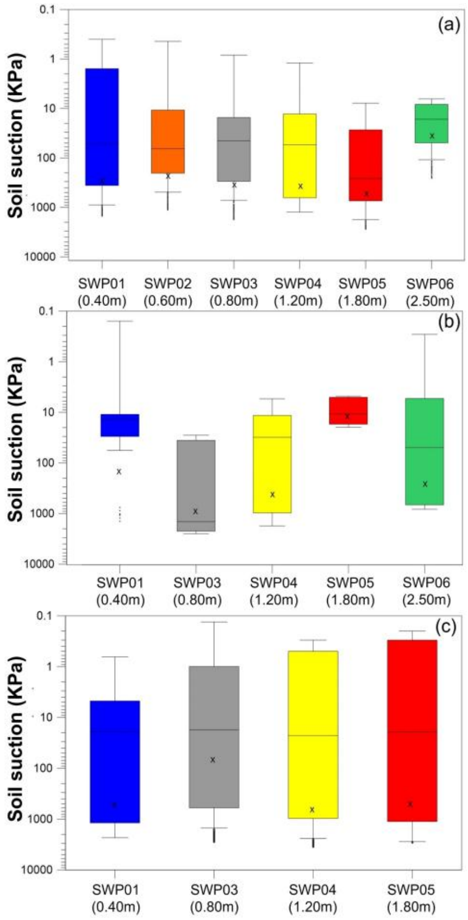

Figure 3. Box plots of soil suction recorded by sensors deployed at different depth, from 0.40 to 2.50 m, at (a) Sarno, (b) Quindici and (c) Pimonte monitoring stations

4 DISCUSSION

The goal of the research is to advance the comprehension of soil hydrological regimes and processes predisposing and triggering rainfall-induced flow-like landslides in the mountain ranges surrounding the volcanic centers of the Campania region (southern Italy). Based on a statistical analysis of the soil suction time series derived the monitoring activity, two values corresponding to the

5% percentiles (exceeding percentiles of 95%) were recognized as representative of the winter period, spanning across winter and partly spring, and the dry one, including summer and early autumn. The first one was identified for the winter with soil suction values measured for the shallower B horizon, ranging within the whole soil mantle from 3.0 kPa to 8 kPa. These values were evaluated as being consistent with those measured for the same season by other hydrological monitoring campaigns on ash-fall pyroclastic soils (Fusco et al., 2022). Moreover, theese values were considered as representative of a very wet hydrological status occurring after relevant rainfall events and conceived as indicating a high predisposition to flow-like landslides triggering under heavy rainfall events and then considerable as a landslide alert threshold. Similarly, typical dry conditions occurring between summer and early autumn were identified approximately with values of soil suction ranging above 100 kPa.

These values can be identified and used as antecedent hydrological conditions of a coupled hydrological and slope stability model, thus dealing with uncertainties in assessing rainfall thresholds triggering debris flows.

5 CONCLUSIONS

The proposed approach, based on field hydrological monitoring of ash-fall pyroclastic soils mantling the peri-volcanic hillslopes, is fundamental for assessing the hazard of flow-like landslides initiation. The preliminary results identified soil-root-water interactions within the ash-fall pyroclastic soils and recognized them as a complex geo-hydrological system, with a strong seasonal pattern controlling slope stability after rainfall events. The monitoring activity will be used to define alert thresholds based on soil suction.

6 ACKNOWLEDGEMENTS

This work was carried out within the Work Package 3 of the PNRR GeoSciences IR project, Operating Unit UNINA 02 – Department of Earth, Environmental and Resources Sciences – University of Naples Federico II.

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