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On the Rainfall Induced Shallow and Deep-seated Landslide Hazard in Central Taiwan

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Due to active tectonic activity, the rock formations are young and highly fractured in Taiwan area. The dynamic changing of river morphology makes the highly weathered formations or colluviums prone to landslide and debris flow. In addition, due to the impact of 1999 Chi-Chi earthquake, the hazards of landslides and debris flows were significantly increased. For the past decade, the effect of climate change is significant and creates more and more extreme weather events. The change of rainfall behavior significantly changes the landslide behavior, which makes the large-scale landslides, like the Shiaolin landslide, possible. Therefore, it is necessary to develop the new technologies for large-scale landslide investigation, monitoring, analysis, early warning, etc.

Since the landslide hazards are mainly induced by heavy rainfall, due to climate change and the subsequent extreme weather events, the probability of large-scale landslides is also increased. Focusing on the slate formation area in the upstreams of the Tachia River, Wu River, and Chuoshui River, this project studied the behavior and hazard of shallow and deep-seated landslides. This study adopts the SHALSTAB model with the consideration of slope angle to classify the landslides, and then established the landslide susceptibility models based on the classified landslide inventories. Different types of susceptibility models in different catchment scales were tested, in which the control factors were analyzed and discussed. This study also employs rainfall frequency analysis together with the atmospheric general circulation model (AGCM) downscaling estimation to predict the extreme rainfalls in the future. Such that the future hazard of the shallow and deep-seated landslide in the study area can be predicted. The results of predictive analysis can be applied for risk prevention and management in the study area.

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Engineering geological investigation for landslide hazard zonation in the Sino-Nepal Road corridors.

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Road construction in the Trans-Himalaya is always challenging task because of having fragile and rugged topography with the strong influence of monsoon. Three different road corridors namely Kaligandaki (Pokhara-Jomsoom-Zhongba), Trishuali (Kathamndu-Trishuli-Gyirong) and Bhotekoshi rivers (Kathmandu-Tatopani-Nyalam) cross the Himalaya with different geological discontinuities i.e. South Tibetan Detachment System (STDS), Main Central Thrust (MCT). The Himalayan range is acting a topographic barrier resulting different climate in the southern and northern part. These three roads are very strategic for the connectivity between Trans-Himalaya and midland. People have been living in these valleys for a long time. After the road construction, people have started to build houses along this road. However, people have are often forgetting the influence of these large scale mass movement that occurred in the past. Therefore, an attempt has been done to analyze these past events and their impacts. Preparation of engineering geological map, landslide inventories and investigation of large scale past mass movement have been done in detailed field investigations in 2018 and 2019 supported by remote sensing. Slope stability analysis has been done in different critical sections for the landslide hazard assessment. It is clearly seen that the road passes some of these large scale paleo-landslides and responsible for toe cutting. The road sections are critical in all three roads but more vulnerable in the southern slope of the Himalaya. The road between Beni to Larjung of the Kaligandaki has critical slope and susceptible for landslide occurrences. Therefore, proper mitigation measures have to be implemented for the stabilization of these mountain slope.

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Redistribution of landslide debris through episodic heavy rainfall events as revealed by multi-period Lidar DEMs

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Landslides are commonly triggered by heavy rainfall events, but how the loose landslide debris is redistributed through time and how fast the landslide scars are healed by vegetation are not well and precisely documented. Due to recent advances in airborne Lidar-derived digital elevation models, we are able to obtain precise DEMs at different time periods and analyze the redistribution of landslide debris that was once difficult to measure because of relatively minor elevation changes. Three periods of Lidar-derived DEMs were used to analyze a drainage basin that was affected by a heavy rainfall event and generated several landslide deposits and scars within the drainage basin in Taiwan. We selected a single drainage basin to better constrain the source of landslide debris for subsequent observations of landslide debris removal. How the landslide debris is transported and redistributed remains an important topic for understanding debris removal and evaluating post-landslide hazards in downstream areas. The multi-period high-resolution Lidar DEMs give the necessary accuracy to calculate small but significant volume changes that were not easily detectable from previous measuring techniques. Our results show that the landslide debris redistributed most effectively during later large rainfall events, and the landslide materials are minimally redistributed during small rainfall events. Areas without existing landslides were also insignificantly affected in terms of volume change even during large rainfall events. The standard deviation of elevations in the drainage basin is used to show how the topography was changed due to heavy rainfall events within the drainage basin. The concept of surface roughness may be useful to characterize the dissipation of landslide debris because the roughness values become lower during the debris redistribution process. The redistribution of landslide debris over the observed years suggests that the dissipation of landslide debris is mainly affected by by episodic heavy rainfall events and the landslide scars recover relatively quickly for smaller affected landslide regions.

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Estimation of the hourly snowmelt based on the heat balance method using the Japan Meteorological Agency observation data alone and application for analyzing groundwater level fluctuation in a landslide site

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The heat balance method has often been used for calculating the snowmelt for the purpose of estimating watershed water resources in the form of snow in winter and analyzing snowmelt runoff. Because the method requires many weather elements, some of which are not observed frequently (e.g., longwave radiation), methods of estimating such less frequently observed weather elements from more frequently observed ones have also been proposed. However, few previous studies have developed a method of estimating the hourly snowmelt based on the heat balance method using the frequently observed weather elements alone and applied for analyzing the hourly groundwater level fluctuation in a landslide site in snow-covered area. In this study, we developed a model of estimating the hourly snowmelt based on the heat balance method using the Japan Meteorological Agency observation data, the most commonly available weather data in Japan, alone, (i.e., temperature, precipitation, wind speed, sunshine duration, atmospheric pressure, and vapor pressure), and applied the model to a past landslide site with deep sliding surface (approximately 20 m) in snow-covered area in Hokkaido, Northern Japan. Moreover, we applied the functional models based on the antecedent precipitation index calculated using (the meltwater and/or rainwater) instead of the rainfall to reproduce the hourly groundwater level fluctuation observed in the site. The results showed good agreement between the observed and calculated snowmelt and groundwater level. The models proposed and used in this study are useful for estimating the hourly snowmelt and analyzing groundwater level fluctuation in a landslide sites in snow-covered area, and should be tested for other landslide sites to further verify the applicability.

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Performance analysis of regional landslide early warning based on soil moisture simulations

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In mountainous regions, rainfall-triggered landslides pose a serious risk to people and infrastructure, particularly due to the short time interval between activation and failure and their widespread occurrence. Landslide early warning systems (LEWS) have demonstrated to be a valuable tool to inform decision makers about the imminent landslide danger and to move people or goods at risk to safety. While most operational LEWS are based on empirically derived rainfall exceedance thresholds, recent studies have demonstrated an improvement of the forecast quality after the inclusion of in-situ soil moisture measurements.

The use of in-situ soil moisture sensors bears specific limitations, such as the sensitivity to local conditions, the disturbance of the soil profile during installation, and potential data quality issues and inhomogeneity of long-term measurements. Further, the installation and operation of monitoring networks is laborious and costly. In this respect, making use of modelled soil moisture could efficiently increase information density, and it would further allow to forecast soil moisture dynamics. On the other hand, numerical simulations are restricted by assumptions and simplifications related to the soil hydraulic properties and the water transfer in the soil profile. Ultimately, the question arises how reliable and representative landslide early warnings based on soil moisture simulations are compared to warnings based on measurements.

To answer this, we applied a state-of-the-art one-dimensional heat and mass transfer model (CoupModel, Jansson 2012) to generate time series of soil water content at 35 sites in Switzerland. The same sites and time period (2008-2018) were used in a previous study to compare the temporal variability of in-situ measured soil moisture to the regional landslide activity (currently under review in *Landslides*). The same statistical framework for soil moisture dynamics analysis, landslide probability modelling and landslide early warning performance analysis was applied to the modelled and the measured soil moisture time series. This allowed to directly compare the forecast skill of modelling-based with measurements-based landslide early warning.

In this contribution, we will highlight three steps of model applications: First, a straight-forward simulation to all 35 sites without site-specific calibration and using reference soil layering only, to assess the forecast skill as if no prior measurements were available. Second, a model simulation after calibration at each site using the existing soil moisture time series and information on the soil texture to assess the benefit of a thorough calibration process on the forecast skill. Finally, an application of the model to additional sites in Switzerland where no soil moisture measurements are available to assess the effect of increasing the soil moisture information density on the overall forecast skill.

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Global soil water estimates as landslide predictor: the effectiveness of observations, simulations and data assimilation results

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Hydrological triggering of landslides is strongly connected to the water content of the soil. Previous local studies showed that the inclusion of predisposing soil hydrological conditions, such as soil moisture, improved the landslide prediction abilities over using rainfall only as predictor variable. Existing global models that predict landslides however still mostly rely on antecedent rainfall indices as a proxy for soil moisture conditions, because global precipitation data has been more readily available than soil moisture data. Soil moisture data are now available from satellite observations or modeling, or combinations thereof (data assimilation). Our research seeks to quantify to which extent global landslide prediction can benefit from these data products.

To tackle this question, we examined soil hydrological conditions at the times and locations of known landslide occurrences (Global Landslide Catalog, Kirschbaum et al. 2015). More specifically, we investigated soil moisture estimates retrieved from the Soil Moisture Ocean Salinity (SMOS) mission, simulated by the Catchment Land Surface Model (CLSM), or resulting from assimilation of SMOS or Gravity Recovery And Climate Experiment (GRACE) data into CLSM.

A first coarse-scale, univariate global analysis for the years 2011 through mid-2016 indicates that soil moisture and total water storage estimates are adequate alternatives for antecedent rainfall indices to predict landslides. In particular, the assimilation of SMOS or GRACE data into CLSM improves root-zone soil moisture and preferentially increases root-zone soil moisture at landslide events. Whereas both assimilation schemes help to predict landslides based on an increased landslide probability with increased water content, the SMOS or GRACE satellite observations alone (that is, without data assimilation) are too sparse, noisy or coarse to clearly distinguish the different hydrological conditions between landslide and non-landslide events.

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Post-Seismic Shallow Landslide Triggering: Stress States and Hydrology

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Earthquakes are major drivers of landslides. After shaking has passed, landslide activity remains elevated, eventually returning to baseline landslide activity dictated by climactic forcing. While this phenomenon has been observed worldwide, there has been limited quantitative insight towards describing some of the physical drivers behind this occurrence. We describe the role of shear band propagation and permanent changes in the stress state of the soil mantle in post-seismic landslide activity. This this described through a coupled seismic-hydro-mechanical slope failure model, which quantitatively describes the damaged state of the hillslope from shaking. This model enables quantification of the influence of alterations in the stress-states caused by shaking, decreased triggering precipitation, and shear-induced weakening of soil on post-seismic landslide activity. The results provide new insights on the roles of soil depth, hillslope characteristics as well as climate on increased landslide susceptibility and gradual return to baseline conditions.

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Post-earthquake changes in debris flow susceptibility in the Upper Minjiang catchment (Sichuan, China), as revealed by meteorological and hydro-meteorological thresholds

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On May 12, 2008, a Mw 7.9 earthquake struck Wenchuan, Longmen Shan Area, in western Sichuan, China, at the eastern margin of the Tibetan Plateau. This earthquake was the largest and most destructive event in the last 60 years, causing more than 87000 casualties. The economic loss was estimated at some 1100 billion RMB. The major fault rupture produced surface displacements up to 3-4 meters, spreading from the epicenter (near the town of Yingxiu) for 240 km along the mountain range.

The Wenchuan Earthquake triggered almost 200000 co-seismic landslides over a region larger than 110000 km^2, leading to the accumulation of large volumes of loose material either along slopes or in gullies. After the earthquake, this material caused a strong increase of debris flow occurrence in the subsequent years, mainly in the worst-hit areas, such as Wenchuan, Beichuan and Mao counties. During the years immediately after the earthquake, the rainfall required for debris flow triggering resulted clearly smaller than before (Guo et al., 2016). Afterwards, the response of the debris deposits to rainfall changed, leading to a general recovery of stability and a reduction of debris flow frequency and magnitude (Domènech et al., 2019).

In this study, the assessment of debris flows occurrence throughout upper Minjiang catchment, to which Wenchuan county belongs, is modeled with two empirical approaches, both based on the available record of precipitations and debris flows in the years 2008-2015. In the first approach, a threshold to predict debris flow occurrence is defined based on intensity and duration of potentially triggering rainfall events (meteorological threshold). With the second approach, also the hydrological conditions predisposing the slopes to debris flows are considered, by assessing the water balance in the catchment with a simplified lumped hydrological model, based on the Budyko framework (Zhang et al., 2008), and defining a threshold to predict debris flows based on rainfall depth and estimated soil storage prior the onset of rainfall (hydro-meteorological threshold).

The obtained results indicate that the hydro-meteorological threshold allows catching the progressive recovery of stability of the debris deposits much better than the meteorological threshold, leading to identification of increasing thresholds, both in terms of pre-event soil storage and triggering rainfall amount, in the years from 2008 onward. Such a result shows that the adoption of process-based approaches , even empirical and strongly simplified as in the presented case, leads to predictions of debris flow occurrence more robust than those based solely on rainfall information.

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Enhancing the completeness of statistical landslide susceptibility modeling by integration of release and propagation zones

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Statistical landslide susceptibility models have been satisfactorily fulfilling the aim of predicting where future slides might happen, or more specifically, be initiated. By aiming to answer where landslides are likely to be initiated, those models mostly build upon mapped landslide release zones to create spatial predictions. The potential downslope propagation zones are usually neglected. This is a substantial limitation with regard to their applicability in the context of risk assessment in areas characterized by steep slopes. In fact, slide-type movements often evolve into flow-like movements, traveling long distances and thereby impacting also moderate and even nearly flat slopes. At this point, the integration of modeling approaches able to predict downslope landslide routes can contribute to enhance the completeness of the model.

This study aims to explore the added value of combining statistical modeling of landslide release areas with a data-driven runout model for a 54 km² catchment in the Nova Friburgo area in southern Brazil. In January 2011, a severe rainfall event in that mountainous region triggered numerous landslides, some of them evolving into hillslope debris flows affecting downslope areas. The hundreds of slides mapped after this event are here used as reference data.

The methodology consists of three steps: (a) the creation of multiple statistical landslide release susceptibility models; (b) back-analyzing the probability density functions of the angle of reach and travel distance, derived from the observed runout zones with the r.randomwalk model; (c) integration of the best performing release susceptibility model with r.randomwalk, computing the propensity of downslope regions to be affected, based on the release susceptibility and the probability density functions derived in (b).

Despite the appropriateness of purely statistical models for predicting future slide release zones, these models indeed overlook downslope propagations. The combined model, in its turn, not only succeeds in informing where landslides would initiate, but also about their downslope impact areas. The difference between the models is even more evident when analyzing how both models would predict the susceptibility for settled areas. While the release susceptibility model assigns more than 60% of this area to the low and very low susceptibility classes, the combined model predicts that actually less than 30% of this area would be assigned to the same classes. In a region where thousands of people are living, this difference might inform a large number of people and

key infrastructure prone to be landslide affected. This greatly enhances the potential of landslide susceptibility models to be applied for hazard and risk management purposes also in those areas where landslides develop into hillslope debris flows.

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Rainfall induced-landslides and man-made landforms mapping for underground utility networks management in a mediterranean metropolitan area (Genoa, Northwest Italy)

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Extreme precipitation has become increasingly frequent in the last years in Liguria, a hilly and mountainous region in Nortwest Italy. In particular, the Genoa metropolitan area is internationally known for rainfall ground effects: from the beginning of this millennium four intense flash floods have been recorded and as many rainfall-induced landslide periods with significant impacts in roads, buildings and underground utility networks.

These phenomena are also related with more than a century of urbanization that has completely changed landforms and increased the vulnerability of the area.

The research consists of preliminary study based on the production of three different maps: Landslide inventory map, Landslide susceptibility zoning map and a preliminary Man-made landform map that could help to describe better the Urban Geomorphology of Genoa metropolitan area, characterized by isolated and spread houses laying on terraced slopes mixed with high density urban area with aged decametric retaining walls.

On site monitoring, satellite interferometric data and historical maps were used to support the production of cartography work.

In a second step, the above maps were associated with underground utility networks (water and energy) categorized by age, diameter and material to know the potential failure risks induced both by geomorphological and structural factors.

Thanks to this research underground assets management is expected to be more efficient, determining priorities for actions in areas with higher risk.

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Ground effects triggered by the 19-21 October 2019 extreme rainfall in the middle-lower Lemme River catchment (NW Italy)

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From 19 to 21 October 2019 a severe rainfall event occurred in the south eastern part of the Piemonte Region, in particular in the catchments of the Orba and Scrivia Rivers (NW Italy). It originated widespread shallow landslides, soil erosion processes, flood peaks, debris transport along the minor hydrographic network, morphological changes along the main rivers and flooding of lowland areas. All of this caused one casualty and severe damage to transport infrastructure, private homes and agricultural activities. The most critical phase of the event was registered in the afternoon and evening of Monday 21, and it was associated with a thunderstorm cell formed on the Ligurian Sea and then extended northward on the aforementioned catchments, where it remained stationary for some 12 hours. This dynamic resulted into exceptional rainfalls in terms of both cumulated values and intensity.

The rainfall-induced geomorphic effects were particularly severe within the Stura, Piota, Albedosa and Lemme Valleys, namely all the main right-bank tributaries of the Orba River. This contribute aims at documenting the rainfall magnitude and presenting the preliminary results concerning the analysis and mapping of landforms and geomorphic processes related to this rainfall event, within the middle and lower Lemme River catchment. The research is based on field survey and interpretation of aerial photographs taken along the main valley floor.

Considering the entire Lemme River catchment (180 km^2), all rainfall-induced ground effects were substantially surveyed in its middle and lower parts, which present a mountain-hilly landscape and large fluvial terraces, respectively. Within the study area, with reference to the Gavi Ligure rain gauge, a cumulative rainfall of 428 mm in 12 h was registered, along with maximum values of rainfall intensity of 76.4 mm in 1 h, 205.8 mm in 3 h, 318.4 mm in 6 h. The cumulative rainfall measured during the 19-21 October 2019 event was 548,6 mm, that is approximatively half of the mean annual rainfall.

As a result, wide lowland areas were flooded by both the main channels and the minor hydrographic network. Wide plots of land on slopes were affected by sheet erosion and rills development. Numerous and widespread landslides were mapped both on slopes and on terrace scarps. Generally, they were shallow and involved eluvial-colluvial and anthropically reworked deposits directly overlying the bedrock. These landslides often evolved into debris-avalanches or debris-flows. A relevant sediment input affected the minor channels and newly-formed in-channel deposits and alluvial fans were observed along them. The main fluvial stems experienced severe riverbed widening and intense sediment mobilization. These ground effects involved facilities, infrastructures and cultivated areas causing widespread and severe damage.

The findings of this study are useful: i) to document another relevant case in this area of Piemonte Region that has been often affected by serious geo-hydrological events; ii) to implement future researches on landslides, surface erosion processes and flood-related fluvial dynamics; iii) to provide relevant information for land management under a geo-hydrological risks mitigation perspective.

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Monsoon-driven landslide dynamics in Nepal – the complex mass movement system in the Muktinath Valley

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The Nepalese Himalaya is affected by a major rift valley, the Thakkhola half graben (THG). Along this fault-bounded basin, the Kali Gandaki (KG) flows from the Tibetan plateau southwards to the Dhaulagiri and Annapurna massifs, where it forms the deepest gorge on earth. The THG has been filled with up to 1 km thick Plio- and Pleistocene sediments, underlain by clay shales of the Jurassic Spiti Formation that are strongly water swellable and prone to landslides. These pre-conditions led to a series of large and complex landslides, particularly along the eastern flank of the THG, with strong effects on infrastructure and the local population. One of these landslide systems (c. 15 km²) is located in the semi-arid Muktinath Valley, a tributary basin of the KG (c. 92.5 km²). Water as most important driver of the system is provided by precipitation mainly during the summer monsoon (annual rainfall: ~ 350 mm), snowmelt and irrigation.

Against this background, we aim i) to better understand regional-scale landslide systems (spatial pattern, drivers/controls), ii) to establish a long-term monitoring of local-scale landsliding in the Muktinath Valley, and iii) to share our findings with local communities to support the development of mitigation strategies.

Reconstruction of landslide dynamics over the past 30 years is based on local information (interviews), field observations (damaged buildings and walls), geomorphological mapping and multi-temporal (ortho-) photo analyses (WorldView, Pleiades). Since 2018, annual UAV surveying is applied.

Results include a geomorphological map of the area focusing on landslide related processes and landforms, indicators of recent landslide activity, hydrologic characteristics and irrigation infrastructure, as well as the distribution of Spiti shale outcrops. Surrounding the presently most active landslide, we observed an average displacement of c. 20 cm/a since 1988 with an increasing trend towards present (30 - 50 cm/a since 2011). In the center of the most active landslide significantly higher displacements of up to 15 m have been detected since 2011, which corresponds to an average of about 2 m/a. The landslide monitoring based on UAV surveying, structure-from-motion processing and different approaches of high-resolution topographic

change and error modelling (DEM resolution: 2.6 - 4.3 cm) shows massive change between April 2018 and March 2019 (gain: 33395 ± 5489 m^3; loss: 50276 ± 10781 m^3), accompanied by a total sediment export of 16881 ± 12098 m^3 to the Jhong River. Detailed orthophotos (resolution: 1.29 - 2.15 cm) provide valuable supplementary information not only on recent landslide propagation and dynamics but also with regard to future threatened areas (opening cracks). Boosted landslide activity in 2018 is associated to the strong monsoon that heavily impacted in the larger region as well (debris flows, flash floods, multiple bank collapses): In August 2018 Muktinath recorded the highest monthly rainfall since 1978 (172 mm, DHM Nepal).

The research is located at the interface between humans and the environment. The "symbiosis" of the local population and the landslide system is unique - and enables to deconstruct various interacting landslide processes driven and modified by climate (change) and human impact.

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Influence of infiltration on Babaoliao shallow landslide in Taiwan using hydro-mechanical coupled model

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Babaoliao landslide is located in Chiayi County of Taiwan. The geological drilling and core interpretation in previous investigation showed that exist 1 to 2 meter depths of residual soil layer above the bedrock. In this area, shallow landslides frequently occur due to the intense rainfall events. An understanding of the hydro-mechanical change under rainfall infiltration within hillslope is critical to capture the slope stability. This study used hydro-mechanical coupled model and finite element analysis to compute the field water content and stress suction, and then assess the field slope stability based on theory of local of factor. Results showed the response of internal hydraulic behavior distribution is related to terrain and the depths of bedrock. The impact of rainfall on slope stability concentrated in shallow residual soil area, since higher permeability of soil cause rainfall infiltrate into hillslope easily and form lateral flow paths, thus limiting the depths of wetting front. The discontinuity of water content distribution within hillslope may accelerate the change of hydro-mechanical behavior and unstable slope development in the hillslope. This study demonstrated the varied distribution of water content, suction stress and LFS over time and space and got the insight into the relativity unstable range of the shallow slope affected by rainfall event.

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Observation on change of physico-chemical properties of crystalline rocks caused by freezing-thawing experiment

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Groundwater and surface water may be contaminated by a range of soluble chemical compounds in regions where rocks are weathered by freeze–thaw cycles. To reduce this type of pollution, which is particularly common in mining areas, the effects of freeze–thaw weathering need to be investigated to help determine how the rock is weathered and what chemical compounds result from the weathering. The physical conditions of a rock's surface generally change during freeze–thaw cycles, and voids on weathered surfaces tend to increase in number because of chemical dissolution of the minerals in the rock.

In this study, freeze–thaw experiments were performed using rock samples taken from near a mine. The physical changes in equally sized rock samples were observed during the experiment. To understand how chemical compounds were released during freeze–thaw cycles, powdered rock samples were added to distilled water and the chemical characteristics of the distilled water were determined. Information on physical changes in rocks can be used to understand how weathering affects the stability of cut slopes or tunnels, while the data from chemical analysis provide insights into the release of chemical species that can affect the surrounding natural environment.

We used physical and chemical (e.g. inductively coupled plasma–mass spectrometry) analysis methods to observe how the physical properties of the rocks and the chemical forms in a solution changed during a freeze–thaw experiment. The results show that the porosity and the dry density of the rock samples changed slightly during the experiment. The electrical conductivity and concentrations of chemical forms varied as the freeze–thaw cycle progressed. This study shows that weathering can be enhanced during freeze–thaw cycles and that groundwater is easily contaminated by the dissolved chemicals produced during this weathering.

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Slope stability study of the 2001 Taipei National University of the Arts landslide

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Situated within a subtropical and mountainous region where frequent typhoons hit, rainfall-induced landslides have been a critical issue in Taiwan. On September 29, 2001, due to the torrential rainfall brought by the Typhoon Nari and Lekima, a downslope in Taipei National University of the Arts failed. The sliding source hit and severely damaged the Tao-Yuan junior high school. Before the 2001 Taipei National University of the Arts landslide, several landslides had already occurred in this landslide-prone region. In this study, a two-dimensional (2D) slope stability analysis, based on the limit equilibrium analysis (LEA), is conducted to analyze the 2001 Taipei National University of the Arts landslide. LEA has been the most popular and widely used technique given that it can estimate the factor of safety of a slope with some preliminary site investigation information. By comparing the failure surface and factor of safety (FOS) suggested in the post-disaster report [1], reasonable soil parameters, which are in an agreement with the experimental results [1], can be obtained through the study. The obtained soil parameters can later be applied to coupled transient unsaturated seepage-stress finite element analysis (FEA) [2] that will help practical engineers to understand the onset of failure in the future study.

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Composite nature of Eco-Hydro-Geological (EHG) stability of slopes

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Nature always educates us to explore more scientific meaning of surrounding stability of the earth. Rain triggered landslides are common in many terrains and cost for such remediation is usually high in drainage improvement. In many instances, ground water recharge, stagnation of water within soil, rock-soil interface saturations, influence of artesian water pressures, subsurface saturation due to geological complexity and many more hydro-geological regiments are responsible for landslides. However, water is the major component of ecological stability of mountain slopes which contains soil, rock, water, flora & fauna. It deals with all natural and man-made stresses from the grass root level until long term stability of the slope or slope failure event. Some large natural reservations developed as control measures against slope erosion are commonly visible in hill country slope management in Sri Lanka, dating back to year 1800. The hill country area is generally subjected to very heavy rainfall of 4000mm to 6000mm annually. The objective of this paper is to report on the progress of development techniques and studies of natural slope instabilities in saturated and unsaturated soils in order to improve our understanding of such phenomena within multiphase environments. Observations are naturally site specific. The study is to assess the impact of deviation of first principal of ecological stability during slope stability designs, understanding capacity of draining water pathways within heterogeneous regolith soils under vegetative complexity and predicting the hydrological exchange between a potentially unstable slopes and its surroundings. An approach of site specific investigations, incorporation of principal mechanism of eco-hydro-geological(EHG) techniques and isolation methods for stability will be discussed.

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Towards a probabilistic assessment of sediment yields in a mountainous area: the case study of Valle Camonica

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Sediment production and delivery are hillslope processes characterized by significant variability and uncertainty, especially in mountain drainage catchments. Although sediments can be originated from several phenomena, such as slope instabilities, soil erosion and streambank failures, rainfall-induced landsliding, eventually turned into debris flows, is the dominant mechanism producing and conveying huge volumes of solid material to downstream areas through the channel network and therefore causing an increase of flood frequency.

Such landslide-derived mechanisms cause damage, directly and indirectly, to public and/or private properties and infrastructure on alluvial fans that are basically due to the increase of clogging probability of bridges, instream sediment accumulation, and significant geomorphological change. Identifying the sediment upstream source areas and quantifying a probability distribution of the mobilized- and delivered-sediment volume, then, is crucial for the protection of downstream areas. However, such purpose still remain extremely challenging because of scarcity, or even lack, of time-consuming direct measurements that are generally carried out at small scale and cover short time periods.

On this background, this work proposes a simplified procedure to estimate a probability distribution of the sediment yields combining: (i) rainfall intensity-duration-frequency (IDF) relationships for estimating synthetic precipitation with specific return time; (ii) a three-dimensional slope stability model to assess the rainfall-induced shallow landslides susceptibility; (iii) a connectivity index for mapping the probability of sediment delivery; and (iv) a simple hydrological model based on SCS-CN method to estimate the flood peak, and furthermore the probability distribution of sediment flux. The procedure requests low-resolution maps, usually available at the regional scale, such as digital elevation model, land cover, geology, lithology, and IDF curves, and represents a planning tool for climate and land cover change mitigation that can be extremely useful for forest managers, hydraulic engineering and watershed planners.

The procedure was tested on several small mountainous headwater catchments in Valle Camonica, located into the Central Italian Prealps, mostly covered by forests, with settlements on alluvial fans, and prone to shallow landslide, debris flood, and debris flow. It was qualitatively validated on the landslide inventory and the mapped flood areas, showing comparable results.

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Estimating additional root cohesion by exploiting a root topological model based on Leonardo's Rule

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Root topological models are schematic representations of the root structure based on a defined topology graph theory. In the context of hillslope stabilization modeling against rainfall-induced shallow landslides, the root topological models may be used in combination with root strength models assessment, such as the Root Bundle Model (RBM), to estimate the ultimate root reinforcement. The effect of plant roots on slope stabilization is determined by the interaction between soil and the hydrological processes (within the root zone) and the biotechnical characteristics of the root system, such as root length, root density, root tensile strength, root area, root diameter profile and the total number of roots. Describing adequately the root architecture of a plant species is useful, for example, to evaluate how the root structure may change in different soil and/or climatological conditions and, ultimately, as an example, to assess the most suitable plant species to be adopted.
This study exploits the potentiality of a root topological model based on Leonardo's rule in describing root architectures of (i) different species (and tree individual) at given growth conditions, (ii) same species at different environmental conditions, e.g., exposure to light, water and nutrient availability. The former is supported by field campaign measurements from Tuscany region, the latter are reproduced starting from a reference case and imposing growth assumptions. Next, the information of the root system, in terms of root length, density, root diameter profile, total number of roots, are used to estimate, through a RBM approach, the additional root tensile force, deriving it from the force-deformation theory of linear elasticity in a rigorous framework aimed to derive the additional shear resistance from the Mohr-Coulomb's failure plane.
The preliminary results demonstrated the capability of the root topological model of reproducing different types of root system; additional data are required to further validate the model, with regard to the growth conditions simulation. Similarly, laboratory test of root strength would allow to quantify the improvement derived from the rigorous method adopted to estimate the additional root strength.

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Shallow landslides along the pyroclastic-mantled slopes of mount Partenio (Campania, Italy): the events of 16.12.1999 and 21.12.2019

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As other mountainous areas of Campania (Italy), mount Partenio consists of carbonate rocks covered with layered air-fall deposits originated by eruptions of the two volcanic complexes of the area (Somma Vesuvius and Phlegrean Fields). The deposits are alternated layers of ashes (loamy sands) and pumices (sands with gravel), both materials characterized by negligible effective cohesion. The thickness of the deposit ranges between few centimeters along the steepest slopes (up to 50°) to some meters at the foot of the slopes, with gentle inclination. The equilibrium of the covers along the steepest slopes is guaranteed by the contribution of suction to soil shear strength. After intense and prolonged rain, this contribution is reduced by infiltrating water being stored within the cover, sometimes leading to shallow landslide triggering.

The two most recent landslide events in the area occurred on 16.12.1999 and 21.12.2019. In the first case, several landslides were triggered along slopes with inclination larger than 40°, in an area of about 10 km^2, some of which evolved in the form of fast debris flows which caused damages to buildings and some victims in the town of Cervinara. In the second case, two major landslides were reported, one of which, along a slope with inclination between 42° and 45°, very close to two of the landslides of 1999, damaged roads and buildings in the town of San Martino Valle Caudina.

After the event of 1999, a hydro-meteorological monitoring station was installed near the scarp of the major landslide. Thanks to the monitoring data and laboratory investigation on the hydraulic properties of the involved soils, a mathematical model of the response of the slope to precipitation was developed (Greco et al., 2013). The model couples unsaturated flows in the pyroclastic cover with the groundwater system developing in the underlying fractured limestone bedrock, and it allows satisfactorily reproducing the seasonal trends of the terms of the hydrological balance of the slope (Greco et al., 2018).

In this study, the two events of 1999 and 2019 are compared, in terms of pre-event and event rainfall characteristics, as well as by simulating the response of the slopes by means of the mathematical model during the entire year until the day of the landslides. The obtained results show the importance of the interplay between predisposing conditions, related to the rainfall history during the months before the event, and the characteristics of the triggering event. The model simulations indicate that, while in 1999 failure conditions are predicted along slopes with inclination larger than 40°, regardless cover thickness, in 2019 landslide triggering is predicted only on slopes mantled by a cover thinner than 1.5 meters with inclination larger than 42°.

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Time-lapse CSAMT measurements to record the hydrological response of the Lodève landslide to heavy meteorological events

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The Lodève landslide is a slow moving (3 to 4 mm/yr) and deep (60 m) rotational instability, located in the South-East of France, 60 km North from Montpellier (Hérault department). It is located in the Lodève basin, a set of connected steep head valleys marking the southern limit of the karstic Larzac plateau, and particularly prone to hydraulically triggered landslides. The unstable slope was progressively formed by the erosion of the upper limestone and sandstone units. The local tectonics build up resulted in a series of vertical North/South faults and fissures, allowing the water to infiltrate down to the deeper Triassic clay and evaporite layers. During heavy rainfall events, an amount of the meteoritic water infiltrates along these flow paths, down to the clay and evaporite layers from the Norian and Rhaetian era, leading to the rapid recharge of the units, the onset of high pressure in the confined layers and the decrease of the cohesion of the rock material and of the shear strength.

The Controlled Source Audio-frequency Magneto-Telluric (CSAMT) method is a low-impact, non-invasive active frequency domain electromagnetic sounding technique, deriving from the Magneto-Telluric (MT) method. An electromagnetic signal is produced a few km away from the studied site, and the electric and magnetic transfer functions of the plane wave signal are recorded at multiple frequencies, permitting the computation of far-field MT impedance tensor. CSAMT is characterized by a good vertical resolution and large depths of investigation, but poor sensitivity to the first tens of meters. For these reason, it is expected to be a good candidate method to conduct time-lapse studies in the context of pseudo-1D layered subsurface.

CSAMT data were acquired at the landslide from November 2018 to March 2019 at 8 different stations. The landslide is assumed to be a pseudo-1D medium with a tilted flat surface topography. The aim was to observe the variations of electrical resistivity related to the hydrogeological response to the heavy rains observed during the monitoring period. Sensitivity tests were realized with the software custEM. Measurements were taken at ten fundamental

frequencies ranged from 510 to 9600 Hz with a Phoenix's System-2000.net equipment and were repeated every months except in February.

The data quality is uneven from one station to another next. Most station showed significant variations in apparent resistivity. The observed variations were interpreted in a one-dimensional context, revealing lateral variations in the hydrogeological response of the slide. Complementary TDIP and DC data and high temporal geochemical and geophysical monitoring of properties at two boreholes were used to constraint the CSAMT interpretation.

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Hydrological effect of vegetation against landslides

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The hydrological effect of vegetation against landslides has rarely been quantified and its integration into slope stability methods remains a challenge. To adequately address this knowledge gap, the effect of vegetation against landslides should be assessed under both wet (i.e. with precipitation) and dry (i.e. without precipitation) conditions. Furthermore, the establishment of novel frameworks that integrate hydrological processes occurring at the plant-soil-atmosphere interface is paramount. This goals of this presentation are (i) to critically evaluate the hydrological effect of vegetation against landslides by showcasing novel results from field and modelling experiments, and (ii) to highlight relevant plant traits regulating the hydrological cycle at the plant-soil-atmosphere interface in a context of landslide occurence.