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Slope instability following extreme precipitation events: analysis of predisposing factors in two study cases in Central Apennine, Italy

Abstract: Aringoli D., Gentilucci M., Pambianchi G., *Slope instability following extreme precipitation events: analysis of predisposing factors in two study cases in Central Apennine, Italy.* (IT ISSN 0391-9838, 2024). All over the world extreme precipitation events are generating increasingly significant problems in terms of slope stability. Central Italy, similarly, has shown in recent years an increase in the intensity and frequency of rainfall phenomena that can cause hydrogeological instability. The aim of this study is to propose a new methodology to assess landslide triggering thresholds in light of predisposing factors analysed using satellite indices. The procedure is mainly based on the evaluation of extreme rainfall events that occurred in the years following the extreme event under investigation, trying to find the connection between the slope dynamics and the geomorphological setting investigated in detail. At the same time, soil moisture and vegetation conditions in the area before, during and after each extreme event are also assessed using the NASA products, Landsat 7 and Landsat 8. The research focuses on an extreme precipitation event that occurred in a small area of central Italy in November 2013, which triggered some landslides. The evaluation of satellite indices of vegetation and moisture (NDVI and NDMI) and the analysis of geological and geomorphological context, allows to define landslide hazard. The results of the study made it possible to identify the daily precipitation between 150 and 200 mm as triggering threshold for two landslides in the investigated areas under low vegetation conditions. The geomorphological analysis showed that these landslides involved debris accumulated in specific slope and bedrock conditions. The type of landslides most susceptible to reactivations ruled by high-magnitude meteorological events in predisposed hydrogeological contexts have also been highlighted. However, the two studied landslides have a different genesis linked to different debris grain size, which induced, in one case, an earth flow, while in the second case produced a debris flow.

Key words: Landslides, Geomorphological hazard, Precipitation, Satellite imagery, NDVI, NDMI.

Riassunto: Aringoli D., Gentilucci M., Pambianchi G., *Instabilità dei versanti a seguito di eventi piovosi estremi: analisi dei fattori predisponenti in due casi di studio nell'Appennino centrale, Italia.* (IT ISSN 0391-9838, 2024). In tutto il mondo gli eventi di precipitazioni estreme stanno generando problemi sempre più rilevanti in termini di stabilità dei versanti. L'Italia centrale, analogamente, ha mostrato negli ultimi anni un aumento dell'intensità e della frequenza dei fenomeni pluviometrici che possono causare dissesti idrogeologici. L'obiettivo di questo studio è quello di proporre una nuova metodologia per la valutazione delle soglie di innesco delle frane alla luce dei fattori predisponenti analizzati mediante indici satellitari. La procedura si basa principalmente sulla valutazione degli eventi pluviometrici estremi che si sono verificati negli anni successivi all'evento estremo in esame, al fine di trovare la connessione tra la dinamica del versante e il contesto geomorfologico indagato in dettaglio. Allo stesso tempo, vengono valutate anche le condizioni dell'umidità del suolo e della vegetazione nell'area prima, durante e dopo ogni evento estremo, utilizzando immagini NASA Landsat 7 e Landsat 8. La ricerca si concentra su un evento estremo di precipitazione verificatosi in una piccola area dell'Italia centrale nel novembre 2013, che ha innescato alcuni fenomeni franosi. Attraverso la valutazione di alcuni indici satellitari di vegetazione e umidità (NDVI e NDMI) e l'analisi delle caratteristiche geologiche e geomorfologiche dell'area studiata, è possibile definire la pericolosità da frana. I risultati dello studio hanno permesso di identificare la precipitazione giornaliera tra 150 e 200 mm come soglia di innesco per due frane nelle aree indagate in condizioni di bassa vegetazione. L'analisi geomorfologica ha mostrato che queste frane hanno coinvolto detriti accumulati in particolari condizioni di pendenza e di substrato. È stata inoltre evidenziata la tipologia di frane più suscettibili a riattivazioni governate da eventi meteorologici di elevata magnitudo in contesti idrogeologici predisposti. Sono stati rilevati due fenomeni franosi caratterizzati da una genesi diversa, legata alla diversa granulometria dei materiali coinvolti, che in un caso sviluppano una colata di terra, nell'altro una colata detritica.

Termini chiave: Fenomeni franosi, Pericolosità geomorfologica, Precipitazioni, Immagini satellitari, NDVI, NDMI.

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INTRODUCTION

Hydrogeological instability is a set of land degradation processes that have destructive effects on soil, buildings and, in the most serious cases, human lives. This issue is becoming increasingly important as it represents a major loss of economic resources due to poor prevention. The entire planet has been experiencing an increase in hydrogeological instability in recent years (Ellena *et al.*, 2020) and Italy is among the most affected and susceptible countries. In fact, the 2018 report on hydrogeological instability in Italy showed that 91% of total municipalities are at risk of landslides or floods, with 16% of the Italian territory considered to be at greater risk. In particular, in Italy there are 620,880 landslides, occupying 23,700 km^2, equal to 7.9% of the national territory (Trigila *et al.*, 2021). The increase in hydrogeological instability is mainly linked to extreme precipitation and temperature events that can lead to flooding, landslides and avalanches. A significant increase in extreme precipitation events has been observed worldwide and also in the area covered by this research (Donat *et al.*, 2016; Gentilucci *et al.*, 2019; Wang and Zhou, 2005). In particular, in the study area, two municipalities close to the Sibillini Mountains in the Marche region (central Italy), the extreme indices show an increase in term of number of continuous dry days (CDD), the continuous wet days (CWD) and rainfall above the 99th percentile (R99) over the last 60 years has been verified (Gentilucci *et al.*, 2020). Climate change can manifest itself in many ways, either through climatic extremes as observed in the study area, or through a constant change in climatic parameters that favour drier (Gao and Giorgi, 2008; Huo *et al.*, 2013) or wetter conditions (Shi *et al.*, 2007). In particular, it has been shown that climate change, even on monthly or seasonal level, can have a negative impact on slope stability (Stoffel *et al.*, 2014). Considering the context of slope stability assessment, climate change is responsible for two processes, one direct and related to the extreme precipitation event or drought event preceding the rainfall event, and one indirect caused by the influence it has on vegetation. There are many studies highlighting the relationships between climate change and changes in vegetation (Hopkins and Del Prado, 2007; Lindner *et al.*, 2010). Moreover, Schwarz *et al.* (20210) highlight the influence of vegetation on landslides, along with many other parameters including slope, soil type and root systems (Schwarz *et al.*, 2010). The influence of vegetation plays a relevant role in the case of debris flows (Wang *et al.*, 2017), which are also the most easily activated by extreme precipitation events (Turkington *et al.*, 2016). The most effective way to assess the vegetation cover of an area is to use satellite imagery, calculating some dedicated satellite indices for this purpose (Fensholt and Sandholt, 2005; Berner *et al.*, 2011). Vegetation health is often assessed through other indices such as the NDMI, which measures possible water stress of vegetation (Schultz *et al.*, 2016), which can cause vegetation thinning due to drier climatic conditions (Lucas *et al.*, 2020). In addition to vegetation, land use and its changes are another factor in slope instability. Unexpectedly, land use can confuse and make useless the signals shown by satellite vegetation indices, e.g. due to seasonal anthropogenic changes, as in the case of agricultural areas (Tasser *et al.*, 2003; Persichillo *et al.*, 2017). At the same time, when assessing the stability of an area, the most important characteristics, which are undoubtedly geological (e.g. bedrock lithology) and geomorphological (slope inclination, runoff and river dynamics, etc.), cannot be neglected (Avanzi *et al.*, 2004). Therefore, it follows that all these features should be combined to assess the stability of an area. In some studies, these critical features are combined, often using GIS software (Dai and Lee, 2002), in order to obtain a model that can estimate the landslide susceptibility, through the use of various methods such as: Weight of Evidence (Gentilucci *et al.*, 2021; Antonetti *et al.*, 2022), Frequency Ratio (Aghdam *et al.*, 2017), Evidence Belief Function (Li and Wang, 2019), etc. Susceptibility maps certainly give important indications on slope stability, but knowledge of the triggering thresholds of landslide events would favour the possibility of more targeted and precise interventions. There are several studies that have investigated trigger thresholds due to extreme precipitation events (Verdonen *et al.*, 2020; Giannecchini *et al.*, 2012), however, the aim of this study is to use the analysis of indices extracted from satellite data to identify trigger thresholds. It would be interesting to assess how vegetation and soil moisture as measured by satellite maps can contribute as preparatory factors to landslides in case of extreme precipitation events. Obviously, in addition to this, an analysis of the geological-geomorphological features is also necessary to predispose for any slope movements (Aringoli *et al.*, 2010, 2021). This could lead to the definition of rainfall ranges and vegetation and moisture values that could constitute an alarm for slope stability in the future. In addition, this methodology could be extended to a wider area to create a statistical model.

MATERIALS AND METHODS

Geographical and climatological framework of the area

To support the above described analyses, two study areas were identified in which landslide phenomena were triggered by extreme weather conditions in November 2013. The study sites are located close to the Sibillini Mountains, in the Apennine area of Central Italy (figs 1 and 2). The altitude of the two sites is very similar, in fact they are both located at an altitude of 800 m. The first is placed in Varluscio, in the municipality of Ussita, and the other in Torricchio, in the municipality of Pieve Torina, both in the province of Macerata (figs 1 and 2).

The study area, according the Köppen-Geiger classification, is characterized by a Cfc climate (Subpolar oceanic climate) with the coldest month with temperature above -3°C and abundant rainfall well distribute over all

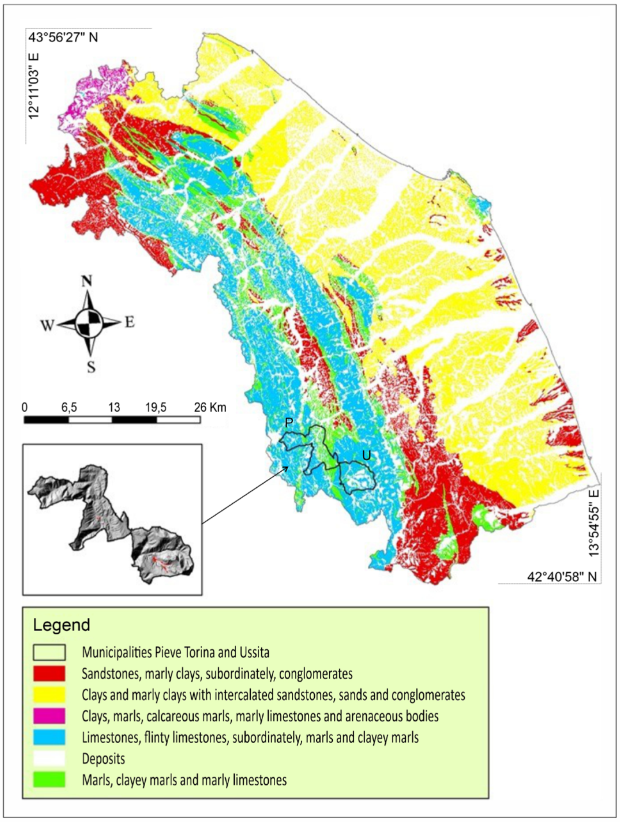

Figure 1 - Map of lithologies of Marche region (Italy) with boundaries of the municipalities of Ussita (U) and Pieve Torina (P).

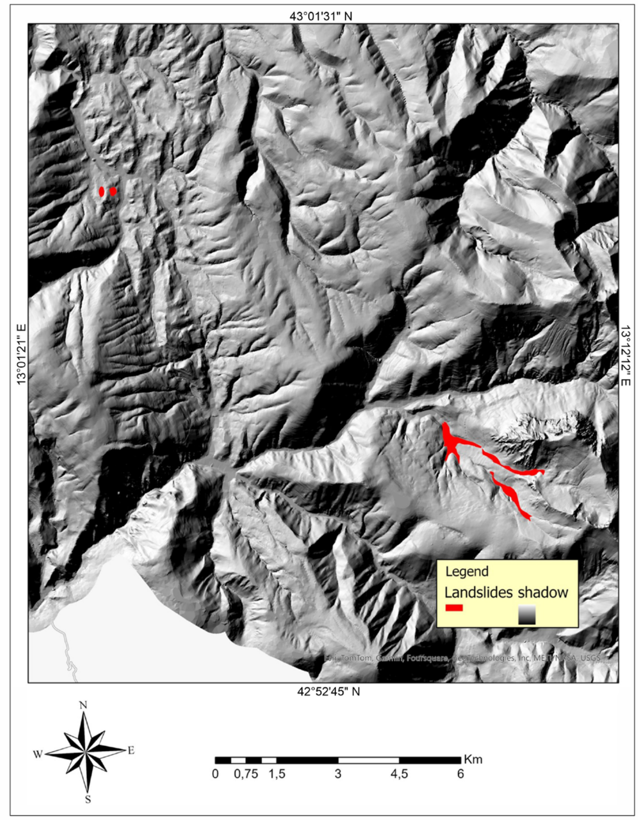

Figure 2 - Hillshade map of the SW portion of the Macerata province in the Marche region, in red the landslides under investigation.

months. In the surroundings areas moving westwards, altitude climate (H) is recorded, while moving eastwards, it becomes gradually closer to the Mediterranean climate (Csa).

Geological and geomorphological features of the study area

The study area is part of the Umbria-Marche Apennines and is made up of two anticlinal ridges that merge to the south into the Sibillini Mountains. Here, intense slope processes are active not only because of the high relief energy but also because of the seismicity of the area (Aringoli *et al*., 2010 and 2021). The complete geology of this region is characterised by the Umbro-Marchean Succession already known in literature (Centamore and Deiana, 1986; Pierantoni *et al*., 2013), with prevalently limestone formations at the bottom (Calcare Massiccio, Corniola, Rosso Ammonitico, Calcari a Posidonia, Calcari Diasprini and Maiolica), limestone and marly-limestone formations above (Marne a Fucoidi, Scaglia Bianca, Scaglia Rossa, Scaglia Variegata), followed by marls (Scaglia Cinerea, Bisciaro, Schlier, Marne con Cerrogna e Marne a Pteropodi), and then by arenaceous pelitic turbidites (Laga Formation) and pelitic arenaceous formations (sedimentary sequence of the peri-adriatic basin).

More in detail, as depicted in the figs 3 and 4, the two examined areas differ in terms of outcropping lithology. In the first case (VU, Varluscio-Ussita area) we have a predominance of calcareous formations, ranging from the Calcare Massiccio to the Maiolica formations, while in the second case (TP, Torricchio-Pievetorina area) marly lithologies dominate, ranging from the Scaglia Cinerea to the Marne con Cerrogna. In both cases, the lithologies are arranged according to a generic east-verging folding structure, with the difference that the first area (VU) is located in the axial part of a large anticline, while the second area (TP) falls on the eastern slope of another gentler anticline. Both the anticlines belong to the complex folds and overthrusts that characterise this section of the Apennine chain (Sibillini Mountains).

As a consequence of the lithostructural arrangement summarised above, the relief in the two areas appears different, as well as the geomorphological processes. In the first case (VU area, fig. 5) the landscape is more rugged and the relief is highly significant, with gradients over 1000 m. In the second case (TP area, fig. 6), the landscape has lower gradients (relief less than 300 m) although there is no lack of steep slopes. The valleys where the landslides were triggered have a NNW-SSE direction in both cases.

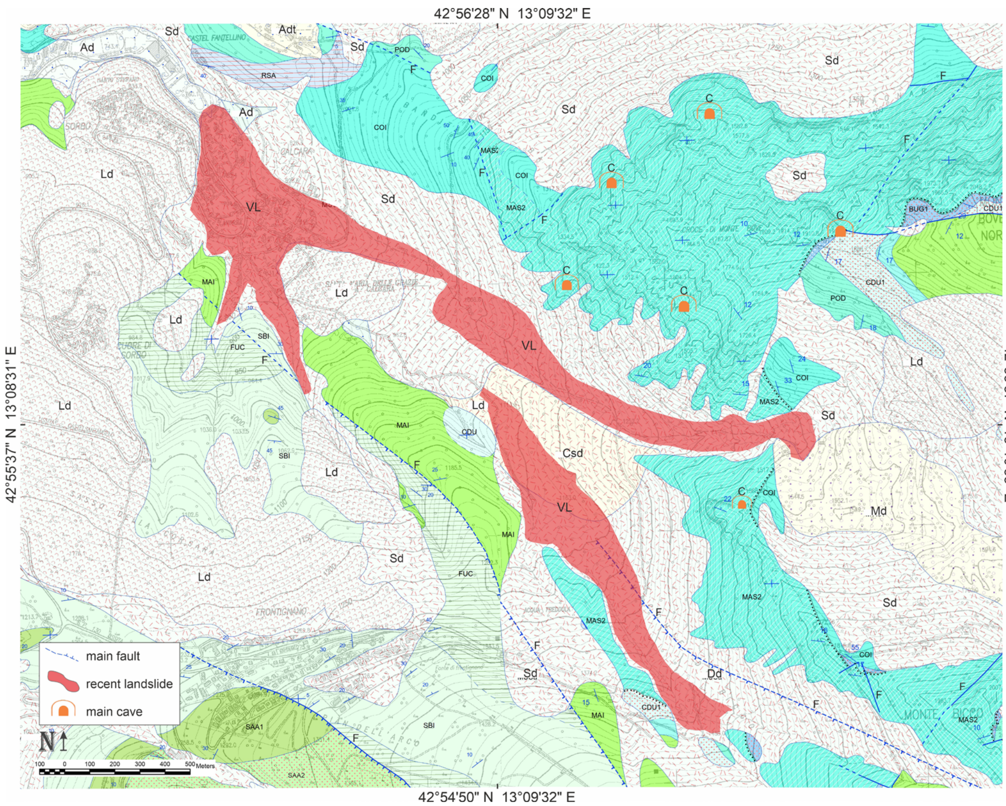

Figure 3 - Geological map of the Varluscio Landslide (VL): Cd-Colluvial deposits, Ad- Alluvial deposit, Adt-terraced alluvial deposit, Md-Moraine, Sd-Slope debris, Csd-cemented slope debris, Ld-Landslide, C-cave, SAA1-2-Scaglia rosata, SBI-Scaglia bianca, FUC-Marne a Fucoidi, MAI-Maiolica, CDU-1-Calcari diasprini, POD-Calcari e Marne a Posidonia, RSA-Rosso ammonitico, COI-Corniola, BUG1-Calcari nodulari del Bugarone, MAS2-Calcare Massiccio. The blue number indicates the dip angle, the blue dashed lines are the main faults (F); (base map from the open data of the Marche Region geological database, https://www.regione.marche.it/Regione-Utile/Paesaggio-Territorio-Urbanistica/Cartografia/Repertorio/Cartageologicaregionale10000, modified).

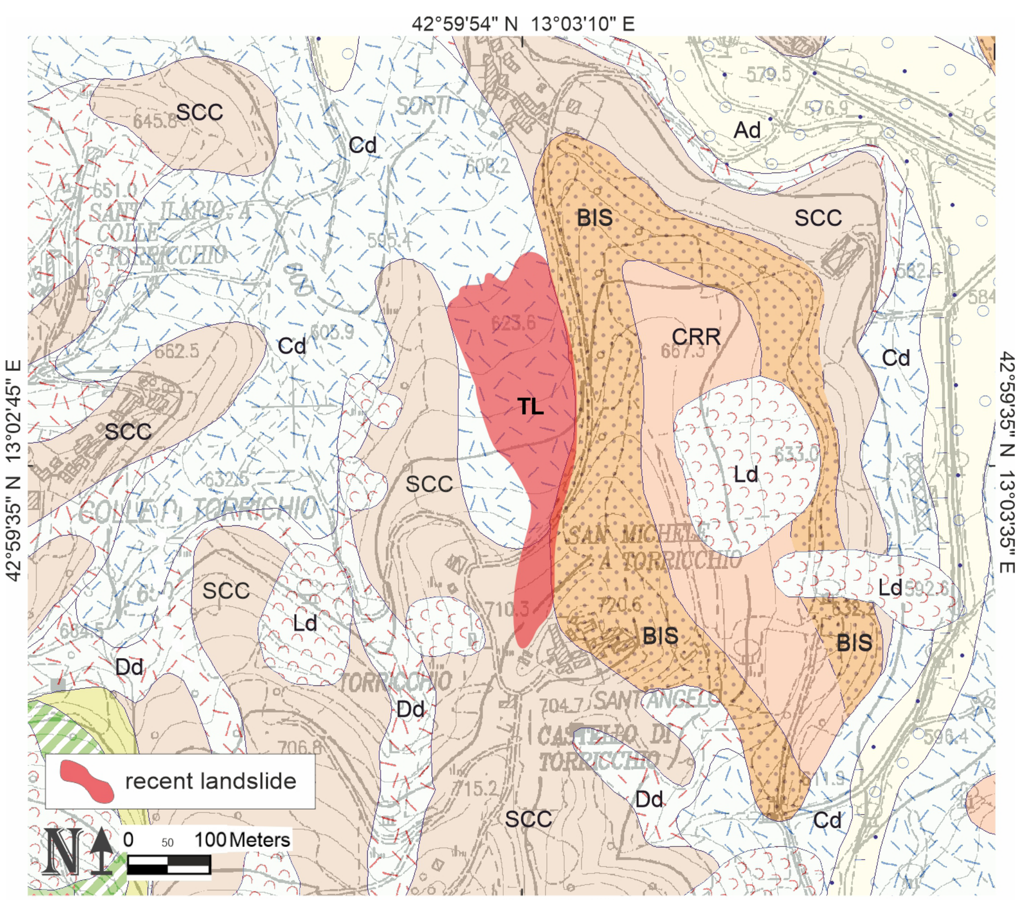

Figure 4 - Geological map of the Torricchio Landslide (TL): Cd-Colluvial deposits, Ad-Alluvial deposit, Dd-Debris deposit, CRR-Marne con Cerrogna (marls), BIS-Bisciaro (marls and marly limestones), SCC-Scaglia cinerea (marly limestones and marls, with intercalations of argillites); (base map from the open data of the Marche Region geological database, https://www.regione.marche.it/Regione-Utile/Paesaggio-Territorio-Urbanistica/Cartografia/Repertorio/Cartageologicaregionale10000, modified).

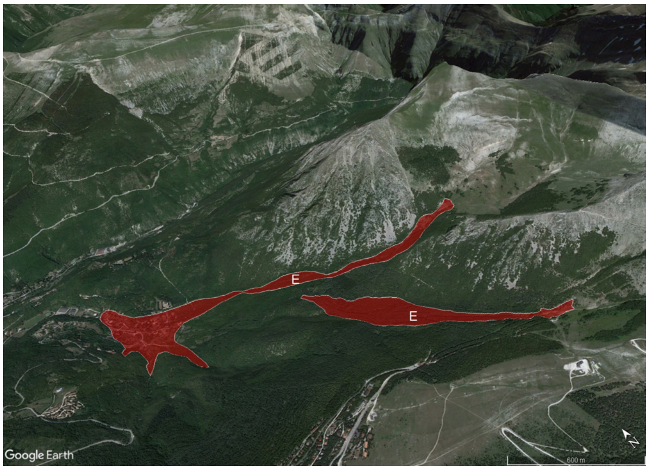

Figure 5 - 3D view of the sketch map of the last Varluscio Landslide Event (in red) (Google Earth aerial view).

Figure 6 - 3D view of the sketch map of the last Torricchio Landslide Event (in red) (Google Earth aerial view).

In the VU area, the degradation of limestones is very deep and rocky scarps evolve in many cases by falls/toppling phenomena. Other significant types of landslides are sliding phenomena, especially rotational ones, and, very important, debris flows originated from the massive debris accumulations. In fact, the latter deposits are often involved in remobilisation phenomena (debris flows), as occurs during extreme weather events (Aringoli, 2024). Furthermore, a particular mechanism that also occurs during these mass transport phenomena in very permeable terrains, is the occurrence of siphoning phenomena, whereby real 'torrents of water' are formed underground, move in depth and re-emerge with high pressures covering considerable distances (fig. 7). Moreover, a detail not to be overlooked is also the progressive abandonment of cultivated lands and especially of the related drainage/stabilisation works observed along the main valley floor (fig. 8).

Detecting methodology

An extreme precipitation event can be defined as: "rare weather event at a particular place and time of year with unusual characteristics in terms of magnitude, location, timing, or extent" (WMO). The extreme rainfall event that occurred from 10 to 13 November 2013 showed very significant amounts of precipitation on a regional scale, with the highest values recorded in the Macerata area and reaching up to 499 mm at the Pintura di Bolognola rain gauge and 490 mm at the Fiastra rain gauge (fig. 9) (Regional Civil Protection Event Report 10-13 November 2013 https://www.regione.marche.it/Portals/0/Protezione_Civile/Manuali%20e%20Studi/Rapporto_Evento_2013_11_30.pdf?ver=2016-04-19-121004-000).

The rainfall event gave rise to numerous mass movements in the province of Macerata: landslides and mudslides were reported everywhere in the area of San Severino, Fiuminata and San Liberato, mainly along the roads

Figure 7 - Effects of the recent debris-flow (left) and siphoning phenomena (right) where the water from the upper parts of the slope seeps into the first subsoil, goes under pressure and rises again pushing, deforming and eroding the soil (images from the Ussita Municipality archive).

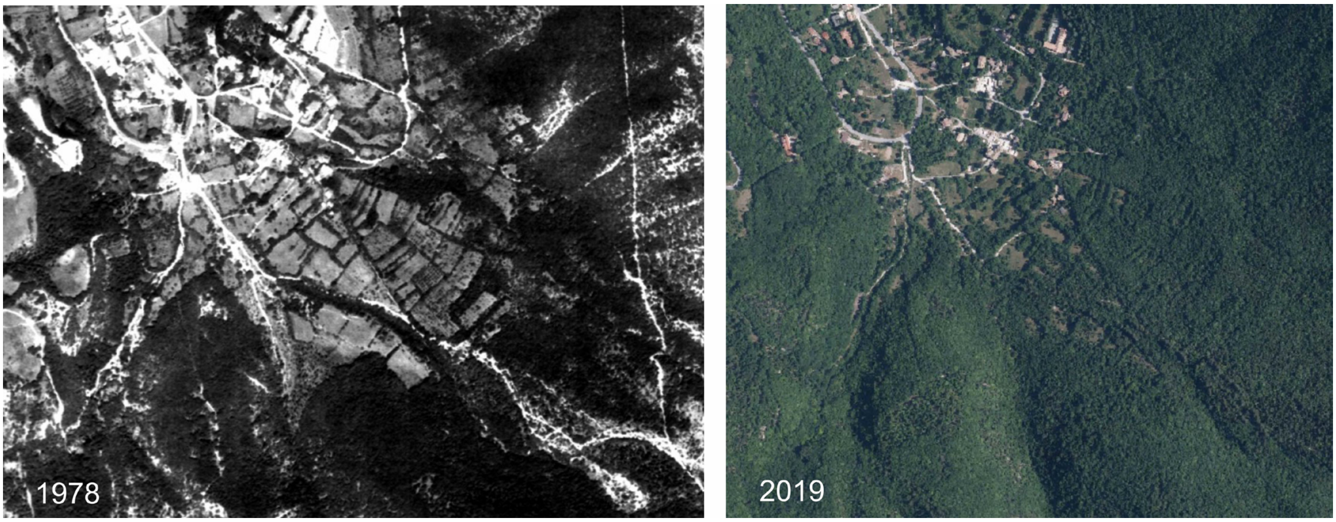

Figure 8 - Comparison of aerial images of the Varluscio area taken in 1978 and in 2019, testifying the abandonment of cultivation and soil stabilisation techniques (images from the Marche Region archive).

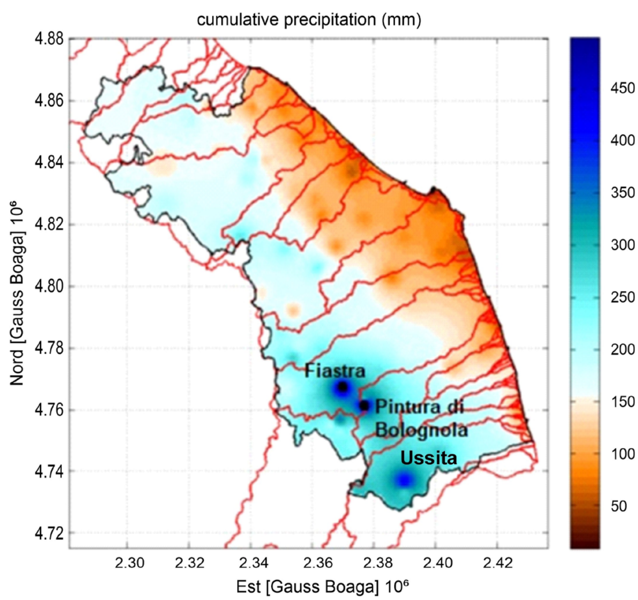

Figure 9 - Map of cumulative precipitation over the entire region from 12.00 on 10/11/2013 to 24.00 on 13/11/2013, obtained by interpolating rain gauge data (Regional Civil Protection Event Report 10-13 November 2013, https://www.regione.marche.it/Portals/0/Protezione_Civile/Manuali%20e%20Studi/Rapporto_Evento_2013_11_30.pdf?ver=2016-04-19-121004-000).

(the provincial road system was heavily affected, with numerous closures), but also near to some houses (in Ussita). Flooding occurred in several localities, including Castelraimondo, Sant'Elena, Belforte del Chienti and Pievebovigliana. Families were evacuated in Fiuminata and Fiordimonte. The present study starts after the extreme precipitation event occurred on November 11, 2013, which caused numerous hydrogeological instabilities in the area, such as those of Varluscio and Torricchio, VU area and TP area respectively. The research focuses on these two sites for the study of the extreme event of November 2013, as they underwent remediation works thus implying the use of considerable economic resources. In order to assess the rainfall thresholds for triggering ofthese landslides, it was first necessary to investigate the magnitude of the extreme weather event, the rainfall in the days before the event and compare it with that of previous years. For this purpose, data were collected from two weather stations owned by the Civil Protection Service of the Marche Region, located in Ussita and Camerino, a few kilometers further North. In addition, land use data were acquired from the European Environment Agency (EEA), through the CORINE Land Cover dataset, from 2012 and previous years (2006, 2000). At the same time, the geological map was acquired in digital format from the Marche Region, and information on bedrock units were subsequently detailed by field surveys. In order to assess the slope gradient, a Digital Elevation Model with a geometric resolution of 5×5 m was interpolated in GIS environment from the regional technical maps of the Marche region, which were realised from aerial photograps taken on August 1999 (carta tecnica numerica, https://www.regione.marche.it/Regione-Utile/Paesaggio-Territorio-Urbanistica/Cartografia/Repertorio/Cartatecnicanumerica110000). Finally, Satellite images were acquired from Landsat-5 (TM), Landsat-7 (ETM+) and Landsat-8 (OLI-TIRS) sensors, through USGS (United States Geological Survey) dataset. Landsat-5 has 7 bands, while Landsat-7 has 8 bands and Landsat-8 has 11 bands, but the resolution is 30 meters for all satellites used. The satellite images were collected to analyse the landslide areas and calculate satellite indices. In particular, the images have been taken for each month of September, October, November and December from 2006 to 2016. The satellite indices investigated were the Normalized Difference

Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI), aimed at knowing the vegetation status of the area and the moisture conditions of the vegetation (Gentilucci *et al.*, 2021b; Malakhov and Tsychuyeva, 2020). The calculation of these indices follows the equations:

NDVI=(NIR Band-RED Band)/(NIR Band+RED Band) (1)
NDMI=(NIR Band-MIR Band)/(NIR Band+MIR Band) (2)

where NIR indicate Near Infrared Band and MIR Mid Infrared Band.

Based on a calibration performed on a small portion of the territory, thresholds for the values of the NDVI and NDMI satellite indices were drawn up (table 1).

RESULTS

Analysis of remote sensing data

The area analysed for both landslides from a geological point of view, showed a clear prevalence of recent coarse and even thick cover deposits, for the landslide area in the municipality of Ussita with more than 74% of the territory occupied (fig. 10).

On the other hand, in the municipality of Pieve Torina are present finer-grained deposits characterised by sands, silts and clays in the 36.4% of territory, then there are outcropping of marly formations for 42.8% of the territory (fig. 11).

Obviously, the above-mentioned deposits are quite sensitive to extreme precipitation, but also the marls, due to their composition. The different distribution of slope gradient values in the landslide areas was also evaluated in order to understand, if it could be a discriminator or at least differentiate between the two areas. Subsequently, the vegetation indices, both NDVI and NDMI, were calculated and it was decided to analyse these values for the months preceding and following the landslide events studied, starting in August and ending in December, over 3 different years, 2013, 2014, 2015 (figs 12 and 13). In this sense, there is of course a certain degree of uncertainty relating to the fact that the season's climatic trends, especially in relation to vegetation, could mislead by not fully understanding the causes of variation of the values.

Rather low values of vegetation cover are evident, especially in October and November 2013, the year of the landslide, but also in the same months during 2015 (fig. 13). The absence of vegetation cover is certainly a preparatory factor that could have negatively affected slope stability, so having this evidence in 2013 and in 2015 is very interesting and allows a more accurate assessment of the triggering factors that led to the landslide movements.

As shown in fig. 14, water stress does not appear to be enough high, such that it could cause landslides. However, a relationship between NDMI and NDVI values has been noted, i.e., low NDMI values may cause low NDVI values in the following month.

Geological, geomorphological and hydrogeological analysis

Following specific geological, geomorphological and hydrogeological surveys, the analyses allowed us to derive different evolutionary models for the discussed areas. Based on applied geomorphological and geological surveys, conducted over several decades in these areas and with particular detail on mass movements since the 1997 seismic crisis, we have derived some evolutionary patterns. These patterns are valid not only for the interpretation of mentioned phenomena, but also for the prediction of the same dynamics in comparable geological and climatic contexts.

Table 1 - Range and interpretation of values for the NDVI and NDMI satellite indices in relation to vegetation cover (v.c.) (AGRICOLUS, https://www.agricolus.com/en/vegetation-indices-ndvi-ndmi/).

NDVI		NDMI	
Range	Interpretation	Range	Interpretation
-1-0	Water present	-1--0.8	Bare soil
0-0.1	Bare soil	-0.8--0.6	Almost absent v. c.
0.1-0.2	Almost absent v. c.	-0.6--0.4	Very low v. c.
0.2-0.3	Very Low v. c.	-0.4--0.2	Low v. c. with high water stress or very low v. c. with low water stress
0.3-0.4	Low v. c.	-0.2-0	Mid-low v. c. with high water stress or low v. c. with low water stress
0.4-0.5	Mid-low v. c.	0-0.2	Medium v. c. with high water stress or medium-low v. c. with low water stress
0.5-0.6	Medium v. c.	0.2-0.4	Mid-high v. c. with high water stress or medium v. c. with low water stress
0.6-0.7	Mid-high v. c.	0.4-0.6	High v. c. and no water stress
0.7-0.8	High v. c.	0.6-0.8	Very high v. c. and no water stress
0.8-0.9	Very high v. c.	0.8-1	Total v. c. and no water stress or clouds
0.9-1	Total v.c.		

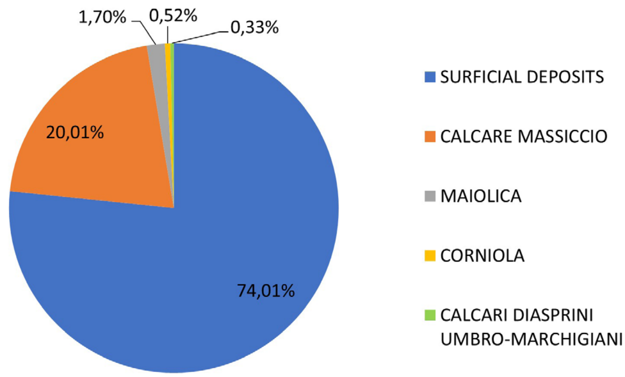

Figure 10 - Areal distribution (%) of surficial deposits and rocky outcrops in the area of the Varluscio landslide in Ussita.

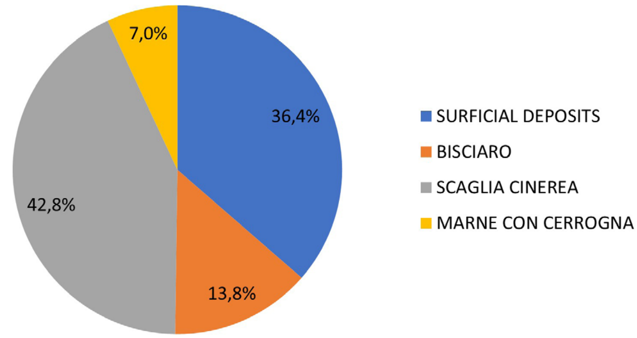

Figure 11 - Areal distribution (%) of surficial deposits and rocky outcrops in the area of the Torricchio landslide in Pieve Torina.

For the first area (VU), a possible evolutionary trend of the analysed slope can be as shown in fig. 16. As noted in similar geological context and in neighboring areas by the authors (Aringoli *et al.*, 2010), the dynamics are also strongly affected by seismic events (such as those that occurred during the years 1997, 2009 and 2016), in fact, repeated seismic stresses strongly weaken rock masses and widen fractures, disconnecting large portions of rock (Aringoli *et al.*, 2021).

Furthermore, it should be emphasized that these stresses add to the meteo-climatic events under study.

To summarise, we identified the following phases.

Phase 1 (pre-seismic): in the absence or low frequency of landslides, the slope dynamics is slowly evolving, with weak bedrock degradation and limited debris production, so the vegetation is able to colonise the edges of the debris accumulations with some efficiency, stabilising them. Phase 1 considerations, derive from observations that have been constantly recorded in these areas for many years (Aringoli *et al.*, 2010) and reported on official maps (produced since the 2000s and recently in the geological and geomorphological surveys of Institute for Environmental Protection and Research projects, ISPRA).

Phase 2 (post-earthquakes): simultaneous and widespread slumps are triggered, the slope dynamics has considerably accelerated through landslide phenomena, which produce a considerable amount of accumulations and debris material, that become even more unstable also by the rapidly rising of the water table.

The evolutive pattern above, in these seismically active areas, has been repeated over time and we can hypothesise that the situation in 2013 was similar considering the previous seismic crises (1997, 2009) that may have produced the rapid accretion of the debris layers.

The destabilisation of the latter is triggered by the surface contributions of extreme meteorological events and also by deep inputs related to the rapid underground water circulation, favoured by karstic conduits within the rock walls of the Calcare Massiccio (fig. 17). Regarding deep water circulation in the aforementioned karstic aquifer, at the moment there are no local data to support it, but it is undisputed that transmissivity is very high, resulting in high outward flow velocities (Gale, 1984; White, 2003; Medici and West, 2021).

Considering this various and complex scenario (as summarized in fig. 18), when such specified conditions occur, the triggering of impressive debris flows can happen, that flow down the steep valley to human settlements can occur.

In the TP area, on the other hand, the degradation of the marly bedrock occurs producing mainly sandy-silty deposits due to lithologies of different composition and more erodible, resulting in the formation of thin colluvial bodies. These are frequently reworked by fluvial-torrential processes and do not allow tall vegetation to take root; moreover, they are often exploited for agricultural purposes. These deposits, especially during particularly intense meteorological events, can become saturated, unstable and give rise to landslide phenomena, which sometimes originate rotational slides in the upper part of the slope evolving into major earth flows (fig. 19).

In this second case, it should be emphasised that in addition to the extreme climatic event, there is also the strong contribution of the shallow water circulation. In fact, after the initial draining in the upper portions of the slope, the water infiltrates and reaches the deep geological structure, which in cases of heavy saturation runs out, triggering flow landslides (fig. 20).

In fact, the geological structure of the Schlier formation, at the transition with the Bisciaro above, favours both the collection of water in the upper part of the slope and then its outflow, both superficial and deep with sometimes siphoning phenomena (red arrow), towards the small valley, destabilising it. When meteorological conditions are extreme (prolonged or very intense rainfall), major landslides can be triggered.

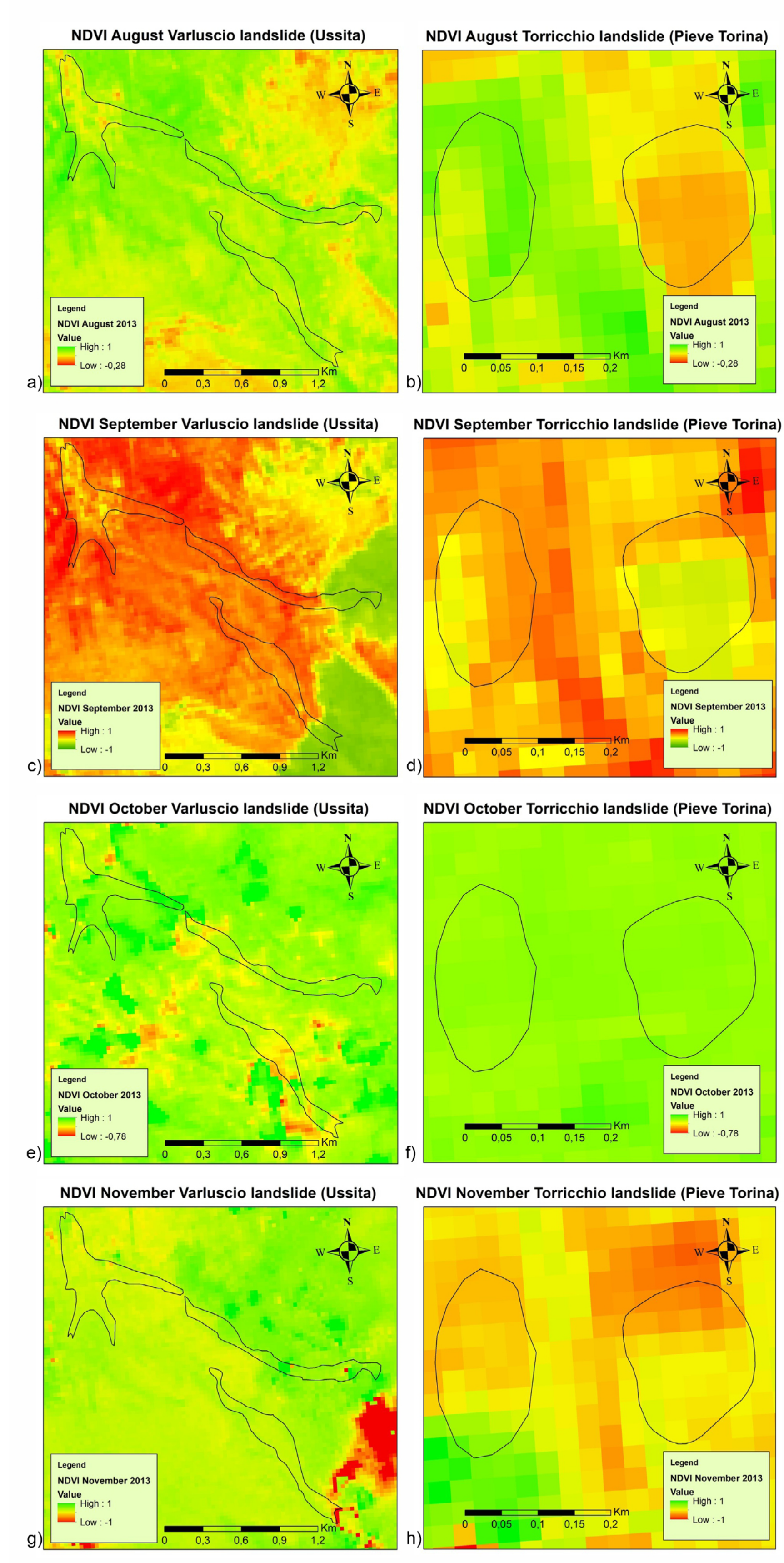

Figure 12 - NDVI maps for 2013 for Ussita on the left (a, c, e, g) and Pieve Torina (b, d, f, h) on the right.

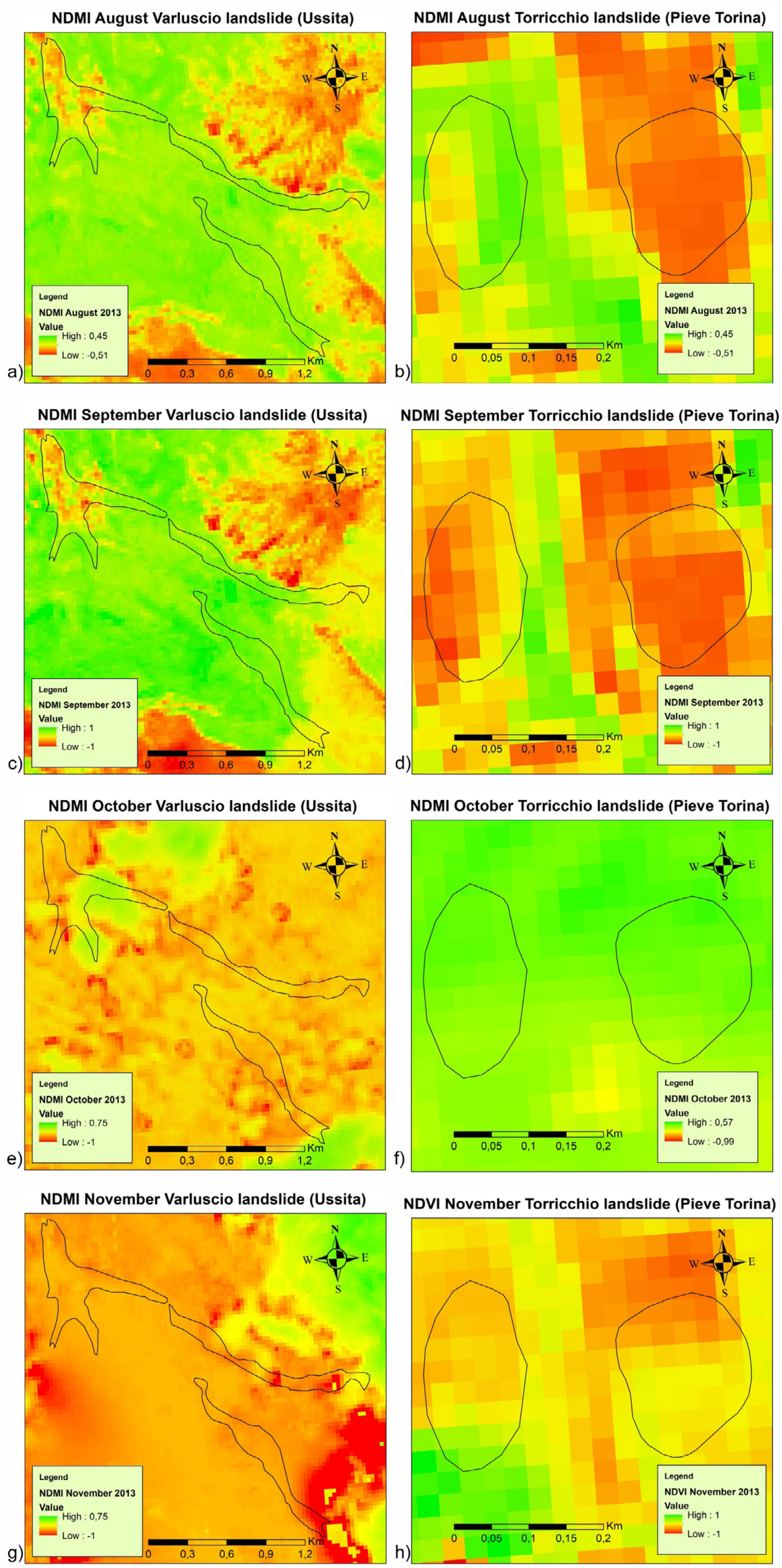

Figure 13 - NDMI maps for 2013 for Ussita on the left (a, c, e, g) and Pieve Torina (b, d, f, h) on the right.

Figure 14 - Results of analysis of NDVI showing index class ranges for Ussita on the left and Pieve Torina on the right; X axis and Y axis indicate the NDVI value and the area (in m^2), respectively.

Figure 15 - Results of analysis of NDMI showing index class ranges for Ussita on the left and Pieve Torina on the right respectively. X axis and Y axis indicate the NDMI value and the area (in m²), respectively.

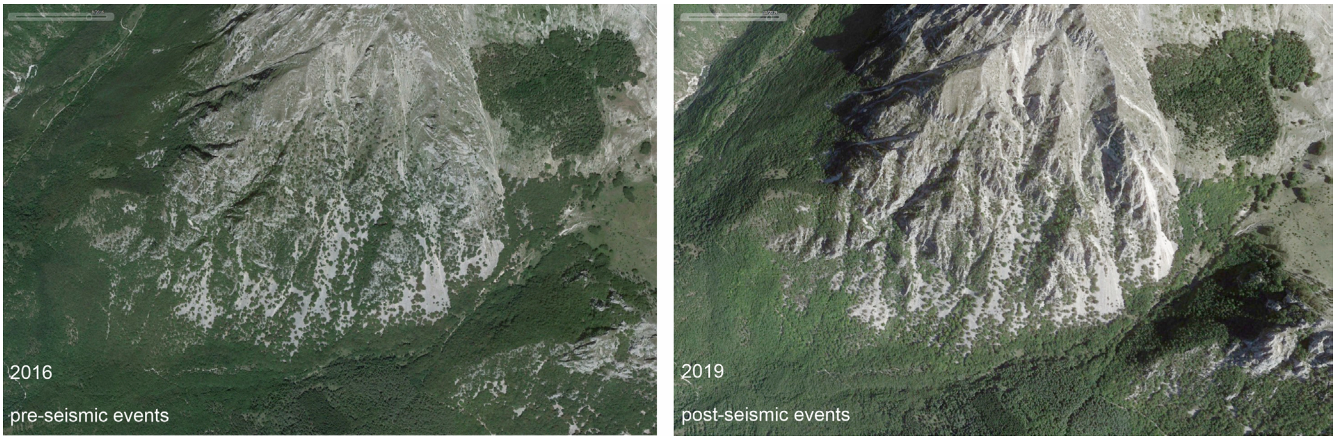

Figura 16 - Comparison of the two evolutionary phases of the VU area close to Monte Bove (images from Google Earth).

DISCUSSION

The present study has addressed the analysis of causal factors that may affect slope instability after an extreme precipitation event. In particular, preparing factors (where NDVI and NDMI indices can provide some measure of the factors involved) and triggering factors such as extreme precipitation events can be distinguish. Analyses were performed on two cases of landslide reactivation of landslides during the occurrence of the same weather event. Two landslide reactivations were recorded, in the investigated areas, involving different materials and showing different processes of triggering and evolution. Case 1-VU (Ussita), there was a prevalent mass movement of debris-flow type occurred with coarse-grained materials, extensive and locally very thick. These deposits are very stable under normal conditions, mainly due to their high permeability and high friction angle, so that they can also be found on slopes with angles greater than 30°. Since they are also more stable over time, they allow the growth of a vegetation cover of fair height, but nevertheless, during the extreme event analysed, the triggering of a landslide movement, even of considerable volume occurred. In summary, the phenomenon occurred with exceptional loading, through the sliding of large amounts of debris (coarse and with high friction) and subsequent channelling and movement towards the anthropised valley floor. It should be noted that the entire Mount Bove complex is rich in debris cover at the base of the steep slopes and cliffs, but frequently, as on this occasion, only along the SW slope mass movements of this type are triggered. The explanation is supported by the geological and hydrogeological survey that showed the presence of several draining karst channels within the mountain complex. These, due to the structure of the bedrock, surface in this sector of the mountain and occasionally carry large quantities of water. Similar situations are found in some cases known in the literature, where strong water flows occur in deep karstic environments, triggering rapid saturations of the debris cover with associated exceptional debris flow phenomena (Leone *et al.*, 2021). Such movements can also cover considerable distances and, especially in areas of economic interest, it is necessary to carry out hydrogeological risk zoning, assessment of the impacts and land responses (Santi *et al.*, 2010; Aringoli, 2024). In this regard, the present work also provides an initial analysis of the data, which processed with GIS procedures can lead to a functional assessment of the hazard scenario, similar to what has been observed in analogous contexts (Grelle *et al.*, 2019).

Case 2-TP (Pieve Torina), however, the same extreme event led to the triggering of a flow landslide that, in volume and covered distance, was more limited than the previous one. Here the movement involved finer-grained materials, derived from the degradation of the bedrock that was also different. The study area is exploited for agricultural purposes, so there is no well-developed vegetation and traces of probable old water regulation works are present. The movement occurred by sliding/flowing, reactivating an area previously affected by landslides with certainly greater frequency than in the first case. The peculiarities of the landslide, however, were the greater thickness of deposits and part of the bedrock involved. This is testified both by the secondary morphologies, such as some swellings in the landslide body, and by the disruptions found in the upper slope portion where a roadway was strongly deformed. This major movement was triggered in a specific area of the slope due to the particular hydrogeological setting that shows, on the right slope of the valley, the Bisciaro bed with deep permeable levels arranged draining towards the deformed area, while the opposite slope appears as not being involved in active movements. Predictably, the hydrogeological structure of the area is predisposed to run-off processes triggered by the large amount of precipitated water. In addition, the other side of the valley, did not present significant activations of mass movements, thanks not only to the different geological setting but also to the anthrop-

Figure 17 - View of the northern slope of Mount Bove with the Calcare massiccio formation (MAS) walls affected by recent falls and karst conduits outflow.

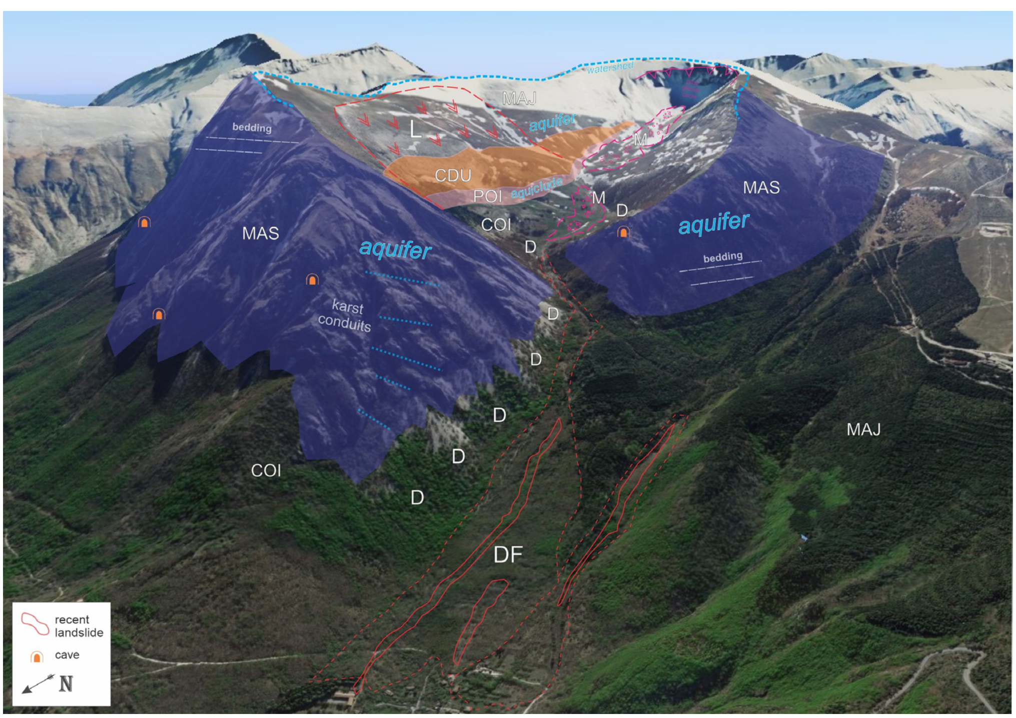

Figure 18 - Geological and geomorphological sketch interpreting the dynamics of processes in the VU area (Monte Bove relief). MAS-Calcare massiccio, COI-Corniola, POD-Marne a Posidonia, CDU-Calcari Diasprini U.M., MAJ-Maiolica, M- relict glacial deposits, L-gravitational movements, D-coarse Debris and blocks, DF-debris flow area, in continuous red line the recent ones (base image from Google Earth, 2024).

ic works that favoured the dispersion of rainwater in safer areas. The literature on the subject is not very exhaustive, and it is not easy to find comparable cases. It is therefore possible to state that the present study has interpreted and explained the dynamics of the phenomenon that occurred above all by reconstructing the deep geological-hydrogeological structure (hydrogeological basin), therefore this dynamic would not have been fully interpreted with a surface analysis alone (hydrological basin).

Finally, a common factor present in both different phenomena above, can be emphasized. This is the knowledge of the local hydro-geological setting, that in different

Figure 19 - Overview of the TP site, in the foreground the area of activation of the landslide.

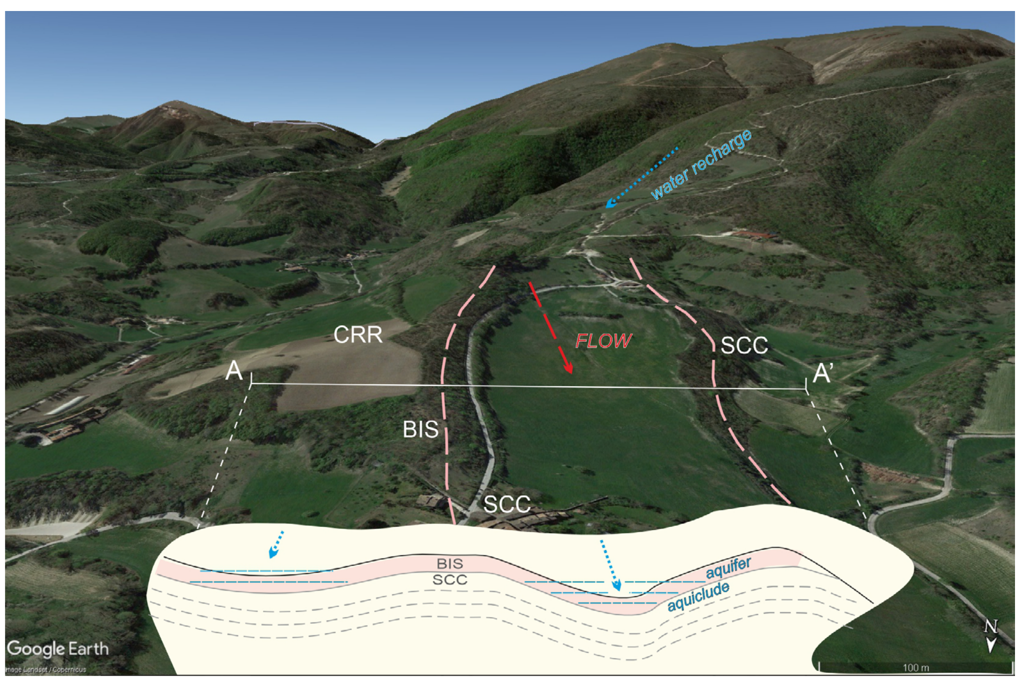

Figure 20 - Interpretative 3-D sketch of the hydrogeological structures that favour the accumulation and occasional overflow of water triggering flow landslides. CRR (Marne con Cerrogna), BIS (Bisciaro) and SCC (Scaglia cinerea) represent the bedrock formations; A-A' schematic cross section (base image from Google Earth, 2024).

ways predisposed and led to the triggering of the surveyed flows landslides, which probably would not have occurred otherwise despite the extreme rainfall conditions (Gentilucci *et al.*, 2023). This factor is also decisive not only for interpreting the activation and development of the landslides above, but also for zoning the area predisposed to this hazard.

A further and common analysis regarding the two case studies is the one conducted on the effects of vegetation, especially in the triggering phases of the flow landslide. Indeed, it is known how plant roots can influence and vary the cohesive strength within soils (Schmidt *et al.*, 2001). Although in the examined context, no dynamic models were derived that could be compared with other examples in the literature (Lida, 1999), it was not nevertheless possible to establish defined threshold values, but rather ranges, using NDVI indices as shown below.

Findings from NDVI tell us that in our study area, for the months under observation, most of the area has almost absent canopy cover or bare soil with most of the index class ranging from 0-0.1 and 0.1-0.2. There are few months when there is very low canopy cover, however there is also very low vigour. From data obtained throughout the years under review, the most notable is that of 2013. We observe that in the year 2013, among all the months in consideration, there is a sharp increase in the total area of bare soil value (0-0.1) in the month of October. The months preceding have values of 0.1-0.2, and 0.2-0.3, indicating the presence of some canopy cover, although very little. The absence of canopy cover in October and the resulting high precipitation in the month of November, which spiked over three days in neighbouring areas to almost 500 mm, leads to the activation of landslides in Case 1-VU area, which suggests that it is a trigger for a landslide event in the Municipality of Ussita. For the year 2013 just like in Ussita, we observe a sharp increase in the total area of bare soil value (0-0.1) in October when compared to the preceding months, probably due to low rainfall and high temperatures in September. Another very important observation, is that in the year 2015, there is a similar change in the NDVI value range with a sharp increase in the value of bare soil containing water corresponding to the range (-1-0). This condition makes the slope even more susceptible to landslides, however activation of landslides in the subsequent month like in the year 2013 was not recorded. This can be attributed to the lack of significant rainfall events after the month of October, such as that which occurred in the month of November 2013. During the month of November, in the year 2013, abnormally high monthly precipitation values of 235.6 mm and 149.4 mm were recorded respectively in Ussita and Camerino stations, whereas in the year 2015 we have the highest recorded precipitation values of 59 mm and 34.8 mm in Ussita and Camerino, respectively. Thus, we could say in this situation that with the same vegetative condition of the soil and soil saturation, a suitable range of triggering rainfall values for this area is between 59 and 235 mm. Obviously, having more data available and continuing the research in the past, it would be possible to obtain an even more accurate landslide triggering threshold for this area. After analysis, the NDMI values for the area under observation are within the index range of 0-0.2 and -0.2-0, indicating that, in general, there is not enough water stress in the soil to cause or trigger landslides. For the water stress in the soil to be high enough to trigger landslides the NDMI must be within a range index from 0.4-0.6 to 0.6-0.8. Significant however is the evidence that low NDMI values for a particular month tend to produce a similarly low NDVI value in the subsequent month. For instance, in the Case2-TP (Torricchio), in September 2013, we have a higher water stress in the NDMI values and this is the reason why for the subsequent month of October 2013, there are low NDVI values of bare soil area. In the Case1-VU (Ussita), we observe a similar phenomenon in October creating a higher bare soil value for NDVI in the following month of November. In terms of soil and lithological properties, most of both areas (VU and TP) fall in a detrital or predominantly calcareous bedrock. A larger observation at the scale of whole Marche region shows that soils are largely Calcific Cambisols, Calcic, Calcific and Calcic Vertisols. These are clayey in texture and retain limited excess water. Most of the land is mostly small forest, meadows and used for agricultural purposes. The slope of Torricchio reaches a high of 30 percent of gradient whiles that of Ussita reaches about 52 percent of slope gradient. This is a significant percentage with regards to slope and is therefore important. However, a further analysis using ArcGIS slopes tool reveals that the surrounding municipalities in the region have higher slopes of approximately 75 per cent, and no landslide activations have occurred in these areas. Additional data collected on other municipalities in the Marche region reveal that in the month of the event, November 2013, similar extreme precipitation events were recorded which indicate that rainfall for that month was not only confined to one part of the region but was spread across the whole region. Rainfall data recorded in the following years revealed an absence of similar abnormal extreme events in the region. Actually, rainfall values recorded for the months under observation in Camerino and Ussita stations, for the years 2014-2015 have normal values with the highest values in Camerino being 40.6 mm in September 2014 and 43.6 mm in October 2015 respectively. For Ussita, highest values recorded in 2014 and 2015 are both in September with values of 65.2 mm and 59.6 mm. The temperature values recorded for both Ussita and Camerino did not reveal any abnormal values.

CONCLUSION

Satellite indices allow to assess moisture and vegetation, introducing preparatory factors into landslide analysis. There were no drastic changes in vegetation cover in the study areas, except for October 2013. High slope gradient is a potential preparatory factor for landslides, but temperature is not. Moreover, the extreme precipitation event that caused the landslides may not have been sufficient without the sudden loss of vegetation cover in the previous month. The landslides analyzed were triggered after a rainfall of 149 mm, but this value cannot be considered a definitive threshold without further study and without a statistical model (Berti *et al.*, 2012; Puglisi *et al.*, 2013). Furthermore, it will be interesting to use other satellite images such as Synthetic Aperture Radar (SAR) in case of similar anomalous precipitation events.

The study interpreted the geomorphological dynamics of two significant landslides, also related to vegetation cover, and identified bedrock structure and hydrogeological structures as predisposing factors. It also attempted to clarify how they occurred in certain contexts (slopes) rather than others, given the same weather conditions (extreme precipitation). Thus, the study showed that structures that respond rapidly to deep water circulation, such as intense fracturing and karstification, allow the rapid return of large amounts of water to slopes, de-stabilizing debris aquifers.

These analyses, in our opinion, could provide an exportable survey and study guide useful for hydro-geomorphological risk assessment.

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