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Supplement of

RER2023: the landslide inventory dataset of the May 2023 Emilia-Romagna meteorological event

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Supplementary description of landslide characteristics and influential factors

The Emilia-Romagna Region Geoportal offers open access to a comprehensive collection of geospatial data, including geology, geomorphology, soil use, vegetation, and more (https://geoportale.regione.emilia-romagna.it/). This data can be used for a detailed analysis of the landslides listed in the inventory. The additional section here presents findings from such an analysis, utilizing six spatial layers: bedrock lithology, land cover, Quaternary deposits, slope, curvature, and aspect. At first glance, these factors seem to be the main contributors to the landslides in May 2023.

Table S1 details the features of the six spatial layers and their classification into distinct categories. Bedrock lithology, land cover, and Quaternary deposits are categorical variables and are available as polygon shapefiles through the Geoportal. Slope, curvature, and aspect are continuous variables, extracted from the Digital Elevation Model (DEM) of the Emilia-Romagna Region using ArcGIS software. This DEM, with a resolution of 10 meters, was created in 2015 by digitizing the Regional Technical Map at a scale of 1:5,000. As such, it represents the slope morphology as it was before the May 2023 event.

The methodology used to extract landslide features aligns with the objectives of the study. Our primary goal is to identify the typical slope conditions that lead to failure. Therefore, the statistical analysis focuses specifically on the source areas of the landslides, intentionally omitting the runout zones. This distinction is essential as numerous landslides developed—either partially or entirely—into flows that move downslope, causing the polygons to extend over areas that do not accurately reflect the initial conditions that triggered the landslides.

Bedrock lithology (source: Geological Map of the Emilia-Romagna Region, 1:10.000 scale)	
Class	*Description*
1	Clays, silty clays, and marly clays
2	Marls and marly clays
3	Clay shales, clay breccias, tectonized clays, olistostromes
4	Massive rocks: basalts, serpentines, limestones, arenites
5	Flysch rocks made of rhythmic alternations of sandstones, limestones, pelites, and shales
6	Weakly cemented sandstones and conglomerates
7	Flysch rocks made of rhythmic alternations of sandstones and pelites
8	Weakly cemented sandstones with interbedded pelitic layers

Land cover (source: SU2014 dataset – Soil Use Emilia-Romagna Region)	
Class	*Description (Corine Land Cover directive classification)*
1	Urban areas, roads, ports, airports, isolated houses (111-124)
2	Extraction areas, quarries, landfills, mines, construction sites, remodeled or artificial soils (131-133)
3	Artificial green areas, parks, campsites, golf courses (141-143)
4	Agricultural lands: arable land (211-213)
5	Agricultural lands: vineyards, orchards, tree crops (221-224)
6	Agricultural lands: permanent grasslands (231)
7	Heterogeneous agricultural lands (241-243)
8	Forested areas (311-313)
9	Shrub and/or herbaceous areas (321-323)
10	Areas with sparse or no vegetation (331-334)
11	Wetlands: peat bogs, inland wetlands, valleys, salt pans (411-422)
12	Water environments: rivers, canals, lakes, waterways (511-521)

Quaternary deposits (source: Geological Map of the Emilia-Romagna Region, 1:10.000 scale)	
Class	*Description*
1	No Quaternary deposits
2	Active landslide
3	Dormant landslide, Deep-seated gravitational slope deformation (DGPV), Lateral spread, Stabilized or undetermined landslide
4	Slope debris, Eluvial-colluvial deposit, Glacial or periglacial deposit

5	Alluvial deposit, Alluvial deposit fixed by vegetation, Alluvial fan
6	Marsh deposit, lacustrine deposit, aeolian deposit, salt deposit
7	Terraced deposits
8	Anthropogenic deposit, landfill, quarry

Slope (source: Digital Elevation Model of the Emilia-Romagna Region, 10 m resolution)	
Class	*Description*
1	0°-5°
2	5°-10°
3	10°-15°
4	15°-20°
5	20°-25°
6	25°-30°
7	30°-35°
8	35°-40°
9	40°-45°
10	45°-50°
11	50°-50°
12	55°-60°
13	>60°

Curvature (source: Digital Elevation Model of the Emilia-Romagna Region, 10 m resolution)	
Class	*Description*
1	Concave slope (curvature<-0.5)
2	Planar slope (curvature between -0.5 and 0.5)
3	Convex slope (curvature>0-.5)

Aspect (source: Digital Elevation Model of the Emilia-Romagna Region, 10 m resolution)	
Class	*Description*
1	Flat (-1)
2	N (0-22°)
3	NE (22-67°)
4	E (67-112°)
5	SE (112-157°)
6	S (157-202°)
7	SW (202-247°)
8	W (247-292°)
9	NW (292-337°)
10	N (337-360°)

Table S1. Spatial variables utilized to characterize the May 2023 landslides and to analyze the factors predisposing to instability.

The source area for each landslide was determined by locating a point inside the upper part of each polygon, and a circle with a 10-meter radius was created around this point. These circles were subsequently overlaid to the six spatial layers using the Zonal Statistics tool in ArcGIS. For categorical variables, the characteristics were identified based on the majority of the sampled pixels within each circle. For continuous variables, average values were calculated. Consequently, each landslide was characterized by six distinct features derived from its source area.

Figure S1 provides a summary of the analysis results. Each plot displays a frequency histogram illustrating a specific factor for a particular landslide type. Landslides are categorized into primary types by combining informal subclasses (for instance, debris slides encompass both high-mobility DS1 and low-mobility DS2 debris slides; see section 3.2). For each factor, the y-axis represents the number of landslides with source areas that fall within each class. Based on these data, the following observations can be made:

- The majority of landslides occurred in the Miocene flysch rocks of the inner foredeep (bedrock lithology - class 7) and in the Pliocene clay of the outer foredeep (bedrock lithology - class 1). This suggests a strong influence of the structural geological domain on the landslides triggered by the May 2023 event.
- Debris slides and debris flows were more frequent on forested slopes (Land cover - class 8), whereas rock-block slides were primarily observed on agricultural lands (Land cover - class 4). Rock-block slides, however, involved the bedrock deep beneath the soil layer, suggesting that agricultural activities are not the cause of the instability. Instead, these landslides were controlled by the orientation of bedding layers, which, when dipping parallel to the slope, create gently inclined homoclinal slopes suitable for agricultural use.

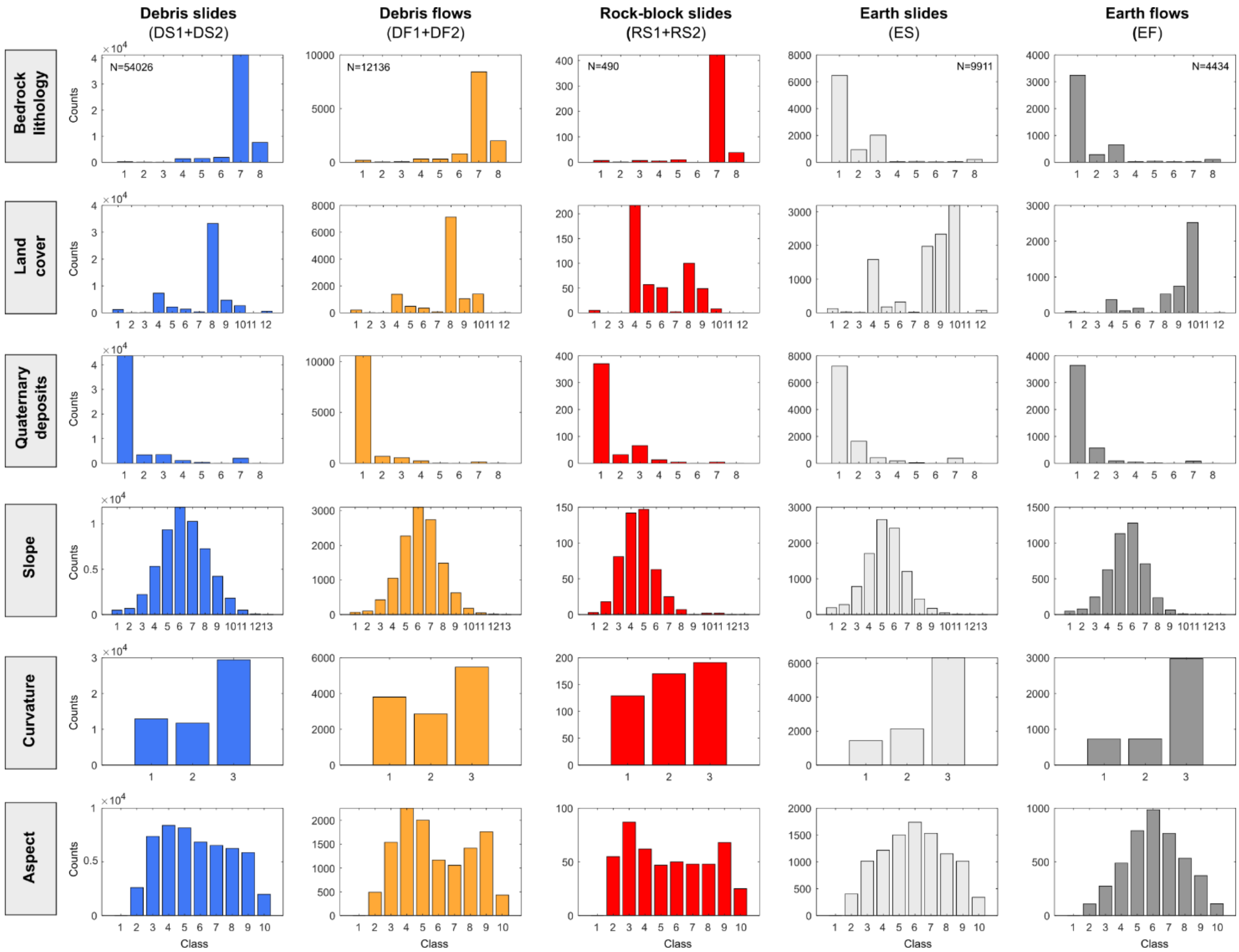

Fig. S1. Frequency histograms for the six spatial variables detailed in Table S1, across different types of landslides. Each histogram represents the number of landslides whose source area—defined by a 10-meter radius circle at the upper part of the polygon—falls within specific factor classes

- Earth slides and earth flows were mostly observed in areas with shrubs, herbs, sparse vegetation, or no vegetation (Land cover - classes 9 and 10). Such sparse vegetation is typical of unstable clay slopes, which, unlike those in coarse-grained soils, are subject to frequent instability that prevents the growth of tall trees.

- Landslides in soils, including debris slides (DS), debris flows (DF), earth slides (ES), and earth flows (EF), predominantly occurred on steep slopes with inclinations between 20° and 35° (Slope - classes 5 to 7). In contrast, rock-block slides, which are influenced more by the orientation of bedding layers than by slope angle, typically affected gentler slopes, most commonly ranging from 10° to 25° (Slope - classes 3 to 5).

- Nearly all the landslides occurred on slopes where no previous landslides had been mapped (Quaternary deposits - class 1). This is a critical point for the landslide mitigation strategy. In the regional protection plan, high-risk slopes are typically identified based on the presence of existing landslides, as landslides in the Emilia-Romagna region are often reactivations of previous events. However, the May 2023 event shifts this perspective, as the majority of the landslides were first-time failures. This will necessitate a change in the criteria used for developing the new landslide mitigation plan.

- Landslides in soils tend to occur more frequently on convex slopes (Curvature - class 3), while there is no a preferred slope curvature for rock slides. Slope aspect does not show a clear trend for debris slides, debris flows, and rock-block slides. However, earth slides and earth flows are more commonly observed on slopes facing SE, S, and SW (Aspect - classes 5 to 7). A preliminary explanation for this pattern is that southward-facing slopes in clay soils are generally drier and steeper, making them potentially more susceptible to instability during intense, short-duration rainfall events.

It is important to emphasize that the plots in Fig. S1 only show the frequency of the considered factors in the landslide source areas and cannot be used to assess the significance of a factor in relation to landslide occurrence. For instance, the plot of slope angle for debris slides shows a frequency peak in the 25°-30° class, with lower values for both smaller and larger angles. This distribution indicates that debris slides are "more commonly observed" within this slope range, but it does not imply that steeper slopes are less prone to instability. Very steep slopes may simply be less common, resulting in lower counts in the frequency histogram.

To determine which factor classes are most influential for landslides, it is essential to evaluate both the presence and absence of a given factor class, in addition to considering the prior probability of that factor class occurring in the area. This can be achieved by calculating the Contrast Index using the Weight of Evidence method (Bonham-Carter, 1994). The Contrast Index measures the difference between the positive weight (W+) and the negative weight (W-) associated with a factor class. W+ represents the strength of the association between the factor class and the occurrence of evidence (landslide), while W- represents the association between the factor class and the absence of evidence. By computing the Contrast Index (C = W+ - W-), both aspects are considered, providing a balanced measure of the factor's influence on the landslides occurrence.

Figure S2 displays the Contrast Indexes calculated for each factor class and the various types of landslides. Positive values of the Contrast Index (C) indicate a positive association between the feature and the event, meaning the presence of that particular factor class increases the likelihood of a landslide occurring. The greater the positive value, the stronger this association. Conversely, a negative Contrast Index suggests that the feature serves as a deterrent to the event's occurrence. The values of C presented in Fig. S2 support and elucidate the true significance of the frequency distributions illustrated in Fig. S1.

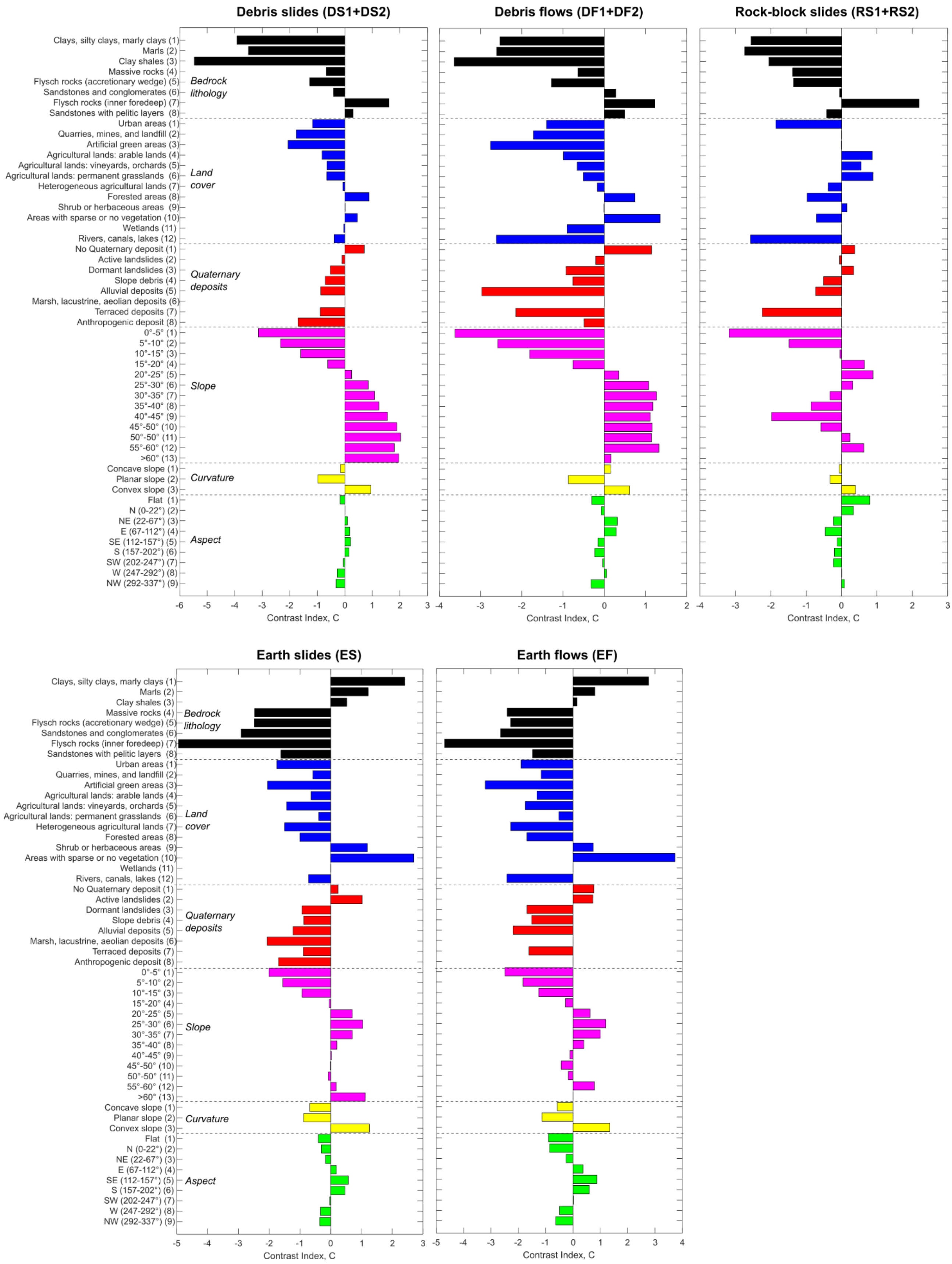

Fig. S2. Contrast Index derived using the Weight of Evidence method for the evaluated factor classes. Positive values suggest that the presence of the factor contributes to an increased likelihood of landslide occurrence.

Specifically:

- The slopes most susceptible to debris slides were those made up of Miocene flysch with an incline greater than 25°; these slopes were characteristically convex, forested, and lacked evidence of prior landslides.
- Debris flows typically occurred under similar conditions, displaying similar Contrast Index values across all factor classes, consistent with field observations that debris flows were primarily initiated by debris slides
- The main factor influencing rock-block slides is the bedrock lithology (Unit 8). The presence of gentle slopes and agricultural fields also shows a positive association with these slides. However, as already noted, these are not direct causal factors but rather outcomes of the peculiar slope morphology found in the homoclinal slopes of the Marnoso-Arenacea formation.
- Earth slides and earth flows are largely affected by the same conditions, specifically steep inclines (over 20°) in areas with fine-grained soil, often marked by shrubby vegetation or minimal to no vegetation cover. In contrast to debris slides and debris flows, landslides occurring in these fine soils are positively associated with the presence of existing landslides and tend to have slope aspects facing southeast, south, or southwest.

The findings discussed here are derived solely from the six spatial factors considered. However, more comprehensive analyses could incorporate additional variables such as flow accumulation, topographic wetness index, and proximity to roads or streams, all of which are accessible via the Geoportal of the Emilia-Romagna region. Further studies could also include rainfall data as a significant factor, or utilize deterministic or statistical models to assess landslide susceptibility and replicate the conditions observed in May 2023. While these analyses fall outside the scope of this current study, we strongly encourage our colleagues to utilize our landslide inventory and invite them to contact us for any support or additional data they might require.