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Shallow landslides in Northern Tuscany (Italy): a new multi-temporal inventory and its spatial and statistical analysis

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Shallow landslides are among the most frequent and impactful geomorphological phenomena in areas affected by intense rainfall and complex lithological settings. In this study we present and analyse a new multi-temporal shallow landslide inventory for the Apuan Alps area (Northern Tuscany, Italy). The study area, covering 625 km², is characterized by high landslide susceptibility due to both occurrence of intense rainfall events and complex morphology and structural geology conditions. A visual interpretation of high spatial resolution orthophotos was performed to recognize and map both landslide features and examples of stable areas. The aerial images used for landslide mapping cover a period of 67 years, from 1954 to 2021. The acquisition was not evenly distributed over time, with intervals between successive images varying from 2 to 24 years and averaging approximately 6 years. Nevertheless, the last two decades (2003-2021) saw a more consistent acquisition rate, with aerial images captured every 3 years. The dataset, made up of 1433 positive landslide entities and 100 stable areas, was validated through field surveys, achieving an overall accuracy of 91%. During field validation, further information were acquired, such as movement type, material involved and scarp height. The overall inventory underwent spatial, temporal and statistical analysis. Spatial analysis revealed two high-density clusters (>25 landslides/km²), primarily associated with extreme rainfall events occurred in 1996, 2010, and 2012. Temporal analysis highlighted a significant increase of normalized annual landslide frequency during the recent decades; also the relationships with the increase of intense rainfall events was explored. Magnitude–frequency distribution analysis exhibited a negative power-law relationship for medium and larger landslides, with a rollover at areas around 100 m². The shape and the parameters of the magnitude-frequency relationship well fit to other functions published in the literature. In a general perspective, the new inventory shows high frequency of “small” landslides, which instead are almost lacking within published landslide inventories for the study area (e.g. IFFI*, Inventario Fenomeni Franosi Italiani*). The intersection between shallow landslides and bedrock lithological units allowed us to recognize highest landslide density for silt and clay-rich lithologies, such as flysch and metarenites, while carbonate units is characterized by higher stability. Analysis of morphometric variables revealed that south- and southeast-facing concave hillslopes with gradients between 30° and 50° are particularly susceptible to landslides. These results align with previous research highlighting the role of slope aspect, steepness, and contributing area in landslide initiation. Field validation provided further insights into the dynamics

and geometry of shallow landslides. Avalanches were the most common type (50%), followed by slides (30%), flows (15%), and falls (5%). The variability for scarp height and sliding surface location highlights the involvement of both slope deposits and bedrock, providing relevant clues to help both understanding failure mechanisms and improving approaches for susceptibility models. This research highlights the added value of integrating remote sensing – based data extraction, spatial analyses, field validation and statistical methods to enhance the understanding of shallow landslide processes. Moreover, the inventory represents a new robust, high-quality dataset suitable for landslide susceptibility and hazard zoning.