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A dynamic machine learning–based early warning system for daily landslide hazard prediction

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Regional Landslide Early Warning Systems (LEWS) typically rely on rainfall thresholds, that correlate precipitation data with past landslide occurrences to forecast future events. While these systems are simple and accessible, they often lack spatial resolution and fail to capture the complex relationships driving landslides, as they consider only rainfall as input, neglecting critical hydrogeological soil properties. On the other hand, Machine Learning (ML) techniques offer the advantage of incorporating multiple geoenvironmental factors, and have been widely applied to generate landslide susceptibility maps. However, these methods are constrained to spatial predictions, limiting their applicability to LEWSs.

This study presents a dynamic ML methodology using the Random Forest (RF) algorithm to generate daily Landslide Hazard Maps (LHMs), which allow to predict the probability of landslides occurrence in both space and time. The proposed approach integrates dynamic rainfall data (both daily and antecedent rainfall) with static geoenvironmental attributes.

The proposed dynamic methodology involves using a temporally-explicit landslide inventory and identifying non-landslide events over time and space. This allows the inclusion of dynamic variables, such as daily and antecedent rainfall, in the model. It also allows the inclusion of traditional static parameters such as lithology and geomorphologic attributes.

Key innovations achieved are: (1) integration of dynamic rainfall variables as model input, (2) interpretation of model decisions through Partial Dependence Plots (PDPs) to assess their geomorphological plausibility, (3) iterative training on imbalanced datasets to improve predictive accuracy, and (4) the identification of a warning criterion for integrating the generated LHMs into a prototype LEWS.

The methodology was applied using the ITALICA landslide inventory, which provides spatiotemporal information for each event, along with satellite-based precipitation data (GPM

IMERG). The use of slope units instead of pixels enhances the representation of geomorphological processes. The model was trained and tested in the Ligu-C Alert Zone (Liguria, Italy), an area with complex geology and high annual rainfall (>3000 mm). Subsequently, the generated predictor model was applied to an independent dataset to obtain daily LHMs for the period February-March 2024, (a period affected by several landslide events), demonstrating the predictive capabilities of the model.

Results confirm the potential of dynamic RF models to overcome the limitations of static ML approaches, providing actionable and interpretable outputs for operational LEWS.