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Applying a hierarchical Generalized Additive Model to integrate predisposing, preparatory and triggering factors for landslide prediction

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Shallow landslides are frequently caused by an interplay of static predisposing factors (e.g., topography), mid-term preparatory factors (e.g., prolonged rainfall, seasonal changes of vegetation, snow melt), and short-term triggers (e.g., heavy rainfall). For large-area assessments, statistical analyses and data-driven approaches are often used to model landslide susceptibility based on spatial environmental variables or to derive critical landslide-triggering rainfall conditions through the definition of empirical rainfall thresholds. Attempts to integrate the spatial and temporal domains in the context of quantitative regional-scale landslide prediction are still rare.

This contribution focuses on the landslide-prone area of South Tyrol, northern Italy (7,400 km²) and presents a novel data-driven modelling procedure that integrates spatial predisposing factors and dynamic preparatory and triggering factors to predict the probability of landslide occurrence in space and time. The approach is based on time-stamped landslide inventory data from 2000 to 2021, high-resolution gridded daily precipitation observations for the same period, and a set of relevant static environmental variables (e.g., including topographic indices, lithology). Data preparation included an initial filtering of rainfall-induced landslide presence observations and a rule-based stratified sampling of landslide absence observations at landslide locations and at non-landslide locations. Cross-validation was implemented in the model developing stage to select optimal time windows to represent pre-landslide preparatory and triggering cumulative rainfall conditions. Modelling was based on a binomial Hierarchical Generalized Additive Model (HGAM) that considered the non-linear influence and interactions (i.e., via tensor products) of static and dynamic environmental variables on landslide occurrence (presence vs. absence) while simultaneously accounting for the nested data structure (i.e., multiple considerations of each location) and seasonal effects. The study also considered different biases inherent in the input data, such as the known underrepresentation of landslide data in locations far from infrastructure or potential reporting biases across years, by averaging-out associated random effect variables. The results were validated quantitatively (spatial and temporal cross-validation) and qualitatively (geomorphic plausibility) and visualized as maps

and probability surface plots.

The assessment and validation confirmed the high generalizability and predictive performance of the model. A closer look at the derived relationships allowed to uncover the effects of predisposing, preparatory and triggering factors on landslide occurrence as well as the associated season-dependent variations. From our perspective, this new approach represents a good compromise between the high model flexibility for landslide prediction purposes and the high interpretability for understanding the underlying relationships.

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