



Testing a Coordinate Tensor-Product Descriptor for Spatial Autocorrelation in a Shallow Landslide Susceptibility Model

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Landslides are among the most frequent natural hazards worldwide, significantly threatening human life, infrastructure, and ecosystems. Identifying areas prone to slope failures is therefore essential for effective land management, particularly under changing climatic conditions. This study develops a robust statistical model for assessing shallow landslide susceptibility at the slope-unit level across the Aosta Valley, while explicitly evaluating the role of spatial autocorrelation. A comprehensive shallow landslide inventory, compiled by integrating the Italian Landslide Inventory (IFFI) database with the Regional Inventory of Instabilities of Aosta Valley, was used as the binary response variable indicating shallow landslide occurrences. A broad set of geo-environmental predictors was assembled and optimised through a novel structured variable selection workflow, combining multicollinearity analysis, stepwise selection, Random Forest classification, and Generalised Additive Models (GAMs). GAMs were used for modelling susceptibility and exploring predictor–response relationships via smoothing functions. To assess spatial autocorrelation effects, the coordinates of slope-unit centroids were incorporated into the GAM framework using a tensor-product smooth. This resulted in two models: model_A, excluding the spatial term, and model_B, including it. Model performance was evaluated using spatial and non-spatial k-fold cross-validation, assessed through mean Decrease in Deviance explained (mDD%), Effective Degrees of Freedom (EDF), and Area Under the Receiving Operating Characteristic curve (AUROC). Both models are statistically significant and exhibit high discriminatory power (AUROC > 0.85) under both validation schemes. Including the spatial tensor modestly improved model fit and predictive capacity for model_B relative to model_A, with higher deviance explained (39.0 vs. 35.9), R^2 (0.42 vs. 0.39), and lower AIC (714.2 vs. 724.5). Distributions of mDD% and EDF indicate greater stability for model_B, whereas model_A shows higher variability. However, the improved training performance of model_B likely reflects sensitivity to local spatial structure rather than enhanced generalisation. Under spatial cross-validation, testing performance decreases relative to non-spatial validation and becomes variable for both models, while the performance gap between model_A and model_B narrows (testing AUROC: 0.877 vs. 0.890; training AUROC: 0.854 vs. 0.856), highlighting the influence of spatial partitioning and the limited generalisation gains once spatial dependence is accounted for. Model predictions were used to generate shallow landslide susceptibility maps for the Aosta Valley. Although both models

assign similar proportions of slope units to each susceptibility class, notable differences emerge in their spatial distribution, with class-specific discrepancies reaching up to 30%. Standard error analysis shows that the model including spatial tensor does not uniformly improve prediction confidence: uncertainty is reduced only in spatially clustered areas with potentially homogeneous geomorphological conditions and worsens elsewhere. This confirms a spatially selective benefit due to the inclusion of the spatial tensor, along with its limited contribution to the overall spatial generalisation. Landslide density patterns across susceptibility classes are consistent between training and testing subsets, supporting the robustness of the classification framework. Model_B yields slightly higher densities in the highest susceptibility class, whereas calibration analysis indicates marginally better probabilistic accuracy and stability for model_A. Overall, both models provide comparable and reliable representations of landslide susceptibility, revealing a trade-off between spatial sensitivity and calibration performance.