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Integrating climate change models and geological hazard inventories provides a new approach for resilient natural hazard management

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ABSTRACT: Recent climate models have revealed a significant intensification of seasonal climate dynamics over the past three decades, with projections indicating continued intensification up to the year 2100. Despite increasing traffic, future challenges will likely arise from the resulting variability in high-intensity rainfall or drought events in specific locations, as well as changes in vegetation on adjacent slopes. These long-term effects of climate change pose an additional challenge to the maintenance and safety of highways and railways. Changing environmental conditions and natural hazards affect infrastructure directly by causing damage and indirectly by accelerating deterioration. Identifying the primary climate parameters that control each hazard type and the zones of increasing vulnerability is a key challenge for the effective management of assets and hazards. This study combines geological event databases with climate models to identify the climate indices that control the spatial distribution of geological hazards, and to predict future event hotspots for the year 2100 and the RCP8.5 scenario. The results indicate that annual frost days and daily rainfall intensity are the primary climate indices influencing the regional occurrence of rockfalls, debris flows, and landslides. Potential new hazard zones and zones of increasing vulnerability were identified and linked to assets and terrain conditions to determine their local impact on the infrastructure. The results provide a flexible approach for the combined assessment of natural hazards and climate change models in geotechnical asset management.

KEYWORDS: Geological Hazards, Climate Change, Infrastructure Inspection, Natural Hazard Management

1 INTRODUCTION

The expansion of roads and railways into alpine terrain required the construction of infrastructure within areas with increased risk from geological hazards such as landslides, rockfalls and debris flows (Donnini et al., 2017; Klose et al., 2015). Protection from these hazards forms an integral part of asset management to ensure reliability, unimpeded access and reduce life cycle costs (Sanford Bernhardt et al., 2003; Shah et al., 2014). Current risk assessment strategies for infrastructure assets combine event inventories with susceptibility analysis to identify high-risk areas and evaluate the effectiveness of existing mitigation measures (Alcántara-Ayala and Sassa, 2023; Gransberg et al., 2018). The hazard inventories provide information on triggering factors, recurrence dates, and intensities of debris flows, landslides, and rockfalls. This information is usually derived from witness reports, geomorphological field assessments, or remote sensing (Bernat Gazibara et al., 2019; Del Ventisette et al., 2014; Lee and Jones, 2014). Combined with terrain models, land cover and traffic counts, these inventories are used to determine the specific risk for infrastructure and provide mitigation strategies (Alcántara-Ayala and Sassa, 2023; Gallina et al., 2016; Lee and Jones, 2014).

The downside of event-based risk models is their focus on past events and their limited ability to account for future conditions. Consequently, these models require regular revision and refinement to remain a reliable source for asset management. In addition, the effectiveness of existing protective infrastructure including retaining walls, rockfall protection structures, and basins should be systematically reviewed and adapted to meet future demands (Fuchs et al., 2012; Ward et al., 2020). Environmental changes significantly affect rock weathering, vegetation coverage, and the frequency of extreme precipitation events, thereby altering preconditioning and triggering factors for natural hazards (Kaitna et al., 2023; Mishra et al., 2023; Stoffel et al., 2024). Terrain and land cover changes can be effectively detected through the integration of remote sensing technologies and targeted field assessments conducted during extended inspections in critical zones. As temperatures, freeze–thaw cycles, and precipitation rates gradually shift, these dynamics pose additional challenges for accurate natural hazard risk assessments (Chimani et al., 2016). A central task in resilient hazard management is identifying the climate parameters that control geological hazards, enabling the delineation of future high-risk areas caused by climate change (Fuchs et al., 2012; Gransberg et al., 2018).

This paper presents a regional analysis of spatial relationships between climate change signals and the occurrence of landslides, rockfall and debris flow events along Austrian motorways. The core contribution lies in identifying the key climate indices that have historically governed the spatial clustering of hazard hotspots and subsequently applying these indices to forecast future high-risk zones. Event databases are integrated with climate scenarios, encompassing both the reference period from 1971–2000 and projections for the year 2100. Within these potential hotspot areas, a simplified terrain classification scheme is applied to assess local vulnerability and to guide adjustments in natural hazard management strategies. The goals are to: (i) uncover spatial relationships between climate indices and event density; (ii) use model-based climate change signals to pinpoint future hotspots; and (iii) implement the results for site-specific evaluation of climate change impacts in asset management. The findings support a GIS-based approach to delineating priority areas for remote-sensing-based monitoring and for refining existing mitigation measures.

2 RELATED RESEARCH

Simulations of hydrological and sediment transport processes suggest that the predicted reduction in winter precipitation will lead to fewer debris flow events in the Alpine region (Deganutti et al., 2018; Kaitna et al., 2023). This results in episodic high-intensity events following increased sediment accumulation and delayed mobilization. The findings align with broader international studies, that indicate that climatic shifts reduce the frequency of debris flows while amplifying episodic extreme events (Van Den Heuvel et al., 2016). Rising temperatures result in increased thermal stress and intensified freeze-thaw cycles acting on exposed rocks. These changes shift the seasonality of rockfalls toward warmer periods, accompanied by a rising magnitude and unpredictability of the events (Birien et al., 2024; Stoffel et al., 2024). The intensification of extreme rainfall has been strongly linked to an increase in shallow landslide events (Sharma et al., 2023; Zhao et al., 2025). A comprehensive impact analysis by Mishra et al. (2023) demonstrated that at least 10% of landslides during a major event in 2009 could be attributed directly to increased rainfall caused by anthropogenic warming. Similarly, Zhao et al. (2025) used machine learning and numerical simulations to show that rainfall-induced landslides are becoming more frequent and spatially extensive, with susceptibility zones expanding under future climate scenarios.

GeoSphere Austria conducted dedicated studies on the Austrian infrastructure as part of the project “clim_ect” (Fian et al., 2021) for Austrian railway lines and a climate risk assessment for the Austrian motorways (Ulrich, 2023). Both studies related climate change models to subsections of the corresponding infrastructure network and identified zones that would be affected by climate change. However, the event datasets were limited to records from asset owners. Additionally, selecting organizational network subsections as analytical units introduced artificial boundaries. In contrast, the presented study integrates publicly available event datasets with climate change projections, terrain conditions, route networks and infrastructure assets. This approach provides insight into regional event distributions and their local impacts on the scale of the route network. This approach offers a flexible and updatable framework that enables a dynamic evaluation of hotspots and the systematic adaptation of asset management strategies.

3 METHODS AND DATA SOURCES

3.1 *Research concept*

The analysis combines raster-based climate predictions and network-based infrastructure routes. The goal is to integrate past events and terrain conditions with climate records and predictions. The GIS-based analysis can be expanded flexibly with additional data during future evaluations. Dominant climate indices from the ÖKS15 scenarios (Chimani et al., 2016) are derived for each hazard type using spatial cross-correlation based on the reference epoch (1971–2000). These indices are further applied to predict upcoming hotspots for the 2100 epoch and the RCP8.5 scenario. The GIS-based inclusion of terrain conditions and infrastructure assets allows to adapt existing structures and mitigation processes to future challenges. The complete aggregation and spatial analysis process is summarized in Figure 1.

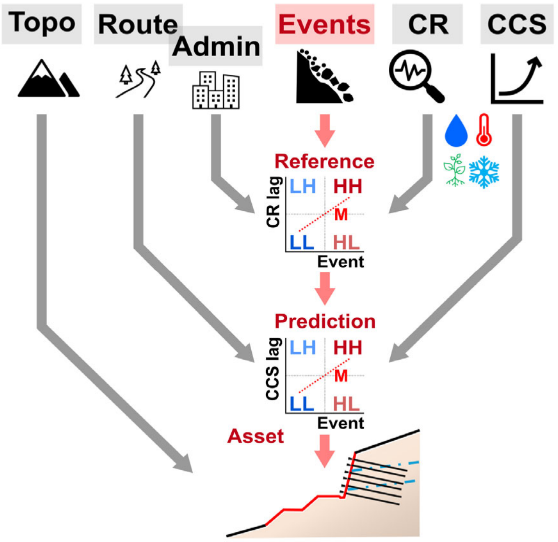

Figure 1. Analytical workflow for the combined analysis of hazards (events), climate records (CR), and climate change signals (CCS), as well as topographic conditions (topo), based on the Austrian terrain model (BEV, 2025) and the ÖKS15 scenarios (Chimani et al., 2016). Hotspots are identified by examining the spatial correlations between events and climate change scenarios on a regional scale and further evaluated using topographic information and asset locations.

3.2 Data Sources

The spatial analysis integrates regional event datasets provided by GeoSphere Austria (GeoSphere Austria, 2025) and the Service for Torrent and Avalanche Control (BMLUK/A14, 2025). These events are connected to the infrastructure network and the ÖKS15 climate scenarios (Chimani et al., 2016). The ÖKS15-scenarios represent the current model for the effects of climate change in Austria. The scenarios cover the reference period 1971-2000 (climate reference, CR), as well as the future impacts for the representative concentration pathways RCP4.5 (“moderate mitigation” scenario) and RCP 8.5 (“business as usual” scenario) scenarios (climate change signal, CCS). ÖKS15 utilizes a downscaled and bias-corrected version of the EURO-CORDEX climate simulations to deliver thermal, hydrological, and radiative climate indices at a high spatial resolution of 1x1 km. However, the practical application of ÖKS15 model has limitations due to the temperature bias from the reference period and the inability to account for localized extreme events and terrain conditions (Chimani et al., 2018). This study’s analytical approach mitigates these limitations by shifting the emphasis from absolute values to the spatial relationships between climate change indices and geological hazards.

3.3 Analytical Framework for spatial data analysis

The analytical framework is implemented in Python using GeoPandas (Jordahl et al., 2020) for data aggregation and the Spatial Analysis Library PySAL (Rey et al., 2023; Rey and Anselin, 2007) for spatial data analysis based on global and local Moran’s I statistics (Anselin, 1995; Moran, 1950). Moran’s I is a statistical measure of spatial autocorrelation that quantifies the extent to which the values of a variable are spatially clustered or dispersed across geographic locations, using a spatial weights matrix to define neighborhood relationships (regression line “M” in Figure 1). Spatial autocorrelation reflects the tendency for values within a dataset to form clusters in space, assessing whether nearby locations exhibit similar values (positive autocorrelation) or dissimilar values (negative autocorrelation). The local application of

Moran's I, combined with a statistical permutation test, classifies spatial patterns into five categories: High-high (HH) and low-low (LL) clusters (agglomerations of similar values); high-low (HL) and low-high (LH) outliers (significant contrasts to the surrounding areas); and areas with no statistically significant spatial autocorrelation. Hazard event locations that are surrounded by with spatial clusters of climate indices reveal locations where the two phenomena are significantly associated, highlighting potential risk zones (Dahal et al., 2023; Wang et al., 2024).

This study uses the co-occurrence of events and climate records (CRs) within the reference timeframe to identify the climate parameters that control spatial clustering and to locate future hotspots. The spatial interaction of each variable is measured by its spatial lag, which describes the weighted average value in each neighborhood ("CR lag" or "CSS lag). The neighborhood structure is defined by a spatial weights matrix. This matrix can be either contiguity-based, using edge-only contacts ("rook" geometry), or edge- and corner-based ("queen" geometry). Alternatively, it may be distance-based, such as through distance bands or k-nearest neighbors (Rey et al., 2023). The significance of Moran's I analysis is evaluated with 999 random permutations and a threshold pseudo p-value of 0.05 to differentiate significant spatial clusters from those that could have occurred randomly.

The climate indices "precipitation amount" (rr), "number of wet days" (rr1), "daily rainfall intensity" (sdii), "temperature" (tm), "growing season length" (gsl), and "frost days" (fd0) were derived from the ÖKS15 dataset. During the reference period from 1971 to 2000, the occurrence of geological hazards influenced by these parameters was analyzed using municipal boundaries for event aggregation. Administrative units were favored over regular sampling grids in the regional analysis, because they more accurately capture variations in topography and population density. Spatial relationships were represented using a queen contiguity spatial weights matrix, where neighboring units share borders or corners.

Future hotspots along motorways are derived from a route-based buffer that integrates events, terrain features, and projected climate change indicators for the year 2100 ("CCS", scenario RCP 8.5). The road network was divided into 25-meter segments, each of which was defined by three spatial perimeters that were parallel to its central axis: central (20 meters), inner (30 meters), and outer (90 meters). Hazard events were linked to these segments using a 1000-meter buffer. Unlike the regional analysis, the road-based approach used a distance-based spatial weights matrix with a 5-kilometer threshold, prioritizing proximity over administrative boundaries to model interactions along transportation corridors. Empty segments along the road without events were removed to avoid bias effects. Additionally, the average elevation of each cell was extracted from the Austrian elevation model (BEV, 2025) to assess topographic conditions. Elevation differences between the central and inner perimeters were used to classify road segments into five topographic categories: "flat," "embankment," "slope, crest," "slope, toe," and "slope". A threshold of >1.1 meters in mean elevation difference was set to distinguish cuts from embankments. This corresponds to a slope angle of 34 degrees over a 10-meter width averaged across the inner perimeter. These classifications provide insights into geotechnical vulnerability at the segment level and inform remote sensing–based monitoring strategies and the refinement of existing mitigation measures.

4 RESULTS

4.1 *Spatial clustering of geological hazards*

The consolidated hazard inventories provided by the Service for Torrent and Avalanche Control and GeoSphere Austria include a total of 18 000 landslides, debris flows and rockfall events. Debris flows and landslides make up roughly 85% of the records, while rockfalls account for the remaining 15%. These proportions remain largely consistent within the route-based analysis perimeter (Table 1). Positive global Moran's I values indicate that high-hazard areas form regional concentrations or clusters. The effect is more prominent for debris flows than for rockfalls. In contrast, landslides tend to be more randomly distributed, with only limited tendency to form localized high-intensity clusters.

Table 1. Global spatial autocorrelation of rockfall, debris flow, and landslide events. The associated Global Moran's I values indicate the degree of spatial clustering (p-values are based on 999 permutations).

Event	Total Events	Events in Road Perimeter	Morans'I	p_{sim}
Rockfall	2877	240	0.19	0.001
Debris Flow	7585	546	0.33	0.001
Landslide	7565	640	0.13	0.001

The bivariate analysis of the reference period from 1971 to 2000 revealed that debris flow and rockfall events predominantly occur in regions with a high number of annual frost days (fd0) as shown in Table 2 and Figure 2A. In contrast, these events are negatively correlated with higher temperatures and longer vegetation periods. Similar to the global analysis, the cross-correlation of landslide events with climate parameters is less pronounced, with daily rainfall intensity (sdii) emerging as the primary factor.

Table 2. Bivariate analysis of geological hazards and climate indices based on municipal boundaries and climate indices for the ÖKS15 reference period (1971-2000). fd0 = annual frost days; sdii = daily rainfall intensity; gsl = growing season length; tm = air temperature.

Event	Climate Index (+)	Morans'I	Climate Index (-)	Morans'I
Rockfall	fd0	0.21	gsl	-0.23
Debris Flow	fd0	0.34	tm	-0,34
Landslide	sdii	0.13	tm	-0.12

The local hotspot analysis for the future scenario integrates climate change signals that correspond to indices that were positively correlated with event clusters during the reference period. Annual frost days were selected as a proxy for rockfalls and debris flows, while daily rainfall intensity was selected for analyzing landslides. The temperature increase resulting from climate change leads to a general reduction in frost days and a shift in areas of high precipitation to the Alpine foreland. Consequently, most results plot in the high–low (HL) Moran's I quadrant (Figure 2B), representing sites that were affected by past events but exhibit relatively low future conditioning factors (negative Moran's I). In contrast, high-high (HH) zones, where frequent past events coincide with rising climate indices, signal emerging hotspots. Projected HH clusters for rockfalls and debris flows are – for example – frequent along the A10 and A12 motorways, and the A2 in Carinthia. Emerging landslide hotspots appear in the northern and southern alpine forelands, particularly along the A2 in Carinthia and at the Styrian–Lower Austrian border and along the A1 in Upper Austria. While high-high zones (HH) reflect an unfavorable combination of past events and an increase in the conditioning factor, the effect of low-high (LH) zones is more complex. These are clusters of low event activity, surrounded by zones with increased climate parameters. Depending on the topography, these areas pose a potential future risk, that should be considered in natural hazard management and regular infrastructure asset inspection.

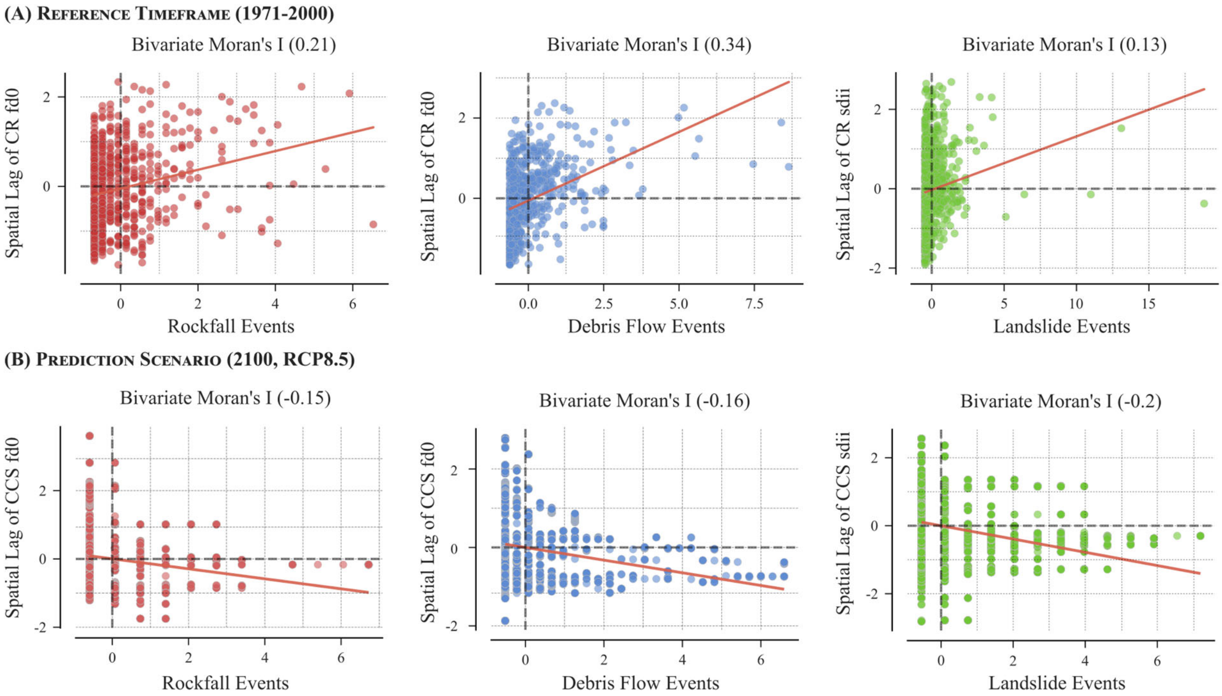

Figure 2. Bivariate Moran's I (z-standardized) for the (A) reference epoch and (B) prediction epoch. Rockfall and debris flow are associated with frost days (fd0) while landslides are associated with rainfall intensity (sdii). Note the shift from positive to negative spatial autocorrelation.

4.2 *Local impacts on asset management*

Both HH (indicating areas of increasing vulnerability), and LH zones (representing potential locations for future events), are critical areas for the adaptation of natural hazard and asset management strategies. However, the analytical concept does not explicitly account for topographic conditions, or the specific assets located within these hotspots. This limitation can be overcome by integrating structural and geotechnical assets, such as bridges and retaining walls, with detailed terrain data to improve risk assessment and strategic planning. Assets positioned on slopes—categorized as “cut,” “slope base,” and “slope”—are especially prone to geological hazards, while embankments typically face lower exposure.

Figure 3 illustrates the combination of GIS-based spatial cluster analysis and terrain classification, focusing on a subsection of the A10 motorway in Salzburg, Austria. The region features steep valley flanks, tectonically stressed rock formations, karstified mountains, and extensive Quaternary sediment deposits along the valley floor. Both the A10 motorway and the Salzburg–Villach railway line are exposed to considerable geological hazards (Bechtold, 1990; Schober and Delleske, 2017). South of Golling, the A10 crosses the Salzach Valley, where the Ofenau Tunnel briefly surfaces after passing beneath the Arbeskogel, before continuing under the Große Hiefler (km 31; Figure 3A). In this section, the 400-meter-high rock slope of the Arbeskogel poses a serious rockfall threat to the Salzach bridges and has been designated as a future high-risk zone (HH) for rockfall events. Similarly, the subsection between motorway km 38.5 and 41.5, which intersects several active torrent channels, is increasingly vulnerable to debris flows (Figure 3B). Future high-risk assets are located at cut slopes, bridge abutments, and especially where the motorway intersects contributing channels (marked with star symbols in the figure). In contrast, the risk of landslides is projected to decline due to anticipated reductions in rainfall intensity in the region. The integrated analysis has enabled the identification of future hazard-prone sections along the route and highlighted areas where current hazard management strategies should be proactively revised and adapted to future challenges.

5 DISCUSSION

The evaluation revealed a significant geographic correlation between climate indices and the occurrence of geological hazards. The key climate indicators frost days (fd0) and daily rainfall intensity (sdii) controlling the spatial clusters are consistent with previous studies, that identified both parameters as crucial for weathering and mass movements. The findings confirm the research goal (i) and provide the starting point for the inclusion of climate parameters in natural hazard models. There is a marked westward increase of debris flow and rockfall clusters, with both events being particularly prevalent in areas with steep torrents and exposed rock faces (Kaitna et al., 2023; Stoffel et al., 2024). In contrast, landslides exhibited relatively low spatial clustering, reflecting their tendency to occur wherever terrain or ground conditions are unfavorable, rather than being concentrated in specific areas. This pattern can be attributed to the distinct triggering factors for landslides, which are generally more influenced by anthropogenic activities (e.g. land use, construction) than debris flows and rockfalls. This result is consistent with previous studies that linked climate variables to an increase in landslide activity. However, these studies have also stated that local factors, such as topography and ground conditions, appear to play a more significant role (Gariano and Guzzetti, 2016; Mishra et al., 2023). Future hotspots of increased vulnerability (HH and LH zones) align with existing hazard models and provide focus areas for the adaptation of natural hazard management. This result supports research goal (ii), offering a model framework for the network-wide identification of priority areas. The specific focus on spatial relationships provides a flexible framework in which key components, such as climate indices and events, can easily be updated and expanded with additional data. However, the coarse resolution and the inherent bias of large-scale climate models require additional local assessments to verify the results. This can be achieved by including geotechnical and structural assets, as well as an additional terrain model (research goal iii). Without this additional data, areas beneath motorway slopes experiencing rockfalls would be classified as high-risk zones.

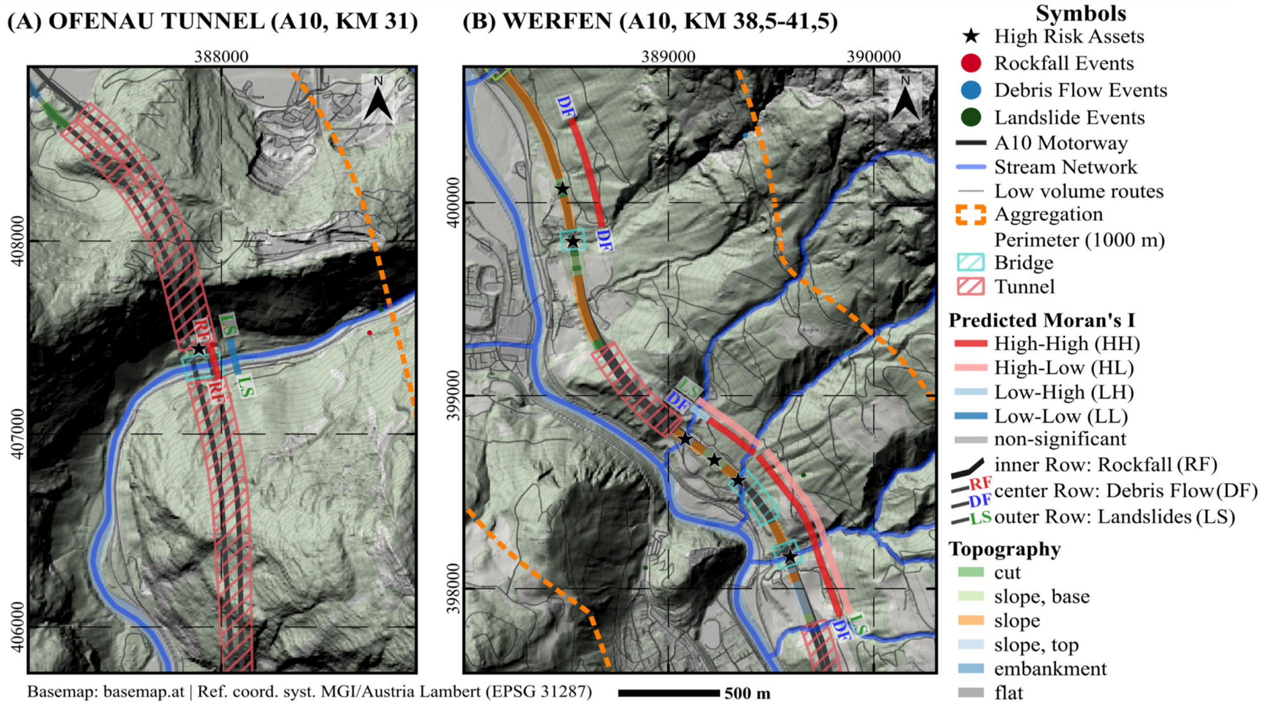

Figure 3. Local Evaluation of the analytical results along the A10 Tauern motorway between Golling an der Salzach and Werfen (Salzburg, Austria). The predicted Moran's I was aggregated in linear segments running parallel to the motorway. (A) Rockfall hazard affecting the portal area of the Ofenauer Tunnel; (B) Torrent channels exhibiting an increased risk potential for bridge abutments and piers.

Although zones with low event density and climate impact do not require proactive mitigation measures, the analysis revealed several zones do require active focus. The suggested focus for natural hazard management, as outlined in the proposed analytical framework, is summarized in Table 3.

Table 3. Suggested focus for natural hazard management strategies based on bivariate spatial cluster analysis of events and climate indices.

Quadrant	Event Activity	Climate Impact	Management focus
HL	High	Low	Maintain existing measures including periodic review
HH	High	High	Expand the inspection and monitoring perimeter; adapt structures and mitigation measures
LH	Low	High	Expand inspection and monitoring perimeter; include remote sensing methods
LL	Low	Low	Keep standard monitoring and inspection process.

In zones where activity and climate change effects are both high (HH), the resilience of the existing infrastructure against changing boundary conditions should be evaluated. In road sections where recorded activity and predicted change of the climate index are both high (HH), the resilience of the existing infrastructure against changing boundary conditions should be evaluated. The same applies to zones with a low incidence of events but significant changes in climate indices, particularly if they are in regions with adverse topographic conditions (LH zones). These areas pose a potential future hazard to infrastructure if changes in land use or morphology create the necessary preconditions. Road sections traversing areas with known hazards and reduced climate impact (HL zones) remain problematic.

6 CONCLUSIONS

Combining a spatial analysis of climate change models and geological hazard events enabled us to identify the controlling climate parameters and future hotspot zones. Based on the results, the following conclusions can be drawn:

- There is a strong connection between frost action and local clusters of debris flow and rockfall events. This relationship includes both environmental and climate impacts, enabling the identification of future high-risk zones based on climate models.
- Landslide events behave differently, primarily being controlled by local conditions and only secondarily affected by climate. Therefore, monitoring land use or changes to it should be a priority in regions affected by landslides.
- Including asset classes and terrain conditions enables the predicted results to be accurately integrated into the asset management strategy and enables high-risk assets to be identified.

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