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Multi-Sensor Satellite Detection of Rapid Landslide Activation in the Ukrainian Carpathians: a Case Study of the January 2024 Event Using Sentinel-1 SAR and Sentinel-2 NDVI in Google Earth Engine

***O. Stelmakh** (*Ivano-Frankivsk National Technical University of Oil and Gas*), **K. Hadiatska** (*Taras Shevchenko National University of Kyiv*), **L. Shtohryn**, **D. Kasiyanchuk** (*Ivano-Frankivsk National Technical University of Oil and Gas*)

SUMMARY

Rapid mass movement events in forested mountain terrain are frequently under-documented due to limited ground access, particularly in the immediate aftermath of the triggering episode. The landslide of 26 January 2024 in Krasnenska Forestry, Dubivska hromada (Tyachiv district, Zakarpattia Region, Ukrainian Carpathians) exemplifies this challenge: the event mobilised a large debris mass on a steep flysch slope, causing significant damage to forest stands and infrastructure, yet quantitative characterisation of its geometry and spatial extent required remote sensing analysis. This study presents a cloud-based, reproducible workflow for rapid landslide detection and area quantification implemented entirely within Google Earth Engine (GEE), combining Sentinel-1 Synthetic Aperture Radar (SAR) backscatter change detection with Sentinel-2 Normalised Difference Vegetation Index (NDVI) difference mapping. The analysis zone was constrained to a 500 m buffer around roads within slopes exceeding 5° – a spatial filter designed to focus detection on geomorphologically susceptible terrain with infrastructure exposure. SAR change detection applied dual-channel thresholding ($\Delta VV < -1.5$ dB and $\Delta VH < -1.5$ dB) on pre-event (December 2023 – January 2024) and post-event (January – March 2024) Sentinel-1 IW descending-orbit acquisitions. Vegetation disturbance was quantified via dNDVI > 0.15 between a cloud-free pre-event scene (2023-08-29) and a post-event scene (2024-06-21). Spatially intersected SAR and NDVI change masks were vectorised and filtered by minimum area threshold. Slope-corrected surface areas were computed using SRTM-derived cosine correction. Ground-truth validation was provided by the State Enterprise "Forests of Ukraine", confirming the presence and approximate location of the landslide body on the identified slope section. The largest detected landslide body reached a horizontal projected area of 3.64 ha and a slope-corrected surface area of 3.86 ha.

Keywords: Landslide detection; SAR; NDVI; Sentinel; Carpathians.

Corresponding Author: oleh.stelmakh-hz231@nung.edu.ua

Introduction

The Ukrainian Carpathians represent one of the most landslide-prone mountain regions in Central Europe, where flysch lithology, steep terrain, and pronounced precipitation seasonality combine to produce frequent slope failures. The event of 26 January 2024 in Krasnenska Forestry (Dubivska hromada (territorial community), Tyachiv district, Zakarpattia Region) followed an episode of intense rainfall and snowmelt, triggering a rapid translational slide on a northwest-facing slope. The State Emergency Service of Ukraine (SESU) classified the event as a significant geohazard incident affecting forest stands and local road infrastructure (SESU, 2024). However, precise delineation of the landslide body and quantification of the affected area remained unavailable from ground surveys alone due to difficult access in the immediate post-event period.

Satellite remote sensing offers an operational alternative for rapid post-event landslide mapping, particularly where field accessibility is limited (Mondini et al., 2021). Sentinel-1 C-band SAR is well suited to densely vegetated terrain where optical imagery is obstructed by cloud cover, as surface roughness changes from mass movement cause measurable backscatter decreases detectable shortly after an event (Burrows et al., 2022; Bianchi & Grahn, 2025). Studies have demonstrated that Sentinel-1 backscatter change detection can identify landslide bodies in forested landscapes even under unfavorable conditions, especially when combined with automated classification (Phakdimek et al., 2023). Sentinel-2 multispectral imagery complements this through NDVI differencing, which effectively captures abrupt vegetation loss from slope failures and distinguishes landslide scars from agricultural, seasonal, or anthropogenic anomalies (Lindsay et al., 2026; Hadiatska et al., 2025; Ivanyshyn et al., 2024). The integration of SAR amplitude change with relative NDVI differencing (rdNDVI) significantly improves detection accuracy over single-sensor approaches in complex mountainous terrain (Deijns et al., 2020; Phakdimek et al., 2023; Fu et al., 2024). Implementing such workflows within Google Earth Engine enables rapid, scalable, and reproducible analysis without local computational infrastructure, which is increasingly critical for near-real-time geohazard assessment and emergency response (Fu et al., 2024; Davybida, 2025).

The present study demonstrates this integrated workflow on the January 2024 Krasnenska landslide event, with three objectives:(I) to detect and spatially delineate landslide-affected terrain using SAR backscatter change detection and NDVI differencing; (II) to quantify the affected area using slope-corrected surface area calculation; and (III) to validate detection results against field confirmation provided by the State Enterprise “Forests of Ukraine”.

Method and Theory

The analysis was implemented in Google Earth Engine (GEE) following a seven-step workflow (Figure 1). All computations were performed at 10 m spatial resolution, with the study area (AOI) defined by the administrative boundary of Dubivska hromada. The AOI encompasses the Dubivska hromada territory in Tyachiv district. The analysis zone was spatially constrained to the intersection of: (a) a 500 m buffer around the road network, reflecting the infrastructure-exposure dimension of landslide risk; and (b) terrain with slope angle exceeding 5°, derived from the USGS SRTM GL1 30 m DEM. This spatial filter reduces false positive detections in flat agricultural areas while targeting the geomorphologically susceptible terrain relevant to the 2024 event.

Change detection and spatial integration

Sentinel-1 SAR change detection. Sentinel-1 Ground Range Detected (GRD) images were retrieved from the COPERNICUS/S1_GRD collection, filtered to Interferometric Wide (IW) swath mode, descending orbit pass, and dual polarisation (VV+VH). Edge pixels below −30 dB were masked to remove acquisition artefacts. The pre-event image was the latest available acquisition in the period 15 December 2023 – 20 January 2024; the post-event image was the earliest available acquisition in the period 27 January – 1 March 2024. Backscatter difference was computed independently for VV and VH channels. A decrease threshold of −1.5 dB was applied to each channel, yielding two detection classes: (1) single-channel change (VV or VH); (2) dual-channel change (both VV and VH). Class 2 indicates stronger surface modification and was considered the primary indicator of landslide-induced backscatter suppression consistent with vegetation removal and soil exposure.

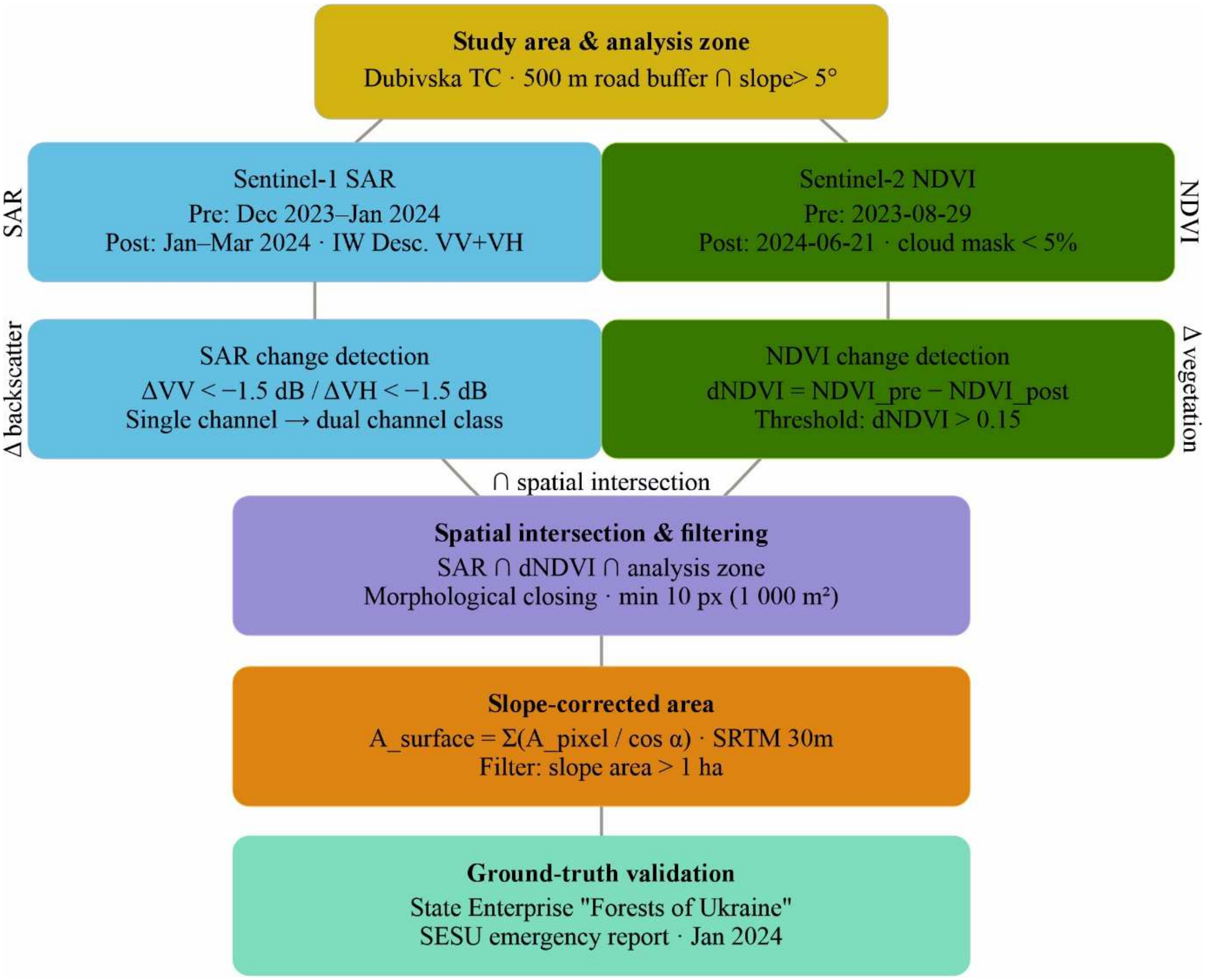

Figure 1. *Processing workflow for multi-sensor landslide detection and area quantification in Google Earth Engine*

Sentinel-2 NDVI differencing. Sentinel-2 Surface Reflectance imagery (COPERNICUS/S2_SR) was filtered for the AOI. Cloud masking applied the scene-level cloud probability band (MSK_CLDPRB < 5%). The pre-event image with minimum cloud cover in the summer growing season (2023-06-01 – 2023-09-15) was the acquisition of 29 August 2023; the post-event image was the acquisition of 21 June 2024, selected from the 2024 growing season after vegetation re-establishment had begun. NDVI was computed as $(B8 - B4)/(B8 + B4)$. The difference $dNDVI = NDVIpre - NDVIpost > 0.15$ was used as the vegetation disturbance threshold, consistent with published thresholds for Carpathian forest disturbance mapping (Hadiatska et al., 2025).

Spatial integration and area calculation. The refined landslide mask was computed as the spatial intersection of the dual-channel SAR change mask, the NDVI disturbance mask ($dNDVI > 0.15$), and the analysis zone. Morphological closing (dilation followed by erosion, circular kernel radius = 1 pixel) was applied to merge spatially adjacent detections. Objects smaller than 10 connected pixels (~1,000 m²) were removed. The resulting raster was vectorised using 8-connectivity at 10 m scale. Slope-corrected surface area was computed as $A_{surface} = \Sigma\ A_{pixel} / \cos(\alpha)$, where α is the slope angle at each pixel from the SRTM DEM. Only polygons with slope-corrected area > 1 ha were retained for final analysis.

Results

The multi-sensor detection workflow identified multiple landslide-affected polygons within the analysis zone. After morphological filtering and minimum-area thresholding, detected objects ranged from 0.070 ha to 3.638 ha in horizontal projected area. After applying the slope-corrected area filter (> 1 ha), the largest event-related landslide body was characterised by a projected horizontal area of 3.638 ha and a slope-corrected surface area of 3.863 ha (Figure 2). The mean difference between projected and slope-corrected area across all detected objects was +4.5%, with individual objects reaching up to +52.1% correction on the steepest slopes – confirming that projected area measurements systematically underestimate true disturbed surface extent in Carpathian terrain. The SAR dual-channel class (both VV and VH decreased by > 1.5 dB) coincided spatially with the core of the NDVI anomaly (dNDVI up to 0.40+ in the landslide scar), indicating complete vegetation removal over the main depositional lobe. Peripheral areas showing single-channel SAR change only were characterised by lower dNDVI values (0.15–0.25), consistent with partial canopy disturbance rather than full scarp exposure. The landslide body is elongated along the slope aspect (northwest-facing), with a length-to-width ratio of approximately 4:1, typical of translational slides in flysch lithology (Shtohryn et al., 2026).

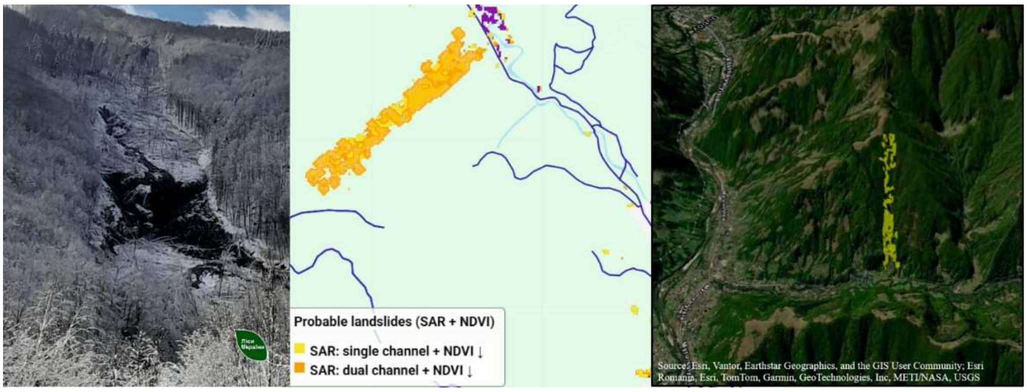

Figure 2. *Google Earth Engine detection results: Dubivska hromada, Tyachiv district, Zakarpattia Region, January 2024*

Conclusions

This study demonstrates a reproducible, cloud-native workflow for rapid post-event landslide detection and area quantification using freely available Sentinel-1 SAR and Sentinel-2 NDVI data in Google Earth Engine. Three principal findings are reported. First, the integration of dual-polarisation SAR backscatter change detection (ΔVV and ΔVH, threshold −1.5 dB) with NDVI differencing (dNDVI > 0.15) substantially reduces false positives relative to either sensor alone: SAR detects surface roughness change regardless of canopy closure, while NDVI differencing discriminates vegetation removal from non-vegetated change sources such as seasonal snowcover or agricultural surfaces.

Second, slope-corrected surface area calculation using SRTM-derived cosine correction reveals a mean 4.5% underestimation of true disturbed area by projected measurements across the study population, with individual objects on steep flysch slopes showing corrections exceeding 50%. This has direct implications for damage assessment, timber volume estimation, and erosion modelling – all of which are conventionally based on projected area data. Third, the validated detection of the 26 January 2024 Krasnenska landslide (3.86 ha slope-corrected area, confirmed by the State Enterprise "Forests of Ukraine") establishes the operational readiness of the proposed workflow for institutional integration into the Ukrainian geohazard monitoring system. Future work should address: (I) temporal density improvement using the full Sentinel-1 six-day repeat cycle to constrain event timing; (II) automated threshold optimisation via ROC analysis against expanded inventory data; and (III) extension of the workflow to systematic monitoring of all road-proximal slopes in the Carpathian region.

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