

COMPARING MULTIPLE SOURCE SPATIAL DATA FOR LANDSLIDE MAPPING

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Abstract

When a landslide occurs, one of the most challenging tasks is to provide detailed maps for area analysis, enabling geotechnical engineers, other experts, and authorities to determine appropriate protection and remediation measures. For such analysis, it is important to obtain a comprehensive view of both the landslide area and the surrounding terrain. This paper presents multiple mapping data sets for the landslide that occurred in the village of Gornja Plemenščina, Croatia. Spatial data used for the analysis of this landslide were generated from four independent sources. The first source is spatial data collected using a classical geodetic surveying method with a GPS RTK device. The next two sources are spatial data collected using modern, advanced surveying methods with UAS, employing two different types of sensors: an RGB camera for photogrammetry and a LiDAR sensor. The fourth spatial data set is LiDAR data provided by the Croatian State Geodetic Administration. The analysis of all these spatial data sets, combined and merged into a single map, compares the advantages and disadvantages of each data set used for landslide mapping.

Keywords

Landslide, Mapping, GPS, UAV, Photogrammetry, LiDAR, Spatial Data

1 Introduction

Landslides are a significant natural hazard in many parts of the world, especially in regions with complex geological conditions, steep terrain, and intense precipitation. Their occurrence often causes substantial damage to infrastructure, disrupts human activities, and, in severe cases, leads to loss of life. Immediately following landslide events, engineers, geoscientists, and decision-makers are confronted with the critical task of efficiently acquiring high-precision, high-resolution geospatial data for comprehensive terrain assessment and hazard analysis. High-quality mapping of the affected area is essential for understanding landslide mechanisms, assessing stability conditions, and designing effective remediation and protection measures.

Traditionally, landslide mapping has relied on classical geodetic surveying techniques, which, although highly accurate, are often time-consuming and limited in spatial coverage. With advances in geospatial technologies, new methods have emerged that significantly improve the efficiency and resolution of terrain data acquisition. In particular, Unmanned Aerial Systems (UAS) equipped with various sensors have become increasingly important tools for rapid and detailed terrain mapping. Their use in landslide investigations has been demonstrated in previous studies, highlighting their ability to provide high-resolution data and improved access to hazardous or difficult-to-reach areas (Car et al., 2016).

Despite these technological advances, each data acquisition method has its own advantages and limitations regarding accuracy, resolution, cost, processing requirements, and suitability for specific terrain conditions. Consequently, a key question in contemporary landslide studies is how to effectively integrate multiple data sources to produce a comprehensive and reliable representation of the terrain. As noted by Car et al. (2016),

UAS-based techniques significantly enhance data quality and efficiency, but their optimal use often depends on integration with other surveying approaches.

This paper addresses these challenges by analysing a landslide which occurred in the village of Gornja Plemenščina, Croatia. The study focuses on generating and comparing multiple spatial data sets from four independent sources: classical geodetic surveying using GPS RTK technology, UAS-based photogrammetry with an RGB camera, UAS-based LiDAR surveying, and airborne LiDAR data provided by the Croatian State Geodetic Administration. By integrating these diverse data sets into a unified mapping framework, the research evaluates their respective performance and identifies optimal approaches for landslide mapping, building on methodologies discussed in earlier research.

The main objective of this study is to provide insights into the strengths and weaknesses of different surveying techniques and to demonstrate the benefits of data fusion in improving the quality and completeness of landslide maps. The results support more informed decision-making in hazard assessment and risk mitigation, aiding the development of effective and timely responses to landslide events.

2 Study Area and Landslide Description

The study area is a landslide in the village of Gornja Plemenščina in Krapinsko-zagorska County, northern Croatia located at E=443754 and N=5116005 (HTRS96/TM coordinates, EPSG:3765), with approx. landslide area of 2800 square meters, a hilly region with a high incidence of landslides. Krapinsko-zagorska County is considered one of the most landslide-prone regions in Croatia, with approximately 6,600 documented landslides, of which 76 have been remediated between 2013 and 2025, reflecting significant ongoing risk and management efforts (Zagorje.com, 2025).

The landslide analyzed in this study (Figure 1.) affected a slope with a distinct head scarp and displaced material downslope, representing typical shallow to medium-depth slope failures in the region. Vegetation is present over much of the area, which influences the effectiveness of GPS and UAS photogrammetry-based survey methods, but not LiDAR methods.

Gornja Plemenščina was selected for this case study because it represents common landslide conditions in Krapinsko-zagorska County and provides access to multiple spatial datasets, including classical field surveys, UAS-based photogrammetry and LiDAR, and airborne LiDAR data. This enables a practical comparison of mapping techniques under realistic field conditions.



Figure 1. High resolution orthophoto map showing outer contours of the landslide in red color

3 Data Acquisition

Spatial data for the Gornja Plemenščina landslide were obtained from four independent sources to enable comprehensive mapping and comparison of methods. The first dataset was collected using Real-Time Kinematic (RTK) GNSS surveying, providing high-precision point measurements across the landslide area. RTK GNSS enables centimetre-level positioning suitable for establishing control points and validating remote sensing products (Jakopec et al., 2023).

The second dataset was acquired using an Unmanned Aerial System (UAS) equipped with an RGB camera. UAS photogrammetry is widely applied in landslide research to generate dense point clouds, digital terrain and surface models, and orthomosaic images, which support detailed representation of terrain features (Raji et al., 2022). Despite its high resolution, photogrammetry can be limited by surface cover when penetrating vegetation.

The third source was UAS-mounted LiDAR, which emits active laser pulses to capture highly accurate three-dimensional point clouds. UAS LiDAR is particularly effective in vegetated or complex terrain because it can penetrate foliage and produce reliable ground returns (Puig et al., 2019).

Finally, airborne LiDAR data made available through national surveying efforts were incorporated as a baseline dataset. Airborne LiDAR provides consistent coverage over larger areas and serves as a reference against locally acquired datasets (LandSlidePlan, 2021).

The integration of these four datasets enables a robust assessment of each method's strengths and limitations for landslide mapping.

3.1 GPS RTK Survey

The first dataset for the Gornja Plemenščina landslide was acquired using Real-Time Kinematic (RTK) GNSS surveying, a classical geodetic technique providing high-precision positional data. RTK GNSS relies on a base station transmitting correction signals to a rover unit, enabling real-time determination of coordinates with centimetre-level accuracy. This method is widely used for landslide mapping, monitoring and deformation analysis, providing a reliable reference framework for validating remote sensing datasets and geospatial products (Huang, Du and Wang, 2023).

Field measurements focused on key features of the landslide, including the head scarp, displaced material downslope, toe, and surrounding stable points. These points were selected to accurately capture both the geometry of the affected slope and the variability of the adjacent terrain and approx. 270 points were surveyed for this location. The high positional accuracy of RTK measurements allows digital surface models from photogrammetry or LiDAR to be precisely georeferenced.

Despite its precision, RTK GNSS has limitations in coverage and accessibility, especially in steep, heavily vegetated, or otherwise difficult terrain. Measurements require line-of-sight between the base station and rover, and extensive surveys can be time-consuming.

Mapping the Gornja Plemenščina landslide using RTK GNSS proved particularly challenging due to restricted accessibility both within and around the landslide, primarily caused by dense vegetation and hazardous terrain. Nevertheless, RTK remains essential for landslide mapping, providing a robust foundation for calibration and validation of modern remote sensing datasets.

3.2 UAS Photogrammetry

The second dataset for the Gornja Plemenščina landslide was acquired using an Unmanned Aerial System (UAS) equipped with an RGB camera shown in Figure 2., a method increasingly applied in landslide research for high-resolution terrain mapping. UAS photogrammetry employs Structure-from-Motion (SfM) algorithms to reconstruct dense three-dimensional point clouds, enabling the generation of digital surface models (DSMs), orthomosaic images, and high-resolution topographic maps (Westoby et al., 2012). This technique allows rapid coverage of large and complex areas, providing detailed visual and geometric information critical for landslide assessment and monitoring.

Flight mission was planned to ensure sufficient longitudinal and lateral image overlap, typically between 70–80%, to enhance image matching and reduce reconstruction errors. Ground control points, obtained from RTK GNSS survey, were used to georeference the photogrammetric products, ensuring spatial accuracy and compatibility with other datasets (Huang, Du and Wang, 2023). The RGB imagery captured both the landslide area and surrounding terrain, allowing detailed delineation of the head scarp, displaced mass, accumulation zones, and adjacent stable slopes.

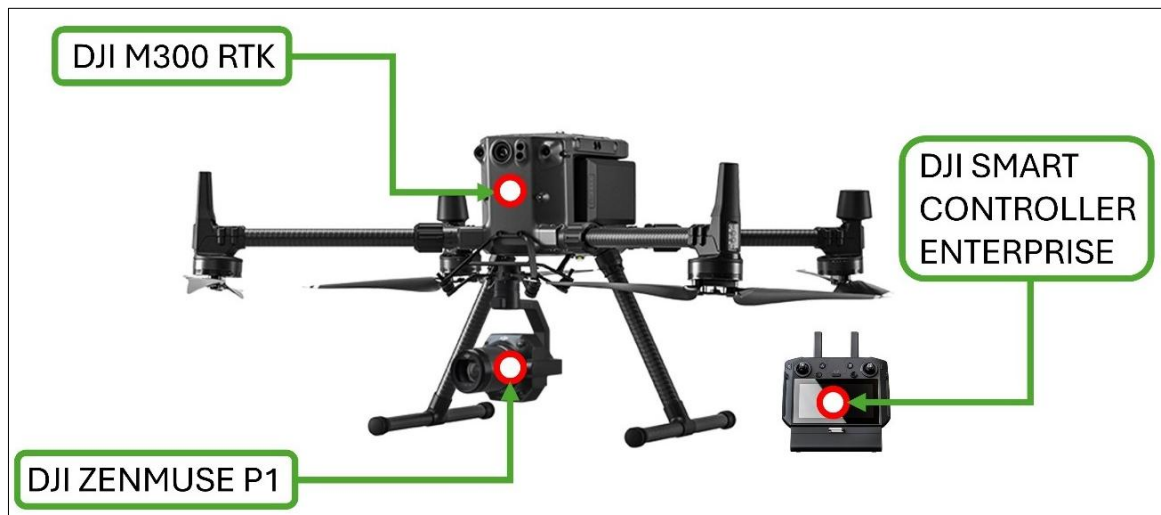


Figure 2. UAS with attached full frame RGB digital camera

While UAS photogrammetry provides high spatial resolution and rapid data acquisition, its accuracy is influenced by environmental conditions and surface cover. Dense vegetation (which was the case for Gornja Plemenčcina landslide), steep slopes, or shadows can obstruct the ground surface, reducing the completeness and precision of the generated DTM (Digital Terrain Model). Consequently, integration with LiDAR or RTK GNSS datasets is often required to fill gaps and validate measurements (Jaboyedoff et al., 2012). Additionally, weather conditions, battery limitations, and regulatory restrictions may constrain flight duration and survey planning.



Figure 3. Photogrammetry 3D point cloud of Gornja Plemenčcina landslide marked with red line and surrounding area

The final photogrammetry 3D point cloud shown in Figure 3, produced by SfM contained 108 million of georeferenced points, representing the landslide surface with centimetre-scale horizontal and vertical resolution. This point cloud served as the basis for generating DSMs and orthophotos, and it allowed quantitative analysis of slope geometry, volumetric estimation of displaced material, and detection of micro-topographic features. Although high-resolution, the point cloud accuracy can be affected by dense vegetation or steep slopes, potentially resulting in local gaps or noise.

Overall, RGB-based UAS photogrammetry provides a cost-effective and flexible method for landslide mapping, complementing traditional surveys and other remote sensing techniques. Its ability to rapidly capture high-resolution imagery makes it a valuable tool for assessing surface morphology, monitoring changes over time, and supporting hazard analysis and risk mitigation strategies.

3.3 UAS LiDAR Survey

The third dataset for the Gornja Plemenščina landslide was acquired using a UAS-mounted Light Detection and Ranging (LiDAR) system, specifically the DJI L1 sensor, which integrates a LiDAR scanner with an RGB camera. This sensor was operated in triple-return mode, allowing each emitted laser pulse to record up to three distinct returns. Triple-return capability is essential in densely vegetated or forested areas because it enables the capture of canopy, understory, and bare-earth surfaces, ensuring a comprehensive 3D representation of the terrain (DJI, 2022; Persico et al., 2020).

Flight missions were carefully planned with 70% front and 70% side overlaps to optimize point density, and terrain coverage resulting in creating 55 million points. Mission parameters were adjusted according to slope steepness, vegetation density, and the extent of the landslide area. The DJI L1 system, with its integrated RGB camera, allowed simultaneous collection of imagery for visual interpretation and point cloud colorization. Onboard GNSS and IMU data provided preliminary georeferencing, while RTK GNSS ground control points were used to enhance spatial accuracy and ensure alignment with datasets obtained from UAS photogrammetry and field RTK surveys (Huang, Du and Wang, 2023). This integration facilitated the generation of high-resolution digital terrain models (DTMs), slope gradient maps, and 3D visualizations, which are critical for analyzing landslide geometry and potential hazard zones.

The final LiDAR point cloud generated for the Gornja Plemenščina landslide consisted of 55 million georeferenced points shown in Figure 4. with centimeter-level vertical accuracy. Triple-return data enabled the differentiation of vegetation layers and ground surfaces, allowing accurate measurement of the landslide morphology, detection of micro-topographic features, and volumetric estimation of displaced material. Compared to photogrammetric point clouds, LiDAR demonstrated superior performance in areas with dense vegetation, shadows, or steep slopes, where optical imagery often fails to capture underlying terrain accurately. This high-density, multi-layered point cloud provided a robust dataset for slope stability assessment, mapping of the head scarp and toe, and planning of potential remediation measures.

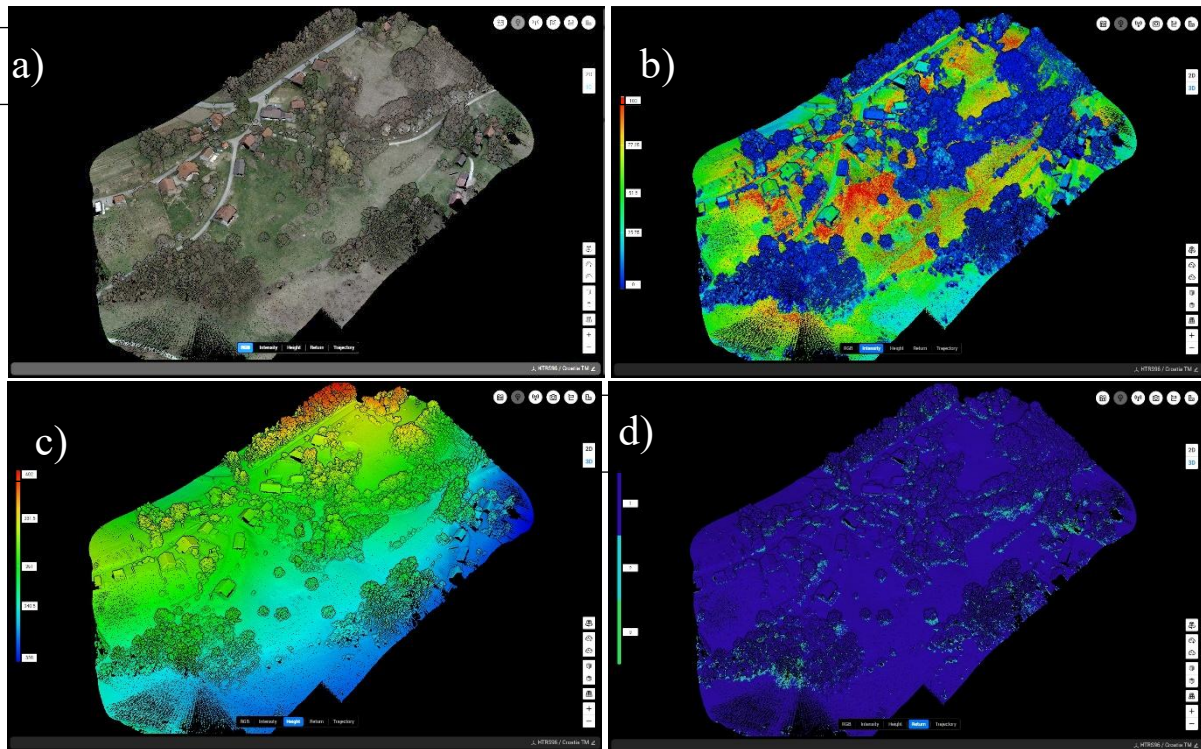


Figure 4. 3D point cloud of Gornja Plemenščina landslide and surrounding area surveyed with L1 LiDAR sensor with various visualizations: a) in RGB color, b) intensity colored, c) height colored and d) return number colored

Despite its advantages, UAS LiDAR requires specialized equipment, advanced processing workflows, and careful operational planning. Flight duration is limited by battery capacity, and dense canopy or extreme slope variability can necessitate multiple flight lines to achieve full coverage. Additionally, post-processing of LiDAR data—including filtering, classification, and alignment with other datasets—is computationally intensive but essential to generate reliable DTMs and derivative products. Nevertheless, when combined with photogrammetry and RTK GNSS surveys, UAS LiDAR provides a highly accurate, multi-source representation of landslide terrain, enabling comprehensive hazard analysis and informed decision-making for risk mitigation.

Overall, DJI L1 triple-return UAS LiDAR proved to be a versatile and precise tool for mapping the Gornja Plemenščina landslide, capturing both surface and subsurface details in vegetated terrain. Its integration with complementary datasets strengthens the accuracy of landslide models and supports effective monitoring, planning, and mitigation strategies.

3.3 State LiDAR Data

The fourth dataset used for the analysis of the Gornja Plemenščina landslide was obtained from the Croatian State Geodetic Administration, as part of the national project “Multisensor aerial survey of the Republic of Croatia for disaster risk assessment”. This large-scale airborne data acquisition campaign was conducted between 2020 and 2023 and completed in 2023, providing homogeneous, high-resolution geospatial data for the entire territory of Croatia (Državna geodetska uprava, 2023).

The dataset was acquired using airborne laser scanning (ALS) from manned aircraft equipped with high-performance LiDAR sensors. The resulting data includes a classified point cloud, as well as derived products such as digital terrain models (DTMs) shown in Figure 5., digital surface models (DSMs), and orthophoto imagery. The DTM used in this study has a spatial resolution of approximately 1×1 m, enabling detailed representation of terrain morphology at a regional scale. According to available specifications, the LiDAR data

achieve a minimum point density of approximately 4 points/m² in forested areas, with a vertical accuracy of about ± 0.1 m and horizontal accuracy of approximately ± 0.2 m (Lovrinčević et al., 2025).

The final point cloud provides a consistent and reliable representation of the terrain, particularly valuable for analyzing broader geomorphological features beyond the immediate landslide area. Compared to UAS-based datasets, the airborne LiDAR offers lower spatial resolution but superior regional coverage and uniform quality, making them well suited for identifying large-scale terrain characteristics such as slope continuity, drainage patterns, and potential zones of instability. The inclusion of classified ground points allows for accurate extraction of bare-earth models even in vegetated areas, although with less detail than high-density UAS LiDAR data.

In addition, orthophoto products derived from the same survey provide high-resolution imagery (approximately 25cm/pixel) in the HTRS96/TM coordinate system, supporting visual interpretation and integration with other spatial datasets (Croatian NSDI, 2024). These datasets ensure compatibility with national geospatial standards and facilitate seamless integration into GIS-based analysis.

Despite its advantages, the airborne LiDAR dataset has certain limitations. The lower point density compared to UAS LiDAR restricts the detection of fine-scale features such as minor scarps or small displacements within the landslide body. Furthermore, as the dataset represents a snapshot in time, it may not fully capture terrain changes that occurred immediately after the landslide event. Nevertheless, it serves as a critical reference dataset for multi-scale analysis.

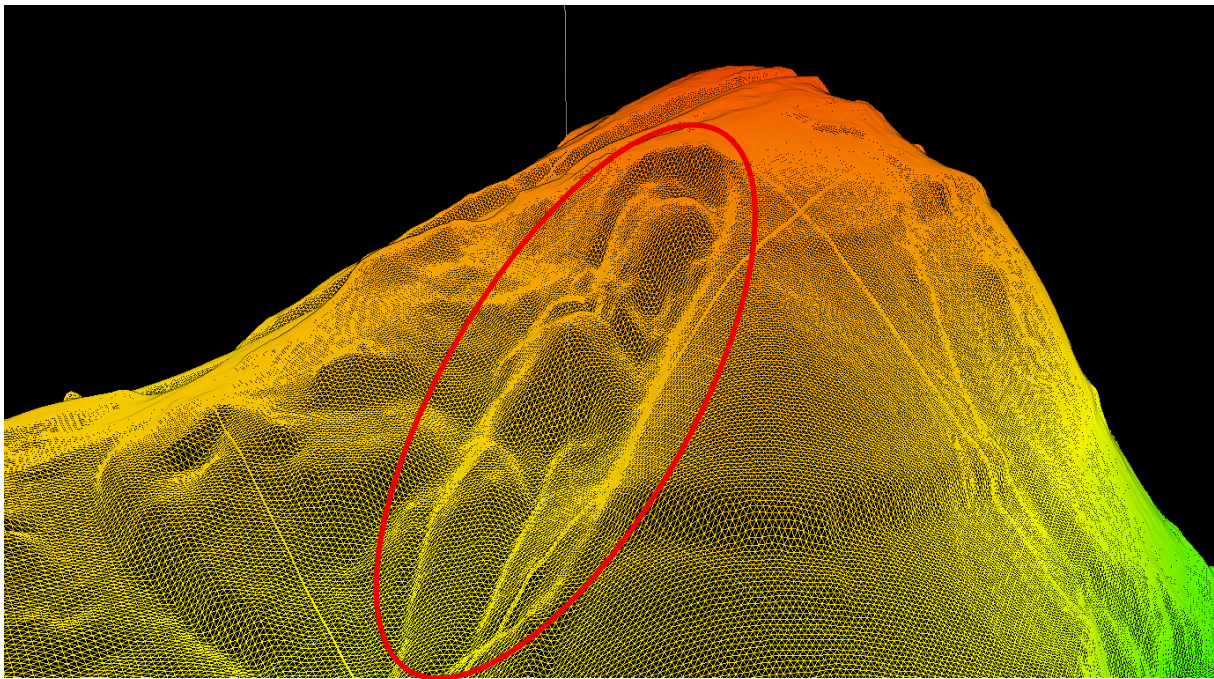


Figure 5. Wireframe view of DTM received from State Geodetic Administration with vertical exaggeration of 3.00 and landslide area marked with red line

In this study, the state LiDAR data were integrated with RTK GNSS, UAS photogrammetry, and UAS LiDAR datasets to provide a comprehensive multi-source representation of the landslide and its surrounding environment. This integration enables both detailed local analysis and broader regional interpretation, supporting improved understanding of landslide processes and contributing to more reliable hazard assessment and mitigation planning.

4 Results and Data Integration

All datasets were pre-processed, georeferenced to the HTRS96/TM coordinate system, and integrated into a unified spatial framework to enable direct comparison. The combined analysis of RTK GNSS, UAS photogrammetry, UAS LiDAR, and state airborne LiDAR datasets provided a comprehensive representation of the Gornja Plemenščina landslide and its surrounding terrain.

The UAS photogrammetry dataset produced high-resolution orthomosaics and dense point clouds, allowing detailed visual interpretation of the landslide features, including the head scarp, displaced material, and accumulation zones. This method proved particularly effective in open areas, where surface visibility was not obstructed. However, in regions with dense vegetation, the photogrammetric point cloud showed reduced accuracy and incomplete terrain representation.

In contrast, the UAS LiDAR dataset (DJI L1, triple return) provided a more reliable representation of the terrain in vegetated and complex areas. The ability of LiDAR pulses to penetrate vegetation enabled the extraction of bare-earth models, resulting in more consistent digital terrain models. The LiDAR point cloud also allowed identification of subtle geomorphological features, such as minor scarps and surface irregularities, which were not clearly visible in the photogrammetric data.

The RTK GNSS dataset served as a high-accuracy reference for validation. Comparison of elevation values indicated that LiDAR data showed better agreement with RTK measurements in vegetated areas, while photogrammetry performed comparably in open terrain. The RTK method provided centimetre-level accuracy but was limited in spatial coverage due to accessibility constraints within the landslide. The state airborne LiDAR dataset offered a broader spatial context, enabling analysis of the landslide within the surrounding geomorphological framework. Although its lower point density limited the detection of fine-scale features, it provided consistent terrain information and supported regional interpretation.

Overall, the comparison highlights that no single dataset is universally optimal. Instead, each method contributes specific advantages: photogrammetry offers high visual detail, UAS LiDAR provides reliable terrain data in vegetated areas, RTK GNSS ensures high positional accuracy, and state LiDAR enables regional analysis. The integration of these datasets results in a more complete and accurate representation of the landslide, supporting improved hazard assessment and decision-making. For the purpose of this article, the analyzed landslide area of 10,210 m² shown in Figure 6. a) was taken into account, surveyed using GNSS RTK (GPS) technology. This approach provided high-accuracy ground point measurements, serving as a reliable reference dataset for comparison with photogrammetric and LiDAR-derived data. For remediation design this area was not sufficient so along a cross-section profile there was missing data. Profile length was 250 meters, and it is shown in Figure 6.b).

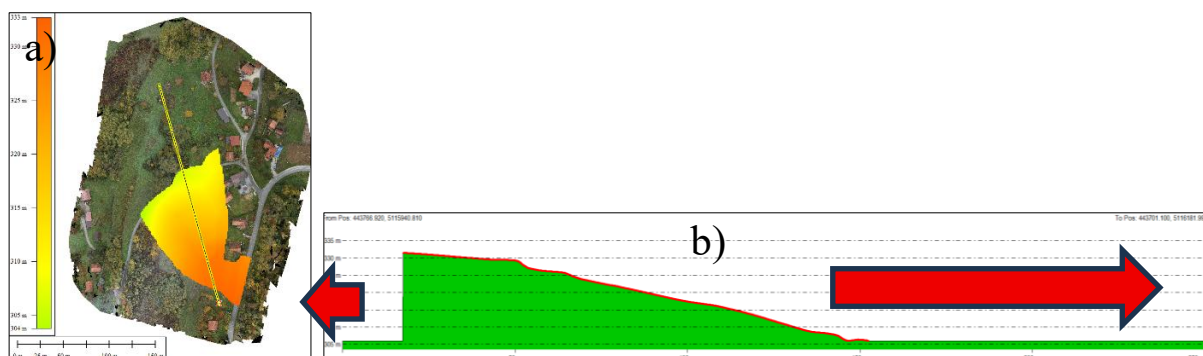


Figure 6. Landslide area surveyed with GPS-RTK and cross section: a) DTM generated from GPS-RTK in yellow/orange color and b) cross section with red line showing terrain profile and red arrows showing parts of no data available

In Figure 7. same cross section was pulled out from classified point cloud produced from photogrammetry mapping. This profile did not have any missing data but did not have almost any ground points along the cross-section profile.

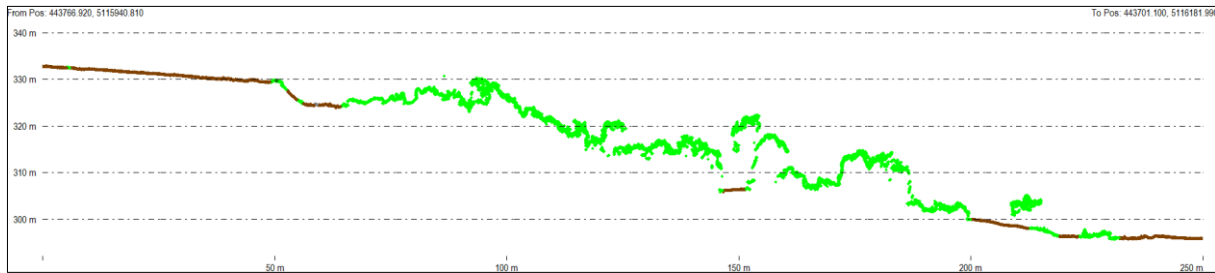


Figure 7. Cross section profile from photogrammetry mapping showing brown points classified as ground and green points classified as high vegetation

Figure 8. shows the same cross section profile, 250 meters in length from LiDAR mapping. The points classified as ground provide a good representation of the terrain for this landslide.

Figure 9 presents a 250 m cross-section profile derived from the State Survey, conducted between 2020 and 2023. Although these data are insufficient for detailed geometric analysis of the landslide due to the timing of acquisition, they provide valuable context for evaluating the surrounding terrain and regional morphology.

Integrated spatial datasets were used to map and analyze the Gornja Plemenščina landslide shown in Figure 10. RTK GNSS measurements are represented as a red line, providing high-accuracy reference points. UAS photogrammetry and UAS LiDAR data capture detailed local terrain, with LiDAR offering improved coverage in vegetated areas. The state airborne LiDAR dataset, shown as a blue line, provides broader regional context and terrain continuity. The combination of all datasets highlights differences in terrain representation and demonstrates the benefits of a multi-source mapping approach.

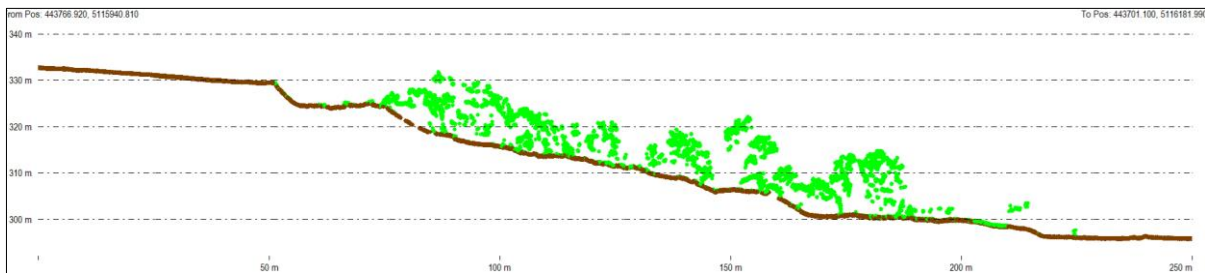


Figure 8. Cross section profile LiDAR mapping showing brown points classified as ground and green points classified as vegetation

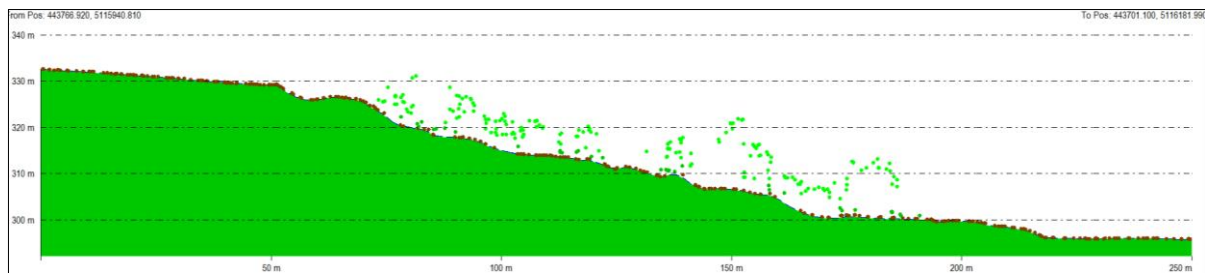


Figure 9. Cross section profile State survey mapping, showing brown points classified as ground and green points classified as high vegetation

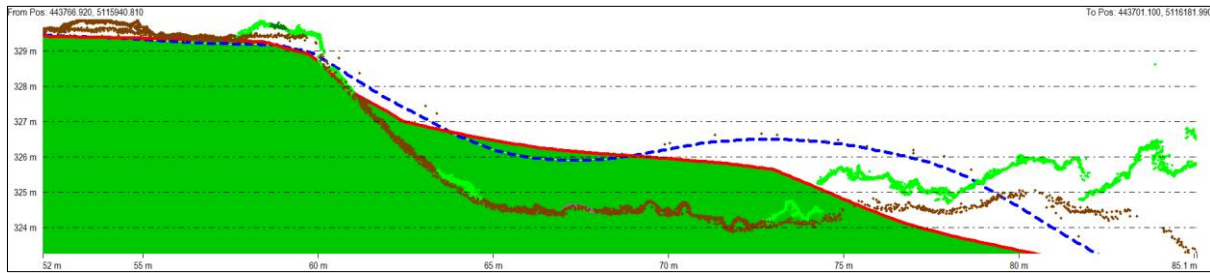


Figure 10. Integrated spatial datasets RTK GNSS (red line), UAS photogrammetry, UAS LiDAR, and state airborne LiDAR (blue line) used for landslide mapping and analysis.

5 Conclusion

This study presented a comparative analysis of multiple spatial datasets for landslide mapping in the area of Gornja Plemenščina, Croatia, including RTK GNSS, UAS photogrammetry, UAS LiDAR, and state airborne LiDAR data. The results demonstrate that each data source provides distinct advantages and limitations depending on terrain conditions, vegetation cover, and required level of detail.

UAS photogrammetry proved effective for generating high-resolution visual and geometric information in open areas, while UAS LiDAR, particularly with triple-return capability, enabled more reliable terrain representation in densely vegetated and complex environments. RTK GNSS measurements provided highly accurate reference data but were limited by accessibility and spatial coverage. The state airborne LiDAR dataset, although lower in resolution, offered valuable regional context and supported broader geomorphological analysis.

The integration of these datasets allowed for a more comprehensive and accurate representation of the landslide than any single method alone. This multi-source approach enhances the reliability of terrain analysis and supports more informed decision-making in hazard assessment and risk mitigation. Future work should focus on temporal monitoring and the application of multi-temporal datasets to better understand landslide dynamics and evolution.

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