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Satellite InSAR for Dam Safety and Landslide Risk in the Drin River Basin

S. R. Presezzi, M. Douglas, C. Giannico
TRE Altamira S.r.l, Milan, Italy
stefano.presezzi@tre-altamira-com
0009-0001-5983-9041

Abstract

The Drin River Cascade, one of the largest hydroelectric systems in the Balkans located in Albania, is crucial for national energy production. However, its location in a mountainous and seismically active region, subject to intense rainfall and partly influenced by fluctuations in reservoir levels, making it particularly vulnerable to slope instability and landslides.

This paper explores the application of InSAR (Interferometric Synthetic Aperture Radar) satellite technology, in particular analysis with ALOS-2 L-band data, for the monitoring and proactive management of areas of instability in the Drin Cascade area.

The principles of InSAR will be discussed, along with the advantages it offers in detecting millimetric movements in vegetated and difficult-to-access areas and the implications for the safety of infrastructure and local communities. InSAR is proving to be a transformative tool for improving landslide inventories, supporting planning and predictive maintenance surrounding the hydroelectric complex. Using InSAR alongside other traditional ground-based monitoring programs, has broadened the scope of long-term monitoring in time, sensitivity and area size.

By applying a Line-of-Sight (LOS) velocity threshold of +/-15 mm/yr to classify active movement, this analysis identified over 15 active areas within the project area. These findings demonstrate that InSAR technology can be effectively deployed to provide accurate, large-scale monitoring data essential for the prevention and mitigation of landslide-related risks in such critical contexts.

Keywords

InSAR, ALOS-2, Landslides, Hydropower, Albania.

1 Introduction: the role of InSAR in dam safety

Dams are frequently situated in challenging mountainous terrains to leverage natural topography for water regulation. However, these environments present inherent risks to structural stability. Ground movements, whether natural (seismic activity) or induced by changes in soil stress, pose a constant threat, compounded by the gradual deterioration of materials over time. Given that dam failure results in catastrophic environmental and socio-economic consequences, continuous monitoring of both the structure and the reservoir is essential to protect downstream populations and ensure economic continuity (Raventós et al. 2017).

The primary drivers of dam failure involve ground instability surrounding the reservoir. Phenomena such as landslides, slumps, or subsidence can compromise geomorphological stability, while overtopping can lead to structural erosion. Historically, safety management relied on manual visual inspections, which often failed to detect subtle precursor movements. Over the last 50 years, monitoring has evolved to include precise in-situ instrumentation such as GPS stations, pendulums, and seismometers.

Modern monitoring now integrates digital real-time sensors with satellite-based Interferometric Synthetic Aperture Radar (InSAR). InSAR is highly sensitive to slow-moving deformations and subtle trend changes, allowing for the detection of instability long before it becomes visible to the naked eye. By combining multiple satellite geometries (ascending and descending orbits), researchers can derive vertical and East-West displacement vectors, significantly improving geotechnical interpretations (Presezzi and Anderssohn 2025).

In the context of dams and reservoirs, InSAR applications are generally divided into two distinct technical approaches based on the area of interest:

1. Dam-Focused (Structural Analysis): This approach focuses exclusively on the dam wall and immediate infrastructure. It aims to detect deformation anomalies with millimeter precision. For this specific application, X-band satellitesare recommended. Their high spatial resolution provides a dense network of measurement points over man-made structures, facilitating early warning of structural fatigue.

2. Reservoir and Surrounding Area (Wide analysis): This approach monitors the wider reservoir and the surrounding mountainous valley to identify slope failures and high-vulnerability zones. For these vast, often vegetated areas, C-band (Sentinel-1) or L-band (ALOS-2) satellites are preferred. Specifically, L-band sensors are superior for penetrating dense vegetation, ensuring reliable data where shorter wavelengths would lose coherence.

For this project, TRE Altamira used the ALOS-2 (L-band) satellite to focus on the reservoir-scale context, leveraging its high resolution and vegetation penetration capabilities.

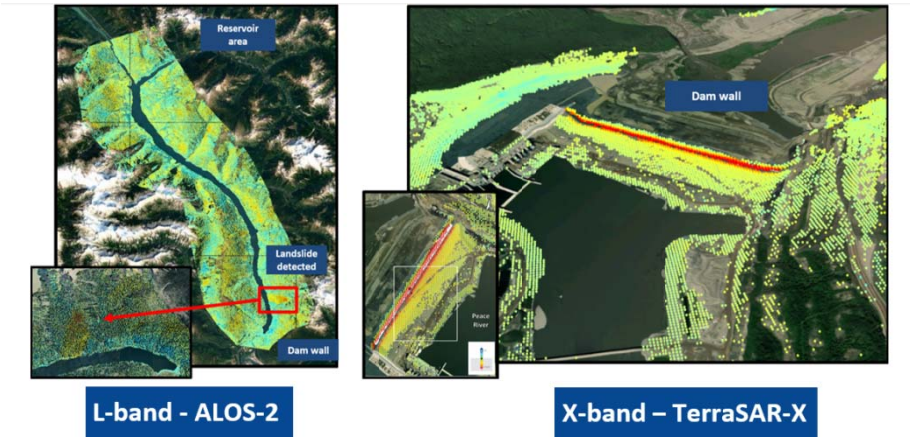


Fig. 1 General comparison between L-Band data application (on the left) and X-Band data application (on the right).

2 Vulnerability to landslides in the Drin Cascade area

The Drin River Cascade, a hydroelectric system of fundamental strategic importance for Albania and the entire Balkan energy landscape, is inherently complex to manage. Located along the course of the Drin River, this infrastructure comprises a series of dams and hydroelectric power plants, including Fierza, Koman, and Vau iDejës Dams, which create vast artificial lakes crucial for water regulation and energy production. While vital for Albania's electricity output, the area is notably prone to slope instability and landslides, compounding its operational challenges (Jovani et al. 2025).

The region's vulnerability stems from a combination of the geologic conditions and the sensitive infrastructure in the area. It is predominantly characterized by steep slopes and proximity to the Dinaric Alps exposing this area to tectonic activity and seismic events. Surrounding the Drin River the rock types are primarily comprised of ophiolites and flysch (Meco and Aliaj 2000). The geologic environment has led to the creation of unstable terrains and the accumulation of loose material in the valley. These factors necessitate constant monitoring of slope stability around dams and along hydroelectric reservoir banks.

Mountainous and forested areas, such as those surrounding the Drin Cascade, present inherent difficulties for traditional monitoring methods. However, InSAR technology effectively overcomes these challenges. Its remote, large-scale coverage enables the monitoring of extensive areas without physical access (Ferretti 2014), significantly reducing the costs and risks associated with field surveys. Furthermore, the ability of specific satellites to penetrate vegetation ensures reliable measurement points, even in densely wooded regions.

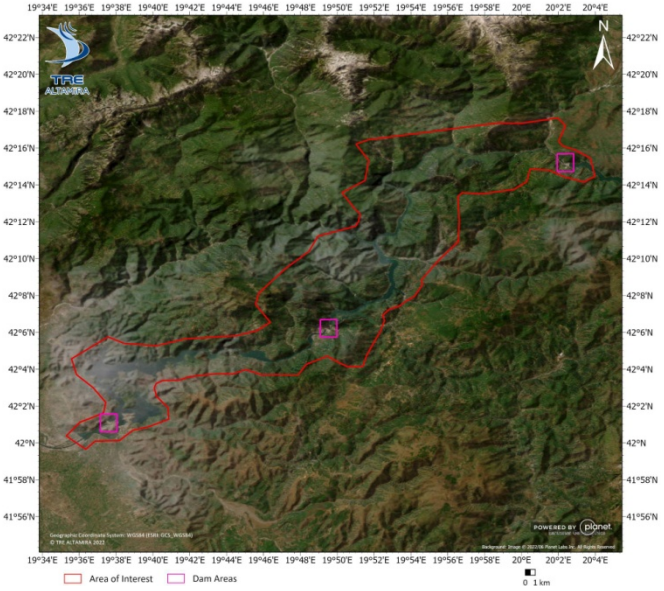


Fig. 2 Overview of the Drin River area, highlighting the existing dam locations.

3 Interferometric Synthetic Aperture Radar (InSAR)

InSAR is a remote sensing technique that can measure ground displacement with a very high sensitivity (mm). Depending on the wavelength used, this sensitivity can be as small as < 1 mm/yr and < 5 mm for a single measurement (Ferretti 2014). InSAR satellites make use of microwave frequencies that are able to detect motion in a variety of environmental conditions e.g. daytime or nighttime, sun or rain.

There are some limitations with the InSAR technique such as snow cover, vegetation growth and visibility incompatibilities. The InSAR signal has very low / no backscatter from snow covered areas or areas with standing water and can have low backscattered signal from vegetation (depending on the wavelength). Visibility limitations can occur when the line of sight angle from the satellite is incompatible with the angles of topography on site.

This case study makes use of TRE Altamira's patented technique SqueeSAR®, which has increased the detected measurement points from other InSAR techniques by including both persistent scatterers (PS) and distributed scatterers (DS). The result being a higher density of measurement points when compared with analyses that only make use of PS points.

4 Results of the InSAR analysis and risk identification

To understand and assess the geological risks in the area of the Drin River Cascade, a historical analysis was conducted to demonstrate the potential and benefits of InSAR technology applied to landslides. The analysis focused on the use of historical InSAR data to support the updating of landslide inventories and to verify the presence of existing or new landslides.

The analysis was performed using data from the ALOS-2 (Advanced Land Observing Satellite-2) satellite, operating in the L-band. The technical characteristics of the acquisition include an Ascending satellite geometry with a resolution of 5 x 9 metres.

The analysis encompassed a significant temporal interval, spanning from 20 August 2015 to 4 April 2024. During this period, 15 radar scenes were successfully processed, constituting the requisite minimum dataset for robust SqueeSAR® analysis.

The InSAR processing yielded a substantial volume of highly precise measurement points (MP) across the area of interest:

- Total number of measurement points (MP): 97,458.
- Area analysed: 237.7 km².
- Measurement point density: 410 MP/km².

The InSAR analysis highlighted widespread and previously unrecorded ground instability within the Drin reservoir area. Active movement zones were systematically delineated based on two primary criteria.
First, Measurement Points exhibiting Line-of-Sight (LOS) velocities beyond a threshold of ±15 mm/yr were classified as active.
Second, these points were required to form spatial clusters of at least five points demonstrating consistent displacement behavior.
The ±15 mm/yr tolerance was derived from the standard deviation observed in the regional data and is specifically calibrated to the temporal length and ALOS-2 wavelength of the dataset utilized. This thresholding strategy was applied to ensure that the designated active areas reflect true deformation rather than signal noise.

Through this rigorous InSAR satellite analysis, more than 15 active areas were identified within the project area. Of these, at least 7 clusters are situated directly along the course of the Drin River, underscoring a clear and immediate risk to hydroelectric infrastructure and the surrounding regions.

An example of the dynamics detected is a cumulative displacement of 60 centimetres over 8 years in several areas, with periods of stability alternating with phases of activity and potential future accelerations, as shown by the displacement time series. This type of information is vital for understanding the evolution of landslides and predicting potential failures.

The InSAR analysis revealed no significant movement over the primary dams' walls in the study area. While the analysis, utilizing a specific L band sensor, was primarily designed to monitor ground displacement in vegetated zones adjacent to the reservoir, it nonetheless identified active areas in the vicinity of local communities and infrastructure such as:

1. The school within Gralishteis located in an area that shows on average 12 mm/year of displacement, many houses are also located within the bounds of this displacement area. Another school located in Bugjon is also with this active area.
2. The road from Berishë and Vogël to Berishë and Sipërme is threatened by two zones of displacement (approximately 0.8 km^2 and 0.6 km2 in size) with average displacement rates of -28 mm/year and -25 mm/year.
3. Villages such as Toplane, Salce, and Palc, are located above or near active landslide areas.
    a. Larger area (1.5 km^2) identified with average displacement rate of -25 mm/year was also identified downslope from the village of Kishe-Arre.

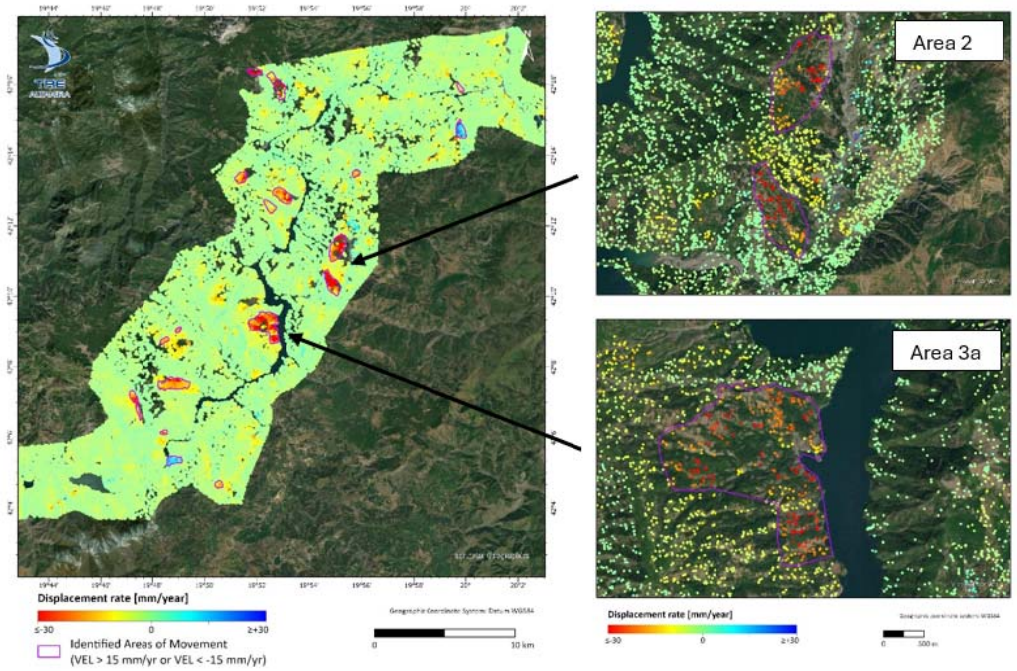


Fig. 3 The overview on the left displays the spatial distribution of the identified active areas. On the upper right, multiple active areas are shown affecting the Berishë e Vogël road. The lower right highlights a significant active area situated downslope from Kishe-Arre.

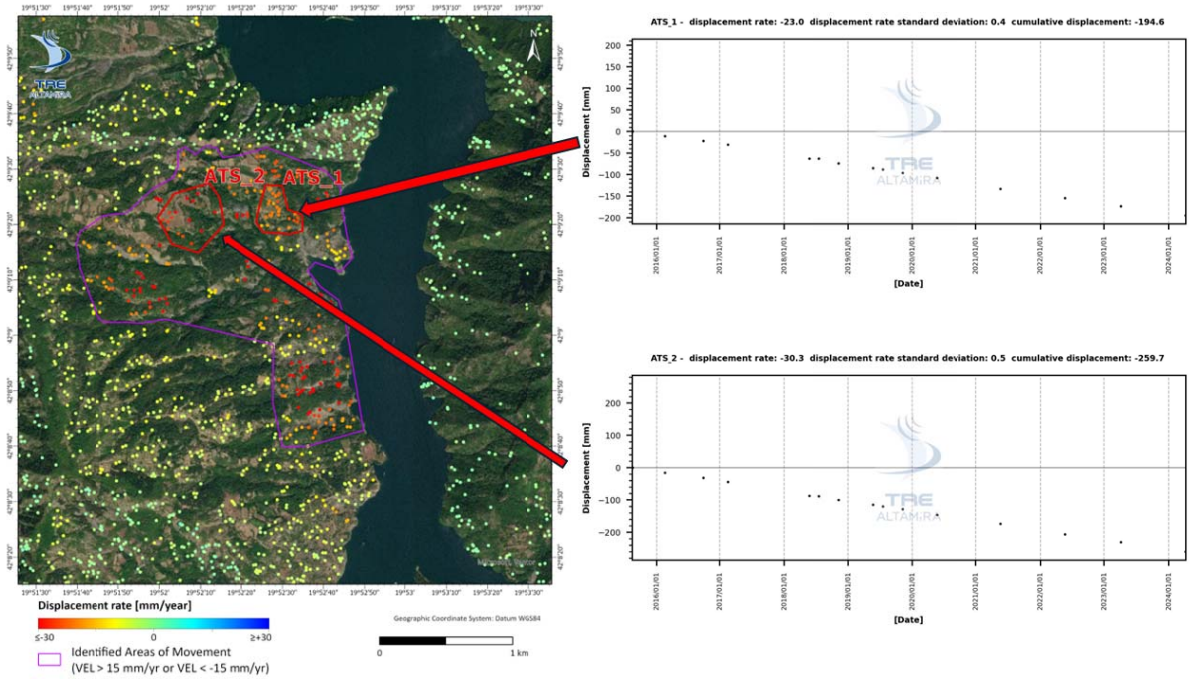


Fig. 4 On the left, close up over the Kishe-Arre active area. On the right, average time series from within the polygons.

5 Conclusion

The Drin River Cascade is an indispensable energy pillar for Albania, yet it faces constant threats from inherent geological instability. The application of InSAR technology, specifically using L-band ALOS-2 data, has proven to be a transformative tool for addressing this critical risk. Its ability to detect millimetric movements across vast, vegetated, and difficult-to-access terrain, coupled with the identification of previously unknown landslides, provides unprecedented insight into terrain dynamics.

Our analysis reveals a concerning picture of active landslides along the Drin River, situated in the immediate vicinity of schools, roads, and villages. This proximity underscores the critical importance of proactive monitoring to inform risk management strategies, target interventions, and implement

effective warning systems. Such capabilities are vital for safeguarding both hydroelectric infrastructure and local communities.

Failures in dam and reservoir slopes are often exacerbated by seismic activity and broader slope instabilities, resulting in significant material and environmental damage. Therefore, continuous monitoring is paramount. While each dam requires tailored consideration, InSAR offers compelling advantages:

- Sensitivity: Detects slow movements and subtle trend changes.
- Synoptic Coverage: Allows for simultaneous monitoring of the dam structure and reservoir with millimetres precision.
- Historical Analysis: Leverages extensive satellite archives dating back to 1992 (2007 for L-Band).
- Validation: Capable of integration and comparison with ground-based instruments.

While InSAR provides an innovative and highly effective solution for monitoring infrastructure in Albania, we acknowledge the current limitations regarding ground-truthing. Due to the data-scarce nature of the study area, obtaining historical data from local GNSS stations or in-situ topographic instruments for direct quantitative validation was not feasible. As a critical next step, future work will focus on integrating targeted field surveys and in-situ monitoring to empirically validate these InSAR-derived landslide inventories.

Specific project considerations must guide satellite selection. In the Drin River area, coverage was influenced by topography and the satellite's Line-Of-Sight (LOS) angle; for instance, Ascending geometry identified more points on the western slope than the eastern slope. To optimize stakeholder utility, incorporating additional ALOS images in medium resolution (e.g., ScanSAR) and with opposite geometry, would significantly expand the dataset for comprehensive analysis.

The data obtained offers a valuable baseline for proactive risk management. Stakeholders can adopt two primary paths for managing instability:

1. Continuous InSAR Monitoring: Using historical analysis as a baseline to track landslide evolution, identify acceleration, and evaluate intervention effectiveness.
2. Integration with In-Situ Monitoring: Using InSAR maps to identify critical areas where specific topographic instrumentation should be installed for intensive, localized monitoring.

Ultimately, these findings confirm that strategic radar wavelength selection is crucial. Longer wavelengths (L-band) are superior for monitoring vegetated reservoir slopes, while shorter wavelengths (C- and X-band) are preferable for the high-precision structural assessment of dams. By providing high spatial density measurements comparable to in-situ instruments, InSAR stands as an invaluable tool for comprehensive dam safety programs.

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