Napredno Insar opazovanje pregrade Lisiče v Severni Makedoniji

Advanced Insar Monitoring of the Lisice Dam in North Macedonia

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IZVLEČEK

Zagotavljanje dolgoročne stabilnosti pregrad je ključnega pomena za javno varnost in upravljanje voda. Klasične geodetske merske tehnike so sicer natančne, vendar so deloma omejene v prostorskem in časovnem vidiku, kar govori v prid naprednejših rešitev za spremljanje stabilnosti. V študiji je predstavljena prva uporabo tehnike InSAR za spremljanje stabilnosti pregrad v Severni Makedoniji, in to na primeru pregrade Lisiče. Skupno 466 posnetkov Sentinel-1 SLC iz dvižne tirnice in 467 posnetkov iz vpadne tirnice za obdobje 2014–2025 je bilo obdelanih z uporabo tehnik PSInSAR in QPSInSAR. Rezultati obeh geometrij so pokazali stabilnost na opornikih, prelivu in okoliškem terenu, pri čemer je največje posedanje preseglo 20 centimetrov v osrednjem delu pregrade, kar ustreza posedanjem približno 2 centimetra na leto. Rezultati so skladni s pričakovanim posedanjem v zemeljskih pregradah, vendar zahtevajo potrditev s podatki opazovanj na kraju samem. Opazili smo tudi omejitve InSAR, vključno z nizko koherenco na poraščenih pobočjih okrog jezu in odsotnostjo stalnih sipalcev (PS) na pregradi. Za premagovanje teh izzivov je priporočljiva namestitev kotnih odbojnikov. Na splošno ugotovitve potrjujejo, da je InSAR zanesljivo in stroškovno učinkovito dodatno orodje, ki bi ga bilo v prihodnje smiselno uporabljati pri spremljanju deformacij pregrad v Severni Makedoniji.

ABSTRACT

Ensuring the long-term stability of dams is vital for public safety and water management. Conventional geodetic techniques, though accurate, have limited spatial and temporal coverage, underscoring the need for advanced monitoring solutions. This study presents the first application of advanced InSAR techniques for dam monitoring in North Macedonia, focusing on the Lisiche Dam. A total of 466 Sentinel-1 SLC images from the ascending orbit and 467 from the descending orbit fot the period 2014–2025 were processed using PSInSAR and QPSInSAR approaches. Both geometries indicate stability at the abutments, spillway, and surrounding terrain, while subsidence over 20 cm was detected at the central crest, averaging about 2 cm per year. These results align with expected settlement in earth-fill dams, but require validation through in-situ measurements. Limitations of InSAR were also observed, including low coherence in vegetated slopes surrounding the dam and the absence of PS points on the dam body. To overcome these challenges, the installation of corner reflectors is recommended. Overall, the findings confirm that InSAR is a reliable and cost-effective complementary tool that should be integrated into future dam monitoring frameworks in North Macedonia.

KLJUČNE BESEDE

PSInSAR, QPSInSAR, monitoring pregrad, Sentinel-1, analiza časovnih vrst, daljinsko zaznavanje

KEY WORDS

PSInSAR, QPSInSAR, Dam monitoring, Sentinel-1, Time-series analysis, Remote sensing

1 Introduction

Dams are critical components of hydraulic infrastructure, and their structural health and stability must be continuously monitored to prevent failures that could result in catastrophic economic, environmental, and human losses. Recent analyses of global dam accidents in the 21st century highlight that, although such events are relatively rare, their impacts can be devastating, underscoring the importance of systematic monitoring and risk management (Zhou, et al., 2025).

In North Macedonia, the monitoring of dam displacements is traditionally performed using classical geodetic methods, such as precise leveling, total station measurements (Bogdanovski, et al., 2021), and GNSS campaigns (Gegovski, et al., 2019). Although these techniques provide reliable data, they are limited by sparse control points and discrete epochs, highlighting the need for continuous and spatially comprehensive monitoring.

In recent years, several studies have advanced the application of InSAR in dam monitoring, highlighting both methodological innovations and practical challenges. A recent study applied PSInSAR analysis using Sentinel-1 data to a rockfill dam, detecting millimeter-scale external deformations and demonstrating its potential for maintenance management (Abo, et al., 2023). Similarly, other research has shown that PSInSAR time series combined with advanced statistical approaches can detect trend changes in ground deformation and provide valuable insight into stability assessment (Ghaderpour, et al., 2024). Building on these advances, more recent work has demonstrated that the integration of electronic corner reflectors, together with optimized placement strategies, significantly improves the applicability of PSInSAR for operational dam and reservoir monitoring (Jänichen, et al., 2025). In addition, SBAS-InSAR applications have further confirmed the reliability of advanced interferometric techniques, showing strong consistency with independent ground-based observations and reinforcing their value for long-term deformation monitoring of dam structures (Pang, et al., 2023).

This study makes several key contributions:

- First application of advanced InSAR methodologies for dam monitoring in North Macedonia, specifically on the Lisiche Dam.
- Use of PSInSAR and QPSInSAR techniques on multi-temporal Sentinel-1 data (October 2014 – May 2025) provided a detailed picture of the Lisiche Dam deformation patterns.
- Demonstration of InSAR as a complementary tool, showing its potential to enhance conventional geodetic monitoring methods for assessing dam stability.

The remainder of this paper is structured as follows. Section 2 introduces the study area and its main characteristics. Section 3 presents the applied methodology, including the concepts of PSInSAR and QPSInSAR, the utilized SAR dataset, and the processing workflow. Section 4 summarizes the results and discussion, with emphasis on the deformation patterns of the Lisiche Dam. Finally, Section 5 provides the main conclusions and outlines outlines directions for future work.

2 Study area

The Lisiche Dam is an embankment dam located in the central part of North Macedonia, approximately 23 kilometers west of the city of Veles. It is constructed on the Topolka River, a right tributary of the

Vardar River, and forms an artificial reservoir also named Lisiche. The reservoir is primarily used for drinking water supply and irrigation, serving around 60,000 inhabitants in the municipalities of Veles and Chashka, and supporting agricultural activities in the surrounding region.

The dam is a rockfill embankment structure with a central clay core, a design commonly used to combine structural stability with impermeability. Construction of the dam began in 1987, and the main technical characteristics are as follows:

- Crest length: 660 meters;
- Maximum height above terrain: 67 meters;
- Crest width: 8.0 meters;
- Crest elevation: 428.5 meters above sea level (Dam Lisiche, 2025).

The reservoir formed by the dam covers a surface area of approximately 1 km² and stores up to 25 million cubic meters of water, classifying it among the medium-sized reservoirs in North Macedonia.

Figure 1: Satellite image of the Lisiche embankment Dam (Google Earth, 2025).

The surrounding terrain is moderately mountainous. Detailed geotechnical data are not available in this study. However, the geological map of North Macedonia from the National Strategy for Nature Protection shows that the Lisiche Dam lies within a Neogene sedimentary basin with clays, sands, and conglomerates. Parts of the reservoir are bordered by Cretaceous rocks and smaller granite intrusions.

Embankment dams in such geological settings are generally exposed to long-term subsidence and slope-related processes (MEPP, 2016).

Due to the limited spatial coverage and temporal resolution of traditional geodetic in-situ monitoring systems, satellite-based interferometric techniques such as InSAR provide a practical and efficient solution for detecting and tracking ground movements across the dam body and its surrounding areas.

3 Methodology

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that measures ground surface displacements by analyzing the phase difference between two or more radar images acquired from nearly the same orbital position at different times, allowing displacement to be measured along the satellite's line-of-sight (LOS).

Traditional InSAR techniques, which rely on a limited number of interferometric pairs, often suffer from decorrelation, geometric distortions, and atmospheric disturbances, limiting their effectiveness for long-term deformation monitoring. To overcome these issues, the PSInSAR technique was introduced (Ferretti et al., 2001), focusing on point-like, coherent targets such as buildings or exposed rock that remain stable over time.

While PSInSAR provides reliable results in urban areas with dense man-made structures, its applicability decreases over non-urban terrains where persistent scatterers are scarce. To overcome this limitation, the Small Baseline Subset (SBAS) technique was introduced (Berardino et al., 2002), enabling the use of distributed scatterers (DS) across natural surfaces. Based on this principle, the Quasi-PSInSAR (QPSInSAR) method was later developed to enhance distributed scatterer–based techniques (Perissin & Wang, 2012). In the following, the basic concepts of the two techniques applied in this study, PSInSAR and QPSInSAR, are briefly presented.

3.1 The basic concept of PSInSAR

The PSInSAR technique is founded on three key principles (Crosetto, et al., 2016). First, it processes only those pixels that contain a persistent scatterer (PS) (Figure 2b). There are several approaches for selecting PS points, but the most commonly used criterion is the amplitude stability index (ASI).

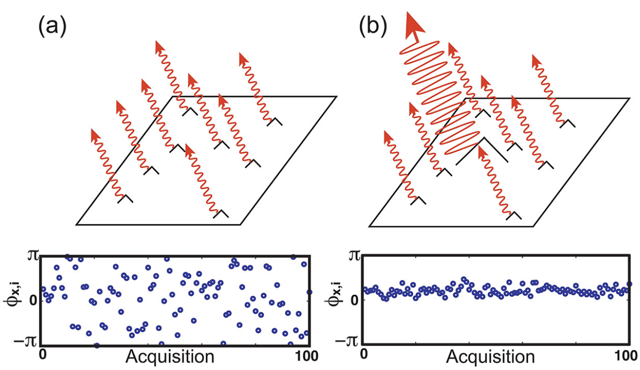

Figure 2: Phase variation in a) DS and b) PS pixels (Hooper, 2006)

The second principle involves selecting one SAR acquisition as a reference image, relative to which differential interferograms are generated (Figure 4a). The reference is typically chosen to minimize both the normal baseline (B_n) and the temporal baseline (B_t) with respect to the secondary images.

The third principle is the spatio-temporal modeling, performed in two steps: first on the newtwork of PS candidates (PSC) to estimate the atmospheric component ($\Delta\varphi_{atmo}$) from Eq. 1 and derive the Atmospheric Phase Screen (APS), and second on the PS network to extract the topographic ($\Delta\varphi_{topo}$) and displacement ($\Delta\varphi_{disp}$) component. The interferometric phase can be expressed by the following equation, which defines a linear model for the topographic and displacement components:

$$\Delta\varphi = \underbrace{\frac{4\pi}{\lambda}\frac{B_n}{R}\frac{h_{err}}{\sin\theta}}_{\Delta\varphi_{topo}} + \underbrace{\frac{4\pi}{\lambda}B_t \cdot \upsilon}_{\Delta\varphi_{disp}} + \Delta\varphi_{atmo} + \Delta\varphi_{noise} \tag{1}$$

In this study, the standard PSInSAR approach was employed to estimate the displacement velocity (v), linearly related to the temporal baseline (B_t), and the residual elevation error (h_{err}), linearly related to the normal baseline (B_n). The SARPROZ software was used for data processing, and Figure 3 illustrates the complete workflow of the PSInSAR technique.

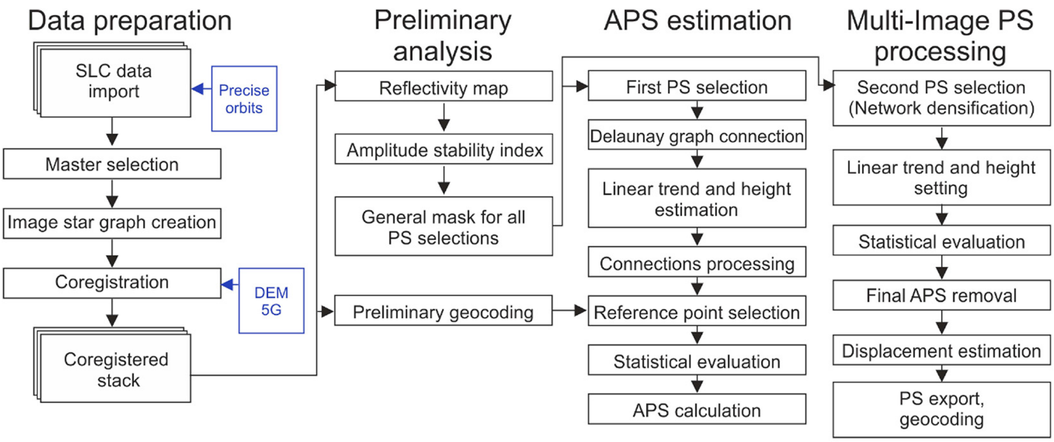

Figure 3: Simplified workflow of PSI Processing in SARPROZ (Fárová, et al., 2019)

3.2 The basic concept QPSInSAR

The basic idea of the Quasi Persistent Scatterers InSAR (QPSInSAR) approach is to enhance InSAR results in areas with a low density of PS, such as rural, bare soil, or sparsely vegetated regions. While pixels in such environments may exhibit low reflectivity or a weak ASI, the presence of a minimum level of spatial coherence enables the application of the QPS technique. PS pixels typically show very low phase variation over time due to their stable and coherent radar response (e.g., buildings or rocks), while DS pixels generally have higher phase variability and are more sensitive to noise (Figure 2a). However, with appropriate spatial filtering, many DS pixels can still provide usable phase information for deformation monitoring (Luo et al., 2012).

The QPSInSAR technique is based on two core principles. First, it exploits a redundant number of interferograms, significantly more than those used in the PSInSAR. The most effective implementation relies on the Full Graph, where each acquisition is combined with every other acquisition. A modified version typically limits the temporal baseline to a maximum of one year. In our study, the modified graph configuration was applied (Figure 4b). Second, unlike PSInSAR, in which the pixel phases are used without modification, QPS applies spatial filtering of the interferometric phase to improve the signal-to-noise ratio (Parizzi & Brcic, 2011). SARPROZ offers several filtering strategies that can be applied depending on the characteristics of the study area, enhancing the detectability and reliability of displacement signals from DS points (Perissin, 2012).

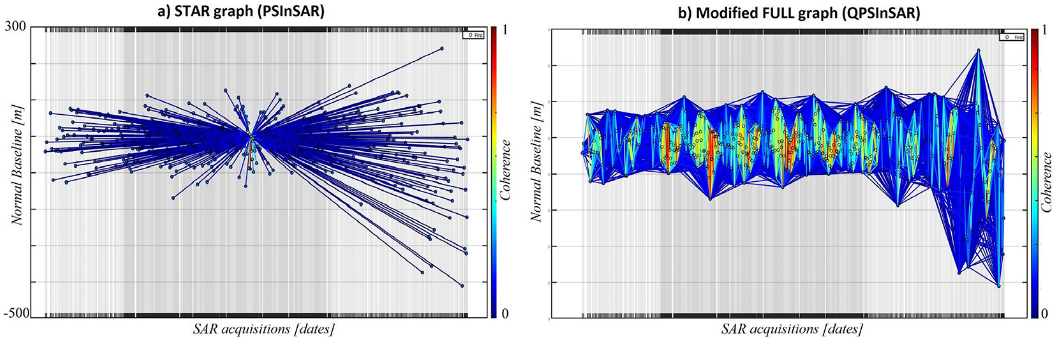

Figure 4: a) Star graph PSInSAR) b)Modified Full graph QPSInSAR (Lisiche Dam, ascending orbit)

The main advantage of QPSInSAR over other InSAR techniques that rely on distributed scatterers is that the algorithm operates on the wrapped phase, following a processing workflow identical to PSInSAR (Figure 3) up to the final step. The difference occurs during the Multi-image processing (in this case Multi-image QPS processing), where in the QPS case the spatial coherence of the generated interferograms is introduced as a weighting factor. This additional constraint improves the reliability of the estimated deformation parameters and distinguishes QPSInSAR from the standard PSInSAR implementation. (Perissin & Wang, 2012). However, a limitation of the method is that the APS estimation still depends on the classical PSInSAR analysis, meaning that if a sufficiently dense and reliable PSC network is not available, its applicability may be significantly limited.

3.3 Overview of the SAR dataset used for Lisiche Dam monitoring

To apply the PSInSAR and QPSInSAR techniques described in the previous sections, a multi-temporal dataset of Sentinel-1 (C-band) SAR images was acquired for the Lisiche Dam area. All Sentinel-1 SLC images used in this study were obtained free of charge from the ASF Vertex data portal, which provides open access to Copernicus SAR archives for scientific use. Sentinel-1 is part of the EU Copernicus Programme and is operated by ESA, and it ensures consistent, high-quality SAR acquisitions that are suitable for long-term deformation monitoring. The dataset ensures continuous temporal coverage with an average revisit time of 12 days, which was reduced to 6 days after the launch of Sentinel-1B, and has been restored to 6 days again with the recent operational deployment of Sentinel-1C. For both ascending and descending orbits, the acquisitions span the period from October 2014 to May 2025.

The specifications of the SAR acquisitions utilized for this study are summarized in Table 1.

Table 1: Specifications of the SAR data utilized.

Satellite Orbit	Ascending	Descending
Number of SLC images	466	467
Polarization	VV	VV
TOPS Sub swath	1	2
Orbit path	102	80
Incidence angle (θ)	33.7571°	39.2778°
Heading(azimuth) angle	-169.296° (349.296°)	-9.988° (189.988°)

Figure 5 illustrates the Lisiche Dam study area with coverage from ascending (red) and descending (green) Sentinel-1 orbits, showing orbit directions, looking geometry, and the selected reference point.

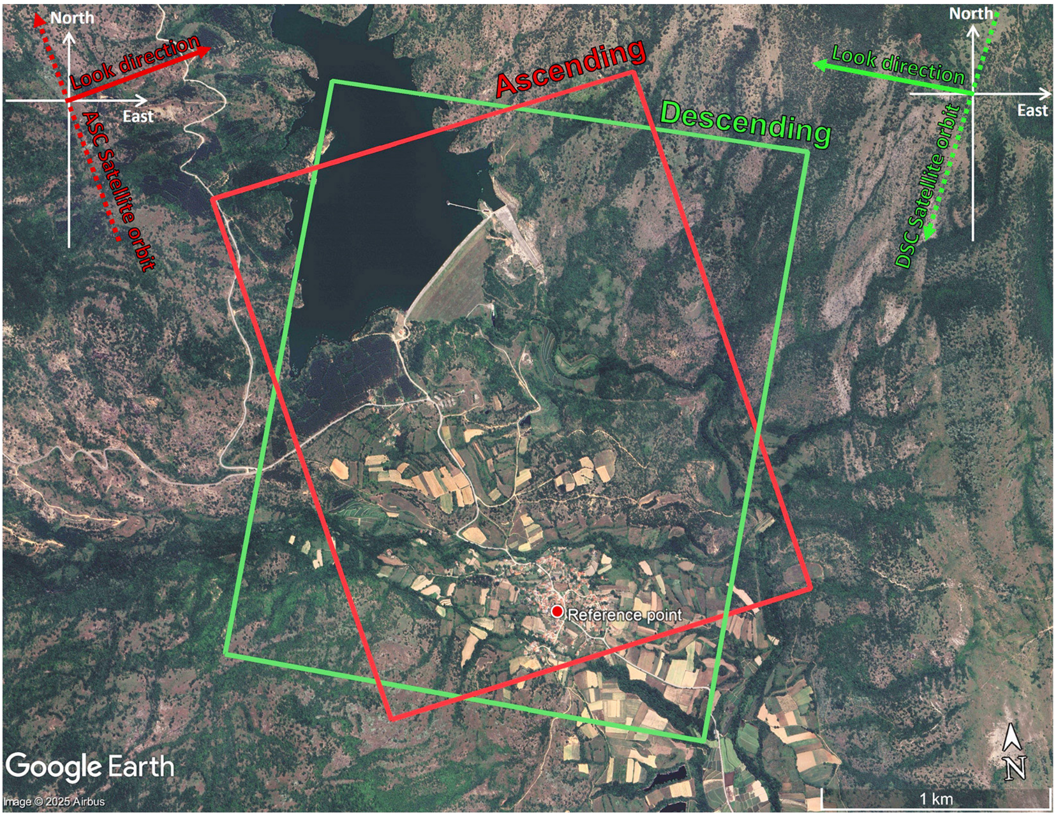

Figure 5: Study area around the Lisiche Dam covered by ascending and descending orbits (Google Earth, 2025).

3.4 Processing workflow for the Lisiche Dam dataset

Since the analysis relies on both ascending and descending Sentinel-1 acquisitions, the processing was performed independently for each orbit. Although the workflow follows the same methodological steps, the two orbit geometries differ in incidence angle, heading, and the number of available acquisitions, which may influence the spatial coverage and density of coherent scatterers.

[1] *Heading angle values are reported according to the SARPROZ metadata. More precisely, the azimuth value is defined as the angle measured clockwise from the geographic north (meridian of the study area) to the satellite's movement direction.*

For the ***ascending dataset***, a total of 466 SLC images were processed, spanning the time period from October 12, 2014 to May 29, 2025. The analysis was first conducted using the PSInSAR approach. Following the processing workflow illustrated in Figure 3, a total of 465 differential interferograms were generated using the Star Graph configuration, in which all interferograms are connected to the reference image (Figure 4a). All images were co-registered to a master acquisition dated December 15, 2019, selected for its temporal centrality and coherence quality, while also ensuring favorable weather conditions (absence of snow cover or heavy rainfall) as verified through historical meteorological data obtained from the Visual Crossing platform. This ensured a balanced interferometric network and minimized temporal decorrelation.

Preliminary steps included the generation of a reflectivity map and the ASI from all 466 images to identify coherent radar targets. Geocoding was performed using the Copernicus DEM, which was geometrically aligned with the reflectivity map using Ground Control Point (GCP). Points with ASI values greater than 0.65 were selected as PSC, forming a robust network that enabled a successful inversion and the estimation of the atmospheric component at each point. On this basis, the APS was estimated for each acquisition using spatial filtering and interpolation. The spatial distribution and connectivity of the selected PSC network, along with their temporal coherence following APS removal, are illustrated in Figure 6.

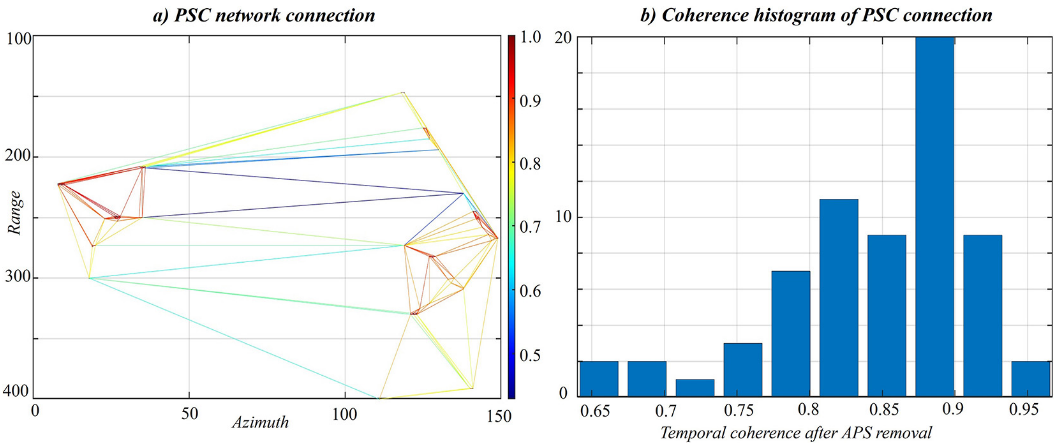

Figure 6: Coherence of PSC connection network for APS estimation (ascending dataset)

A control check of the APS estimation was performed using the APS coherence test option in SARPROZ. This test evaluates the quality of the APS removal by calculating the average coherence of the residual phase for each SAR acquisition. Higher coherence values, typically greater than 0.6, thus indicate successful modeling and removal of the atmospheric component.

The results of this evaluation are presented in Figure 7.

Once the APS was estimated for all SAR acquisitions, the analysis proceeded to the final step of Multi-image PS processing. For this purpose, spatio-temporal modeling was performed on all points of the dam, as well as on the surrounding points within the analyzed area that have an ASI greater than 0.4. The subsequent spatio-temporal modeling was carried out using the standard linear model adopted in PSInSAR, enabling the estimation of residual hight errors and displacement rates with high reliability.

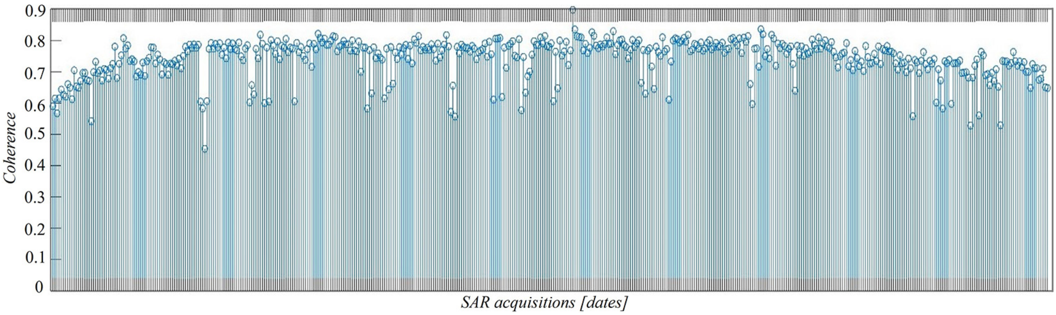

Figure 7: Results of APS coherence test for the analysis of the ascending dataset.

Following the PSInSAR analysis, the QPSInSAR processing was performed using the same APS estimated in the PSInSAR. A modified full Graph configuration was applied, where the maximum temporal baseline between image pairs was limited to one year to mitigate decorrelation effects. This setup resulted in a total of 21,364 differential interferograms, providing a highly redundant network for the estimation of deformation parameters (Figure 4b). Spatio-temporal modeling was performed on the same selection of points as in the PSInSAR analysis. In this case, a spatial coherence map, previously generated from the differential interferograms, was employed as a weighting factor in the spatio-temporal modeling for determining displacement velocity and residual height error.

Since InSAR is a relative technique, the displacement time series are referenced to a single stable point within the scene. For this purpose, a reference point was selected based on its ASI, ensuring strong amplitude consistency over the full observation period. To avoid the influence of potential structural displacement, this point was carefully positioned outside the Lisiche Dam body and is shown in Figure 5. Its coordinates in both WGS84 and SAR geometry are presented in Table 2.

Table 2: Geographic (WGS 84) and SAR coordinates of the selected reference point

WGS 84		**SAR coordinates**	
Latitude	**Longitude**	**Range**	**Azimuth**
41° 40’ 36.42”	21° 36’ 22.95”	250	27

For the ***descending dataset***, a total of 467 SLC images were processed, covering the period from October 23, 2014 to May 22, 2025. The same procedure as for the ascending orbit was applied, resulting in 466 differential interferograms for the PSInSAR analysis, with September 27, 2019 selected as the reference acquisition. PSC points were identified using the ASI threshold of 0.65, forming a relatively dense network that served as the basis for APS estimation. The spatial distribution and connectivity of the selected PSC network, as well as their temporal coherence after APS removal and APS validation, are illustrated in Figure 8.

From the results presented in Figure 8, it can be observed that the testing of the estimated APS for the descending dataset yielded slightly weaker performance compared to the ascending dataset. Nevertheless, the procedure can still be considered successful, given that the average coherence of all acquisitions exceeds the threshold of 0.6. Spatio-temporal modeling was carried out on the network of points, including all points of the dam together with the surrounding points that have an ASI greater than 0.4. Subsequently, a QPSInSAR analysis was performed on the previously selected dataset. For the QPS analysis, a total of 21,456 differential interferograms were generated. The displacement velocity and relative height error were determined with respect to the reference point with SAR coordinates: *Range 106, Azimuth 135*, which happened to be located only a few meters away from the one used in the ascending dataset, as shown in Table 2.

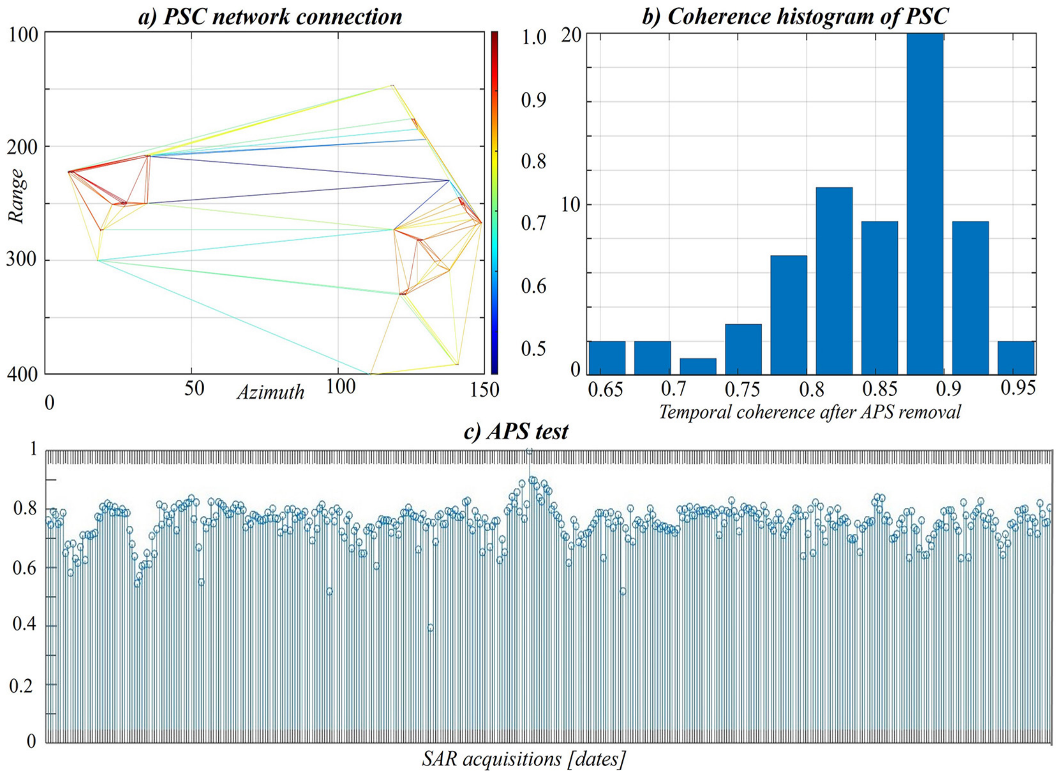

Figure 8: Coherence of PSC connection network and test for APS estimation (descending dataset)

4 Results and Discussion

4.1 PSInSAR and QPSInSAR results: ascending dataset

For the PSInSAR analysis of the ascending dataset, a total of **426 PS points** were identified, with temporal coherence values ranging from 0.5 to 0.97. The highest density of PS points was observed along the dam crest and in the rocky area near the spillway. This spatial distribution is consistent with expectations, since the crest consists of concrete structures, steel railings, and a roadway with sidewalks, all of which provide a persistent and coherent radar backscatter. Figure 9 illustrates the results of the PSInSAR analysis, where only PS with temporal coherence values greater than 0.5 are visualized.

Regarding the displacement pattern, the results indicate relatively stable conditions along the edges of the embankment dam, while the central portion of the crest shows the most pronounced movement. The observed velocity rates range from **+1** to **-11 mm/year** in the LOS direction of the ascending orbit. The maximum cumulative displacement, reaching **-117 mm (subsidence)**, is observed at a point located near the central section of the dam crest during the analyzed period.

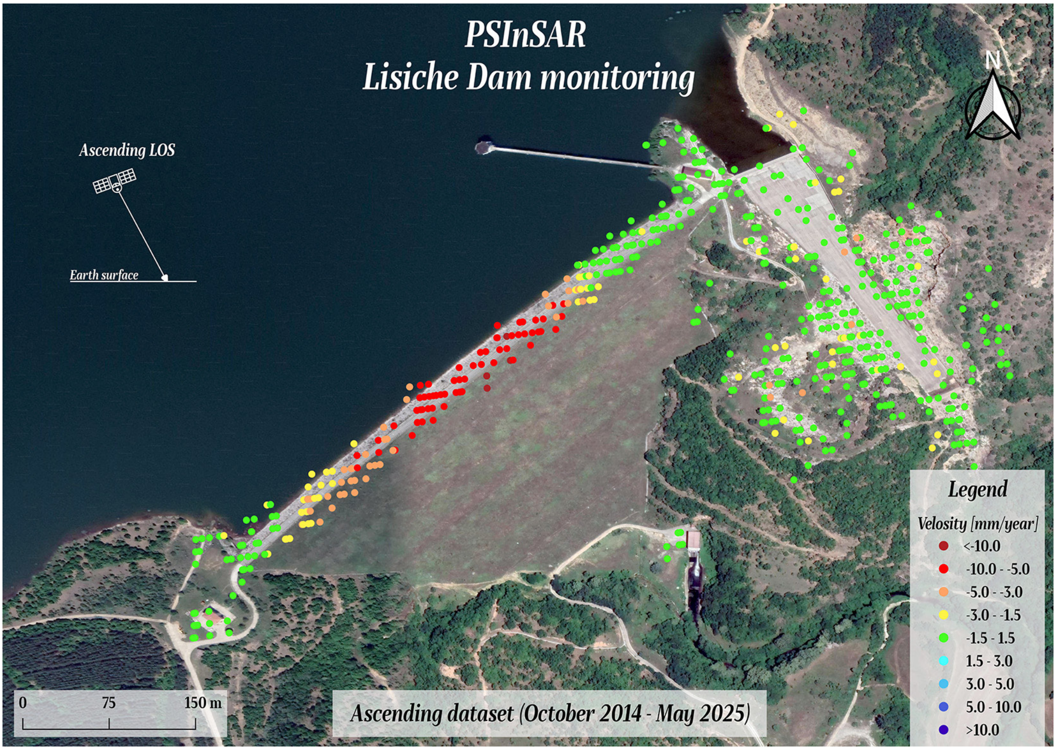

Figure 9: PSInSAR displacement velocity map over the Lisiche Dam area (ascending dataset)

The QPSInSAR analysis increased the spatial density of measurement points by identifying DS targets. A total of **3,172 DS** points, with coherence ranging from 0.71 to 0.98, were identified across the dam and surrounding terrain. QPSInSAR thus provides broader spatial coverage than PSInSAR, particularly over areas lacking strong reflectors.

Regarding the displacement values, the QPSInSAR results confirm the trends observed in the PS analysis, particularly along the dam crest and the area near the spillway. However, QPS reveals the displacement pattern in greater detail across the entire structure. The most significant cumulative LOS displacements are observed in the central part of the dam body, where values reach up to **-223 mm (subsidence)** in LOS direction of the ascending orbit. The estimated displacement rates range from **+1** to **-20 mm/year.** Figure 10 shows only DS with temporal coherence above 0.7.

Both PSInSAR and QPSInSAR enable the derivation of displacement time series at individual measurement points, providing detailed temporal information on deformation behavior. Representative examples are shown in Figure 11.

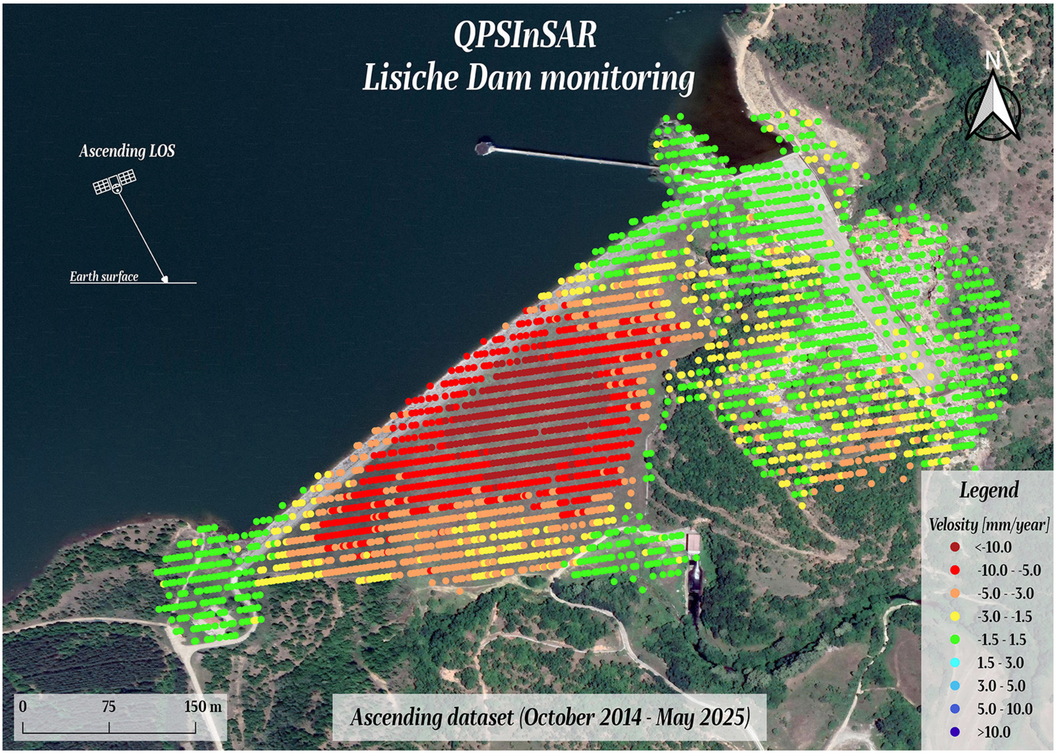

Figure 10: QPSInSAR displacement velocity map over the Lisiche Dam area (ascending dataset)

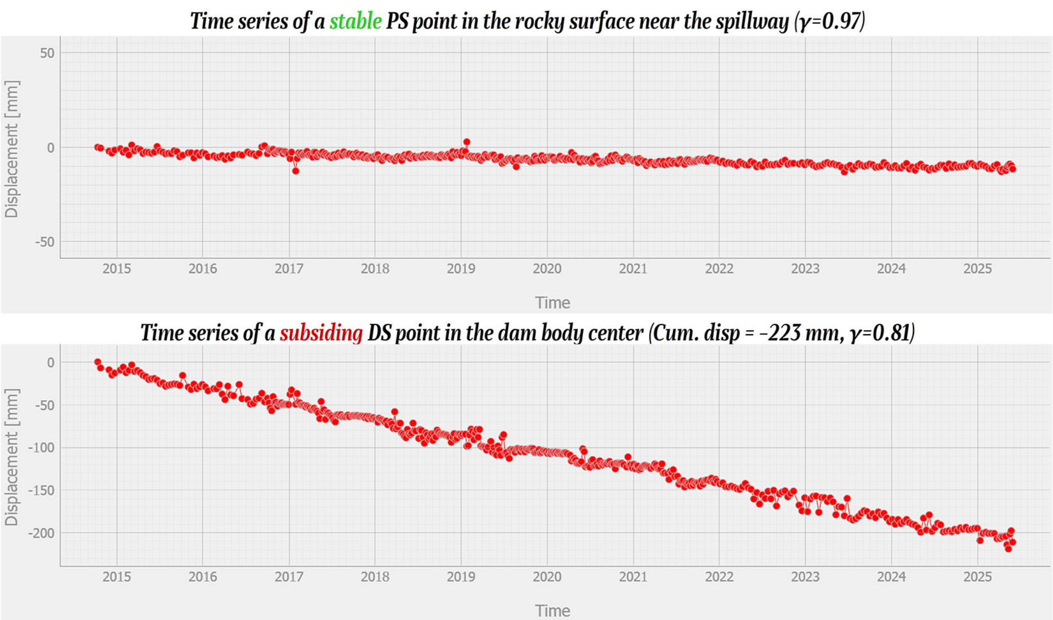

Figure 11: Time series PS and DS points, illustrating stable and subsiding behavior (ascending dataset)

4.2 PSInSAR and QPSInSAR results: descending dataset

The PSInSAR analysis of the descending dataset identified a total of **539 PS** points with temporal coherence values ranging from 0.51 to 0.97. The results are presented in Figure 12.

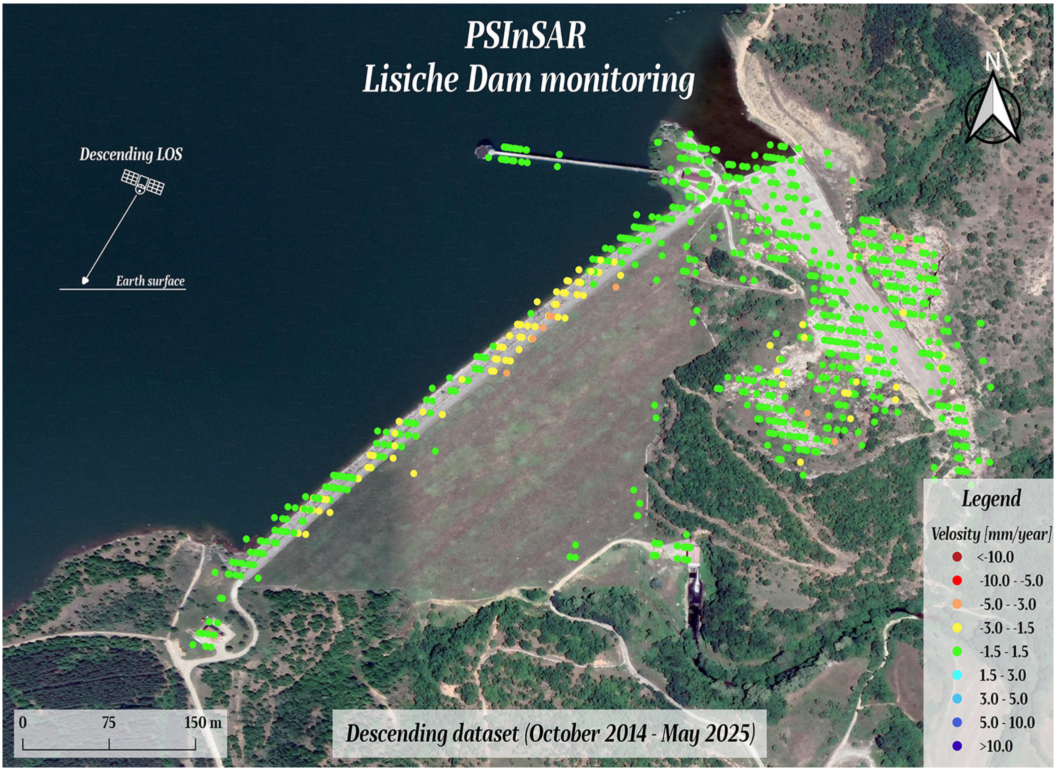

Figure 12: PSInSAR displacement velocity map over the Lisiche Dam area (descending dataset)

Similar to the ascending dataset, the PS points are concentrated along the dam crest and in the rocky surface near the spillway, but they exhibit much smaller displacements, which is expected given LOS geometry. The observed velocity rates range from **+1** to **–3 mm/year** in the LOS direction. The maximum cumulative displacement reaches **–37 mm (subsidence)** near the central part of the dam crest.

Figure 13 illustrates the results of the QPSInSAR analysis of the descending dataset. A total of **3,038 DS** points were identified with temporal coherence values ranging from 0.71 to 0.97, densely distributed across the entire dam body, the spillway, and the surrounding area. The displacement velocity rates range from **+1** to **–7 mm/year** in the descending LOS direction. The maximum cumulative displacement of **–60 mm (subsidence)** was recorded near the central core of the dam during the analyzed period. In this case as well, the QPSInSAR results provide a more comprehensive picture of the dam surface condition compared to PSInSAR. From the perspective of the descending geometry, the structure appears relatively stable, with the exception of the central core area where subsidence is observed.

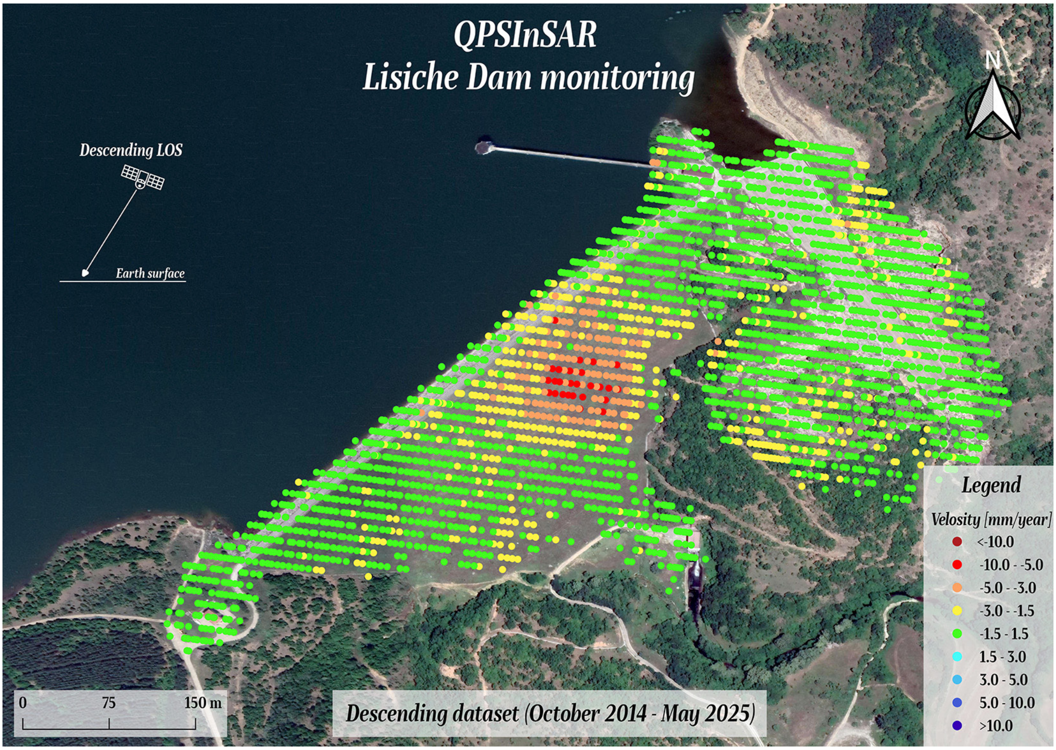

Figure 13: QPSInSAR displacement velocity map over the Lisiche Dam area (descending dataset)

4.3 Discussion of Results

The results show that the analyses from the two orbits, reveal different displacements magnitudes across the dam body during the analyzed period. This outcome is expected, given the differences in acquisition geometry (LOS orientation and heading angle). Considering the geometric configuration of the dam, the ascending acquisition is more suitable, as its LOS is parallel to the dam surface, whereas in the descending orbit the LOS is nearly perpendicular to the dam surface. Consequently, the results from the ascending orbit provide a more accurate representation of the dam's condition during the analyzed period. Nevertheless, the displacement trends are nearly identical in both analyses, as both indicate stability at the dam abutments, the spillway, and the surrounding area, while the most pronounced movements occur in the central part of the dam.

The results further demonstrate that the QPSInSAR technique provides more comprehensive and detailed information on the condition of the Lisiche Dam, since the grassy surface of the embankment is particularly suitable for identifying distributed scatterers. Consequently, the QPSInSAR results from the ascending dataset are considered the most representative of the dam's actual condition. These results indicate that the largest displacements occur in the central part of the dam, where cumulative subsidence exceeds 20 cm in LOS during the analyzed period. Displacements gradually decrease from the central core toward the abutments, where stability is observed (Figure 10). In the absence of geodetic and geotechnical measurements evaluating the stability of the Lisiche Dam, the observed annual maximum subsidence of about 2 cm in the ascending LOS direction is consistent with engineering expectations for an earth-fill embankment dam. However, to confirm this interpretation, the results should be compared with dam auscultation data from the analyzed period. Moreover, as the InSAR-derived displacements are obtained along the LOS directions of the ascending and descending geometries, decomposition into horizontal and vertical components is required. For the estimation of the horizontal displacement component, the crest orientation of the dam should be defined as the null line, following the Strap-down approach (Brouwer & Hanssen, 2024).

One of the main limitations of InSAR analyses is their limited applicability in vegetated areas. This was also confirmed in our study, where almost no coherent points were detected on the vegetated slopes surrounding the dam. Another limitation is that InSAR captures displacements only along the LOS direction, which does not allow for an intuitive interpretation of the actual ground deformation and requires additional processing to separate vertical and horizontal components. Another important observation is that the PSInSAR approach did not identify persistent scatterer points on the dam body itself, which limits its direct applicability for assessing deformation of the embankment surface. To address this, we recommend exploring the installation of corner reflectors on the dam body, as these would enhance radar visibility and ensure more reliable long-term monitoring. Similar conclusions have been reported in recent studies, where electronic corner reflectors were shown to significantly improve the applicability of PSInSAR for operational dam and reservoir monitoring (Jänichen, et al., 2025).

Considering the potential for retrospective monitoring of the Lisiche Dam as well as other dams in North Macedonia, we recommend that InSAR techniques be employed in the future as a complementary tool, alongside geodetic and geotechnical measurements, for assessing the geometric stability of dams. Given the legal requirement for annual geodetic and geotechnical auscultations, InSAR offers an excellent supplementary approach, with Sentinel-1 providing acquisitions at intervals of up to 12 days.

5 Conclusion

This study represents the first application of advanced InSAR techniques, specifically PSInSAR and QPSInSAR, for monitoring the geometric stability of the Lisiche Dam. Results from both ascending and descending datasets indicated stability at the abutments, spillway, and surrounding terrain, with the most significant deformations concentrated in the central part of the dam body. QPSInSAR provided denser coverage than PSInSAR due to the suitability of the grassy surface for distributed scatterers, enabling a clearer characterization of the displacement field. The cumulative displacements in the central crest exceeded 20 cm during the analyzed period, corresponding to an average annual subsidence rate of about 2 cm in ascending LOS, which is consistent with engineering expectations for an earth-fill dam. However, validation with geodetic and geotechnical measurements remains essential.

In the discussion, several recommendations were outlined, including the need for validation with in-situ auscultation data, the decomposition of LOS displacements into horizontal and vertical components, and the potential installation of corner reflectors to improve radar visibility. Overall, the results highlight the potential of InSAR for retrospective and operational dam monitoring in North Macedonia. Considering the legal obligation for annual geodetic and geotechnical auscultations, InSAR represents an excellent supplementary tool, with Sentinel-1 acquisitions available at intervals of up to 12 days, thus providing a cost-effective and reliable approach for continuous dam stability assessment.

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