Analyzing the Impact of Soil Moisture Dynamics on Ground Deformation in Salar de Atacama Using PSI and Sentinel Imagery

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Abstract

The surface properties' effect on ground deformation measurement using Persistent Scatterer Interferometry (PSI) techniques is well-documented. One such effect can arise from soil moisture dynamics due to changes in the surface's dielectric properties.
Salar de Atacama, a salt flat in Chile's Atacama Desert, is one of the driest places on Earth and a significant part of the Lithium Triangle. The southern part of the salt flat is exploited for brines. Surrounding wetlands with low perennial herbs add to the region's biodiversity and cultural significance for indigenous communities.
This study utilizes Sentinel-1 imagery from 2020 to 2024 to estimate ground deformation and Sentinel-2 imagery from the same period to characterize soil moisture and vegetation dynamics. The project's primary focus is to analyze the relationship between soil moisture and ground deformation.
The study site was divided into regions based on soil moisture behavior and the presence of vegetation and water bodies. Results were compared with ground deformation estimates, revealing key findings: 1) The largest region, the salt flat, shows reliable PSI results due to the absence of vegetation and surface water or soil moisture. 2) In the brine pool zone, low temporal coherence prevents identifying persistent scatterers, though periods without water or soil moisture might allow PSI application. 3) Areas with vegetation or surface water/temporal flooding require case-by-case analysis to identify persistent scatterers.

Keywords: PSI, Soil Moisture, Sentinel-1, Salar de Atacama

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1 Introduction

The Salar de Atacama, a vast salt flat nestled within the hyper-arid Atacama Desert in Chile, stands as one of the driest and most extreme environments on Earth. This unique landscape holds immense significance, both geologically and ecologically.

The Salar de Atacama forms a crucial part of the "Lithium Triangle," a region encompassing parts of Chile, Argentina, and Bolivia, renowned for its vast reserves of lithium. This element is increasingly critical for the renewable energy sector, particularly for the production of lithium-ion batteries used in electric vehicles and energy storage systems.

The southern portion of the salt flat is actively exploited for the extraction of lithium-rich brines. This industrial activity presents potential environmental challenges that require careful management (Gutiérrez et al., 2022), (Bonelli & Dorador, 2021).

Persistent Scatterer Interferometry (PSI) is a technique for analyzing ground motion by estimating deformation over time using radar satellite data. PSI relies on identifying the so-called persistent scatterers (Crosetto et al., 2016).

Changes in surface properties, such as variations in land cover/land use, vegetation dynamics, temporal water presence, and soil moisture can induce phase shifts in the radar signal, potentially leading to misinterpretations of ground displacement (Ansari et al., 2021).

To mitigate these uncertainties, a deeper understanding of the influence of environmental factors on PSI measurements is essential. The Copernicus Programme, with Sentinel-1 and Sentinel-2 missions, provides a unique opportunity to integrate environmental data with PSI analysis. This research aims to investigate the relationship between soil moisture and the ground deformation of persistent scatterers.

2 Study Area

Salar de Atacama is located in the Atacama Desert, in northern Chile (Figure 1). This region is characterized by extremely arid conditions with minimal precipitation.

Between May 2022 and November 2024, the maximum daily precipitation recorded was 10 mm (Figure 2). Furthermore, only 17 days within this period experienced precipitation exceeding 0.1 mm.

Figure 1. Study Area.

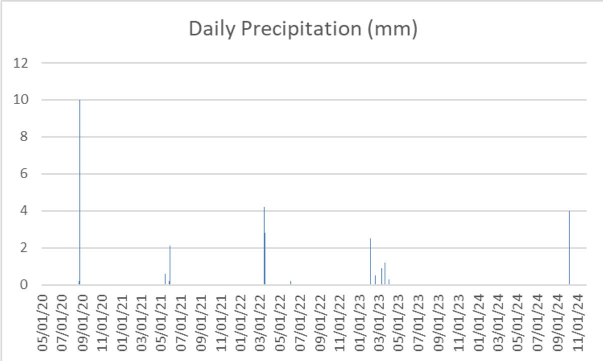

Figure 2. Daily Precipitation.

Two mining companies operate within the salt flat, extracting lithium-rich brines. SQM is the primary operator, the brine extractions its shown in Figure 3.

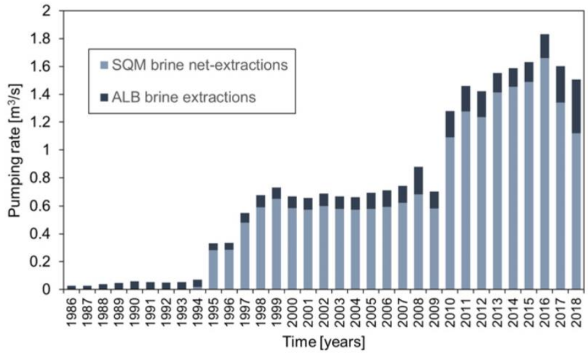

Figure 3. Temporal evolution of the brine extractions in the Salar de Atacama (Marazuela et al., 2020).

3 Materials and Methods

3.1 Persistent Scatterer Interferometry

The Persistent Scatterer Interferometry was obtained by using the CTTC processing chain, which can be seen in detail in (Crosetto et al., 2014).

For the processing, 72 ascending orbit Sentinel-1 images acquired between January 6, 2022, and June 12, 2024, were utilized. A Dispersion Amplitude Threshold of 0.23 was applied to improve the quality of the PS.

3.2 Topographic Data

For the topograpahic analysis it was considered the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model.

The first step was to clean the SRTM due to the presence of artificial artifacts in the area of the salar.

Later, it was computed the Slope (degrees), Aspect and Hillshade (in direction of the Line-of-Sight to the satellite). This was performed using ArcGis Pro.

3.3 Vegetation and Water Bodies Time Series

Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) were calculated at a monthly level from Sentinel-2 Level-2A imagery acquired between July 2015 and June 2024 using Google Earth Engine. Level-2A products provide surface reflectance data, eliminating the need for pre-processing within the platform.

The analysis utilized Sentinel-2 Level-1C data with a 30% cloud cover threshold for initial data selection.

3.4 Unified Analysis

The variables were subsequently integrated into a unified database, enabling the identification of temporal relationships between them.

The first step was the identification of anomalous mean velocity areas, investigating their dynamics in relation to Slope, Hillshade, Aspect, NDVI, and NDWI.

Later, a logistic regression was performed to determine which variables most influence the presence of PS in the study area.

4 Results

4.1 Persistent Scatterer Interferometry

The Persistent Scatterer Interferometry (PSI) analysis yielded 18 million persistent scatterers (PS), providing comprehensive coverage across most of the study area. Minor gaps in PS coverage were observed near San Pedro de Atacama and along the eastern border of the salt flat (Figure 4).

Figure 4A presents the PSI ground deformation time series. Three areas of interest are highlighted:

A: Pumping area associated with SQM mining operations, showing a velocity of around -5 to -20 mm/yr.

B: A brine pool associated with SQM mining operations, exhibiting surrounding subsidence (in the dumps next to the pools).

C: A southeastern area characterized by subsidence zones along the edge of the salt flat core.

The ground deformation is located near the evaporation pools of brines and the south-east border of the saltflat.

4.2 Unified Analysis

Three anomalous areas within the salt flat were identified, exhibiting distinct mean linear velocities compared to their surroundings. These velocity differences ranged from 0.5 to 1 mm/year.

Area A: located in the southern part of the salt flat near brine extraction sites. Displaying the most significant differences in mean amplitude (39). The average velocity difference within this area was 0.5 mm/year. Vegetation indices (NDVI) and Water Presence (NDWI) indicated a higher median NDVI outside the anomaly and higher mean NDWI within. However, both indices remained below thresholds for vegetation or water presence. Persistent Scatterer (PS) time series exhibited higher values outside the anomalous area.

Area B: situated in the western part of the salt flat near the Cordillera de la Sal, this area showed a velocity difference of 1 mm/year. The mean amplitude difference was 14. NDVI indicated a slightly higher median within the anomaly, while mean NDWI was higher outside. As with Area A, both indices remained below relevant thresholds. PS time series demonstrated higher values outside the anomalous area.

Area C: located in the core of the salt flat. Exhibited a velocity difference of 0.8 mm/year and a mean amplitude difference of 12.5. Similar to Areas A, NDVI was higher outside, while mean NDWI was higher within the anomaly. Both indices remained below relevant thresholds. PS time series again showed higher values outside the anomalous area.

These results suggest that the observed changes in mean velocity are not primarily influenced by vegetation or water presence distribution within the study area. Furthermore, the significant difference in average amplitude observed only in Area A indicates potential variations in surface properties, such as rugosity, within this specific region. In contrast, Areas B and C exhibit no significant differences in amplitude, suggesting that variations in surface characteristics, such as rugosity, are unlikely to be the primary cause of the observed velocity differences in these areas.

A logistic regression was performed to determine which variables most influence the presence of PS in the study area. The result of the analysis is as follows:

$$logit(p) = 1.5944 + 0.3301 * S + -1.7577 * A + 1.7503 * H - 1.2104 * NDVI\_aver - 1.7556 * NDVI\_disp + 0.3868 * NDVI\_vari - 1.2277 * NDWI\_aver + 1.4301 * NDWI\_disp - 0.0683 * NDWI\_vari \quad (1)$$

Where:

S: Slope
A: Aspect
H: Hillshade defined with the Line-of-Sight direction from the Sentinel-1 sensor on the study area.
NDVI_aver: Average of the monthly NDVI
NDVI_disp: Dispersion of the monthly NDVI
NDVI_var: Variability of the monthly NDVI
NDWI_aver: Average of the monthly NDWI
NDWI_disp: Dispersion of the monthly NDWI
NDWI_vari: Variability of the monthly NDWI

The most influential variables were identified as Aspect, NDVI dispersion, Hillshade, and NDWI dispersion, while Slope exhibited lower importance. This suggests that topographic factors, particularly hillside orientation (Aspect) and its associated shading (Hillshade), significantly influence amplitude stability. Furthermore, the dispersion of vegetation indices (NDVI and NDWI), rather than their average values, emerged as key factors in controlling persistent scatterer (PS) stability.Future works will be focused on the quantitative analysis of the presence of PS related to environmental conditions and the effects of this on the mean velocity and the effects on the ground deformation time series.

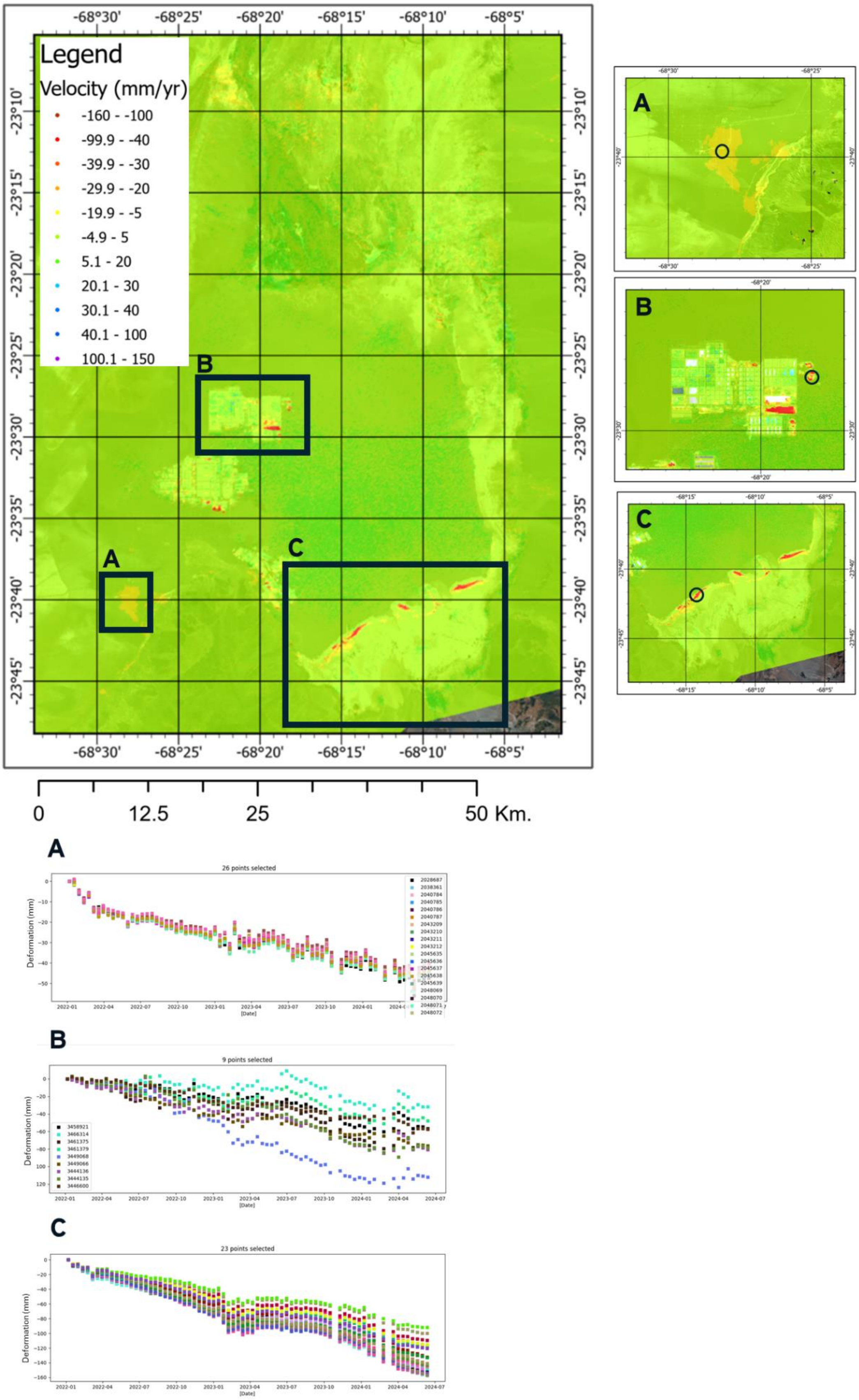

Figure 4. PSI Ground Deformation in Salar de Atacama, most of the area shows values between -5 to 5 mm/yr. There is subsidence in three regions: A) near the pumping area, B) in the dumps near the pools, and C) in the south-east border of the salt flat.

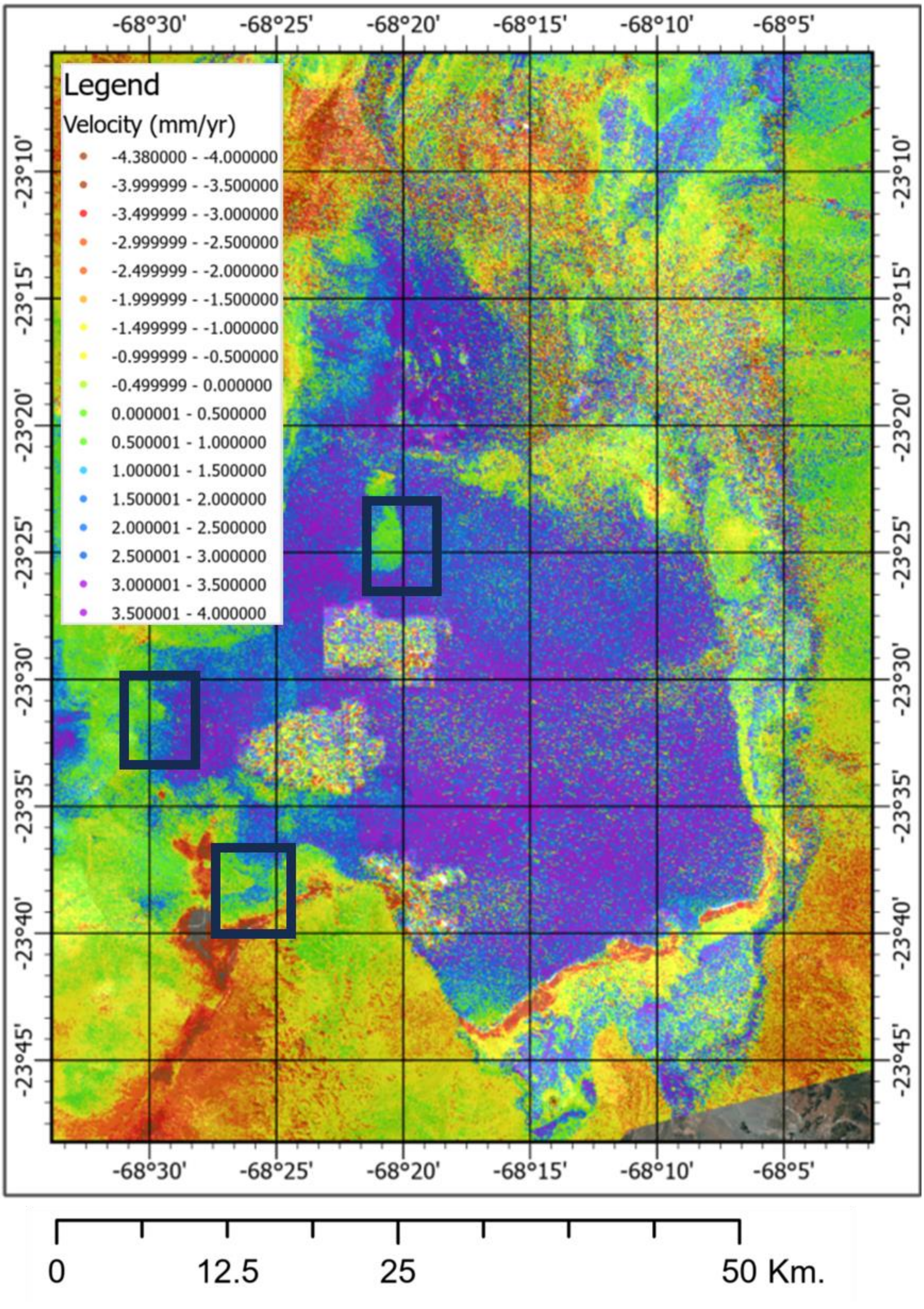

Figure 5. PSI Ground Deformationadjusted velocity (-5 to 5 mm/yr) to enhance the heterogeneous areas inside the salt flat and location of three selected areas with spatial patterns of mean velocity

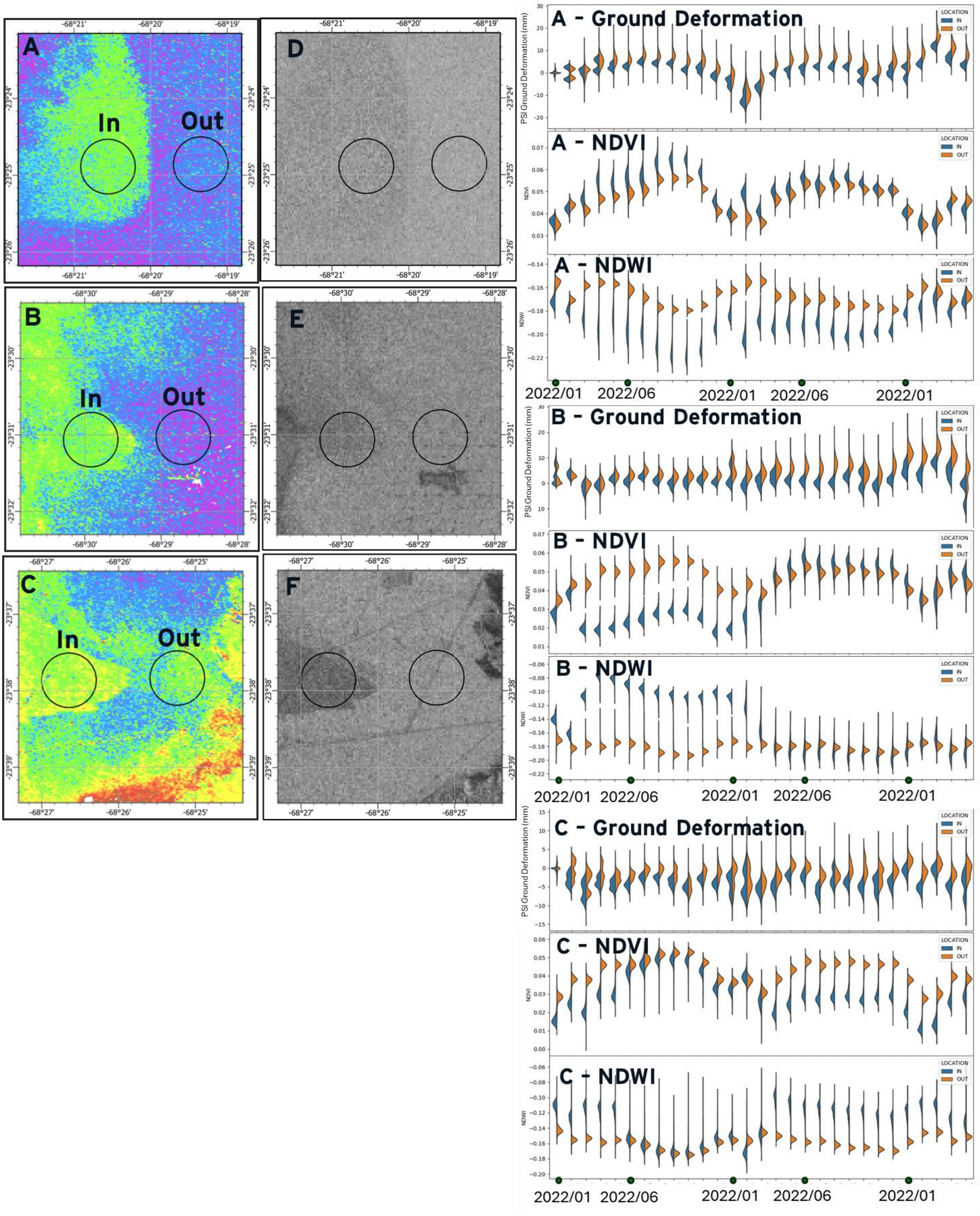

Figure 6. Median Velocity Map (A, B & C), Mean Amplitude Map (D, E & F), along with time series of PSI ground deformation, NDVI index, and NDWI index for each selected area.

5 Conclusion

Some areas within the study region exhibit distinct mean velocities compared to their surroundings. In certain areas, these velocity differences correlate with variations in mean amplitude, suggesting potential changes in surface properties.

Other areas show lower NDVI values and higher NDWI values, indicating potential influences of soil moisture on the observed velocity differences.

The analysis indicates that Aspect and Hillshade are the most significant topographic factors influencing the observed phenomena. Regarding Environmental indices, NDVI dispersion exhibited a stronger influence than NDWI dispersion. This suggests that temporal variability (dispersion) of the land cover is more critical than the average vegetation or water presence in controlling the observed patterns.

Acknowledgements

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