

SBAS-InSAR–Based Landslide Monitoring in Hunza Valley, Northern Pakistan

Ihtisham Khan¹, Kazimierz Bęcek^{1*}, Said Mukhtar Ahmad², Basit Ali Khan³

¹ Faculty of Geoengineering, Mining and Geology, Wrocław University of Science and Technology, 50-421 Wrocław, Poland, ihtisham.khan@pwr.edu.pl, kazimierz.becek@pwr.edu.pl

² State Key Laboratory of Geohazard Prevention and Geo environment Protection, Chengdu University of Technology, Chengdu 610059, China, mukhtargeo44@gmail.com

³ School of Surveying and Land Information Engineering, Henan Polytechnic University, Henan, 454099, China, basitgeologist543@gmail.com

* Corresponding author: kazimierz.becek@pwr.edu.pl

Abstract

Landslides are one of the most common natural hazards in mountainous areas and directly or indirectly impact local communities' lives. In northern Pakistan, Hunza Valley exemplifies such high-risk environments. In this study, we analysed Sentinel-1 SAR data spanning three years (March 2018 to March 2021) using the Small Baseline Subset (SBAS) InSAR technique implemented through SNAP and StaMPS to examine ground deformation in the region and identify zones of significant displacement. Line-of-Sight (LOS) deformation was measured independently from ascending and descending orbits. The ascending LOS results show velocities of approximately -660 to -1200 mm yr⁻¹ with a standard deviation of 342.50 mm, while the descending LOS indicates velocities of about -79 to -250 mm yr⁻¹ with a standard deviation of 830.09 mm. The most notable deformation occurs at Sas and Hopper landslides, with time-series data displaying persistent downslope movement and episodic acceleration. Validation with Google Earth imagery confirms that areas of high deformation correspond with observable geomorphic landslide features. The detected deformation is consistent with active landslide movements in steep terrains influenced by tectonic activity and seasonal rainfall variability, demonstrating the effectiveness of SBAS-InSAR in regional landslide monitoring and detection.

Keywords: SBAS-InSAR, Sentinel-1, Landslide deformation, Hunza Valley

Introduction

Globally, landslides represent one of the most destructive natural hazards, posing a significant threat to infrastructure, property, and communities, as well as a considerable loss of human life annually (Froude & Petley, 2018; Kelkar et al., 2022). Tectonically active mountainous areas with high elevation are particularly vulnerable to these dangers. Hunza Valley, located in the northwestern Karakoram Mountains of Pakistan, serves as a natural laboratory for landslide processes due to the combined influence of extreme geomorphic, geological, and climatic factors (Rehman et al., 2020).

The Hunza Valley is of significant strategic and economic importance as it hosts the Karakoram Highway, a key corridor of the China–Pakistan Economic Corridor (CPEC). Recurrent landslides pose a persistent threat to this vital infrastructure, as demonstrated by the catastrophic Atta Abad landslide in 2010, which resulted in loss of life and long-term disruption of transportation and river systems (Ahmad et al., 2024; Bacha et al., 2018). Such events often occur with limited warning, highlighting the need for effective monitoring and early detection of slope deformation (Pandey et al., 2022).

Traditional landslide inventories based on field surveys and optical remote sensing often fail to detect slow or early-stage ground deformation, resulting in incomplete hazard assessments (Guzzetti, 2000; Martha et al., 2013). In contrast, time-series Interferometric Synthetic Aperture Radar (InSAR), particularly the Small Baseline Subset (SBAS-InSAR) technique,

enables precise monitoring of centimeter-scale surface deformation over large areas (Kang et al., 2017). This study aims to apply the SBAS-InSAR approach using ascending- and descending-Sentinel-1 SAR data to monitor landslide deformation in the Hunza Valley, improve understanding of slope instability processes, and support more reliable landslide hazard assessment and mitigation.

Data and Method

Study Area

The Hunza-Nagar region is located in northern Pakistan within the Karakoram Mountain range and is characterised by extreme topographic relief, with elevations ranging from approximately 1,503 m to 7,788 m above sea level. The terrain is predominantly steep, with slope angles commonly between 30° and 60°, favouring slope instability. The regional geology is complex and consists mainly of schist, gneiss, limestone, and volcanic rocks. The area lies within an active tectonic zone associated with the collision of the Indian and Eurasian plates (Searle et al., 1999) and is structurally controlled by major fault systems, including the Main Karakoram Thrust and the Karakoram Fault (Figure 1). Vegetation cover is sparse, with more than 90% of the area being barren, and most landslides occurring in low-vegetation zones. The region is drained by major rivers such as the Hunza, Hisper, and Gulmit, which increase erosion and contribute to slope instability.

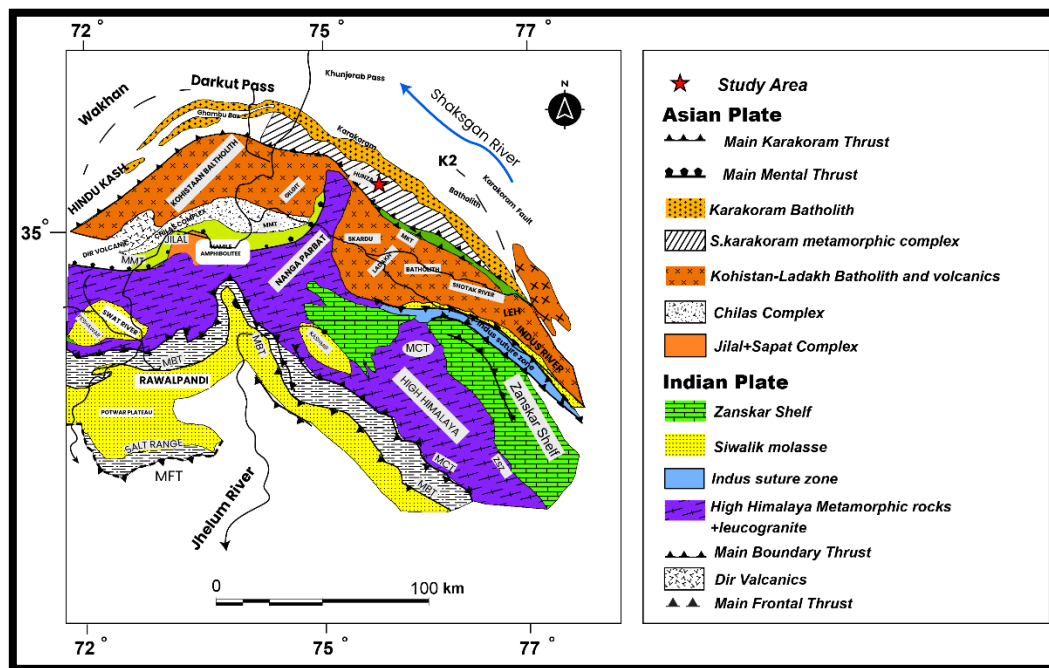


Fig. 1. Regional tectonic map showing major tectonic features of Northern Pakistan.

In this study, we used Sentinel-1 C-band SAR scenes acquired between March 2018 and March 2021. Data was downloaded from the ASF Alaska Satellite Facility, including both standard Sentinel-1 SLC products and selected Hyp3 on-demand products. Both ascending and descending tracks were processed to minimise geometric distortions. The ascending data set corresponds to Path 27–117, while the descending data set was assembled as a mosaic of multiple tiles (Path 117–468 and Path 117–473) to ensure full spatial coverage.

To preprocess SAR data and generate an interferogram, we used the ESA SNAP v9.0 software (Figure 2). During quality control, some Hyp3 interferograms showed phase inconsistencies; these were excluded and reprocessed directly from the raw SLC data to preserve phase

integrity. The SNAP workflow included precise orbit application, TOPSAR split, debursting, DEM-assisted back-geocoding, Enhanced Spectral Diversity co-registration, interferogram formation, topographic phase removal using the SRTM 1-arcsecond DEM, filtering, and coherence estimation before export to StaMPS. Time-series inversion was conducted using the SBAS approach with perpendicular baselines restricted to 150 m to reduce decorrelation.

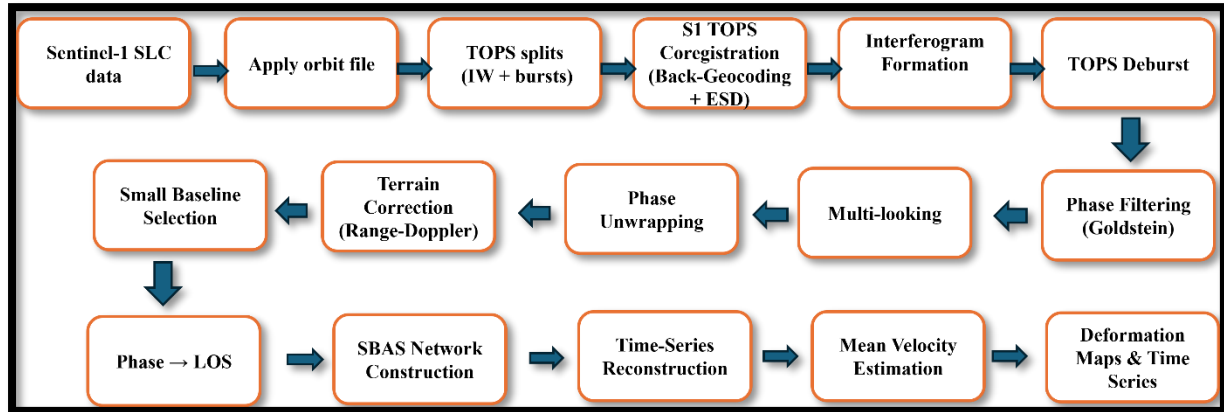


Fig. 2. Methodological framework for the SBAS-InSAR processing using the SNAP software.

Results

The analysis revealed spatially heterogeneous LOS deformation throughout the Hunza valley between 2018 and 2021. SAS and Hopper landslides are consistently being identified as the most actively deforming zones within the study area by both ascending and descending tracks.

For the ascending track, the cumulative LOS displacement ranges from -3500 to -2000 mm, with corresponding mean velocities of -1200 to -660 mm/year (Figure 3).

The statistical variability of the deformation field was further evaluated by computing the standard deviation of the cumulative displacement values derived from the SBAS-InSAR results. The ascending LOS deformation exhibits a standard deviation of 342.50 mm, indicating substantial spatial variability in ground movement across the monitored slopes (Figure 5). The histogram of deformation values shows a negatively skewed distribution dominated by downslope displacement values, while the boxplot highlights the presence of several extreme deformation pixels corresponding to active landslide zones. The spatial distribution of deformation variability confirms that the highest dispersion occurs in the Sas and Hopper landslide areas, which are characterised by steep slopes and fractured lithology.

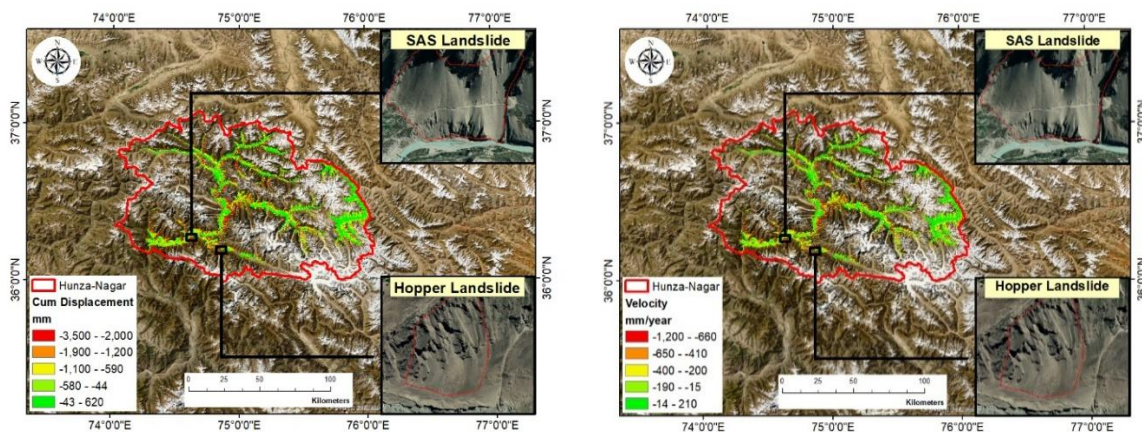


Fig. 3. Ascending LOS cumulative displacement map (left side), displacement velocity map along the line of sight (V_{los}) (right side).

The descending track shows cumulative LOS displacement between -740 and -240 mm and velocity values ranging from -250 to -79 mm/yr (Figure 4). The motion away from the satellite is denoted by negative LOS values, which in this case corresponds to downslope movement. Although the magnitudes differ between the viewing geometries, both tracks spatially coincide over the same deforming zones, confirming persistent slope instability in the identified landslides.

The descending track deformation statistics show a standard deviation of 830.09 mm, reflecting comparatively lower but still significant variability in surface displacement (Figure 6). The histogram distribution indicates a concentration of moderate deformation values with fewer extreme outliers compared to the ascending track. This difference is expected due to the differing viewing geometries of the SAR acquisitions, which influence the sensitivity of LOS measurements to slope-parallel movement. Nevertheless, the spatial pattern of variability remains consistent with the deformation hotspots identified in the displacement maps.

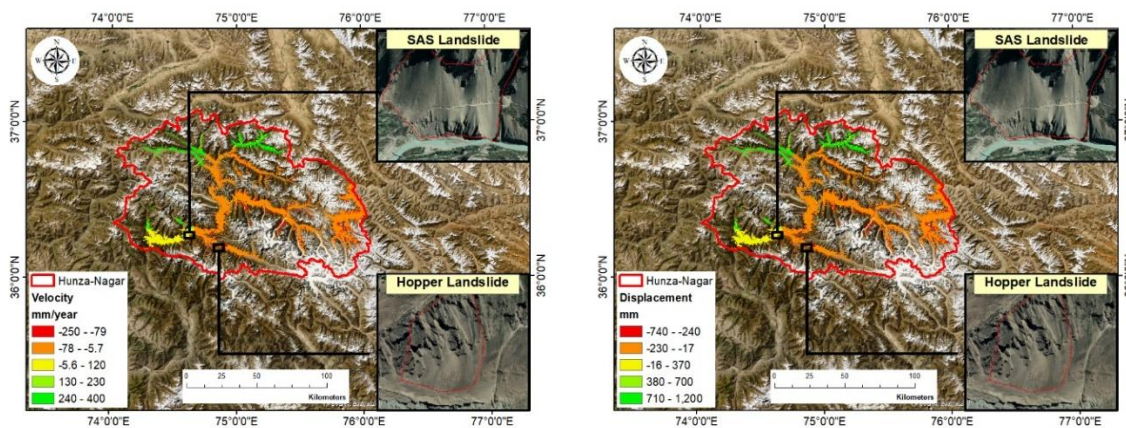


Fig. 4. Descending LOS cumulative displacement map (left side), displacement velocity map along the line of sight (V_{los}) (right side).

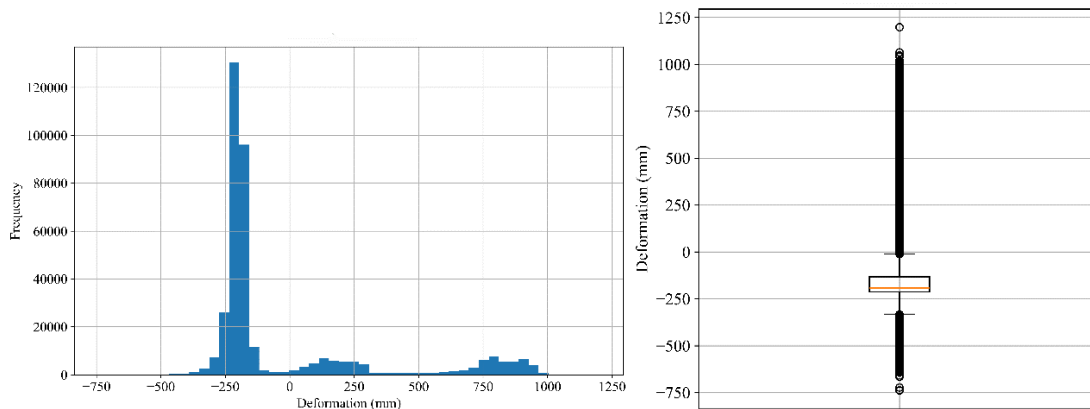


Fig.5. Statistical analysis of ascending LOS cumulative deformation including histogram distribution, and boxplot representation showing variability of displacement values derived from SBAS-InSAR processing.

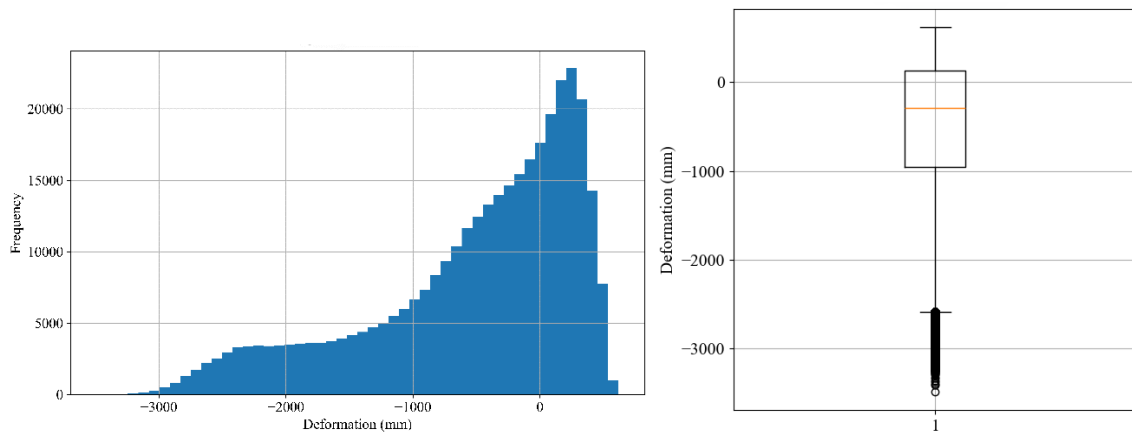


Fig. 6. Statistical analysis of descending LOS cumulative deformation including histogram distribution, and boxplot representation showing the variability of LOS displacement values.

Time-series analysis shows increasing deformation over the studied period, with acceleration phases aligning with seasonal variations (Figures 7 and 8). The deformation patterns agree with the regional tectonic setting of the Karakoram-Himalayan orogenic belt, where slope destabilisation is worsened by active faulting and crustal shortening. Seasonal rainfall and snowmelt may also raise pore-water pressure and reduce shear strength, promoting further movement. The identified deformation hotspots match mapped scarps, disrupted slope surfaces, and debris accumulation zones, as confirmed by visual comparison with high-resolution Google Earth Pro images. This provides independent geomorphic validation of the results obtained from InSAR.

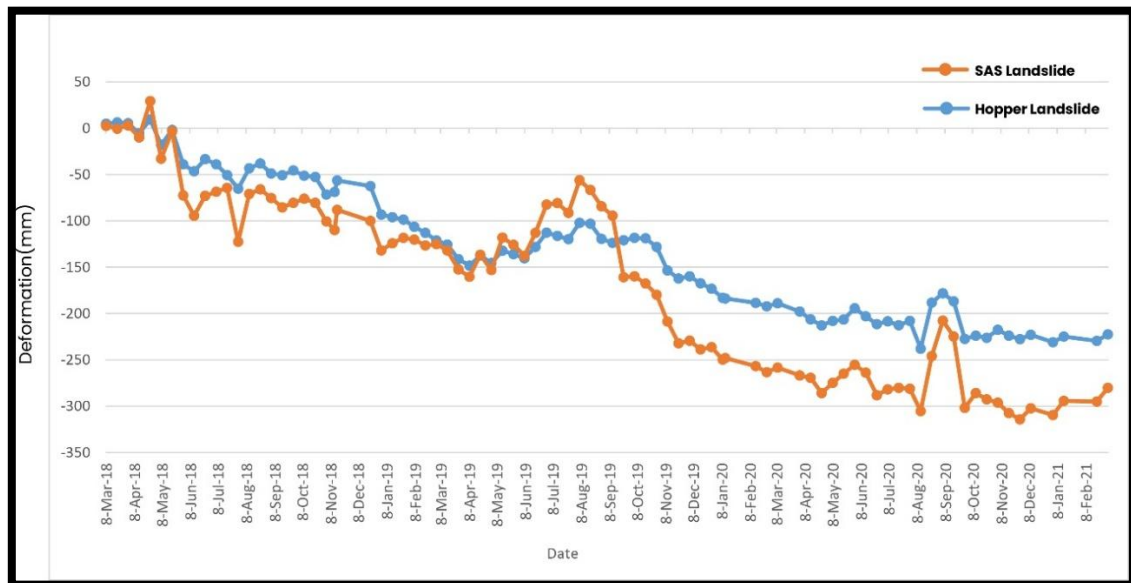


Fig. 7. Displacement time series for ascending orbit for SAS and Hopper landslides (2018-2021).

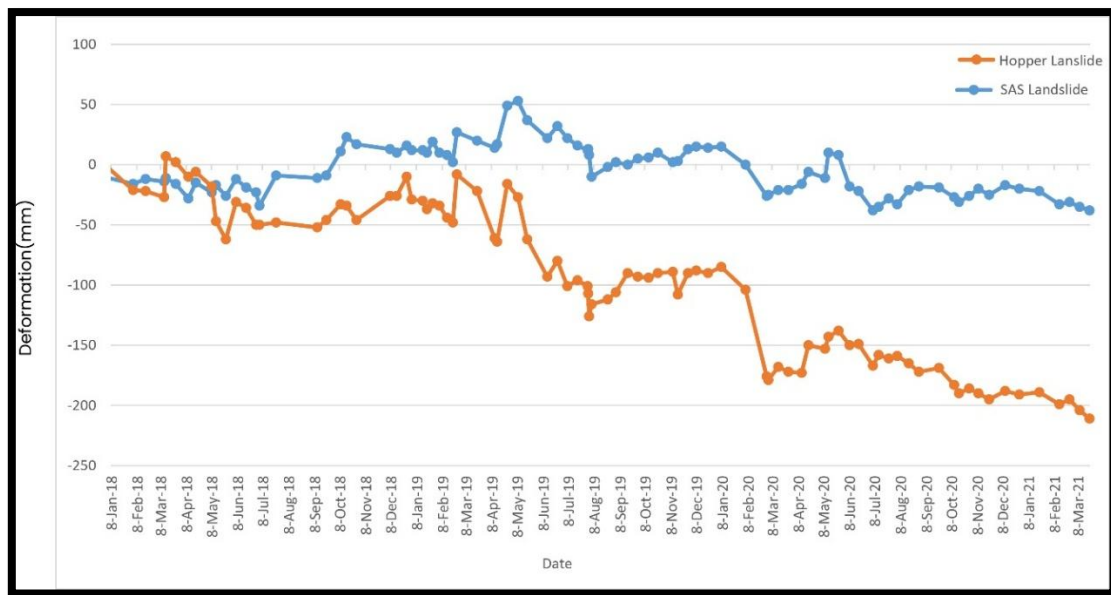


Fig. 8. Displacement time series for descending orbit for SAS and Hopper landslides (2018-2021).

To further investigate the seasonal behaviour of slope deformation, meteorological data were analysed for the same observation period (Figure 9). Monthly precipitation records indicate increased rainfall during the summer monsoon season (June–September) and additional moisture input during spring snowmelt. Comparison of rainfall variability with the InSAR-derived displacement time series reveals that periods of accelerated deformation generally correspond with months of elevated precipitation. Increased rainfall and snowmelt likely raise pore-water pressure within the slope materials, reducing effective stress and shear strength, thereby promoting enhanced landslide movement. This seasonal relationship suggests that hydro-meteorological conditions play an important role in controlling landslide dynamics in the Hunza Valley.

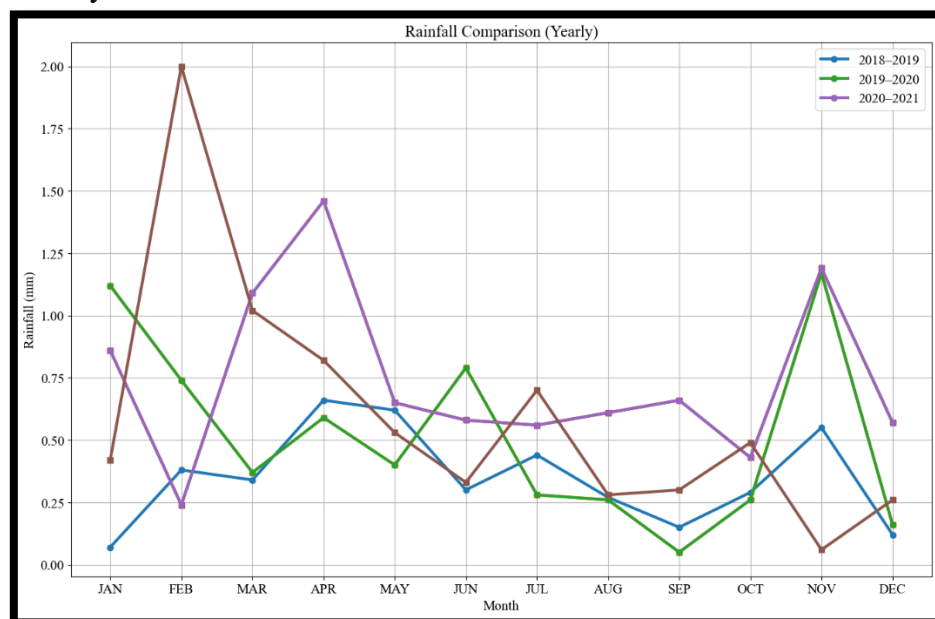


Fig. 9. Monthly average precipitation recorded in the Hunza Valley during the observation period (2018–2021), illustrating seasonal rainfall variability.

Conclusion

This study demonstrates the capability of the SBAS-InSAR technique, using SNAP and StaMPS, to monitor active landslide deformation in Hunza Valley using multi-orbit Sentinel-1 data. The ascending and descending LOS results consistently identify the same unstable landslide zones, confirming persistent downslope movement within this tectonically active mountainous environment. The temporal evolution derived from the InSAR time series indicates progressive deformation during 2018-2021, highlighting the ongoing instability of these slopes.

Future research should extend the temporal coverage, integrate additional SAR missions, and incorporate ground-based validation, such as GNSS or field investigations. Importantly, further work should include decomposing ascending and descending LOS measurements into vertical and horizontal deformation components to better understand landslide kinematics and enhance the physical interpretation of slope movement processes.

References

- Ahmad, M. S., Lisa, M., & Khan, S. (2024). Assessment and mapping of landslides in steep mountainous terrain using PS-InSAR: A case study of Karimabad Valley in Chitral. *Kuwait Journal of Science*, 51(1). <https://doi.org/10.1016/j.kjs.2023.09.007>
- Bacha, A. S., Shafique, M., & van der Werff, H. (2018). Landslide inventory and susceptibility modelling using geospatial tools, in Hunza-Nagar valley, northern Pakistan. *Journal of Mountain Science*, 15(6), 1354–1370. <https://doi.org/10.1007/s11629-017-4697-0>
- Froude, M. J., & Petley, D. N. (2018). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, 18(8), 2161–2181. <https://doi.org/10.5194/nhess-18-2161-2018>
- Guzzetti, F. (2000). Landslide fatalities and the evaluation of landslide risk in Italy. In *Engineering Geology* (Vol. 58). www.elsevier.nl/locate/enggeo
- Kang, Y., Zhao, C., Zhang, Q., Lu, Z., & Li, B. (2017). Application of InSAR techniques to an analysis of the Guanling landslide. *Remote Sensing*, 9(10). <https://doi.org/10.3390/rs9101046>
- Martha, T. R., van Westen, C. J., Kerle, N., Jetten, V., & Vinod Kumar, K. (2013). Landslide hazard and risk assessment using semi-automatically created landslide inventories. *Geomorphology*, 184, 139–150. <https://doi.org/10.1016/j.geomorph.2012.12.001>
- Pandey, V. K., Tripathi, A. K., & Sharma, K. K. (2022). Implications of landslide inventory in susceptibility modeling along a Himalayan highway corridor, India. *Physical Geography*, 43(4), 440–462. <https://doi.org/10.1080/02723646.2021.1872857>
- Searle, M. P., Khan, M. A., Fraser, J. E., Gough, S. J., & Jan, M. Q. (1999). The tectonic evolution of the Kohistan-Karakoram collision belt along the Karakoram Highway transect, north Pakistan. In *Tectonics* (Vol. 18, Number 6, pp. 929–949). <https://doi.org/10.1029/1999TC900042>
- Shobhan Kelkar, Ajinkya Niphadkar, Dr. Sudhir Chavan, & Dr. P. R. Bamane. (2022). Research Paper on Science Research for Infrastructure Improvement in the Wake of the Landslide Disaster. *International Journal of Advanced Research in Science, Communication and Technology*, 198–203. <https://doi.org/10.48175/ijarsct-7091>
- Rehman, M., Zhang, Y., Meng, X., Su, X., Catani, F., Rehman, G., Yue, D., Khalid, Z., Ahmad, S., & Ahmad, I. (2020). Analysis of landslide movements using interferometric synthetic aperture radar: A case study in Hunza-Nagar Valley, Pakistan. *Remote Sensing*, 12(12). <https://doi.org/10.3390/RS12122054>