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Advancing InSAR Applications in Detecting Land Movement and Sinkhole Precursors in Post-Mining Landscapes

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Mining, a critical global economic activity, disturbs the geomechanical and hydrogeological equilibrium of aquifer systems. This disturbance becomes particularly evident after mining operations cease. In post-mining areas, one of the most significant phenomena is the groundwater rebound. This process restores original groundwater levels in depleted mines, leading to land uplift and the formation of sinkholes. Such changes can be detrimental to infrastructure and pose a threat to public safety. These complex dynamics necessitate continuous monitoring of ground movements to mitigate potential hazards effectively. Interferometric Synthetic Aperture Radar (InSAR) technology has emerged as a valuable tool in this context, providing detailed insights into land movements. However, the complex geological, hydrogeological, and mining conditions in post-mining areas demand advanced InSAR data processing techniques to detect early signs of phenomena such as sinkholes, thereby enhancing our ability to respond to these geohazards.
Our study was conducted in the historical zinc and lead mining region near Olkusz, northeast of Krakow, Poland. This area, with a long history of underground mining, witnessed the conclusion of its mining operations in 2022. Since then, significant land surface deformations and sinkholes have been observed, impacting both rural and urbanized areas. To understand these land movements, our approach involved two primary methods: Persistent Scatterer Interferometric Synthetic Aperture Radar (PS InSAR) for long-term analysis and Differential InSAR (DInSAR) for short-term changes, employing ESA Copernicus Sentinel-1 data. For long-term land surface movement analysis, we analyzed 165 radar images from January 2020 to June 2023, captured using ascending orbital geometry. The data acquisition frequency varied due to changes in satellite operations. Short-term land surface movements were examined through 54 interferograms covering various time intervals (12-24-36 days) between July and December 2023, using both ascending and descending geometries.
We observed a complex pattern of land movement in the study area, with both subsidence and uplift. The average movement rates varied from -14.5 mm/year to +7.7 mm/year, with about 90% of the area experiencing changes within ±2.0 mm/year. The closed zinc and lead mine region showed significant uplift, reaching up to +7.7 mm/year, highlighting pronounced geomechanical changes. Seasonal movements, with amplitudes of ±15 mm, were dominated by winter-summer variations. A positive linear trend across a considerable portion of the study area suggests widespread land uplift since early 2022. The accuracy of the DInSAR method was approximately ±2

cm, while PSInSAR achieved finer resolution at ±0.5 cm. Short-term changes indicated potential ongoing terrain deformation, especially in shorter-time base interferograms. However, confirming these observations was challenging due to low signal quality in longer intervals. The impact of vegetation on DInSAR signal quality, particularly in forested areas, underscored the need for improved methodologies.

This study enhances our understanding of aquifer system deformation mechanisms in post-mining areas. The use of InSAR techniques, particularly in urbanized regions, is crucial for the effective monitoring of ground movements, highlighting the importance of ongoing research to refine interferometric calculation efficiency, especially in areas with dense vegetation and urban structures.