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Review Article

Integration of PSInSAR Using SAR Data for Regional Subsidence Mapping in Pakistan

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Abstract

In Pakistan, land subsidence has become a serious geohazard, with the major factors being rapid urbanization, overextraction of groundwater, overloading of infrastructural facilities, and natural compaction. Conventional terrestrial methods of monitoring, such as leveling and GNSS, are highly accurate but spatially sparse, costly, and cannot monitor deformation over a regional scale. Here, satellite-based Synthetic Aperture Radar Interferometry (InSAR) especially Persistent Scatterer InSAR, provides a stable and economical method of long-standing subsidence monitoring on extensive and uneven surfaces. The paper demonstrates an attempt to integrate PSInSAR with multi-temporal SAR data to map and analyze subsidence trends of the area land of selected urban and peri-urban areas of Pakistan. The PSInSAR method allows the stable radar target of interest to be identified and allows the time series of millimeter-scale surface deformation to be extracted, which is likely to reduce the atmospheric disturbance and time-correlation effects of traditional InSAR methods. This study will measure spatial variability, temporal change, and subsidence hotspots of anthropogenic and geological nature by using the high-resolution SAR datasets. The paper also compares the patterns of deformation that are observed with the root causes that include: groundwater depletion, land-use change, and expansion of infrastructure. The results present important information about the processes of subsidence in data-sparse areas of Pakistan and indicate that PSInSAR is a valid instrument of monitoring hazard control, urban development and sustainable resources utilization. This study helps to enhance geospatial decision-support systems and provides a scientific foundation of risk-based policymaking in the regions with subsidence risks.
Keywords: PSInSAR, Land Subsidence, Synthetic Aperture Radar (SAR), Ground Deformation, Geohazard Monitoring.

1. INTRODUCTION

Land subsidence is a geohazard that can be destructive but occurs slowly and undermines the stability of infrastructure, groundwater security, and sustainable urban development at the global level (Mishra *et al.,* 2023). It is a product of natural occurrences like the compaction of sediments and the tectonic movement as well as anthropogenic processes such as excessive ground water abstraction, fast urban growth, mining, and the heavy surface loading. Subsidence in most developing nations develops silently because of the lack of adequate monitoring systems, and later on, results in damage of buildings, roads deterioration, higher risks of floods and economic losses (Huning *et al.,* 2024). Pakistan, with its rising population growth rate, sudden urbanization, and growing reliance on the groundwater sources, is more susceptible to the given phenomenon. The source of land subsidence in Pakistan is the most significant production of groundwater, primarily in the large cities and highly cultivated areas (Sajjad *et al.,* 2023). The decrease of surface water, fluctuations in climate and the increasing demand of industries have increased dependence on aquifers, which have led to the compaction of unconsolidated sediments in the long term. Systematic subsidence monitoring in Pakistan is however still disjointed despite the gravity of this issue. The conventional ground-based methods like leveling and Global Navigation Satellite System are very accurate but expensive, spatially constrained and operationally intensive. These limitations render them inappropriate in constant, regional and large-scale deformation measurement of large and variable landscapes (Clark *et al.,* 2006).

The recent development of satellite remote sensing has revolutionized monitoring ground deformations because it became possible to observe large areas, repeatable, and non-invasive (Ali *et al.,* 2025). Interferometric Synthetic Aperture Radar has become one of the most potent methods of measuring the displacement of the surface with high spatial resolution and with a sensitivity of millimeters. However, traditional differential InSAR methods are usually affected by time-based decorrelations, atmospheric delays, and orbital errors, especially in arid and semi-urban and dynamically varying areas that dominate Pakistan (Živanović *et al.,* 2025). These constraints do not allow their use as a long-term and reliable tool of subsidence monitoring. Persistent Scatterer InSAR was created to overcome such difficulties taking advantage of the stable radar targets which can preserve the coherent backscatter characteristics over a long period of time. PSInSAR can distinguish deformation signals and atmospheric noise and phase inconsistencies by comparing multi-temporal stacks of SAR images, providing the accurate time-series measurement of ground movement (Besoya *et al.,* 2021). The technique is especially effective in the urban as well as peri-urban areas with buildings, roads and other objects as continuous scattering agents. PSInSAR has been extensively utilized in subsidence prone areas of the world such as mega cities, coastal plains, and agricultural basins and has proven to be robust in identifying slow and small-scale processes of deformations (Haghshenas *et al.,* 2024).

In Pakistan, however, PSInSAR has been used in limited and very localized applications. Available literature tends to be limited to local scales, brief periods of observation, or individual causes of subsidence, and does not give the full picture of subsidence in a region (Higgins *et al.,* 2016). Comprehensive, long-term, regional-scale mapping of subsidence with advanced multi-temporal InSAR methods is an important gap in the research. Moreover, not many studies combine the results of deformation with more general contextual issues like groundwater use patterns, land-use alteration, and infrastructure development that are critical to the valid assessment of hazards and the development of policies (Yihdego *et al.,* 2017). Such gaps are important in order to build sustainable groundwater management strategies and urban resilience. Consistent subsidence maps can be used to provide early warning mechanisms, infrastructure planning and in risk-sensitive land-use decision-making. By incorporating PSInSAR-obtained deformation data into geospatial decisions and planning models, the ability of policy makers and planners to reduce the risks associated with subsidence in data-poor areas such as Pakistan could be enhanced by a significant margin (Jeong *et al.,* 2025).

In the current research, the researcher intends to combine PSInSAR methodologies with multi-temporal SAR data to map and analyze the land subsidence patterns in the selected regions of Pakistan (Hussain *et al.,* 2024). The study aims at determining subsidence hotspots and the spatial and temporal variability of the latter by creating high-resolution maps of deformation velocities, and displacement time series. The study also examines possible correlations between recorded patterns of deformation and anthropogenic contributing factors, specifically, groundwater abstraction and urban sprawl (Gao *et al.,* 2021). In this manner, the paper reveals the feasibility and usefulness of PSInSAR to monitor large-scale subsidence and offers a scientific background of risk-based planning and sustainable management of resources in Pakistan. This study goes further to inform a comprehensive view of the subsidence behavior under complex socio-environmental settings by focusing on a regional view-point rather than site-specific assessments of the same in Pakistan. It is hoped that the results will help narrow the gap between the science of remote sensing and practice through converting the measurements of deformations to actionable knowledge to planners, engineers and decision makers. This form of integration is necessary to empower the disaster risk reduction systems that would streamline groundwater management towards resilient infrastructure development and to facilitate evidence-based sustainable urban and environmental management systems in the country.

2. Regional Subsidence Mapping Using PSInSAR in Pakistan

2.1. Study Area and SAR Data Description

Pakistan is a country with a wide spectrum of geological, climatic and land-use environments, which clearly affect the behavior of land subsidence. Large city centers like Lahore, Karachi, Islamabad-Rawalpindi and Faisalabad are constructed on unconsolidated sediments of alluvial plains that are very susceptible to compaction due to extended extraction of groundwater. Moreover, highly developed agricultural areas along the Indus Basin are under prolonged aquifer stress owing to the irrigation demand, and therefore, form significant areas of concern in terms of the assessment of subsidence around the region. These environments have spatial heterogeneity, which requires extensive views on deformation over time and area that can record localized and distributed patterns of deformation (Tsatsaris *et al.,* 2021).

Such assessments are well accomplished on Synthetic Aperture Radar data because of their capability to image up-to-the-day and also during the night besides their sensitivity to surface movement. Recent works also turn to spaceborne missions of SAR like Sentinel-1, ALOS and TerraSAR-X which can provide decent revisit time and predictable data collection that is appropriate to multi-temporal analysis. The Sentinel-1 data have been especially useful in the framework of Pakistan because this type of data can be accessed freely and the information is dual-polarized with the required time resolution to conduct deformation observations over the long-term (Ma *et al.,* 2024). The geometry of upper and lower orbits is also beneficial in making deformation measurements more reliable, by providing a better spatial sampling of deformation, and by minimizing directional bias in the interpretation of displacement. In the case of regional subsidence mapping, long SAR image time series is necessary to provide strong identification of persistent scatterers, as well as, good estimation of deformation trends. The built-up features of urban infrastructure, road networks and stable targets are dominant radar targets and dense spatial coverage of deformation measurements is achieved. Conversely, rural and vegetated environments are also of the problem of temporal decorrelation, which explains why combining multi-year SAR data is crucial in enhancing measurement consistency within the heterogeneous terrain.

2.2. PSInSAR Processing and Deformation Analysis

Persistent Scatterer InSAR is a significant improvement of the traditional InSAR methods because it targets stable radar reflectors which remain phase coherent when stationary and over extended durations. The PSInSAR process consists of accurate co-registration of the SAR image stacks, the generation of persistent candidates of the scatterers upon amplitude and phase consistency, and the recurring estimation of the deformations rates together with the reduction of the atmospheric phase delays and the satellite orbits. The method allows accuracy on the time-series analysis of deformation at the millimeter scale, despite atmospheric variability and variations at the surface (Liu *et al.,* 2025).

PSInSAR processing can be used in the regional studies to extract both linear and non-linear deformation signals with information about both gradual subsidence trends and episodic events of deformation. The method works especially well in the city, where dense concentrations of artificial buildings are good sources of persistent scatterers. In Pakistan, the advantage is essential to track the fastest growing cities in which the subsidence can develop disproportionately under the impact of groundwater abstraction, construction, and loading of infrastructure. The major advantage of PSInSAR is that it can produce spatially continuous deformation velocity fields and displacement time series (Taloor *et al.,* 2023). These products can be used to compare results between various regions and periods, thus providing an opportunity to determine long-term subsidence behavior. Nevertheless, there are still difficulties in the regions with low density of persistent scatterers, including agricultural fields, and floodplains, which underlines the importance of paying close attention to interpretation and supplementary geospatial data sets. Being a review viewpoint, the recent literature presents the trend of increasing the integration of PSInSAR outputs with hydrogeological and land-use data to enhance subsidence attribution and reliability.

2.3. Spatial Patterns of Regional Land Subsidence

Spatial analysis of PSInSAR obtained deformation shows that there are specific subsidence patterns across Pakistan which represent differences in geological conditions and human activities. The more common high subsidence rates are found in urban centres with high population and industrial areas where groundwater extraction is clustered and the surface loading is high. These subsidence hotspots are usually spatially clustered meaning there is localized pressure on the system of aquifers as well as the infrastructure. By contrast, the peri-urban and agricultural areas exhibit patterns of deformation that are more distributed and gradual and they are mainly caused by long-term irrigation. Subsidence is widespread and spatially heterogeneous in the Indus Basin, due to a disparity in the properties of aquifers, pumping rate, and the nature of recharge (Mehmood *et al.,* 2022). These regional trends indicate the necessity to study the subsidence at more than the site-specific level. Regarding a review perspective, PSInSAR-linked literature always shows that subsidence in Pakistan is not evenly distributed but highly governed by socio-environmental interactions. The determination of deformation gradients and transitional zones between stable and subsiding regions gives important information to hazard zoning and urban planning. Generally, PSInSAR spatial pattern analysis is an effective tool to define the specifics of subsidence dynamics in the locality and develop specific mitigation measures in areas with subsidence in Pakistan (Lenardón Sánchez *et al.,* 2024).

3. PSInSAR-Based Assessment of Ground Deformation

3.1. SAR Data Acquisition and Preprocessing

Synthetic Aperture Radar (SAR) data form the foundation of PSInSAR-based ground deformation analysis, as their all-weather, day-and-night imaging capability enables continuous monitoring across large spatial extents. For subsidence assessment, multi-temporal SAR datasets acquired from spaceborne platforms such as Sentinel-1, ENVISAT, and ALOS have been widely utilized due to their consistent revisit cycles and long-term data archives (Salvi *et al.,* 2012). In the context of Pakistan, Sentinel-1 C-band data are particularly advantageous because of their open access, high temporal resolution, and suitability for monitoring slow deformation processes in urban and peri-urban environments.

SAR data preprocessing is a critical step that directly influences the reliability of PSInSAR outputs. Preprocessing typically includes precise orbit correction, radiometric calibration, co-registration of SAR images to a common master, and generation of interferometric pairs. Accurate co-registration is essential to ensure phase consistency at the pixel level, especially when analyzing long temporal stacks. In subsidence-prone regions characterized by heterogeneous land cover and rapid urban growth, maintaining sub-pixel co-registration accuracy is particularly challenging yet indispensable. Interferogram generation involves the removal of topographic phase contributions using an external Digital Elevation Model, such as SRTM or TanDEM-X (Ali *et al.,* 2019). While DEM quality significantly affects phase accuracy, residual topographic errors can be effectively estimated and corrected during PSInSAR processing. Additional preprocessing steps include phase filtering and masking of low-coherence areas to reduce noise and enhance the identification of stable scatterers. Atmospheric artifacts, which are often pronounced in arid and semi-arid regions of Pakistan, represent a major source of error and necessitate advanced temporal and spatial filtering techniques. Proper preprocessing ensures that deformation signals are preserved while minimizing atmospheric, orbital, and decorrelation effects.

3.2. Persistent Scatterer Interferometry Methodology

Persistent Scatterer Interferometry is an advanced multi-temporal InSAR technique designed to extract reliable deformation measurements from stable radar targets over extended periods. The methodology is based on the identification of pixels that exhibit consistent amplitude and phase stability across a SAR image stack. These persistent scatterers typically correspond to man-made structures such as buildings, roads, and bridges, making PSInSAR particularly effective in densely populated and rapidly urbanizing regions (Si *et al.,* 2025).

The PSInSAR workflow begins with the selection of a master image, followed by the formation of interferograms between the master and all slave images. Candidate persistent scatterers are identified using statistical indicators such as amplitude dispersion or coherence stability. Once selected, phase components associated with deformation, atmospheric delay, orbital errors, and residual topography are separated through iterative modeling and time-series analysis (Hu *et al.,* 2019). Linear and non-linear deformation trends can be retrieved with millimeter-level precision. One of the key strengths of PSInSAR is its ability to mitigate atmospheric phase delays by exploiting the temporal behavior of stable scatterers. This capability is particularly valuable in Pakistan, where climatic variability and atmospheric heterogeneity often limit the effectiveness of conventional InSAR approaches. However, PSInSAR performance may be constrained in rural or vegetated areas with limited persistent scatterer density. To address this limitation, recent studies have proposed hybrid approaches that integrate PSInSAR with distributed scatterer techniques, thereby improving spatial coverage while maintaining high accuracy.

3.3. Subsidence Rate Mapping and Interpretation

Subsidence rate mapping represents the primary output of PSInSAR-based deformation analysis and provides quantitative insights into both spatial and temporal deformation patterns. Velocity maps typically express average line-of-sight displacement rates, which can be converted into vertical deformation components when appropriate assumptions are applied. In regional subsidence studies, these maps enable the identification of deformation hotspots, gradual subsidence zones, and relatively stable areas (Chen *et al.,* 2018).

Interpretation of subsidence rates requires careful consideration of local geological conditions, hydrogeological settings, and anthropogenic activities. In Pakistan, high subsidence rates are frequently associated with intensive groundwater extraction, particularly in urban centers and agricultural basins. Temporal displacement profiles derived from PSInSAR time series further allow the detection of acceleration or deceleration trends, which may reflect changes in groundwater pumping intensity, land-use transitions, or regulatory interventions. From a hazard assessment perspective, subsidence rate maps serve as essential tools for infrastructure risk evaluation and urban planning (Chai *et al.,* 2024). Areas exhibiting sustained or accelerating subsidence can be prioritized for detailed geotechnical investigation and mitigation planning. Moreover, integrating PSInSAR-derived deformation products with ancillary datasets such as groundwater level records and land-use maps enhances the interpretability and practical relevance of the results. As such, PSInSAR-based subsidence mapping not only advances scientific understanding of ground deformation processes but also provides actionable knowledge for sustainable development and geohazard management in Pakistan.

Table 1: Overview of the PSInSAR methodological framework for ground deformation and land subsidence assessment, summarizing key processing stages, data requirements, outputs, strengths, limitations, and relevance for subsidence monitoring in developing countries, particularly Pakistan

Analytical Stage	Description and Key Processes	Data Inputs / Technical Requirements	Commonly Used Platforms or Algorithms	Primary Outputs	Strengths and Advantages	Limitations and Challenges	Relevance for Subsidence Monitoring in Pakistan	Representative References
SAR Data Acquisition	Acquisition of multi-	C-band (Sentinel-1),	Sentinel-1A/B,	Multi-temporal	All-weather, day–night	Temporal decorrelation	Sentinel-1 provides	Ferretti *et al.,* 2001;

Analytical Stage	Description and Key Processes	Data Inputs / Technical Requirements	Commonly Used Platforms or Algorithms	Primary Outputs	Strengths and Advantages	Limitations and Challenges	Relevance for Subsidence Monitoring in Pakistan	Representative References
	temporal SAR images to capture phase differences related to surface deformation. Emphasis on long-term, consistent orbital geometry and revisit cycles for time-series analysis.	L-band (ALOS), C-band historical datasets (ENVISAT); long temporal coverage (≥30 scenes preferred); stable imaging geometry.	ENVISAT ASAR, ALOS PALSAR; ascending and descending tracks.	SAR stack suitable for PS analysis.	capability; wide spatial coverage; free and continuous Sentinel-1 data enables national-scale studies.	in vegetated areas; data gaps in older missions; limited historical L-band coverage.	cost-effective, continuous monitoring of subsidence in megacities (Karachi, Lahore) and agricultural basins.	Crosetto *et al.,* 2016; Ali *et al.,* 2019
SAR Preprocessing	Precise orbit correction, image co-registration, interferogram generation, removal of flat-earth and topographic phase using DEM, and noise reduction.	Precise orbit files; high-resolution DEM (SRTM, ALOS World 3D); computational resources for large stacks.	SNAP, GAMMA, ISCE; StaMPS preprocessing chain.	Differential interferograms with reduced geometric and topographic errors.	Standardized and reproducible workflows; compatible with open-access datasets and software.	DEM inaccuracies introduce residual phase; high computational demand for large areas.	DEM correction is critical in tectonically complex regions of Pakistan (Potohar Plateau, Himalayan foothills).	Hooper *et al.,* 2012; Salvi *et al.,* 2012
Persistent Scatterer (PS) Identification	Identification of radar targets with stable backscattering behavior over time using amplitude dispersion or phase stability criteria.	High temporal sampling; urban or rocky surfaces favorable; statistical thresholds for stability selection.	PSInSAR (Ferretti), StaMPS, IPTA.	Spatial distribution of persistent scatterer points.	Enables millimeter-level deformation detection; effective in dense urban environments.	Low PS density in agricultural and floodplain areas; sensitivity to land cover change.	Urban centers of Pakistan offer high PS density, while Indus floodplain areas remain challenging.	Ferretti *et al.,* 2001; Hooper *et al.,* 2007
Time-Series Modeling and Phase Decomposition	Separation of deformation phase from atmospheric delay, orbital ramps, and residual topography using spatial–temporal filtering.	Long time series; stable reference points; atmospheric filtering parameters.	StaMPS time-series module; PSInSAR algorithms.	Clean deformation time series for each PS point.	Robust mitigation of atmospheric artifacts; high temporal resolution deformation trends.	Residual atmospheric effects in humid climates; assumptions of linear deformation may not always hold.	High atmospheric variability during monsoon seasons requires careful filtering in Pakistan.	Ferretti *et al.,* 2011; Chen *et al.,* 2018
Subsidence Velocity Estimation and LOS Conversion	Estimation of linear and non-linear deformation rates along satellite Line-of-Sight (LOS); conversion to vertical displacement using geometric	Ascending and descending tracks; incidence angle information; reference point stability.	StaMPS, MATLAB-based PSInSAR tools.	Subsidence velocity maps (mm/year); vertical deformation estimates.	Quantitative assessment of long-term subsidence rates; suitable for hazard mapping.	LOS measurements sensitive to horizontal motion; vertical conversion assumptions introduce uncertainty.	Enables identification of high-risk subsidence zones linked to groundwater over-extraction in Pakistan.	Crosetto *et al.,* 2016; Ali *et al.,* 2019

Analytical Stage	Description and Key Processes	Data Inputs / Technical Requirements	Commonly Used Platforms or Algorithms	Primary Outputs	Strengths and Advantages	Limitations and Challenges	Relevance for Subsidence Monitoring in Pakistan	Representative References
	assumptions or multi-track data.							
Interpretation of Subsidence Patterns	Analysis of spatial–temporal deformation in relation to anthropogenic and natural drivers such as groundwater pumping, urban load, and sediment compaction.	Deformation maps; hydrogeological and geological context.	GIS-based spatial analysis; statistical correlation techniques.	Identification of subsidence hotspots and driving mechanisms.	Enhances process understanding beyond mere deformation mapping.	Attribution uncertainty when multiple drivers coexist; limited in-situ validation data.	Critical for linking subsidence in Pakistani cities to unregulated groundwater extraction.	Chaussard *et al.,* 2017; Chai *et al.,* 2024
Integration with Ancillary Datasets	Fusion of PSInSAR outputs with groundwater levels, land-use/land-cover data, population density, and infrastructure maps for hazard assessment.	Groundwater well data; land-use maps; infrastructure inventories; GIS platforms.	ArcGIS, QGIS; multi-source data integration frameworks.	Subsidence risk maps and vulnerability assessments.	Supports evidence-based urban planning and disaster risk reduction.	Limited availability and quality of ancillary data in developing regions.	Provides actionable insights for infrastructure safety and sustainable water management in Pakistan.	Salvi *et al.,* 2012; Si *et al.,* 2025

4. Monitoring Land Subsidence in Pakistan Using SAR and PSInSAR

4.1. Geological and Environmental Setting of the Study Area

Pakistan exhibits complex geological and environmental conditions that strongly influence land subsidence processes. Large parts of the country, particularly the Indus Basin, are characterized by thick sequences of unconsolidated alluvial sediments composed of clay, silt, and fine sand. These deposits, formed through long-term fluvial activity, are highly compressible and sensitive to changes in effective stress, making them prone to compaction under sustained groundwater withdrawal. Urban centers such as Karachi, Lahore, Faisalabad, and Islamabad are largely situated on these sedimentary formations, where rapid population growth and infrastructure expansion exacerbate subsidence susceptibility (Amin *et al.,* 2022).

Climatic conditions further intensify subsidence dynamics in Pakistan. The country experiences strong seasonal variability associated with monsoon-driven precipitation and prolonged dry periods. During dry seasons, excessive groundwater pumping compensates for limited surface water availability, accelerating aquifer depletion and sediment compaction (Foster *et al.,* 2003). Conversely, monsoon-induced recharge can introduce transient uplift or deformation signals, complicating the interpretation of surface displacement patterns. These hydro-climatic fluctuations necessitate long-term, high-temporal-resolution monitoring to distinguish between elastic seasonal responses and irreversible inelastic subsidence. From an environmental perspective, land-use change plays a significant role in modifying surface stability. The conversion of agricultural land to urban and industrial zones increases surface loading while reducing natural recharge areas. In coastal regions such as Karachi, subsidence is further influenced by seawater intrusion, sediment consolidation, and anthropogenic modifications to the shoreline. The geological heterogeneity, coupled with intense human activity and climatic variability, underscores the need for advanced monitoring approaches capable of capturing subtle and spatially variable deformation signals across Pakistan.

4.2. PSInSAR Time-Series Deformation Analysis

PSInSAR has emerged as a powerful tool for quantifying long-term ground deformation in complex geological and urban environments. Unlike conventional InSAR techniques, PSInSAR exploits stable radar targets that exhibit consistent backscattering behavior over extended time periods, enabling the extraction of precise deformation time series at millimeter-scale accuracy. This capability is particularly advantageous in Pakistan, where heterogeneous land cover, atmospheric variability, and temporal decorrelation often limit the effectiveness of traditional differential InSAR methods (Liang *et al.,* 2023).

Time-series deformation analysis using PSInSAR allows for the separation of linear, non-linear, and seasonal deformation components. In subsidence-prone regions, long-term linear trends are typically associated with irreversible aquifer compaction caused by sustained groundwater extraction. Seasonal oscillations, on the other hand, often reflect elastic responses to groundwater recharge during monsoon periods and subsequent drawdown during dry seasons. By analyzing multi-year SAR datasets, PSInSAR enables the discrimination of these deformation modes, providing deeper insight into the underlying physical mechanisms driving subsidence (Das Adhikari *et al.,* 2025). In the context of Pakistan, PSInSAR-based time-series analysis facilitates continuous monitoring of urban growth zones, industrial corridors, and agricultural basins. The dense spatial distribution of persistent scatterers in built-up areas enhances deformation detectability, while long temporal coverage improves the reliability of trend estimation. Moreover, PSInSAR outputs can be integrated with ancillary datasets such as groundwater level records, land-use maps, and infrastructure inventories to support comprehensive subsidence assessments. This integrative capability represents a significant advancement over episodic and spatially sparse ground-based observations.

4.3. Identification of Subsidence Hotspots

The identification of subsidence hotspots is a critical outcome of PSInSAR-based monitoring, providing actionable information for risk assessment and urban planning. Hotspots are typically defined as areas exhibiting consistently high subsidence rates, pronounced non-linear deformation, or accelerating displacement trends over time. In Pakistan, such hotspots frequently coincide with zones of intensive groundwater abstraction, dense urban development, and industrial activity (Huang *et al.,* 2013).

PSInSAR-derived velocity maps enable the spatial delineation of these high-risk zones with unprecedented detail. Urban districts with concentrated pumping wells, high-rise construction, and aging infrastructure often exhibit the most pronounced subsidence signals. Agricultural regions relying on tube-well irrigation also show widespread but spatially variable deformation patterns. The identification of these hotspots allows for the prioritization of mitigation efforts, including groundwater regulation, infrastructure reinforcement, and land-use planning interventions. Importantly, hotspot analysis also reveals previously unrecognized subsidence zones that may not be captured by conventional monitoring networks (Zhang *et al.,* 2025). In data-scarce regions of Pakistan, this capability is particularly valuable for early warning and proactive risk management. By systematically mapping subsidence hotspots, PSInSAR provides a scientific basis for targeted policy action and supports the development of sustainable strategies to reduce long-term geohazard impacts.

5. Integration of PSInSAR for Large-Scale Subsidence Detection

The integration of Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) has significantly advanced the capability to detect and analyze land subsidence over large spatial extents. Unlike conventional InSAR techniques, which are often constrained by temporal decorrelation and atmospheric disturbances, PSInSAR enables consistent monitoring of slow deformation processes by exploiting stable radar targets over long time periods. For regional-scale subsidence assessment, particularly in data-scarce and rapidly urbanizing countries such as Pakistan, PSInSAR provides a scalable, cost-effective, and repeatable solution (Pohanková *et al.,* 2025). The successful implementation of PSInSAR at large scales, however, depends critically on appropriate SAR dataset selection, robust processing strategies, reliable persistent scatterer identification, and meaningful regional zonation of deformation patterns.

5.1. SAR Dataset Selection and Processing Strategy

The selection of suitable SAR datasets is a fundamental step in large-scale PSInSAR-based subsidence mapping. Key considerations include sensor wavelength, temporal resolution, spatial coverage, and data continuity. C-band sensors such as Sentinel-1 have become the primary data source for regional subsidence studies due to their open-access availability, regular revisit cycles, and wide swath coverage. These characteristics are particularly advantageous for monitoring extensive and heterogeneous regions, including urban, agricultural, and semi-arid landscapes prevalent across Pakistan (Almalki *et al.,* 2022). In contrast, X-band sensors offer higher spatial resolution but limited coverage, while L-band sensors provide improved coherence over vegetated areas but are often constrained by data availability.

A robust processing strategy is essential to ensure reliable deformation retrieval at regional scales. Multi-temporal PSInSAR processing typically involves precise orbit correction, co-registration of SAR stacks, interferogram generation, and phase filtering. Atmospheric phase screen estimation plays a critical role in isolating deformation signals, especially in regions characterized by strong seasonal variability. The use of long time-series data enhances signal-to-noise ratios and improves the stability of deformation estimates (Hooper *et al.,* 2012). For large-scale applications, automated and semi-automated workflows are increasingly adopted to handle computational complexity while maintaining consistency across extensive spatial domains.

5.2. Persistent Scatterer Identification and Validation

The identification of persistent scatterers is a defining feature of the PSInSAR technique and directly influences the accuracy of subsidence measurements. Persistent scatterers are typically associated with man-made structures such as buildings, bridges, roads, and other infrastructural elements that exhibit stable backscattering behavior over time. In urban and peri-urban environments of Pakistan, these features provide a dense network of reliable measurement points, enabling detailed deformation analysis even in the absence of ground-based monitoring networks (Khan *et al.,* 2023).

Validation of identified persistent scatterers is a critical step in ensuring the reliability of deformation results. Statistical criteria such as amplitude dispersion index, temporal coherence, and phase stability are commonly used to distinguish true persistent scatterers from noise-prone pixels. Cross-validation with external datasets, including GNSS observations, leveling data, or historical infrastructure damage records, further enhances confidence in PSInSAR-derived deformation patterns ((Das Adhikari *et al.,* 2025).). However, the scarcity of in situ validation data in Pakistan highlights the need for methodological rigor and uncertainty assessment within PSInSAR frameworks.

5.3. Regional Subsidence Zonation

Regional subsidence zonation represents a key outcome of large-scale PSInSAR integration, translating point-based deformation measurements into interpretable spatial patterns. Zonation involves classifying regions into distinct subsidence intensity categories based on deformation rates, spatial continuity, and temporal trends. This approach facilitates the identification of subsidence hotspots and stable zones, supporting regional hazard assessment and spatial planning.

In the context of Pakistan, subsidence zonation enables comparison across urban centers, agricultural basins, and transitional landscapes. Linking zonation results with groundwater extraction intensity, land-use patterns, and infrastructural development provides valuable insights into the underlying drivers of deformation (Zhu *et al.,* 2021). Importantly, regional zonation transforms PSInSAR outputs from purely technical measurements into actionable geospatial information, supporting evidence-based decision-making. As PSInSAR integration continues to mature, standardized zonation frameworks are expected to play a pivotal role in operational subsidence monitoring and long-term risk mitigation strategies.

6. PSInSAR-Derived Subsidence Analysis for Hazard Assessment

Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR)–derived deformation products provide a powerful basis for translating ground displacement measurements into actionable hazard information. Beyond detecting subsidence, PSInSAR enables the spatial characterization of deformation intensity, temporal persistence, and acceleration trends, all of which are critical for hazard assessment and risk-informed decision making. In subsidence-prone regions such as Pakistan, where ground-based monitoring networks are sparse, PSInSAR offers an effective framework for integrating deformation analysis with hazard mapping and urban risk evaluation (Lee *et al.,* 2025).

6.1. Study Area Characterization and SAR Data

Accurate hazard assessment begins with a comprehensive characterization of the study area, including its geological, hydrogeological, and socio-environmental context. Regions of Pakistan exhibiting unconsolidated alluvial deposits, thick sedimentary basins, and intensive groundwater abstraction are particularly susceptible to subsidence. Urban centers, peri-urban expansion zones, and irrigated agricultural belts often represent high-risk environments due to the combined effects of aquifer compaction and surface loading. From a remote sensing perspective, the suitability of PSInSAR analysis is strongly influenced by land cover and surface characteristics. Built-up areas, transportation networks, and industrial zones typically provide a high density of persistent scatterers, enabling reliable deformation retrieval. In contrast, agricultural fields and vegetated surfaces may exhibit lower coherence, necessitating careful data selection and processing strategies. The choice of SAR data is equally critical for hazard-oriented subsidence analysis. C-band sensors such as Sentinel-1 offer dense temporal coverage and long-term data continuity, making them particularly suitable for regional-scale monitoring (Bioresita *et al.,* 2019). Multi-year SAR time series allow the detection of gradual deformation trends and the identification of emerging subsidence zones before visible surface damage occurs. For hazard assessment, consistent acquisition geometry, sufficient temporal density, and long observation periods are essential to distinguish persistent subsidence from short-term or seasonal surface fluctuations.

6.2. PSInSAR-Based Deformation Monitoring

PSInSAR-based deformation monitoring enables the extraction of millimeter-scale displacement velocities and time-series information for thousands of stable ground targets. This capability is particularly valuable for hazard assessment, as it allows not only the mapping of subsidence magnitude but also the evaluation of deformation persistence and acceleration patterns. Areas exhibiting high subsidence rates over extended periods are more likely to experience structural damage and secondary hazards such as surface cracking or infrastructure failure. A key advantage of PSInSAR in hazard analysis is its ability to differentiate spatially heterogeneous deformation within urban environments. Subsidence is rarely uniform; instead, it often manifests as localized bowls or linear features associated with groundwater pumping centers, fault zones, or differential soil compaction. PSInSAR deformation maps reveal these patterns with high spatial detail, enabling the identification of critical infrastructure corridors, residential zones, and industrial areas exposed to elevated subsidence risk. Temporal deformation analysis further enhances hazard interpretation (Roýan *et al.,* 2014). Linear trends may indicate steady aquifer compaction, while nonlinear or accelerating displacement signals can suggest increasing stress on subsurface systems. Seasonal oscillations in deformation time series may reflect groundwater recharge and extraction cycles, which are important for understanding short-term variability but also for distinguishing reversible elastic deformation from irreversible inelastic compaction. Such insights are essential when translating deformation observations into hazard-relevant indicators.

6.3. Subsidence Risk Mapping and Assessment

The integration of PSInSAR-derived deformation products into subsidence risk mapping represents a critical step toward hazard assessment. Risk mapping typically involves combining subsidence rate information with exposure and vulnerability factors, such as population density, land use, infrastructure distribution, and critical facilities. High subsidence rates occurring in densely populated or infrastructure-intensive zones represent significantly greater hazard potential than similar deformation in sparsely inhabited areas. PSInSAR deformation velocity maps serve as the primary hazard layer, identifying zones of low, moderate, and high subsidence intensity. These zones can be further refined using temporal indicators, such as deformation persistence and acceleration, to prioritize areas requiring immediate attention (Crosta *et al.,* 2017). When integrated with ancillary geospatial datasets, PSInSAR-based hazard maps enable a more comprehensive assessment of potential impacts on buildings, transportation networks, pipelines, and water distribution systems. In the context of Pakistan, subsidence risk mapping is particularly relevant for urban planning and groundwater governance. Many cities lack formal subsidence monitoring frameworks, resulting in delayed responses to emerging hazards. PSInSAR-derived risk maps can support early warning systems, guide land-use zoning regulations, and inform infrastructure design standards. Moreover, these products provide objective, spatially continuous evidence that can strengthen policy decisions related to groundwater extraction limits and sustainable urban development. Overall, PSInSAR-derived subsidence analysis offers a scientifically robust foundation for hazard assessment by linking precise deformation measurements with spatial risk evaluation. As Pakistan continues to face increasing pressure on its groundwater resources, integrating PSInSAR into national hazard assessment frameworks can significantly enhance resilience, reduce economic losses, and support evidence-based mitigation strategies.

CONCLUSION

The integration of PSInSAR with multi-temporal SAR data represents a significant advancement for regional subsidence mapping in Pakistan, where conventional monitoring remains spatially limited. This review highlights the growing relevance of PSInSAR not only as a deformation detection tool but also as a strategic component of hazard assessment and sustainable land management. By enabling high-resolution, long-term deformation analysis, PSInSAR provides critical insights into subsidence behavior under complex hydrogeological and urbanization pressures. The synthesis of existing studies reveals a clear need for region-wide, standardized deformation datasets that can support early warning systems, infrastructure resilience, and groundwater governance. Future research should focus on integrating PSInSAR outputs with hydrogeological models, socio-economic exposure data, and policy-driven risk frameworks to translate deformation measurements into actionable mitigation strategies. Establishing a national subsidence monitoring framework based on PSInSAR would significantly strengthen Pakistan's capacity to manage subsidence-related risks in an era of accelerating urban and environmental change.

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