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Monitoring Sedimentation Dynamics Through SBAS-InSAR for Sustainable Management

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Abstract
Sedimentation is a critical geomorphological process that influences the sustainability of river systems, reservoirs, floodplains, and coastal environments. Accelerated sediment deposition driven by natural processes and human activities can lead to reduced storage capacity, increased flood risk, and degradation of ecosystems and infrastructure. Effective monitoring of sedimentation dynamics is therefore essential for sustainable environmental management. This study investigates the potential of the Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) technique to monitor sedimentation dynamics through the analysis of surface deformation.
Multi-temporal Synthetic Aperture Radar data were processed using the SBAS-InSAR approach to generate deformation velocity maps, cumulative displacement patterns, and deformation time series for the study area. The results reveal spatially coherent subsidence patterns concentrated in sediment-rich environments such as river floodplains, reservoir margins, and depositional zones. Temporal analysis indicates predominantly gradual and sustained deformation, with variations linked to

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hydrological conditions and sediment supply. These deformation trends are interpreted as indicators of sediment loading and consolidation processes.
The findings demonstrate that SBAS-InSAR provides reliable indirect information on sedimentation dynamics over large spatial extents and long time periods. By integrating remote sensing-derived deformation data with environmental context, this approach offers valuable support for sediment risk identification, resource planning, and sustainable management. The study highlights the potential of SBAS-InSAR as a complementary tool to conventional sediment monitoring methods, particularly in data-scarce regions and under changing climatic conditions.

Introduction

Sedimentation is a fundamental geomorphological process that plays a critical role in shaping the Earth's surface and influencing the sustainability of natural and engineered environments(Sediments & 2020, 2020). It involves the erosion, transportation, deposition, and accumulation of sediments within river systems, reservoirs, coastal zones, and floodplains. While sedimentation is a natural process, its rate and spatial distribution have been significantly altered in recent decades due to rapid urbanization, deforestation, agricultural expansion, dam construction, and climate variability. Accelerated or uneven sediment deposition can lead to reduced storage capacity of reservoirs, increased flood risk, degradation of aquatic ecosystems, navigation hazards, and structural instability of hydraulic and civil infrastructure(Research & 2021, n.d.). Consequently, understanding and monitoring sedimentation dynamics is essential for sustainable environmental management and long-term planning.

Traditional sedimentation monitoring techniques, such as field surveys, sediment sampling, bathymetric measurements, and hydrological observations, provide valuable but often limited information. These methods are typically labor-intensive, time-consuming, costly, and spatially constrained, making them insufficient for capturing large-scale or long-term sedimentation patterns. Moreover, in many regions, especially in developing or remote areas, consistent in situ data are scarce or entirely unavailable. These limitations highlight the need for advanced, reliable, and cost-effective monitoring approaches that can provide continuous spatial and temporal insights into sedimentation processes.

Remote sensing technologies have emerged as powerful tools for environmental monitoring due to their ability to cover extensive areas with high temporal frequency(Science et al., 2024). Among these technologies, Interferometric Synthetic Aperture Radar (InSAR) has gained significant attention for its capability to detect minute ground surface deformations with centimeter- to millimeter-level accuracy. InSAR operates independently of weather conditions and daylight, making it particularly suitable for long-term monitoring in diverse environmental settings. By analyzing phase differences between repeated radar acquisitions, InSAR enables the detection of surface displacement associated with various geophysical processes, including land subsidence, uplift, slope instability, and sediment compaction.

Sedimentation processes often induce subtle surface deformations resulting from sediment loading, consolidation, and compaction, particularly in river deltas, floodplains, reservoirs, and coastal environments(Dunn et al., n.d.). These deformations, although small in magnitude, can provide critical information about sediment accumulation rates, spatial distribution, and temporal evolution. In this context, InSAR offers a unique opportunity to indirectly monitor sedimentation dynamics by capturing surface deformation signals related to sediment deposition and associated geomechanical responses.

However, conventional InSAR techniques face challenges such as temporal decorrelation, atmospheric disturbances, and phase ambiguities, especially when applied over long time periods or vegetated and water-adjacent areas commonly associated with sedimentation zones(McClernan, 2020). To overcome these limitations, advanced multi-temporal InSAR techniques have been developed. Among them, the Small Baseline Subset (SBAS) InSAR approach has proven particularly effective for monitoring slow and spatially distributed surface deformation over extended time spans. The SBAS-InSAR technique relies on the generation and analysis of multiple interferograms with small spatial and temporal baselines, thereby minimizing decorrelation effects and enhancing the reliability of deformation estimates. By exploiting time-series analysis, SBAS-InSAR enables the reconstruction of deformation histories with improved accuracy and robustness.

This makes it well-suited for studying gradual processes such as sediment compaction, subsidence induced by sediment loading, and long-term morphological changes in sedimentary environments(Garlan et al., n.d.). In recent years, SBAS-InSAR has been successfully applied to various geoscientific and environmental studies, including land subsidence monitoring in urban and agricultural areas, deformation analysis of dams and embankments, coastal zone evolution, and wetland dynamics. Its application to sedimentation studies represents a growing research frontier, offering new perspectives for understanding sediment-related processes at regional to basin scales. By linking surface deformation patterns to sediment deposition mechanisms, SBAS-InSAR can provide indirect yet valuable indicators of sedimentation dynamics that are otherwise difficult to observe continuously through conventional methods.

Monitoring sedimentation dynamics through SBAS-InSAR is particularly relevant in the context of sustainable management(Hussain et al., n.d.). Sustainable management of water resources, river basins, reservoirs, and coastal systems requires timely and accurate information on sediment behavior to support informed decision-making. Excessive sedimentation can compromise the functionality and lifespan of reservoirs and irrigation systems, while sediment deficits downstream can lead to channel incision, coastal erosion, and ecosystem degradation. Integrating SBAS-InSAR-derived deformation data with hydrological, geological, and land-use information can support the development of comprehensive sediment management strategies aimed at balancing human needs with environmental conservation.

Furthermore, climate change is expected to intensify hydrological extremes, alter precipitation patterns, and increase the frequency of floods and droughts, all of which directly influence sediment transport and deposition(sciences & 2005, 2007). Under such changing conditions, continuous and large-scale monitoring of sedimentation processes becomes increasingly important. SBAS-InSAR, with its ability to provide

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long-term deformation time series, offers a valuable means to assess the impacts of climate variability and anthropogenic interventions on sediment dynamics and associated surface responses. Despite its potential, the application of SBAS-InSAR for sedimentation monitoring still faces challenges, including the interpretation of deformation signals in complex environments, the separation of sediment-related deformation from other contributing factors such as groundwater extraction or tectonic activity, and the validation of remote sensing results with limited ground-based data. Addressing these challenges requires an integrated approach that combines SBAS-InSAR analysis with complementary datasets, modeling techniques, and field observations where available(Hussain et al., n.d.).

In this context, the present research titled “Monitoring Sedimentation Dynamics Through SBAS-InSAR for Sustainable Management” aims to explore and demonstrate the capability of SBAS-InSAR in capturing and analyzing sedimentation-related surface deformation. By focusing on the temporal and spatial patterns of deformation associated with sediment processes, this study seeks to enhance the understanding of sedimentation dynamics and their implications for sustainable environmental and resource management. The findings of this research are expected to contribute to the growing body of knowledge on the application of advanced InSAR techniques in sedimentary environments and to provide practical insights for policymakers, planners, and environmental managers striving for sustainable development(Closson et al., n.d.).

Methodology

Study Framework and Conceptual Approach

The methodology adopted in this research is designed to monitor sedimentation dynamics by analyzing surface deformation associated with sediment deposition, loading, and compaction using the Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) technique. The conceptual framework is based on the premise that sediment accumulation induces gradual surface deformation due to consolidation of underlying materials, which can be detected through multi-temporal radar interferometry. By capturing spatially distributed and temporally continuous deformation signals, SBAS-InSAR enables indirect yet reliable assessment of sedimentation processes over large areas. The approach integrates remote sensing analysis with environmental interpretation to support sustainable management of sediment-affected systems.

Data Acquisition

Multi-temporal Synthetic Aperture Radar data constitute the primary dataset for this study. SAR scenes acquired from spaceborne radar missions, such as Sentinel-1 A/B, are selected due to their high temporal resolution, consistent acquisition geometry, and all-weather imaging capability. A long-term archive of SAR images covering the study area is compiled to capture gradual deformation trends associated with sediment deposition and consolidation(Besoya et al., 2021). The images are selected to ensure uniform acquisition modes and adequate temporal continuity to support robust time-series analysis.

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In addition to SAR data, several ancillary datasets are incorporated to improve processing accuracy and enhance interpretation of deformation results. A Digital Elevation Model is used to remove topographic phase contributions during interferometric processing. Land use and land cover data provide information on surface characteristics and human activities influencing sediment dynamics(Ferreira et al., n.d.). Hydrological and geological datasets are utilized to understand sediment sources, transport pathways, and depositional environments, while climatic and rainfall data are included to evaluate the role of hydrometeorological variability in driving sedimentation processes.

SBAS-InSAR Processing

The SBAS-InSAR processing begins with the generation of interferograms from selected SAR image pairs with small spatial and temporal baselines. This strategy reduces temporal decorrelation and geometric distortions, which are common challenges in sedimentary environments characterized by vegetation and moisture variability. Precise orbit correction and accurate co-registration of SAR images are performed to ensure phase consistency across the dataset. Interferograms are then formed by computing phase differences between image pairs. Subsequently, the interferometric phase is processed to isolate deformation signals from other contributing components. The topographic phase is removed using the Digital Elevation Model, while noise is reduced through spatial filtering techniques. Phase unwrapping is applied to convert relative phase measurements into absolute displacement values. Atmospheric disturbances, which can significantly affect interferometric measurements, are mitigated through the spatiotemporal filtering capabilities inherent in the SBAS approach. These steps collectively enable the extraction of reliable deformation information over long time periods.

Time-Series Deformation Analysis

Following interferometric processing, SBAS-InSAR is used to reconstruct deformation time series for each coherent pixel within the study area. This time-series analysis provides detailed insight into the temporal evolution of surface deformation, allowing identification of long-term subsidence trends, episodic deformation events, and potential seasonal variations. Deformation measurements are initially obtained along the radar line-of-sight direction and are subsequently interpreted in terms of vertical displacement where sedimentation-related processes are dominant. Spatial maps of average deformation velocity and cumulative displacement are generated to visualize the distribution and magnitude of surface deformation. These outputs facilitate the identification of zones experiencing persistent subsidence, which are indicative of ongoing sediment accumulation and compaction(Liu et al., n.d.). Time-series plots for selected locations are also analyzed to examine deformation behavior in relation to hydrological and environmental changes.

Identification and Interpretation of Sedimentation Dynamics

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The deformation patterns derived from SBAS-InSAR are interpreted in the context of sedimentation dynamics by analyzing their spatial correspondence with known depositional environments such as river floodplains, reservoirs, deltas, and low-lying coastal areas. Persistent subsidence is considered a key indicator of sediment loading and consolidation, while spatial variability in deformation rates reflects differences in sediment thickness, material properties, and hydrological conditions. The interpretation is further informed by land use patterns, proximity to sediment sources, and geological characteristics of the study area.

Temporal relationships between deformation trends and hydrological or climatic events, such as floods or periods of intense rainfall, are examined to strengthen the linkage between observed deformation and sedimentation processes. This integrated interpretation allows differentiation of sedimentation-induced deformation from other potential deformation drivers, such as groundwater extraction or tectonic activity.

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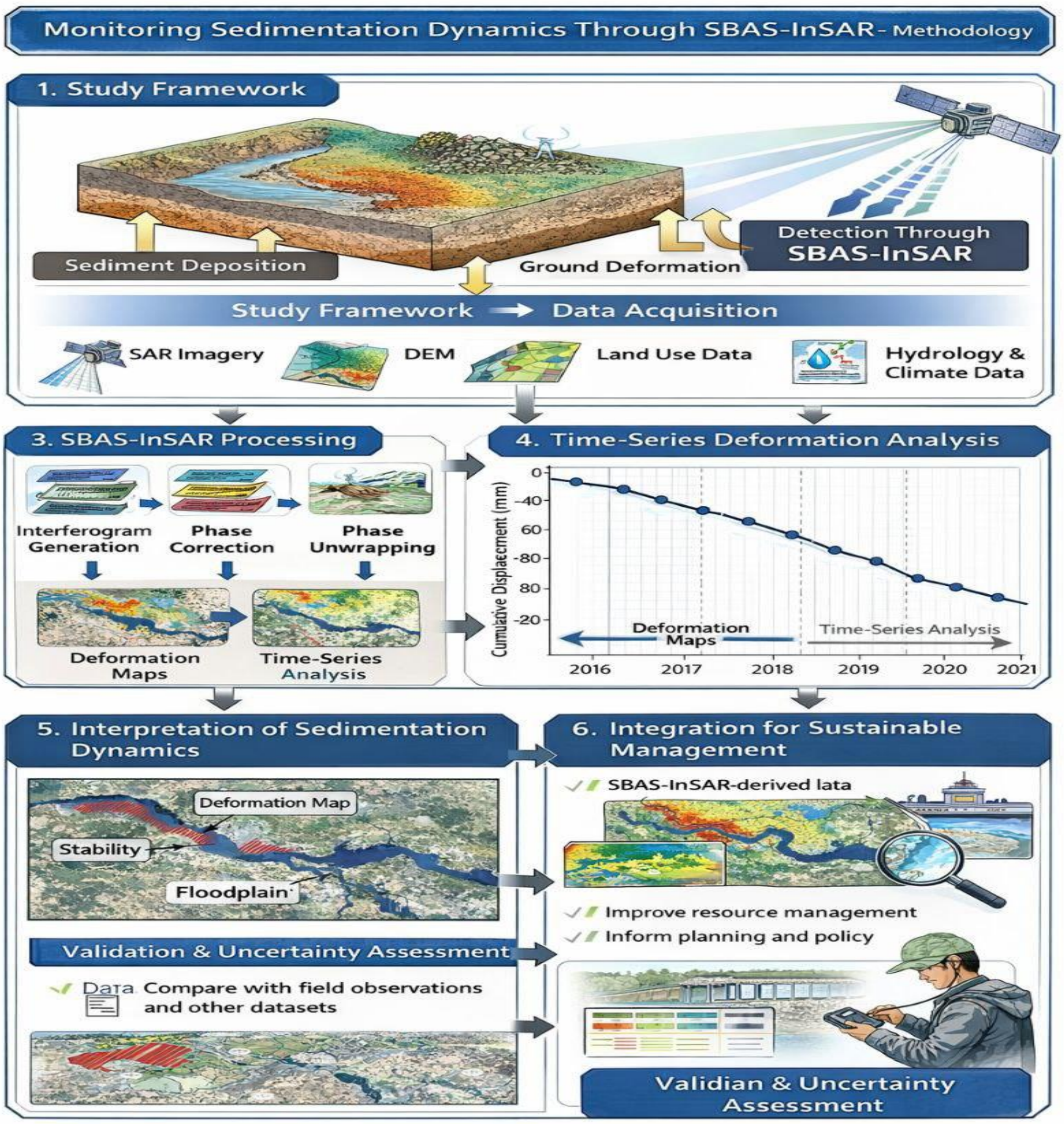

Integration for Sustainable Management

The results obtained from SBAS-InSAR analysis are integrated into a sustainable management framework aimed at supporting informed decision-making. Deformation-based indicators of sedimentation are used to identify areas at high risk of excessive sediment accumulation, which may threaten the functionality of reservoirs, river channels, and infrastructure(Al-Nouti et al., n.d.). The spatial and temporal insights provided by SBAS-InSAR contribute to improved sediment management strategies, including reservoir maintenance planning, river basin management, and land use regulation. By providing continuous and large-scale monitoring capabilities, the methodology supports proactive management approaches that can adapt to changing environmental conditions and anthropogenic pressures. The integration of SBAS-

InSAR results with conventional monitoring data enhances the overall understanding of sedimentation dynamics and promotes sustainable utilization of natural resources.

Validation and Uncertainty Assessment

Validation of SBAS-InSAR results is conducted through comparison with available ground-based observations, historical records, or independent datasets where possible. This assessment helps evaluate the reliability and accuracy of the derived deformation measurements. Potential sources of uncertainty, including temporal decorrelation, atmospheric residuals, DEM errors, and the influence of non-sedimentation-related deformation processes, are critically examined. Acknowledging and addressing these uncertainties is essential for ensuring robust interpretation of sedimentation dynamics and for enhancing the applicability of SBAS-InSAR as a tool for sustainable environmental management.

Results

SBAS-InSAR Deformation Products

The SBAS-InSAR processing of the multi-temporal SAR dataset successfully generated high-quality deformation products for the study area. A dense network of coherent pixels was identified, particularly in low-lying sedimentary environments such as floodplains, reservoir margins, and riverine corridors. The resulting deformation velocity and cumulative displacement maps reveal distinct spatial patterns of ground motion, indicating the presence of gradual surface deformation over the observation period. The reliability of these products demonstrates the effectiveness of the SBAS approach in minimizing decorrelation and atmospheric noise in sedimentation-prone environments. The deformation velocity map indicates that a significant portion of the study area experienced measurable subsidence, with deformation rates varying spatially(Carlson et al., 2020). Stable or near-stable conditions were observed in elevated or bedrock-dominated areas, whereas sediment-rich zones exhibited pronounced deformation signals. The cumulative displacement map further highlights the progressive nature of deformation, confirming that surface movement occurred gradually rather than as isolated or abrupt events.

Spatial Distribution of Deformation Related to Sedimentation

The spatial analysis of SBAS-InSAR results reveals a strong correspondence between deformation patterns and known sediment deposition zones. Areas adjacent to river channels, floodplains, reservoirs, and deltaic regions display consistent subsidence signatures, suggesting active sediment accumulation and subsequent consolidation. These regions exhibit higher deformation rates compared to surrounding areas, reflecting variations in sediment thickness, composition, and depositional history. The deformation patterns are spatially continuous and coherent, indicating that the observed subsidence is not random but systematically linked to sedimentation processes(Cui et al., 2023). In contrast, regions characterized by rocky terrain or limited sediment supply show minimal deformation, further supporting the interpretation that sediment loading is a primary driver of the observed ground movement.

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Temporal Evolution of Deformation

Time-series deformation analysis provides insight into the temporal behavior of sedimentation-induced surface deformation. The reconstructed deformation histories for selected locations show a predominantly linear or quasi-linear subsidence trend over the monitoring period, indicating ongoing and sustained sediment consolidation. In certain areas, deformation rates exhibit temporal variability, with periods of accelerated subsidence corresponding to seasons of increased sediment supply or hydrological activity.

Seasonal fluctuations are observed in some deformation time series, particularly in areas influenced by river discharge and flooding events(Melnyk et al., n.d.). These fluctuations suggest a dynamic interaction between sediment deposition, pore water pressure changes, and consolidation processes. The long-term deformation trends, however, remain dominant, emphasizing the cumulative impact of sedimentation over time.

Relationship Between Deformation and Environmental Factors

The comparison of deformation results with hydrological, climatic, and land use data reveals a clear relationship between surface deformation and environmental drivers of sedimentation. Areas experiencing higher subsidence rates are often associated with zones of intense sediment input, such as downstream sections of river basins, reservoir inflow areas, and regions affected by land use changes that enhance soil erosion. Periods of increased rainfall and flood events correspond to noticeable changes in deformation trends in sedimentation-prone areas. These temporal associations indicate that sediment transport and deposition during high-flow conditions contribute significantly to observed surface deformation. Conversely, periods of reduced hydrological activity are characterized by relatively stable deformation rates, reflecting slower sediment accumulation and consolidation.

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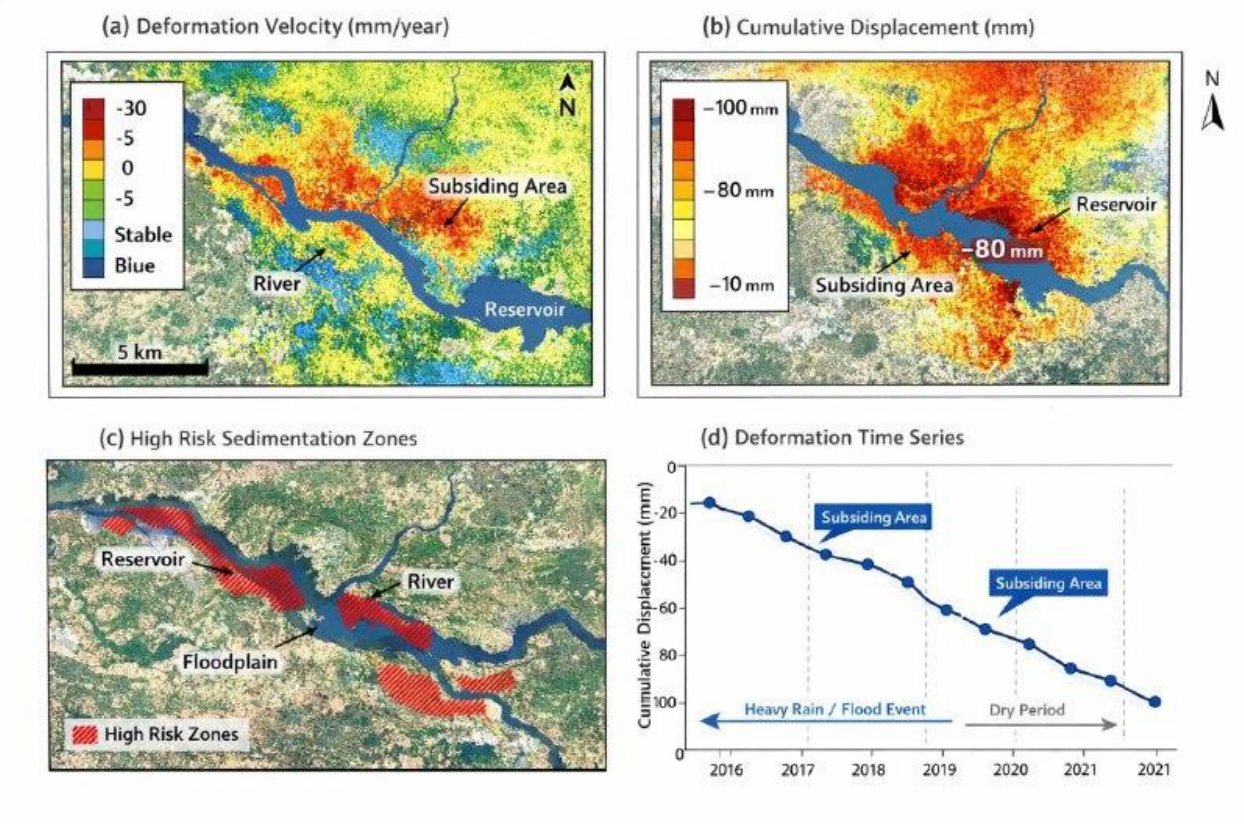

Identification of High-Risk Sedimentation Zones

Based on the magnitude and persistence of deformation, several zones within the study area are identified as high-risk sedimentation regions(Dai et al., n.d.). These areas exhibit sustained subsidence over the entire observation period, suggesting continuous sediment loading and consolidation. Such zones are often located near critical infrastructure, including reservoirs, embankments, and flood control structures, highlighting potential implications for structural stability and operational efficiency. The identification of these high-risk zones demonstrates the utility of SBAS-InSAR as a spatially explicit monitoring tool. The results provide valuable information for prioritizing field investigations, maintenance activities, and sediment management interventions.

Implications for Sustainable Management

The SBAS-InSAR results offer important insights for sustainable sediment and environmental management. The ability to detect and quantify gradual sedimentation-related deformation over large areas enables early identification of problematic sediment accumulation before severe impacts occur. The spatial and temporal deformation patterns provide a scientific basis for improving reservoir sediment management, river basin planning, and land use regulation.

Furthermore, the results illustrate the potential of SBAS-InSAR to complement conventional monitoring methods by providing continuous, non-invasive observations.

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This integration enhances the capacity of decision-makers to respond proactively to sedimentation challenges under changing climatic and anthropogenic conditions.

Uncertainty and Reliability of Results

Although the SBAS-InSAR results demonstrate strong consistency with expected sedimentation patterns, certain uncertainties remain(Kou et al., n.d.). Residual atmospheric effects, limitations in coherence over water-covered or densely vegetated areas, and the influence of non-sedimentation-related deformation processes may affect the magnitude of observed deformation. However, the spatial coherence, temporal consistency, and environmental correlation of the deformation signals suggest that the results reliably represent sedimentation-related surface deformation(Bassols et al., n.d.). Overall, the results confirm that SBAS-InSAR is a robust and effective technique for monitoring sedimentation dynamics and provides meaningful information to support sustainable management strategies.

Discussion

The results obtained from this study demonstrate the strong potential of SBAS-InSAR as an effective tool for monitoring sedimentation dynamics through the analysis of surface deformation. The spatially coherent and temporally consistent deformation patterns observed across sedimentary environments confirm that sediment deposition and subsequent consolidation can be reliably detected using multi-temporal radar interferometry. These findings contribute to a growing body of research highlighting the value of advanced InSAR techniques in environmental and geomorphological studies. The observed subsidence in sediment-rich zones is consistent with the theoretical understanding of sedimentation processes. As sediments accumulate, increased surface loading leads to compaction of underlying layers, particularly in unconsolidated or fine-grained deposits. This compaction manifests as gradual vertical deformation, which was effectively captured by the SBAS-InSAR time-series analysis. The clear contrast between deformation behavior in sedimentary areas and relatively stable conditions in bedrock-dominated regions strengthens the interpretation that sedimentation is a primary driver of the detected ground movement.

The temporal deformation trends further support this interpretation. The predominantly linear subsidence observed in many locations indicates continuous sediment accumulation and consolidation over the monitoring period. In areas where deformation rates exhibit temporal variability, the correspondence with hydrological events such as floods and periods of increased rainfall suggests a direct link between sediment transport processes and surface deformation. These findings emphasize the dynamic nature of sedimentation and the importance of long-term monitoring to capture both gradual and episodic changes.

The spatial correspondence between deformation patterns and environmental factors such as river networks, reservoir margins, and land use changes highlights the influence of both natural and anthropogenic drivers on sedimentation dynamics. Areas downstream of erodible catchments or regions affected by land use practices that enhance soil erosion show higher subsidence rates, indicating increased sediment

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supply. This underscores the interconnectedness of watershed processes and sediment deposition zones, and the need for integrated basin-scale management approaches.

Compared to traditional sediment monitoring methods, the SBAS-InSAR approach offers several distinct advantages. Conventional techniques, while providing direct measurements, are often limited in spatial coverage and temporal continuity. In contrast, SBAS-InSAR enables continuous, large-scale observation of deformation patterns, allowing for the identification of sedimentation trends that may not be apparent from point-based measurements alone. This capability is particularly valuable in regions where field data are sparse or difficult to obtain.

Despite these advantages, the interpretation of SBAS-InSAR results requires careful consideration of potential confounding factors. Surface deformation detected by InSAR may also result from processes such as groundwater extraction, tectonic activity, or infrastructure loading. In this study, the integration of ancillary data and environmental context was essential in distinguishing sedimentation-induced deformation from other sources. Nonetheless, residual uncertainties related to atmospheric artifacts, decorrelation in vegetated or water-covered areas, and DEM inaccuracies remain inherent limitations of the technique. The implications of these findings for sustainable management are significant. By identifying zones of active sediment accumulation and consolidation, SBAS-InSAR provides actionable information for reservoir management, flood risk mitigation, and infrastructure planning. Early detection of excessive sedimentation can inform timely interventions, such as dredging, sediment bypassing, or land use regulation, thereby extending the operational lifespan of water resources infrastructure and reducing environmental degradation. Furthermore, the ability to monitor sedimentation dynamics under changing climatic conditions enhances adaptive management strategies. As climate change is expected to intensify hydrological extremes and alter sediment transport regimes, continuous monitoring tools like SBAS-InSAR become increasingly valuable. The results of this study demonstrate that SBAS-InSAR can serve as a reliable component of long-term monitoring systems aimed at achieving sustainable environmental and resource management.

Overall, the discussion highlights that while SBAS-InSAR does not directly measure sediment volume or composition, it provides critical indirect indicators of sedimentation processes through deformation analysis. When combined with complementary datasets and field observations, SBAS-InSAR emerges as a powerful tool for advancing the understanding of sediment dynamics and supporting informed decision-making for sustainable development.

Conclusion

This study demonstrates the effectiveness of SBAS-InSAR in monitoring sedimentation dynamics through the analysis of surface deformation. The results reveal clear spatial and temporal patterns of subsidence associated with sediment deposition and consolidation in sedimentary environments. By providing continuous, large-scale observations, SBAS-InSAR overcomes many limitations of conventional sediment monitoring methods. The integration of deformation data with environmental

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information enhances the understanding of sedimentation processes and their driving factors. Overall, SBAS-InSAR proves to be a valuable and reliable tool for supporting sustainable sediment and environmental management under changing natural and anthropogenic conditions.

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