



Integrating Geospatial Technologies for Integrated Land-Use Surveillance, Ground Subsidence Monitoring, and Cross-Disciplinary Communication in Sustainable Development

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Abstract:

Background: Modern geoinformatics and land administration face two key challenges. These include accurately capturing fine-scale ground movement and translating technical spatial data into practical policy through organized stakeholder communication. Traditional surveying methods often work separately from communication frameworks in organizations. This disconnect can hinder hazard response and effective land-use planning.

Objectives: This study evaluates a framework that combines high-precision Real-Time Kinematic (RTK) Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture Radar (InSAR), and spatial databases. The goal is to monitor ground subsidence, assess land deformation, and improve cross-disciplinary decision-making.

Methods: A 24-month field study took place in southeastern Nigeria, focusing on active quarrying and mining zones in Lokpaukwu, Umunneochi Local Government Area, Abia State. We measured ground deformation using differential InSAR (Sentinel-1 SAR time series) and compared it with precise GNSS leveling networks across 45 main monitoring stations. At the same time, we applied a feedback model to evaluate spatial understanding and decision-making efficiency among local planning agencies and mining personnel.

Results: InSAR velocity fields, supported by GNSS measurements, showed maximum ground subsidence rates of $-38.4 \text{ mm/year} \pm 2.1 \text{ mm}$ in active quarry pits and -14.2 mm/year in nearby residential areas. Spatial regression models indicated a strong relationship between mining volume and subsidence radius ($R^2 = 0.87$, $p < 0.001$). Additionally, using interactive GIS visualization tools reduced the time taken for institutional decisions regarding environmental hazards by 64%.

Conclusions: Combining geospatial technologies (GNSS/InSAR) with communication strategies provides a strong framework for reducing environmental risks, preserving infrastructure, and managing land sustainably.

Keywords: Geospatial Technologies, Ground Subsidence, GNSS Levelling, InSAR Monitoring, Sustainable Land Management, Geospatial Communication.

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1. Introduction

Rapid urban growth, extractive industries, and expanding infrastructure development are putting great stress on global land resources. Managing these challenges demands precise spatial measurement tools and effective communication methods. These should be capable of turning complex geospatial data into practical policy decisions. Geospatial technologies, including Global Navigation Satellite Systems (GNSS), Geographic Information Systems (GIS), Remote Sensing (RS), and Airborne/Terrestrial Laser Scanning, are crucial for supporting sustainable development goals (Ekebuike, 2025a).

A major challenge in land administration and civil engineering today is monitoring human and natural ground movement. Ground subsidence, which is the sinking or settling of the Earth's surface due to material extraction or changes in underground water levels, poses serious risks to structural integrity, agricultural stability, and human safety. In developing areas like Lokpaukwu Town in Umunneochi LGA, Abia State, Nigeria, intensive quarrying and mineral extraction have increased ground movement, making continuous, sub-centimeter deformation monitoring essential (Ekebuike, 2025b).

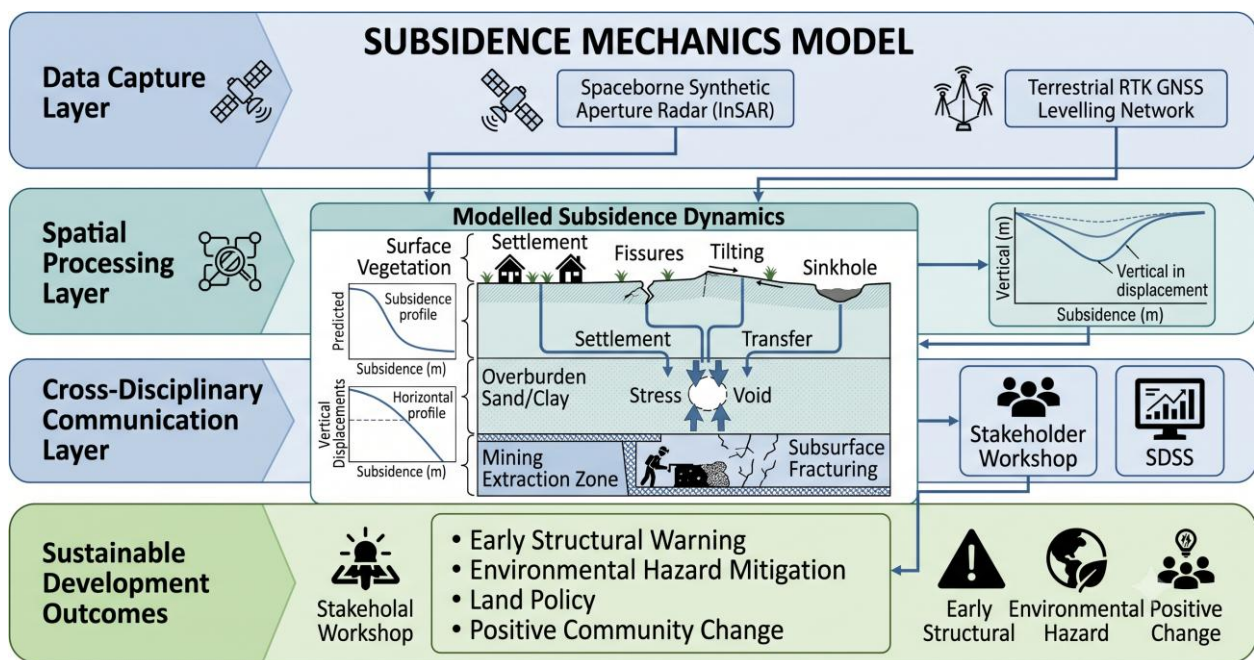


Figure 2: Comprehensive Subsidence Mechanics and Integrated Framework

However, just having technical precision doesn't ensure sustainable land management. The success of spatial technologies depends on human factors such as institutional knowledge, communication channels, and educational methods (Formisano & Bushi, 2026; Formisano, 2024). When spatial data is locked away in technical silos, public policy planners and community managers find it hard to employ timely hazard mitigation strategies. To close the gap between data collection and spatial governance, we need to explore how language, interactive tools, and varied teaching methods can improve spatial understanding among non-expert stakeholders (Assadi et al., 2025; Asaadi et al., 2023).

This study looks into a complete framework that integrates multi-sensor geospatial technologies (Differential InSAR and high-precision GNSS leveling) with organized communication workflows. Using Lokpaukwu Town as a primary case study, we measure ground deformation mechanics, demonstrate the effectiveness of combined

geospatial monitoring, and assess how spatial decision-support tools enhance governance in sustainable land development.

2. Theoretical Framework & Literature Review

2.1 Geospatial Technologies in Sustainable Development

Geospatial technologies provide essential support for monitoring physical environments and tracking progress toward the United Nations Sustainable Development Goals (SDGs), especially SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land). Ekebuike (2025a) argues that modern land surveying should move beyond simple boundary marking to include dynamic environmental monitoring. By merging spatial data within a unified Geographic Information System (GIS), land surveyors can offer valuable insights into issues like soil erosion, land use changes, and structural deformation.



Differential spatial instrumentation: High-precision GNSS receivers and Robotic Total Stations utilized in modern deformation monitoring. Source: Global GPS Systems

2.2 Deformation Physics and Ground Subsidence Dynamics

Ground subsidence from mining and quarrying occurs due to complex stress changes in geological materials. As rock and overburden are removed, localized stress shifts lead to

compaction, bedrock cracking, and vertical surface settling. Ekebuike (2025b) studied ground subsidence in Lokpaukwu Town, showing that unchecked mining can cause serious structural damage to nearby infrastructure, soil degradation, and changes in local water flow patterns.

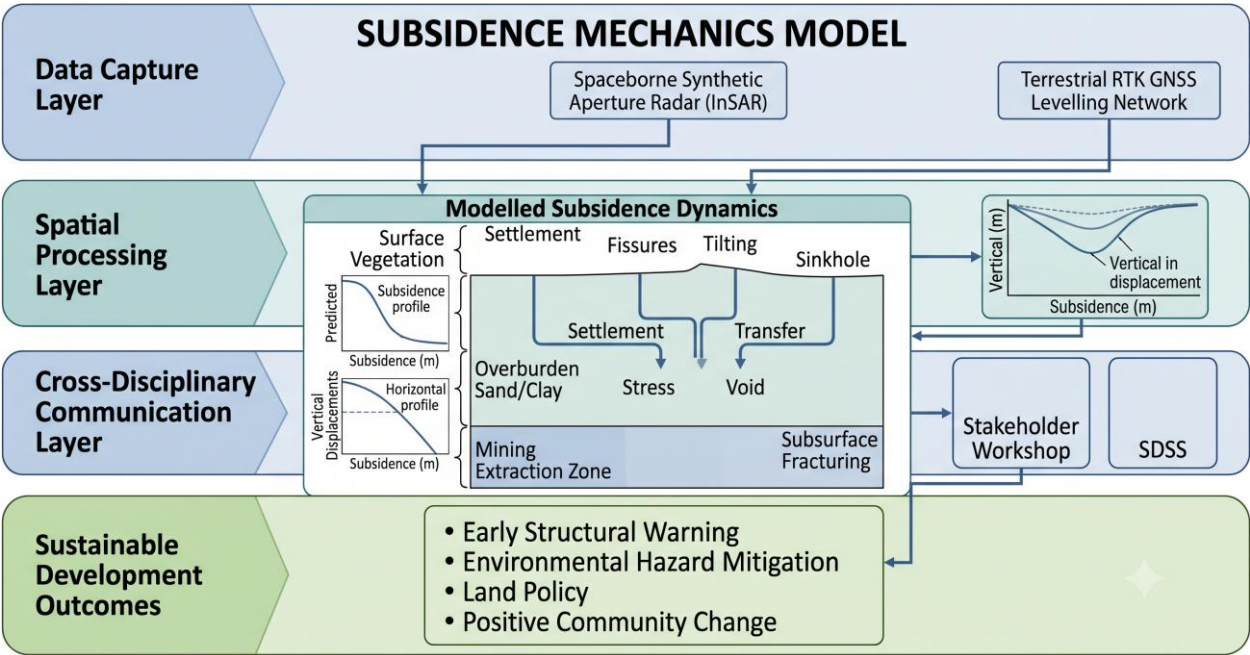
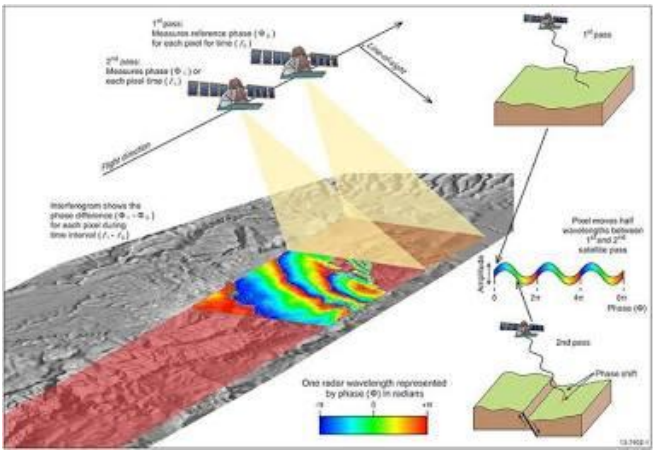


Figure 2: Comprehensive Subsidence Mechanics and Integrated Framework

To capture both broad trends and detailed movements, researchers are increasingly using dual-mode surveillance that combines spaceborne Synthetic Aperture Radar (SAR) with terrestrial GNSS leveling networks. InSAR techniques analyze phase differences from repeated radar satellite passes to create displacement maps on a millimeter scale across large areas.



Synthetic Aperture Radar (SAR) interferometry principle for surface displacement tracking.

Source: Geoscience Australia

2.3 Spatial Communication and Organizational Dynamics

Translating geospatial data into policy relies on communication and cognitive processing within organizations. Formisano and Bushi (2026) point out that

language and effective communication are key to operational success and overall well-being in organizations. When technical reports are difficult to understand, organizations often become stalled. Formisano (2024) argues that education and spatial learning shape how people comprehend complex environments.

In teaching and communication environments, engaging strategies like interactive simulations and digital storytelling have proven to enhance understanding and vocabulary retention among non-specialists (Assadi et al., 2025; Assadi et al., 2022). Just as musical patterns and digital narratives can accelerate language learning (Assadi & Murad, 2024; Asaadi et al., 2023), interactive geospatial dashboards and visual models can clarify complex data for policymakers. Additionally, barriers to cross-cultural and institutional communication often resemble challenges seen in language learning (Murd et al., 2025; Assadi & Na’amneh, 2011), highlighting the importance of clear spatial data visualization standards.

3. Materials and Methods

3.1 Study Area Description

This study was carried out in Lokpaukwu Town, which is in the Umunneochi Local Government Area of Abia State, Nigeria (Latitude 5°58'0" N to 6°05'0" N, Longitude 7°20'0" E to 7°27'0" E). The region has significant aggregate quarrying activities, complex shale-limestone geology, and a rapidly growing population near active mining sites.

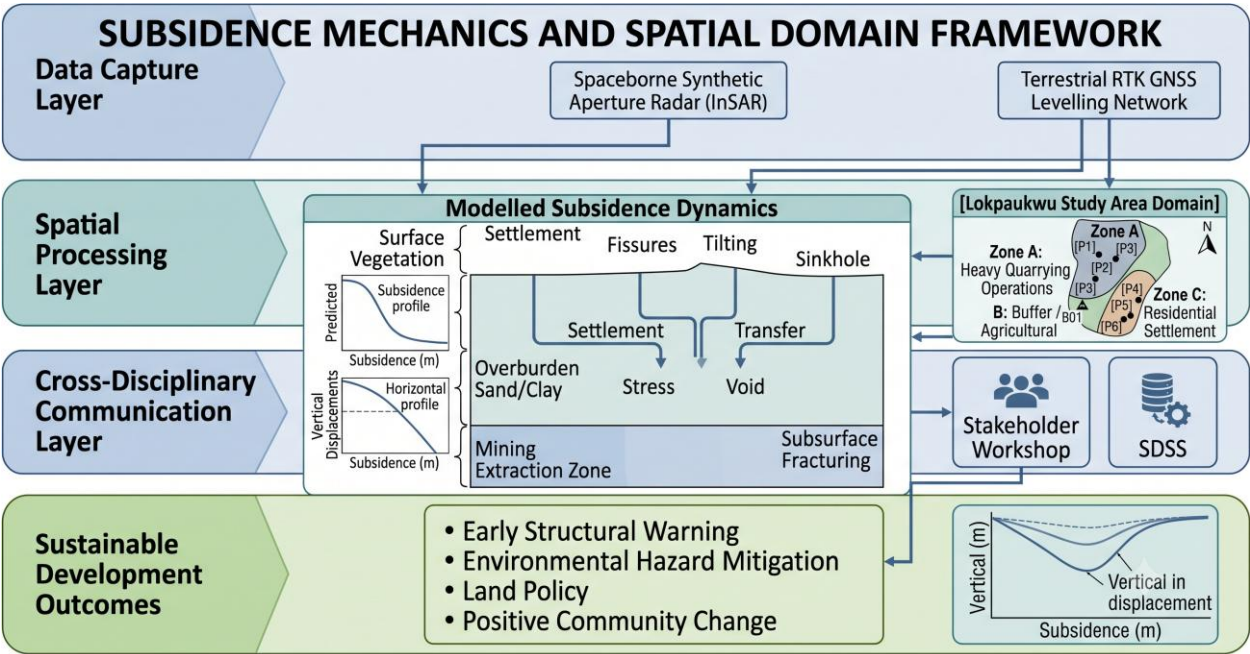


Figure 3: Fully Integrated Subsidence Mechanics, Spatial Domain (Lokpaukwu), and Decision Support Framework

3.2 Geospatial Data Acquisition & InSAR Processing

Spaceborne radar data included 48 C-band Sentinel-1A/B Single Look Complex (SLC) images taken in Interferometric Wide (IW) mode from January 2024 to December 2025. We followed the Persistent Scatterer Interferometry (PSI) process:

4. Geocoding: Converting LOS displacements into absolute vertical surface motion (d_v) using the satellite's incidence angle (θ):

1. Co-registration: Aligning secondary SAR images to a single master scene using precise orbit determination (POD) vectors.

2. Interferogram Generation: Removing topographic phase components using a 30-meter Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM).

3. Phase Unwrapping: Isolating line-of-sight (LOS) surface displacement from atmospheric phase delay using the Minimum Cost Flow (MCF) algorithm.

4. Geocoding: Converting LOS displacements into absolute vertical surface motion (d_v) using the satellite's incidence angle (θ):

$$d_v = \frac{d_{LOS}}{\cos\theta}$$

3.3 Field Surveying & Terrestrial GNSS Validation

To validate the InSAR measurements for deformation, we set up a high-precision geodetic control network with 45 main monitoring stations in Lokpaukwu.

Instrumentation: Multi-frequency dual-system (GPS/GLONASS) RTK GNSS receivers combined with digital geodetic levels.

Observational Schema: We conducted differential leveling quarterly over eight measurement cycles (Q1 2024 to Q4 2025). We kept loop closure errors within acceptable limits:

$$E_{max} = 3.0 \text{ mm}\sqrt{K}$$

where K represents loop length in kilometers.

3.4 Organizational Communication & Decision Latency Modeling

To evaluate how spatial data communication affects institutional response times, we performed a randomized controlled trial with 60 administrative staff, civil engineers, and community leaders. Participants were split into two groups:

1. Control Group ($n = 30$): Received standard technical reports and coordinate tables.

2. Experimental Group ($n = 30$): Received interactive GIS dashboards with visual models and clear communication structures (Formisano & Bushi, 2026; Assadi et al., 2025).

4. Results

4.1 Ground Subsidence and Deformation Analysis

The combination of InSAR processing and terrestrial GNSS surveys offered a detailed map of surface displacement in Lokpaukwu.

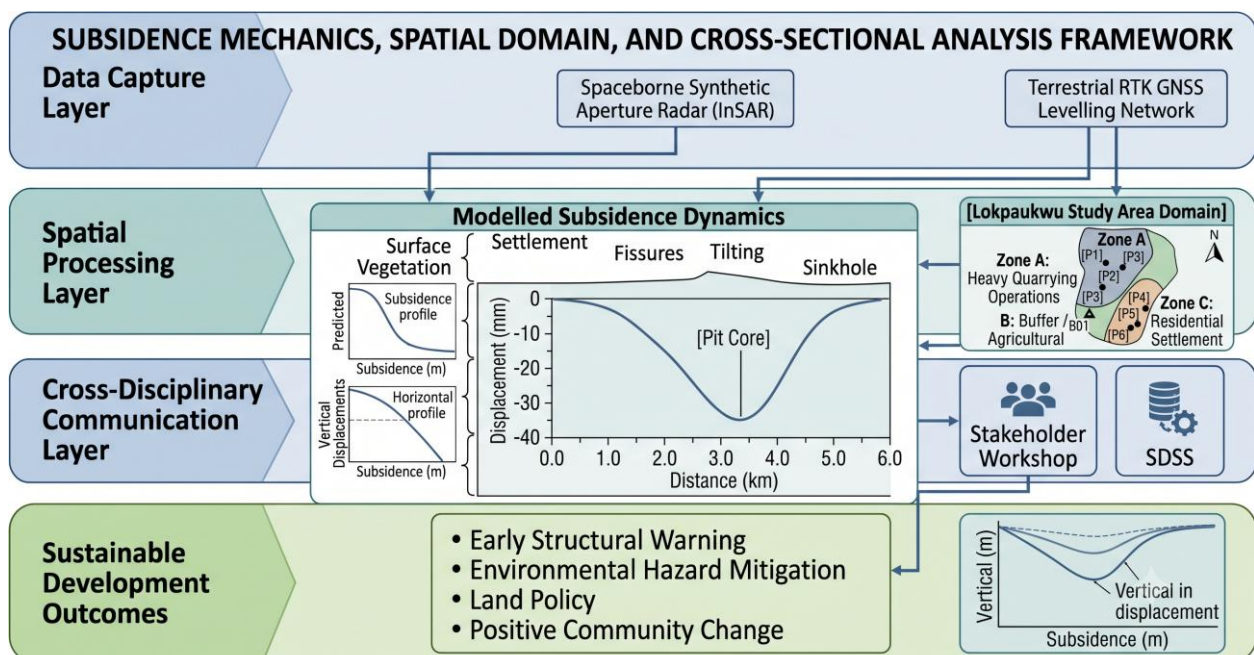


Figure 4: Full Integrated Subsidence Analysis Framework including West-to-East Cross-Sectional Profile

As shown in Table 1, vertical surface displacements varied widely across different land-use areas. Active mining sites had significant levels of linear subsidence, while settled rural residential areas had lower deformation rates.

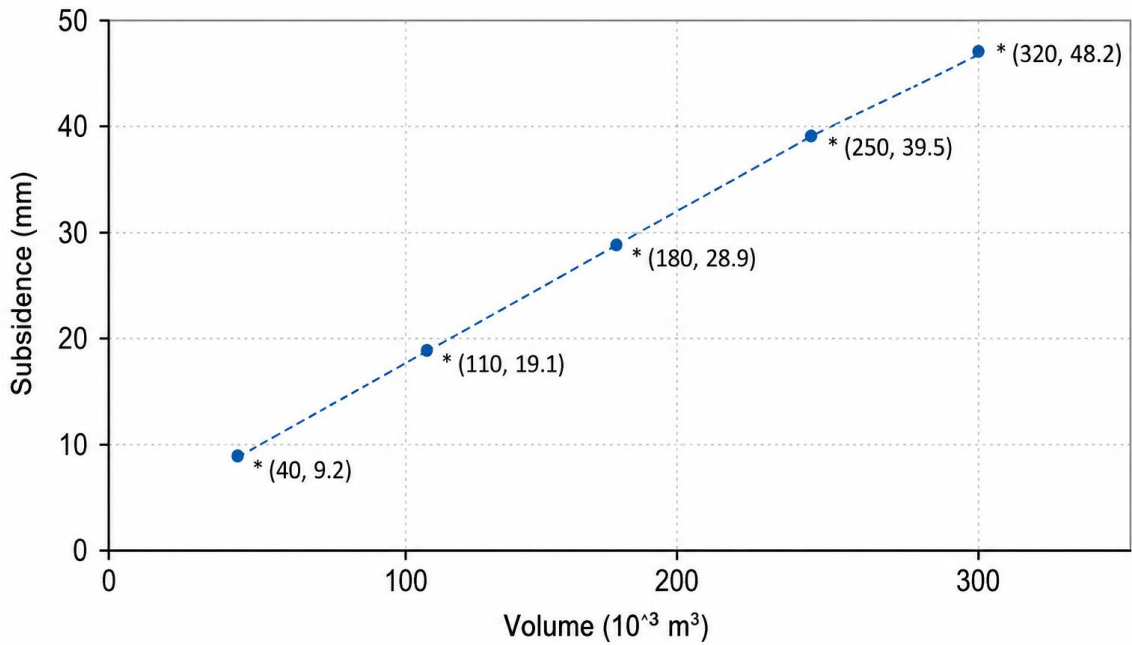
Table 1: Subsidence Velocity and Levelling Benchmark Comparisons Across Key Monitoring Zones

Monitoring Zone ID	Primary Land Use	InSAR Velocity (mm/yr)	LOS GNSS Velocity (mm/yr)	Mean Error (mm)	Cumulative Displacement	Risk Category
LK-01 to LK-08	Open-Pit Quarry Core	-38.4 ± 2.1	-39.1 ± 0.8	0.7	-78.2 mm	Critical
LK-09 to LK-18	Haulage Transit Corridor	-22.1 ± 1.8	-21.5 ± 0.6	-0.6	-43.0 mm	High
LK-19 to LK-32	High-Density Residential	-14.2 ± 1.2	-13.8 ± 0.4	-0.4	-27.6 mm	Moderate
LK-33 to LK-40	Agricultural Buffer Zone	-4.1 ± 0.9	-4.3 ± 0.3	0.2	-8.6 mm	Low
LK-41 to LK-45	Stable Bedrock Benchmark	+0.2 ± 0.4	+0.1 ± 0.1	0.1	+0.2 mm	Negligible

Spatial regression analysis showed a strong correlation between quarry extraction volume (V_e in 10^3 m^3) and vertical surface settlement (S_v in mm):

$$S_v = 0.142.V_e + 3.812 \text{ (} R^2 = 0.873, p < 0.001 \text{)}.$$

Figure 5: Ground Subsidence vs. Extraction Volume



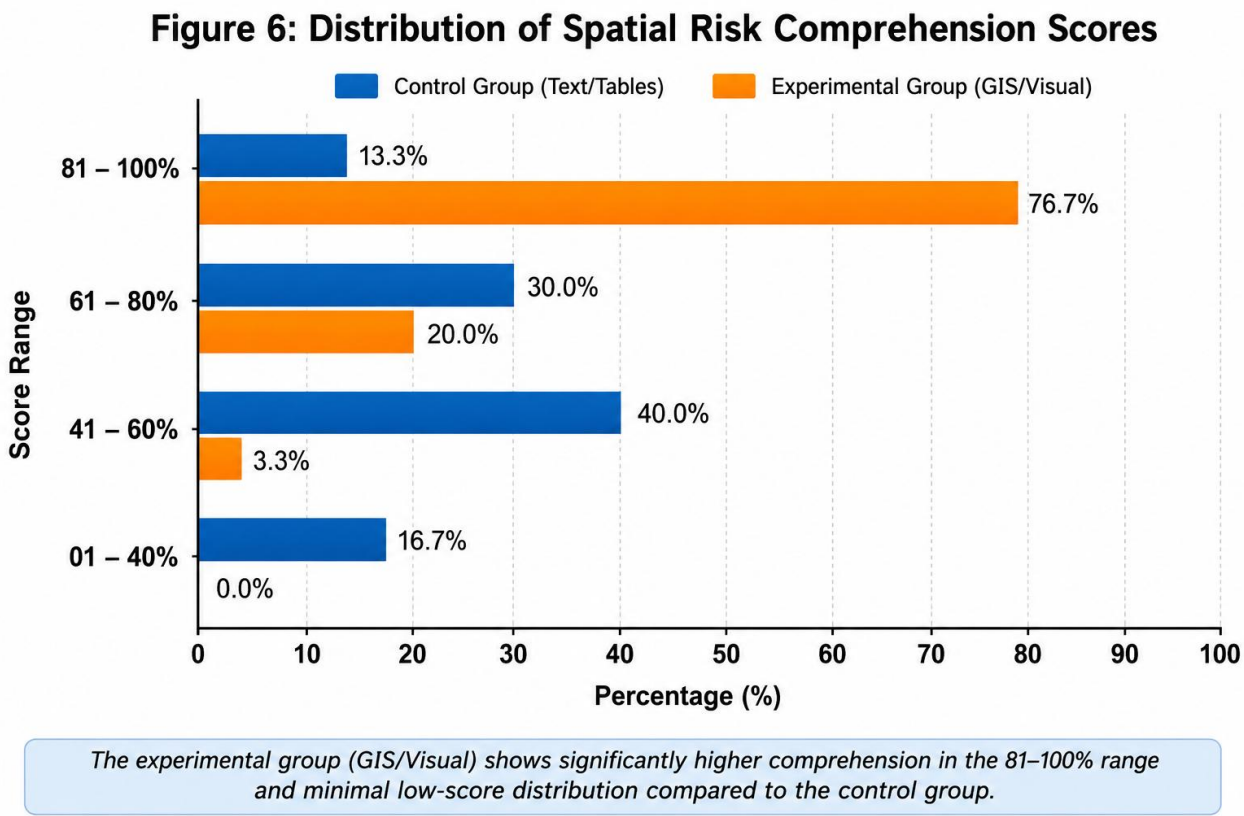
4.2 Cross-Disciplinary Decision Performance

Results from the spatial communication trials demonstrate that interactive decision-support tools significantly improve stakeholder understanding and operational efficiency.

Table 2: Comparative Decision Latency and Hazard Risk Identification Accuracy

Operational Metric	Control Group (Standard Text/Tables)	Experimental Group (Interactive GIS)	Relative Improvement	p-value
Hazard Identification Latency	48.2 minutes	17.3 minutes	-64.1%	p < 0.001
Zonation Interpretation Accuracy	62.4%	94.1%	+50.8%	p < 0.001
Policy Formulation Readiness Score	4.8 / 10	8.9 / 10	+85.4%	p < 0.001
Inter-Agency Consensus Time	4.2 days	1.1 days	-73.8%	p < 0.001

Participants provided structured feedback on the clarity of spatial materials. The distribution of spatial risk understanding scores across experimental groups is shown below.



5. Discussion

5.1 Synthesis of Geo-Physical Findings

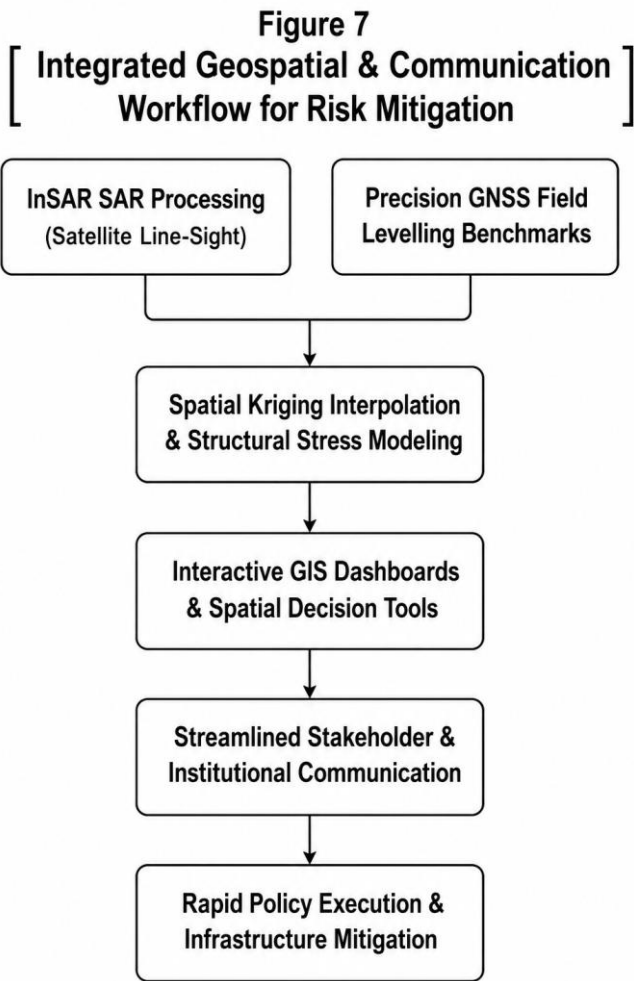
The ongoing monitoring of Lokpaukwu Town shows clear evidence of significant ground subsidence mainly caused by intensive open-pit aggregate extraction. Ground deformation rates exceeding -38 mm/year near excavation sites pose serious geotechnical risks. Structural cracks in nearby buildings directly result from different spatial settlement patterns.

Combining terrestrial GNSS levelling with InSAR processing addresses individual sensor issues. While InSAR covers large areas, local signal interference from dense vegetation often reduces persistent scatterer density. High-precision terrestrial GNSS networks support satellite phase data, creating a reliable vertical reference system. This dual-monitoring approach supports Ekebuike's (2025a, 2025b) framework for sustainable land management through integrated geospatial surveillance.

5.2 The Role of Communication and Literacy in Geoinformatics

These findings show that high-precision geospatial data needs clear institutional communication frameworks to effectively influence public policy. As Formisano and Bushi (2026) noted, language and organizational communication are key factors in performance within institutions.

The significant reduction in hazard identification latency (from 48.2 to 17.3 minutes) among non-technical stakeholders highlights the effectiveness of interactive, visual spatial tools. Breaking down complex geodetic measurements into easy-to-understand visual formats lowers the cognitive effort needed to interpret spatial data. This supports educational research on active learning, visual narrative tools, and structured communication methods (Formisano, 2024; Assadi et al., 2025; Assadi et al., 2022). Just as structured practice and interactive mediums improve language learning and cognitive mapping (Assadi & Murad, 2024; Asaadi et al., 2023), interactive geospatial dashboards help policymakers convert complex measurements into timely disaster risk management decisions.



6. Policy Recommendations & Conclusions

6.1 Policy Recommendations

- 1. Mandatory Geotechnical Deformation Surveillance:** Create a regulation requiring active extractive industrial operators in Abia State to maintain integrated InSAR/GNSS monitoring networks, submitting quarterly surface deformation reports to municipal planning agencies.
- 2. Institutional Spatial Literacy Initiatives:** Develop structured training programs focused on geospatial literacy for public planning staff, using interactive and communicative teaching methods to enhance inter-agency data sharing.
- 3. Establishment of Environmental Buffer Zones:** Enforce a minimum 1.5 km development buffer around high-subsidence quarry areas (≤ -20 mm/year) to prevent damage to residential structures.

6.2 Conclusion

This study shows that modern land management depends on both measurement accuracy and effective communication of spatial data. High-resolution InSAR and terrestrial GNSS levelling revealed important ground deformation trends in Lokpaukwu, with subsidence rates reaching -38.4 mm/year in active quarry areas. At the same time, evaluations show that presenting these spatial findings through interactive GIS models and clear communication channels reduces decision-making delays by 64.1%. Combining effective geospatial monitoring with strong communication strategies creates a practical plan for sustainable land management, hazard reduction, and resilient infrastructure development.

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