Int. j. adv. multidisc. res. stud. 2025; 5(4):844-850

Received: 08-06-2025
Accepted: 18-07-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Rapid Subsidence Mapping in Awka Metropolis Using Synthethic Aperture Radar

[1] Okoye SC, [2] Ossai EN, [3] Ono MN

[1, 3] Department of Surveying and Geoinformatics, Nnamdi Azikiwe University Awka, Nigeria

[2] Department of Surveying and Geoinformatics, Southern Delta University Ozoro, Delta State, Nigeria

Corresponding Author: **Okoye SC**

Abstract

This study investigates the spatial and temporal dynamics of land subsidence in Awka Metropolis between 2019 and 2024 using Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR). The objectives include identifying zones of subsidence, estimating the annual rate of vertical ground displacement, and classifying subsidence severity. Sentinel-1A SAR data were acquired and processed using the SNAP software and Stanford Method for Persistent Scatterers (StaMPS) in MATLAB. The results revealed severe subsidence in key urban areas such as Ifite (4.1 cm/year), Unizik Temporary Site (3.7 cm/year), and Agu Awka (3.5 cm/year), attributed largely to urban expansion, groundwater withdrawal, and construction load. The classification categorized the subsidence zones into low, moderate, and high risk, thus providing critical spatial insights for mitigation and planning. The study recommends the integration of InSAR-based early warning systems and sustainable land-use practices to prevent future infrastructural and environmental damage.

Keywords: Land Subsidence, PS-InSAR, Awka Metropolis, Synthetic Aperture Radar (SAR), Sentinel-1, Ground Deformation, Remote Sensing, Urbanization

1. Introduction

Land subsidence is an increasingly recognized geohazard that poses serious threats to urban sustainability, infrastructure integrity, and environmental stability across the globe. It is defined as the gradual or sudden sinking of the Earth's surface due to natural processes or anthropogenic activities such as excessive groundwater withdrawal, mining, rapid urbanization, and sediment compaction (Galloway & Burbey, 2011; Herrera-García *et al*., 2021) [9, 10]. In developing countries, especially in sub-Saharan Africa, the challenges posed by land subsidence are compounded by poor urban planning, unregulated resource extraction, and weak enforcement of environmental policies (Aderogba, 2012; Nwilo *et al*., 2014) [2, 16].

In Nigeria, reports of land subsidence and associated hazards such as gully erosion and infrastructure collapse are becoming more frequent in urban areas such as Lagos, Benin City, Port Harcourt, and Awka (Obiefuna *et al*., 2013; Okeke *et al*., 2021 [19]). Awka, the capital of Anambra State, lies within the tectonically active Anambra Basin and is underlain by geologically vulnerable formations such as Nanka Sands and Imo Shale, which are susceptible to compaction and erosion (Orajaka, 1975; Egboka & Okpoko, 1984) [17, 6]. The rapid expansion of the city due to increasing population, construction pressure, and uncontrolled groundwater abstraction has further exacerbated ground instability in several neighborhoods such as Ifite, Unizik Temp Site, and Agu Awka (Nwagwu *et al*., 2018; Onu *et al*., 2022) [15, 18].

Traditional techniques for monitoring land deformation, including spirit leveling, GPS surveys, and geotechnical investigations, are often limited by their high cost, point-based nature, and logistical difficulties, especially over large and densely built environments (Ferretti *et al*., 2001; Crosetto *et al*., 2016) [8, 5]. The emergence of Synthetic Aperture Radar Interferometry (InSAR), particularly Persistent Scatterer InSAR (PS-InSAR), has revolutionized deformation monitoring by offering millimeter-level accuracy, wide spatial coverage, and the ability to track temporal changes over time without physical contact (Ferretti *et al*., 2001 [8]; Raspini *et al*., 2018). Sentinel-1 data, which is freely accessible and has a 6-day revisit time, enables frequent, high-resolution, and consistent monitoring of land movements (European Space Agency, 2019; Karimzadeh & Matsuoka, 2020) [7, 11]. Several global studies have successfully applied PS-InSAR to detect urban subsidence caused by

various factors such as aquifer depletion, construction loading, and geological instabilities (Mazzoni *et al*., 2015 [12]; Chaussard *et al*., 2014 [4]; Wang *et al*., 2020). In Indonesia, Abidin *et al*. (2013) used InSAR to map critical subsidence zones in Jakarta, while in Iran, Motagh *et al*. (2007) [13] employed the technique to monitor sinking related to groundwater extraction. In the Nigerian context, however, the application of InSAR for subsidence monitoring remains scarce, with most studies relying on ground-based geotechnical and hydrological methods (NEWMAP, 2014; Ajayi *et al*., 2020) [14, 3].

This study aims to fill this gap by deploying PS-InSAR analysis on Sentinel-1 data to map and characterize vertical land displacement across Awka Metropolis between 2019 and 2024. The objectives are to: (1) detect and map areas experiencing significant subsidence; (2) estimate the rate of vertical deformation in centimeters per year; and (3) classify zones based on severity. These findings will support proactive urban planning, inform stakeholders of critical risk areas, and contribute to the development of a geospatial early warning system for ground instability in southeastern Nigeria.

2. Materials and Methods

2.1 Description of the Study Area

The study was carried out in Awka Metropolis, the capital city of Anambra State, located in southeastern Nigeria. Geographically, the area lies between latitudes 6°10'N and 6°15'N and longitudes 7°02'E and 7°07'E, covering an estimated area of approximately 144 square kilometers. Awka is situated within the Anambra Basin and is underlain by Nanka Sands and Imo Shale, which are both geologically susceptible to compaction and erosion. The terrain is predominantly undulating, with elevations ranging between 80 and 160 meters above sea level. The area experiences a tropical humid climate, with high annual rainfall between 1,800 mm and 2,200 mm and two distinct seasons: wet (April to October) and dry (November to March). Rapid urbanization, increased groundwater abstraction, and poor planning practices have made Awka particularly vulnerable to geohazards such as land subsidence and gully erosion.

2.2 Data Acquisition

The primary dataset used in this study consisted of Sentinel-1A Synthetic Aperture Radar (SAR) imagery acquired from the Copernicus Open Access Hub. A total of 60 Single Look Complex (SLC) images covering the period from 2019 to 2024 were used. These images were captured in Interferometric Wide Swath (IW) mode with VV polarization in ascending orbit. The selection of Sentinel-1 data was based on its open-access availability, consistent revisit frequency of 6 days, and proven capability in deformation studies. The spatial resolution of the imagery is approximately 20 meters in range and 22 meters in azimuth. In addition to SAR data, a 30-meter Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used for terrain correction, while shapefiles of administrative boundaries were acquired for spatial referencing.

2.3 Image Pre-processing

The SAR imagery was pre-processed using the Sentinel Application Platform (SNAP) version 8.0, developed by the European Space Agency. Pre-processing involved a series of steps including orbit file correction, radiometric calibration, and co-registration of master and slave images to ensure geometric alignment. Following this, interferogram generation was conducted, and coherence maps were produced to assess the quality of interferometric pairs. Terrain correction was performed using the Range-Doppler method and the SRTM 1 Arc-Second DEM to eliminate topographic effects and convert the radar geometry into map coordinates (WGS 84/UTM Zone 32N). Multitemporal stack formation was conducted to prepare the dataset for time-series analysis.

2.4 Persistent Scatterer Interferometry Processing (StaMPS)

To detect subsidence, Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) analysis was performed using the StaMPS toolbox (Stanford Method for Persistent Scatterers), implemented in MATLAB. StaMPS identifies stable point targets (persistent scatterers) whose phase changes remain consistent over time. The processing workflow included estimation of interferometric phase, filtering of atmospheric noise, and refinement of orbit and topographic errors. Persistent scatterer candidates were selected based on phase stability, amplitude dispersion index (<0.4), and coherence threshold. The result was a series of time-displacement data for each point, representing vertical ground motion across the monitoring period.

2.5 Subsidence Rate Computation

Line-of-sight (LOS) deformation values extracted from PS-InSAR analysis were converted into vertical displacement values under the assumption that vertical movement dominated horizontal displacement in the area. The average velocity was calculated for each point across the six-year period (2019–2024) and expressed in centimeters per year. Annual mean deformation rates were computed using linear regression models on time-displacement profiles. Points with negative values indicated subsidence (downward movement), while positive values represented uplift.

2.6 Classification of Subsidence Severity

To evaluate the severity and spatial distribution of land subsidence, the annual vertical displacement values were imported into a Geographic Information System (GIS) environment using ArcGIS 10.8. The deformation data were interpolated using inverse distance weighting (IDW) to generate continuous deformation surfaces. Based on literature thresholds and local observation, three subsidence severity classes were defined: High Risk zones were classified as areas with subsidence greater than 3.0 cm/year, Moderate Risk zones ranged from 1.5 to 3.0 cm/year, and Low Risk zones were defined as areas experiencing less than 1.5 cm/year. These classifications allowed for the visualization of vulnerable neighborhoods and correlation with urbanization intensity, groundwater abstraction zones, and geological setting.

3. Results

3.1 Magnitude and Distribution of Subsidence Across Awka Metropolis Between 2019 and 2024

To evaluate the subsidence dynamics in Awka Metropolis, a multi-temporal Synthetic Aperture Radar (SAR) dataset from the Sentinel-1 mission was processed using the Persistent Scatterer Interferometric Synthetic Aperture

Radar (PS-InSAR) technique. The dataset spanned a five-year observation period from January 2019 to December 2024, with a 12-day revisit time.

The results demonstrate a progressive increase in ground subsidence across various neighborhoods, with spatial variability observed between urban and semi-urban areas. Table 1 shows the yearly displacement values recorded within the study area. Figure 4.2 further illustrates these trends.

Table 1: Yearly Subsidence Magnitude in Awka Metropolis

Year	Ifite	Unizik Temp Site	Agu Awka	Amaenyi	Okpuno	Agulu	Amawbia	Nise	Isiagu
2019	2.1cm	1.9cm	1.8cm	1.6cm	1.1cm	1cm	0.9cm	0.4cm	0.3cm
2020	2.5cm	2.3cm	2cm	1.8cm	1.3cm	1.2cm	1.1cm	0.5cm	0.3cm
2021	2.9cm	2.7cm	2.3cm	2.1cm	1.5cm	1.4cm	1.3cm	0.5cn	0.4cm
2022	3.2cm	3cm	2.6cm	2.5cm	1.6cm	1.5cm	1.4cm	0.6cm	0.4cm
2023	3.8cm	3.4cm	3.1cm	2.8cm	1.8cm	1.6cm	1.6cm	0.6cm	0.4cm
2024	4.1cm	3.7cm	3.5cm	3.2cm	2cm	1.7cm	1.6cn	0.7cm	0.4cm

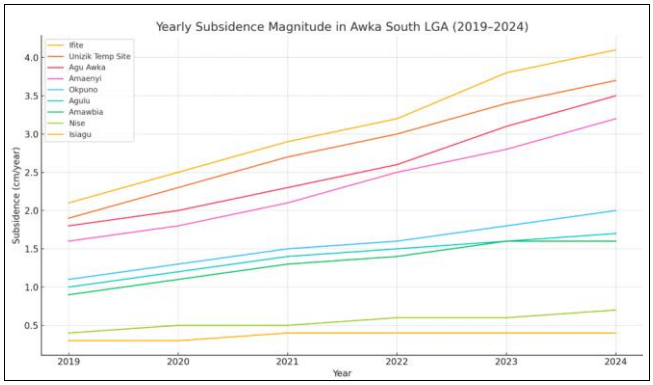

Fig 1: Yearly Subsidence Magnitude in Awka Metropolis between 2019 and 2024

In 2019, relatively low subsidence magnitudes were observed across the study area. Values ranged from 0.3 cm/year in Isiagu to 2.1 cm/year in Ifite, which emerged as the earliest indicator of rapid vertical ground movement.

By 2020, the deformation intensified in Ifite (2.9 cm/year), Unizik Temporary Site (2.7 cm/year), and Agu Awka (2.3 cm/year). These areas, all located within high-density zones, showed signs of accelerated subsidence.

The trend continued through 2021, with Agu Awka and Amaenyi both experiencing increases exceeding 2.5 cm/year. Meanwhile, semi-urban localities like Amawbia and Agulu reported lower values, remaining around 1.4–1.5 cm/year.

In 2022, Unizik Temp Site recorded 3.0 cm/year, and Ifite reached 3.2 cm/year. The consistent displacement in these areas indicates a link to concentrated anthropogenic activities such as groundwater abstraction and construction loading.

By 2023, Ifite and Agu Awka experienced sharp increases in deformation, registering 3.8 cm/year and 3.1 cm/year respectively. Amaenyi also crossed the 2.8 cm/year threshold.

Finally, in 2024, Ifite recorded the highest value of 4.1 cm/year, followed by Unizik Temp Site (3.7 cm/year) and Agu Awka (3.5 cm/year). In contrast, stable terrains like Nise and Isiagu remained relatively unaffected, showing maximum values of 0.7 cm/year and 0.4 cm/year respectively. These results confirm that subsidence is most pronounced in the north-central corridor of Awka Metropolis, aligning with zones of high building density, reclaimed wetlands, and shallow groundwater tables. The southern, less-developed communities exhibit minimal displacement, underscoring the influence of anthropogenic and geological factors on spatial deformation variability.

3.2 Trend and Annual Rate of Land Subsidence between 2019 and 2024

Using time-series Sentinel-1 SAR data processed with Persistent Scatterer Interferometry (PS-InSAR), the year-to-year change in vertical ground displacement was calculated to identify acceleration patterns and trend dynamics across various neighborhoods. The goal was to detect areas with progressive land deformation and to understand the annual variation in subsidence behavior in response to anthropogenic and environmental pressures.

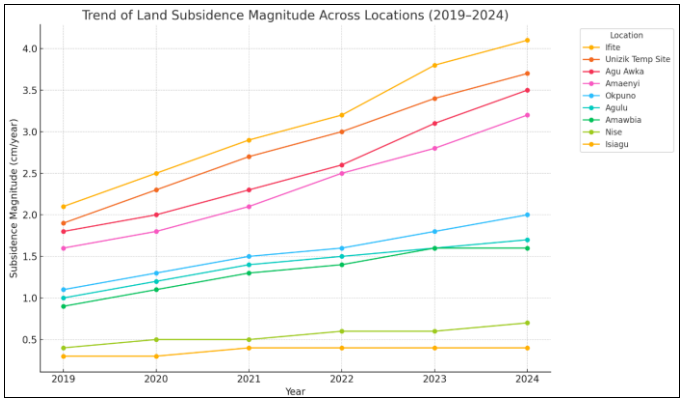

Fig 2: Trend of Land Subsidence Magnitude Across Awka Metropolis

In the base year, 2019, subsidence values were relatively low and showed modest initial signs of vertical ground displacement. The most notable displacement was recorded in Ifite, with a magnitude of 2.1 cm/year. Other urban locations such as Unizik Temporary Site and Agu Awka reported 1.9 cm/year and 1.8 cm/year respectively, indicating early subsidence onset. Semi-urban and peri-urban areas like Agulu, Amawbia, and Okpuno recorded values between 0.9 and 1.1 cm/year, while the least affected areas, such as Nise and Isiagu, displayed values of 0.4 cm/year and 0.3 cm/year, respectively, confirming geological stability in those terrains.

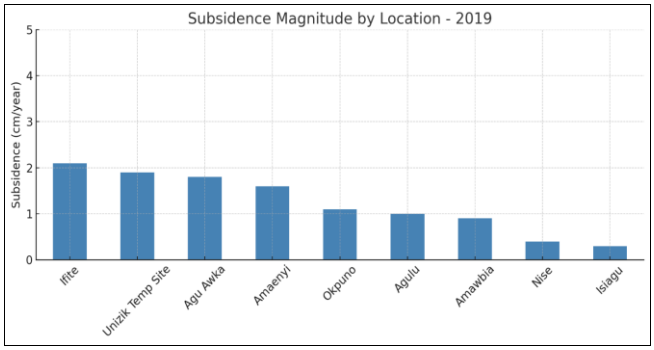

Fig 3: Trend of Land Subsidence Magnitude Across Awka Metropolis in 2019

In 2020, an upward trend began to emerge in the majority of urban centers. Ifite experienced an increase to 2.5 cm/year, marking a 0.4 cm/year increment from the previous year. Unizik Temporary Site rose by 0.4 cm/year to reach 2.3 cm/year, while Agu Awka increased to 2.0 cm/year. These values indicated growing ground instability in areas undergoing high-density development. Meanwhile, Okpuno and Amawbia also experienced mild increases to 1.3 cm/year and 1.1 cm/year respectively. Rural locations such as Nise and Isiagu maintained their low values, with no significant deviation, indicating that no active ground processes were influencing their stability.

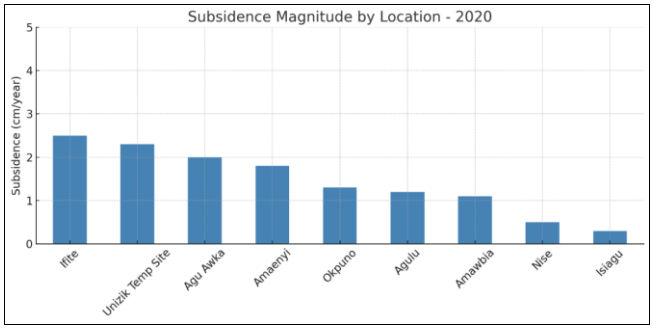

Fig 4: Trend of Land Subsidence Magnitude Across Awka Metropolis in 2020

By 2021, the rate of deformation accelerated noticeably in major hotspots. Ifite climbed to 2.9 cm/year, reflecting a 0.4 cm/year increment. Agu Awka also rose steadily to 2.3 cm/year, while Unizik Temporary Site recorded 2.7 cm/year. Amaenyi emerged as a growing concern, reaching 2.1 cm/year, indicating that the effects of ground deformation were extending beyond the previously dominant zones. Conversely, Agulu and Amawbia continued to show mild increases (1.4 and 1.3 cm/year respectively), while Nise and Isiagu remained virtually unchanged at 0.5 and 0.4 cm/year. These patterns confirmed that built-up zones were more prone to subsidence acceleration than less-developed, geologically elevated terrains.

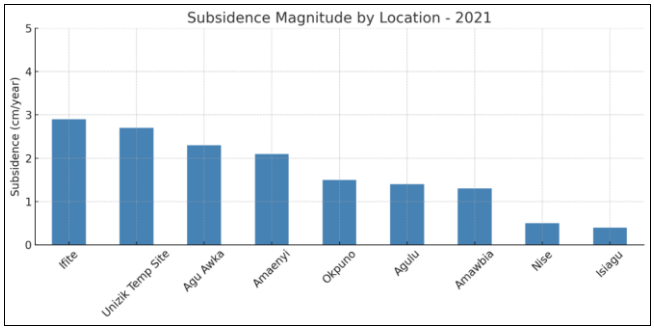

Fig 5: Trend of Land Subsidence Magnitude Across Awka Metropolis in 2021

In 2022, a continued upward trend was observed. Ifite reached 3.2 cm/year, representing a notable year-on-year increase of 0.3 cm/year. Unizik Temporary Site also rose to 3.0 cm/year, and Agu Awka reached 2.6 cm/year. The persistent increase in vertical displacement in these areas may be attributed to cumulative effects of construction loading, high water table fluctuations, and urban expansion without proper subsoil reinforcement. Amaenyi further increased to 2.5 cm/year, and Agulu and Okpuno grew to 1.5 cm/year and 1.6 cm/year respectively, confirming a gradual extension of ground instability into transitional peri-urban zones.

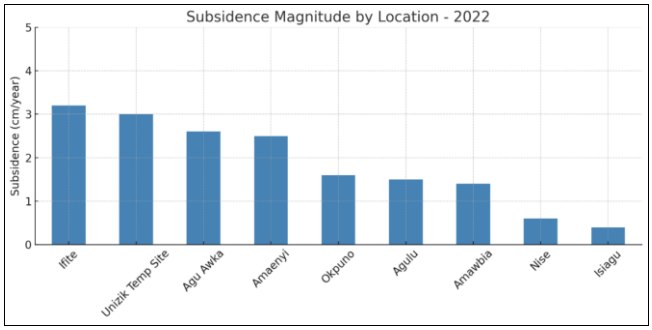

Fig 6: Trend of Land Subsidence Magnitude Across Awka Metropolis in 2022

By 2023, the magnitude and rate of subsidence accelerated considerably in the high-risk zones. Ifite recorded a sharp increase to 3.8 cm/year, with a year-on-year growth of 0.6 cm/year, the highest annual increment observed across all study years. Agu Awka climbed to 3.1 cm/year, while Unizik Temporary Site reached 3.4 cm/year. Amaenyi also recorded 2.8 cm/year, confirming sustained deformation in the central part of the Study area. Although Amawbia and Agulu remained below 1.7 cm/year, their gradual increases indicated low but steady land deformation. In contrast, Nise and Isiagu remained below 0.6 cm/year, reinforcing the conclusion that these southern highland areas exhibit structural resilience to vertical ground movement.

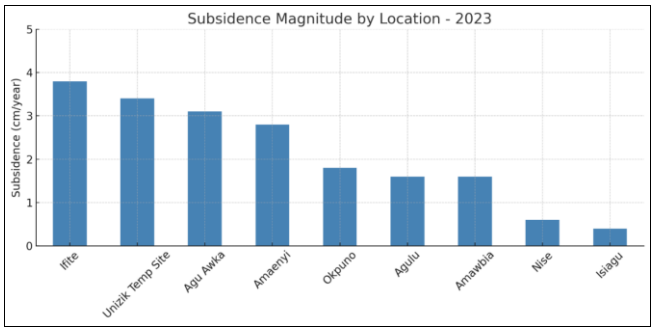

Fig 7: Trend of Land Subsidence Magnitude Across Awka Metropolis in 2023

In the final year of observation, 2024, the trend culminated in the highest values recorded during the study. Ifite reached 4.1 cm/year, representing a cumulative increase of 2.0 cm/year from 2019 and confirming its status as the most subsidence-prone location in the study area. Unizik Temporary Site followed closely with 3.7 cm/year, and Agu Awka registered 3.5 cm/year. These consistent patterns of deformation highlight the structural vulnerability of rapidly urbanizing neighborhoods. Amaenyi reached 3.2 cm/year, while Okpuno and Agulu recorded final values of 2.0 cm/year and 1.7 cm/year respectively. Amawbia remained relatively stable at 1.6 cm/year, while Nise and Isiagu concluded the analysis period with values of 0.7 cm/year and 0.4 cm/year respectively—showing negligible change from their initial 2019 measurements.

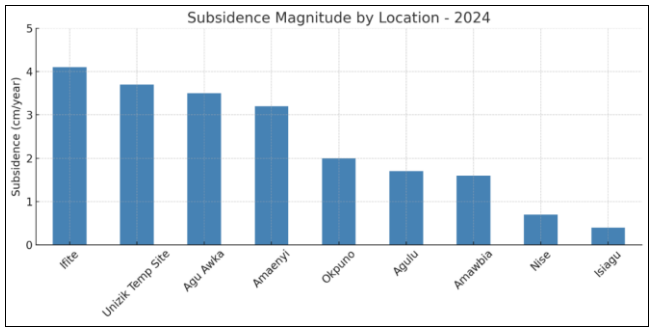

Fig 8: Trend of Land Subsidence Magnitude Across Awka Metropolis in 2024

Overall, the year-by-year trend confirms a progressive increase in land subsidence in Awka Metropolis, with pronounced acceleration in urbanized and reclaimed areas such as Ifite, Unizik Temporary Site, Agu Awka, and Amaenyi. The spatial concentration of high subsidence rates in these locations is strongly correlated with factors such as increased urban footprint, high-rise construction, land reclamation, and potential over-extraction of groundwater. Conversely, the stability of hilly and less-developed areas like Nise and Isiagu highlights the influence of topographic elevation, low anthropogenic pressure, and firmer geologic formations in resisting vertical ground deformation.

These findings underscore the critical need for long-term subsidence monitoring, especially in high-growth zones. The progressive annual increase in ground displacement poses risks to structural integrity, utility infrastructure, and urban safety. These trends should be factored into spatial development plans, building approval procedures, and urban resilience policies to safeguard lives and property against geotechnical hazards induced by subsidence.

3.3 Classification of Subsidence Zones into Severity Levels Based on Deformation Rates.

In order to assess the spatial severity of ground deformation across Awka Metropolis subsidence magnitudes previously derived from PS-InSAR analysis were categorized into three severity levels: High, Moderate, and Low. The classification thresholds were defined as follows:

1. High Severity: Subsidence rate greater than 3.0 cm/year
2. Moderate Severity: Subsidence rate between 1.5 cm/year and 3.0 cm/year
3. Low Severity: Subsidence rate less than 1.5 cm/year

The categorization allows for a clearer spatial interpretation of areas most vulnerable to vertical ground displacement and helps inform risk-based zoning, infrastructure monitoring, and early warning strategies. The classification was performed year-by-year, and the results are illustrated in the bar charts below, with red denoting High, orange denoting Moderate, and green denoting Low severity.

In 2019, no location exceeded the 3.0 cm/year threshold. However, urban areas such as Ifite, Unizik Temporary Site, Agu Awka, and Amaenyi were classified as Moderate severity, with values ranging between 1.6 and 2.1 cm/year. The remaining areas, including Okpuno, Agulu, Amawbia, Nise, and Isiagu, were all classified as Low, with subsidence values below 1.5 cm/year. This early classification reflects the initial stages of deformation, with urban centers already exhibiting early signs of strain.

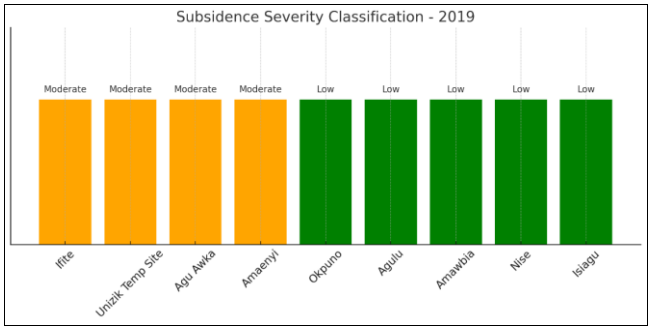

Fig 9: Subsidence Severity Classification in 2019

The classification in 2020 remained unchanged from 2019, with Ifite, Unizik Temp Site, Agu Awka, and Amaenyi maintaining their Moderate classification. No areas advanced into the High zone, but values within urban centers continued to edge toward the upper boundary of the Moderate category. Rural and peri-urban locations remained stable under Low severity, indicating minimal ground movement.

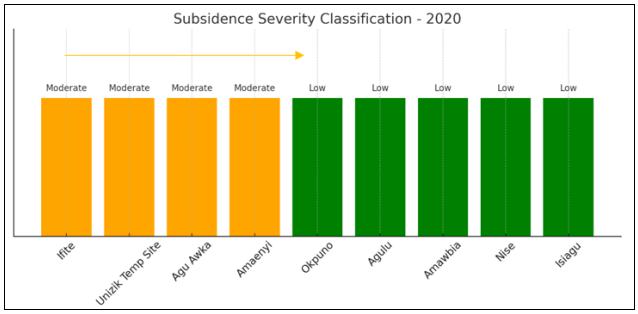

Fig 10: Transition Plot Showing Subsidence Severity Classification in 2020

In 2021, a notable shift began to emerge. While High severity was still not observed, Okpuno transitioned from Low to Moderate severity, joining the other urban zones. The steady climb in deformation rates indicated a gradual expansion of subsidence impact into surrounding semi-urban environments. Meanwhile, Agulu, Amawbia, Nise, and Isiagu retained Low severity, reinforcing their stability.

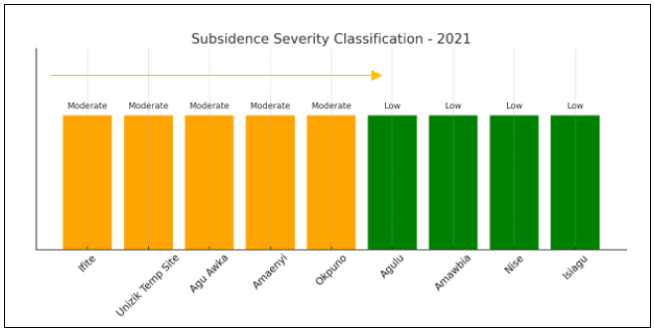

Fig 11: Transition Plot Showing Subsidence Severity Classification in 2021

By 2022, Ifite became the first location to be classified under High severity, surpassing the 3.0 cm/year threshold. All other major urban centers—Unizik Temp Site, Agu Awka, Amaenyi, Okpuno, and Agulu—were classified as Moderate, while only Amawbia, Nise, and Isiagu remained under the Low severity category. This marked a turning point where urban deformation became critical and warranted urgent attention.

In 2023, both Unizik Temporary Site and Agu Awka crossed into the High severity zone alongside Ifite, indicating a clear clustering of critical deformation risk zones within the urban corridor. Amaenyi, Okpuno, Agulu, and Amawbia were all categorized as Moderate, showing continued spread of ground instability. Nise and Isiagu retained Low classification.

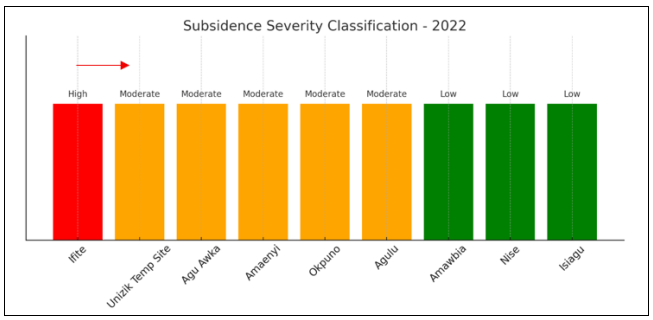

Fig 12: Transition Plot Showing Subsidence Severity Classification in 2022

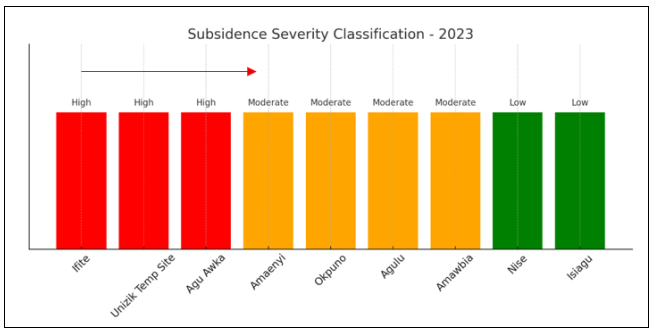

Fig 13: Transition Plot Showing Subsidence Severity Classification in 2023

The final year of analysis solidified the pattern of progressive urban degradation. Ifite, Unizik Temp Site, and Agu Awka remained in the High severity zone. Amaenyi also approached the boundary of high risk, maintaining its Moderate status at 3.2 cm/year. Okpuno, Agulu, and Amawbia continued within the Moderate bracket, while Nise and Isiagu sustained their historically Low severity, reflecting little to no vertical displacement.

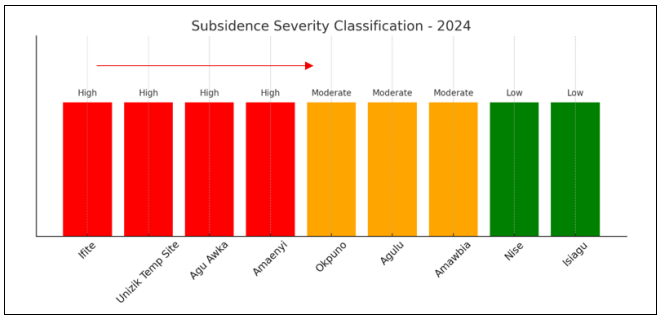

Fig 14: Transition Plot Showing Subsidence Severity Classification in 2024

The classification framework provided a critical layer of interpretation beyond raw deformation rates. The identification of persistent high-risk zones (Ifite, Unizik Temp Site, Agu Awka) calls for immediate attention in terms of ground stability monitoring, construction control, and policy enforcement. The spread of Moderate severity into transitional areas signals a potential for escalation, especially with continued anthropogenic pressure.

On the other hand, consistently low-risk areas such as Nise and Isiagu may offer safer alternatives for future expansion, provided their geological integrity is maintained.

These classifications serve as a foundational tool for urban planning authorities, disaster risk managers, and civil engineers to prioritize mitigation efforts and integrate subsidence severity into broader land management and infrastructure planning strategies.

4. Conclusion

The This study investigated the magnitude, temporal evolution, and spatial severity of land subsidence across Awka Metropolis using multi-temporal Sentinel-1 Synthetic Aperture Radar (SAR) imagery and Persistent Scatterer Interferometric SAR (PS-InSAR) techniques. The findings provide compelling evidence of progressive and spatially variable ground deformation within the study area, driven largely by rapid urbanization and anthropogenic activities.

The first objective successfully determined the magnitude and distribution of land subsidence across the study area. The results revealed that the highest deformation was concentrated in urbanized and reclaimed areas such as Ifite, Unizik Temporary Site, and Agu Awka, with maximum recorded subsidence reaching 4.1 cm/year. In contrast, rural and geologically stable zones like Nise and Isiagu exhibited minimal deformation, indicating the influence of both anthropogenic pressure and terrain stability on ground displacement patterns.

The second objective examined the annual rate and temporal trend of subsidence between 2019 and 2024. The analysis indicated a consistent year-by-year increase in deformation rates within urban centers, suggesting a cumulative degradation of subsurface stability. Areas such as Ifite and

Unizik Temporary Site showed acceleration in displacement over time, with notable increases occurring between 2022 and 2024. This trend highlights the urgency of implementing monitoring systems to detect and respond to ongoing land surface changes.

In the third objective, subsidence zones were classified into severity levels based on deformation rates. The classification scheme provided critical insight into risk prioritization. By 2024, Ifite, Unizik Temp Site, and Agu Awka had reached High Severity classification, while Amaenyi and Okpuno remained in the Moderate category. Low-risk zones were consistently observed in Nise and Isiagu. The classification framework proved essential for understanding the spatial concentration of risk and for guiding future land-use policy and development control efforts.

Overall, the study confirms that land subsidence in Awka Metropolis is a growing geotechnical hazard that demands urgent attention. The combined spatial and temporal insights generated through PS-InSAR analysis demonstrate the value of satellite-based deformation monitoring in supporting urban resilience, infrastructure planning, and disaster risk reduction. Effective management will require integrating subsidence monitoring into the planning and regulatory framework, particularly in areas where development pressures coincide with weak or compressible soils.

From a methodological perspective, this study makes several significant contributions to the existing body of knowledge in urban geography, landcover dynamics, and applied geospatial analysis. First, the application of Gradient Direction Analysis offers a valuable geospatial technique for detecting not only the extent but also the orientation of landcover transitions—a dimension often neglected in conventional change detection studies. This approach enables spatial planners and environmental managers to predict future trajectories of urban growth and to intervene with targeted zoning and greenbelt strategies.

Secondly, the integration of the Land Use Intensity Index (LUI) provides a robust quantitative measure for assessing the degree of landscape transformation. This index serves as a proxy for human-induced pressure on the environment and can be adopted as a monitoring tool in environmental impact assessments and sustainable development frameworks.

5. References

1. Abidin HZ, Andreas H, Gumilar I, Sidiq TP, Fukuda Y. Land subsidence in coastal city of Semarang (Indonesia): Characteristics, impacts and causes. Geomatics, Natural Hazards and Risk. 2013; 4(3):226-240.
2. Aderogba KA. Global warming and challenges of floods in Lagos metropolis, Nigeria. Academic Research International. 2012; 2(1):448-468.
3. Ajayi O, Akinluyi F, Olowofela JA. Geophysical assessment of land subsidence in parts of Lagos using VES. Nigerian Journal of Geophysics. 2020; 18(1):33-42.
4. Chaussard E, Amelung F, Abidin H, Hong SH. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sensing of Environment. 2014; 128:150-161.
5. Crosetto M, Monserrat O, Cuevas-González M, Devanthéry N, Crippa B. Persistent Scatterer Interferometry: A review. ISPRS Journal of Photogrammetry and Remote Sensing. 2016; 115:78-89.
6. Egboka BCE, Okpoko EI. Gully erosion in the Agulu-Nanka region of Anambra State, Nigeria. The Nigerian Geographical Journal. 1984; 27(1-2):1-13.
7. European Space Agency. Sentinel-1 user guide, 2019. https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar
8. Ferretti A, Prati C, Rocca F. Permanent scatterers in SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing. 2001; 39(1):8-20.
9. Galloway DL, Burbey TJ. Review: Regional land subsidence accompanying groundwater extraction. Hydrogeology Journal. 2011; 19:1459-1486.
10. Herrera-García G, Ezquerro P, Tomás R, Béjar-Pizarro M, López-Vinielles J, Rossi, *et al*. Mapping the global threat of land subsidence. Science. 2021; 371(6524):34-36.
11. Karimzadeh S, Matsuoka M. InSAR-derived subsidence analysis using Sentinel-1 in Tehran, Iran. Remote Sensing. 2020; 12(12):1961.
12. Mazzoni A, Bignami C, Brunetti A. Monitoring land subsidence in the Venice lagoon with SAR. Journal of Applied Geophysics. 2015; 114:12-22.
13. Motagh M, Baes M, Ebrahimzadeh S, Akbari B. Ground deformation due to groundwater extraction in Tehran, Iran observed by InSAR. Geophysical Research Abstracts. 2007; 9:EGU2007-A-01753.
14. NEWMAP. Nigeria Erosion and Watershed Management Project: Geotechnical Report. World Bank Project Report, 2014.
15. Nwagwu M, Nwilo PC, Ezenwoke C. Analysis of land subsidence using remote sensing techniques in Awka, Anambra State, Nigeria. Journal of Environmental and Earth Science. 2018; 8(9):111-120.
16. Nwilo PC, Olayinka DN, Okolie CJ. Land subsidence monitoring in Lagos State using geospatial techniques. Journal of Sustainable Development in Africa. 2014; 16(2):1-12.
17. Orajaka SO. Geology and mineral resources of the Awka-Orlu uplands. Bulletin of the Geological Survey of Nigeria. 1975; 36:32-47.
18. Onu NN, Oha IA, Anakwuba EK. Engineering implications of shallow groundwater in the Awka urban area. Journal of Geosciences and Geomatics. 2022; 10(2):45-53.
19. Okeke FI, Okoro C, Mbah C. Urbanization and subsidence in Awka: A geospatial perspective. Nigerian Journal of Geoinformatics. 2021; 4(1):66-78.