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Multi-Temporal SBAS InSAR Technique for Monitoring and Assessing Land Instability for Sustainable Construction: A Case Study of El-Qantarah Gharb, Northwestern Ismailia District, Egypt

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Abstract

A detailed multi-temporal interferometric analysis was carried out at El-Qantarah Gharb in the northwestern Ismailia District, Egypt. Ground instability issues, particularly land subsidence, are understudied in this area despite its significance. The study applies the advanced Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) technique to address this gap using Sentinel-1 SAR data from May 2017 to August 2022. The analysis, performed with GAMMA RS software, integrates ascending and descending orbit data to evaluate movement patterns comprehensively. The findings show significant westward displacement across the majority of the region, with a low rate in the south and more dynamic subsidence in the north, where velocities reach up to 10 mm per year. Localized subsidence was observed in western, central, and Suez Canal-adjacent zones, with descending geometries showing lower values due to observational dependencies. This research highlights the precision of the SBAS-InSAR technique for mapping and monitoring subsidence and uplift, offering critical insights into instable zones. The results support the development of targeted mitigation strategies to minimize risks, enhance structural resilience, and promote sustainable planning for the region’s economic growth.

Introduction

El-Qantarah Gharb area is situated in the northwestern region of the Ismailia District, west of the Suez Canal, and is geographically defined by latitudes 30° 42' 30" N to 30° 49' 31" N and longitudes 32° 07' 00" E to 32° 19' 31" E (Figure 1). This strategically located area forms a critical part of Egypt's vision for sustainable development under the 2030 Egyptian Sustainable Development Strategy. This strategy emphasizes three interconnected dimensions-economic growth, societal inclusion, and environmental sustainability, as outlined in the national voluntary review on the sustainable development goals [1].

Within this framework, the Suez Canal Corridor emerges as a cornerstone of national development, incorporating agricultural expansion, industrial zones, and establishment of modern urban communities. Given the scale and significance of these projects, expanding infrastructure and construction activities in this region necessitates precise and efficient site evaluation. Comprehensive multi-temporal interferometric and feasibility studies are imperative to ensure the successful implementation of these initiatives and to create opportunities for both national and international investors to participate in these transformative projects.

Without up-to-date and accurate techniques to assess the soil conditions where major infrastructure projects are planned, various engineering issues may arise, including land subsidence, which can lead to structural cracks, collapses, and significant financial costs. An assessment of the different degrees of degradation in the investigated area has been carried out by integrating remote sensing, in particular, SBAS-SAR interferometry techniques, as well as GIS, and the Global Assessment of Soil Degradation (GLASOD) approach.

Mitigating the effects of ground instability in urban areas is a critical research field. One of the primary objectives is to predict this instability in both time and space, thus allowing for proactive measures to prevent damage. Advanced technologies, such as Synthetic Aperture Radar (SAR), offer significant improvements in measuring displacement with millimeter-level accuracy. SAR, a satellite-based remote sensing tool, uses microwave radiation to capture both the intensity and phase of returned signals, providing detailed data that can be applied to urban planning. This data proves invaluable for local authorities and city planners in reducing risks associated with urban development and in designing more effective strategies for future city growth [2].

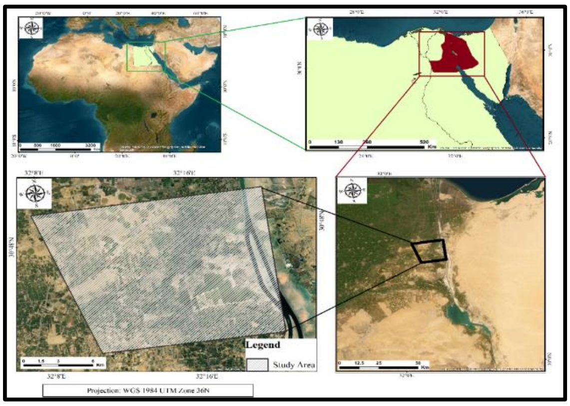

Figure 1 Location map of the study area.

Particularly, the Small Baseline Subset (SBAS) InSAR technique [3]; [4], [5]. was employed to monitor and detect high-resolution ground displacement in the Qantarah Gharb area, using the Single Look Complex (SLC) format at the local scale, this technique achieved a spatial resolution of 5m*5m, providing detailed insights into ground movement.

Despite the region's strategic significance for future construction projects, there is a limited body of work on soil stability and ground instability in this area. The most relevant study utilizing SAR interferometry in ground instability monitoring in the present study area was conducted by [6]. This research focused on combining SAR data with geotechnical information to monitor ground instability across the Ismailia District, including the study area. Their findings indicated that ground instability in this region is primarily influenced by three factors: the depth to groundwater, the thickness of the clayey layer, and the soil's swelling potential. Areas prone to instability, such as El-Ferdan and Al-Mostaqbal, exhibited shallow groundwater levels, a thin clayey layer, and high swelling potential. The study underscored the need for continuous monitoring of these regions, given the ongoing trend of ground instability, making it highly relevant to the application of the SBAS technique in the current research.

Geology

The area is primarily composed of Quaternary sediments, including sands, gravel, and occasional clay lenses [7] (Figure 2). [8] conducted an extensive study of the Late Pleistocene and Holocene lithofacies in the northeastern Delta, which includes the study area. The most recent Quaternary deposits consist of sand dunes, clay and sandy clay around sabkha deposits, Nile River sediments, and undifferentiated Quaternary materials such as gravel, alluvial deposits from river valleys, and beach sands with corals from the Mediterranean Sea.

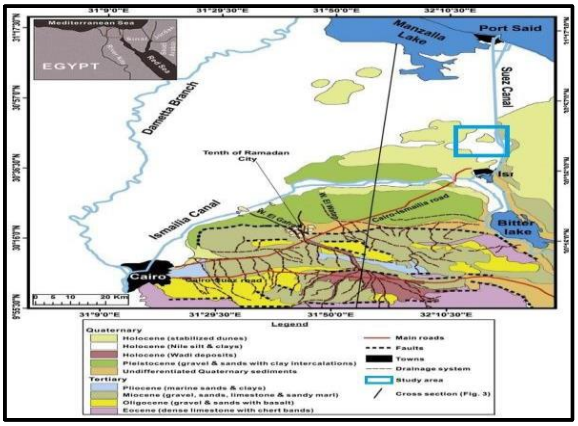

Figure 2 Geological map of the eastern Nile Delta including the study area [43]; [44], [45].

Holocene deposits, including alluvial and fluvial sediments, are also present and have been transported and deposited by the rivers in the Nile Delta and surrounding regions. These sediments, typically a mixture of sand, silt, and clay, are often rich in organic matter [9]. In the northwestern part of Ismailia district, fluvial sediments, consisting of silt, sand, gravel, and clay up to 40 m. in thickness, are found along the Nile River valley [9]. Saline alluvial deposits, consisting of argillaceous and sandy sediments with soluble salts, are located in depressions and low-lying coastal areas [10].

Other types of alluvium in the region include poorly sorted gravel, sand, silt, and clay deposits from alluvial fans as well as deltaic deposits at the mouths of the Nile containing sand, silt, and clay. The alluvial fan deposits, formed by fluvial processes, were sourced from various upstream locations. The gravel content increases toward the base of the aquifer, indicating proximity to the source areas in the southern region [11].; [12].

The sabkhas in the Suez Canal region, described by [13], consist of sand, mud, organic matter, and calcium carbonate, which serves as a cementing agent in the study area. These flat formations, with reliefs ranging from 10 to 50 cm, form in arid climates and are influenced by factors such as rainfall and temperature. Although the surface of a sabkha is not a free-water surface, groundwater rarely exceeds a depth of 1.5 meters and flows toward the sea, being replenished by seawater [14]; [15].

Tectonic activity plays a major role in shaping the geo-environmental characteristics of the study area through interactions between fault systems, geological formations, and tectonic movements. This influence is attributed to the area's location within the

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Northern Nile Delta structural province. Subsurface fault groups are predominantly oriented in an E-W direction and are characterized by normal faulting, formed during the rifting of the African-Arabian plate from the Eurasian plate in the Late Triassic to Early Jurassic period [16]. Over time, these faults have undergone reactivation, resulting in the deformation of Upper Cretaceous and Tertiary rock formations [17]. At the surface, structural lineaments are primarily aligned in an NW-SE direction, with fewer features trending NNW-SSE. These alignments represent the northern extension of the Gulf of Suez graben [18], as portrayed in Figure (3).

Data and methodology

This study employed cost-free, open-access C-band SAR data from the Sentinel-1 satellite constellation, provided by the Alaska Satellite Facility (ASF) DAAC platform, to perform interferometric analysis. A total of 157 Sentinel-1A images from the ascending pass and 135 Sentinel-1A and Sentinel-1B images from the descending pass, covering the period from May 2017 to August 2022, were analyzed, with Frame 95 (ascending) and Frame 491 (descending) highlighted. The Sentinel-1 satellites, developed by the European Space Agency (ESA) under the Copernicus Program, consist of Sentinel-1A, Sentinel-1B, and Sentinel-1C, which enhance Earth observation with C-band SAR instruments operating at a frequency of 5.405 GHz. These satellites provide continuous imaging capabilities in all weather conditions, day and night, with single and dual-polarization modes for diverse applications [19]; [20]; [21]; [22].

The Shuttle Radar Topography Mission (SRTM), a collaboration between NASA and the [23], supplied digital elevation data with a resolution of 30 meters, freely available in GeoTIFF format via the USGS Earth Explorer platform.

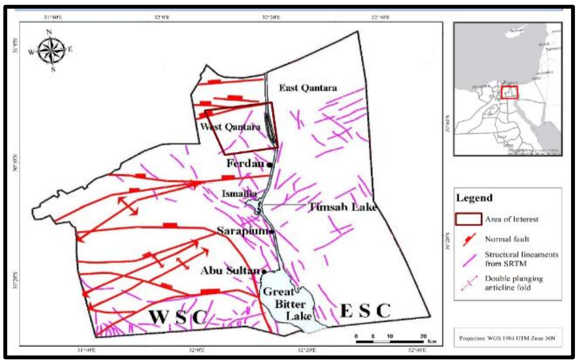

Figure 3 Tectonics of the study area (based on [17], [6].

This data was corrected, void-filled, and geographically projected, ensuring global coverage for use in conjunction with SBAS interferometry in the study area [24]; [25]. For processing, GAMMA RS software, developed by GAMMA Remote Sensing Research and Consulting AG, was used on a Linux system. This advanced toolbox, with its SBAS interferometry module, enabled time-series analysis of surface changes and the creation of deformation maps [26]; [3]. The integration of these datasets and technologies facilitated detailed monitoring and assessment of ground instability El-Qantarah Gharb area.

InSAR image processing

The maps of both the ascending and descending movement rates (velocities) are displayed in Figure (4). Positive values, with cool colors, demonstrate movement towards the sensor, while negative values, with warm colors, demonstrate movement away from the sensor. The obtained results exhibit scattered displacement patterns, which can be primarily attributed to the presence of vegetation. This vegetation has passive impact on the coherence of the SAR images, leading to partial or complete decorrelation in certain blank locations. These blank regions indicate missing data, which is a direct consequence of the decoherence caused by vegetation in those areas.

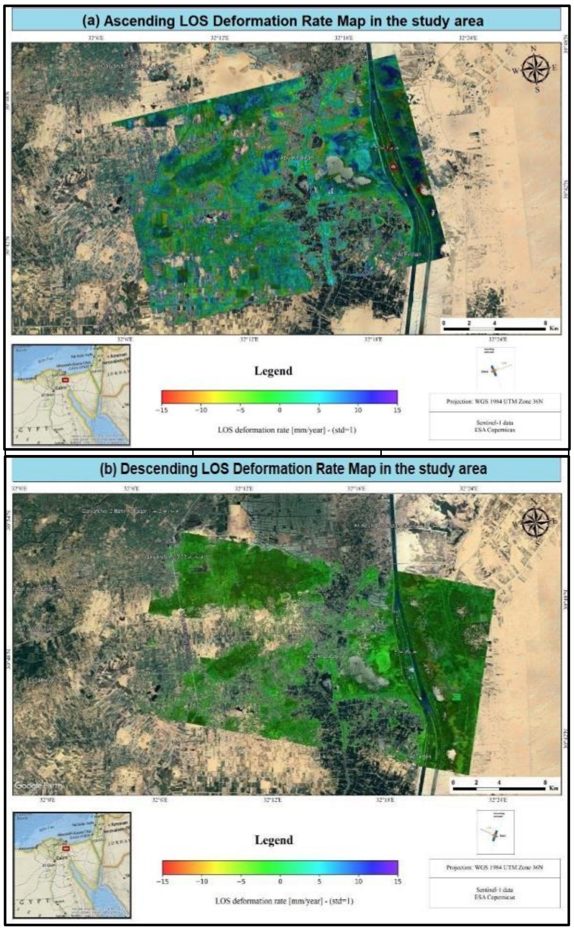

Figure 4 Sentinel-1 average LOS movement rate maps over the period from May 2017 to August 2022 for ascending (a) and descending (b) acquisition geometries in the arid area in El- Qantarah Gharb area.

Urban planning and management utilizing the Interferometric Synthetic Aperture Radar (InSAR) technique has proven to be an effective approach. Geospatial analysis through these methods has demonstrated success in predicting ground movement and identifying locations prone to geotechnical issues. Specifically, Line-of-Sight (LOS) motion rates were analyzed in eight distinct areas of the study region for ascending acquisition and in five areas for descending acquisition, covering the period from May 2017 to August 2022 (Figures 5 & 6). The average LOS displacement rate maps, derived over five years for descending acquisition, highlight spatio-temporal ground movement patterns in the arid region of El-Qantarah Gharb, along with the selected affected areas.

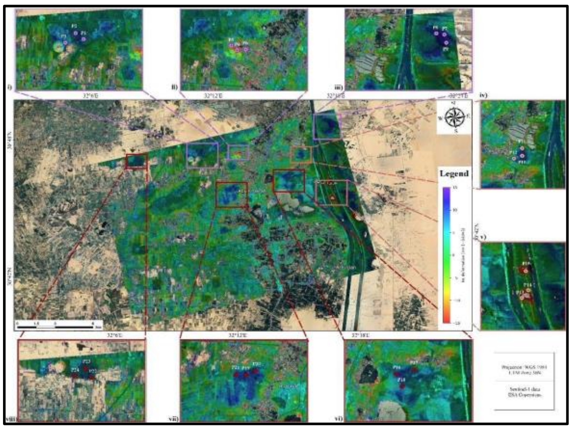

Figure. 5 Average LOS displacement rate map over a 5-year period for ascending acquisition geometry in the arid area in El-Qantarah Gharb area and selected distinct parts where spatio-temporal ground movements were detected.

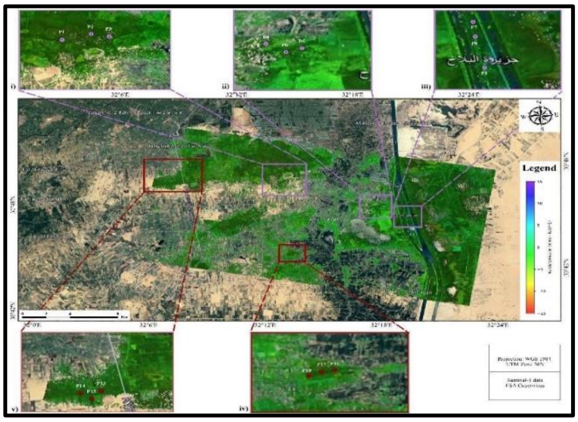

Figure 6. Average LOS displacement rate map over a 5-year period for descending acquisition geometry in the arid area in El-Qantarah Gharb and selected distinct parts where spatio-temporal ground movements were detected.

The maps of both the East-West (horizontal) and Up-Down (vertical) displacement rates (velocities) are displayed in Figure (7). In the up-down map, positive values, with cool colors, signify the ground surface is moving upwards over time, while negative values, with warm colors, in the vertical map denote the surface is subsiding downwards. Examining the east-west horizontal velocities, positive rates reflect eastward movement across the surface, while negative rates indicate westward motion. The maps identify nine distinct areas within the study region, both in the East-West (horizontal) and Up-Down (vertical) displacement rate maps, as shown in Figure (8).

Table (1) provides a summary of the East-West (horizontal) movement rates across nine distinct areas in the study region, detailing their corresponding locations. Negative values indicate westward movement, such as the Northernmost Sector with -18.5 mm/year, while positive values reflect eastward motion, like the Suez Canal Bifurcation with +28.4 mm/year. Table (2) summarizes the Up-Down (vertical) movement rates, where positive values represent upward movement (e.g., +9.1 mm/year in the Northernmost Sector) and negative values signify subsidence (for example: -22.9 mm/year near the Suez Canal Bifurcation).

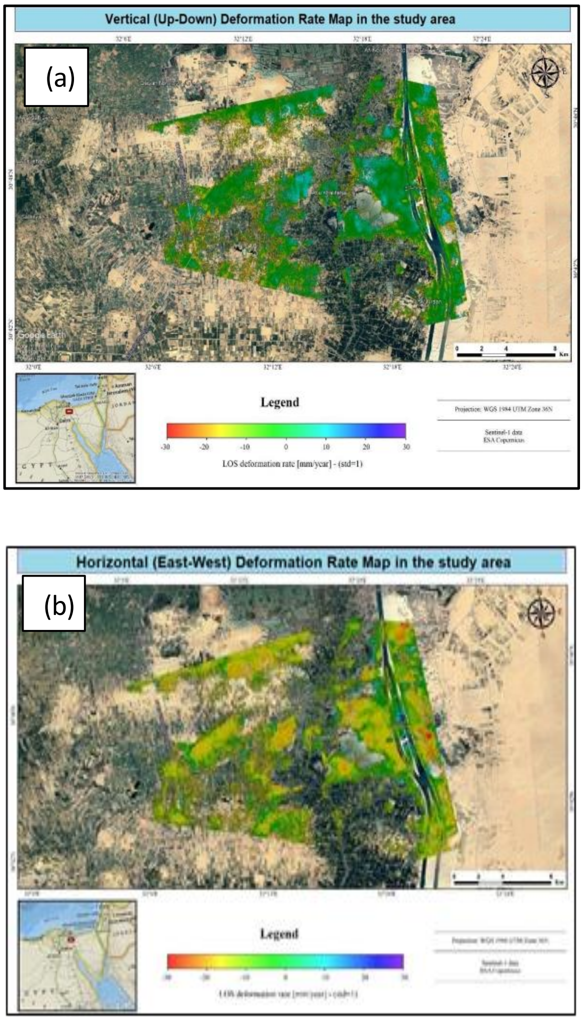

Figure 7 (a) Up-Down (vertical) and (b) East-West (horizontal) displacement rate maps overthe period from May 2017 to August 2022 in the arid area in El-Qantarah Gharb.

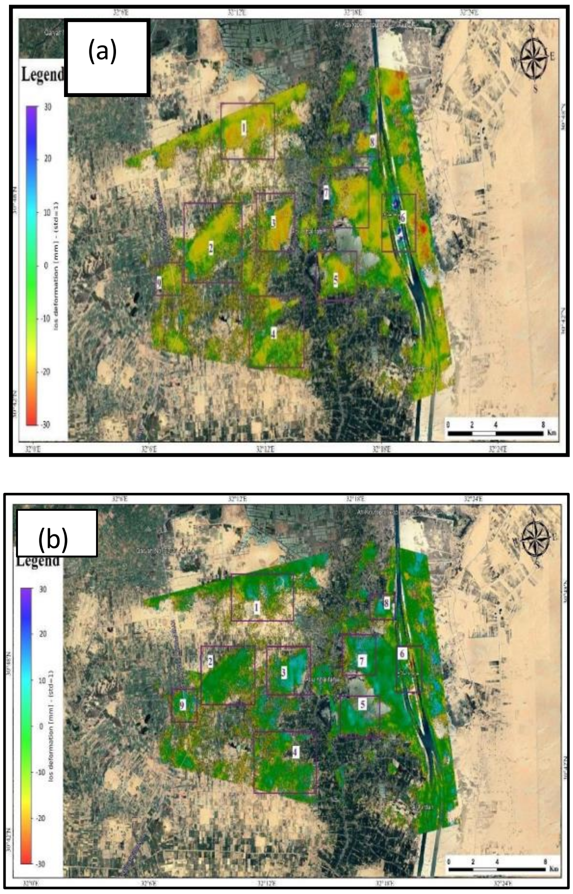

Figure 8 (a) East-West (horizontal) and (b) Up-Down (vertical) displacement rate maps over the 5- year time-span from in the arid area in El-Qantarah Gharb and selected distinct parts spatial and temporal patterns of ground motion were observed over the monitoring period.

Table 1 The summary of East-West (Horizontal) movement rates and the corresponding sites.

Site	Location	Average movement rate (mm/y)	Motion
1	Northernmost Sector	-18.5	Westward (Negative)
2	Western Periphery	-8	Westward (Negative)
3	Central Region	-13	Westward (Negative)
4	Southernmost Region	-11.6	Westward (Negative)
5	Central-Eastern Region	-10.5	Westward (Negative)
6	Suez Canal Bifurcation	+28.4	Eastward (Positive)
7	Central-Eastern Region	-11.8	Westward (Negative)
8	Near the Suez Canal	-14.2	Westward (Negative)
9	Western Periphery	-12	Westward (Negative)

Table 2. The summary of Up-Down (vertical) movement rates and the corresponding sites.

Site	Sites	Maximum movement rate (mm/y)	Motion
1	Northernmost Sector	+9.1	Upward (Positive)
2	Western Periphery	+6.5	Upward (Positive)
2	Western Periphery	-12.3	Downward (Negative)
3	Central Region	+7.2	Upward (Positive)
4	Southernmost Region	+6	Upward (Positive)
5	Central-Eastern Region	+5.7	Upward (Positive)
6	Suez Canal Bifurcation	-22.9	Downward (Negative)
6	Suez Canal Bifurcation	+5.9	Upward (Positive)
7	Central-Eastern Region	+5.6	Upward (Positive)
8	Near the Suez Canal	+5.3	Upward (Positive)
9	Western Periphery	+7.8	Upward (Positive)

Discussion

The analysis was carried out using the SBAS InSAR technique, and the results show varying rates of ground instability across El-Qantarah Gharb area. Where, some sites exhibite significant subsidence rates of up to -22.9 mm/year, particularly near the Suez Canal, while others such as the northern part displays uplift rates reaching +9.1 mm/year. The sites which show a significant subsidence rate include the northernmost part (-18.5 mm/year), western part (-8 mm/year to -12 mm/year), central part (-13 mm/year), southernmost part (-11.6 mm/year), central-eastern part (-10.5 mm/year and -11.8 mm/year), near the Suez Canal (-14.2 mm/year), and the Suez Canal bifurcation, which exhibited the highest instability with subsidence reaching -22.9 mm/year and localized uplift up to +5.9 mm/year. In agricultural and sabkha areas, uplift rates reached +9.1 mm/year in the northernmost part and +7.8 mm/year in the western part.

The observed subsidence/uplift patterns are clearly affected by geological, hydrological, and anthropogenic factors. Geological factors include the presence of clay layers, intercalated with the subsurface soil section, which have high swelling and shrinkage potential. The study area primarily consists of Quaternary deposits, including sabkha deposits, Nile River sediments, and undifferentiated deposits like river valley alluvium and beach sands [9]. These formations, characterized by interbedded sands, silts, and clays, are prone to differential compaction and settlement, resulting in gradual subsidence over time

[27]. Clayey layers exhibit high plasticity and significant swelling potential due to their montmorillonite content, making them particularly vulnerable to instability [28]; [29]; [30].

Sandstorms are another significant geological factor which are greatly affecting the ground instability. These natural events, common in desert regions like the Suez Canal area, which led to transportion and deposition of large volumes of sand and dust. The deposition of these windblown sediments during sandstorms contributes to temporary ground uplift, as observed in areas like northwestern Ismailia [31]; [32]; [33]. Conversely, wind erosion in source regions causes surface lowering, creating a dynamic landscape of uplift and subsidence.

Hydrological factors are represented by the fluctuations of the groundwater level and waterlogging causing structural disturbances. Waterlogging contribute to the land instability by increasing pore water pressure, which enhances moisture content and induces sediment compaction and consolidation([34]. Additionally, a continuous rise in groundwater level may result in liquefaction failure [35]. Also, fluctuations in the groundwater level can cause clayey layers to undergo swelling and shrinkage cycles, damaging infrastructure and buildings [36]. Excessive groundwater extraction near the Suez Canal leads to soil compaction and settlement, whereas groundwater recharge and salt accumulation in agricultural zones contribute to surface expansion. In agricultural zones, the accumulation of dissolved salts in sabkha areas contributes to soil compression and infrastructure damage. Sabkhas, or salt flats, further complicate ground stability. The accumulation of evaporite minerals and groundwater recharge in these areas can lead to subsidence, particularly in agricultural zones, causing damage to infrastructure and loss of coastal properties [37]; [38].

Finally, the anthropogenic factors are exemplified by the human activities such as urban expansion and resource exploitation, particularly near the Suez Canal. Studies by [39], [40], [41], and [42] attribute subsidence primarily to the weight of modern and historical construction on these loose sediments, which compress over time. Additionally, canal construction and maintenance activities, including material removal or deposition, and groundwater extraction, influence local stress fields and exacerbate subsidence.

On the other hand, stable areas include the south, where minimal movement rate (<5 mm/year) and this can be attributed to the presence of coarser sandy deposits that ensure relative stability. Similarly, the central and east-central regions show horizontal movement rates up to 5 mm/year, reflecting moderate stability which can be explained by the presence of mixed deposits with lower compressibility.

The interplay of lithology, groundwater level fluctuations, aeolian processes, and human activities are effective factors on subsidence and uplift rates recorded by the SBAS-InSAR technique. Hence, it is strongly recommended to carryout a detail geotechnical investigation in the study area to evaluate the appropriateness of soil for construction and urban expansion.

Conclusions

This study highlights critical findings regarding ground instability in El-Qantarah Gharb area, where, some sites exhibits significant subsidence rates of up to -22.9 mm/year. Agricultural and sabkha areas display uplift rates reached +9.1 mm/year in the northernmost part and +7.8 mm/year in the western part. On the other hand, stable areas include the south, where minimal movement rate (<5 mm/year), the central and east-central regions which show horizontal movement rates up to 5 mm/year.

The subsidence/uplift rates in the region are influenced by geological, hydrological, and anthropogenic factors. The highest rates of land subsidence are concentrated near the Suez Canal due to excessive groundwater extraction and construction activities that alter soil stress conditions, while uplift is observed in agricultural and sabkha areas, attributed to groundwater recharge and salt accumulation. Geological factors play a crucial role, with compressible clay-rich sediments increasing vulnerability to subsidence, whereas sandy deposits provide greater stability. Human activities, including infrastructure expansion and land use changes, exacerbate instability, necessitating improved urban planning and groundwater management.

Although SBAS InSAR provides valuable movement data, further validation with GNSS and field surveys is required for enhanced accuracy, and future research should incorporate predictive modeling to anticipate long-term trends.

The study underscores the need for integrated monitoring approaches and sustainable land management policies to mitigate risks associated with ground instability, ensuring long-term stability and resilience of infrastructure in the region.

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Conflicts of interest

This research has no conflict of interest with other research and researchers

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