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Exploring the potentiality of InSAR data to estimate land subsidence of the Nile Delta

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ABSTRACT

Nile Delta has been historically targeted for various types of human activities since the Pharaohs' era due to abundance of its natural resources. The increasing land subsidence in the northern delta is a significant concern for the Egyptian government. Moreover, the cumulative subsidence coupled with the scenarios of sea level rise worsens the situation. In the present work, we utilize SNAPPING service on the Geohazards Exploitation Platform (GEP) to measure the spatial and temporal trends, as well as the extent of subsidence in urban areas within the Nile Delta. The study analyzed the period between 2015 and 2020 using 225 Copernicus Sentinel-1 radar imagery using the Persistent Scatterers Interferometry (PSI) technique and reported surface motion with an average of -5 mm/year in the Nile Delta surface. Subsidence is relatively higher in the eastern part with more patterns specific to particular regions. The northern part recorded subsidence ranged from 0 to 7 mm/year. High rates of subsidence up to 17 mm/year localized in locations of Port Said, Damietta, Ad Dakahlia and Al Sharkia governorates and around Manzala Lake. On the other side, medium uplift rates up to 6 mm/year concentrated around Bardaweel Lake, Parts of Ismailia governorate and Baltim city. On-site visual inspections in these areas documented tilting in buildings and clear cracks which confirm the impact of land subsidence on the structural integrity of the buildings. The GEP platform and the SNAPPING service demonstrated the capability of cloud-based solutions to provide precise surface motion information within a short time.

1. Introduction

Throughout history, the Nile Delta has been a focal point for a range of human endeavours and necessities dating back to the time of the Pharaohs. This can be attributed predominantly to the abundance of natural resources present in the Delta since its formation, encompassing fresh water, rich and level soils, areas for recreation, mineral deposits, coastal lakes, and opportunities for fish farming (Abou El-Magd and Hermas, 2010; Ali and El-Magd, 2016; El-Demerdash et al., 1990; Mashaly, 1987; Mashaly et al., 1993; Shaltout and El-Din, 1988). This attracted an excessive increase in population, civilization, and developmental plans to accommodate such population growth.

The Nile Delta originated from the development of intricate deltaic fans during the Pleistocene, evolving into its modern form through sediment deposits from at least ten distributaries during the Holocene. The average elevation is around 1 m above sea level within 30 km of the coast, and with a projected sea level rise of 5 to 6.76 mm/year for Alexandria and Port Said respectively(Dawod et al., 2019), the issue of land subsidence in the northern delta has become a significant concern for both the Egyptian populace and the government. It varies from 1 to 8.4 mm/year depending on the location. Maximum estimated land subsidence levels are in the eastern part of the Nile Delta that exceeded 8.4 mm/year (Gebremichael and Sultan, 2018). Hence it creates a major impact on the infrastructure and development in the area. Moreover, it worsens the impact of sea level rise due to climate change; since the cumulative subsidence together with the scenarios of sea level rise will increase the flooded area (Dawod et al., 2019; El-Raey, 2010; Frihy et al., 2008; Stanley et al., 2016).

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Recently, the excessive exploration and production of oil and gas in the area accelerated the subsidence and might create a high risk for the Nile Delta and local communities. Multiple techniques have been used for measuring land subsidence in the Nile Delta during the past periods as radiocarbon dating of clays (Stanley, 1988; Stanley and Warne, 1993; Stanley and Clemente, 2014). GPS measurements of fixed stations have been also used (Mohamed et al., 2016; Saleh and Becker, 2019). These two techniques are point measurements used to measure land subsidence in the Nile Delta and, thus, provide a spatially confined understanding of the ongoing land movements. However, precise measurements of land subsidence could be achieved by core samples and C^{14} analysis, which could be simulated to provide a wider picture of the Delta geographical extent. This method is costly and time-consuming given the lack of response to such risk.

The Interferometric Synthetic Aperture Radar (InSAR) technique was previously used to identify the spatial and temporal trends, as well as the extent of urban land subsidence in the Nile Delta and various coastal cities in Africa (Aly et al., 2011; Becker and Sultan, 2009; Cian et al., 2019; El-Asmar and Hereher, 2011; Gebremichael and Sultan, 2018; Rateb and Abotalib, 2020). Such remote sensing technology could solve this problem and provide an operational tool to estimate the land subsidence to the level of millimeters on large coverage of the whole Nile Delta. Moreover, it could be used frequently to keep monitoring and validate the subsidence (Quinn and Ponte, 2010). The challenge for this technique, using C-band SAR data, is the decorrelation of InSAR measurements over agriculture fields and generally highly vegetated lands. However, such technology needs to be applied with an in-depth study on the Nile Delta to provide an understanding of the land subsidence and become a tool for supporting decision-makers.

During the last decades, many fragmented studies on the land subsidence in the Nile Delta varied from precise estimation using core samples and C^{14} analysis to remote sensing techniques. Still, the gap is to have a consolidated method that provides a seamless layer of land subsidence for the entire delta. Becker and Sultan used ERS-1 and ERS-2 coarse resolution remotely sensed data and estimated the land subsidence in the northern part of the Nile Delta at a maximum of 8 mm/year and an average of 2–6 mm/year (Becker and Sultan, 2009).

Therefore, the objectives of this research are:

- 1. Evaluate the effectiveness of the Persistent Scatters Interferometry (PSI) technique, implemented through the SNAPPING service with Sentinel-1 images, to assess land surface changes in the Nile Delta.
- 2. Quantify and updating rates of land subsidence occurring across the Nile Delta region by recent data for the period 2015–2020.
- 3. Establish a correlation between areas exhibiting the highest subsidence levels and their geographical locations, investigating potential drivers contributing to the observed land subsidence.

2. Study area

The Nile Delta of Egypt extends on the Mediterranean coast for nearly 240 km from Port Said to Alexandria and around 160 km from north to south. The Nile Delta features deltaic sandy beaches ranging from medium to very fine sand, extending from Alexandria to Port Said. These alterations heighten the susceptibility of the coastal area to rising sea levels, particularly when natural protection is diminished, thereby increasing the risk of land subsidence. The Nile Delta experiences shifts in its shoreline due to factors such as erosion, accretion, subsidence, and sea level rise, all interconnected with the effects of climate change.

The Nile Delta is a mosaic of governorates, each contributing distinctively to the socio-economic and cultural tapestry of the area. The governorates of Cairo, Giza, Qalyubia, Damietta, Dakahlia, Sharqia, Kafr El-Shikh, Gharbia, Menoufia and Behera collectively shape the character of this fertile land.

3. Materials and methods

3.1. Data

To cover the area of interest (AOI) shown in Fig. 1, Copernicus Sentinel-1 TOPSAR Single Look Complex (SLC) products acquired on two adjacent descending relative orbits, number 65 and 167 have been used as seen in Fig. 2.

Table 1 summarizes the dataset employed, and it should be highlighted that due to the large dataset needed to cover the total extent of the AOI, only Sentinel-1A satellite images have been selected (Fig. 3).

3.2. Models and methods

In this work, the SNAPPING services available on the Geohazards Thematic Exploitation Platform (Foumelis et al., 2021) have been employed to derive the land stability motion information based on Copernicus Sentinel-1 mission data.

The exploitation of the GEP environment was decided, as it is currently a mature operational cloud platform that has offers advanced interferometric services to be executed on-demand, directly by endusers. This allows for the use of sophisticated algorithms as online services without the need for downloading locally massive amount of satellite data and The SNAPPING PSI Med service was utilized since the PSI technique is well suited for measuring surface motion over targets exhibiting stability of the radar signal (i.e., coherent targets), namely man-made structures and due to the capacity of the service to generate results over wide areas in relatively short time and at low cost. Despite the medium resolution outputs of the service, proper point densities were obtained for the totality of the urban centers, even over some isolated rural areas.

The SNAPPING app includes 2 services that need to be run in consecutive steps to obtain the final PSI results, i) SNAPPING IFG for the creation of the interferometric stack followed by ii) SNAPPING PSI utilization for the analysis of time series. SNAPPING PSI service is offered at two spatial resolutions, PSI Med for medium resolution analysis dedicated for wide area investigation and PSI Full for detailed investigation at sensor resolution. For the needs of the current study, SNAPPING PSI Med was utilized.

3.2.1. Inteferometric stack generation using SNAPPING IFG service

This service applies differential interferometric SAR processing using the ESA Sentinel Application Platform (SNAP) (Veci et al., 2017) to a stack of Sentinel-1 SAR Single Look Complex (SLC) images to generate single master interferograms. The processing workflow is described in (Fourmelis et al., 2018).

The service does not allow to process Sentinel-1 data acquired before April 2015 to avoid the processing of data before and after the antenna pattern correction EAP. This correction has been introduced in March 2015 with the IPF V243. As a consequence, performing interferograms between products generated with the IPFV243 and the former version V236 leads to range varying phase offset (Miranda, 2015).

The user has some mandatory parameters and others that can be used by default, such as polarization, DEM to be employed, etc. Fig. 4 shows an overview of the SNAPPING IFG service along the GEP geobrowser interface where satellite footprint and user AOI are shown. The user shall use the GEP catalogue to search and select the Sentinel-1 data to be processed.

This service selects automatically the reference date as the oldest date in the SLC stack and assembles the SLCs acquired on the same acquisition date (same relative orbit). This automatic selection represents a simplification possible to the Sentinel-1 orbital tube makes possible any dependency on the master selection as all perpendicular baselines will be distributed within the tube [-250 m, 250 m] and the differences on Doppler Centroid are controlled and limited by the acquisition system. We employed SRTM 3 arc-second to remove the



Fig. 1. Area of study, the Nile Delta.



Fig. 2. Area of interest (red) and Sentinel-1 footprints for relative orbit 65 (green) and 167 (blue).

topographic phase component on each interferogram as well as precise orbit state vectors for the SNAPPING processing. Moreover, the data is subsetted over the AOI using the user input parameters and it is ready to be imported into the SNAPPING PSI service.

Finally, A comprehensive field visit was meticulously conducted to visually inspect sites characterized by elevated subsidence rates. During

Table 1

Main characteristics of the dataset employed.

Mode	First/Last	Rel. Orbit	N. Dates	Orbit pass
IW SLC	2015/11/22 - 2020/12/25	65	115	descending
IW SLC	2015/11/17 - 2020/12/20	167	110	descending

this field exploration, close scrutiny was given to high subsidence areas to corroborate the remote sensing data with real-world conditions. The purpose of the visit was to validate and augment the findings derived from satellite imagery and other analytical methods. Visual inspections of buildings encompassed the assessment of structural integrity, the identification of visible fractures, and the documentation of any discernible impacts of subsidence on the landscape and built environment. These on-site observations play a crucial role in enhancing the accuracy and reliability of the study, providing valuable empirical evidence to support and refine the broader analysis of land subsidence

dynamics.

3.2.2. Persistent Scatters Interferometry using SNAPPING PSI Med service

In this step, the interferometric stack generated by SNAPPING IFG is used as an input to derive the displacement histories using the Persistent Scatters Interferometric technique (Aslan et al., 2020; Delgado Blasco et al., 2019). The user can apply the default parameters suggested by the service. Parameters such as amplitude dispersion are critical and directly related to the number of point measurements that will be obtained at the end of the processing. In our case, a value of 0.40 was used as the most appropriate ensuring high quality of PS targets accepted as well as proper density and spatial distribution.

The expected result will be measurement points distributed over man-made structures as the C-band is usually not able to provide longterm terrain motion information over cropland, still capable of detecting more coherent targets such as roads, houses, bridges, and other man-



Fig. 3. View of the SNAPPING app on Geohazards Thematic Exploitation Platform.



Fig. 4. SNAPPING IFG input parameters (right panel) along the GEP geobrowser.

made structures. The SNAPPING PSI Med resolution service provides a reduced number of point measurements where the density is high, maintaining the points that exhibit differences with their surrounding (Foumelis et al., 2022). This is most suitable when working on wide areas, as in the current study. The service relies on the Standford Method of PSI (Hooper et al., 2012), which has no assumption regarding the linearity or seasonality of the final possible behaviour on time on the PS provided results, and provides user-friendly outputs (Foumelis et al., 2022), suitable for direct exploitation in common GIS environments.

3.3. Visual inspection and Verification

Locations of high subsidence rates have been visited and inspected visually. Visual inspection is a crucial method for assessing buildings affected by land subsidence, particularly when it comes to identifying and evaluating cracks. This process involves a meticulous examination of the exterior and interior of a structure to detect any visible signs of damage caused by ground movement. External assessments focus on the building's façade, searching for cracks in walls, foundation, and surfaces. Internally, inspectors scrutinize walls, ceilings, and floors for cracks, as well as any misalignment or distortion of structural elements.

Documentation through photographs and notes has been done for analysis. Additionally, the surrounding environment has been assessed for signs of subsidence, such as uneven terrain or shifting foundations.

4. Results

Using the SNAPPING services on GEP, we have obtained over the entire AOI more than 450 thousand PS points at medium resolution. The spatial distribution of the PS measurements is shown in Fig. 5.

The main statistics of the Sentinel-1 LoS displacement rates are summarized in Table 2, showing that the highest subsidence rate reaches -45.5 mm/year. Given that no local reference is considered, the average motion rate is put to zero.

Fig. 6 (left) illustrates the histograms of the average LoS velocities, showing that the main group shows a deformation ranging from [-5.64, +5.64] for which the maximum and minimum values reported in Table 3 are extreme and punctual values localized in very specific areas of the Nile Delta. The standard deviation of obtained velocities (average uncertainties) is contained in the interval [0, 0.92] mm/year (Fig. 6).

Land subsidence is one of the critical issues of the northern coastal zone of Egypt particularly in the eastern Suez Canal area, probably Table 2

Summary of the deformation velocity statistics.

	vel [mm/year]	vs[mm/year]
Mean	0.00	0.14
Std	1.88	0.07
Min	-45.50	0.02
25 %	-0.68	0.09
50 %	0.18	0.12
75 %	0.92	0.16
Max	14.21	0.92

related to the large thickness of the geological sedimentary column. The difficulty to retrieve subsidence information with C-band InSAR processing in the Nile Delta is due to its large extent of agricultural land which is highly decorrelated and hence with very low coherence. Hence, it was only possible to retrieve to obtain subsidence information over roads and villages surrounded by croplands, as seen in Fig. 7.

Therefore, the average deformation in the northern Nile Delta is up to -7 mm/year based on SNAPPING Med results.

An illustrative demonstration of the SNAPPING medium resolution service's capabilities lies in its adept handling of point measurements aligned with linear features, such as roads or channel borders (refer to Fig. 8). This service strategically adjusts the resolution, lowering it in regions with denser point measurements, as observed in urban areas. This approach preserves intricate details for isolated targets while judiciously minimizing information granularity in other expanses. Such adaptability proves particularly valuable in the management of extensive datasets covering expansive geographical areas.

We have computed the point measurement density per administrative border level 2 where we can see that the density of point measurement augment inversely related to the area of the region and that on the rocky desert areas, the point density is much higher in urban areas than on the regions within the Nile Delta, where main cropland and villages are found as shown in Fig. 9.

Field investigation, as illustrated in Figs. 10 and 11, has been done for locations with pronounce subsidence rates reaching up to -17 mm/ year, notably in Port Said, Damietta, Dakahlia, and Sharkia around Manzala Lake. Conversely, elevated uplift rates up to 6 mm/year were observed concentrated around Bardaweel Lake, parts of the Ismailia governorate, and Baltim City.

During the field visits, numerous locations exhibited significant indicators of land subsidence, including leaning buildings and visible



Fig. 5. SNAPPING PSI Med results over Built-up Areas. Average displacement rates from 2015 to 2020.



Fig. 6. Histograms of average LoS velocities (left) and standard deviation of velocities (right).

Table 3

Comparing l	land vertical	changes of the	e Nile Delta	from	published	studies
1 0		0			1	

Author, Study Area, Period & Data					Land vertical movement (mm/year)							
						Alexandria	Damietta	a Port Said	l Cairo	Mansoura	Mahala	Tanta
(Stanley, 1988) Northeastern Nile Delta 7500 Years, 87 Wells					 Lake Manzala, Port Said, and the northern Suez Canal have experienced rapid subsidence, with rates reaching up to 5 mm/year for the past approximately 7500 years 							
(Stanley an 35,000 Y	nd Warne, 1993), Ni Tears	ile Delta				 Reassess 	ed the subsid	ence rates al	ong the coast	to vary betw	een 1 and 5	mm/year.
(Becker and Sultan, 2009), Northeastern Nile Delta, 1992–1999, 14 ERS-1 and ERS-2 scenes						(-8) maximum (- 2: - 6) average (-4: - 6) Manzala						
(Aly et al., 2011), Mansura and Greater Mahala, 1993–2000, 39 descending ERS scenes (Stanley and Clemente, 2014) 1262 clay samples from 87 cores (Gebremichael and Sultan, 2018) Entire Delta, 2004–2010, 84 SAR scenes					 (-7) (-9) (-5) The coastal margin of the northern delta experiences substantial subsidence, ranging from 3.7 mm/year to 8.4 mm/year—reflecting notably high rates. Considering a regional sea-level rise of 1.7 mm/year in this area (Wöppelmann and Marcos, 2012), the rates of relative sea-level increase vary from approximately 5.4 mm/year in the western section of the delta to around 9.4 mm/year in the middle, and up to 10.1 mm/year in the eastern section. The general subsidence patterns in the Nile Delta exhibit various rates in different regions: (1) an average rate of 2.4 mm/year in the northern delta with slight subsidence in the southern delta and a flexure zone (width: 20–40 km) 							
						experien rates (up compact mm/yea (Menouf governo gas field:	cing uplift at to -8.9 mm ion of recent r) in areas w ia governora rate); and (4) s, notably the	t an average : /year) in the Holocene see ith high grou te) and in rec) significant s e Abu Madi ga	rate of 2.5 m north-centra diments; (3) ndwater ext laimed deser ubsidence (1 s field, linke	m/year; (2) of al and northeat heightened su- raction rates t land in the v up to -9.7 min d to substantiat	astern delta astern delta absidence (in the sout western del n/year) ov al gas extra	due to the up to -9.7 hern delta ta (Beheira er onshore ction rates.
(Saleh and 71 Envis	Becker, 2019) 2006 at interferograms	5–2012 six GPS s	stations, 2004	-2010 Ale - 2	ex Damies 2.9 ± 0.9 - 10.3	tta Por ± 1.6 -4.	t Said C 9 ± 1.6 –	airo - 6.4 ± 0.4	Mansoura -10.0 ± 1	Mahal 1.2 – 4.9	a T ±1.0 −	anta 4.0 ± 0.6
 (Elsaka et al., 2020) Nile Delta, 2013–2017 (Flsaka et al., 2013–2017 <li< td=""></li<>												
Current Stu	ıdy	Alexandria	Damietta	Port Said	Kafr Al Sheikh	Dakahlia	Beheira	Gharbia	Sharkia			
Statistics	Mean value	-1.05	-3.96	-2.43	-2.2	-2.77	-1.23	-1.6	-0.96			
	St. Deviation	1.35	3.35		2.37	3.24	1.48	1.62	1.33			
	First quartile	-1.34	-5.85	-3.31	-3	-3.66	-1.55	-2.17	-1.17			
	Third quartile	-0.29	-1.24	-0.68	-0.56	-0.8	-0.32	-0.5	-0.21			
 Max Subsidence -19.62 -18.76 -15.66 -22.01 -45.5 -15.3 -17.9 -21.53 Comprehensive land movement measurements over 45 thousand permanent scatter points across the Nile Delta, reveal intricate details of surfadynamics with an average range of both upward and downward deformations, reaching up to 5 mm/year. Subsidence patterns in the northern part ranged from 0 to 7 mm/year. Estimated land subsidence is higher in the eastern part of the Nile Delta with more patterns specific to particular regions. Subsidence rates with a maximum of -45 mm/year and unlift with a maximum of + 15 mm/year have been recorded. 									s of surface			

cracks as shown in Fig. 12.

Notably, the site around Port Said, particularly Ashtoum Al-Gamil Bridge, which spans one of the water inlets from the Mediterranean Sea to Manzala Lake, demonstrated a subsidence rate of up to $-8.3~\rm mm/$

year according to PSI analysis. Visual inspection at the location (Fig. 12) revealed both vertical and horizontal cracks in the water gate, with one concrete slab noticeably sunk. Restoration efforts were observed on the bridge, particularly in the car-passing section.



Fig. 7. Example of point measurement locations over roads and villages on the Nile Delta.



Fig. 8. SNAPPING PSI Med results over Port Said, being able to capture de movement along the channel, road, houses, and harbor.

Furthermore, the Emirati residential area, a recent development on an old landfill beside Manzala Lake in Port Said, exhibited multiple subsidence points ranging from -4 to -10 mm/year and up to -16 mm/ year. Wet areas were visibly observed at the base of the buildings, as depicted in Fig. 12. Nearby, a new industrial area was constructed, featuring predominantly new and short buildings (no more than two floors) with no apparent signs of damage.

In Damietta governorate, numerous locations exhibit significant subsidence, exceeding -8 mm/year. Particularly, Kafr Saad city show-cases subsidence rates of up to -13 mm/year, with reports from locals indicating buildings experiencing leaning (Fig. 13) and the presence of wetlands. Noteworthy instances of building leanings are observed in both Wahed and Al Anainia villages, with high reported subsidence rates reaching up to -15 mm/year in Wahed village and up to -12 mm/year in Al Anainia village.

In Ad Dakahlia governorate, there are notable instances of very high subsidence rates, reaching up to -17 mm/year, as illustrated in Fig. 14. Mataria Dakahlia emerged as the most severely affected among the visited locations, situated near Manzala Lake and experiencing subsidence rates of up to -17 mm/year. The buildings in Mataria Dakahlia exhibit severe leaning, and the land is visibly saturated, as depicted in Fig. 14.

Furthermore, villages in Al Sharkia, such as San Al-Hajar and Kafr Ash Shawwafin, demonstrated high subsidence rates of up to -11 mm/year. Notably, a new five-floor building in San Hajr village was found leaning, leading to its demolition by the authorities. Additionally, numerous cracks were observed in old houses in Kafr Ash Shawwafin Village (Fig. 15).

In Alexandria, notable observations include evident structural issues in Abis city, with buildings displaying clear cracks both externally and internally, prompting renovation efforts. Additionally, Izbet Al Talateen has experienced unauthorized construction on agricultural land, featuring buildings exceeding 20 floors. The official buildings of Muharram Bek Bus Station exhibit severe impacts from land subsidence, with substantial cracks and uneven first-floor levels attributed to a prolonged waterline crack that remained unrepaired according to employees (Fig. 16).

5. Discussion

The SNAPPING services enable wide-area mapping of the Nile Delta in a way it has never done before, providing density of point



Fig. 9. Point measurement density per administrative border level 2.



Fig. 10. Verification of subsidence results through On-Site visits to 40 Locations.

measurements that allow to handle such amount of information and allow to identify and contrate efforts on the most critical areas found. Additionally, this service has time series updates as an option to avoid extra time consumed in replicating interferogram computation. The service also allows the extension of the interferogram stack and running step 2 (PSI computation) reducing time and minimizing efforts. The land subsidence has a major negative impact on the socio-economic process within this area including infrastructures, buildings, tourism compounds, etc. Precise determination of the land subsidence and its location is essential to support decision-makers, and planners to take the



Fig. 11. Zoomed map displaying main locations visited in the field study.

necessary actions, particularly during the implementation of national projects.

The usage of cloud platforms enables wide-area processing and simplifies the burden on scientists and non-experts to obtain reliable and precise information in only few days.

Regarding the findings, the SNAPPING PSI Med results are consistent with previous studies performed with SAR historical missions on the common areas, showing that the North-Eastern part of the Nile Delta is the most affected by the subsidence phenomenon.

A more detailed analysis of the time series needs to be performed to correlate with construction dates, water extraction, and other area available ancillary information. It is quite necessary to compare the results of this research with the wide range of previous research studies. Stanley et al using C^{14} analysis on few-core samples determined the vertical land changes of the eastern part of the Nile Delta (Lake Manzalla) at 5 mm/year. Our research study estimated this corner at 16 mm in 3 years, which means 5.1 mm/year. It is highly aligned with the C^{14} results.

For more understanding of the land subsidence results of the Nile

Delta in correlation to the previous studies with different tools and methods, Table 3 lists the detailed comparatives of previous land subsidence studies results in the Nile Delta.

Photographic documentation reveals compelling evidence of building cracks, leaning structures, and instances of building collapse attributed to land subsidence in various urban areas across Alexandria, Damietta, Port Said, Kafr El-Shikh, Behera, Al Sharkia and Ad Dakahlia governorates. The prevalence of subsidence cases is notably concentrated in cities, particularly in areas where wetlands have expanded into agricultural zones during the period from 2011 to 2022. This expansion is exacerbated by unauthorized construction with elevated building heights, exerting substantial loads on unprepared ground. The visual evidence underscores the critical intersection of land use dynamics, urbanization, and the consequential impact on ground stability.

The limitations of Persistent Scatterer Interferometry (PSI) in the context of the Nile Delta, particularly when utilizing C-band Synthetic Aperture Radar (SAR) data, stem from the phenomenon known as decorrelation. Decorrelation occurs when the radar signals reflected from the Earth's surface undergo significant changes between



Fig. 12. Snapshots of visited locations in Port Said.

subsequent acquisitions. This is particularly evident in areas with dense vegetation, such as agriculture fields and highly vegetated lands.

In the case of the Nile Delta, where agriculture is prevalent and the landscape is characterized by various land covers, the effectiveness of PSI can be compromised due to the decorrelation effect. Vegetation can introduce substantial changes in the radar backscatter properties, leading to difficulties in maintaining the coherent phase information essential for accurate interferometric measurements.

Despite these challenges, it is crucial to highlight that PSI technology has the potential to provide valuable insights into land subsidence when applied judiciously. To mitigate the impact of decorrelation, a thorough and localized study focusing on the unique conditions of the Nile Delta is essential. This involves considering the specific characteristics of the region, such as land cover types, agriculture practices, and environmental factors, to optimize the application of PSI.

In the Nile Delta, subsidence and uplift patterns are intricately linked to a range of possible natural and anthropogenic factors, shaping the dynamic landscape of this vital region. Groundwater extraction in the newly reclaimed lands stands out as a prominent contributor to subsidence phenomena. As communities rely on groundwater reservoirs for agricultural irrigation and urban water supply, excessive pumping accelerates the lowering of the water table. Consequently, this induces soil compaction and subsequent land subsidence, a phenomenon extensively documented in deltaic regions globally.

Furthermore, sediment compaction plays a significant role in altering the delta's topography. Millennia of sediment deposition from the Nile River have formed the fertile soils sustaining agriculture and settlements. However, human activities, including urbanization over agricultural land happened after 2011, disrupt natural sediment deposition processes. Compaction of sediment layers under the weight of urban infrastructure and agricultural machinery leads to gradual subsidence, exacerbated by drainage efforts to reclaim marshlands for cultivation.

Moreover, the geological context of the Nile Delta within a tectonically active region adds another layer of complexity to subsidence dynamics. While tectonic activity in the delta may be relatively subdued compared to neighboring areas, localized faulting and seismic events influence subsidence and uplift patterns. Research suggests that interactions between regional tectonics and sediment loading contribute to differential subsidence across the deltaic landscape. By addressing these challenges through an in-depth study, PSI can serve as a valuable tool for understanding land subsidence in the Nile Delta. This understanding, in turn, can contribute valuable information for decisionmakers involved in land management, infrastructure planning, and environmental conservation in the region. Therefore, while acknowledging its limitations, PSI holds significant potential as a supportive technology for decision-making processes related to land subsidence in the Nile Delta.

Finally, the juxtaposition of conservative estimates and extreme projections of sea level rise scenarios against the backdrop of observed subsidence unveils a complex interplay of factors shaping the coastal landscape. The implications of this integrated analysis extend beyond theoretical considerations. Rising sea levels, coupled with land subsidence, pose tangible risks to the Nile delta's ecosystems, agricultural



Fig. 13. Snapshots of visited locations in Port Said.



Fig. 14. Snapshots of visited locations in Damietta.

productivity, and coastal communities. Increased salinity in freshwater sources, heightened vulnerability to storm surges, and potential displacement of populations are among the specific challenges we aim to identify and articulate.

6. Conclusion and recommendations

In summary, the emergence of land subsidence in the northern Delta

has become a pressing concern for both the Egyptian populace and the government, posing substantial challenges to infrastructure development in the Nile Delta region. This issue is further compounded by the looming threats of climate change, with the average elevation of the delta just around 1 m above sea level within a 30-kilometer radius of the coast. Coupled with projected sea-level rise, the combined challenges of subsidence and coastal flooding have become pivotal areas of concern.



Fig. 15. Snapshots of visited locations in Ad Dakahlia and Al Sharkia.



Fig. 16. Snapshots of visited locations in Alexandria.

SNAPPING PSI Med services through the Geohazards Exploitation Platform (GEP) to systematically measure and analyze spatial and temporal trends, as well as magnitudes of urban land subsidence in the Nile Delta. The findings, derived from the Copernicus Sentinel-1 mission data for the period 2015–2020, disclosed a maximum subsidence rate of -45 mm/year and uplift of up to +15 mm/year, predominantly observed in localized areas.

The study underscores the potential of Earth Observation platformbased solutions as operational tools for measuring and monitoring land subsidence at millimeter-level accuracy over wide areas like the entire Nile Delta. The PSI technique, employed in this research, demonstrated reliability in identifying subsidence locations, primarily attributed to unauthorized construction with elevated building heights on highly saturated and agricultural land.

Proactive measures are recommended to assess the structural integrity of cracked buildings, ensuring safety. Furthermore, future city development should strictly adhere to regulations dictating building heights based on the state of land subsidence, in order to mitigate the potential risk.

Potential socioeconomic impacts of land subsidence on infrastructure, agriculture, and human settlements underscore the need for monitoring and understanding this phenomenon to develop effective mitigation strategies. Monitoring land subsidence is crucial for anticipating and addressing its adverse effects on infrastructure integrity, agricultural productivity, and human settlements' stability. By comprehensively understanding land subsidence patterns and their socioeconomic implications, policymakers can implement proactive measures to mitigate risks and enhance community resilience. Therefore, integrating ongoing monitoring efforts with interdisciplinary research is essential for informed decision-making and sustainable development in subsidence-prone regions.

In conclusion, the comprehensive land movement measurements across the Nile Delta have provided valuable insights into the intricate dynamics of surface deformations. The observed variability in subsidence rates across governorates necessitates careful consideration for infrastructure planning and urban development, emphasizing the importance of resilient and adaptive strategies. The study's recommendations for improved monitoring systems, sustainable land-use practices, and region-specific engineering solutions aim to contribute to informed decision-making in the realms of infrastructure development and urban resilience in the face of land subsidence.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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