remote sensing

Article

Vertical Ground Displacements and Its Impact on Erosion along the Karachi Coastline, Pakistan

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Abstract: This study employed remote sensing (optical and synthetic aperture radar) and data analysis techniques to quantify vertical ground displacements and assess their contribution to coastline erosion. To provide evidence from Pakistan, we selected the coast of Karachi—a mega-city located along the dynamic coastline of the Indus River Delta—which has been experiencing severe coastal erosion during the last few decades. Observations from the C-band Envisat/ASAR and Sentinel-1A sensors over the 2004–2010 and 2014–2016 periods, respectively, enabled us to study vertical ground displacements in the study area, providing a long-term assessment during 2004–2016. Results suggest that some areas along the Karachi coastline are subsiding at comparable rates to or even much higher than the relative sea-level rise (SLR, ~1.9 mm/yr), which may amplify the rates of relative SLR in coming years, along with accelerating coastal erosion. Various parts of the study area along the coast are unstable and undergoing displacement. Landsat images from 1989 to 2018 (10-year temporal resolution) were further used to examine the state of coastline erosion using three statistical approaches (i.e., End Point Rate (EPR), Linear Regression Rate (LRR), and Least Median of Squares (LMS)). While the erosion underlaid the majority of the eastern sections of the study area, the ground displacements were spatially heterogeneous across the study area and along the coastline. Erosion rates of ~2.4 m/yr spatially corresponded with ground displacement rates of up to ~−1.4 cm/yr, but not all the coastline segments with high annual mean erosion rates were associated with local mean subsidence. The causes of ground displacements and coastline erosion were analyzed, and results were interpreted by integrating spatial ancillary information. Results indicate that rapid urbanization, construction on reclaimed land, coastline erosion favoring seawater intrusion, failed drainage/sewerage networks, and soil liquefaction are contributing to the site-specific variations in the land displacement in Karachi.

Keywords: remote sensing; coastal dynamics; coastline erosion; vertical ground displacement; InSAR

1. Introduction

Various large-scale and long-term environmental processes, such as seismic events, construction activities, soil liquefaction, and groundwater abstraction along with climate change in a particular low-lying coastal area, may manifest in the form of ground instabilities (e.g., Long Beach in the United States, Venice in Italy, Tokyo in Japan, Bangkok in Thailand, or Shanghai in China), making these problems more severe [1–3]. The damage is not always known until it is too late. Many of the river deltas are experiencing accelerated subsidence and coastline erosion. As a result, these vulnerable deltaic coasts and communities are at increased risk of permanent flooding and sea-level rise (SLR) caused by reduced sediment supplies due to upstream dam constructions and anthropogenic intrusions of the estuaries themselves [4]. It is noted that parts of coastlines around the world are undergoing tectonic subsidence (e.g., the south-eastern coast of England, Atlantic coast of the US, south-western Denmark, the Netherlands, northern Germany, and the Campania Region of Italy coast), while in other areas an increase in natural resource exploitation (e.g., parts of the Sindh coast, Pakistan) has induced subsidence [5,6]. In comparison, a myriad of factors contributing to the erosion of coastlines along the subsiding Indus River Delta (our area of interest, located along the Arabian Sea) have been identified; this erosion is associated with a drastic reduction in sediment influx, mangrove depletion, seawater intrusion, and sea-level rise [7]. While ground instabilities negatively impact the environment, urban infrastructure, and human life, the scientific evidence on ground subsidence in the study area is inadequate and its role in driving coastal erosion is not quite clear [1,8–10].

Geographically, being a constituent part of the Indus Deltaic Region (IDR), the NW-SE-oriented Karachi coastline spans more than 70 km. This coastal area is exposed to monsoon-induced waves and tides. Being influenced by coastal and riverine processes of the Arabian Sea (such as sediment discharge, storm surges, and currents), the study area's coastline has been enduring dynamic changes [7]. As a result, several segments along the IDR have undergone subsequent severe erosion, particularly along the coastline of East Karachi. The Karachi coastline has experienced an average landward retreat rate of ~2.43 m/yr, with the highest erosion rate being along the banks of the creeks where the Indus River Delta begins. More recently, several studies have emerged that postulate causative factors aggravating erosion along the Karachi coast.

SLR and coastal erosion are mutually interconnected. Khan, et al. [11] carried out a relative SLR analysis through calculations with Karachi station's ten years of hourly tide-gauge (TG) data. In their study, authors estimated ~3.6 mm/yr of mean SLR from 2007–2016. SLR of ~1.9 mm/yr was reported for the Karachi coastline by Kanwal, et al. [7] from 1916 to 2015 using the Permanent Service for Mean Sea Level (PSMSL) data archive. Considering the evidence from these studies, it seems that the coastline erosion along the Karachi coast is linked with rising sea levels.

Another viewpoint is that abrupt reduction in sediment load and water reaching the Arabian Sea has amplified the effects of waves' actions and tidal currents, thus impeding mangrove growth and resulting in accelerated seawater intrusion (SWI) and coastline erosion along the entire Sindh coastline. Kidwai, et al. [12] reported a significant drop in the sediment load reaching the IDR coastal plains, mainly due to dams, barrage construction, and channeling in upstream areas. This reduction in the sediment supply has escalated the erosional effects of tides and waves, resulting in seawater intrusion (SWI) into coastal plains. The results from these studies agreed well with those of Kanwal, et al. [13], who investigated the evolution of the barrier islands (BIs) along Sindh coastal regions in Pakistan and concluded that ~65% of these BIs underwent high erosion (i.e., >2 m/yr), during 1989–2018. Their study implies that the ~15% of these BIs experiencing moderate erosion (i.e., <2 m/yr), are likely to be subjected to high erosion (i.e., >2 m/yr) in the wake of SLR and reduced sediment influx received by the IDR plains in the near future, without proper measures.

Erosional effects could be severe and damaging in low-lying coastal regions if this phenomenon is coupled with other hazards, such as ground displacement, storm surges, and SLR. Although ground displacements have been observed in different parts of Karachi and reported by various media outlets, the issue has not been frequently discussed in published literature until recently [3,14–17]. For instance, Amin, et al. [18] and Kanwal, et al. [19] utilized synthetic aperture radar images to identify ground instabilities in the coastal megacity of Karachi. Comprehensive historical information on the characteristics of ground subsidence is neither readily available nor applied in the planning of mitigation efforts. Such integration is being hindered by the unavailability of chronological data. However, earlier research has not fully established the relationship between the subsidence at the coast and the ongoing erosion. The lack of published data highlights the gravity of the issue. It further suggests that the serious implications of the induced subsidence on accelerating the coastline deterioration have been underestimated. In this context, the present study aims to assist evidence-based decision-making by: (i) leveraging the synthetic aperture radar interferometry (InSAR) techniques to determine the spatial distribution and rates of vertical ground displacement in Karachi and (ii) unraveling the link, if any, between vertical ground displacement and coastline erosion derived from Landsat images along low-lying regions of the developing coast of Karachi.

The capability of remote sensing satellites carrying Synthetic Aperture Radar (SAR) sensors to achieve regular and frequent data acquisition has been proven to have significant advantages in terms of wide-area coverage, cost, and equipment installation for improved ground displacement detection, mapping, and monitoring. In addition, the collected data have facilitated the recording of longitudinal information over large geographical areas. The prodigious InSAR technique has been utilized worldwide in various fields for the extraction of ground displacement ascribed to landslides [20], deltaic subsidence [21], and coast deformation [22,23] among other related factors. InSAR measures ground displacements along a line of sight (LOS) by estimating the phase difference between two SAR images. In rapidly changing landscapes, some landmarks (scatterers) may be only visible in a subset of the SAR acquisition but not for the entire observation period. In rapidly developing areas, these partially/temporarily as well as persistently available scatters, collectively termed Temporarily Coherent Points (TCPs), can allow us to estimate the ground displacement in such changing landscapes.

In such urban developing areas, particularly those characterized by the complex geographic and geologic environments found near low-lying coasts, the InSAR technique can help monitor ground instabilities [24]. Integrating multi-scale standpoints of ground displacements that could cause widespread instability with its quantitative assessment provides essential information to study the relative sea-level rise scenarios in coastal lands. This information could be useful for effective and efficient resource planning and management to implement conservation practices in a particular area of interest to avoid damages and minimize risks, such as frequent flooding, and increase in relative sea level.

2. Study Area

The metropolitan city of Karachi is located on the southern-most border of Pakistan along the coast of the Arabian Sea (Figure 1), with its geographical extent marked by longitudes 66°37′E–67°37′E and latitudes 24°45′N–25°15′N. At present, Karachi appears to be in the unfortunate position of having precarious tectonic framework, as it sits next to the Arabian, Indian, and Eurasian plates' triple junction [14,25,26]. Neotectonics of this area show various NE—SW-trending fold structures crossed by numerous active NW-SE-trending active faults of local and regional extents and transcurrent or transverse nature in and around the city, endangering about 23 million lives inhabiting an area of about 3527 km^2. Comprehensive information about these faults, along with the structural elements and coastal geology of Karachi, can be found in [25]. The known faults and their movements are expected to provide reasonably good information for assessing the potential of vertical ground displacements in the Karachi area.

In addition to the larger tectonic framework, shown in Figure 1, the city faces multiple environmental and geological issues. Karachi is a constituent part of the indented coastline of the Indus River Delta, which is highly vulnerable to erosion and inundation, mainly due to anthropogenic activities, such as groundwater extraction, and development, in conjunction with hazards, such as strong tides, wave action, and increases in relative sea level. In most parts of the city, slopes are between 0–4°, particularly in areas near the coast with flat topography. Such a minimal decrease in ground elevation relative to mean sea level can impede the city's existence due to the intensification of coastal erosion and acceleration of other environmental issues, such as seawater intrusion, sea-level rise, and changes in the natural lagoon environment nearby to the Indus Deltaic system. To address this problem, this study aims to map ground displacements through interferometric processing of the available historical archives of C-band SAR datasets and study his displacement's influence on coastline erosion identified through Landsat images.

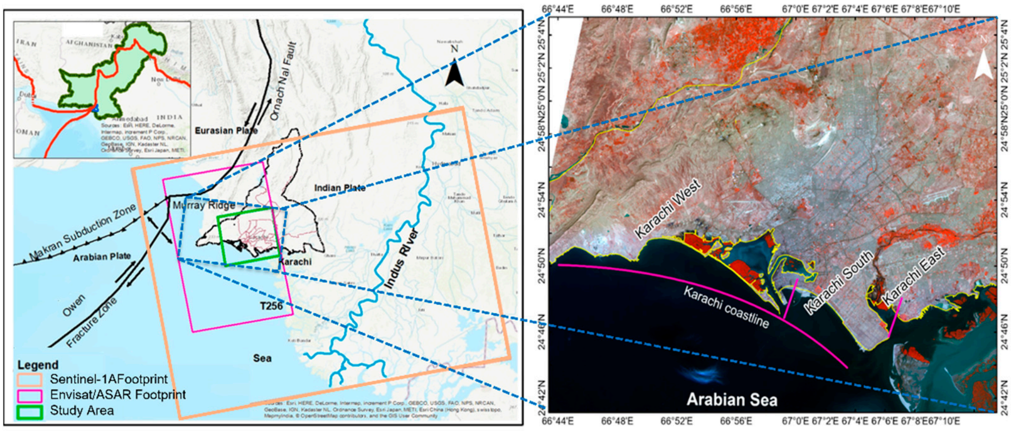


Figure 1. Inset (left) maps the location of the coastal mega-city of Karachi relative to the Arabian-Indian-Eurasian plates' tectonic triple junction. The green box marks the coverage of the study area, for which 33 scenes from ENVISAT/ASAR (2004–2010), 23 images from Sentinel-1A (2014–2016), and 4 images of Landsat (1989–2018) are processed. Each administrative unit along the Karachi coastline is represented on the right, overlaid upon a Landsat Operational Land Imager (OLI) false color image (2018).

3. Materials and Methods

To conduct this study, a two-fold methodology is adopted: (i) assess the coastline's spatial changes using the Digital Shoreline Analysis System (DSAS) tool from the United States Geological Survey (USGS) for 1989–2018 and (ii) quantify the vertical ground displacements using InSAR analysis of images acquired for the 2004–2010 and 2014–2016 periods. The results are demonstrated and contrasted to corroborate the relationship between coastline erosion and vertical ground displacements in the study area.

3.1. Vertical Ground Displacement Detection Using TCPInSAR

To quantitatively extract the ground displacement in the changing landscapes of the low-lying coastal mega-city of Karachi, where ground motion is likely to affect the rate of relative sea-level rise, the multi-temporal InSAR method is used. For this purpose, this study mines the historical archives of the European Space Agency (ESA) SAR C-band mission Envisat/ASAR (available at http://eo-virtual-archive4.esa.int/) and extracts time-series acquisitions suitable for ground displacement monitoring through interferometric processing to demonstrate the capabilities of SAR datasets and sensors. Table S1 (given in separate Supplementary Materials File) lists all the 33-ascending single-look complex images (Track 256, IM mode, and HH polarization) used in this study, acquired during the 2004–2010 period by the ESA. This approach allows us to visualize the ground displacements in Karachi from 2004–2010.

As part of the new European Copernicus Programme, the C-band Sentinel-1A satellite has been in orbit since April 2014. The presented analysis is further extended over the same area using a set of 23 images from Sentinel-1A (IW mode, path 42, and VV polarization) retrieved from the ASF DAAC and processed by ESA (see Supplementary Table S2). Careful selection of the SLC images enables us to study ground displacements over the same geographical extent by Envisat/ASAR from Sentinel-1A. Despite some data gaps, this study allows us to construct a longitudinal analysis of the Karachi coast from 2004 to 2016. The results are interpreted, and the causes of the ground displacements are examined by integrating multidisciplinary geospatial data layers (i.e., land use, faults, lithology, and topography) [26].

The Temporary Coherent Point InSAR (TCPInSAR) approach (see Figure 2), which is designed to monitor displacement in the changing landscapes of metropolitan areas [27] as persistent scatterers are more abundant in such environments [28], is applied to investigate the ground displacements in the study area. However, this approach can also investigate ground displacements in rural areas and wetlands [29,30]. A temporary coherent point

(TCP) preserves its coherence value through multiple SAR acquisitions [31]. The procedures for identifying TCPs have been reported in detail by Zhang [32]. All the identified TCPs are used to construct a Local Delaunay Triangulation Network [31]. This is useful for preventing the island effect due to the removal of considered arcs (generated from a pair of TCPs) containing phase ambiguities as part of the data processing chain. The TCPInSAR algorithm separates orbital artifacts and ground displacement signals through a joint model mechanism [33]. This model simultaneously analyzes the difference of interferometric phase at arcs, the rate of ground displacements, the topographic residuals, and the polynomial coefficients indicative of orbital errors at TCPs, and reflects their relationship with each other.

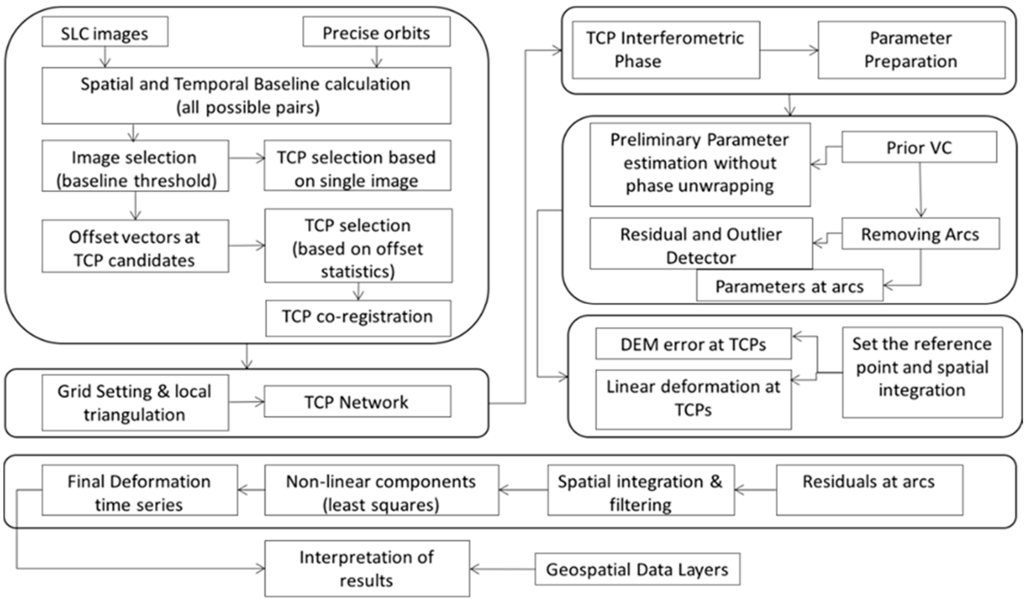


Figure 2. Flow chart of the methodology adopted in this study.

All the raw data are processed into readable SLC images. Every second SLC image is carefully chosen, co-registered, and interferograms (IFG) are created. An IFG in its raw form is potentially affected by various sources of errors, such as atmospheric contamination, topographic artifacts, and decorrelation noise. To find the optimal phase value for ground displacement rate estimation, it is required to eliminate as many of these aforementioned errors as possible from the IFG phase value [34]. For subsequent interferometric processing, an Envisat/ASAR image taken on 2 September 2005 is selected as the reference. In order to reduce the decorrelation noise, 28 ENVISAT/ASAR images are selected to generate IFGs per their perpendicular baseline and temporal baseline criteria (220 m Bp and 420 days Bt), as shown in Figure S1 of the Supplementary Materials. The temporal and perpendicular baseline criteria are chosen to ensure that all of the involved images produce a good quality IFG. Similarly, for Sentinel-1A datasets, only selected interferometric pairs are utilized to generate the IFGs, per the perpendicular and temporal baseline criteria.

To remove the topographic artifacts, a 1-Arc-Second digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM) is processed via a standard two-pass differential InSAR (DInSAR) method [20,35]. The coherence method is used to choose the TCPs. The optimum coherence threshold value is selected through the process of trial and error. The coherence value of the IFGs is further enhanced with a multi-looking step (down-sampling with one look in the azimuth and five looks in the range direction), and de-noised using a non-local framework for SAR images known as NL-SAR [36]. It should be noted that the technique of TCPInSAR can find the observations represented by arcs (pairs of TCPs) without ambiguities by analyzing the least-squares (LS) residuals [25], and without requiring phase unwrapping.

In this study, approximately 2.1 million TCPs are identified and used to construct 410,529 arcs by processing 28 interferometric pairs from Envisat/ASAR with Bp less than 220 m. To estimate the rate of ground displacements and various noises, such as topographic residuals, and orbital errors, a large design matrix (14,368,515 $\times$ 2,830,907) is constituted representing the number of observations (i.e., 14,368,515) and the number of unknowns (i.e., 2,830,907) representing topographic residuals and ground displacements rates at those identified TCPs with five polynomial coefficients of polynomial denoting the orbital artifacts in the observations, keeping one image as reference image and one TCP as the reference coherent point. These parameters are resolved by employing the LS method. The arcs of TCPs containing phase ambiguities are removed by employing a phase ambiguity detector [37], which leaves fewer resultant TCPs at the end (i.e., ~2 million). The examination of topographic residuals depicts the difference between the observed topography and 1-arc SRTM DEM from -10 m to 20 m, with 4.28 m standard deviation (SD). One point location is selected as a reference point for retrieving the ground displacements in the study area.

For Sentinel data processing, the process mentioned above (see Figure 2) is repeated with a reference image dated 28 August 2015. Only 34 Sentinel-1A image pairs are utilized to produce the IFGs, meeting the perpendicular (Bp 100 m) and temporal baseline (Bt 100 days) criteria, as shown in Figure S1 of the Supplementary Materials. This is done to maintain optimal coherence value and lessen the probability of the phase wrapping step. Then, the TCPInSAR procedure is applied burst-wise over the good quality IFGs. Table S2 given in the Supplementary Materials, describes the details of the relevant bursts that cover the same geographical area as Envisat/ASAR to generate mosaic SLC images for interferometric analysis.

Processing of Sentinel-1A images requires good care, especially if they are from different paths and frames. It is imperative to keep the number of bursts in each observation image the same; otherwise, it might cause various errors/noise, e.g., co-registration errors. However, the set number of bursts for each frame can vary. The Sentinel-1A images are comprised, in total, of three bursts for sub-swaths 1 and 2 of the Sentinel-1A images that show the broad area coverage offered by Sentinel-1A. This ensures an overview of the ground displacement status over a large area at a good spatial resolution. TCPInSAR (coherence method) is applied to the Sentinel-1A images over the Karachi area using burst information, and details are given in Table S2 and provided in the Supplementary Materials. By processing Sentinel-1A IFGs, ~6.3 million TCPs are identified and processed to construct ~810,119 arcs. Similarly, a sizeable sparse design matrix (27,544,046 $\times$ 3,674,889) is constructed to estimate the rate of ground displacements, topographic residuals, and orbital errors. After applying the method of LS for resolving the parameters, arcs containing phase ambiguities are removed. It is worth noting that LOS ground displacements combine both vertical and horizontal displacements. Vertical ground displacements are separated from LOS displacements in the final step for further analysis. Even though it would be ideal to validate the displacements using ground-survey-based GPS data, we cannot incorporate them at this stage due to the unavailability of any data, which is a major issue in developing countries. However, as the approach utilized here has been validated with GPS data in many parts of the world [38,39], it is reasonable to proceed and make best use of the available data to provide important insights regarding the subject matter.

Lastly, vertical displacement velocities from both datasets were computed and overlaid on the land-use map of Karachi to examine the role of different land-use activities in causing these displacements. The land-use/land-cover dataset was developed by a research group from the University of Karachi, Pakistan in 2010. About 85% of land-use data were developed using High-Resolution Imagery from QuickBird (available at https://earth.esa.int/eogateway/catalog/quickbird-full-archive). The remaining 15% were developed through field surveys and ground truthing conducted by a group of students from the Department of Geography at the University of Karachi. Since the core land-use map of the city has not changed significantly since, and the year of mapping lies within the time period of this study, we have obtained and use this data for the comparison and analysis of ground displacement results. Furthermore, the vertical displacement rates in each administrative zone along the coast and their coastline erosion rates are compared and analyzed to examine the influence of vertical ground displacement in deriving coastline changes. Details of coastline change estimation are given in the following section, Section 3.2.

3.2. Coastline Change Estimation Using DSAS

In the present study, coastline positions are derived from Landsat data using the DSAS tool [40,41] developed by the USGS as an extension of the ArcMap software. We select high-quality images from Landsat climate data records (CDR) captured in the pre-monsoon (December–April) non-flooding season to delineate the coastline positions. Table S3 (see Supplementary Materials) details the acquisition details of the images used in this study. The astronomical tidal height prediction records for the tide gauge station of Port Muhammad Bin Qasim (24.7833°N, 67.3500°E) from Tides 4 Fishing (https://tides4fishing.com/) shows that the tidal level range is ~0.20–2.80 m during the Landsat pass-overs for the 1989–2018 period. Due to the constraints of tidal level (i.e., $\leq$2.8 m) and availability of images of the study area, four atmospherically corrected and cloud-free Landsat images from 1989, 1999, 2009, and 2018 (path-152 and row-043) at 30 m spatial resolution are considered for extraction of the coastline positions and are pre-processed for change analysis.

The land-water boundary is delineated by computing the Normalized Difference Water Index (NDWI) using the near-infrared (NIR) band and short-wave infrared (SWIR) band. To extract the coastline change rate from NDWI images, the following steps are carried out: (i) delineating coastline; (ii) generating baseline; (iii) casting transects; (iv) computing distances between the baseline and the coastline at each transect; and (v) estimating the rate of coastline change at each transect [4]. To compute the rate of coastline change, 1500 transects with 500 m spacing along the baseline for the study area are analyzed, employing three statistical methods (i.e., End Point Rate (EPR), Least Median of Squares (LMS), and Linear Regression Rate (LRR)). The first model, EPR, estimates the coastline change between coastline positions separated by a certain number of years using:

$$EPR = \frac{dist_1 - dist_2}{\mathrm{y}_1 - \mathrm{y}_2} \tag{1}$$

where $dist_1$ and $dist_2$ represent the distance of coastline positions from the baseline, and y_1 and y_2 are the dates the coastline positions are observed.

The second method, Linear Regression Rate (LRR) of coastline change, determines the least-squares regression of all the coastline points for each casted transect. The line of regression takes the following form:

$$\mathrm{D} = \mathrm{a} + mt \tag{2}$$

where D represents the distance separating the observed coastline and the baseline, a represents the y-intercept, t represents time in years [41], and m denotes the slope of the linear regression line (i.e., coastline change rate). The value of linear regression (i.e., R-squared, R^2), is computed for each transect:

$$\mathrm{R}^2 = 1 - \sqrt{\frac{\sum_{i=1}^{n}(dist - distp)^2}{\sum_{i=1}^{n}\left(dist - \overline{dist}\right)^2}} \tag{3}$$

where $dist$ represents the known distance separating the observed coastline and the baseline; $distp$ represents the predicted value of $dist$ estimated using the regression equation; $\overline{dist}$ represents the mean position of the observed coastlines; and n represents the number of the observed coastlines. Following Nassar et al. (2019) $\mathrm{R}^2 > 0.87$ is considered as the limit of certainty in this study [41]. The standard error of the regression line slope representing an uncertainty of the calculated rate of coastline change is noted as Confidence Interval of regression line (LCI). In this study, the LCI is considered at a 95% confidence interval (p = 0.05, LCI95).

In the third method based on the Least Mean Square (LMS) model, the best-fit equation for the regression slope line is determined using the median of the squared residuals. The LRR model is based on the mean offset of the sample to compute the slope line equation by contrast.

We compare the affinity between results from these various methods using R^2 measures. Compared to the affinity between EPR–LMS (R^2 = 0.80) and LMS–LRR (R^2 = 0.91), the obtained value of R^2 is high for EPR-LRR (0.94). For this reason, and with LRR being the most widely used approach for coastline change and analysis, the LRR method is applied for further analysis of the coastline changes and erosion rate estimation. The quality of the statistical results from LRR model is validated through correlation analysis between the model-predicted coastline and image-based delineated coastline for the year 2018. The correlation between the model-predicted and the image-derived coastlines was found to be 90%. Since the LRR model-predicted coastline values and the image-based coastline values were in close agreement (~90%), the LRR model coastline change estimates are considered acceptable for further analysis.

4. Results

4.1. Displacement along the Karachi Coast (2004–2016)

The TCPInSAR algorithm is applied to the selected IFGs to estimate the vertical ground displacement rate of the Karachi area, as shown in Figure 3. The maps obtained in SAR image coordinates are initially geocoded into Universal Transverse Mercator (UTM) coordinates. This is done purposely to integrate the results with ancillary geospatial information (i.e., land use, geological features, and coastline erosion rates). The vertical ground displacement results are color-coded red to blue. The green shades represent ground displacement values around zero; the tones of blue correspond to uplifts, and the tones of red correspond to subsidence.

The local ground displacements are evident in Envisat/ASAR results, with a maximum vertical ground displacement velocity greater than ±15 mm/yr. The magnitude of the vertical ground displacement rate is spatially dynamic in the study area (Figure 3). The sites experiencing the most conspicuous uplift are located in the town of Baldia and some neighboring areas from the town of Kemari. This uplift trend is related to the water level variations in underground reservoirs, as this location is surrounded by the Liyari river to the east and the Hub River to the west. An unusual positive ground displacement rate is also observed in the Port Muhammad Bin Qasim area (see Figure 4), although the reason for uplifting requires further investigation. It is acknowledged that these ground displacements are estimated relative to a reference location deemed stable during the period of this study. It is likely that the chosen reference point might also have experienced some instability and movements during the period selected for this study. Despite the unavailability of in situ data for result validation, the SAR-based analysis in this study and observations from field visits suggest that the site-specific ground displacements in the coastal mega-city of Karachi could be attributed to multiple factors, mainly excessive extraction of groundwater for domestic and industrial usage, or SWI engendered by geomorphological variations in the sub-soils (more details provided in the Discussion section). However, additional evaluations might be a prerequisite for confirming this—presenting an interesting research question for future studies. In addition, the underlying geology should also be considered to understand the drivers triggering the ground displacements in the study region, as highlighted in the results [26]. Therefore, in this case study, a revised and updated geological map of Karachi (Map Series No. 3) prepared by the Geological Survey of Pakistan is combined with ancillary geospatial information to understand the role of geology and lithology in causing displacements in the study area. See Section 5.1.1 for more details.

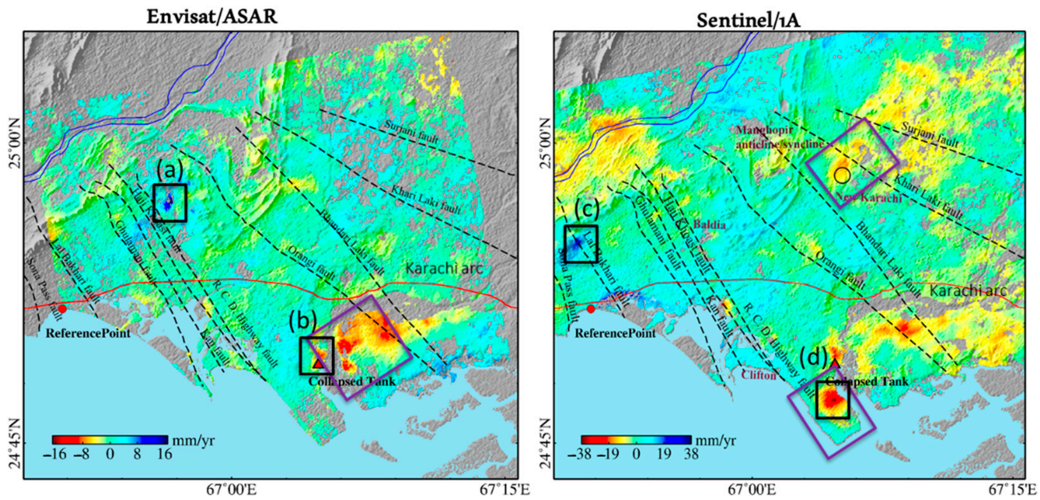


Figure 3. Vertical ground displacements in Karachi mapped through ENVISAT/SAR images over 2004–2010 (**left**) and Sentinel-1A images over 2014–2016 (**right**). Geologic features are overlaid, and major locations undergoing ground displacements are labeled (a–d) and highlighted. Positive values represent uplift, negative values represent ground subsidence.

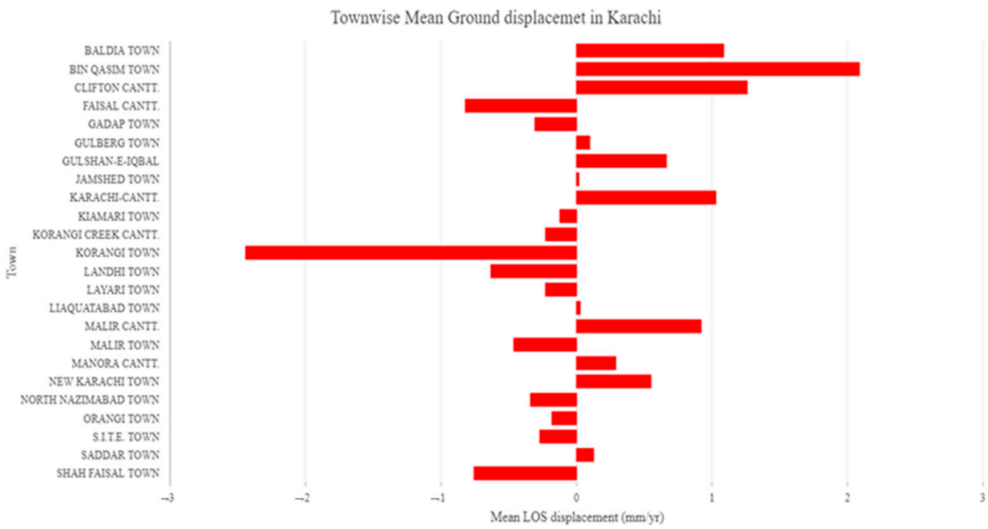


Figure 4. Town-wise mean ground displacements in Karachi.

The highest negative vertical ground displacement (subsidence) rates are found in the town of Clifton Cantonment, in the Defense Housing Authority (DHA) and Korangi Industrial Area (KIA) located on the downside of the seasonal river of Malir, both with a mean rate of vertical ground displacement greater than ~−5 mm/yr (see Figures 3 and 4). The town of Korangi houses about 3000 facilities for various industries, including steel, textile, automobile, pharmaceutical, chemical, flour, and engineering mills. This area is topped with irregular and loose deposits of semi-consolidated gravel in and around Karachi, such as the Malir River area, which are excessively used for construction purposes. The Malir Riverbed is formed by the recent/sub-recent stream bed deposits (Qsd) comprising loose fine-to-coarse sand, gravels, pebble, and boulders. Some of these materials, such as gravel, are of economic importance. Therefore, the subsidence in Korangi is most likely associated with this area's industrial and construction activities.

Uplift is also evident in some areas in the western end of the area of study, mainly those neighbouring the Mangopir Anticline (MA). The MA, and the adjoining Lalji syncline, are major large fault-induced Kirthar fold structures of the region that are cut across by the numerous northwest-trending sinistral fault lines (such as the Sona Pass fault), as shown in Figure 3. Displacement and movement of these wrench faults are antithetic to the southward-creeping Karachi Arc [42], which supports and reflects the ongoing uplift in the areas highlighted in the map (Figure 3). Sarwar and Alizai [43] also report that the triple junction tectonics [44] and the active fold belt geologic activity in the coastal region [43] reflect on the ground displacements in this area.

It is evident from the TCPInSAR-derived vertical map from Sentinel-1A acquisitions (Figure 3) that quite a large part of the area remains unstable after 2010. The map shows a spread of higher ground-displacement values to the new areas seen by Envisat/ASAR, particularly in the industrial zones of the city and reclaimed lands of the DHA Phase-VIII. Figure 5 summarizes the minimum, maximum, and mean regional change in vertical ground displacement in Karachi during 2004–2016. Subsidence in Karachi's east zone (with the highest subsidence rate reaching ~16 mm/yr in 2004–2010) has increased up to 38 mm/yr during 2014–2016 in Karachi's southern zone, including the neighboring Bundal and Buddo Islands (BI-5) (See Table 1).

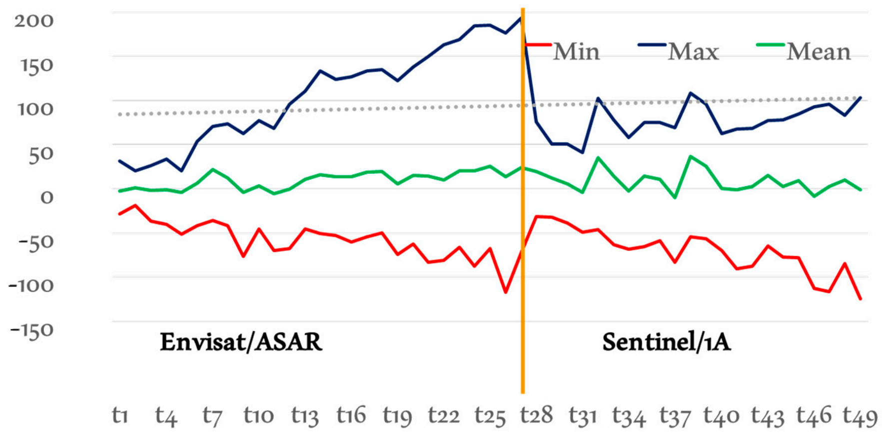


Figure 5. Minimum, maximum, and mean regional change in vertical ground displacement in Karachi during 2004–2016. The vertical orange line marks the data gap between two datasets (i.e., 2011–2013).

Similarly, in a rapidly urbanizing world, land-use and land-cover changes are also important factors to account for. Figure S2 in the Supplementary Materials reveals that most of the ground subsidence is identified in built-up and residential areas—particularly in Karachi's eastern region in the study area. Both of these are well-known factors of ground subsidence. On the contrary, the uplift is notable in Karachi's southern region, particularly in areas of commercial land use, followed by areas of transportation and build-up.

Table 1. Administrative-zone-wise statistical summary and trend of vertical ground displacements in Karachi (2004–2016).

Zone	Sites	Envisat/ASAR			Sentinel/1A			Trend
	(Towns)	Min	Max	Mean	Min	Max	Mean	
West Karachi	Baldia, S.I.T.E, Orangi	−10.81	24.04	−0.21	−18.93	33.082	0.58	↓
South Karachi	Kiamari, Saddar, Layari, Clifton, DHA, Manora	−9.92	5.96	0.797	−37.96	12.792	0.46	↑
East Karachi	Shah Faisal, Korangi, Landhi, Korangi Creek Cantonment, Gulshan e Iqbal, Jamshed	−15.62	6.57	−1.04	−22.44	10.929	−1.83	↑
Malir	Bin Qasim, Malir Cantonment, Gadap	−18.49	10.90	1.061	−16.03	11.78	−3.35	↑
Central Karachi	North Nazimabad, New Karachi, Gulberg, Liaqatabad	−5.28	5.86	0.134	−16.23	12.683	−0.97	↑

4.1.1. Vertical Ground Displacement Time Series

To examine the trends of ground displacement over time, the vertical ground displacement time series of four sites are represented in Figure 6; see Figure 3 for locations. Figure 6a illustrates the time series of an area of highest uplift bounded by the RCD Highway fault and the Orangi faults. Figure 6b profiles the time series of the area around the location of the collapsed tank. Figure 6c shows the time series of an area with the relatively lowest and most-stable subsidence over time, whereas Figure 6d shows profiles of the area of highest subsidence, which is increasing over time in the lands of the DHA reclaimed from the Arabian Sea.

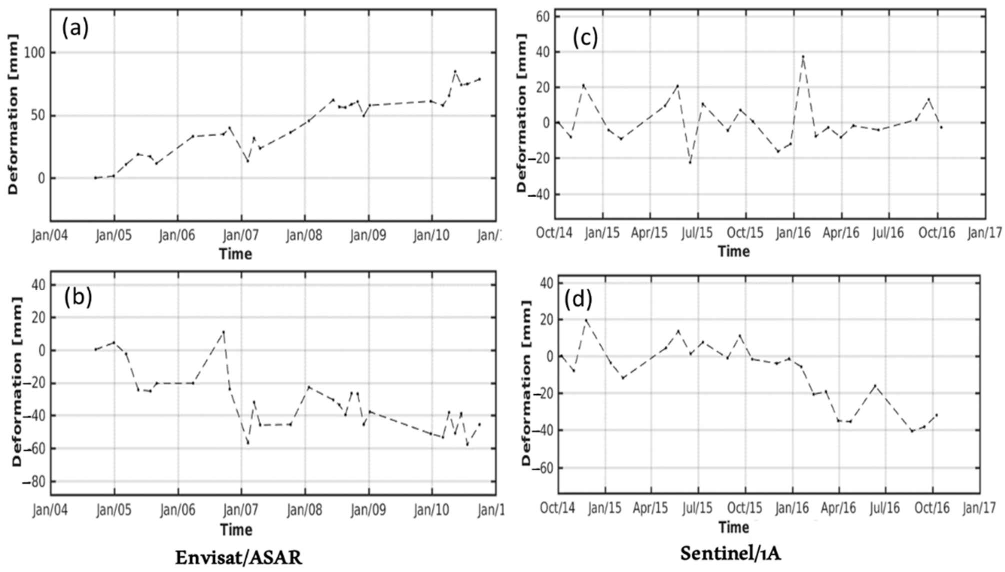


Figure 6. Time series of vertical ground displacement for the selected representative points (**a**–**d**) mapped in Figure 3. (**a**) Represents the location undergoing uplift near the Mangopir Hills in West Karachi; (**b**,**d**) mark the subsiding location in the area where water tanker collapsed in the DHA in South Karachi; whereas (**c**) represents a relatively stable location between the Haji Khoast Fault and Sona Pass fault in West Karachi.

4.2. Erosion Rate along the Karachi Coast (1989–2018)

The most developed part of the Sindh coast is the NW-SE-oriented coastal stretch of Karachi, characterized by raised beaches, marine terraces, sand dunes, shallow lagoons, and sea cliffs. A closer inspection of the coastline's change shows that the coastline of the study area oscillates between accretion and erosion (Figure 7). Annual coastal erosion is increasing along the west-east axis (same as the littoral drift), reaching its maximum of ~2.4 m/yr in East Karachi, located next to the Buddo and Bundal barrier islands, which have been eroding at an even higher rate (i.e., ~14.33 m/yr) [13]. In contrast, the displacement patterns are variable across the city over the 2004–2016 timeframe and along the coastline, precluding the probability of a relationship between coastline erosion and ground subsidence in general. The spatial distribution map of erosion along the coastline shows large distinctiveness for South Karachi relative to the other two sub-zones (East Karachi and West Karachi). An accretion rate up to ~8.34 m/yr is noted at the south side of the entrance to Korangi creek and the southern segments of the study area's coastline (i.e., the South Karachi sub-zone) (Figure 7). These noticeable changes in accretion observed along South Karachi's coastline are apparent in Figure 7, and they surface notably in the corresponding images from Landsat in different years. This finding is consistent with that of Luijendijk, et al. [45], who also found South Karachi to be experiencing very high accretion during 1984–2016. It is worth mentioning that the accretion measured in this sub-zone is artificial and predominantly attributed to the lands reclaimed from the Arabian Sea for the development of coastal infrastructure [46]. A comparison of the satellite images before and during the study period (more details are given in the following sub-section, Discussion) corroborates the coastline assessment's findings in this sub-zone (South Karachi).

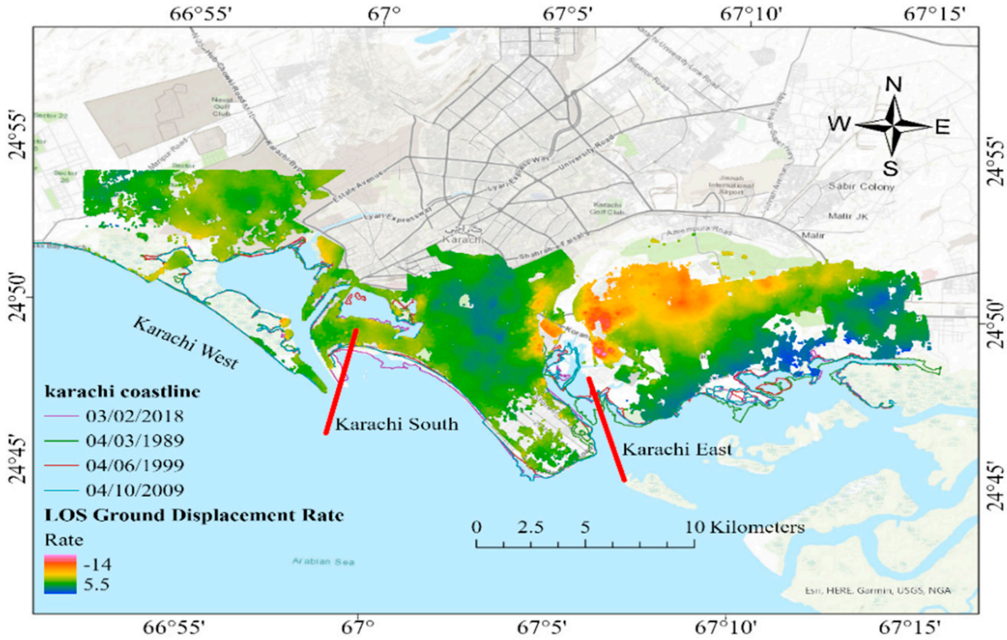


Figure 7. Evolution of Karachi's coastline from 1989–2018, obtained from Landsat along with LOS ground displacement (2004–2010).

Topographic slope controls vulnerability to coastal erosion, seawater intrusion, and permanent flooding. In comparison, the West Karachi sub-zone in the far west of the study area has a steep gradient (i.e., ~0–15.5%), whereas the other two sub-zones (i.e., South Karachi and East Karachi) have ~0–3.5% slope gradients. Most of the inland areas along the coastline are already at the same elevation level of the Arabian Sea. The slope of the land along Karachi's coastline is decreasing eastward while coastline erosion is increasing eastward [7], endangering the eastern segments of the study area, where Port Muhammad Bin Qasim, a major deep seaport of the country, is located towards Korangi creek. The development of a navigational channel to facilitate the passing of cargo ships via Phitti Creek to the port has caused erosion of up to ~−2.43 m/yr. In 1970, when this seaport started functioning, natural barrier islands located next to Port Muhammad Bin Qasim formed the first line of shielding against coastal flooding and storms. Erosion in the East Karachi sub-zone suggests that these natural barriers gaurding against the erosional effects coming from the Arabian Sea have already been badly impacted. This finding is broadly in accord with the earlier work of Kanwal, et al. [13], which also found that the islands were undergoing very high erosion (~8.9 m/yr). However, more assessment in this regard is required—this is left for future work.

4.3. Influence of Ground Displacement on Coastal Erosion in Karachi

The coastline changes and vertical ground displacement findings are not contrasting. While erosion processes underlie most of the eastern parts of the study area, the rate of vertical ground displacement is spatially variable along the coastline across the study area (See Figure 8). In other words, not all coastline segments with high annual mean erosion rates are linked with mean subsidence (Table 2). This implies that subsidence can exacerbate ongoing erosion and its impacts. Regions that exhibit coastal erosion show a variable ground subsidence signal along the coastline, with larger values in Karachi's southern and eastern zones, particularly in the areas located next to the Indus Delta during 2004–2010 [17]. A similar interaction is observed for the coastline segment where the rate of coastline erosion up to ~2.4 m/yr corresponds spatially with a rate of vertical ground displacement up to ~−1.4 cm/yr. These observations illustrate the regional variability of these complex drivers responsible for coastal changes of the low-lying deltaic coasts.

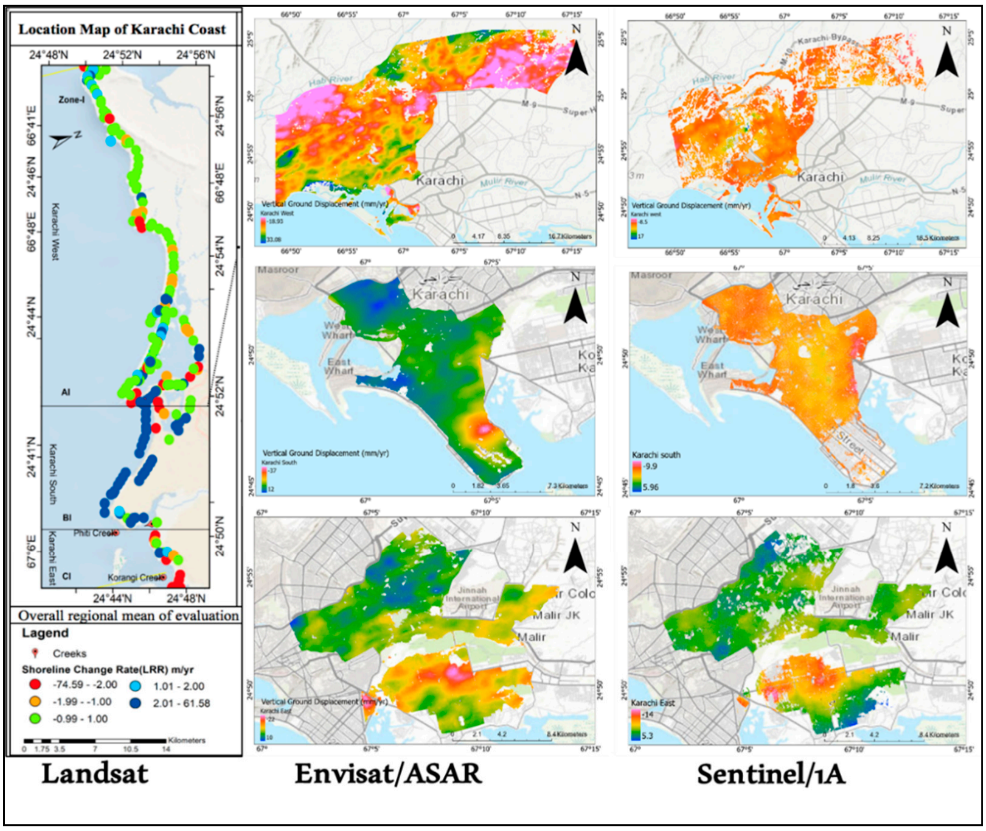


Figure 8. Karachi coastline change rates estimated by the LRR method using USGS DSAS for the period 1989–2018 (**left**). The zone-wise map shows the regional distribution of mean vertical ground displacement in the coastal zones (**middle** and **right**). These distribution maps show an expansion in extent between subsidence and uplifting over the time in the study area from 2004 to 2016 with substantial subsidence in the DHA, Korangi, and Landhi areas.

It is noted that the present trend of coastline erosion increasing (west-east) will continue to cause coastal changes in the eastern segments of Karachi (including Korangi Creek and the outlying natural barrier islands), mainly due to both marine processes and human intervention, if timely and appropriate actions are not taken. In Karachi's eastern zone, the subsidence rate reached its highest at 16 mm/yr during 2004–2010, but this has increased up to 38 mm/yr during 2014–2016 in Karachi's southern zone and the neighboring Bundal and Buddo barrier islands. The maximum subsidence rate quantified in this study is greater than the tide gauge-measured rate of SLR (i.e., 1.9 mm/yr) measured by Kanwal, et al. [7] and 3.6 mm/yr Khan, et al. [11] (see Table 2). This indicates that although subsidence alone does not account for the high rates of coastline erosion, it can intensify the erosive processes by inviting more seawater inland and is associated with more frequent over-washes and lagoon breaching [47].

Table 2. Coastal evolution and possible contribution of erosion, ground displacement, and mean sea levels along different section of Karachi's coast.

Section	Coastline Change Rate (m/yr)—Landsat			Coastal Zone Displacement Rate (m/yr)—TCPInSAR			Mean Sea Level (mm/yr)
	Min	Max	Mean	Min	Max	Mean	
West Karachi	−0.43	−4.112	2.168	−0.33	−7.14	8.60	1.9
South Karachi	8.34	−74.59	62.04	0.22	−5.8	2.92	
East Karachi	−2.43	−10.66	2.5	2.1	−13.95	7.7	

5. Discussion

This study provides a detailed assessment of ground displacements and their possible association with coastal erosion in the largest city of Pakistan—Karachi—via leveraging integrated remote sensing (RS) and geographic information systems (GIS) practices. The results presented here are of particular interest to coastal/urban planners, decision-makers, and relevant stakeholders. For instance, the areas with the largest ground subsidence (i.e., Korangi and reclaimed areas) should be prioritized when evaluating the possible causes and designing measures to prevent them. This could progressively help avoid impacts to society and reduce the likelihood of financial losses. In addition, this research provides a roadmap to establish a baseline inventory of ground displacement information at localized levels (i.e., Figure 3). This assessment can further be extended to higher-resolution administrative units to provide reference to local bodies for designing appropriate action plans. For example, Figure S3 in the Supplementary Materials provides a comparison of different union councils (the smallest admin-level for resource allocation in Pakistan). The LOS ground displacement in ~55% of union councils (29 out of 52) should be a point of immediate concern for the relevant authorities.

5.1. Potential Factors Inducing Ground Displacement

5.1.1. Role of Geology and Lithology

As mentioned earlier, the entirety of Karachi lies on the junction where two tectonic plates meet, with several active faults passing through the city and causing geological activity in the study area, as shown in Figure 9 [48]. Although these geological movements may cause ground displacements in this area of interest, the amount and distribution of ground displacements are not fully understood. Sarwar and Alizai [43] suspect that epicenters of a group of earthquakes located between the Malir River and Hyderabad motorway might explain the current shallow ground displacements in this area (Figure 9). Areas along and south of the suspected Malir-Lyari Rivers fault zone, from where earthquake reports regularly come, are the same places where higher ground displacement rates are observed. This could be a sign that the Malir River fault is active. To understand the role of currently mapped geologic faults in the study area and their contribution to cause ground displacements estimated through interferometric processing, ancillary geospatial information related to the current faults in the study area is incorporated. However, no significant association between the currently mapped faults and ongoing vertical ground displacements is observed in the study area. Sarwar and Alizai [43] anticipate geological structures in the city that are currently unmapped, as marked by the deflection in the riverine flow. Another potential factor causing ground displacements could be flash flooding in the Malir Riverbed, which might, in turn, increase the moisture level of the soils, weaken the bond strength between the soil particles, and thus causing the ground to subside. The Malir River Basin used to have an extensive network of streams that is now being lost from the city's geomorphology due to unplanned urban encroachments. Our results put emphasis on paying due care and consideration to the environmental aspects of aforesaid unplanned urban and geological development activities and encroachments.

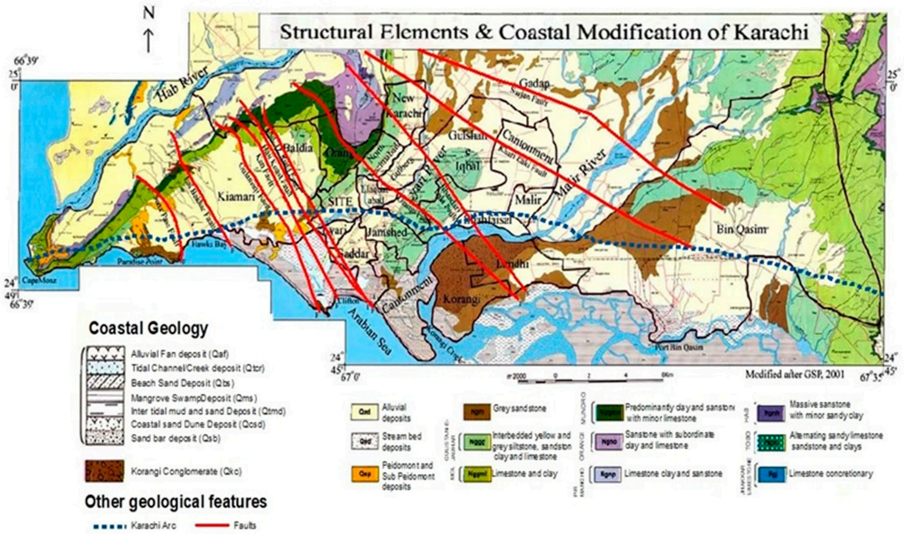


Figure 9. Fault lines (red lines) and Karachi Arc (thick dotted blue line) overlaid on the Geological Map of Karachi. Karachi Arc appears to be creeping eastward, which is directly related to active subsidence of the Hyderabad graben that underlies it (Source: [27,43]).

5.1.2. Unregulated and Excessive Groundwater Extraction

Another factor related to the site-specific variability in the displacement rate is the uneven distribution and unregulated installation of private groundwater extraction wells. In line with other studies [18,49,50], it is noticed during field visits for this study that acute water shortages in the Karachi city have forced residents to install private groundwater extraction wells on a large scale to meet their domestic water needs. The lack of water supply has given way to excessive groundwater extraction in the Clifton and DHA coastal areas, which is likely to cause subsidence, a phenomenon identified along the National Highway [51]. Amin, et al. [18] argued that uncontrolled groundwater withdrawal has caused ground subsidence in the Karachi city, based on the recorded data of the depleting groundwater levels in Qayyumabad, investigated by Khan, et al. [52]. However, no data on groundwater table for areas along the coast and sewerage network plan for the city are available. Consequently, it cannot be included in the analyses. If available, integration of this information could facilitate simulation of aquifer compaction and scenario analysis. Assessment of vertical ground displacements (subsidence) can provide more information with respect to different factors, such as interbed storage, aquifer compaction due to groundwater extraction, and overuse of the land. For example, Jafari, et al. [49] has undertaken similar work for one of the cities in Iran. Similarly, Jafari, et al. [50]) forecasted subsidence due to the over-extraction of water using a MODFLOW model and InSAR integration.

5.1.3. Structural Damage Due to Failed Sewerage System

Vertical ground displacements in the study area are also linked to land-use activities, such as mining, shallow compaction or structural instabilities, and sewerage network breakage. During the collection of photographic evidence (Figure 10), it was learned from the local people and petroleum experts that another probable source of site-specific/localized variations in the ground displacements, observed in different parts of the study area (accelerating SWI), could be broken sewerage and water supply lines (a potential source of soil liquefaction in the study area) [53]. A drain collapse could cause the ground around it to subside over time via water leaking from the pipe and into the soil. The structural damage caused by failed sanitation and drainage networks explains the site-specific variability in the ground displacement rates.

Figure 10. Signs of ground displacements in the study area. (**a**) Cracks in the building walls due to differential ground displacement; (**b**) elevation of a residential house in the University of Karachi's Professors colony has dropped to ~2 m below its base-level due to soil liquefaction caused by seawater intrusion. During the field visit, signs of soil salinity were observed in different parts of the University of Karachi.

Lodi, et al. [54] also posited immense leakage and overflows from damaged water supply and sewerage lines throughout the Karachi, particularly in the coastal areas, which is likely to wash away the underlying soil and cause soil liquefaction and settlement. Furthermore, JICA [53] reported that sewer line waste had been mixed with water supply in some areas, causing unhygienic conditions and diseases. It is unfortunate that no comprehensive GIS information about the water supply system and sewerage network is currently available or accessible to researchers, hindering the ground displacement evaluation along the broken sewer lines and the health of this mega-city's sewerage as well as its water supply system. From reports from various media sources, the National Institute of Oceanography (NIO), and other institutions, it is evident that Karachi is indeed facing the dual threat of ground displacements and sea-level rise. However, it is unclear whether ground displacement gives rise to sea levels, favoring coastline erosion, or vice versa.

5.1.4. Land Reclamation

Many high-rise buildings along Clifton beach, DHA Phase-VII, and several housing projects have been developed on offshore reclaimed lands, as shown in Figure 11. Observations from different stakeholders, reported in the final Environmental Impact Assessment (EIA) reports of various housing projects, highlight that signs of subsidence are apparent in the coastal area and any further stress is likely to produce a catastrophic situation [55,56].

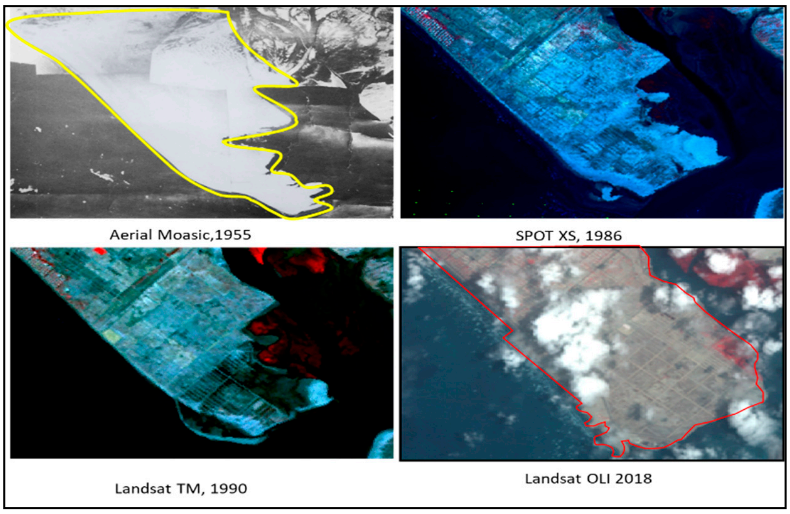
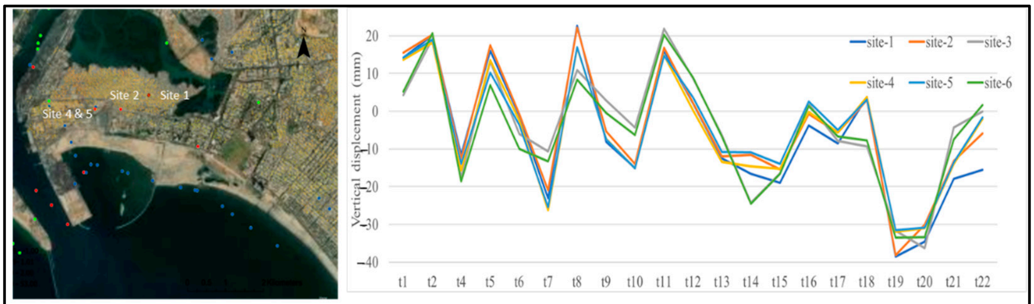


Figure 11. Expansion of Defense Phase VIII over land reclaimed from the Arabian Sea during the 1955–2018 period.

5.1.5. Liquefaction

The coastal region of Karachi is highly prone to soil liquefaction in the case of any severe seismic events of magnitude seven or above [54]. This problem was realized after scientific investigations of the water storage tank collapse in 2006 in the DHA. Mahmud and Sheikh [57] reported that an 80-foot high water tank in the DHA collapsed and was vertically submerged 70 feet into the ground in 8 min due to an earthquake event that induced liquefaction. The remaining 10 feet of the tank stayed above the surface. Soils in this part of the study area are particularly susceptible to liquefaction threats, being rich in water and increased salinity with poor cementation of soil grains [25]. This study found a higher average subsidence rate (>15 mm/yr) near the location of the water tank collapse, as shown in Figure 11. Different areas in the DHA and Clifton regions are unstable and are thus undergoing ground deformation, as large parts of these areas are comprised of land reclaimed from the sea. Another potential reason for these localized ground displacements is damaged sewerage and water lines, which might increase the possibility of soil liquefaction. Recently, various commercial projects have been announced for the coast, which raises many concerns [58] due to the land's potential for liquefaction and subsidence. Along the study area's coastline, the analysis of six specific sites for comparison of their coastline erosion and InSAR derived coastal displacement (Figure 12) shows the potential of InSAR to examine and explain localized changes in coastal areas. However, as the specific sites selected for the time series analysis are not all located close to the coastline, their vertical ground displacement is not directly affected by the coastline's erosive regime. Therefore, it can be considered to reflect subsidence only [47].



Site	Town	Land use	Erosion (m/yr)	Mean vertical displacement (mm)
site-1	Karachi south	Residential, and Residential with Commercial Services	−1	−6.14
site-2	Karachi south	Built-up Open/Barren Land,	−9.63	−4.186
site-3	Bin Qasim	Built-up Open/Barren Land	−0.25	−4.204
site-4	Karachi south	Industrial and Manufacturing	−9.97	−5.50
site-5	Karachi south	Built-up Open/Barren Land	51.54	−4.71
site-6	Korangi Cantonment	Military Area (built-up)	2.52	−5.39

Figure 12. Location of six sites selected for coastline erosion and mean vertical displacement (**left**) spatial analysis. Mean vertical ground displacement time series from Envisat/ASAR 2014–2016 (**top right**) and land use, coastline change rate, and displacement values at each site in different coastal towns of the study area (**bottom right**).

6. Limitation and Way Forward

There are some limitations of this ground displacement study that restrict the generalization of the results at this stage. For instance, because GPS records were not available in the Karachi city and neighboring Indus River Delta, subsidence could only be detected relative to a reference point that was assumed to be stable. Calibration with in-situ GPS devices allows precise measurements of absolute ground displacement rates and allows InSAR to resolve more processes. Wherever possible, in situ GPS records should be exploited to ensure that InSAR can provide absolute subsidence measurements. However, GPS specialists measuring absolute subsidence might collaborate with oceanographers or wetland botanists who understand local oceans and flora in order to evaluate the true stability of low-lying lands in the coastal regions. Furthermore, validation of the ground displacements observed using InSAR data was mainly inhibited by the unavailability of ground surveys. Therefore, the present study primarily focused on analyzing the results from Envisat and extending the analysis using Sentinel-1A for further investigation and validation. We believe that monitoring the progressive ground displacement with SAR interferometry can offer valuable evidence for assessing the impacts of ground displacement and its influence on coastal erosion and relative sea levels, and provide important references for adaptation strategies [59]. The results presented in this study will potentially influence the monitoring of risk to infrastructure on a regular basis, the collection of ground surveys for validation of future data, and outcomes based on the location of the ground displacements and geological patterns.

Similarly, with the launch of new SAR satellites and sophisticated processing of the altimetry products, unprecedented near real-time monitoring of vulnerable coastal/delta cities will become possible. SAR data must be made freely and easily accessible to researchers by space agencies for all of these applications. A priority for future work may also be extending ground displacement work to the other two zones from the IDR (i.e., the East and West Indus River zones).

7. Conclusions

It is well documented that the location of the coastline in sinking basins depends on the rates of ground displacement and sediment influx. For the Indus River Delta and its surroundings, including the Karachi coastline, these two factors have varied together with relative sea-level rise, causing coastline regression and transgression over time. Therefore, we believe that the SLR-based assessments of inundation risk due to flooding have underestimated the actual risk in Karachi's coastal regions. The analysis of datasets shows visible displacement in various sections of the city and erosion along the low-lying Karachi coastline. To gauge the risk to infrastructure based on the spatial distribution and pattern of ground displacements, available high-resolution remote sensing satellite data and geological information should be acquired and incorporated. In this context, the primary purpose of this study was to examine the interplay between ground displacements (2004–2016) and coastline changes (1989–2018) in Karachi (the most populous city in Pakistan) via combining the Landsat images and InSAR data.

It was observed that the annual mean coastline erosion increased from west to east. In contrast, the ground displacement patterns were highly variable across the city and along the coastline, precluding a link between coastal erosion rates and subsidence in general. Using InSAR in the proximity of the coastline was quite complex due to the ever-changing condition of the dynamic coastal landscape. Within a distance of a few hundred meters from the coastline, the ground displacement rates obtained by InSAR could be affected by sediment deposition. The vertical ground displacements obtained through interferometric processing of both the Envisat/ASAR and Sentinel-1A images showed that quite a large part of the study area was not stable. This is unsurprising since the Indus River delta, which is about 79 miles from Karachi, is already subsiding at the rate of 1.3 mm/yr, as confirmed by Syvitski, et al. [3]. Taken together, the findings of this study suggest that some areas along the Karachi coast are subsiding at rates comparable to the SLR, which may amplify the rates of the relative SLR in years to come. The miscellaneous data suggest that the coastal areas face the hazard of seismo-tectonic incidents leading to settling the land in some parts and uplifts in other areas caused by mining activities, shallow compaction, structural instabilities, excessive groundwater extraction, sewerage network breakage, and/or liquefaction.

There is a lack of research in the study area that jointly discusses the localized dynamics of coastal erosion and ground displacements. To the best of our understanding, the present study is among the pioneer attempts, particularly in developing countries, to highlight unseen factors (i.e., sewer lines breaking, overuse of land, and coastline erosion) which might be responsible for ground displacement. In addition, we examined displacement's influence along the Karachi coastline by utilizing Landsat images in combination with InSAR. Kanwal, et al. [7] discussed that the coastline retreat was caused by sediment supply to the Indus River and SLR. Amin et al. (2021) discussed the ongoing subsidence in small segments of Karachi. This study demonstrates that ground displacements and their influence on the coastline erosion in the study region are important drivers for coastal changes and should also be considered along with other factors in further research for coastal hazard assessment at the regional and local scale. This work will serve as a baseline and be used as a blueprint to track coastline changes and ground deformations once longer records of InSAR and in situ data become available. In addition to contributing to the explanation of the longitudinal erosion in the study area, the outcomes of this project are relevant for real estate developers who are reclaiming land from the Arabian Sea to meet the housing needs of the city. This study will potentially influence the monitoring of risk to infrastructure on a regular basis, the collection of ground surveys for validation of future data, and outcomes based on the location of ground displacements and geological patterns.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14092054/s1, Figure S1: Perpendicular and temporal baselines of the selected interferometric pairs (blue line) (a) ENVISAT ASAR, and (b) Sentinel-1A IW SLC (green dots); Figure S2: Ground displacement in different land use land cover areas in the study area; Figure S3: Union council wise localized assessment on ground displacement; Table S1: Coastal Evolution and possible contribution at each section of Karachi coast; Table S2: Sentinel-1A SLC images used for ground displacements monitoring during 2014–2016 period over Karachi (*Master image); Table S3: Details of Landsat images used in the study for coastline delineation and erosion estimation.

Author Contributions: Conceptualization and methodology, S.K.; formal analysis, S.K. and S.W.; investigation and data curation, S.K.; resources, X.D.; and writing—original draft preparation, S.K.; writing—review and editing, S.K., M.S., S.W. and X.D.; visualization, S.K., S.W. and M.S.; supervision, project administration, and funding acquisition, X.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are openly available in the repositories, acknowledged and mentioned in the data source within this article.

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