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SAR-based Subsidence Monitoring and Assessment of the Factors Involved in the Occurrence of Subsidence, Lahore City

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Abstract: The judicious use and management of natural resources is vital to achieve sustainable development. Land and water are prime natural resources, and their depletion and degradation can lead to serious threats like land subsidence. Land subsidence is a phenomenon of the alteration of elevation at a point on the earth through the sinking of the surface. It occurs when the earth's surface loses its support. The major causes of land subsidence include groundwater extraction, mining, construction overload, and other similar factors that increase pressure on the surface and eventually subsidize the land. Urban centers with excessive groundwater extraction and infrastructure development are at a high risk of subsidence. Lahore, the second-largest city in Pakistan, is undergoing an enormous increase in population density, uncontrolled urbanization with very large-scale construction projects, and intensive groundwater extraction which are responsible for subsidence directly or indirectly. Therefore, studies on groundwater status and unplanned urban appraisals have seriously urged monitoring of the subsidence in Lahore. Herein, we used freely available Sentinel-1 data for one year (from August 2018 to August 2019), with a high spatial and temporal resolution, to monitor subsidence in Lahore. The data were processed using the SNAP/StaMPS approach for Persistent Scatterer Interferometric Synthetic Aperture Radar (PSI) analysis, which is an advanced InSAR technique. The displacement velocity map from InSAR processing shows a significant land deformation in the area with values ranging from −114 to 15 mm yr^{-1}. Along with the Sentinel-1 data, we also used supplementary data obtained from various government agencies of Pakistan to study the land cover map, transportation network and waterways of Lahore, soil types, population density, and field points for assessing the results and understanding the roles of various factors in the occurrence of uplift or subsidence. A strong correlation was established between subsidence and various parameters such as groundwater extraction and lowering of the water table, soil type variations, land cover changes, surface water channels, and population density. The deformation map confirms the greatest subsidence in the central part of Lahore, while the uplift is observed in the less populated and rural areas situated near Ravi River. The land subsidence and uplift could be attributed to groundwater extraction and recharge through the canal system and the river, respectively.

Key words: Sentinel-1; subsidence; PSI; groundwater extraction; urbanization; Lahore

1 Introduction

Land subsidence is the steady settling or abrupt sinking of earth's surface due to the subsurface movement of the earth's material as a result of various anthropogenic or/and natural factors. The major anthropogenic activities include mining for mineral extraction or drilling to extract ground-

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water, gas, and oil. Similarly, the natural factors causing land subsidence are the melting of permafrost, movements of plate tectonics, and hydrogeochemical changes which reduce sediment size or reshape the sediment rocks (Holzer, 1991). Land subsidence is globally recognized as a disastrous geological phenomenon, especially in fast-growing urban regions. It destroys urban infrastructure and the environment, leads to the loss of resources, poses a serious threat to human lives and routine activities, and results in economic crises and constraints to progress (Pacheco-Martínez et al., 2013).

Rapid urbanization and the construction of megacities are playing a key role in the occurrence of land subsidence. A huge rise in population demands excessive groundwater extraction which leads to the abrupt sinking of the surface due to the decline in the groundwater level. It is a globally established reality that groundwater extraction is leading to land subsidence in larger cities (Budhu and Adiyaman, 2010; Erkens and Sutanudjaja, 2015; Kanwal et al., 2018; Cian et al., 2019). Furthermore, very large-scale infrastructure development and excessive transportation pressure are also contributing to the sinking of the surface, particularly on soft soils. Cities located on soft un-stratified soils composed of silt, sand, and clay, are more prone to subsidence; and these areas are mainly located on shores and riverbanks. Groundwater extraction causes large-scale subsidence while the infrastructure load is the source of localized and small-scale subsidence (Zeitoun and Wakshal, 2013). Subsidence is a continuous and widespread phenomenon, although its manifestation is usually not prominent enough to alert the stakeholders before the hazard takes place; therefore, continuous monitoring is very important. Land subsidence is a slowly occurring process and produces noticeable changes only over a long period. Therefore, the implementation of advanced techniques for the continuous temporal assessment and monitoring of the changes in the land surface is strongly recommended before the occurrence of any serious damages or losses (Hu et al., 2004).

Conventionally, a large number of techniques and methods are available to detect subsidence at small and large area levels. These techniques include Global Navigation Satellite System (GNSS) based monitoring, groundwater monitoring, photo geological analysis, repeated optical leveling, tape extensometers, and ground reconnaissance. Although, these methods of subsidence assessment are reliable, they are time-consuming, expensive, and not convenient even for the monitoring at regional and smaller scales (Baldi et al., 2009). Advanced techniques such as tiltmeters, array-based microseismic monitoring, and comparatively advanced instruments such as Time-Domain Reflectometry (TDR) and Interferometric Synthetic Aperture Radar (InSAR) could be used as a suitable alternative (Fergason et al., 2015). Synthetic Aperture Radar (SAR) interferometry is capable of monitoring and mapping the changes in land surface with high accuracy, millimeter-level precision and temporal reliability through regular revisits (Strozzi et al., 2001; Herrera et al., 2010; Erkens et al., 2015).

Land subsidence is a global phenomenon, and its impacts are more evident in cities while the results are often unidentified in unpopulated remote areas. Large urban centers such as Bangkok, Jakarta, Beijing and Mexico City are experiencing land subsidence. Urbanization, population growth and excessive groundwater extraction are increasing subsidence hazards in all parts of the world, hence continued monitoring and assessment is vital. In this regard SAR data have been reliably used for subsidence monitoring. Studies have proven the utility of Sentinel-1 data and InSAR techniques to assess land deformation and its relationship with urban development, groundwater exploration, lithology and other parameters. The phenomenon of land deformation in Pakistan, as in various other parts of the world, demands attention from the authorities. The present study is mainly focused on monitoring subsidence in Lahore, the capital city of the province Punjab and the second-largest city in Pakistan, with an estimated population of 11 million as per the 2017 population census statistics. The population has increased immensely as a consequence of the conversion of neighboring rural areas into developed housing societies, and there is significant evidence of unplanned urbanization. Furthermore, massive construction and transportation projects, such as metro bus service, the orange line train, and multiple under and overpasses, have been accomplished in a short period (Rana and Bhatti, 2018).

The sole source of water for Lahore City is groundwater, which is extracted through tube wells. Lahore Water and Sanitation Authority (WASA) have installed about 500 tube wells in the city to extract 1363827 m^3 of water from the aquifers every day. Additionally, tube wells installed in the private sector are reported to extract 681913.5 m^3 of groundwater per day (Kanwal et al., 2015). Several studies have investigated the groundwater quality, the decline in the groundwater level due to over-extraction, the reduction in aquifer recharge, and unplanned urbanization (Hassan et al., 2014; Kanwal et al., 2015; Basharat, 2016). Groundwater removal is an admittedly prominent cause of land subsidence, but current trends of urbanization have significantly influenced land characteristics. Construction activities in urban areas are contributing to more than 30% of the subsidence in these areas (Strozzi et al., 2001), and rapid mega construction is observed in Lahore, but it is not yet monitored in the context of land deformation. All the factors described above make this area more susceptible to land subsidence. Multiple studies have strongly emphasized the need for a comprehensive study on monitoring subsidence in Lahore City (Ahmad et al., 2002; Hassan et al., 2014; Kanwal et al., 2015; Basharat, 2016). These studies pointed out that the continuous lowering of the water table and rise in population, the creation of a depression zone, and the mega construction projects might have caused subsidence in the area and there is a dire need to monitor the status of the land surface in this area.

In the present study, an advanced PSInSAR technique is employed on Sentinel-1 data acquired for one year (from 2018 to 2019) along ascending orbits for the spatial-temporal assessment of subsidence in different regions of Lahore City. The current study provides the first-ever evidence of land deformation in Lahore, and the areas with different deformation rates are highlighted. Freely available Sentinel-1 SAR data and SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model), along with multiple ancillary datasets, are employed for subsidence monitoring and analysis. The relationships between subsidence and various factors, such as groundwater extraction, the static water level in various parts of the city, soil type and nature of the soil, land cover, population density, transportation networks, and surface water channels, are also established to interpret the results and better understand this phenomenon in various parts of city. The unusual trends of subsidence, such as stable land in areas even with a high population density and a large number of tube wells, are also explained by considering the surface water channels and their contribution to recharge.

Our work is significantly important as it not only provides the first deformation map of Lahore and establishes its relationships with various triggering factors, but also aims to achieve the United Nations (UN) 11th goal (SGD 11) which is “the development of sustainable and safe cities” for the residents, addresses current urbanization trends across the globe and considers the impacts of unplanned urbanization (United Nations, 2015). This goal could be achieved by planned urbanization which first requires a suitable area for construction. For example, in 2020, the government of Pakistan launched a mega housing project, named “Naya Pakistan Apartments PC-1,” that promises 35000 houses in Lahore City and even extends beyond this number in upcoming years (Dawn, 2020). The paper also points out areas with stable land surface and groundwater levels which have the potential for use. We believe that our study could help government authorities, especially planning and construction departments, in the selection of appropriate areas and controlling the building pressure index on the ground to mitigate the risks of economic and life losses caused by subsidence. This study also proposes extending the road networks to the parts of the city which are less prone to subsidence, which would ensure the provision of a sustainable transport system for all the residents and improve road safety. Furthermore, another objective of this study is to indicate the areas where artificial recharge structures urgently need to be installed, which parts of the city have a sufficient scope for water extraction, and areas where water extraction must be restricted. In short, our study could help to achieve sustainable settlement planning and make the second largest city of Pakistan (Qureshi and Sayed, 2014) a safe, resilient, and sustainable place to live.

2 Study area

Lahore, the second largest city of Pakistan, lies between 31°20′–31°50′N latitude and 74°05″–74°37′E longitude as shown in Fig. 1, and is located within an alluvial plain of the Ravi River (Naeem et al., 2006). It covers area of 1772 km² and is at elevation of 217 m above sea level. The soil is mainly composed of silt, loam, and sand, consisting of deposits transported from rivers and streams. The alluvial sediments of a few hundred meters in thickness comprise the surface soils (Muhammad et al., 2016).

There are two main aquifers in Lahore, deep and shallow, which are composed of heterogeneous alluvial sediments. A huge decline in the water table has been recorded over recent years due to excessive extraction and inadequate aquifer recharge, which are inversely related (Ahmad et al., 2002; Kanwal et al., 2015). Climatic changes have adversely affected the patterns of rainfall and excessive construction has reduced the runoff rate. Lahore relies on groundwater as the main source to fulfill domestic and in

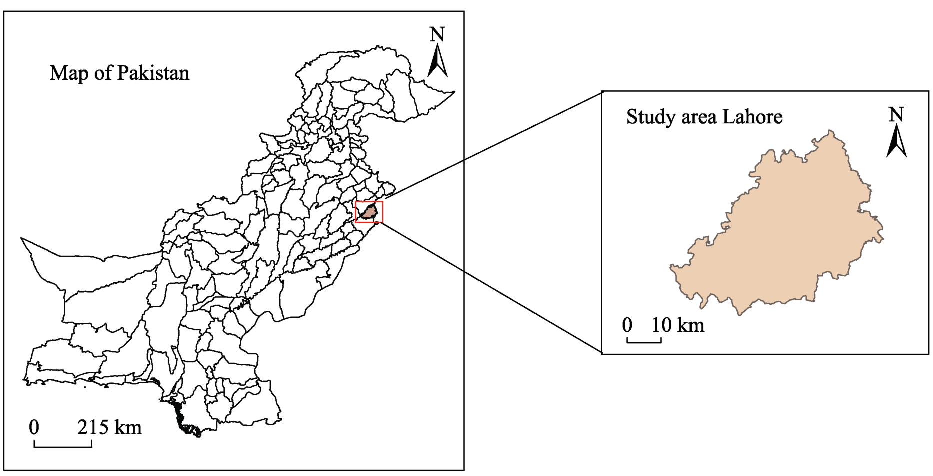

Fig. 1 The map of Pakistan and geographical location of Lahore

dustrial demands (Ahmad et al., 2002). The sunken tiny pore spaces are loaded up with water pockets which make up the hydrostatic pressure factor in a pore. At the point when the molecules of water are removed, a vacuum is generated and the hydrostatic pressure in the void is reduced; as a result, the pore space breaks down, and the entire surface of the earth subsides (Holzer, 1991; Hu et al., 2004; Pacheco-Martínez et al., 2013). In this regard, mega construction activities and transportation networks are also playing a significant role (Nawaz et al., 2019).

3 Methodology

3.1 Data, techniques and software

The main steps of the method employed in the present study include the collection, processing, and analysis of SAR and ancillary data using different software packages and techniques. First of all, freely available Sentinel-1 data were acquired from the Copernicus Open Access Hub developed by European Space Agency (Ferretti et al., 2007). Sentinel-1 data have been widely used in subsidence monitoring. The downloaded data consisted of 33 images. A SNAP-StaMPS based PSInSAR technique was adopted for the processing of the data to monitor land subsidence in Lahore. SNAP (Sentinel Application Platform) is one of the most highly utilized freely available tools for pre-processing of Sentinel-1 data.

The Stanford Method for Persistent Scatterers (StaMPS) was used for post-processing of the data. StaMPS is an open-source package for research-based activities and is compatible with the output generated by SNAP due to the advanced features of SNAP (Budhu and Adiyaman, 2010). StaMPS consists of two algorithms, a small baseline subset (SBAS) and Persistent Scatterer Interferometry (PSInSAR), to assess ground deformations using a time series of SAR acquisitions (Hooper et al., 2010). For continuous subsidence monitoring and to monitor deformations with a low velocity, long-term data is required which in turn leads to decorrelations by reducing the usefulness of the interferogram. Anthropogenic structures in metropolitan territories are expected to be coherent for long periods, so interferograms covering metropolitan zones have meagerly consistent patches with information. An approach that utilizes these coherent point targets is known as Permanent Scatterers Interferometry (PSI).

In the present study, we adopted PSI to monitor subsidence in Lahore. PSI with synthetic aperture radar (SAR) is a robust tool for significantly precise assessments of land deformation (Strozzi et al., 2001; Fergason et al., 2015) and is most suitable for urban areas where land subsidence is triggered by the rapid pumping of water. PS utilizes sizeable stacks of images to produce differential interferograms concerning one common master image. All combinations are used including those which have surpassed the critical baseline. Only pixels that remain coherent and are known as permanent scatterers are considered. For non-urban areas, PS density is considerably low (Baldi et al., 2009; Cian et al., 2019). This approach enables users to identify areas where land deformation is occurring. The steps of SNAP and StaMPS processing are shown in section 3.3. The ancillary data obtained from various agencies were also processed using different software programs for the final assessment of the obtained results. Tables 1–3 show the details of the data and software employed in the present study.

3.2 Sentinel-1 data processing & analysis

First of all, Sentinel-1 data, in the form of 33 images downloaded from the Copernicus Data Hub, were processed to obtain the subsidence results. Sentinel-1 data provides a 20 m spatial resolution and 12-day revisit time for certain parts of the Earth. It has many desirable features such as higher temporal resolution, the capability of its imaging

Table 1 The features of Sentinel-1 data

Mission name (Agency)	Start-end date	Free	Frequency	Repeat cycle	Incidence angle	Resolution	Orbit direction
Sentinel-1	Aug., 2018 to Aug., 2019	Yes	C-Band	12 days	33.725°–43.875°	20 m	Ascending orbit

Table 2 The ancillary data and its sources

Data type	Source
Tube well locations & water level data	Water & Sanitation Agency (WASA)
Landsat 8 imagery	United States Geological Survey (USGS)
Soil type map	Geological Survey of Pakistan (GSP)
Water channels & transportation network data	Local authorities
Field survey points and pictures	Field survey

Table 3 The details of the software used to process data

Software	SNAP	StaMPS	Python IDLE	ERDAS- IMAGINE	Q-GIS/ArcGIS	SPSS
Purpose of use	Pre-processing (Coregistration to DInSAR)	Post processing (PSI analysis)	Baseline (Perpendicular & temporal image)	Satellite image classification	Mapping of results	Statistical data representation (Regression analysis)

resolution to enhance derived coherence, successful implementation, and the consistency of results with other SAR sensors as reported by various studies (Ge et al, 2009; Chen et al., 2020; Khorrami et al., 2020). The processing was achieved in two steps, preprocessing in SNAP and post-processing in StaMPS.

3.2.1 SNAP DInSAR pre-processing of Sentinel-1 data

The sequence of SNAP Differential Interferometric Synthetic Aperture Radar (DInSAR) preprocessing is described here in detail. The data were imported into SNAP (1st step). The Sentinel-1 Single Look Complex (SLC) product has three interferometric widths, and all of the 33 images were split to obtain the 2nd width (IW-2) before the selection of the master image, as our study area lies in IW-2. The splitting was performed using the Sentinel-1 split tool (2nd step). The master selection was done following the shortest temporal baseline method (3rd step). The temporal baseline is an effective method in urban studies (Hooper et al., 2004).

Figure 2 represents the master-slave configuration for land subsidence in Lahore. Each point of Fig. 2 refers to one SAR image and each line refers to an interferometric pair. The horizontal and vertical axes define the temporal and perpendicular baselines, and the green dots represent images and interferograms are connected to the master image in the center. Coregistration (4th step) was performed using Sentinel-1 toolbox 30 m with SRTM DEM to ensure the pixel-to-pixel alignment of the images. Minimizing noise and determining the phase difference coregistration of images is a very important step that was performed to ensure the accuracy of the results. Phasing acquired through image coregistration was removed in the process of interferogram computation (5th step). Interferogram computation was also carried in the SNAP Sentinel-1 Toolbox which provided two stacks, one with master-slave SLC and the other containing

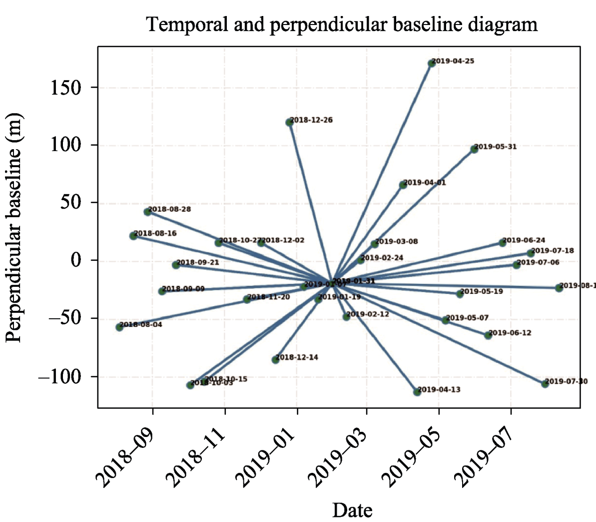

Fig. 2 Master-slave configuration for land subsidence in Lahore

Note: The dots represent each image and lines show the interferograms formed by the master image in the center and the other image.

the interferograms of a master-slave set. Lastly, DEM was used for removal of the topographic phase from the interferograms (6th step). This step also provided additional data to be used in further processing in the StaMPS software. Finally, the data were converted into StaMPS compatible formats to be used for further StaMPS-based PSInSAR processing. The preprocessing steps in SNAP are shown in Fig. 3 (the left Flow chart).

3.2.2 StaMPS PSInSAR post-processing of Sentinel-1 data

PSInSAR processing was performed in StaMPS following the instructions from the StaMPS/MTI manual (Hooper, 2010). PS processing was carried out using the interferograms generated in the previous steps. The sequence of PS processing is described here in detail. The processing started with the loading of data points and conversion of data into a MATLAB useable format (1st step). Then the phase noise was estimated for the PS pixels in the interferograms. This process was applied in a repetitive manner, where phase noise for all PS pixels in every interferogram was estimated iteratively (2nd step).

PS selection was made based on their noise features, and this step tends to select the PSs which are not affected by temporal changes (3rd step). It is a time-consuming step, however, the application of advanced techniques like deep learning algorithms can reduce processing time and increase accuracy. The percentage of random pixels was also estimated in the third step, and it is permissible to allow a high percentage as the next step will further refine the process of selection. After PS selection, PS weeding was performed to select the noise-free points to be processed further for wrapped phase correction. This step eliminates noisy pixels and the misleading pixels that were selected through the signal contribution by the surrounding ground elements. Weed_alpha was used as the smoothing parameter for estimating the phase noise concerning surrounding pixel pairs. Smoothing of the temporal phase for each pair was carried using Gaussian window, in which phase noise is obtained by subtracting the smoothing results from the original phase. The removal of pixels is based on the threshold standard deviation (4th step).

The wrapped phase correction was performed to remove the spatially uncorrelated look angle error calculated in the third step (5th step). Phase unwrapping was performed in the 6th step. After phase unwrapping, the spatially correlated look angle error, master atmosphere, and orbit error (AOE) phase were estimated simultaneously (7th step). This process could produce considerable artifacts in the final displacement result if the phase ramps such as orbit error and topographic-related atmospheric error were not removed. Therefore, a phase ramp was estimated for each interferogram and removed by using ‘scale deramp’. The deformation signals were retained and observed in the corrected interferograms. The 6th step of phase unwrapping was repeated after running the 7th step to improve the phase-unwrapping accuracy and obtain better results. SAR data are not influenced by the weather, but the effect of the atmosphere cannot be neglected, so the final step of atmospheric filtering (Low Pass Filter) was carried out in StaMPS (8^{th} step). To modify the time and wavelength parameters, the following commands were used: scn_time_win: t & scn_wavelength: λ, where the t & λ values tested were 120370, 140375 & 160380, respectively, and atmospheric artifacts were successfully reduced (Hooper et al., 2004). All these steps are shown in Fig. 3 (the right Flow chart).

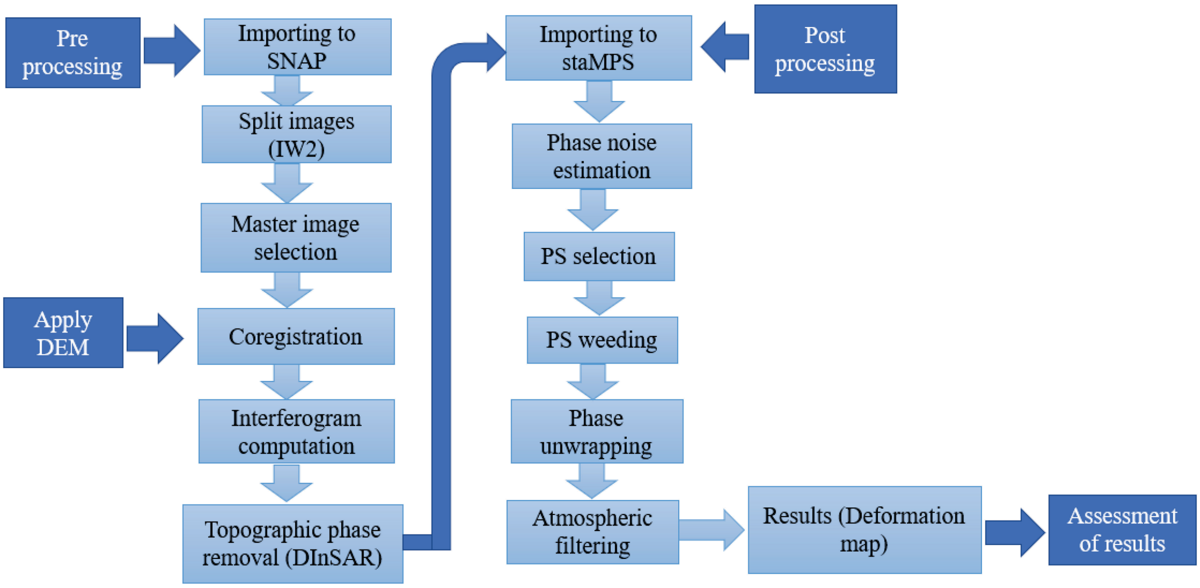

Fig. 3 Flow chart representing the SNAP and StaMPS processing steps

Finally, the measurement points acquired were then preprocessed and analyzed using different software with multiple datasets to find the relationships between subsidence and the other parameters including soil type, water extraction, land cover, transportation and water channels, and population density. A histogram of deformation points was generated to provide a clear view of our data as shown in Fig. 4. The areas with low subsidence are mainly located in less populated rural areas where groundwater extraction is lower and less paved areas allow better recharge, while high subsidence was found in densely populated urban lands.

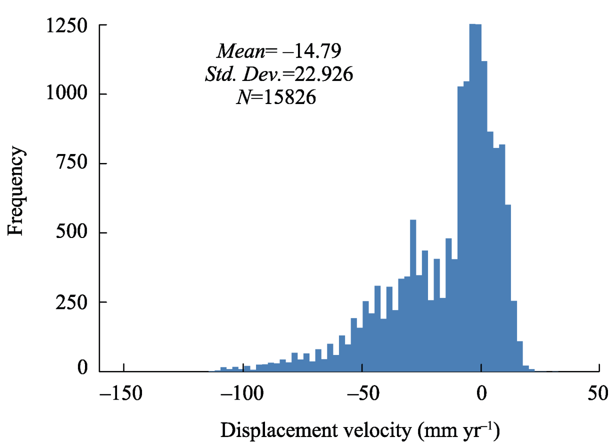

Fig. 4 Histogram of subsidence points

3.3 Ancillary data processing & analysis

The supplementary data obtained from different sources (Table 2) were processed for further assessment of the land deformation results. These data and their sources include groundwater data regarding tube well locations and water levels acquired by the Water and Sanitation Agency (WASA), field survey points and pictures from field surveys, Landsat 8 imagery from USGS for land cover classification, the soil type map acquired by the Geological Survey of Pakistan (GSP), and water channels and transportation network data acquired by local authorities. The most important data in this regard are the data of tube wells which show the water table levels in various parts of the city. By converting the Excel datasheet into a shapefile in ArcMap, a comparative assessment of water level and land deformation was obtained. A scatter plot was also generated using SPSS software to observe how water levels and deformation are related. Landsat Imagery was processed to generate a land cover map of the study area in ERDAS IMAGINE software.

The water channel and transportation network shapefiles consisting of major roads and railway tracks were used to create maps in ArcMap software. These datasets were used to obtain a clear view of the land deformation trends in our study area. The soil type map was digitized in ArcMap to observe the influence of soil type on the land deformation trend. Groundwater extraction is closely related to population density; therefore, a town-based population density map of

Lahore was generated in ArcMap using population census data. Surface water channel data were used to understand the groundwater recharge process that could be associated with the occurrence of uplift in various parts of the city. Land deformation data acquired by SNAP/StaMPS processing were converted to GIS-based formats in QGIS software, and the scaled map was generated to show the rate of deformation in various parts of the study area. To compare the ancillary data with deformation results, two approaches were used; one was overlaying the data such as tube wells, waterways, and transportation network on the subsidence map, and the second was using two views in Erdas imagine and linking both of the views to get a clear comparison.

4 Results

The state of the city itself along with the results of previous studies have strongly suggested a high chance of the occurrence of subsidence in the area (Ahmad et al., 2002; Basharat and Rizvi, 2011; Kanwal et al., 2015; Basharat, 2016). Lahore City has experienced an exponential population growth rate which has reached 3.7% per year according to the latest studies (Farhat et al., 2018). Since 1998, the census urban growth of Lahore has amounted to up to 116.3% (Mohsin et al., 2018), Lahore is the second largest city of Pakistan, and its growth rate is the highest in the province. The last two decades have seen intensive infrastructural development in Lahore. Groundwater, on the other hand, being the only source of water for metropolitan area, is being exploited rapidly. Taking all these parameters into consideration and reviewing land deformation statistics assessed by previous studies, it is believable that land subsidence is occurring in our study area. Studies from other parts of the country have shown evidence of land deformation. Land subsidence in Abbottabad City has reached up to –150 mm yr^{-1} in 2019 (Shahzad et al., 2020), while a GPS-based study of wells in Quetta City showed subsidence values up to –120 mm yr^{-1} (Kakar et al., 2020). The rates of subsidence in other parts of country are higher despite the fact that their urban growth rate and infrastructure development are lower than Lahore City. Urban growth is the second most crucial factor in subsidence, and it provides significant evidence of land subsidence in Lahore. Over the course of one year, from August 2018 to August 2019, a total of 33 images were acquired from the ascending orbit of the Sentinel-1 satellite. These data were used to produce the average displacement velocity map of Lahore using the SNAP-StaMPS based PSInSAR method, as discussed in the Methods section. The displacement velocity in the study area ranges from –114 to 15 mm. There are totally 2181081 PS points in the area and the density of PS points is about 1238 per kilometres. A land subsidence map was generated using the results of the PSI analysis in QGIS as shown in Fig. 5, where the color scale from dark red to light yellow represents different stages of land deformation. The shades of red from dark to light tones represent gradual subsidence zones, with the darkest being the highest and the lighter tones of red being the moderate subsidence zone. The yellow to light yellow colors in Fig. 5 depict the stable zones and uplifts, respectively. Figure 5 also shows the population density of Lahore, with polygons of different colors representing town boundaries and attributed to different population densities.

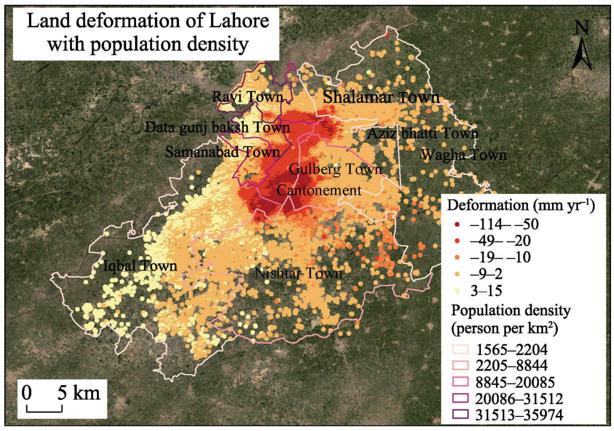

Fig. 5 Map showing the land deformation and population density of Lahore

Using the kriging interpolation method, the velocity points were interpolated to create a deformation rate map. The spatial profiles from northwest to south-east and from north-east to the south-west were created. The spatial profile graphs in Fig. 6(a, b) indicate the rise in subsidence from the north-west towards the south-east in the high population density zone, and it tends to smooth out with the lowering of population density. An increasing subsidence trend was observed from north-east to south-west, which tends to decline in the south-western direction. The areas in this part of the city are less populated and dominated by agricultural activities.

Validation of the results is a crucial step in assessing research quality, and leveling data are commonly used for the validation of subsidence studies (Raspini et al., 2014; Yang et al., 2016; Zhou et al., 2017). Unfortunately, leveling data were unavailable for Lahore; hence, we have relied on other parameters that are considered to be subsidence trigger factors. For interpretation of the PSI results, multiple sources were used that included the tube well data from local government agency WASA, and a field survey of some sites showing deformation along with the land cover and soil type data.

4.1 Role of groundwater extraction in subsidence

WASA has installed approximately 426 tube wells in Lahore that can extract 1363827 m^3 of water every day. It should be mentioned here that we could only access the data for these 426 tube wells in this study; however, the data for a large number of privately installed tube wells were not accessible.

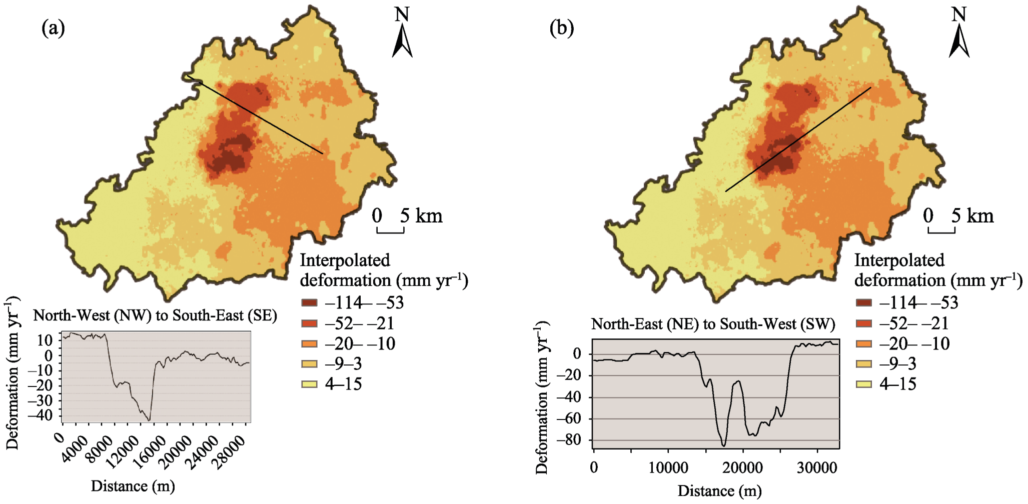

Fig. 6 Spatial profile of the interpolated displacement map (a) from the north-west (NW) to south-east (SE) and (b) from north-east (NE) to south-west (SW)

A previous study found that the increased extraction rate and the reduced recharge rate are simultaneously expected to cause land subsidence (Gabriel and Khan, 2010). Lahore City has two aquifers that are being drilled excessively, more public and private sector wells are being installed continuously and the capacity of the tube wells is also being enhanced over the years, which is considerably lowering the water level (Muhammad et al., 2016).

The unconsolidated alluvial composition of aquifers makes them highly prone to subsidence with excessive water extraction and pressure over the land surface resulting from massive construction. The water table is declining at a faster rate, and according to WASA Lahore has undergone 18.5928 m of average decline in the water level since 1961 (Basharat, 2016). To understand the relationship between water extraction and land subsidence, we plotted the available tube well points in Lahore district as shown in Fig. 7. Tube wells were found to be located in high population density regions with excessive water extraction, as expected; and these locations also represented the high subsidence zones. There is a strong correlation between water extraction and land subsidence. Figure 7 shows that a maximum number of government installed tube wells are located in the city center, also known as urban Lahore. One interesting observation from this map is that although the maximum numbers of tube wells occur in areas with high subsidence, a few are also located in low subsidence areas or even areas with uplift. The connection between uplift and tube wells could be explained by the recharge factor, which is discussed in the subsequent sections of this paper.

The change in water level from 2018 to 2019 was calculated, and a lowering water level trend was found in the study area. The change in water level was plotted against the deformation values and a good correlation was found between these parameters. Figure 8 shows a scatter plot of the change in water level using WASA datasets versus deformation (mm yr^{-1}) acquired from PSInSAR. This trend was plotted using IBM SPSS software. The water table is moving lower where subsidence is higher while the tube wells located in stable areas are showing a rise in water level.

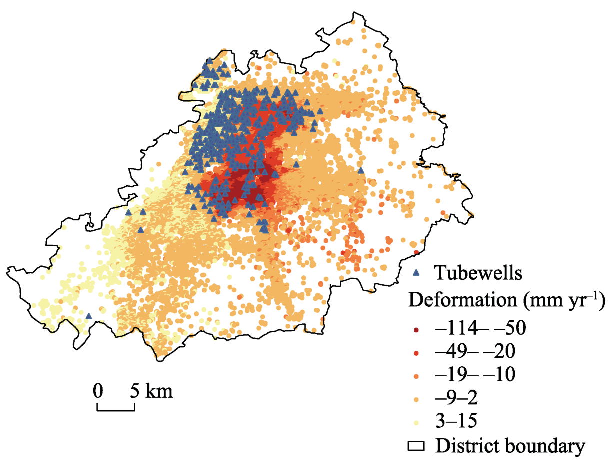

Fig. 7 Map of the locations of tube wells installed by WASA

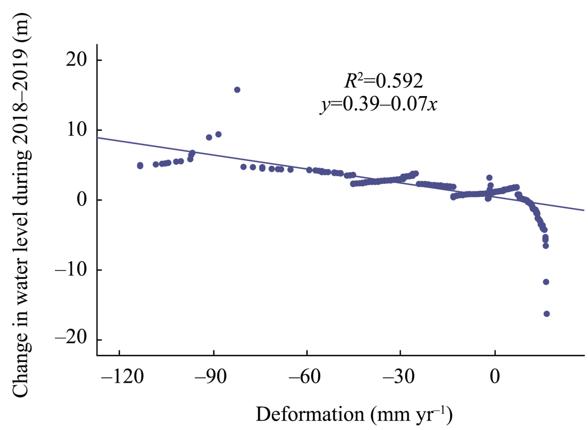

Fig. 8 Scatter plot of land deformation and changes in water level from 2018 to 2019

4.2 Role of soil type in subsidence

As described earlier, the soil in the study area mainly consists of loamy and clayey soil and deposits from rivers and streams. The surface is covered by permeable soil and air transported grains from the Ravi River (Gabriel and Khan, 2010; Muhammad et al., 2016). The results from previous studies show that a high rate of subsidence is observed in alluvial and colluvium plains (Bianchini et al., 2019) which are formed by flooded, streambed, and dead lake deposits. However, the results obtained in the present study indicate that the high subsidence rate in the alluvial plains could be attributed to the excessive aquifer drainage and lower recharge resulting from urbanization and land cover types which do not support rainwater runoff. Figure 9 shows the soil type map of Lahore.

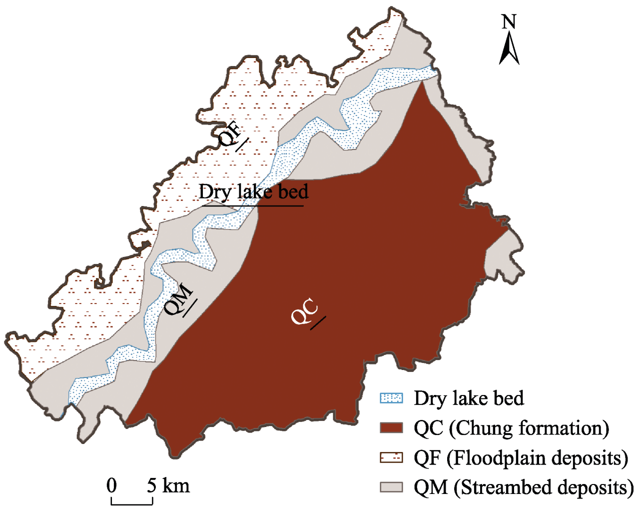

Fig. 9 The soil type map of Lahore

Note: QC refers to the Chung formation, composed of loess deposits of the upper terrace, while QM refers to the meander belt flood plain and QF refers to floodplain deposits.

4.3 Role of land cover and population density in subsidence

The high population density and land cover are directly or indirectly contributing to the land subsidence. Lahore is the second-largest city in the country with many opportunities and facilities; therefore, more people are migrating from remote areas in search of a better education, jobs, and better lifestyles. This has tremendously increased the population of Lahore. A report shows that the population has grown more than two-fold during the last three years (Basharat, 2016; Nawaz et al., 2019). Therefore, a population density map was generated using local population census data (Fig. 10). This map shows a good correlation with our hypothesis that high population density is one of the most important factors that contribute to land subsidence. Although the population is not a direct contributor, it is leading to excessive recharge of groundwater and the need for more construction which contributes to land deformation. The population density in some parts of the city is very high while other parts have a low population density and lower subsidence rates.

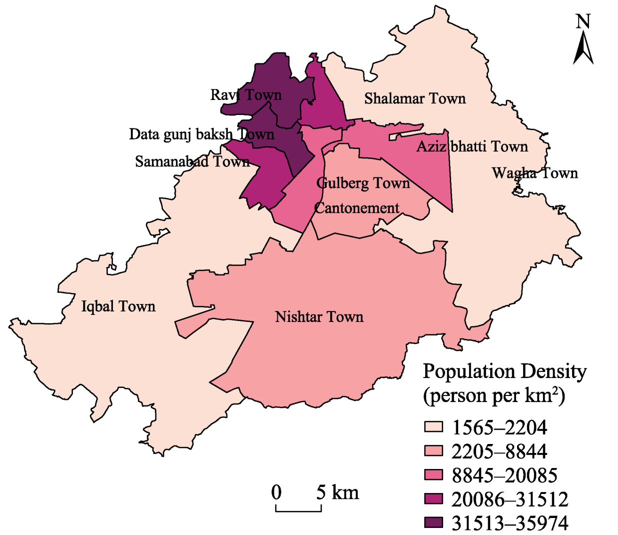

Fig. 10 The population density map of Lahore

A large population requires proper places for people to live, transportation services, and sustainable water resources. Therefore, mega construction projects are accomplished to fulfill their demands. A classified map of Lahore shows that 41% of the total area is under built-up land. The land cover map in Fig. 11 shows that a large area is covered by urban lands with high subsidence, which confirms a clear connection between urbanization and subsidence. However, the relationship between urbanization and subsidence can be attributed to several factors, such as the construction of infrastructure, excessive drilling and drainage of water, reduced infiltration, road mapping, water canal systems, and railway tracks (Rana and Bhatti, 2018). Some green areas, such as parks, are located between urban lands and also lie in high subsidence zones as the tube wells are located in these regions and their water is being consumed by the large population.

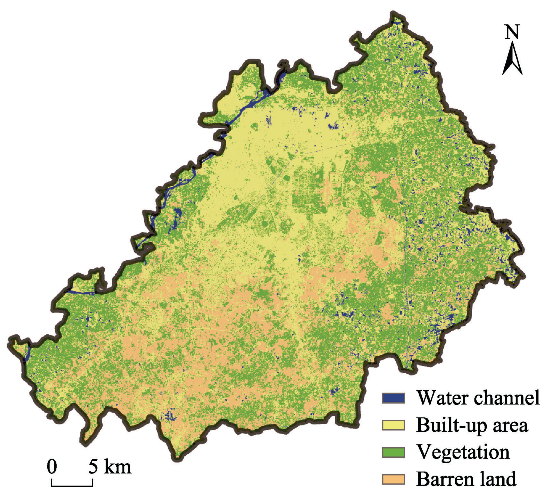

Fig. 11 The land cover map of Lahore

4.4 Field survey

Field survey points gathered using a GPS application were found to be located in the high subsidence zone as shown in Fig. 12a. Several small and large buildings in the highly populated downtown areas showed high subsidence. These regions were marked and we visited these areas to further validate our results. The images of buildings damaged by subsidence are shown in Fig. 12 (b-f) for proof. The evidence recorded during the field survey strongly supports our results obtained from the satellite-based data. Subsidence is a serious hazard that takes place at a slow rate and is generally considered to be irreversible. This study presents significant proof of the occurrence of subsidence in a city that is already facing unplanned rapid urbanization and the dryness of its aquifers. It is very important to give dire attention to this life-threatening hazard.

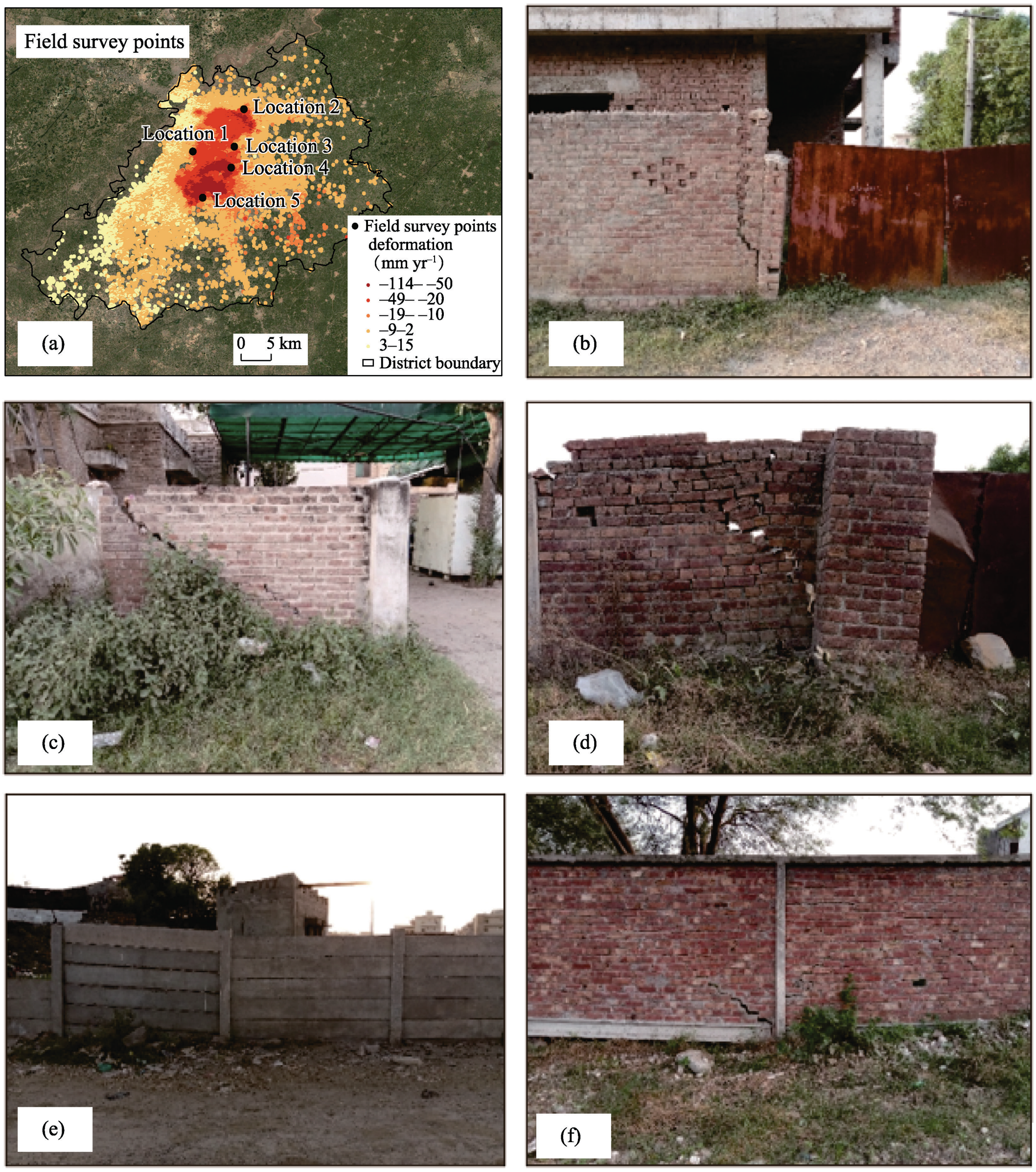

Fig. 12 (a) Field survey points on the map of Lahore district; (b-f) actual photographs of structures or buildings damaged by subsidence.

5 Discussion

Land deformation is a global phenomenon and researchers all around the world are addressing this issue (Whittaker and Reddish, 1989). Land subsidence is one of the most important environmental effects of groundwater pumping. The growing demand of freshwater for domestic and indus trial use in urban areas leads to a high subsidence rate (Holzer and Galloway, 2005; Teatini et al., 2006; Shi et al., 2007; Allis et al., 2009; Famiglietti et al., 2011; Mahmoudpour et al., 2013). Land subsidence studies throughout China have also found that groundwater extraction is the major contributor to land subsidence (Xue et al., 2005). The continued lowering of the water table was also confirmed by ten years' data of the groundwater table, with an estimated annual depletion rate of 0.57–1.53 m (Qureshi and Sayed, 2014).

The detailed studies available on the Lahore aquifers also supported these results. The aquifer is experiencing pressure in the form of changing land-use patterns, reduced recharge, and overexploitation of resources. The main aquifer of Lahore reaches up to Kashmir, with a length that is in line with rivers; therefore, drying rivers also play a role in the reduced recharge rate (Kanwal et al., 2015). The analysis of our data confirms that the lowering of the water table is largely occurring in highly populated urban lands, as presented above, which show a high rate of subsidence as well. The decline in the aquifer level, reduced recharge rate, and increased pressure resulting from dam construction have also been reported in the literature based on the data obtained from WASA tube wells (Zhou et al., 2017). In the present study, the subsidence rate shows a strong correlation with the change in the water table over time, and high subsidence was found in the areas with the lower water table. It can be clearly stated that groundwater extraction is the most important indicator of land subsidence in Lahore.

An analysis of the land deformation rates of Lahore showed that high subsidence zones are located in the central part of the city, and similarly, the maximum number of tube wells is located in the part where the subsidence rate is the highest. A large number of tube wells and massive water extraction leads to a lowering of the water level in aquifers which results in the seasonal dryness of tube wells. Lowering of the water table also requires deep drilling to find water which increases pressure on the government-installed wells, which then leads to more private drillings and consequently increases the risk of land subsidence. The North-Western part of the study area shows stable zones in terms of subsidence, while the population density and number of tube wells are considerably higher in this part. The explanation for this unusual phenomenon is given by the comparatively higher recharge rate in this area. As shown in Fig. 14, Ravi River passes through this area and it contributes 82% of the recharge for Lahore City. A study on the water quality of Lahore aquifers using isotopic techniques confirmed this fact by finding that the isotopic properties of calcium carbonate in the groundwater in areas surrounding the river were similar to the properties in Ravi River water. The excessive water extraction has led to the creation of a cup-shaped depression in the city center which was also found to be the high subsidence zone in our study. This study also found that the BRBD canal was the second major contributor of recharge, which originates from river Chenab, and groundwater in the neighboring areas showed similar isotopic properties. These areas located in the North-Western part also show uplift and stable zones which can be attributed to the recharge from the canal (Ahmad et al., 2002).

The correlation of wells with subsidence data has revealed that the water table is stable or rising in tube wells located near Ravi River, and is higher than most other parts. The trends in groundwater levels also indicate that the situation will get worse in the central parts of the city by the year 2040, but the regions near Ravi River and BRBD canal will remain high, while the southeastern part will also show stability resulting from high seepage and low drilling (Qureshi and Sayed, 2014). Hence, it can be concluded that the city center, which is already exhibiting subsidence, will be highly prone to groundwater depletion in the future and needs considerable attention from the authorities. Groundwater pumping has an undeniable role in triggering subsidence, this fact has been established by multiple studies dedicated to urban regions, and it is suggested that the patterns of groundwater flow must be monitored carefully (Béjar-Pizarro et al., 2017). Over pumping with negligible recharge is capable of affecting the hydraulic structures at local scales, and megacities in developed countries are facing this problem (Ortega-Guerrero and Carrillo-Rivera, 2012). The results from the current study also indicate the areas where artificial recharge structures need to be installed and which parts of the city have a good scope for water extraction. As a highly populated city, the center is showing high subsidence and the areas near Ravi River are stable because of the recharge. Similarly, rural areas are also stable due to agricultural and canal system recharge; and this information can significantly help the government to pinpoint areas where water extraction must be restricted.

The difference between the rate of extraction and recharge was found to be 248×10^6 m^3 per year according to an official study carried in 2013. The detailed contributors of groundwater recharge and discharge are presented in Table 4, where the largest contribution from Ravi River can justify the uplift phenomenon or low subsidence in the surrounding areas.

Table 4 Groundwater balance of Lahore

Components of recharge	Recharge (10^6 m^3 yr^{-1})	Components of discharge	Discharge (10^6 m^3 yr^{-1})
Precipitation	138	Domestic use	1384
Agricultural runoff	150	Industrial use	335
Irrigation network	146	Commercial use	277
Ravi River	1937	Agriculture	623
Total recharge	2371	Total discharge	2619

Note: Source: World Wildlife Fund (WWF) for nature Pakistan (Qureshi and Sayed, 2014).

The average gap between the recharge and discharge rates is 55 cm yr^{-1}, however for rural regions and areas near Ravi River the gap is lower. Understanding the spatial trends of land subsidence will be helpful for future projects in the city.

As the higher population density pressure on natural resources also rises, see the population density map of Lahore shown in Fig. 10, it is obvious that a larger population is residing in parts of the city where infrastructure development is higher and the major road networks are also located in this part (Fig. 13). The population density map of Lahore was compared with the subsidence monitored in the present study, which indicated that subsidence is high in the regions with high population density. By overlaying land deformation data on the town-based shapefile of the study area it was clear that various parts are undergoing land deformation. High subsidence is occurring in Gulberg Town, Cantonment Area, Aziz Bhatti Town, and Shalamar Town, while uplift was observed in some parts of Iqbal Town, Samanabad Town, Ravi Town, and Data Ganj Bakhsh Town. The subsidence in highly populated towns is attributed to the excessive groundwater extraction and the lower recharge resulting from paved urban structures. On the other hand, uplift is mainly found in less populated areas, areas with agricultural activities or those located on the riverbank or rural canals. For instance, Samanabad Town, Ravi Town, and Data Ganj Bakhsh Town have high population density but little or no subsidence because they are located near Ravi River and have a better recharge rate than other parts of the city.

For Lahore, the major sources of aquifer recharge are the canal system, rainfall, and Ravi River, and all these factors play a vital role in the occurrence of uplift. The Government's effort to ensure the provision of all facilities in the administrative center and its vicinities has attracted more people to this area, which has increased pressure on the land both in terms of construction load and loss of support from excessive water extraction.

Alluvial soils are at risk of subsidence and the main cause of subsidence in these areas is also known to be groundwater extraction. Hence, it is very important to monitor these areas regularly and take measures for maintaining a balance between recharge and extraction rates (Bianchini et al., 2019). The dominance of the alluvial soil type and excessive drilling have been considered as significant risk factors for land subsidence by previous studies and the current results are also following this parameter. The study area is mostly covered by only one soil type which is attributed as unconsolidated. It has been established through multiple studies on alluvial soil types that these soils are more prone to subsidence due to infrastructure development and over-extraction of groundwater. It has also been established that alluvial soils are highly prone to subsidence when the extraction rate is higher, but the groundwater recharge is very low (Tewolde, 2008). Therefore, it is suggested that precautionary measures must be taken to ensure aquifer recharge through the injection of treated wastewater and/or the installation of rainwater harvesting structures as these soft soils have external pressure exerted by mega transportation projects and infrastructure development, which combines with the internal loss of strength through extensive pumping and increases soil vulnerability. Therefore, future projects must be carried out only after considering the current state of the study area. Furthermore, detailed soil profiling is strongly suggested for a deep geological analysis.

Unplanned urbanization has also been known as one of the causes of subsidence for a long time, such as in Mexico City, where the Chalco plain was excessively pumped not only for local use but also for water to be transported to meet Mexico City's requirements (Stefan et al., 2012). Lahore City has experienced excessive urban development mainly in terms of transportation infrastructure, and these developments are located in the areas where the subsidence rate is higher. On one hand, construction activities increase the risk of subsidence, but on the other hand, they also pose a potential threat to the lives of commuters and neighboring residents along with economic losses resulting from the subsidence of these mega-structures (Zeitoun and Wakshal, 2013).

To better understand the situation in our study area, it is noteworthy that Lahore has extensive infrastructure development, particularly in the transportation sector, which includes metro bus service and the orange line train projects (Rana and Bhatti, 2018). Developing transportation networks and structures in subsidence-prone areas may unfortunately lead to economic and life losses. The transportation network map of Lahore (Fig. 13) shows that all the major road networks and railway tracks are passing from areas with high land subsidence. Urbanization and infrastructure development have put immense pressure on water resources, which ultimately lead to an exponential rise in water extraction, aquifer depletion, and a high risk of subsidence while the infiltration rate has been extremely reduced. To avoid future hazards, it is very important to consider groundwater recharge approaches by injecting treated wastewater or installing rainwater harvesting structures. Groundwater extraction for an urban areas' construction activities also affects neighboring soil layers (Xu et al., 2016). Lahore is at a high risk of subsidence as it is built on soft soils. It is also noteworthy that areas with high subsidence are covered by urban structures as shown in Fig. 11, and major transportation networks are also passing through the high subsidence zone. Central development projects are attracting more people to these areas and increasing the subsidence risk through both surface pressure and aquifer discharge.

Groundwater depletion is a matter of global concern, particularly in the areas where groundwater is the only source of water. To ensure a sustainable supply of groundwater, if the

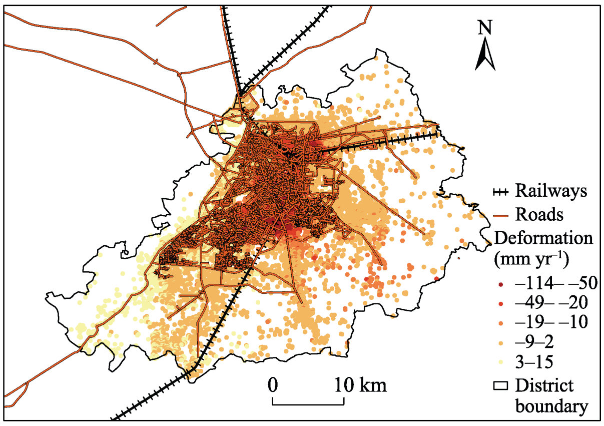

Fig. 13 The transportation network map of Lahore

recharge rate is not exceeded, it should at least match the rate of extraction. Sources of groundwater recharge vary with the area and climatic conditions. For Lahore, major sources of groundwater recharge include Ravi River, the canal network, and rainfall.

Ravi River is responsible for 82% of the groundwater water recharge in Lahore, while the canal network and precipitation collectively contribute to 12% of groundwater recharge, and the remaining 6% is added by agricultural water flow. The recharge process has been seriously affected by several factors. For instance, Ravi River is the smallest of five rivers in the Indus basin which enters Pakistan from India, and the construction of dams in both countries has greatly reduced the water flow (Mohsin et al., 2018). The reduction in recharge from canal networks and rainfall can be associated with urbanization. The urban areas are deprived of canal water rights and urbanization has also reduced the rainfall recharge process (Qureshi and Sayed, 2014). The deformation results (Fig. 8) are in good agreement with the fact that the areas closer to Ravi River and the rural areas with less population show uplift, while the urban areas situated near small nallas and canals show high subsidence. The total recharge rate of these nallas and canals passing through urban areas is much less than the extraction rate.

Despite a large number of studies being conducted, there is still a need to understand the phenomenon of land deformation as uplift and subsidence. We have attempted to understand this phenomenon in this study, where extraction is much higher while recharge is at a lower rate (Xu et al., 2016). The subsidence rate is higher in our study area while some parts have shown uplift as well, which is attributed to recharge. For Lahore, the major cause of subsidence is found to be groundwater extraction, which is the only source of water for this large city, and this finding is in line with the global trend, as outlined in a recent review article which summarizes the severe consequences of groundwater withdrawal (Mohsin et al., 2018).

A detailed study on excessive groundwater extraction and the associated problems can be found in the literature (Kanwal et al., 2015). These problems include the lowering of the water table, which results in the seasonal dryness of tube wells and also requires deep drilling to find water, which increases the government competition for installed wells and consequently increases the risk of land subsidence. Groundwater extraction is increased by urbanization, and the construction of over- and underpasses has led to land subsidence in Lahore (Hassan et al., 2014; Kanwal et al., 2015; Basharat, 2016). Areas with a high population density are areas with major transportation networks, and the con struction of these structures is capable of posing a subsidence threat. It is very important to take significant measures to reduce the economic losses resulting from land subsidence (Gambolati and Teatini, 2015; Guzy and Malinowska, 2020).

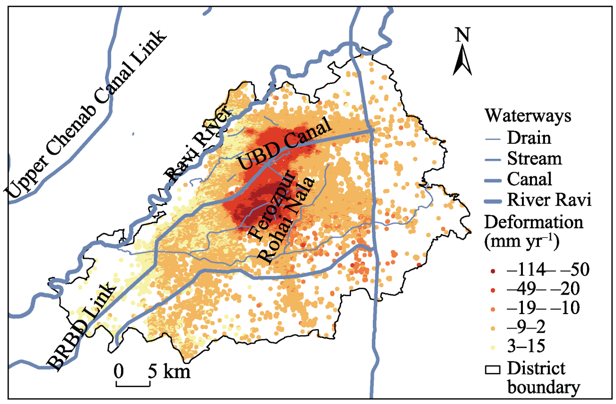

Fig. 14 Map highlighting the waterways in Lahore

Considering the susceptible nature of soils in Lahore and the massive dependence of residents on groundwater, unplanned urban growth needs to be controlled. This study can play a significant role in helping the planners and policymakers to consider the significant levels of land deformation observed in the city. Previously, various studies have suspected the occurrence of land subsidence, considering the high rates of water extraction and soft nature of the soil, but this is the only dedicated study on monitoring land deformation in Lahore. The contributing factors have been assessed, which can help in understanding the trends of subsidence and uplift phenomena in parts of the study area. The contribution from water extraction is the most significant, and this study shows that the parts of the city where the extraction rate is higher and recharge is negligible are exhibiting more subsidence. The depression zone lying in the city center is also dominated by subsidence and needs to be declared as a protection zone, which should include limiting extraction and the construction of recharge structures through artificial means like treated wastewater injection or rainwater harvesting specifically in this area (Qureshi and Sayed, 2014).

Another noteworthy fact is that these areas have maximum infrastructural development, so the effects of subsidence can pose serious economic and life risks if significant attention is not given. This detailed description about the town-level status of the city can be used by the government agencies and authorities for future projects, such as Naya Pakistan Apartments, in order to achieve the UN's 11th Sustainable Development Goal. Iqbal Town, Nashtar Town and Wahga Town have considerable scope for development as these areas are stable both in terms of groundwater availability and land surface. Future construction projects in these parts of the city will ensure equal opportunities for all parts of city, lessen the burden in the city center, relieve pressure on groundwater and reduce the risk from the subsidence hazard. The lowering of the water tables and high subsidence rates in Gulberg Town, Cantonment Area, Aziz Bhatti Town, and Shalamar Town demand the installation of artificial recharge structures for sustainable development.

6 Conclusions and future perspectives

In summary, we have monitored land subsidence in Lahore for the first time by employing the PSInSAR technique. Sentinel-I SAR data acquired for one year (from 2018 to 2019) along the ascending orbits was processed for the spatial-temporal assessment of subsidence in different regions of Lahore City. SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation Model) along with multiple ancillary data were employed for finding correlations between subsidence and various factors such as groundwater extraction, the static water level in various parts of the city, soil type and the nature of the soil, land cover, population density, transportation networks, and surface water channels. Gulberg Town and Cantonment area are lying in a high subsidence zone (–114 to –50 mm) which could be attributed to the high population densities of these areas, major infrastructural development, the presence of transportation networks and tube wells, and alluvial soils. No major surface water channels were found passing through this area. Wahga and Nishtar towns were found to be stable. The areas situated near Ravi River, such as Ravi Town, and Data Ganjbakhsh, show uplift from 2 to 15 mm. These areas have less infrastructural development and obtain recharge from agricultural runoff and water channels. Groundwater extraction was found to have a strong linear correlation with subsidence. The relationship between population density and land deformation shows different behaviors in different regions. For the central part of the city, population density and subsidence are higher and have a direct relationship; but the Northwestern part of the city is stable against subsidence, even with a large population density, which is attributed to recharge from Ravi River. In short, our study area of Lahore, the second-largest city of Pakistan, has experienced excessive infrastructure development, high population density, unplanned urbanization, and extraction of groundwater in the past decades which make this area highly susceptible to subsidence.

Our study is significantly important from future perspectives. For instance, WASA plans to install 358 more tube wells by the year 2025 (Qureshi and Sayed, 2014), and our study could help WASA to choose suitable stable zones in the city. Our study suggests that artificial recharge approaches should be used in areas with high subsidence to control this phenomenon. This can reduce the risks of economic and life losses and ensure sustainable development through the careful and wise use of natural resources. Furthermore, the Government of Pakistan has launched the project of constructing 35,000 houses in the city and our study could lead to planned urbanization in order to achieve the goal of the settlement of sustainable and safe cities set by the United Nations.

Acknowledgments:

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References

Ahmad M, Rafiq M, Akram W, et al. 2002. Assessment of aquifer system in the city of Lahore, Pakistan using isotopic techniques. *International Atomic Energy Agency* (*Austria*), 33(35): 109–133

Allis R, Bromley C, Currie S. 2009. Update on subsidence at the Wairakei-Tauhara geothermal system, New Zealand. *Geothermics*, 38(1): 169–180.

Baldi P, Casula G, Cenni N, et al. 2009. GPS-based monitoring of land subsidence in the Po Plain (Northern Italy). *Earth and Planetary Science Letters*, 288(1–2): 204–212.

Basharat M, Rizvi S A. 2011. Groundwater extraction and waste water disposal regulation—Is Lahore aquifer at stake with as usual approach. Lahore, Pakistan: Pakistan Engineering Congress.

Basharat M. 2016. Groundwater environment in Lahore, Pakistan. In: Sangam S, Vishnu P P, Binaya R S, et al (eds.). Groundwater environment in Asian cities. Amsterdam, The Netherland: Elsevier.

Béjar-Pizarro M, Ezquerro P, Herrera G, et al. 2017. Mapping groundwater level and aquifer storage variations from InSAR measurements in the Madrid aquifer, Central Spain. *Journal of Hydrology*, 547: 678–689.

Bianchini, Solari, Soldato, et al. 2019. Ground subsidence susceptibility (GSS) mapping in Grosseto Plain (Tuscany, Italy) based on satellite InSAR data using frequency ratio and fuzzy logic. *Remote Sensing*, 11(17): 2015. DOI: 10.3390/rs11172015.

Budhu M, Adiyaman I B. 2010. Mechanics of land subsidence due to groundwater pumping. *International Journal for Numerical and Analytical Methods in Geomechanics*, 34(14): 1459–1478.

Chen B B, Gong H L, Chen Y, et al. 2020. Land subsidence and its relation with groundwater aquifers in Beijing Plain of China. *Science of the Total Environment*, 735: 139111. DOI: 10.1016/j.scitotenv.2020.139111.

Cian F, Blasco J, Carrera L. 2019. Sentinel-1 for monitoring land subsidence of coastal cities in Africa using PSInSAR: A methodology based on the integration of SNAP and StaMPS. *Geosciences*, 9(3): 124. DOI: 10.3390/geosciences9030124.

Dawn. 2020. Naya Pakistan Apartments PC-I finalised. https://www.dawn.

com/news/1574148/naya-pakistan-apartments-pc-i-finalised.

Erkens G, Bucx T, Dam R, et al. 2015. Sinking coastal cities. *Proceedings of the International Association of Hydrological Sciences*, 372: 189–198.

Erkens G, Sutanudjaja E H. 2015. Towards a global land subsidence map. *Proceedings of the International Association of Hydrological Sciences*, 372: 83–87.

Famiglietti J S, Lo M, Ho S L, et al. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters*, 38(3): 2010GL046442. DOI: 10.1029/2010GL046442.

Farhat K, Waseem L A, Ahmad Khan A, et al. 2018. Spatiotemporal demographic trends and land use dynamics of metropolitan Lahore. *Journal of History Culture and Art Research*, 7(5): 92–102.

Fergason K C, Rucker M L, Panda B B. 2015. Methods for monitoring land subsidence and earth fissures in the Western USA. *Proceedings of the International Association of Hydrological Sciences*, 372: 361–366.

Ferretti A, Monti-Guarnieri A, Prati C, et al. 2007. In SAR principles: Guidelines for SAR interferometry processing and interpretation. Noordwijk, The Netherlands: ESA Publications.

Gabriel H F, Khan S. 2010. Climate responsive urban groundwater management options in a stressed aquifer system. *IAHS-AISH Publication*, 338: 166–168.

Gambolati G, Teatini P. 2015. Geomechanics of subsurface water withdrawal and injection. *Water Resources Research*, 51(6): 3922–3955.

Ge D Q, Wang Y, Zhang L, et al. 2009. Using permanent scatterer InSAR to detect land subsidence and ground fissures: A case study in Xi'an City. IEEE International Geoscience and Remote Sensing Symposium. July 12–17, 2009. Cape Town, South Africa: II–365–II–368.

Guzy A, Malinowska A. 2020. State of the art and recent advancements in the modelling of land subsidence induced by groundwater withdrawal. *Water*, 12(7): 2051. DOI: 10.3390/w12072051.

Hassan G Z, Hassan F R, Akhtar S. 2014. Environment threats to groundwater in Lahore area. Pakistan Engineering Congress. Lahore, Pakistan: 68–95.

Herrera G, Tomás R, Monells D, et al. 2010. Analysis of subsidence using TerraSAR-X data: Murcia case study. *Engineering Geology*, 116(3–4): 284–295.

Holzer T L. 1991. Mitigating losses from land subsidence in the United States. Washington DC, USA: National Academies Press.

Holzer T L, Galloway D L. 2005. Impacts of land subsidence caused by withdrawal of underground fluids in the United States. Colorado, USA: Geological Society of America.

Hooper A, Spaans K, Bekaert D, et al. 2010. StaMPS/MTI manual (Report). Delft, The Netherlands: Delft University of Technology.

Hooper A, Zebker H, Segall P, et al. 2004. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. *Geophysical Research Letters*, 31(23): L23611. DOI: 10.1029/2004GL021737.

Hu R L, Yue Z Q, Wang L C, et al. 2004. Review on current status and challenging issues of land subsidence in China. *Engineering Geology*, 76(1–2): 65–77.

Kakar N, Kakar D M, Barrech S. 2020. Land subsidence caused by groundwater exploitation in Quetta and surrounding region, Pakistan. *Proceedings of the International Association of Hydrological Sciences*, 382: 595–607.

Kanwal S, Ding X L, Zhang L. 2018. Measurement of vertical deformation in Karachi using multi-temporal insar. IEEE International Geoscience and Remote Sensing Symposium. July 22–27, 2018. Valencia, Spain: 1395–1398.

Kanwal S, Gabriel H, Mahmood K, et al. 2015. Lahore's groundwater depletion—A review of the aquifer susceptibility to degradation and its consequences. *Technical Journal*, *University of Engineering and Technology* (*UET*) *Taxila*, *Pakistan*, 20(1): 26–38.

Khorrami M, Abrishami S, Maghsoudi Y, et al. 2020. Extreme subsidence in a populated City (Mashhad) detected by PSInSAR considering groundwater withdrawal and geotechnical properties. *Scientific Reports*, 10: 11357. DOI: 10.1038/s41598-020-67989-1.

Mahmoudpour M, Khamehchiyan M, Nikudel M, et al. 2013. Characterization of regional land subsidence induced by groundwater withdrawals in Tehran, Iran. *Geopersia*, 3(2): 49–62.

Mohsin Atiq M, Shakir A S, Hashmi H N. 2018. Safe passage of riverine flood from highly urbanized city: A case study of Lahore City in Pakistan. *Journal of Civil & Environmental Engineering*, 8: 320. DOI: 10.4172/2165–784x.1000320.

Muhammad A M, Tang Z H, Sissou Z, et al. 2016. Analysis of geological structure and anthropological factors affecting arsenic distribution in the Lahore aquifer, Pakistan. *Hydrogeology Journal*, 24(7): 1891–1904.

Naeem M, Khan K, Rehman S, et al. 2006. Environmental assessment of ground water quality of Lahore area, Punjab, Pakistan. *Journal of Applied Sciences*, 7(1): 41–46.

Nawaz M, Tariq F, Gul A, et al. 2019. Evaluation of environmental & physical impacts of mega transportation projects: A case of Lahore. *Technical Journal*, *University of Engineering and Technology* (*UET*) *Taxila*, *Pakistan*, 24(4): 8–14.

Ortega-Guerrero M A, Carrillo-Rivera J J. 2012. Land subsidence in urban environment. In: Meyers R A (ed.). Encyclopedia of sustainability science and technology. New York, USA: Springer.

Pacheco-Martínez J, Hernandez-Marín M, Burbey T J, et al. 2013. Land subsidence and ground failure associated to groundwater exploitation in the Aguascalientes Valley, México. *Engineering Geology*, 164: 172–186.

Qureshi A, Sayed A H J L. 2014. Situation analysis of the water resources of Lahore—Establishing a case for water stewardship. Proceedings of the WWF-Pakistan Report, 26 November 2014. Lahore, Pakistan: WWF.

Rana I A, Bhatti S S. 2018. Lahore, Pakistan—Urbanization challenges and opportunities. *Cities*, 72: 348–355.

Raspini F, Loupasakis C, Rozos D, et al. 2014. Ground subsidence phenomena in the Delta Municipality Region (Northern Greece): Geotechnical modeling and validation with Persistent Scatterer Interferometry. *International Journal of Applied Earth Observation and Geoinformation*, 28: 78–89.

Shahzad N, Ding X, Wu S, et al. 2020. Ground deformation and its causes in Abbottabad City, Pakistan from Sentinel-1A data and MT-INSAR. *Remote Sensing*, 12(20): 3442. DOI:10.3390/rs12203442.

Shi X Q, Xue Y Q, Ye S J, et al. 2007. Characterization of land subsidence induced by groundwater withdrawals in Su-Xi-Chang area, China. *Environmental Geology*, 52(1): 27–40.

Stefan H G, Fang X, Gulliver J S. 2012. Lake and reservoir fate and transport of chemicals. New York, USA: Springer.

Strozzi T, Wegmuller U, Bitelli G, et al. 2001. Land subsidence monitoring with differential SAR interferometry. *Photogrammetric Engineering and Remote Sensing*, 67(11): 1261–1270.

Teatini P, Ferronato M, Gambolati G, et al. 2006. Groundwater pumping and land subsidence in the Emilia-Romagna Coastland, Italy: Modeling the past occurrence and the future trend. *Water Resources Research*, 42(1): W01406. DOI: 10.1029/2005WR004242.

Tewolde M. 2008. Subsidence in alluvial soils caused by intensive water withdrawal. Diss., Fribourg, Switzerland: University of Fribourg.

United Nations. 2015. Sustainable developmemt goals. https://www.un.org/sustainabledevelopment/cities.

Whittaker B N, Reddish D J. 1989. Subsidence: Occurrence, prediction and control (Preface). *Developments in Geotechnical Engineering*, 56: V–VI. DOI: 10.1016/B978-0-444-87274-6.50004-6.

Xu Y S, Shen S L, Ren D J, et al. 2016. Analysis of factors in land subsidence in Shanghai: A view based on a strategic environmental assessment. *Sustainability*, 8(6): 573. DOI: 10.3390/su8060573.

Xue Y Q, Zhang Y, Ye S J, et al. 2005. Land subsidence in China. *Environmental Geology*, 48(6): 713–720.

Yang K, Yan L, Huang G M, et al. 2016. Monitoring building deformation with InSAR: Experiments and validation. *Sensors*, 16(12): 2182. DOI: 10.3390/s16122182.

Zeitoun D G, Wakshal E. 2013. Land subsidence analysis in urban areas. Dordrecht, The Netherlands: Springer.

Zhou L, Guo J M, Hu J Y, et al. 2017. Wuhan surface subsidence analysis in 2015–2016 based on Sentinel-1A data by SBAS-InSAR. *Remote Sensing*, 9(10): 982. DOI: 10.3390/rs9100982.

基于 SAR 的拉合尔地面沉降监测与沉降因素评价

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摘　要：合理开发和管理自然资源对于实现可持续发展至关重要，地面沉降作为目前影响城市可持续发展的最重要地质灾害，其与人类活动有着紧密的关系，如地下水开采，基础设施开发导致的施工超载等。巴基斯坦第二大城市拉合尔出现了显著的地面沉降现象，与此同时，拉合尔也正在经历城市化过程中的人口密度急剧增加、大规模城市建设和地下水开采，通过分析拉合尔地面沉降的不同空间模式与人类活动的对应关系，将有助于合理规划拉合尔城市的发展。本文利用永久散射体合成孔径雷达干涉测量(PSI)技术对拉合尔 2018 年 8 月–2019 年 8 月的 Sentinel-1 数据进行 InSAR 处理，获取了该城市的地表形变速率为–114–15 毫米/年，并结合拉合尔的土地覆盖图、交通网络和水道、土壤类型、人口密度和现场点数据，分析各种因素在地面抬升或沉降发生中的作用。结果显示，沉降与各种参数（如地下水抽取和地下水位降低、土壤类型变化、土地覆盖变化、地表水通道和人口密度）之间建立了很强的相关性，其中拉合尔中部人口密集，地下水开采严重，使其成为该地区沉降最为严重的区域，而在拉维河、近人口较少的农村地区，由于通过运河系统，地下水得到河流补给，观察到了地表抬升。

关键词：Sentinel-1；沉降；PSI；地下水开采；城市化；拉合尔