Proposal of Study on InSAR-Based Land Subsidence Analysis as Basis for Subsequent Hydro-mechanical Modeling: A Case Study of Hanoi, Vietnam

Hong Ha Tran, Luyen K. Bui, Hung Q. Ha, Thi Thu Huong Kim, and Christoph Butscher

Abstract In recent years, land subsidence has been intensively studied by many research projects due to its severe impacts on the human and environment. Radar remote sensing for mapping ground movement has been successfully applied in several areas for the quantification of land subsidence. In this paper, previous Interferometric Synthetic Aperture Radar (InSAR) studies for Hanoi, Vietnam, are reviewed. Specifically, SAR data at the X, C, and L bands have been applied successfully using mainly the small baseline subset (SBAS) and Persistent Scatterer InSAR (PSInSAR) methods for extracting deformation movement in the urban setting of Hanoi from 1995 to the present. Whereby, line-of-sight land deformation obtained from these studies was converted into the vertical direction with the assumption that horizontal movement in the urban setting of Hanoi is insignificant. However, the analysis of the relationship between InSAR deformation and triggering factors was not fully

H. H. Tran (✉) · C. Butscher
Faculty of Geosciences, Geoengineering and Mining, TU Bergakademie Freiberg, Saxony, Germany
e-mail: tranhongha@humg.edu.vn

C. Butscher
e-mail: christoph.butscher@ifgt.tu-freiberg.de

H. H. Tran · H. Q. Ha
Faculty of Environment, Hanoi University of Mining and Geology, Hanoi, Vietnam
e-mail: haquanghung@humg.edu.vn

L. K. Bui · T. T. H. Kim
Faculty of Geomatics and Land Administration, Hanoi University of Mining and Geology, Hanoi, Vietnam
e-mail: buikhacluyen@humg.edu.vn

T. T. H. Kim
e-mail: huongktt87@gmail.com

H. Q. Ha
College of Art & Sciences, State University of New York at Fredonia, Fredonia, NY, United States

T. T. H. Kim
AGH University of Science and Technology, Kraków, Poland

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conducted. Therefore, a workflow in the part of the discussion in this paper is introduced that shows how subsidence data can be interpreted with the help of coupled hydro-mechanical simulations conducted with numerical multi-physics software. We present the data basis and model setup for the planned modeling study with the open-source software platform OpenGeoSys.

Keywords Land subsidence · InSAR · Hydro-mechanical modeling · Hanoi · OpenGeoSys

1 Introduction

Land subsidence is a global problem due to natural and human activities with gradually increasing consequences, e.g., infrastructure damage, land surface cracks, increasing the risk of flooding, reducing the capacity of aquifers to store water, and eventually posing a risk to society and the economy [1]. Severe problems caused by land subsidence were observed in megacities in the world, e.g., Bangkok (Thailand), Houston (USA), Mexico City (Mexico), Tokyo (Japan), Shanghai (China), and Venice (Italy) [2]. Over extraction of groundwater, which lowered the water table, was the main cause of land subsidence in these cities [3].

Hanoi, located in the northern part, is the capital city and a cultural, political, and societal center of Vietnam. Since the expansion of the city in 2008 covering parts or the entire adjacent provinces, the newly formed Hanoi with more inhabitants has put a lot more pressure on groundwater extraction and high demand on infrastructure for fast urbanization. Given that more water was pumped out of the ground, the surface soil became more compacted, and increasing severe land subsidence in the populated areas was observed. Some areas had especially high subsidence rates, including Ngo Sy Lien District (32 mm/year), Thanh Cong District ($41 - 42$ mm/year), and Phap Van District (22 mm/year) [4]. Due to the scarcely distributed number of ground monitoring stations in Hanoi, it is challenging to monitor the land deformation in this city both in terms of time and space.

There have been several studies aiming at monitoring surface deformation over Hanoi City based on different types of data (e.g., geotechnical, geological, or hydrological data) [5–7]. These studies used high-quality in situ data but with poor spatial resolutions, restricted coverage, and time discontinuity. These restricted their capacity to monitor surface deformation and patterns in space, particularly to detect deformation hot spots [8]. Interferometric Synthetic Aperture Radar (InSAR) provides the capacity to measure the time series of surface displacements induced by earthquakes, volcanoes, subsidence, and uplift processes with high spatial resolution on a large scale [9]. The analysis of SAR radar data is based on the amplitude and phase. While the amplitude indicates the strength of the signal response, the phase is used to measure the distance between the satellite and the target, and thus the deformation. Differential InSAR (DInSAR) is one of the most widely used phase-related methods for measuring surface displacement [10].

Radar remote sensing data with InSAR have been successfully deployed to monitor the displacement in Hanoi in the 1995–2020 period [4, 8, 11–18]. The authors have successfully proved, from different perspectives, the use of various radar remote sensing techniques for land subsidence monitoring. However, these studies only showed the detection of land subsidence, and there is still a lack of assessment of the connection between land subsidence and triggering factors. Additionally, all of the studies have assumed that the horizontal movement over the city of Hanoi is insignificant and is thus neglected. Based on the literature review of InSAR applications in Hanoi City, including some aspects of the study area, InSAR methods, and SAR data, this study further extends the land subsidence monitoring by introducing the use of radar remote sensing combined with hydro-mechanical modeling to quantify the relationship between hydrogeological factors and land subsidence in the urban setting of Hanoi over the 2016–2019 period. The results presented in this article are the initial phase before the comprehensive assessment using the subsequent hydro-mechanical modeling.

The rest of the study is organized as follows: Sect. 2 introduces the city of Hanoi. InSAR time series analysis methods and data are provided in Sect. 3. Section 4 reviews literary studies on InSAR application over Hanoi City. Section 5 discusses the combination of InSAR and hydro-mechanical modeling, and Sect. 6 concludes the study.

2 The City of Hanoi

Hanoi is located in the northeast of Vietnam between $20^\circ 53' - 21^\circ 23'$ latitudes and $105^\circ 44'–106^0 02'$ longitudes, covering an area of 3.358.9 km^2 (Fig. 1). Hanoi is one of the most populous cities in Asia, with an average population density of 2.087 people per km^2 (population statistics made in 2019 [19]). It is the core city in the Red River Delta with crucial political, socio-economic, cultural, and scientific importance besides Ho Chi Minh City in the Mekong River Delta in the South.

With the average height ranging from 5 to 20 m above sea level, the terrain gradually lowers from north to south and from west to east. Quaternary sediments cover the entire area; specifically, there are different formations divided by the origin and age in Hanoi from top to bottom as follows: Late Holocene alluvial; Early-Middle Holocene deposits, marine and bogged sediments; Late Pleistocene alluvial, lacustrine; Middle-Late Pleistocene alluvial; alluvial-proluvial deposits; and Early Pleistocene alluvial deposits [14]. Hanoi's aquifer system consists of four primary units from the surface down to 80–100 m depth, including the Holocene aquifer, Holocene and Pleistocene aquitards, the Pleistocene aquifer, and Neogene sandstone bedrock [6].

The consequences of ground subsidence in the center of Hanoi (i.e., urban districts) have been recorded since the late 1980s, especially in old apartment buildings. Recently, some new urban areas such as Dong Tau and Van Phu are also affected by high-rate subsidence in the 2017–2019 period. Land subsidence in the setting of

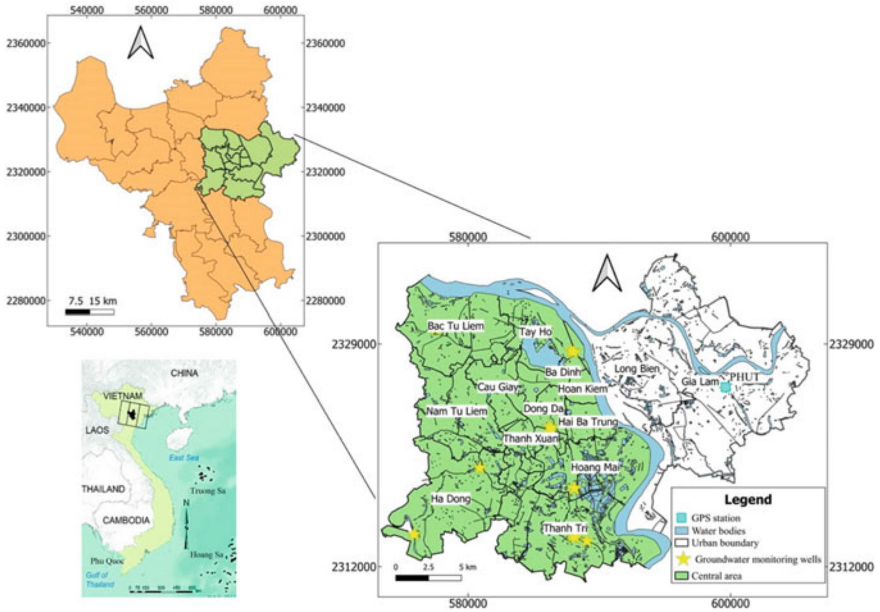

Fig. 1 The city of Hanoi (upper figure) with its urban districts (blue area) and spatial distribution of groundwater and GNSS monitoring stations (right figure)

Hanoi, Vietnam, is mostly considered to be the consequence of human activities such as excessive groundwater extraction, rapid urbanization, and rapid urban population increase [11].

3 Interferometric Synthetic Aperture Radar

3.1 InSAR Time Series Analysis Methods

DInSAR is a remote sensing method for precisely computing the deformation time series for a large area. The phase difference between two complex radar SAR observations over the same area indicates the Earth's surface deformation and other error and noise terms [20]:

$$\Delta\phi = \Delta\phi_{\text{disp}} + \Delta\phi_{\text{flat}} + \Delta\phi_{\text{elev}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{noise}} + \Delta\phi_{\text{err}} \quad (1)$$

where $\Delta\phi_{\text{disp}}$ refers to the differential deformation pattern along the line-of-sight (LOS) direction, $\Delta\phi_{\text{flat}}$ is the phase associated with the assumption of an ideally flat earth terrain, $\Delta\phi_{\text{elev}}$ is the interferometric phase caused by terrain topography, $\Delta\phi_{\text{atm}}$ denotes the atmospheric effect, $\Delta\phi_{\text{noise}}$ refers to the noise contribution from the radar instrument and temporal deceleration, and $\Delta\phi_{\mathrm{err}}$ due to orbital error and topographic height information. In DInSAR, accurate identification of ground deformation ($\Delta\phi_{\mathrm{disp}}$) requires eliminating all the other contributions [20].

Persistent Scatterer InSAR (PSInSAR) [21, 22] and Small BAseline Subset (SBAS) [23, 24] are among the widely used InSAR time series analysis methods working with the DInSAR technique. SBAS is advantageous that multiple interferograms are used in an interferogram network [25], thereby resulting in redundant interferograms adopted to reduce the noise in the InSAR time series, particularly in the case of a low signal to noise ratio [26]. In contrast, PSInSAR exploits a network of interferograms with a single primary image to work with highly coherent scatterers [21, 22]. As a result, it allows for a reduction in the primary image noise contribution, which is present in all interferograms. PSInSAR and SBAS improve the ability to identify ground deformation with millimetric precision, which helps to overcome the limitations of DInSAR [21]. Both PSInSAR and SBAS have recently been applied over the city of Hanoi, which showed consistent results [8]. The main steps applied in SBAS and PSInSAR data processing with the InSAR Scientific Computing Environment (ISCE), Generic InSAR Analysis Toolbox (GIAnT), and Stanford Method for Persistent Scatterer (StaMPS) software packages are shown in Fig. 2.

If the horizontal movement is insignificant, which was an assumption in many literary studies, the deformation in the LOS direction can be converted to that in the vertical direction by [9]:

$$d_U = \frac{d_{\mathrm{LOS}}}{\cos(\theta_{\mathrm{inc}})} \tag{2}$$

where d_U and d_{LOS} are the deformations in the vertical and LOS directions, and θ_{inc} is the radar incidence angle.

3.2 SAR Data

On a global scale, the use of radar satellites for remote sensing has a long history. Starting with Seasat in the late 1970s, numerous missions have contributed to an enormous range of data in the main three radar frequencies (X, C, and L bands) that have improved environmental and Earth system sciences. Figure 3 shows the progress of several SAR platforms in time which are summarized in Table 1.

At present, some active SAR satellites include Sentinel-1 (C-band), Radar SAT-2 (C-band), ALOS-2 (L-band), SAOCOM (L-band), TerraSAR-X (X-band), TanDEM-X (X-band), and COSMO-SkyMed (X-band) (see Fig. 3 and Table 1). However, the rule of the use of data acquisitions of these missions is highly inconsistent in the literature, depending on various factors, e.g., the background missions (regular acquisition over a defined area) or data availability. Typically, a C-band PSI study usually necessitates a minimum of 15–20 images [27]. In contrast, because of the better resolution and shorter wavelength of the X-band PSI, it is possible to employ

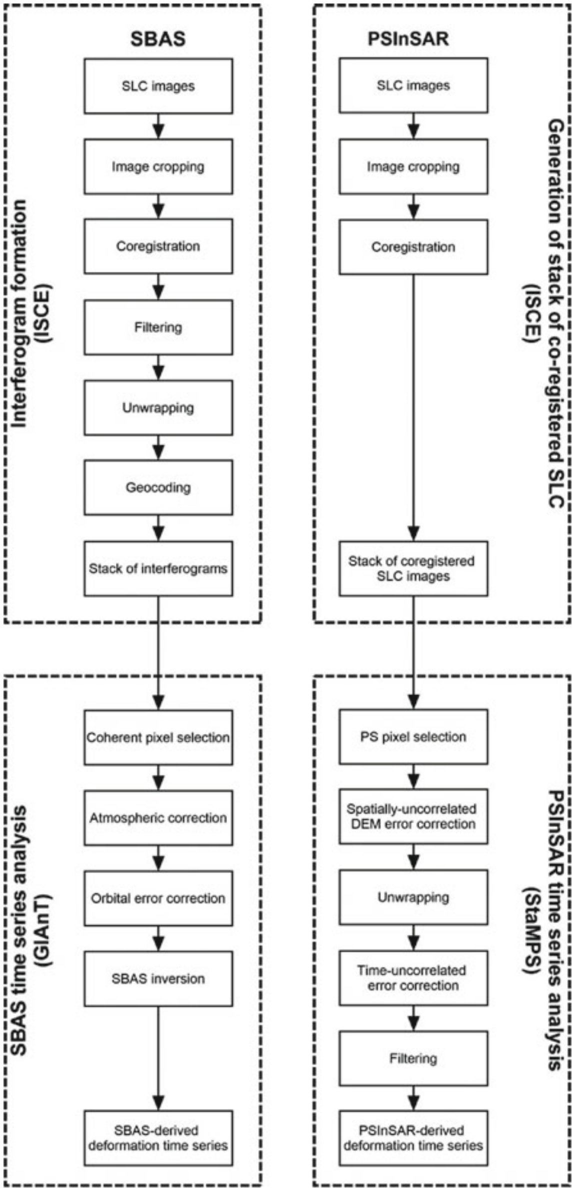

Fig. 2 Processing chain of the SBAS and PSInSAR methods (reused from [8])

shorter datasets [28]. However, the quality of the PSI deformation velocity and time series estimation improves as the number of available scenes increases [27].

At this time, only Sentinel-1 SAR data are freely available with a time interval of 12 days and the microwave spectrum C-band. Sentinel-1 data are accessible through

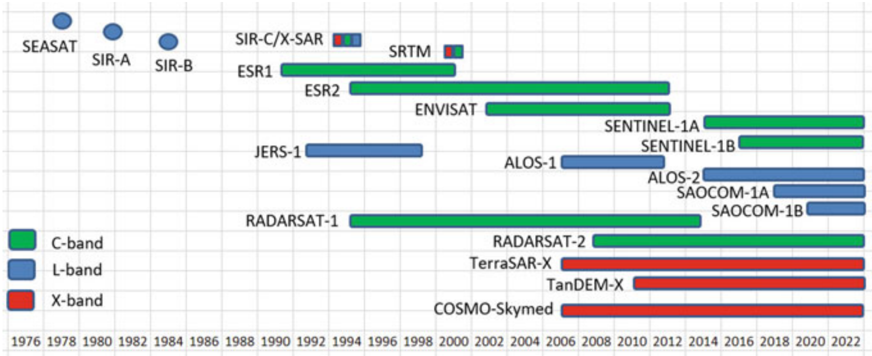

Fig. 3 Radar satellite timeline (*Source* eo-college.org)

Table 1 Summary of several SAR platforms

Radar band	Platforms	Owner	Operated period
L	Seasat	National Aeronautics and Space Administration	Jun – Oct 1978
	JERS-1	Japan Aerospace Exploration Agency	1992 – 1998
	ALOS/PALSAR	Japan Aerospace Exploration Agency	2006 – 2012
	ALOS-2/PALSAR-2	Japan Aerospace Exploration Agency	2014 – present
C	ERS-1	European Space Agency	1991 – 2000
	ERS-2	European Space Agency	1995 – 2011
	Radarsat-1	Canadian Space Agency	1995 – 2013
	ENVISAT	European Space Agency	2002 – 2012
	Radarsat-2	Canadian Space Agency	2007 – present
	Sentinel-1A	European Space Agency	2014 – present
	Sentinel-1B	European Space Agency	2016 – present
X	COSMO-SkyMed	Italian Space Agency	2007 – present
	TerraSAR-X	German Aerospace Centre	2007 – present
	TanDEM-X	German Aerospace Centre	2010 – present

(Reproduced from [29])

Copernicus Open Access Hub (https://sentinel.esa.int/web/sentinel/home) and the Alaska Satellite Facilities (ASF) (https://search.asf.alaska.edu/).

4 Review on the Studies Using InSAR in Land Subsidence Monitoring in Hanoi

During the last decades, the large amount of data from the abovementioned satellites and the development of various techniques enable utilizing the radar images over Hanoi. One of the earliest studies applying radar remote sensing to detect land subsidence in Hanoi was by Tran et al. [17]. In this study, three JERS-1 SAR L-band images from 1995 to 1998 were used with the three-pass differential interferometry (one of the DInSAR methods) to show some areas with high deformation rates in the urban area of Hanoi, such as Yen Phu, Long Bien, Ba Dinh, and Ngo Sy Lien area. However, some high rates of subsidence in the southern part of Hanoi City (Phap Van, Van Dien, or Ba La) could not be detected by DInSAR analysis because of the low coherence from pairs of scenes.

Dang et al. [11] used L-band ALOS-PALSAR images to quantify the spatial distribution of land subsidence in the whole Hanoi urban region using a multi-temporal InSAR technique from 2007 to 2011. Some regions with high deformation rates were found including Hoang Mai, Ha Dong, and Hoai Duc–Tu Liem districts. The unsaturated layer's nature, the reduction of groundwater levels in aquifers due to pumping extraction capacity (Qp aquifer), the expansion of built-up surfaces, and the kind of building's foundation are all factors that were considered to influence the spatial distribution of surface deformation during this study time.

Over the period from 2011 to 2014, some studies combining TerraSAR and COSMO-SkyMed data demonstrated the feasibility of ground subsidence by X-band SAR data in the condition impacted by a strong atmosphere in Vietnam [12, 13, 15, 18, 30]. These studies also concentrated on the urban area of Hanoi using different InSAR time series analysis methods, such as PSInSAR and PS/DS techniques. In specific, Ho et al. [12, 13] showed that subsidence is particularly powerful in the HaiHung silt loam regions in the city's south and one of the primary causes of ground sinking is groundwater overexploitation. Le et al. [14] applied TerraSAR data with the SBAS method to extract the displacement in the historical center of Hanoi. This research denoted that the image oversampling implemented in the SB InSAR processing chain helps to eliminate some of the noisiest locations and allows for the assessment of the status of a single structure or monument, which is required for the monitoring of cultural heritage buildings, monuments, and sites for subsidence.

With the free C-band Sentinel-1 data from the European Space Agency (ESA), researchers have more opportunities to access easily the SAR data in the 2016-present period. Therefore, Sentinel-1 SAR data are used mainly for the ground deformation in the Hanoi area recently [8, 16]. Bui et al. [8] showed the high consistency between the results derived from SBAS, PSInSAR, and stacking methods in the spatio-temporal displacement rate in the urban area in Hanoi from 2016 to 2020.

By applying both PSInSAR and SBAS methods, Nguyen et al. [31] used different SAR sensors including ALOS, COSMO-SkyMed, and Sentinel-1 data to produce a long InSAR deformation time series in the urban area in Hanoi from 2008 to 2018. With InSAR deformations validated by leveling and GNSS data for a time-series ten years, this study denoted that subsidence in downtown Hanoi is waning, whereas the southern and western suburbs (Ha Dong and Hoai Duc districts) have emerged as the new subsidence hotspots in recent years. Besides, Hanoi's subsidence problem is relatively mild in comparison with other Southeast Asian cities.

Table 2 summarizes literary studies of InSAR application to monitor surface subsidence in Hanoi City.

As can be seen from the previous InSAR studies, SAR data of X, C, and L bands were applied successfully for extracting surface deformation mainly in the urban setting of Hanoi from 1995 to the present. It helped to detect the areas of high subsiding rates (e.g., higher than −20 mm/year) in the southern part of Hanoi, including Ha Dong, Hoang Mai, and Thanh Tri. Besides, the common philosophy of

Table 2 Literary studies of InSAR application to monitor surface subsidence in Hanoi City

Reference	SAR data	Time span	Number of images	Time series analysis method
Tran et al. [17]	JERS-1 (L-band)	1995–1998	3	Three-pass DInSAR
Dang et al. [11]	ALOS PALSAR (L-band)	2007–2011	22	SBAS, PSInSAR
Tran et al. [30]	ALOS PALSAR (L-band) TerraSAR (X-band) COSMO-SkyMed (X-band)	2007–2011 2012–2014 2011–2013	22 18 17	PS/DS (SqueeSAR)
Ho et al. [12]	ALOS PALSAR (L-band) TerraSAR (X-band) COSMO-SkyMed (X-band)	2007–2011 2012–2014 2011–2013	22 18 17	PS/DS (SqueeSAR)
Ho et al. [13]	TerraSAR (X-band) COSMO-SkyMed (X-band)	2012–2014 2011–2014	19 27	PS/DS (SqueeSAR)
Le et al. [14]	TerraSAR (X-band)	2012–2013	23	SBAS
Nguyen et al. [15]	TerraSAR (X-band)	2012–2015	23	PSInSAR
Bui et al. [8]	Sentinel-1A (C-band)	2016 – 2020	114	SBAS, PSInSAR
Nguyen et al. [31]	ALOS PALSAR (L-band) COSMO-SkyMed (X-band) Sentinel-1	2007–2011 2011–2015 2015–2018	22 17 98	PS/DS (StaMPS) PS/DS (StaMPS) SBAS

the abovementioned research was to derive the deformation in the vertical direction only (converted from line-of-sight deformation) with the assumption that the horizontal movement in the urban setting of Hanoi is insignificant. Due to a lack of data on ground monitoring stations in Hanoi, some available sources as an alternative for validation of InSAR deformation are Global Positioning System (GPS) deformation, a comparison of deformation hot spots [11].

5 Proposal of a Further Study on the Combination Between InSAR Results and Hydro-mechanical Modeling

The vertical deformation rates in the urban area in Hanoi measured by Sentinel-1 data from 2016 will be used as a basis for subsequent hydro-mechanical modeling. The results [8] are shown in Fig. 4 with the negative displacements shown by yellow to red colors representing the movements away from the satellite (i.e., land subsidence), while the positive values (green) represent the movements toward the satellite (i.e., land uplift). The velocity of ±2 mm/year is characterized by light-green color and is considered stable.

The vertical deformation time series derived from InSAR will be validated with GNSS data at the PHUT station [8] (Fig. 5). The InSAR deformation is calculated

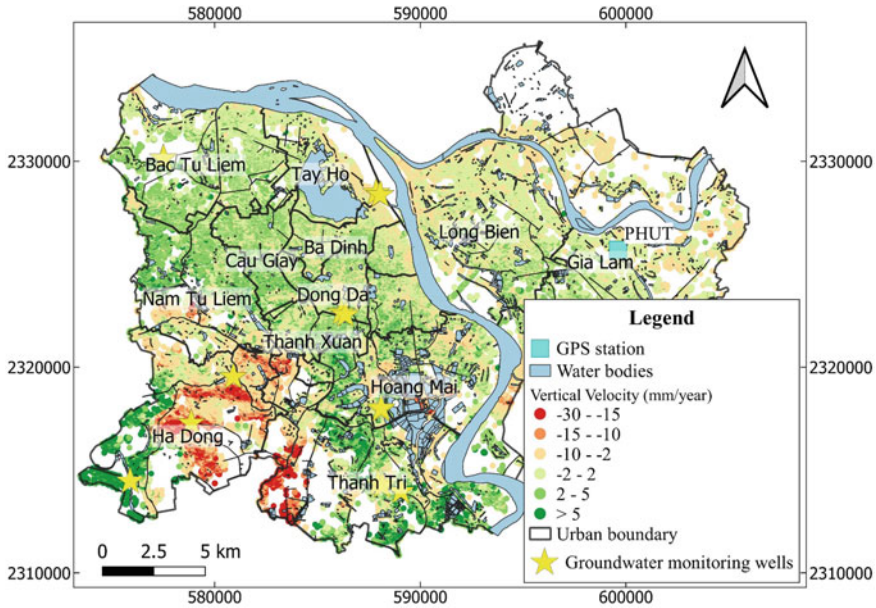

Fig. 4 Displacement in the vertical direction in the urban area of Hanoi from April 03, 2016, to December 20, 2019

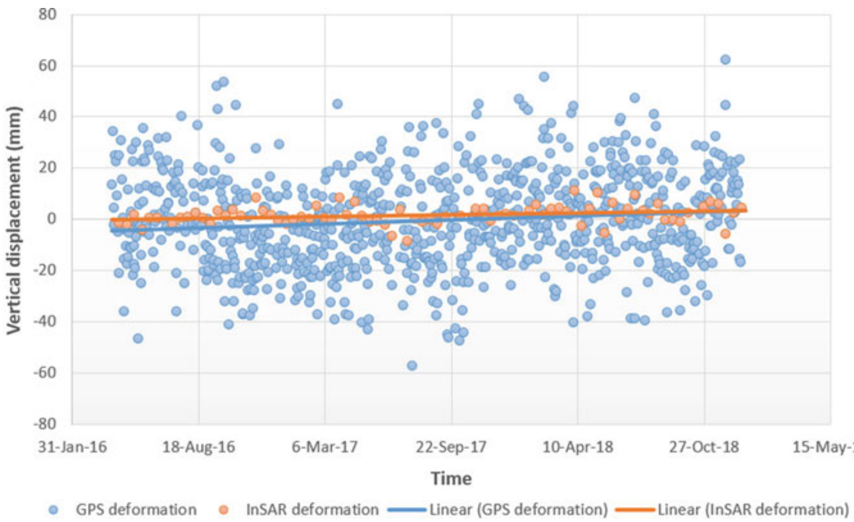

Fig. 5 Comparison between PSInSAR and GNSS-derived deformations in the vertical direction at the PHUT station

by averaging the time series within a 100-m radius centered at the GNSS station. This comparison is to test whether the InSAR and GNSS deformation time series are consistent (i.e., an agreement in the subsidence/uplift trend).

Besides, a large number of data are recently available, including boreholes with geological data, DEM, rainfall distribution, groundwater levels, and pumping rates, which will be used as inputs for a planned study with the hydro-mechanical model. The model will be generated using the open-access software OpenGeoSys [32], a finite element code developed for thermo-hydro-mechanical-chemical coupled modeling of geo-environmental processes. For the hydro-mechanical simulation of land subsidence, a poroelastic constitutive model using the Biot formulation can be used to calculate displacements.

The model will be calibrated using the InSAR-derived deformations mentioned above. The hydraulic conductivities and geotechnical parameters are specifically calibrated in OpenGeoSys. This proposed workflow includes multiple steps, including data standardization, the development of a conceptual and geological model using borehole data, numerical model setup (including boundary conditions, and assignment of hydraulic and mechanical properties to the geological layers), model calibration using InSAR-derived deformations, and analysis and scenario simulations.

The calibrated model will help assess the triggering factors that have impacts on the spatio-temporal distribution of land subsidence observed from the remotely sensed data. Specifically, we will analyze the impact of both pumping rates and the distribution of clay layers (aquitards) in the subsurface to better understand observed subsidence patterns. Scenario simulations with the calibrated model will subsequently be used to forecast the future trend and pattern of land subsidence in the area under various measures of groundwater extraction management as well as under possible changing hydrological conditions in view of climate change.

6 Conclusion

In this paper, previous studies about land subsidence estimation by using InSAR analysis during the 1995–2020 period in Hanoi, Vietnam, were reviewed. These researches successfully proved the feasible application of the main three radar frequencies (X, C, and L bands) for the detection of the areas of high subsiding rates (higher than −20 mm/year) in different parts of Hanoi. The InSAR measurement was shown in the vertical deformation with the assumption that the horizontal movement in the urban setting of Hanoi is insignificant.

Due to the lack of data on ground monitoring stations in Hanoi (especially in the period from 2012 to the present), some available sources as an alternative for validation of InSAR deformation are GPS deformation, a comparison of deformation hot spots [11].

The InSAR deformations derived by Bui et al. [8] that have high consistency with GNSS deformations will be an important input for the calibration of future numerical hydro-mechanical models. Using the open-source software platform OpenGeoSys, subsidence in the entire aquifer system of the area will be simulated. The data needed for the next phase of the numerical analysis include InSAR measurements and other input data. The general modeling workflow was also proposed in this paper.

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