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Recent land subsidence caused by the rapid urban development in the Hanoi urban region (Vietnam) using ALOS InSAR data

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Abstract

Since the 1990s the land subsidence due to the rapid urbanization has been considered a severely destructive hazard in the center of Hanoi City. Although previous studies and measurements have quantified the subsiding deformation in Hanoi center, no data exist for the newly established districts in the south and the west, where construction development has been most significant and where groundwater pumping has been very intensive over the last decade. With a multi-temporal InSAR approach, we quantify the spatial distribution of the land subsidence in the whole Hanoi urban region using ALOS images over the 2007–2011 period. The map of the mean subsidence velocity reveals that the northern bank of the Red River appears stable, whereas some areas in southern bank are subsiding with a mean vertical rate up to 68 mm yr^{-1}, especially within the three new urban districts of Hoang Mai, Ha Dong and Hoai Duc. We interpret the spatial distribution of the surface deformation as the combination of the nature of the unsaturated layer, the lowering of groundwater in the aquifers due to pumping withdrawal capacity, the increase of built-up surfaces and the type of building foundation. The time evolution deduced from the InSAR time series is consistent with previous leveling data and shows that the lowering rate of the surface slightly decreases till 2008. Then, a seasonal variation suggests that the deformation became non-stationary, with upward and downward transient displacements related to the charge and discharge of the aquifer following the changes between rainy and dry seasons.

1 Introduction

The phenomenon of land subsidence due to the underground exploitation of natural resources has usually accelerated over the last decades, because of the increasing demand (Johnson, 1995). The ground deformation is particularly unsettling when it occurs in large cities, where the recent intense urbanization implies a growing water consumption with a significant pumping of the aquifers. This problem has been observed in many large cities such as Mexico-City (Mays, 2009), Bangkok (Aobpaet et al., 2009), Shanghai (Chai et al., 2005), Venice (Brambati et al., 2003), and Las Vegas (Bell et al., 2002). The effects are significant when the urban area is situated on alluvial plains mainly composed of unconsolidated compressible sedimentary formations. Since the 1960s a large number of studies on land subsidence have been carried out using several methods of investigation (Poland, 1984; Galloway and Hoffmann, 2006) for a better understanding of the involved mechanisms (Holzer, 1984; Zhen-Dong and Ya-Jie, 2012) and its environmental consequences (Snelting and Bruchem, 1984; National-Research-Council, 1991; Holzer and Galloway, 2005; UNESCO, 2006). The measurement techniques quantifying the ground deformation related to ground subsidence vary from in situ techniques such as leveling (Bitelli and Russo, 1991) and extensometry (Ireland et al., 1984; Poland, 1984) to spatial techniques such as static Global Positioning System (Ikehara, 1994), radar interferometry (Massonnet and Feigl, 1998), and airborne LiDAR (Froese and Mei, 2008).

The capital of Vietnam, Hanoi City, is a good example of a quickly urbanized city in a developing country, where groundwater is the only resource of drinking water (Jusseret et al., 2010). From the beginning of the 1990s the urban development started to prosper in both socio-economic and land use aspects. With the conversion of agricultural land to urban space, several new urban districts have been created in the south and west of the city center to response to housing needs. That has been led to population concentrations and the intensive water extraction through several groundwater-pumping fields in these new urban districts. Moreover three other water production plants have been added in the 2002–2005 period in suburban districts during the development of the city with a total capacity of $30\,000\,\mathrm{m}^3\,\mathrm{day}^{-1}$ each (PPJ et al., 2011). The lowering of the groundwater level (Montangero et al., 2007) has inevitably induced local land subsidence causing numerous foundation failures of infrastructures, private small houses and old buildings (Ha, 2004). In the context of rapid urbanization after the regulation of the Hanoi City's administrative boundary in 2008, a better understanding of the ground deformation within the new urban region delimited by Master Plan of 2011 appears crucial for the purpose of reasonable urban planning on one hand and for an application of construction engineering safety solutions in the areas affected by land subsidence on the other hand.

Previous studies based on terrestrial measurements (Nguyen and Helm, 1995; Nguyen, 2007; Dinh et al., 2008) or soil characteristics modeling (Trinh and Fredlund, 2000) highlighted that some parts of the central districts have been affected by ground deformation over the last decades. For example, the in situ measurements have pointed out that the ground surface has subsided more intensely in the city center than in its surrounding areas, especially near the groundwater extraction fields. The mean subsidence amplitude ranges from 1.4 to 41 $\mathrm{mm\,yr^{-1}}$ for the 1994–2005 period (Nguyen, 2007). However, these in situ measurement methods are not appropriate for monitoring the large-scale displacement such as land subsidence over an entire new urban region because they provide information at the specific investigation points. On the contrary, measurements based on the remote technique of Synthetic Aperture Radar Interferometry (InSAR) are suitable for providing subsidence magnitude over broad areas with centimetric to milimetric accuracy depending on the available data set. With this method, several studies focused on the ground deformation in central districts using several SAR images acquired by different sensors (Raucoules and Carnec, 1999; Carnec and Raucoules, 2001; Tran, 2007; Noel, 2008; Vöge, 2011). By using the conventional InSAR approach, the study of Carnec and Raucoules, (2001) showed a vertical displacement of an order of 20 mm within the 1996–1998 period. However, they do not obtain an accurate velocity field over the whole new urban region since they focused only on the city center. Also, their approach suffers from some usual key limitations of the InSAR techniques. First, the available catalog of C-band images (mainly ERS and Envisat from the European Space Agency) was too small to properly cover a long time period (Noel, 2008) and unsuitable for combining SAR images separated by reasonable spatial and temporal baselines. Second, the tropical climate generates a significant atmospheric signal in the InSAR data (Takeuchi and Yamada, 2002), particularly in the troposphere from C-band images (Zebker et al., 1997). Finally, the main limitation corresponds to the decorrelation due to the change of scattering properties of the ground, mainly related to significant vegetation within the city (Wei and Sandwell, 2010). In order to overcome this difficulty, Vöge (2011) processed one couple of L-band ALOS-PALSAR images (wavelength 23.62 cm) and evidenced a maximum vertical ground displacement of 90 mm within the February 2007–June 2008 period. But this latter study together with those ones using C-band images (ERS or Envisat) did not provide accurate deformation rates of the ground for the whole study area, for the recently urbanized areas in particular, nor over a large time period.

In this study, we apply the recent multi-temporal InSAR method, (StaMPS-MTI) developed by Hooper et al. (2007). Using a set of ALOS PALSAR's satellite L-band images, the objectives of this study are to (1) precisely map the spatial distribution of land subsidence over the 2007–2011 period by determining the vertical velocity of a maximum of data pixels, (2) describe the temporal evolution of the subsiding areas, and (3) analyze these results with respect to the new urbanized areas built during these last decades, to both the locations and the extraction rate of the water pumping plants, and to the spatial relations of the resistance of the shallow geological layers.

2 Study area

After the renovation (Doi Moi) in 1986, the capital of Vietnam began its economic transformation. The dynamics of economic development together with new management policies have rendered Hanoi City, especially the urban districts more attractive for immigrants from proximate provinces. Currently, this city is divided into ten urban districts, 19 suburban districts after four alternate times of administrative regulation promoting the conversion of peripheral agricultural areas to urban land with the creation of several urban districts such as Tay Ho in 1995, Thanh Xuan and Cau Giay in 1996, Long Bien and Hoang Mai in 2003 and Ha Dong in 2008 (Fig. 1). As a consequence, the population of whole city grew from 2.431 to 3.184 million inhabitants from 1995 to 2006, while the population of urban districts doubled from 1.082 to 2.050 million in the same period. The growth of population went on to reach 6.472 million inhabitants in 2009 with a density of 1979 inhabitants km^{-2} and approximately of 35 000 inhabitants km^{-2} in some central districts such as Dong Da or Hoan Kiem (GSO, 2009).

Hanoi City is located in the northwest of the Red River plain dominated by flat relief with an elevation below 15 m, except for the Tam Dao hills in the north and the Ba Vi mountains in the southwest reaching up to 462 m and 1281 m, respectively (Fig. 1). Currently, the 3325 km^2 territory of Hanoi City (20°35′–21°23′ N, 105°17′–106°02′ E) is affected by a tropical monsoon climate with a hot summer season with heavy rainfalls spanning from May to October and a cool and dry winter season spanning from November to April. The main flow of the Red River goes through Hanoi City and splits into the Day River on the eastern side and Duong River on the western side of the city (Fig. 1). Its hydrology regime varies seasonally following the climate season: the discharge on Red River at Hanoi hydrological station reaches a maximum of $23 \times 10^3\,\text{m}^3\,\text{s}^{-1}$ (accounting for 70–80 % of the annual budget) during the rainy season and a minimum of $700\,\text{m}^3\,\text{s}^{-1}$ during the dry season (Luu et al., 2010). Red River plain is a small part of the Red River basin, which is controlled by the Neogene Red River fault system and surrounded by Precambrian crystalline rocks and Paleozoic to Mesozoic rocks (Tanabe et al., 2006).

The subsoil of Hanoi City comprises the Pleistocene sediments of Vinh Phuc, Ha Noi, Le Chi formations underlying the Holocene sediments of the Thai Binh, and Hai Hung formations (Mathers and Zalasiewicz, 1999). These formations mainly consist of sediments filled in the accumulation process to form the Red River plain, in which costal deposits such as sand and clay are overlaid by fluvial and floodplain deposits (Jusseret et al., 2010). Quaternary sediments directly overlay Neogene deposits and generate two main aquifers: the Holocene unconfined aquifer (Qh) and the Pleistocene confined aquifer (Qp), separated by an impermeable layer of clay (Nguyen, 1996b). The thickness of the Qh aquifer varies laterally from 10 m in the north to 45 m particularly along the Red River. This Qh aquifer is mainly used for small-scale water exploitation by dug wells or drilling shallow wells. The depth of the Qp aquifer ranges from 10 to 43 m and its thickness varies from 13.5 to 62.5 m beneath Hanoi City. This Qp aquifer plays a crucial role in the supply of freshwater with large pumping stations for almost all activities of the urban districts of the city (Rau et al., 1991). The groundwater monitoring including water level, temperature, chemical compositions in Qp and Qh aquifers is measured weekly through the network of observation wells: 21 wells for Qh, 32 wells for Qp dispersed around of Hanoi City (Fig. 1[1]) by *National Groundwater Monitoring Database* project (CWRPI, 2011). From these data sets, interpolated isocontours of the averaged groundwater level for Holocene aquifer and groundwater piezometric head for Pleistocene aquifer are yearly calculated by Northern Division of Planning and Investigation for Water Resources utilizing the commonly-used GIS and Kriging interpolation methods (Bui et al., 2010).

3 Methodology and data

3.1 Methodology

Since the early 1990s, the success of the InSAR technique has been demonstrated for a large panel of applications such as landslides, volcanic activity, glacier motion or seismic deformation (Bürgmann et al., 2000). The classical InSAR method allows the generation of interferograms corresponding to the phase difference, in the case of repeat-pass. This phase difference of a single pixel corresponds to the addition of several contributions:

$$\Phi = \Sigma(\Delta\phi_{\mathrm{orb}} + \Delta\phi_{\mathrm{topo}} + \Delta\phi_{\mathrm{atm}} + \Delta\phi_{\mathrm{N}} + \Delta\phi_{\mathrm{def}}) \quad (1)$$

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[1] In some places, the observation wells for Qp are installed closely to the Qh and whole wells do not appear totally on this figure because they hide them-self each other.

with $\Delta\phi_{\text{orb}}$, $\Delta\phi_{\text{topo}}$, $\Delta\phi_{\text{atm}}$, and $\Delta\phi_{\text{def}}$ being the phase difference due to the orbital positions, the topography, the atmosphere delay, and the ground deformation respectively. The noise term ($\Delta\phi_{\text{N}}$) is related to the variability of scattering, thermal noise, and data processing errors. In order to retrieve with accuracy the deformation term, a good estimate of the other contributions is necessary, based on precise data of both orbital parameters and topography. The deformation term can be expressed as the following:

$$\Delta\phi_{\text{def}} = 4\pi\Delta R/\lambda \tag{2}$$

with ΔR being the change of satellite–ground distance along the Line of Sight (LOS) direction and λ the wavelength of radar system.

Because of its high sensitivity to vertical displacement, the InSAR monitoring of the human-induced subsidence phenomenon became one of the main applications (e.g., Massonnet et al., 1997; Fielding et al., 1998; Galloway et al., 1998; Lazeckỳ et al., 2010), especially in urban areas where the number of coherent pixel over time remains high (e.g., Hoffmann et al., 2001; Watson et al., 2002; Stramondo et al., 2008; López-Quiroz et al., 2009; Crosetto et al., 2010, 2013). The de-correlation noise results either from a variation of the satellite LOS direction for the two images (different look and squint angles) or from a change of the scatterer position or geometry within the resolution cell. If the de-correlation noise is too significant, the interferogram will be not suitable for analyzing the deformation. Also, in the case of high deformation rate, the deformation term ($\Delta\phi_{\text{def}}$) is dominant which offers the opportunity to measure the displacement between two times of image acquisition (Amelung et al., 1999). However, in case of slow motion, the determination of the deformation term can be limited by the preponderance of the non-deformation terms. By stacking several interferograms of the same area, the signal-to-noise ratio is increased allowing the determination of a mean velocity of the ground over the period covered by the interferograms (Peltzer et al., 2001). This approach is effective in the case of steady-state displacements but prevents any evidence of non stationary deformation.

In order to overcome the geometric decorrelation due to the change of scattering properties Zebker and Villasenor (1992) reduce the influence of the atmosphere and measure transient displacements, multi-temporal InSAR techniques have been recently developed. The methods based on multiple acquisitions of SAR images are known as persistent scatterers (PS) and small baseline (SB). In general, these two approaches PS and SB are optimized to process different types of scatterers on the ground. The PS approach aims to process the resolution cells dominated by one single scatterer (Fig. 2a), while SB approach aims to treat resolution cells by many scatterers without dominant one (Fig. 2b). The PS approach takes advantage of the large energy returned by one scatterer within a resolution cell, corresponding to either rock outcrops in natural areas or man-made features such as buildings, towers, and utility poles in urban areas (Ferretti et al., 2000, 2001; Lyons and Sandwell, 2003; Kampes, 2005). For the selection of the stable pixels (or PS pixels), Ferretti et al. (2001) developed a method based on the variation of the pixel amplitude in a series of numerous interferograms and particularly adapted for urban areas and fast displacement rates. Many studies have been focused on land subsidence using the former PS method (e.g., Kim et al., 2007; Stramondo et al., 2008; Cigna et al., 2012; Tung and Hu, 2012). Hooper et al. (2004) developed a method based on the spatial correlation of the phase together with the amplitude and also suitable for natural outcrops and low displacement rates. Both of these methods require forming all interferograms with respect to a “master” image, chosen in order to both maximize the interferometric coherence of all the pairs (small spatial and temporal baselines) and co-register the interferograms. The SB method primarily developed by Berardino et al. (2002) and Schmidt and Bürgmann (2003) overcomes the temporal decorrelation problem by using combinations of multi-look interferograms separated by short time intervals and short spatial baselines. However, Hooper et al. (2004) and Lanari et al. (2004) proposed single-look interferograms via SB algorithms and then Lanari et al. (2007, 2010) and Bonano et al. (2012) used this technique to monitor the temporal evolution of the surface deformation.

In this paper, we follow the MT-InSAR method developed by Hooper (2008) in which one phase for PS pixels has the phase noise component that is neglected and after removal of the contribution topographical with external GDEM, the phase difference depends only on the three others contributions. The estimate of this remaining term is realized by applying their correlation with adjacent pixels and the spatially correlated phase is estimated by band pass filtering. The selection of persistent scatterer pixels is performed firstly using PS approach developed by Hooper et al. (2007), which allows to reduce the noise component of the single master before the processing of phase unwrapping because of its presence in entire interferograms. Then, a full resolution interferograms using SB approach is carried out to extract distributed scatterers and the application of spatial filtering is not realized to prevent the increment of noise for distributed scatterers by multi-looking the images SAR. The algorithm of MT-InSAR method has been developed to merge two sets of pixels in order to obtain more coherent pixels therefore increase the spatial coverage of signal for contributing to a better phase unwrapping, and to improve the signal-to-noise ratio for pixels selected by both PS and SB approaches. A first 3-D phase unwrapping using a statistical cost approach (Hooper, 2010), and then the estimate of the DEM errors by correlation with the values of the perpendicular baselines of each interferograms in order to unwrapped a second time taking into account these corrections. Up to now, few applications of this methodology have focused in land subsidence over urban area (e.g., Aobpaet et al., 2009; Yan et al., 2012).

3.2 Data

We use a total of 21 raw SAR image scenes acquired in L-band (wavelength of 23.6 cm) at the level 1.0 between February 2007 and February 2011 by the Japanese sensor (PALSAR) equipped on the Advanced Land Observing Satellite (ALOS) along its descending track 475, frame 400 (Fig. 1). We limit our study area on the 40 km × 40 km surrounding urban region (Fig. 1). For removing the topographic contribution from the interferograms, the global digital elevation model (GDEM) issued from the Advanced

Spaceborne Thermal Emission and Reflection Radiometer (ASTER) version 2 with a resolution of 1.5 arc-seconds has been used to obtain an external elevation of this area of interest. Otherwise, the contribution of flat-earth was also removed by using of precise orbit data accurate to < 1 m, which are delivered with the level 1.0 product in the header file as 28 state vectors from JAXA.

4 Results

4.1 Spatial distribution of subsidence

Using StaMPS/MTI processing, a large number of persistent scatterers (540 000) have been selected within the region under study (Fig. 3). Most of these scatterers correspond to private houses, buildings and infrastructures, located within the dense settlements in urban districts and the surrounding villages in suburban districts. The places where no persistent scatterers are selected correspond to water bodies or agricultural areas of rice fields surrounding the urban area. Assuming that most of the measured deformation corresponds to vertical displacement of the surface due to the subsidence, we convert the velocity obtained along the satellite line of sight into vertical velocity using the incident angle (θ) at each measurement points (average of $\theta = 38^{\circ}$ for ALOS PALSAR images).

We observe a heterogeneous field of vertical velocity in the Hanoi urban region, with the vertical subsidence rate ranging from 0 to 68 mm yr^{-1} over the four years under study (Fig. 3). First, we note that the deformation is mainly confined within the urban region. The mean vertical velocity field indicates a clear distinction between the northern and southern parts of the Red River. In the northern part, the ground surface appears to be very stable, with few small subsiding spots identifiable in the east of Dong Anh suburban district and between the Red River and the Duong River, such as near the headquarters of Long Bien urban district or in the southwestern part of Gia Lam suburban district (Fig. 3). For these local spots, whose horizontal extension does not exceed 1–2 km^2 each, the mean vertical velocity reaches a maximum of 15 mm yr^{-1}. In the northern part of the southern bank corresponding to the urban districts of Tay Ho, Ba Dinh, Cau Giay, and Tu Liem suburban district, is clearly distinguishable with very little deformation, except along the Red River, where a surface subsidence occurs at a slow rate, lower than 10 mm yr^{-1}.

In the southern bank, the land subsidence occurs in three main areas in the south and the west of the city (Fig. 3) which are similar to the analysis in the study of Vöge (2011). First, the largest area corresponds to the urban district of Hoang Mai at the south of city center. The deformation corresponding to a mean subsidence rate larger than 30 mm yr^{-1} covers a 5 km × 5 km surface, and is bounded to the north by very sharp velocity gradients (Figs. 3 and 4a). The maximum mean vertical rate reaches 68 mm yr^{-1}, only 1 km away from a stable area. We note the particular pointy shape of very low deformation indenting into the main deformed area and at the east of this first subsidence area, some patches of subsidence with a lateral extension not larger than 0.5 km × 0.5 km and a high vertical rate of 50 mm yr^{-1}. The second area of significant deformation is located in the Ha Dong-Thanh Xuan urban district in the southwest city center (Figs. 3 and 4b). The lateral extension of this second subsiding area is significant, up to 7 km × 4 km but very few places within this area exhibit a vertical rate higher than 45 mm yr^{-1}. We distinguish only a small site with vertical rate 60 mm yr^{-1} in the south. In the west of the urban region, the third main area of deformation appears blurred due to the sparseness of scatterers in the suburban districts of Hoai Duc and Tu Liem, where the agricultural fields are still dominant (Figs. 3 and 4c). The patches draw a NS elongated area of 8 km × 3 km, in which the vertical velocity ranges from 30 to 60 mm yr^{-1}.

In the other parts of the urban region, several smaller patches of subsidence with a lateral extension smaller than 1 km^2 are located such as Dong Da, Thanh Xuan or Hai Ba Trung with a vertical velocity ranging from 10 to 25 mm yr^{-1}, i.e., quite small in comparison to the three previously described areas (Fig. 3). These values are consistent with the results of Carnec and Raucoules (2001) for the 1996–1998 period.

4.2 Temporal evolution analysis

The time series decomposition has to be analyzed with caution since our period of observation covers only four years, with only 21 images used. Figure 5 presents the displacement over time for six specific pixels located within the three subsidence areas. For most them, we observe large variations in the evolution, which should be interpreted either as noise in the data due to inaccurate estimates of the baseline for instance, or an actual signal revealing a complex behavior of the ground and/or external processes responsible for this pattern. However, we note that the time evolutions of each of the selected pixels share the following characteristics. In the first half of the period under examination, the surface displacement shows a regular downward motion till the end of 2008. In the second half, the variations are larger in most of the graphs, with a succession of upward and downward ground motions, with a specific pick in July 2010. This difference between the two parts of our observation period suggests that the behavior of the aquifers dramatically changed at this time. We compare these time series of the surface displacement, with the evolution of rainfall during the same period (Fig. 6). Even if our time series are too short to conclude the rain and the surface displacement are correlated, we observe that the subsidence phenomenon in Hanoi seems to follow some seasonal variations from 2009 to the beginning of 2011. This is particularly the case for the pick in July 2010, occurring after a long period of dry season. Significantly, extreme rainfall fell on 31 October 2008, with more than 350 mm recorded causing large scale flooding. Simple explanations are difficult to draw, but the heavy rains may very well have disturbed the behavior of the aquifer.

In order to validate our results, we compare the values of the vertical subsidence rate for a specific area, for which other data are available. Sixteen leveling campaigns have been carried out from 25 June 2007 to 26 September 2008, by the Hanoi Housing and Urban Development Corporation at several building blocks in Van Quan residential zone located in second subsidence area in the Ha Dong-Thanh Xuan districts (location on Fig. 4b). We look more precisely at the leveling data of building blocks TT18A and TT18B due to the presence of PS pixels within these blocks (Fig. 7a). The mean subsidence rate deduced from the leveling data corresponds to a mean velocity of 35.0 $\mathrm{mm\,yr^{-1}}$ for block TT18A and 27.8 $\mathrm{mm\,yr^{-1}}$ for block TT18B, respectively (Figs. 7b). Notably, these mean values are in agreement with our InSAR results giving a mean value of 38.2 $\mathrm{mm\,yr^{-1}}$ and 25.6 $\mathrm{mm\,yr^{-1}}$ for the PS points located at corresponding building blocks. Nevertheless, we note that these values are smaller than the mean velocity of 90 mm during the period of 17 months (from 2 February 2007 to 22 June 2008) corresponding to 63.5 $\mathrm{mm\,yr^{-1}}$ for whole experimental area determined by Vöge (2011). However, as mentioned above, this latter study used only two images processed by DInSAR method, with all the related uncertainties due to atmospheric heterogeneities, time decorrelation, etc. We then look at the time evolution of these measurement points and observe a great similarity between the InSAR data and the leveling data over the period from June 2007 to September 2008, which is crucial for validating our InSAR results (Fig. 7c). During the same period, both of these data sets do not follow a linear function, consistent with a constant velocity, but do describe a polynomial function of second degree. This suggests a slow decrease of the vertical velocity with time, which reveals a mechanical behaviour of the layer submitted to a decrease of its pore pressure due to the water withdrawal. Therefore, unless there was significant noise included only in the data for the period after September 2008, the subsiding signal over Hanoi is clearly not stationary, but includes important transient displacements.

5 Discussion

5.1 Subsidence in relation with quaternary geology

Shallow geology is an important contributing factor to land subsidence phenomenon and the spatial variations of its amplitude. In the north bank of the Red and Duong Rivers, the dominant layers exposed at the surface at Dong Anh and Soc Son suburban districts correspond to clay and gravel of the Vinh Phuc formation with a porous varying from 43 to 47 % and low porous bedrock of middle Triassic (T_2) is −10 m b.s.l., at a maximum depth of 20 m below the topographic surface (Nguyen, 2005). In addition, the two pumping stations are extracting water at low rates. There are two explanations for the very low deformation observed in this part of Hanoi City. In the northern part of the south bank, even though the extraction rate of groundwater is very high and many new residential zones are being developed, little deformation is observed at the urban districts of Tay Ho, Ba Dinh, Cau Giay, and the Tu Liem suburban districts where geological layers are similarly composed by the deposits of the Vinh Phuc formation. However, south of the city center and between the two rivers, in the districts of Long Bien, Gia Lam, Hoang Mai, Thanh Tri, Thanh Xuan, Ha Dong, Hoai Duc, the sedimentary layers below the marshy surface consist of Holocene deposits such as clay, and sand of the Hai Hung formation with the porous varying from 51 to 63 % and gravels, sand and clay with upward fining succession of the Thai Binh formation with the porous varying from 45 to 61 %, which contains some lens of plastic and soft materials with low bearing capacity (Nguyen, 2005). The deeper geological layers below the three largest subsidence areas of Hoang Mai, Ha Dong-Thanh Xuan, and Hoai Duc-Tu Liem districts corresponds to soft soil containing organic matters, sand, sandy clay, loamy sand or clay loam (Figs. 8a and 9a). The groundwater level in Qh aquifer is located at maximum depth of −6 m b.s.l. (11.5 m below the topographic surface) due to withdrawal of main well fields (Fig. 8a).

5.2 Subsidence in relation to human activities

In terms of resource and environmental perspectives, the most apparent consequence of urbanization is the various changes in hydrologic cycle (Mays, 2009), which are considerably perturbed by the modification of soil properties (Haase, 2009). As human spaces become increasingly dominant through the urbanization process, impermeable materials such as concretes, plastics or asphalts increasingly replace natural surfaces. The impermeable coverage induces a reduction of the amount of evapo-transpiration, to increase the runoff and to prevent the infiltration and the recharge of groundwater beneath the city surface. In addition, the rapid growth of human population and growing industry has put a great pressure on water demands for domestic and commercial purposes. Therefore, the extensive housing construction and groundwater extraction that causes significant static and dynamic load are considered to be land subsidence triggers, particularly in an area where unconsolidated sediments in the Red River plain are characterized by high porosity.

5.2.1 Housing development

After the removal of a government subsidized housing system at the end of the 1980s, an explosion of housing construction occurred in the city center in order to accommodate a rising urban population and more immigrants. At its initial stage, private house construction began with a principle of densification within the limit of Ba Dinh, Hoan Kiem, Dong Da, and Hai Ba Trung central districts (Fig. 11a, before 1993). Then, the urban landscape has changed to reflect added urban sprawl, which took place mainly along the major national roads in Thanh Tri suburban district in the south, Tu Liem suburban district in the west, Thanh Xuan urban district in the southwest and Long Bien urban district in the northeast. Then the urban development spread to the western, southwestern and the northern parts of city center with the creation of Tay Ho district in 1995, and Cau Giay, and Thanh Xuan urban districts in 1996 (Fig. 11a, between 1993 and 2000). Although the housing crisis in the urban districts was gradually softened by private construction, most of those developments were realized without permission from the master plan.

At the end of 1990s, a planning measure was applied with a new concept of residential zoning, in which urban infrastructures for green space, drinkable water, electricity, and roads were developed simultaneously with the housing accommodations. Typically each new residential zone now contains several buildings of over 20–30 floors, an area for private individual houses with several floors and an area for adjacent condominiums with four or five floors. Over the last decade, the housing construction has consisted in the deployment of more than 100 new residential zones by public construction or foreign joint venture companies, whose surfaces range from small projects (several ha) in the urban districts to big projects (up to several hundreds ha) in its periphery (Labbé, 2010) and the build-up surfaces have been increasing permanently exceeding in 2007, when the global financial crisis are occurred (Fig. 11b). With the creation of Long Bien and Hoang Mai urban districts in 2003, the built-up surfaces have continued to spread to the west of the city center in the urban district of Cau Giay, to the northwest in the Tay Ho urban district, and to the southeast in the Hoang Mai urban district, where the first subsidence area has arisen in a densely constructed region encompassing many new residential zones and small houses. In this subsidence area, the highest mean velocity corresponds to the constructions in Dong Tau, Dai Kim, Yen So, Dinh Cong, Linh Dam, Den Lu new residential zones and Vinh Tuy industrial park (Fig. 4a). The urban expansion is still limited in the north bank of the Red River and in the southern part of the city center due to natural barriers such as streams or wetland areas (Fig. 5a, between 2000 and 2007).

Until the administrative regulation event in March 2008, 772 new residential and industrial projects have been planned in the new Hanoi City region occupying 145.7×10^3 ha, of which 25 000 ha are located in the former boundary (VET, 2008) and many big projects have been deployed all around the urban region. The isolation of the northeastern territory is removed with the new bridges crossing over the Red River, and new residential zones were set up at eastern Long Bien and Gia Lam districts explaining the appearance of small discrete subsidence spots between the south bank of Duong River and the north bank of Red River. The developed surfaces are expanding to the main directions of previous periods, but are very strong in the west and southwest suburban districts such as Hoai Duc, Phuc Tho, Tu Liem and Ha Dong urban district, where the second and third subsidence areas are located corresponding to the implementation of big residential zones such as Van Quan, Van Phu, Mo Lao, Nam An Khanh. This includes the private house construction in traditional villages such as La Khe, Da Sy, Van Noi, Phu Do, Dai Mo, Song Phuong, Di Trach (Fig. 4b and c). This process is beginning to connect surrounding villages to developed urban spaces. However, the discrete connection of the recently urbanizing villages in Hoai Duc and Tu Liem suburban districts corresponds to of the small patches of the third main subsidence area (Fig. 11a, between 2007 and 2011).

Thus, the three main subsidence areas are located in the new urban districts created after 2003 and their neighborhood suburban districts, in which many new residential zones are being developed and traditional villages are being transformed over the last decade. The variation of persistent scatterers pattern shows a relation between the subsidence with the density of built-up surfaces, which is ranging from the dense construction (urbanized areas) such as the first subsidence area in Hoang Mai urban district to the moderate construction (urbanizing area) such as the second subsidence area in Ha Dong-Thanh Xuan urban districts and to sparse construction (urbanizing villages) such as the third subsidence area in Tu Liem-Hoai Duc suburban districts.

5.2.2 Groundwater extraction

The groundwater supply in Hanoi City has evolved in urban districts since the 19th century, in particular in the recent period with the increase of population density and the economic changes. Two types of groundwater extraction management currently exist for industrial production and drinking water. First, the centralized extraction is managed by the Hanoi Water Supply Company (Hawaco) with eleven well fields and seven small stations accounting for a total of 200 wells, which allow to extract the groundwater from the Pleistocene aquifer (Qp). The average withdrawal from these well fields has been monitored, showing continuous rises of groundwater extraction over the last decades for domestic and industrial demand and for public services in urban districts. The inventories or research results of Nguyen and Helm (1995), Tong et al. (2001), Duong et al. (2003), Montangero et al. (2007) propose the following evolution of the Qp extraction: $86.5 \times 10^3\,\mathrm{m^3\,day^{-1}}$ in the period of 1955–1965, $180 \times 10^3\,\mathrm{m^3\,day^{-1}}$ in the period of 1975–1985, $400 \times 10^3\,\mathrm{m^3\,day^{-1}}$ in 2001, $450 \times 10^3\,\mathrm{m^3\,day^{-1}}$ in 2003, and eventually up to $620 \times 10^3\,\mathrm{m^3\,day^{-1}}$ in 2007. Second, a decentralized extraction

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has been made by many factories or companies, which drilled from their own wells due to inability of Hawaco's system to assure their proper industrial functioning. They directly extract groundwater from the confined Pleistocene aquifer (Qp) and the rate of extraction has been estimated to be $120 \times 10^3\,\mathrm{m}^3\,\mathrm{day}^{-1}$ in 2000 (Tong et al., 2001). Moreover, households in suburban districts extract drinkable water using shallow drilling wells in the Holocene aquifer (Qh), whose number and extraction amounts are impossible to estimate (Tong et al., 2001).

Almost all the centralized water production plants are concentrated in the urban districts of the southern bank of the Red River, where population density is the highest (Fig. 6). The two largest subsidence areas in Hoang Mai and Ha Dong-Thanh Xuan urban districts are located close to groundwater well fields, which have a capacity of exploitation varying from 16×10^3 to $35 \times 10^3\,\mathrm{m}^3\,\mathrm{day}^{-1}$ (PPJ et al., 2011). The first main vertical deformation area identified in Hoang Mai urban district is located between two large Phap Van and Tuong Mai well fields, where the groundwater withdrawal reaches $24 \times 10^3\,\mathrm{m}^3\,\mathrm{day}^{-1}$ each. We note that the groundwater piezometric head level in Qp aquifer is deep, down to −17 m b.s.l. in 2010 (Fig. 12). The second main vertical deformation area is located between three well fields in the Thanh Xuan and Ha Dong urban districts (Ha Dinh, Ha Dong 1 and Ha Dong 2) with a withdrawal capacity reaching $23 \times 10^3\,\mathrm{m}^3\,\mathrm{wellfield}^{-1}\,\mathrm{day}^{-1}$, where the groundwater piezometric head levels in Qp aquifer was located to −5 m in 2010 (Fig. 12). However this value reached −34 m b.s.l. in 2006 in the same area (Winkela et al., 2010) due to the importation of surface water from Da River production plant at 60 km away from Hanoi in the June 2008. The intensive groundwater withdrawal of Qp aquifer from important well fields results not only in the drawdown of piezometric head in Qp aquifer but also in the drawdown of the groundwater level in Qh aquifer due to an interconnection between them in a multi-aquifer system (Alexander and Cheng, 2000). Moreover, the recorded data between 1995 and 2009 in selected monitoring wells show that the groundwater level in Qh aquifer has decreased from 4.1 to 3.1 m a.s.l. at a rate of $-0.07\,\mathrm{m\,yr}^{-1}$ in the south bank of the Red River (Bui et al., 2010). On the contrary, in the western part of urban region, the third largest subsidence area is not associated with any large Hawaco's well fields. In this area, the drinkable water is extracted from Qh aquifer through private shallow wells, whose the extraction amount is impossible to estimate. Since the spatial variations of the vertical velocity field are not consistently associated with the locations of the pumping stations, they should be analyzed with regards to the nature of the underground as an additional parameter.

5.3 Combination of multiple factors

We therefore suggest that the spatial variations of the subsidence observed in our InSAR results over the Hanoi urban region are related to a combination of the lateral variations of the geological composition of the underground, the groundwater level in the Qh aquifer, the density of urban development and the foundation design of the constructions. The first subsidence area in Hoang Mai district is a good example of this combination, which explains variations of the mean velocity from the northern to the southern parts of this area (Fig. 4a). In the north, the first meters of the ground correspond to sandy clay with organic matter and sand layers, i.e. material susceptible to compact due to a loading weight and a reduction of water content in the pore medium (Figs. 8b and 9a). In this area, Phap Van and Tuong Mai water production plants operate with an important withdrawal capacity (Fig. 12). At the northern part of the subsidence area, the density of construction is very high and the groundwater level in the Qh aquifer is down to −5 m b.s.l. which corresponds to a depth of 10 m below the topographic surface (Figs. 8a and 9a). The maximum of deformation is located precisely where the water level in the Qh aquifer is the deeper (Fig. 9a and b). North of the locus of maximum deformation, the presence of sharp gradients of deformation could be explained by the abrupt variation of thickness of sand and clay loam layers surrounding of borehole LKT46 (Figs. 8a and 9a). In the southern part of this subsidence area, in Thanh Tri and Thuong Tin suburban districts, the subsidence rates are very low (Fig. 9b) even if the geology is similarly loamy sand and sand layers (Figs. 3 and 8a). However, below these districts the groundwater level in Qh aquifer remains high, up to +4.5 m a.s.l. (Fig. 9a) and no water production plants are susceptible to affect the water level in the deep Qp aquifer.

The subsidence affecting the second subsidence area at Ha Dong and Thanh Xuan urban districts, where the density of construction is moderate, seems to result from a similar combination of effects. The groundwater level in Qh aquifer has dropped to −6 m b.s.l. (11.5 m below the topographic surface), and at deeper level, the well fields of Ha Dinh, Ha Dong 1 and Ha Dong 2 water production plants operate with an important withdrawal capacity (Fig. 12). The soft soil layers mixed with organic materials presents at the boundary of two districts with a thickness reaching 28 m and it induces a difficulty to impale the piles through this thick layer during the foundation works (Fig. 8c). A large region of sand or sandy clay surrounding this soft soil layer in the south of Ha Dong district is also susceptible with the drawdown of the groundwater level (Fig. 8a). Even in the third subsidence area at Hoai Duc and Tu Liem suburban districts, where the density of construction is much lower, the surface deformation occurs with smaller amplitude than in the two previous areas. Note that the recent urbanization is not yet associated with a high rate of ground water extraction (Fig. 12). However, it represents a potential hazard because soil and sand, sandy clay or loamy sand of Hai Hung and Thai Binh formations are superficial, and the development of the new residential areas is planned in the near future (Fig. 11a).

In all three-subsidence areas, we observe very little damage to the structures of tall buildings. We propose that these buildings that form most of the PS are not affected by subsidence because their steady foundations are based on auger-cast piles reaching the Neogene deposits at a depth of 50–70 m (Fig. 10a and d1). However, their surrounding terrain is collapsing (Fig. 10b and c), and many private houses nearby using pile foundation methods with concrete pillars (Fig. 10d2) or bamboo piles (Fig. 10d3) are subsiding. It could be explained the choice of foundation types: first, if the pile foundation is rooted into the thick soft soil layers with low load-bearing capacity, the houses are naturally sunk due to the compaction effect under the impact of a heavy load (Fig. 8c). Second, if the concrete pillars are impaled through the few meters thick soft soil and reach deeper to a level of sand or loamy sand with moderate bearing capacity (Nguyen, 1996b) (Fig. 8b). The pillars could have been stable initially; the lowering of groundwater in the Qh aquifer will make the higher part of sand or loamy sand layers becoming regularly un-submerged into groundwater. In consequence, it reduces the pore pressure in such geologic layers with high porosity and the decreases of pore pressure in sand or loamy sand will induce the compaction of these layers. The pillars become unstable and the constructions are affected by subsidence (Downing, 1994). Third, many private houses are based on foundations consisting of bamboo piles and an insidious problem is the drying out of the bamboo piles. As long as bamboo piles remain saturated by groundwater, they resist rot and can last for centuries. However, if the Qh water table drops below the pile tops, bamboo rot is rapid and building supports may collapse within a few years (Shanahan, 2009). Fourth, the intensive withdrawal of the Qp aquifer generates the groundwater flows in shallow subsurface medium composed of sand and loamy sand layer to form a problem known as “loss of fines”. This internal process facilitates the removal of sand particles and erosion channels are promoted in the subsurface inducing a collapse of the ground surface (Cashman and Preene, 2002).

6 Conclusion

Over the past five years, Hanoi City has undergone an extensive urbanization process and many construction projects are planned in the near future. The urbanization will trigger the urban sprawl and the infrastructure networks expanding urban districts around Hanoi urban region. Adequate methods for monitoring geo-hazards in the new urban region are crucial for the city authorities to survey the subsidence phenomenon and limit its damaging consequences. Using interferometric radar technique, we investigate the field of ground deformation related to the subsidence from 2007 to 2011. The StaMPS/MTI approach provides a complete spatial coverage of the the area under study and together with the use of new L-band ALOS-PALSAR images allows us to overcome the decorrelation problem in tropical region such as Hanoi. Therefore, for the first time, a map of the mean subsidence velocity over the urban region of Hanoi City has been obtained. This map shows that the mean vertical subsidence rate ranges from 0 to 68 $\text{mm}\,\text{yr}^{-1}$, and the larger zones of deformation correspond to the three main areas in Hoang Mai, Ha Dong-Thanh Xuan and Tu Liem-Hoai Duc districts. We demonstrate that the origin of this phenomenon is a complex combination of the presence of geologic composition of sand, loamy sand, and sandy clay in Hai Hung and Thai Binh formations, the lowering of groundwater in the Qh aquifer due to withdrawal from the one of Qp, the density evolution of built-up surfaces and the choice of foundation type. The temporal evolution of InSAR data compared to leveling data shows a great similarity between these two data sets. A regular lowering of the ground occurred till the end of 2008, then large variations appear from 2009 with a series of upward and downward ground motions, which reveal a non-stationary state of the surface deformation. The existence of transient movements of the surface is probably related to the recharge of the aquifer by rainfalls. This study demonstrates that StaMPS/MTI is effective for the region where human-made structures such as urban development are dominant.

The results of this study raise important consequences for hazard management in the Hanoi urban region. A zoning of different levels of land subsidence susceptibility is crucial in order to help to find the most appropriate solution. This can be achieved through a combination of groundwater reduction withdrawal, restrained construction work, and suitable building foundations in the most susceptible areas.

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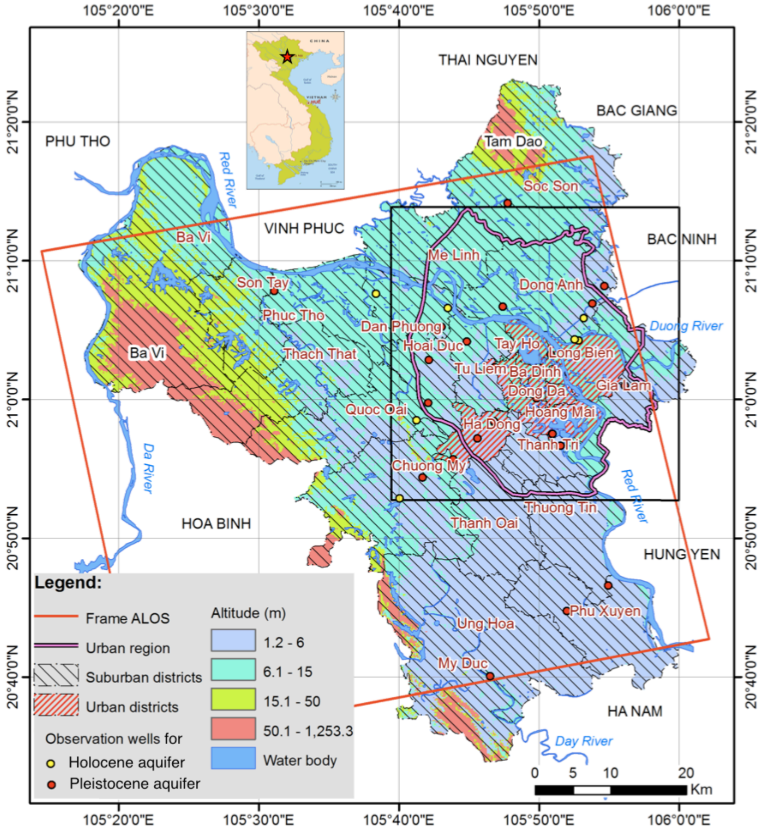

Fig. 1. Map of Hanoi City urban region, with location of urban and suburban districts, after (NARENCA, 2009). The black box corresponds to the area under study with the InSAR approach in Fig. 3.

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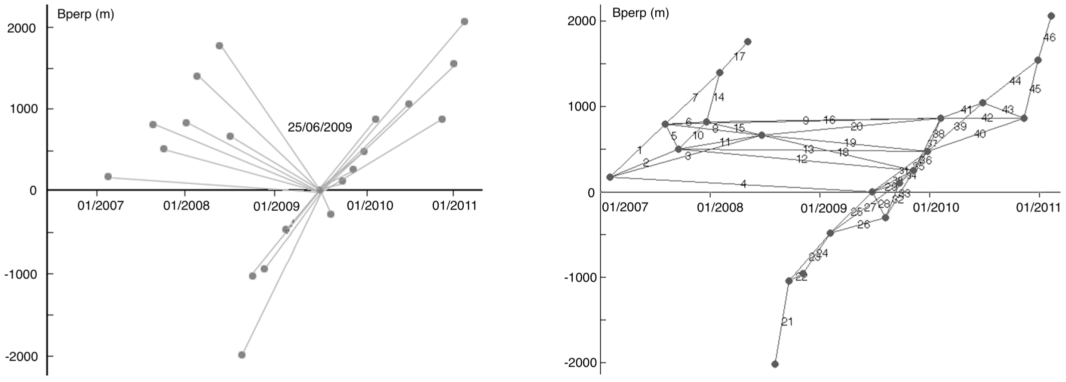

(a) *(b)*

Fig. 2. Baseline plots for **(a)** the PS approach and **(b)** the SB approach. Perpendicular baseline (Bperp) is calculated with respect to the master image (date: 25 June 2009) used in the PS approach.

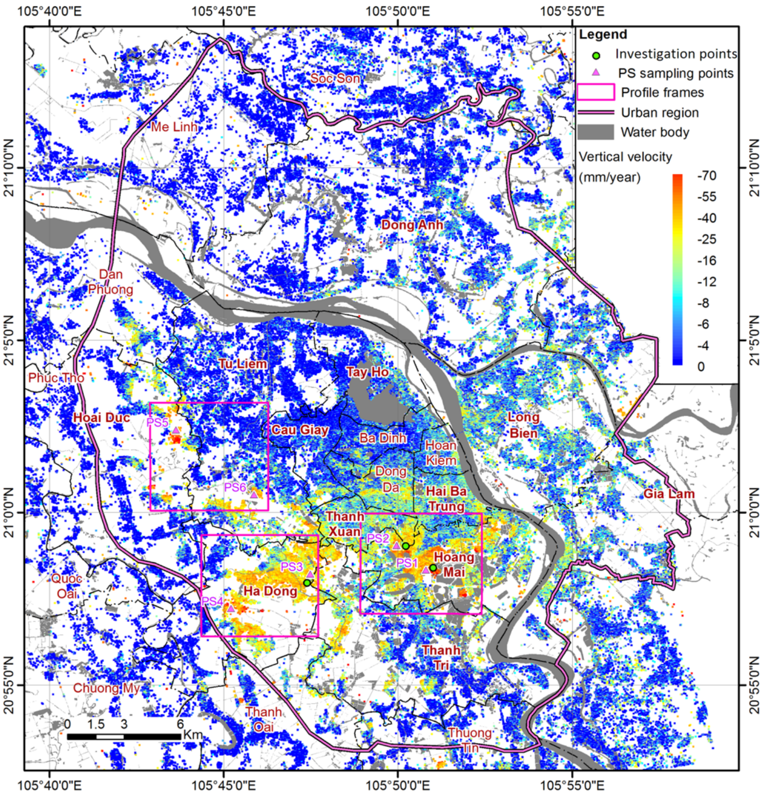

Fig. 3. Averaged vertical subsidence velocity in urban region of Hanoi (location in Fig. 1) issued from InSAR processing for the period February 2007–February 2011. Red boxes are the locations for the Fig. 4a–c.

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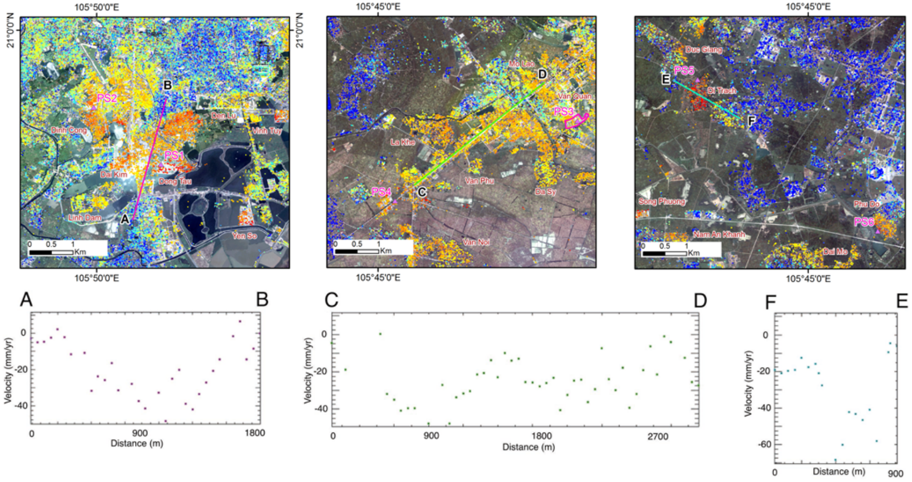
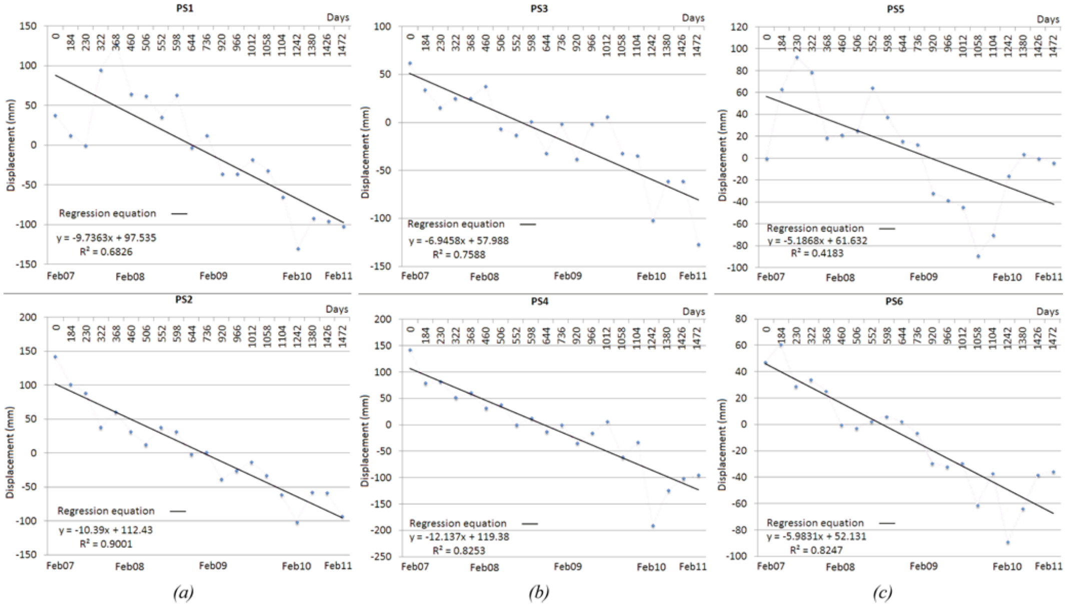


(a) *(b)* *(c)*

Fig. 4. Zooming maps and profiles of vertical velocity at **(a)** the Hoang Mai subsidence area **(b)** the Ha Dong-Thanh Xuan subsidence area (magenta boundary presents monitoring subsidence by leveling at Van Quan residential zone) and **(c)** the Hoai Duc-Tu Liem subsidence area. For location of frame and color scale, refer to Fig. 3.



(a) (b) (c)

Fig. 5. Time series of vertical displacement at several pixels at **(a)** Hoang Mai subsidence area. **(b)** Ha Dong-Thanh Xuan subsidence area. **(c)** Hoai Duc-Tu Liem subsidence area. For location of PS sampling points, refer to Fig. 4.

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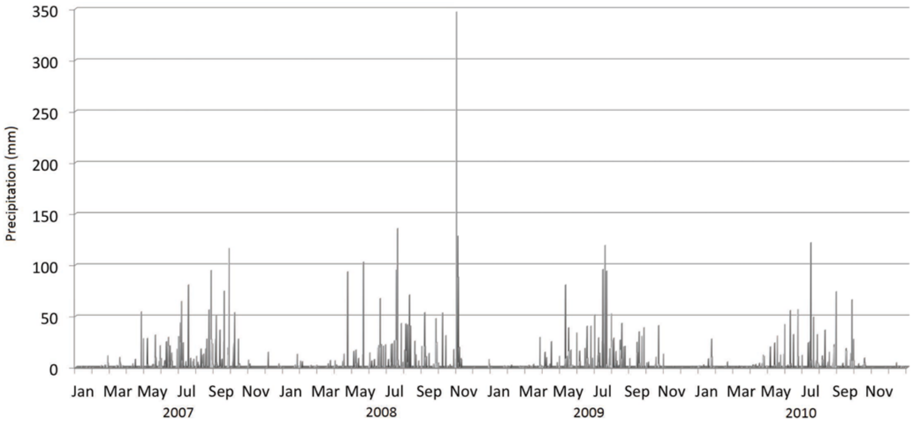


Fig. 6. Precipitation at Lang meteorological station from 2007 to 2010, after National Hydro-Meteorological Service, 2011.

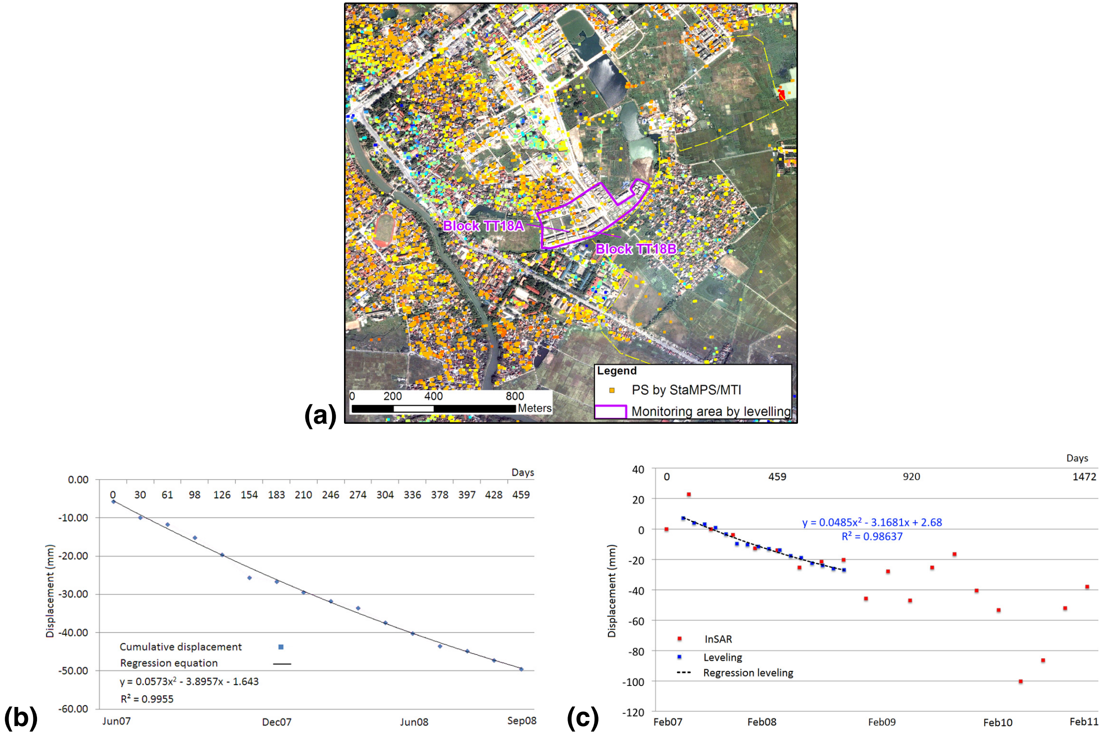
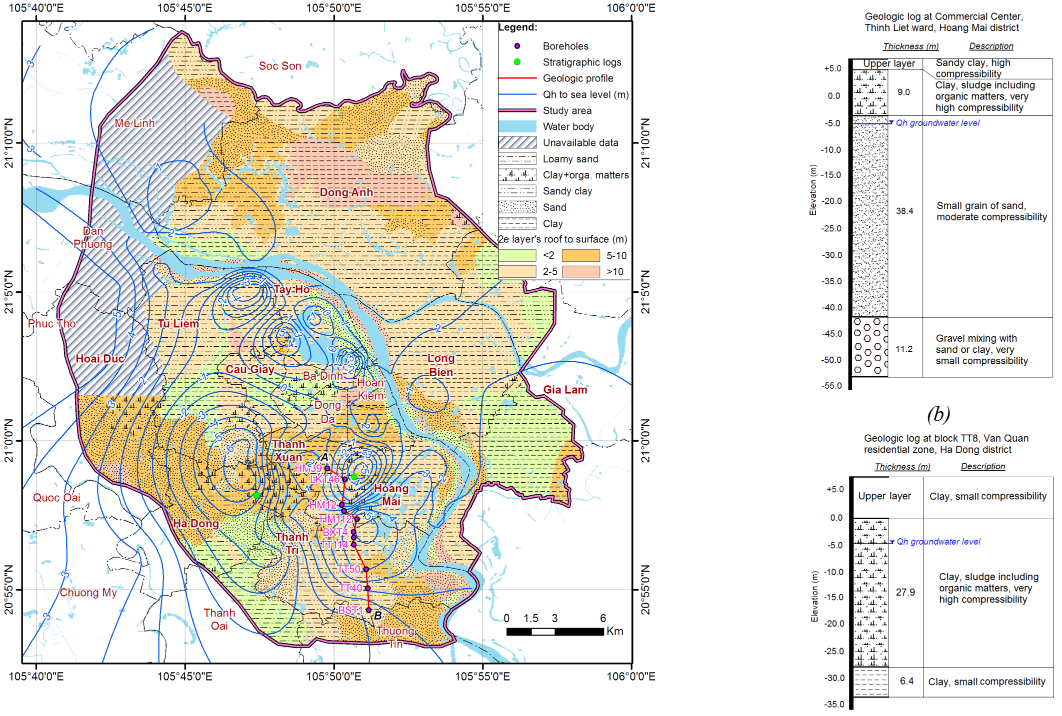


Fig. 7. (a) Monitored area by leveling in the Van Quan residential zone. For location of monitoring zone by leveling, refer to Fig. 4b, and PS pixel in the area (color scale, refer to Fig. 3). **(b)** Leveling subsidence graph of block TT18A, after (Dinh et al., 2008). **(c)** Graphs of one PS located at block TT18B and its leveling measurement. The third point of our InSAR time series was arbitrary located along the regression line of the leveling data.



(a) (b) (c)

Fig. 8. (a) Geological map of second layer, after (Nguyen, 1996a) and averaged groundwater level in Qh aquifer interpolated from in situ measurements in 32 wells (after Vietnam Institute of Geosciences and Mineral Resources, 2010). Stratigraphic logs at **(b)** Hoang Mai district, **(c)** Ha Dong district, after (Nguyen, 2009).

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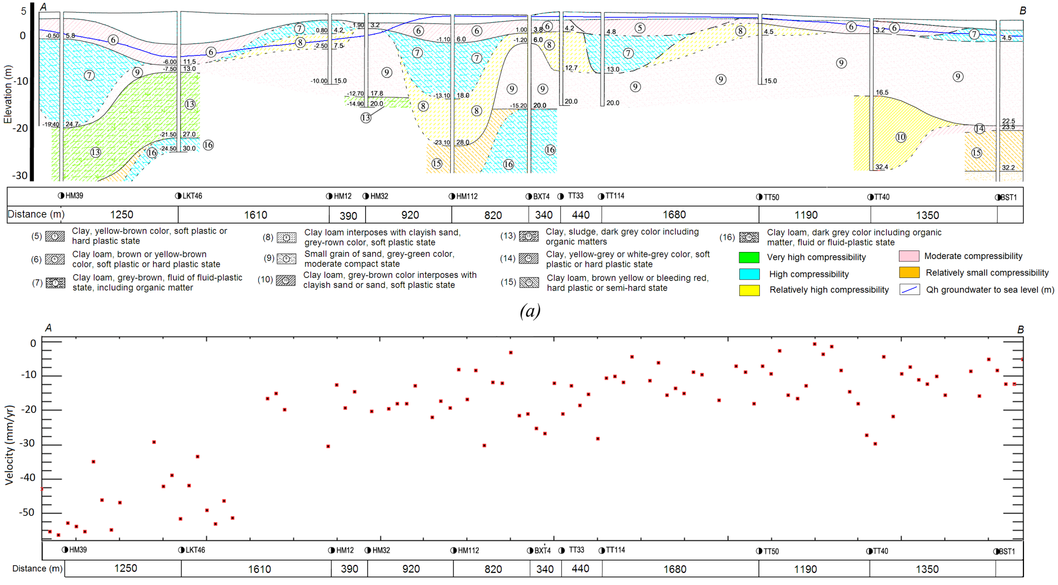
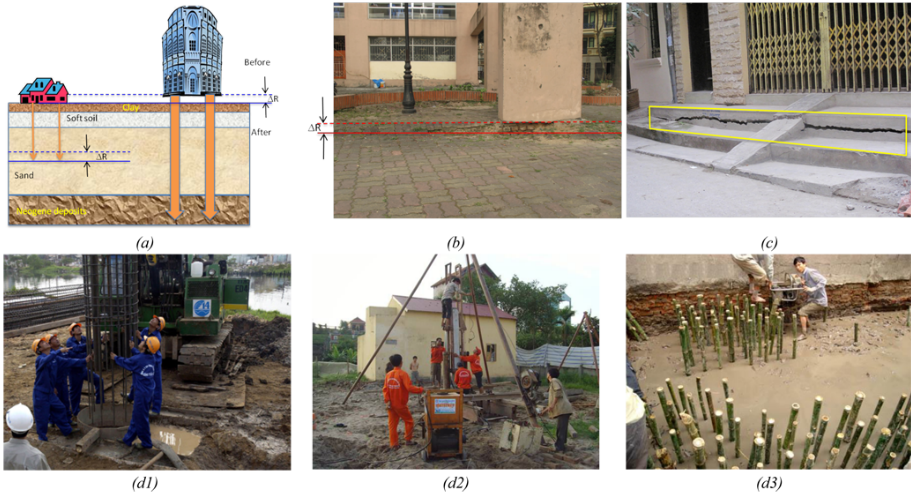


(a)

(b)

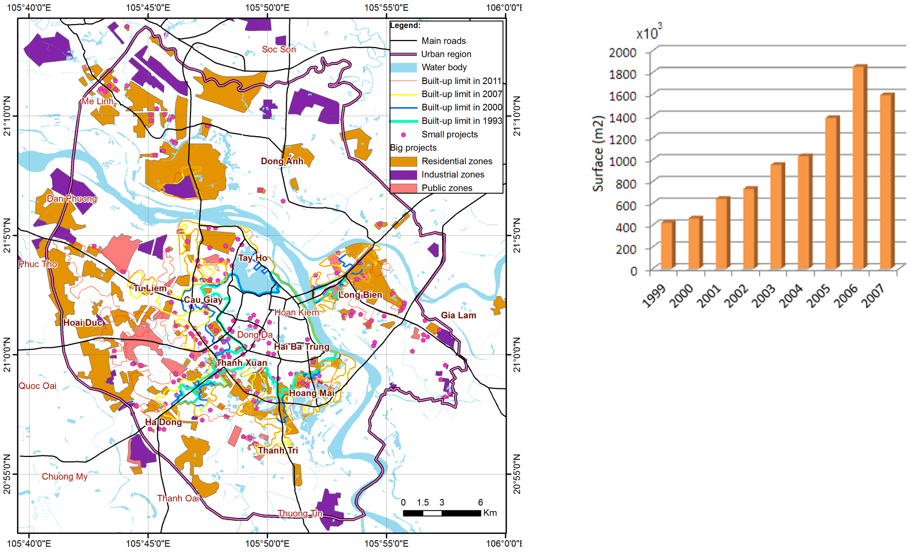
Fig. 9. (a) Geologic profile AB of first subsidence area, modified from (Nguyen, 2005) and groundwater level in Qh aquifer, after Vietnam Institute of Geosciences and Mineral Resources, 2010, **(b)** Graph of vertical velocity following the profiles AB. For location of profile AB, refer to Fig. 7.



(a) (b) (c)

(d1) (d2) (d3)

Fig. 10. (a) Model of subsidence process. Example of subsidence damages in **(b)** Dinh Cong residential zone at Hoang Mai subsidence area. **(c)** Van Quan residential zone at Ha Dong-Thanh Xuan subsidence area. For location of investigation points, refer to Fig. 3. Several type of foundation is using in study area: **(d1)** auger-cast piles, **(d2)** concrete pillars, **(d3)** bamboo piles. Photo: http://www.cocbetong.vn.



(a) (b)

Fig. 11. (a) Location of new construction projects by public construction companies in urban region of Hanoi City after (NARENCA, 2010) and evolution of built-up surfaces until 1993, 2000, 2007, 2011 digitized from Landsat images. **(b)** Evolution of Hanoi housing surfaces constructed ($\times 10^3$ m^2) from 1999 to 2007, after Hanoi Department of Construction, 2009.

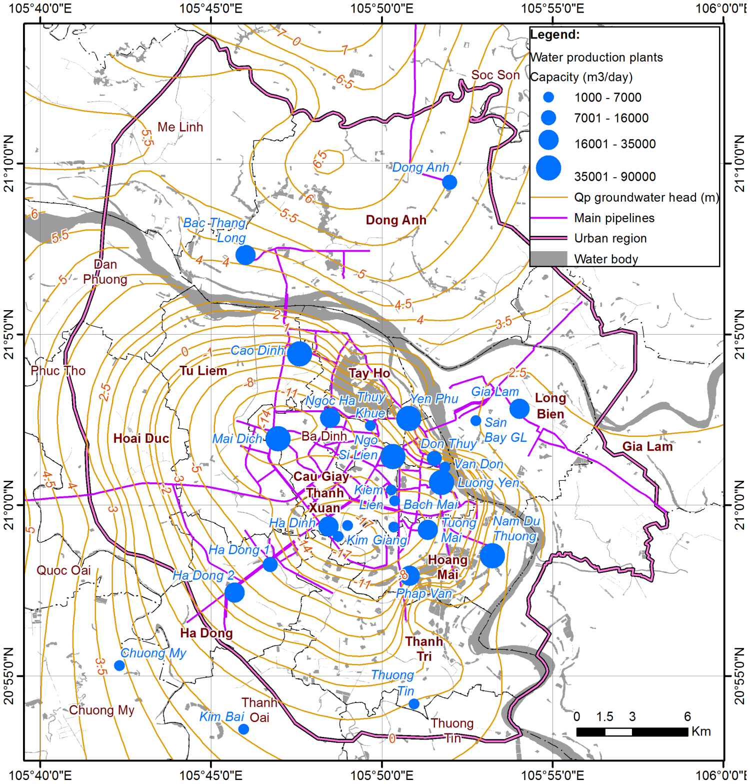


Fig. 12. Isocontours of the averaged groundwater piezometric head level in Qp aquifer interpolated from in situ measurements in 21 wells (after Vietnam Institute of Geosciences and Mineral Resources, 2010) and withdrawal capacity of Hawaco water production plants, (after Hanoi Department of Planning and Architect, 2011).