INSAR technology to monitor subsidence Ho Chi Minh City case study

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Abstract

Groundwater resources are under stress in many regions of the world. A major consequence of the overexploitation of the aquifers, especially in urban areas, is land subsidence which may cause the following impacts:

Increase in flood vulnerability, saltwater intrusion, and risk of permanent inundation in deltaic areas where extreme weather events and rising sea levels further exacerbate subsidence impacts.

Differential settlements that produce relevant damages to the human structures

Nowadays, ground subsidence induced by water overexploitation increases flood vulnerability in many megacities around the world. In response to these urban flooding hazards, it has become essential to have a sound knowledge of ground subsidence, such as the spatial extent and temporal evolution, to respond more appropriately to present and future hydrological extremes.

The use of a methodology based on SAR technology (Synthetic Aperture Radar) to deal with these challenges is presented in this paper. Moreover, a case study to monitor subsidence using InSAR technology in Ho Chi Minh City (HCMC) between 2015 and 2017 is also presented.

Introduction

Traditional monitoring surveys such as leveling, extensometers, and Differential Global Positioning Systems are widely used to measure subsidence in urban contexts. Although all of these techniques are widely accepted and used, they are susceptible to weather conditions (i.e., they are challenging to use during a storm) and still allow only point-like measurements, requiring interpolation and extrapolation to achieve a complete measurement understanding.

Nowadays, the use of Synthetic Aperture Radar Interferometry (InSAR) and Persistent Scatterer Interferometric (PSI) techniques has proven their ability to map ground subsidence of extent areas with short-time data sampling rates.

A significant number of previous projects over the last decades show how the spatially detailed images of ground displacement measured with InSAR have advanced hydrogeological understanding (Galloway et Hoffmann, 2007).

In the early nineties, Galloway et al. 1998 used this technology to quantify the land subsidence produced by groundwater extraction in Antelope Valley, California, between 1993 and 1995. They demonstrated that this technique helps to optimize ground-surface and groundwater control networks for subsidence investigations, especially in arid regions where nonagricultural land uses predominate.

Some years later, Amelung et al., 1999 used InSAR to show that faults control the spatial extension of the subsidence area in Las Vegas valley. The extent and shape of the subsidence bubble in the surface could be correlated with geological features beneath the surface.

Hoffman et al. 2001 take advantage of the possibility of the InSAR technique to retrieve ground deformation data over huge areas to estimate the elastic coefficient of the Las Vegas valley aquifer. InSAR technique allows for obtaining more distributed data compared with other techniques such as extensometer/piezometers installations which provide only a few points of source data; thus, InSAR data can estimate the subsidence better spatially.

Finally, the use of InSAR techniques significantly contributes to the estimation of further parameters relevant to the aquifer deformation characterization, such as (1) inelastic (Skv) and elastic storage (Ske) (Tomas et al., 2009), (2) groundwater storage variations (Béjar-Pizarro et al., 2017) and (3) structural or lithostratigraphic boundaries (e.g., faults) of the groundwater system (Galloway and Hoffmann, 2007, Chen, 2006).

Methods

Radar satellites use a form of active remote sensing termed Synthetic Aperture Radar (SAR) to obtain ground surface information. By actively emitting microwave frequencies and recording the reflected signal, SAR systems capture exact information on the location of the features on the ground surface. We use advanced technology such as SqueeSAR© (Ferretti et al., 2011 and 2013) to process several satellite images and retrieve millimetric displacement. All measurements provided are taken in the Line-of-Sight (LOS) direction, meaning that measurements are a projection of the real motion into the detection vector or looking vector.

Results and discussions

An InSAR study over Ho Chi Minh City was carried out between November 23rd, 2014, and March 12th, 2017. HCMC is reported to suffer from historical sinking, mainly due to water extraction. The town is located over an aquifer system comprising six permeable units from Miocene to the Pleistocene. The aquifers are mainly confined and consist of alluvial and marine deposits (gravel, sand, silt, clay, and peat). Groundwater drawdowns up to 14 meters occur in the three main pumping aquifer units resulting in a cone of depression covering the city's center (Figure 1). Currently, in Ho Chi Minh City, there are more than 200,000 boreholes with a total mining capacity of over 1 million m^3/day. This pumping results in the water table lowering, leading to the subsidence of some areas in the city. Land subsidence at the rate of a few centimeters per year can be measured at many groundwater-pumping stations from 1991 to 2016 (Minderhoud et al. 2017)

For this study, 75 descending Sentinel-1 images were used from November 2014 to March 2017, with a revisited time of 12 and 6 days. Unfortunately, there were no Sentinel-1 available images in the ascending geometry to retrieve 2D measurements, so we assume that most displacement occurs in the vertical axis. The relation between changes in pore fluid pressure and compression of the aquifer system is based on the principle of effective stress first proposed by Terzaghi [1925],

$$\sigma_e = \sigma T - p$$

where effective or intergranular stress (σ_e) is the difference between the total stress (σT) and the pore fluid pressure (p). Under this principle, when the total stress remains constant, a change in pore fluid pressure causes an equivalent change in effective stress within the aquifer system, which causes the aquifer system skeleton to compress or expand under the new load (Galloway et al., 1998).

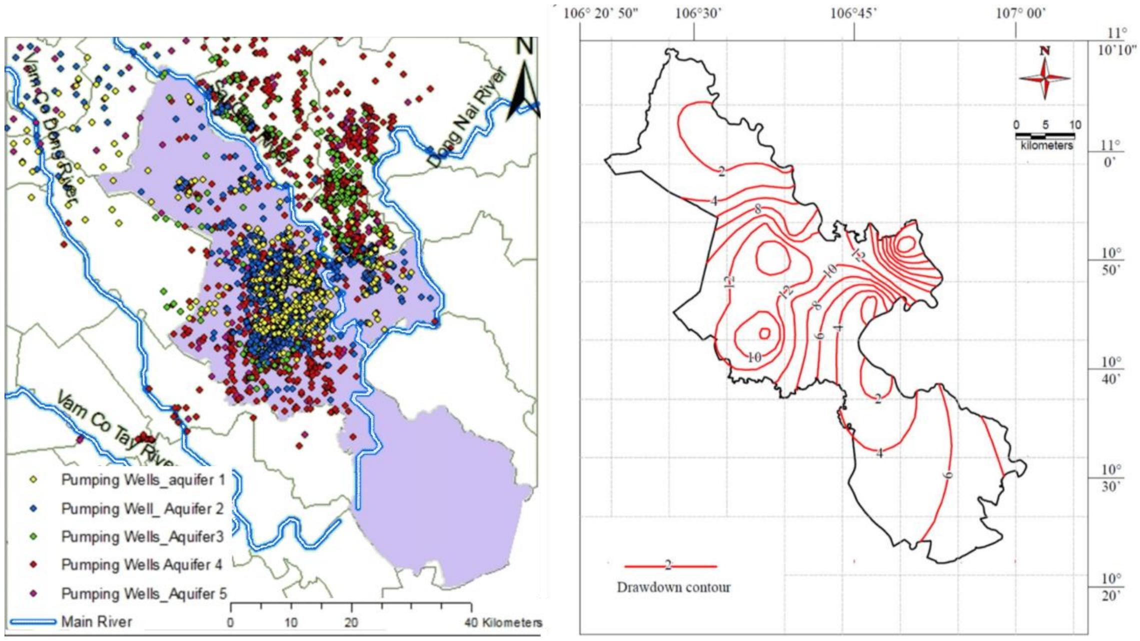

Figure 1 Location of the groundwater pumping wells in the Pleistocene aquifer, 2022 (right) and groundwater drawdown in the Third Aquifer (Lower Pleistocene) from 1999 to 2009 (modified from Thoang et al, 2015)

Figure 2 shows the results over the study area in the center of Ho Chi Minh city. A total of 68 437 points of measurement (75% persistent scatterers vs. 25% distributed) were obtained, meaning a density of 625 MP/Km2. Results show some areas of relevant deformation that can reach more than 7 cm/year of average displacement in Line-Of-Sight. In this sense, most of the deformation occurs to the east of the study area, over a NW-SE corridor located mainly over Holocene materials with high content of silts and loams. As a result, the cumulative displacement during the study period can reach more than 120 mm in some points. The fact that for each acquisition, it is possible to retrieve displacement data allows the technology to study the evolution of subsidence over time and detect changes in deformation trends.

Furthermore, displacement can be correlated with extraction rates to determine how it affects the ground surface. Over the displacement area, the deformation rate ranges from 4 cm/year to 7 cm/year and shows a linear behavior consistent with a confined aquifer that is not significantly affected by recharge from rainfall. However, some time series show a slight deacceleration of the subsidence during last year, probably due to a reduction in water extraction rates.

Literature research has been conducted to determine possible causes of subsidence in Ho Chi Minh. In general, subsidence can be the result of four main drivers (Tosi et al. 2009): (1)deep aquifer deformation due to groundwater extraction, (2) natural and anthropogenic loading (i.e., buildings and infrastructure), (3) shallow subsidence in the unsaturated zone and (4) tectonics. However, in the case of Ho Chi Minh, groundwater extraction and Pleistocene aquifer compaction has been proposed as the primary driver in the period 2006-2010 (Erban et al., 2013; Thoang, 2015, Minh, 2015). According to these authors, "subsidence related to mechanisms of anthropogenic loading unrelated to pumping are not expected to be spatially correlated with pumping-induced compaction," suggesting that the effects of groundwater extraction dominate the deformation signal detected by InSAR.

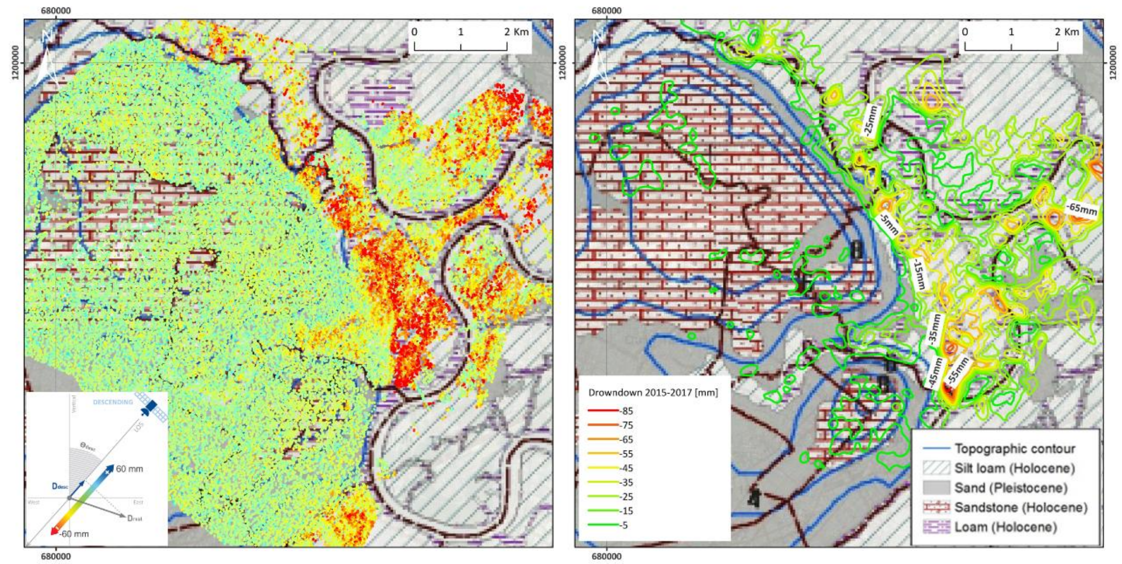

Figure 2 Average displacement results over a geological map of Ho chi Ming city (left) and cumulative displacement isolines over the same background (right). It is possible to see that the deformation occurs over the Holocene silt loam sediments.

In Ho Chi Minh, groundwater extraction started to exceed aquifer recharge at many locations in 1991. Still, extraction rates decreased following the 2007 law that limits groundwater use in the city. In this sense, our data show a poor correlation between the location of wells and the major subsidence areas during the study period 2015-2017 (Figure 2). Moreover, results show a quite stable pattern over the Pleistocene sands, where most of the wells are located. Therefore, it could indicate that during this period (2015-2017), the leading cause of subsidence would be related to the inelastic deformation of the fine-grained Holocene sediments caused by drainage of the shallow deposits and loading by buildings or infrastructure. Therefore, the 2007 law to reduce the groundwater extension would successfully stop the subsidence rate due to the deep aquifer compaction. This point should be addressed in further research, which can also evaluate the possible storage reduction bearing in mind water level changes and aquifer settlement.

Conclusion

The use of Synthetic Aperture Radar Interferometry (InSAR) techniques has proved its ability to map ground subsidence of extent areas. We present a case study over Ho Chi Minh City, Vietnam, which has been reported to suffer historical subsidence phenomena. A total of 68 437 points of measurement were obtained, meaning a density of 625 MP/Km2. Results show some areas of relevant deformation that can reach more than 7 cm/year of average displacement in Line-Of-Sight during the study period and mainly over Holocene materials with high content of silts and loams.

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