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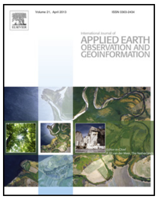

Lithology-controlled subsidence and seasonal aquifer response in the Bandung basin, Indonesia, observed by synthetic aperture radar interferometry

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ABSTRACT

Land subsidence in the Bandung basin, West Java, Indonesia, is characterized based on differential interferometric synthetic aperture radar (DInSAR) and interferometric point target analysis (IPTA). We generated interferograms from 21 ascending SAR images over the period 1 January 2007 to 3 March 2011. The estimated subsidence history shows that subsidence continuously increased reaching a cumulative 45 cm during this period, and the linear subsidence rate reached ~12 cm/yr. This significant subsidence occurred in the industrial and densely populated residential regions of the Bandung basin where large amounts of groundwater are consumed. However, in several areas the subsidence patterns do not correlate with the distribution of groundwater production wells and mapped aquifer degradation. We conclude that groundwater production controls subsidence, but lithology is a counteracting factor for subsidence in the Bandung basin. Moreover, seasonal trends of nonlinear surface deformations are highly related with the variation of rainfall. They indicate that there is elastic expansion (rebound) of aquifer system response to seasonal-natural recharge during rainy season.

1. Introduction

The Bandung basin on the island of Java in West Java Province, Indonesia, has an area of 2340 km^2 and elevations between 660 and 2750 m above sea level. This basin is in the central part of the Bandung zone, a belt of intramontane depressions extending through the center of West Java (Fig. 1). The population of the Bandung metropolitan area was 6.1 million in 2003, and it is predicted to increase to 9.7 million in 2025 (Wangsaatmaja et al., 2006). The growth in population and industrialization, particularly the textile industry, has increased the exploitation of groundwater in the Bandung basin (Wangsaatmaja et al., 2006). Converting agricultural land to housing and industrial sites has worsened environmental impacts (Suhari and Siebenhuer, 1993), and excessive groundwater extraction in the Bandung basin has induced decrease in groundwater level and as a consequence land subsidence occurred. Decrease in groundwater level in the Bandung basin was reported, for example by Iwaco and Waseco (1990). Abidin et al. (2008) reported that land subsidence in the Bandung basin might be caused by several mechanisms, such as excessive groundwater extraction, building loads, sediment compaction, and tectonic activity.

Studies of subsidence due to groundwater extraction have been carried out using GPS observations in Bandung (Abidin et al., 2008) as well as other sites, such as the Rafsanjan plain, Iran (Mousavi et al., 2001), Po Valley, Italy (Bitelli et al., 2000), and Tianjin, China (Lixin et al., 2011). Although GPS surveys can provide subsidence information with high accuracy, they are costly and time consuming, and they offer sparse spatial resolution in inaccessible areas. In this study, we have applied differential synthetic aperture radar interferometry (DInSAR) as well as interferometric point target analysis (IPTA) to investigate the history of land subsidence of the Bandung basin on a synoptic basis over a 4-year period. The resulting subsidence maps revealed by DInSAR were then combined with other data, such as production well and aquifer damage maps, to characterize the subsidence from a geological point of view. Sri Sumantyo et al. (2012) reported that the subsidence in Indonesia

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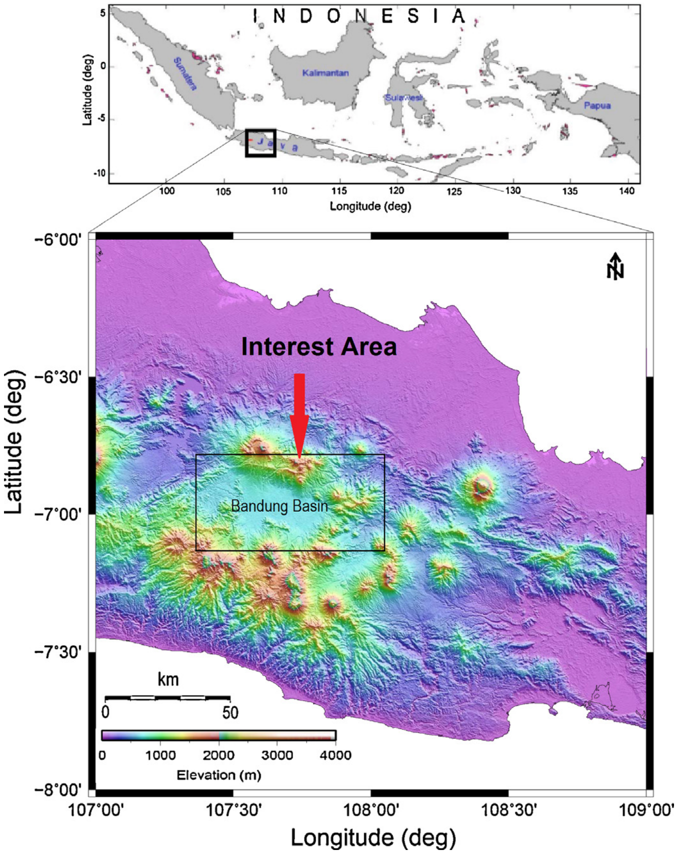

Fig. 1. Location of study area.

is related to the changes in the ground water level due to water pumping, growth in population, industry, and urbanization of the study area. In addition to the water level, furthermore, lithology had been cited as controlling the northern extent of subsidence (e.g., Sneed and Brandt, 2007). Because IPTA further provides information of the time-varying nature of aquifer system compaction, we investigated the factors spatially and temporally controlling subsidence in this area.

2. Data and methods

DInSAR is a means of remote sensing that enables changes in the two-dimensional surface of the Earth to be detected at millimeter to centimeter scales (Massonnet and Feigl, 1998). With applications to natural and artificial sources of deformation such as earthquakes, volcanoes, and land subsidence from groundwater extraction, as well as land uplift from steam injection at oil sand field, InSAR allows us to better understand and analyze the underlying sources of these changes (e.g., Kobayashi et al., 2011; Khakim et al., 2012, 2013; Ishitsuka et al., 2012; Tsuji et al., 2009).

We used raw (level 1.0) SAR data acquired by the Phase Array type L-band (PALSAR) instrument on the Japanese Advanced Land Observation Satellite (ALOS) “Daichi” for the period from 14 January 2007 to 12 March 2011. Data modes are high-bandwidth (FBS-HH, 28 MHz) and low-bandwidth (FBD-HH and HV, 14 MHz) modes, acquired from ascending orbits with an off-nadir angle of 34.3°. Main advantage of the L-band ALOS over C-band ERS is deeper penetration in vegetated areas with less temporal decorrelation enabling to have longer time separation and longer critical baseline, thus it results more usable interferometric pairs (Wei and Sandwell, 2010).

InSAR processing in this study is accomplished with the exception of the lookup table refinement and quadratic phase removal approaches (Khakim et al., 2013). To eliminate the potential of slightly differing azimuth image geometry and maintain coherency, all images were processed using a common Doppler centroid frequency of 63.465 Hz. A global master Single Look Complex (SLC) image for 1 March 2007 was selected that was 9640 pixels wide and 24,705 pixels long, to which all other SLC images were then co-registered. To optimize correlations, the azimuth common band filtering prior to generating interferograms retained only the common segment of the azimuth image spectrum (Ferretti et al., 2007). We applied a two-pass differential InSAR (DInSAR) approach to map land subsidence (Massonnet and Feigl, 1998), using a Shuttle Radar Topography Mission digital elevation model with 3-arcsecond resolution to remove topographic fringes. Adaptive filtering (Li et al., 2006a) was used to reduce the phase noises that cause pseudo phase residues and strongly affect phase unwrapping. The minimum cost flow (MCF) algorithm (Costantini, 1998) was used to minimize areas of low coherence due to layovers and areas of shadowing due to rough terrain.

The mountains surrounding the Bandung basin may impose an altitude dependence on the atmospheric path delay as a result of changes in atmospheric water vapor and pressure above the basin and its surroundings. We therefore generated a phase model of the height-dependent atmospheric phase delay for each unwrapped interferogram and then subtracted it from each interferogram (Li et al., 2006b).

Multiple interferograms were stacked to emphasize temporally coherent signals (including subsidence) and estimate a subsidence rate. Stacking also reduced atmospheric artifacts and phase noise, which are spatially but not temporally coherent. The stacking was done as a weighted sum of individual differential phases using the time interval of the interferogram as the weight (Sandwell and Price, 1998). Longer time intervals yield larger cumulative displacements, making the ratio of phase noise to the differential phase small. Thus, selecting interferograms with long intervals and short baselines yields better results in the stacking calculation.

In order to confirm the resulting subsidence rate obtained by stacking DInSAR data, we applied IPTA (Werner et al., 2003). We also exploited the temporal and spatial characteristics of linear and nonlinear displacements using IPTA. Furthermore, seasonal variation of subsidence trend was extracted using nonlinear least square method with trust-region algorithm (Conn et al., 2000). We first subtracted the known linear displacement from total displacement of each time series to estimate seasonal amplitudes. More details to estimate both linear and nonlinear components of displacement based on IPTA is described in Wegmuller et al. (2004, 2008). Nonlinear trends $y(t)$ are then fit to a Fourier series model, instead of a simple-sinusoidal model (Bell et al., 2008), to each time series as follows,

$$y(t) = a_0 + \sum_{n=1}^{4} a_n \cos(n\omega t) + b_n \sin(n\omega t) \tag{1}$$

where a_0 is a constant shift in the model due to interferometric noise, a_n and b_n are the maximum seasonal amplitude for either subsidence or uplift oscillations, t and ω are time and angular frequency of subsidence or uplift oscillation, respectively. For the seasonal analysis we assumed around 1-year periodicity for initial parameters for inversion, because the ground deformation (uplift and subsidence) is based on the annual cycles of discharge and recharge processes. Some statistical parameters used to evaluate the fit goodness are sum of squares due to error (SSE), R-square, and root mean squared error (RMSE).