Monitoring and characterization of land subsidence in the Bandung basin, West Java, Indonesia using SAR interferometry

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Summary

Monitoring and characterization of land subsidence of the Bandung basin, Indonesia has been carried out based on Synthetic Aperture Radar (SAR) data acquired by ALOS-PALSAR satellite for the period of 1 January 2007 — 3 March 2011. Estimated subsidence continuously increased up to around 45 cm at a rate of about 12 cm/yr for this period. The land subsidence occurred in the industrial and dense-residential regions in the Bandung basin where large amounts of groundwater were consumed. Interestingly the subsidence patterns are uncorrelated to the distribution of groundwater production wells and the map of aquifer zonation in several areas. We concluded that the subsidence expansion not only depended on groundwater production but also was controlled by lithology over the Bandung basin.

Introduction

The Bandung basin is located in the West Java Province, Indonesia. The basin has an elevation ranges between 660 and 2,750 m above the sea level and is part of a chain of depressions in West Java. The basin (a total area 2,340 km^2) is located in the central part of this zone and encircled by mountains.

The population of Bandung metropolitan was 6.1 million in 2003 and it is predicted to increase up to 9.7 million in 2025 (Wangsaatmaja *et al.*, 2006). The growth in population and industry caused an increasing in water demand. For industrial and residential activities groundwater is primary source. Nearly 50% of industries in the Bandung basin are textile industries consuming much amount of groundwater (Wangsaatmaja *et al.*, 2006). Converting a land use from agriculture to some purposes, such as for housing and industrial sites, has worsened environmental impacts (Suhari and Siebenhuer, 1993).

Excessive groundwater extraction in the Bandung basin has induced land subsidence. The subsidence is a type of regional geological hazard, which slowly develops to serious impacts on society, economy, and the natural environment. The subsidence may cause serious problems, such as (1) changes in elevation and slope of streams, canals, and drains; (2) damage to roads, railroads, and bridges; (3) damage to private and public buildings; and (4) failure of well casings; (5) changes in the groundwater flow system. According these impacts, it is very important to monitor the land subsidence in the Bandung basin.

Several studies of subsidence due to groundwater extraction using GPS observations were carried out in several sites, such as Rafsanjan plain, Iran (Mousavi *et al.*, 2001), Bandung, Indonesia (Bitelli *et al.*, 2000, Abidin*, et al.*, 2008) and in Tianjin, China (Lixin *et al*., 2011). Although the GPS surveys can provide subsidence information with high accuracy, it is costly, time consuming and sparse spatial resolution for a large and inaccessible area. On the other hand, SAR interferometry (InSAR) which is one of remote sensing technique provides valuable spatial and temporal information needed to assess and mitigate human induced subsidence. The technique utilizes two or more coherent phase signals acquired at different times for the same land area to map changes in range (satellite to earth distance) at a spatial resolution of tens of meters and a vertical accuracy of centimeters (Massonnet and Feigl, 1998).

This study has applied InSAR to investigate the history of land subsidence in the Bandung basin for long period time and to estimate the subsidence rate per year. The subsidence maps obtained by using InSAR data were then analyzed by combining with other data such as production well and aquifer damage maps in order to characterize the subsidence from a geological point of view. Therefore, the results can provide valuable information for the groundwater management and regulation in future.

Method

In this study we used raw SAR data level 1.0 acquired by 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 34.3 deg.

InSAR method exploits the phase difference between two observations, which can be converted to the surface deformation along the line of sight (LOS) (Madsen and Zebker, 1998). In order to eliminate the potential of slightly different azimuth imaging geometry and maintain coherency, all images were processed using a common Doppler centroid frequency of 63.465 Hz. A global master SLC of 2007/03/01 was selected with 9640 pixels wide and

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24705 pixels long. All other SLC images were then co-registered to the global master SLC in order to make all SLC images having the same geometry.

The co-registration accuracy required is typically 1/8th of a resolution (Balmer and Just, 1993). The azimuth common band filtering prior to interferogram generation was also applied to retain only the common segment of the azimuth image spectrum for the correlation optimization (Ferretti *et al*., 2007). We applied a two-pass differential SAR interferometry approach to map the land subsidence (Massonnet and Feigl, 1998), using 3-arcsecond SRTM DEM to remove topographic fringes. Adaptive filtering (Li *et al*. 2006) was applied to reduce the phase noises which cause pseudo phase residues and play a decisive part in phase unwrapping. The phase unwrapping was performed to retrieve the displacement information and true ground range by adding the correct integer multiple of 2π to the interferometric fringes. Minimum cost flow (MCF) algorithm (Costantini, 1998) was used to deal with low coherence area due to layover and shadowing area caused by rough terrain. Residual phase components, linear or quadratic trends, due to squinted orbits for large baseline changes along track appeared as linear or quadratic trends in the interferograms.

Surrounding area of the Bandung basin is characterized by the distribution of mountains which may have an altitude dependence of the atmospheric path delay with respect to altitude caused by changes in the atmospheric water vapor and pressure profile above the site. We therefore generated the phase model of the height-dependent atmospheric phase delay for each unwrapped interferogram and the phase model was then subtracted from each interferogram.

Stacking of multiple interferograms was performed to emphasize temporally coherent signal (i.e., subsidence) and estimate a subsidence rate while reducing atmospheric artifacts and phase noise, which are coherent in space but not in time domain. The stacking was performed by weighted sum of individual differential phases with the time interval of interferogram as a weight (Sandwell and Price, 1998). The longer time interval, the larger the cumulative amount of displacement that makes the ratio of phase noise to the differential phase small. Thus, selection of interferograms with long interval and short baseline yielded better results in the stacking calculation.

Results and discussion

Figure 1 shows the location of study area and the map of displacement history estimated by using two-repeat pass differential interferometry during 4 years spanning from 1 March 2007 to 12 March 2011.

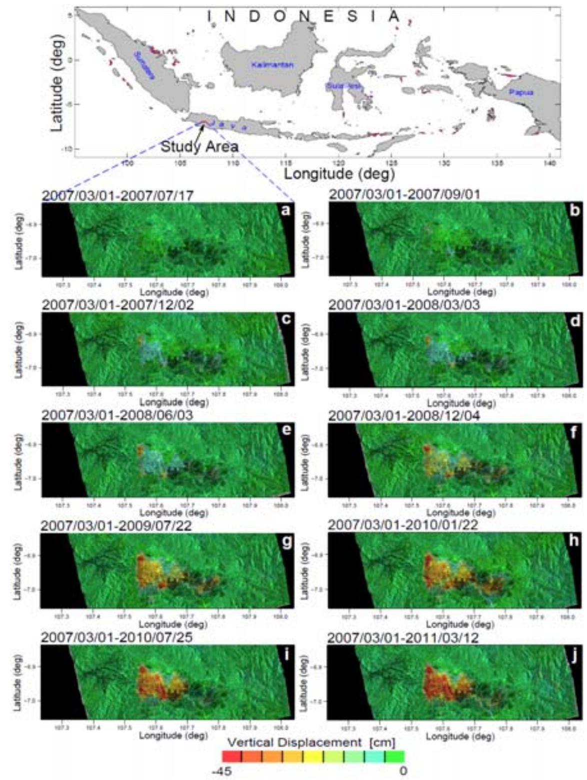

Figure 1: Location of study area and historical subsidence pattern in the Bandung basin with increasing temporal baseline between 138 days and 1472 days over the period of 1 March–3 March 2011

Ten selected displacement maps to investigate the historical-subsidence characteristics were calculated with the same baseline of 1 March 2007. Negative value of vertical displacements indicates land subsidence. These maps revealed spatial detail about the temporal variation of the subsidence. Subsidence features delineated by InSAR technique are generally oriented in the northwest-southeast direction elongated the Bandung basin. The development of subsidence patterns started from several urban areas where industries were established. Smaller subsidence localized in several urban areas spatially extending and temporally increasing with time intervals for the period cumulatively created a larger subsidence pattern over the Bandung basin. Several areas experienced the large land subsidence, such as Cimahi city in the northwest part of the subsidence map with a magnitude of about 45 cm for 4 years. A quite large amount of the subsidence occurred in other urban areas, such as Dayeuh Kolot, Soreang, Majalaya, Banjaran and Rancaengkek.

The stacking technique was applied not only to remove the atmospheric artifacts but also to suppress phase noises due to other decorrelations, especially phase component due to

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temporal decorrelation. A subsidence rate estimated from the stacking technique had a maximum magnitude of about 12 cm/year in Cimahi city (Figure 2a). The rate was in good agreement with that obtained from GPS measurement (Abidin *et al*., 2008).

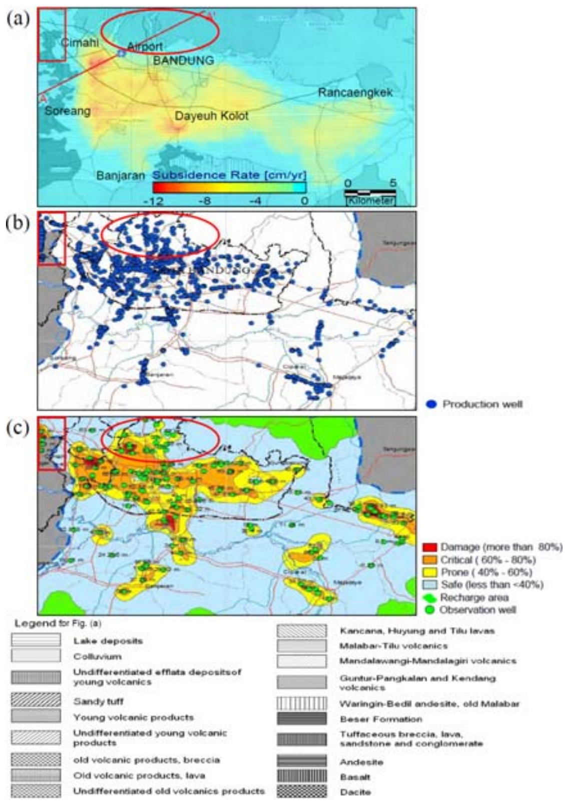

Figure 2: (a) Subsidence rate overlaid with geological map of the Bandung basin, and the geological map developed by Delinom and Sudiadarma (2010), (b) A map of well productin distribution in the Bandung basin. Most of production wells are concentrated in Cimahi and Bandung cities (BPLH and LAPIITB, 2011, Naskah akademik PAPERDA kota Bandung tentang pengelolaan air tanah, ITB, Laporan akhir). (c) A map of aquifer zoning of the Bandung basin updated in 2012 by BPLH and LAPIITB (2011).

Groundwater extraction was suspected of contributing to the subsidence in the study area (Abidin *et al*., 2008). In order to further investigate the subsidence characteristics, we therefore used the maps of groundwater production well and aquifer zonation (Figures 2b and 2c respectively). Amount of subsidence should be correlated with the distribution of production wells and aquifer conditions.

The aquifer was grouped as damage, critical, prone and safe zones which the percentage of groundwater decline were more than 80%, 60-80%, 40-60% and less than 40%, respectively. Larger subsidence happened in area associated with denser production wells and higher groundwater level decline. For most of areas over the study area, the pattern of InSAR-estimated subsidence rate was correlated with the map of production well distribution and aquifer zonation, but not for several areas. Interestingly, the subsidence did not occur in several areas, such as in areas indicated with a red rectangular and red ellipse in Figure 2a even though the areas had damage aquifers and dense production wells.

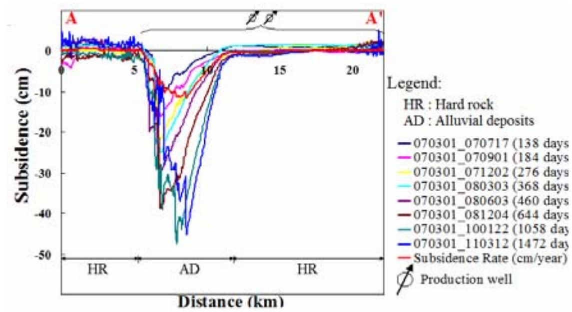

Figure 3: Profiles of time series subsidence across Cimahi city along line A-A’ in Figure 2a obtained from stacking 32 differential SAR interferograms and an individual SAR interferogram with the time intervals from 138 to 1472 days with the baseline date of 1 March 2007.

From Figure 2a, it can be identified that the subsiding area in Cimahi city is located at the top of alluvium deposit. This area is bounded by consolidated rocks, i.e. sandy tuff in the northeast part and tuffaceous breccias, lava, sandstone and conglomerate in the southwest part. However, a large amount of groundwater extraction in the northeast Cimahi city did not lead to land subsidence in the part of consolidated rocks which strongly resist to subsidence. Contrarily, the amount of subsidence is significantly related to soft rocks, i.e., alluvium and lake deposits. This indicates that the characteristic of subsidence in the Bandung basin was controlled by lithology, e.g., rock types. This observation also confirms from that the subsidence patterns are uncorrelated to the numbers of production wells and the groundwater level in several areas.

This geological factor of controlling the land subsidence can also be further investigated from Figure 3 that shows subsidence profiles illustrating the temporal extent and magnitude of subsidence patterns and the subsidence rate crossing Cimahi city along the line A-A′ in Figure 2a. These profiles indicate that the subsidence patterns from eight profiles obtained from differential interferograms with the time intervals from 138 to 1472 days were highly consistent each other. If the layers were horizontally

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homogenous, the subsidence patterns should be symmetry in the direction of the historical profiles. The left part of the profile, however, shows that slopes of the subsidence were relatively constant indicating geologically the presence of rock boundary. This delineated-rock boundary was likely to act as a subsidence barrier and resulted in abrupt change in the land subsidence crossing this boundary. The boundary separates the consolidated rock to the southwest from the compressible alluvial sediment deposits to the northeast. It may also acts as a barrier for groundwater flow that impeded the horizontal propagation of fluid-pressure in water level crossing the boundary.

On the other hand, in the northeast part of Cimahi and Bandung, the subsidence should be expected to be occurred due to large amounts of groundwater over-pumped in that area as indicated in the aquifer zoning map which is categorized as a damage zone. Therefore, the slopes increased in the right part of profile, and the subsidence disappeared starting at the distance of about 12 km from point A, although there were several production wells in the right side of that point.

Conclusions

We have presented the DInSAR technique to reveal the rate and spatial detail about the temporal variation of land subsidence associated with groundwater extraction at the Bandung basin, West Java, Indonesia. The development of the Bandung basin subsidence historically started from several urban areas, where industries were established. Smaller subsidence patterns spatially extending and temporally increasing with time for the period of 1 March 2007 to 3 March 2011 have cumulatively created a larger subsidence pattern. The cumulative and rate of subsidence during this period are about 45 cm and 12 cm/yr.

The magnitude and patterns of the subsidence are not perfectly correlated to the distribution of groundwater production wells and the groundwater level. The abrupt change in the land subsidence and its sharp slope were observed at boundaries between consolidated and unconsolidated rocks in Cimahi city. Subsidence did not occur in area consisting consolidated rocks even though groundwater was withdrawn. Significant subsidence occurred at unconsolidated rocks, i.e. alluvial and lake deposits, whereas it did not occur in consolidated rocks, i.e. tuffaceous breccias, lava, sandstone and conglomerate. Finally, we concluded that the subsidence at the Bandung basin was also controlled by rock types.

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EDITED REFERENCES

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REFERENCES

Abidin, H. Z., H. Andreas, M. Gamal, A. D. Wirakusumah, D. Darmawan, T. Deguchi, and Y. Maruyama, 2008, Land subsidence characteristics of the Bandung Basin, Indonesia, as estimated from GPS and InSAR: Journal of Applied Geodesy, **2**, 167–177, http://dx.doi.org/10.1515/JAG.2008.019.

Balmer, R., and D. Just, 1993, Phase statistics and decorrelation in SAR interferograms: International Geoscience and Remote Sensing Symposium, IEEE, Expanded Abstracts, 980–984.

Bitelli, G., F. Bonsignore, and M. Unguendoli, 2000, Levelling and GPS networks to monitor ground subsidence in the southern Pro Valley: Journal of Geodynamics, **30**, 355–369. http://dx.doi.org/10.1016/S0264-3707(99)00071-X.

Costantini, M., 1998, A novel phase unwrapping method based on network programming: IEEE Transactions on Geoscience and Remote Sensing, **36**, 813–821, http://dx.doi.org/10.1109/36.673674.

Delinom, R. M., and A. Suriadarma, 2010, Groundwater flow system of Bandung Basin based on hydraulic head, subsurface temperature, and stable isotopes: Riset Geologi dan Pertambangan, **20**, 55–68.

Ferretti, A., A. Monti-Guarnieri, C. Prati, and F. Rocca, 2007, InSAR Principles: Guidelines for SAR interferometry processing and Interpretation, ESA.

Li, Z. W., X. L. Ding, C. Huang, D. W. Zheng, W. B. Zou, and Y. K. Shea, 2006, Filtering method for SAR interferograms with strong noise: International Journal of Remote Sensing, **27**, 2991–3000, http://dx.doi.org/10.1080/01431160500522692.

Lixin, Y., Z. Fang, X. He, C. Shijie, W. Wei, and Y. Qiang, 2011, Land subsidence in Tianjin, China: Environmental Earth Science, **62**, 1151–1161, http://dx.doi.org/10.1007/s12665-010-0604-5.

Madsen, S. N., and H. N. Zebker, 1998, Imaging radar interferometry, *in* F, M. Henderson and A. J. Lewis, eds., Principles and applications of imaging radar, 2, Manual of remote sensing, 3rd ed.: John Wiley & Sons.

Massonnet, D., and K. Feigl, 1998, Radar interferometry and its application to changes in the Earth's surface: Reviews of Geophysics, **36**, 441–500, http://dx.doi.org/10.1029/97RG03139.

Mousavi, S. M., A. Shamsai, M. H. Naggar, and M. Khamehchian, 2001, A GPS-based monitoring program of land subsidence due to groundwater withdrawal in Iran: Canadian Journal of Civil Engineering, **28**, 452–464, http://dx.doi.org/10.1139/l01-013.

Sandwell, D. T., and E. J. Price, 1998, Phase gradient approach to stacking interferogram: Journal of Geophysical Research, **103**, no. B12, 30183–30204, http://dx.doi.org/10.1029/1998JB900008.

Suhari, S., and M. Siebenhuner, 1993, Environmental geology for land use and regional planning in the Bandung Basin, West Java, Indonesia : Journal of Southeast Asian Earth Sciences, **8**, 557–566, http://dx.doi.org/10.1016/0743-9547(93)90053-R.

DOI http://dx.doi.org/10.1190/segam2013-0221.1

Wangsaatmaja, S., A. D. Sutadian, and M.A.N Prasetiati, 2006, Groundwater resources management in Bandung, *in* Sustainable groundwater management in Asian cities: IGES Freshwater Resources Management Project, 46–59.