



Correlating the subsidence pattern and land use in Bandung, Indonesia with both Sentinel-1/2 and ALOS-2 satellite images

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ABSTRACT

Continuous research has been conducted in Bandung City, West Java province, Indonesia over the past two decades. Previous studies carried out in a regional-scale might be useful for estimating the correlation between land subsidence and groundwater extraction, but inadequate for local safety management as subsidence may vary over different areas with detailed characters. This study is focused primarily on subsidence phenomenon in local, patchy and village scales, respectively, with Sentinel-1 and ALOS-2 dataset acquired from September 2014 to July 2017. The Sentinel-1 derived horizontal movement map confirmed that the vertical displacement is dominant of the Line-of-Sight (LoS) subsidence. Moreover, both Sentinel-1 and ALOS-2 derived InSAR measurements were cross-validated with each other. In order to understand the subsidence in a more systematic way, six 10-cm subsidence zones have been selected known as Zone A–F. Further analyses conducted over multiple scales show that industrial usage of groundwater is not always the dominant factor that causes the land subsidence and indeed it does not always create large land subsidence either. Regions experiencing subsidence is due to a combined impact of a number of factors, e.g., residential, industrial or agricultural activities. The outcome of this work not only contributes to knowledge on efficient usage of the satellite-based monitoring networks, but also assists developing the best hazard mitigation plans. In the future work, as we cannot draw the conclusion which is the dominant factor within each sub-zone due to the lack of statistical data, e.g., the groundwater consumption rates per square kilometre for different land types, further datasets are still needed to examine the core factor.

1. Introduction

Land subsidence is an environmental, geological phenomenon that often refers to gradual settling or rapid sinking of the ground surface as a result of subsurface movement of earth materials. It is considered to be a global issue, and many cities of the world have been reported suffering from land subsidence at the rate of tens of centimetres per year, e.g., Beijing (Ng et al., 2012b; Du et al., 2017a), Mexico (Chaussard et al., 2014), Yunlin (Tung and Hu, 2012), and California (Hanson et al., 2005). The impacts of the subsidence can be seen mainly in three forms: 1) damage to infrastructure, e.g., buildings, pipelines and dams; 2) affect the serviceability of roads and railways as a result of the distortion of the road surface and rail foundation, and 3) increase exposure to flooding.

Bandung Basin is a large intra-montane basin encircled by a range of

mountains and volcanic highlights in West Java province, Indonesia (Abidin et al., 2008). Table 1 lists the maximum mean velocity detected over Bandung at selected periods of time, and there is evidence that the largest subsidence typically exceeds -20 cm year^{-1} across all periods. Abidin et al. (2013) reported that several types of land subsidence could be expected to occur in this basin. These include 1) compaction of aquifer system due to the lowering of ground-water levels; 2) load of man-made construction, e.g., settlement of highly compressible soil; 3) natural consolidation of alluvium soil; 4) exploitation of underground natural resources, e.g., oil and gas; and 5) crustal geotectonic movements as there is a highland plateau lies within the catchment region of upper Citarum River. The elaborate mechanisms and characteristics of the land subsidence in Bandung were partially known in the earlier research, many studies were conducted based on the hypothesis that the subsidence is mainly induced by excessive groundwater extraction.

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Table 1
Maximum mean velocity (MMV) detected in Jakarta and Bandung, Indonesia.

Area	MMV (cm/ year)	Methods	Experiment Period	References
Bandung	– 24	GPS	2000–2005	Abidin et al. (2008)
	– 20	InSAR + GPS	2000–2010	Gumilar et al. (2015)
	– 23	GPS	2000.02–2011.08	Abidin et al. (2013)
	– 21	InSAR + GPS	2002.12–2008.12	Ge et al. (2014)
	– 23	InSAR	2007–2009	Chaussard et al. (2013)
	– 24	InSAR + GPS	2007.01–2011.03	Ge et al. (2014)

Global positioning system (GPS) has been exploited to monitor the land subsidence with precise measurements since 2000 (Abidin et al., 2001; Abidin et al., 2008; Gumilar et al., 2015). Abidin et al. (2006) studied the correlation between GPS-derived subsidence and registered extracted groundwater, and indicated that the discontinuity between the two measurements might be caused by the unregistered groundwater abstraction volume, which accounts for 70% of the actual amount. Nevertheless, GPS survey itself has a problem resolving the spatial pattern of the subsidence, and indeed, subsidence zones are not always located near the in-situ data collection sites. InSAR technique has been introduced to measure the subsidence in the recent decade as it can provide more insights into characteristics of subsidence phenomenon in the spatial domain (Abidin et al., 2008; Chaussard et al., 2013; Ge et al., 2014). Abidin et al. (2008) integrated GPS surveys and InSAR results together for quality assurance purpose. Chaussard et al. (2013) studied the large-scale land subsidence in eight of nine major cities in Indonesia (including Bandung), covering a total size of 500,000 km², and concluded that industrial groundwater extraction, agricultural water pumping and gas fields exploitation are mainly responsible for the rapid subsidence in cities. Ge et al. (2014) compared the InSAR-derived measurements with the records of groundwater table and confirmed that every 20 mm drop in the ground surface is caused by every 1 m reduction in groundwater level. Maghsoudi et al. (2018) studied the land subsidence in geothermal areas in West Java with both ALOS-1 and Sentinel-1 acquisitions, and found that Sentinel-1 based TS-InSAR analysis is able to identify the measurement points with a much high density in comparison with ALOS-1 case. Furthermore, According to Abidin et al. (2001) and Ge et al. (2014), a large amount of subsidence zones are detected in the textile industry area, where groundwater at deep aquifer has been extracted.

Clearly, previous studies carried out in regional-scale basis might be useful to estimate the correlation between land subsidence and groundwater extraction, but inadequate for local safety management as subsidence may vary over different areas with detailed characters. Due to the significant environmental and social impacts of this subsidence phenomenon, a systematic and continuous study of the spatial and temporal variations of Bandung's subsidence is urgently needed for managing groundwater extraction regulations, and developing recharging policies at various scales. It also assists designing urban development plans, which is crucial to the welfare of the city. To exclude the influence due to various surface geologies in this work, we selected the study region only categorised as surficial deposits (alluvial and lake deposits). Furthermore, following Chaussard et al. (2013), the scale of land subsidence can be categorised into four groups: regional-scale (> 100 km²), local-scale (10–100 km²), patchy-scale (0.25–10 km²) and village-scale (~ 0.25 km²). In this study, we analysed the general spatial subsidence patterns and temporal evolution in the above scales from

May 2015 to January 2017. To the best of our knowledge, there is a lack of knowledge in West Java for the analysis of the most recent land subsidence in such scale basis. To fill this gap, we aimed to 1) analyse the spatial pattern of horizontal movement with both descending and ascending pairs; 2) quantify the rate and magnitude of land subsidence over subsiding zones during the 1.5 year period, and 3) investigate spatially explicit variations in selected hot-spot regions. The result of this work will not only guide the design of local councils' strategies in launching hazard mitigation program to slow down the subsiding process, but will also generate key knowledge of understanding the subsidence pattern in Bandung city.

2. Geological settings

Bandung Basin has an area of about 2, 300 km², which consists of a highland plateau at approximately 650–700 m above sea level (m.a.s.l) and the surrounded high Late Tertiary and Quaternary volcanic terrains at up to 2, 400 m.a.s.l (Dam et al., 1996; Abidin et al., 2013). The average temperature in this basin is about 23.7 °C while the annual precipitation amount is about 1, 700 mm. The main drainage system of the basin catchment, comprises of the Citarum River and its tributaries, is one of the largest watersheds on the land of Java. It provides water for drinking, agricultural, industrial and irrigation usage as well as the main supply for three hydroelectric dams, with the total amount of reservoir accounting for 6, 147 million m³.

The subsurface hydrogeology of Bandung Basin can be simplified into two aquifers: shallow aquifer and deep aquifer while two primary groundwater withdrawers are shallow well pumps and deep well pumps, accordingly. The depths of aquifers are ~ 10–40 m, and 40–250 m, respectively, and both of them are composed of volcanic products from the compound volcanoes. Groundwater extracted from shallow aquifer is primarily used for domestic consumption while the deep water counterpart is mostly utilized by manufacturing factories, textile companies and hotel businesses (Braadbaart and Braadbaart, 1997; Ge et al., 2014).

The entire basin is known as Bandung Metropolitan Area (BMA), which encompasses four administrative zones (Fig. 1): the Bandung municipality, which is the capital city of West Java province, Indonesia, with an urban area of 81 km² in size; the surrounding Bandung regency; the Cimahi City, and part of the Sumedang regency. Urban and industrial regions mostly occur in the central part of the basin, covering an area of about 40 km east-west and about 30 km north-south (Abidin et al., 2013). The population of Bandung Basin increased from about 3.4 million in 1986–8.2 million in 2015 (BPS, 2017). According to Abidin et al. (2008), Indonesian city water supply provides only 25% and 1% for residential and industrial needs, forcing the population and industries relied heavily on the extraction of groundwater as an alternative way to access to the water, which accounts for about 60% and 99%, respectively. In other words, the growth of population and development of industrial activities has led to an increasing demand in groundwater usage from the acquirers beneath the Bandung Basin. Thus, a rapid sinking of the water table is foreseeable.

3. InSAR datasets and methodology

3.1. InSAR datasets

The spatial patterns of subsidence rates in the basin between 2000 and 2011 was given in Abidin et al. (2013). Given the fact that the variations among them are apparent, three datasets have been selected with relatively short temporal coverage under the assumption that the linear deformation model applies during the period of time. More specifically, 24C-band Sentinel-1 images (Orb-98) in ascending mode

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