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ORIGINAL ARTICLE

On causes and impacts of land subsidence in Bandung Basin, Indonesia

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Abstract The Bandung Basin is a large intra-montane basin surrounded by volcanic highlands, in western Java, Indonesia, inhabited by more than seven million people. The basin, an area of about 2,300 km^2, is a highland plateau at approximately 650–700 m above sea level and is surrounded by up to 2,400 m high Late Tertiary and Quaternary volcanic terrain. Based on the results of nine GPS surveys conducted since 2000 up to 2011, it was shown that several locations in the Bandung Basin have experienced land subsidence, with an average rate of about −8 cm/year and can go up to about −23 cm/year in certain locations. A hypothesis has been proposed by several studies that land subsidence observed in several locations in the Bandung Basin has been caused mainly by excessive groundwater extraction. It is found that there is a strong correlation between the rates of groundwater level lowering with the GPS-derived rates of land subsidence in several locations in Bandung Basin. The GPS results in this study detected significant subsidence in the textile industry area, where very large volumes of groundwater are usually extracted. The impact of land subsidence in Bandung can be seen in several forms, mainly in the cracking and damage of houses, buildings and infrastructure. Land subsidence also aggravates the flooding in Bandung Basin, which has brought huge economic losses and deteriorated the quality of life and environment in the affected areas.

Keywords Land subsidence · Indonesia · Bandung · GPS · Groundwater · Flooding

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Introduction

Bandung Basin is a large intra-montane basin surrounded by volcanic highlands, located in West Java province, Indonesia (Fig. 1). The central part of the basin has an altitude of about 665 m and is surrounded by up to 2,400 m high Late Tertiary and Quaternary volcanic terrain (Dam et al. 1996). The catchment area of the basin and surrounding mountains covers approximately 2,300 km^2, and the Citarum River with its tributaries forms the main drainage system of the basin catchment. It is one of the largest watersheds on the island of Java, which provides water for drinking, agriculture and fisheries, as well as the main supply for three reservoirs (hydroelectric dams), with a total volume of about 6,147 million cubic meters (Wangsaatmaja 2004). The mean annual temperature in the basin is about 23.7 °C, with mean annual precipitation amounts to about 1,700 mm (Iwaco-Waseco 1991). Deposits in the basin comprise coarse volcaniclastics, fluvial sediments and notably a thick series of lacustrine deposits.

On the basis of its hydraulic characteristics and its depth, the multi-layer aquifer configuration of the Bandung Basin may be simplified into two systems (Soetrisno 1996): *shallow aquifers* (a few meters to around 40 m below the surface) and *deep aquifers* (more than 40–250 m below the surface). These aquifers are composed of *volcanic products* from the volcanic complexes that bordered this basin, and *lake*

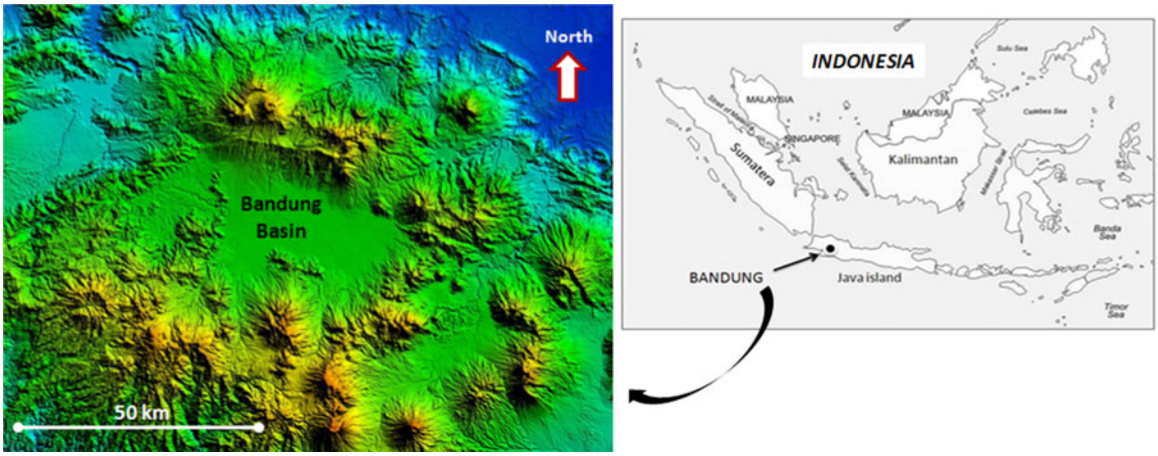

Fig. 1 Bandung Basin and its location in West Java, Indonesia

sediments that were deposited when the central part of the basin was a lake. The lake was fully formed about 50,000 years ago, and was drained away about 16,000 years ago (Dam et al. 1996).

The basin has an area of about 2,300 km^2 and encompasses five administrative units: the Bandung City (municipality) which is an urban area 81 km^2 in size perched against the northern mountain range; the surrounding Bandung regency; part of the Sumedang and West Bandung regencies; and the city of Cimahi. The central part of the basin, mostly comprising urban and industrial areas, is a plain measuring about 40 km east–west and about 30 km north–south. Bandung City itself is the capital of West Java province, Indonesia. The population of the Bandung municipality increased from less than 40,000 in 1906 to nearly one million in 1961, and had grown to about 2.4 million in 2010 (BPS 2011). The population in Bandung Basin itself was about 3.4 million in 1986, became about 4.4 million in 1994, and in 2003 was about 5.9 million people. In addition, with expansion of manufacturing and textile industries in the Bandung Basin, urbanisation increased and in 2010 about 7.7 million people inhabited the basin.

There are several types of land subsidence that can be expected to occur in the Bandung Basin, namely subsidence due to groundwater extraction, subsidence induced by the load of man-made constructions (i.e., settlement of highly compressible soil), subsidence caused by natural consolidation of alluvium soil, and geotectonic subsidence.

As information on land subsidence characteristics will be useful for managing many developmental and environmental aspects, systematic and continuous monitoring of land subsidence in Bandung is obviously needed and is critical to the welfare of the city. Comprehensive information on land subsidence characteristics would be important for several tasks, such as spatial-based groundwater extraction regulation, effective control of floods, conservation of environment, design and construction of infrastructure, and spatial urban development planning in general.

In principle, the land subsidence phenomenon can be studied using several methods, such as hydrogeology methods, e.g., groundwater level observation, extensometer measurement and piezometer measurement, as well as by geodetic methods such as leveling surveys, GPS surveys and interferometric synthetic aperture radar (InSAR). Subsidence phenomena in Bandung Basin has been studied since 2000 using GPS surveys (Abidin et al. 2006) and also InSAR since 2006 (Abidin et al. 2008; Sumantyo et al. 2012). This paper analyzes and discusses the causes and impacts of land subsidence phenomena in Bandung Basin.

Estimating land subsidence in Bandung Basin

Subsidence phenomena in Bandung Basin have been studied using GPS survey method and also InSAR. In estimating land subsidence using repeated GPS surveys, several monuments, which are placed on the ground covering the Bandung Basin and its surroundings, are accurately positioned relative to a certain reference (stable) point, using the GPS survey technique. The precise coordinates of the monuments are periodically determined using repeated GPS surveys at certain time intervals. By studying the characteristics and rate of change in the height components of the coordinates from survey to survey, the land subsidence characteristics can be derived.

To study the land subsidence phenomena in the Bandung Basin, nine GPS surveys have been conducted in February 2000, November 2001, July 2002, June 2003, June 2005, August 2008, July 2009, July 2010 and August 2011. The surveys at all stations were carried out using dual-frequency geodetic-type GPS receivers. In this case, the PSCA station located inside the Institute of Technology

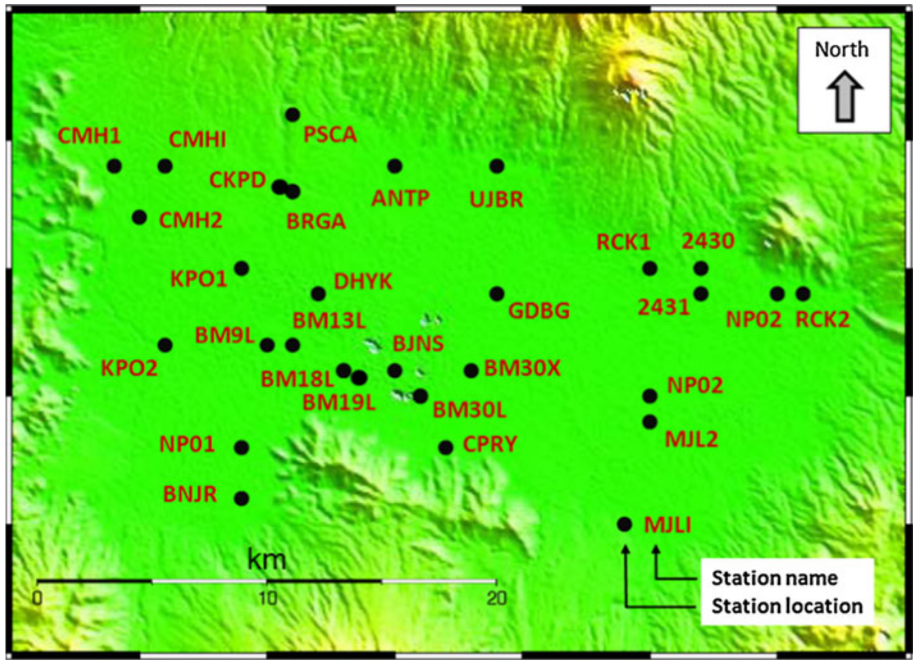

Fig. 2 Distribution of GPS points for studying land subsidence in the Bandung Basin. The PSCA reference station is the northern-most point in the figure

Bandung (ITB) campus was used as the reference point with known coordinates. For all GPS surveys, except for the first survey, the length of sessions was between 10 and 12 h. In the first GPS survey, the length of sessions was about 5–6 h. The data were collected with a 30-s interval, and the elevation mask was set to 15° for all stations. The surveys were mainly carried out by the staff and students from the Department of Geodesy and Geomatics Engineering of ITB. Location of GPS stations used for studying land subsidence in Bandung Basin is shown in Fig. 2.

The data were processed using the software Bernese 5.0 (Beutler et al. 2007). Since this study is mostly interested in the relative heights with respect to a stable point, the radial processing mode was used instead of a network adjustment mode, with baselines that ranged from about 4–25 km in length. In this case, the relative ellipsoidal heights of all stations are determined relative to the PSCA station (northernmost station in Fig. 2). For data processing, precise ephemeris was used instead of the broadcast ephemeris. The effects of tropospheric and ionospheric biases are mainly reduced by the differencing process and the use of dual-frequency observations. The residual tropospheric bias parameters for individual stations are estimated to further reduce the tropospheric effects. In processing baselines, most of the cycle ambiguities of the phase observations were successfully resolved. Based on the estimated ellipsoidal heights obtained from GPS processing, the height differences between two consecutive survey epochs can be calculated. The estimated land subsidence at several locations in Bandung Basin as derived from five GPS surveys (i.e., from 2000 to 2005) are given in Abidin et al. (2006, 2008).

The spatial and temporal variations of subsidence rates in Bandung Basin are shown by the eight interpolated maps in Fig. 3. These maps were interpolated using Kriging method based on the GPS-derived subsidence rates, and then plotted using the Surfer software. Considering the distribution of GPS points shown in Fig. 2, these interpolated maps should be considered just as the indicative rather than final land subsidence maps of Bandung area. In this case, the interpolated and extrapolated values for the areas located several kilometers away from the GPS stations may be misleading and may alter the interpretation of the maps.

The GPS-derived subsidence results shown in Fig. 3 indicate that the mechanism of land subsidence in the Bandung Basin is not simple and may be caused by several factors, such as excessive groundwater extraction, sediment compaction, building load and tectonic activities. In general, rates of subsidence have a mean of about −8 cm/year, which can go up to about −23 cm/year at certain locations and certain time periods. Several stations, e.g., CMHI, DYHK, RCK2, GDBG, BM9L and BM18L (see Fig. 2), have higher subsidence rates compared to others, namely more than 12 cm/year. Stations CMHI, DYHK, RCK2 and GDBG are located in the textile industry areas, where excessive groundwater extraction is expected to occur; while BM9L and BM18L stations are located on the bank of the Citarum River. The results in Fig. 3 also show that subsidence rates are not always linear. Several stations show a slowing down of subsidence, while others do not. The results obtained from InSAR using ALOS/PALSAR data also show that subsidence of over 12 cm occurred during the period between June 2006 and March 2007, near

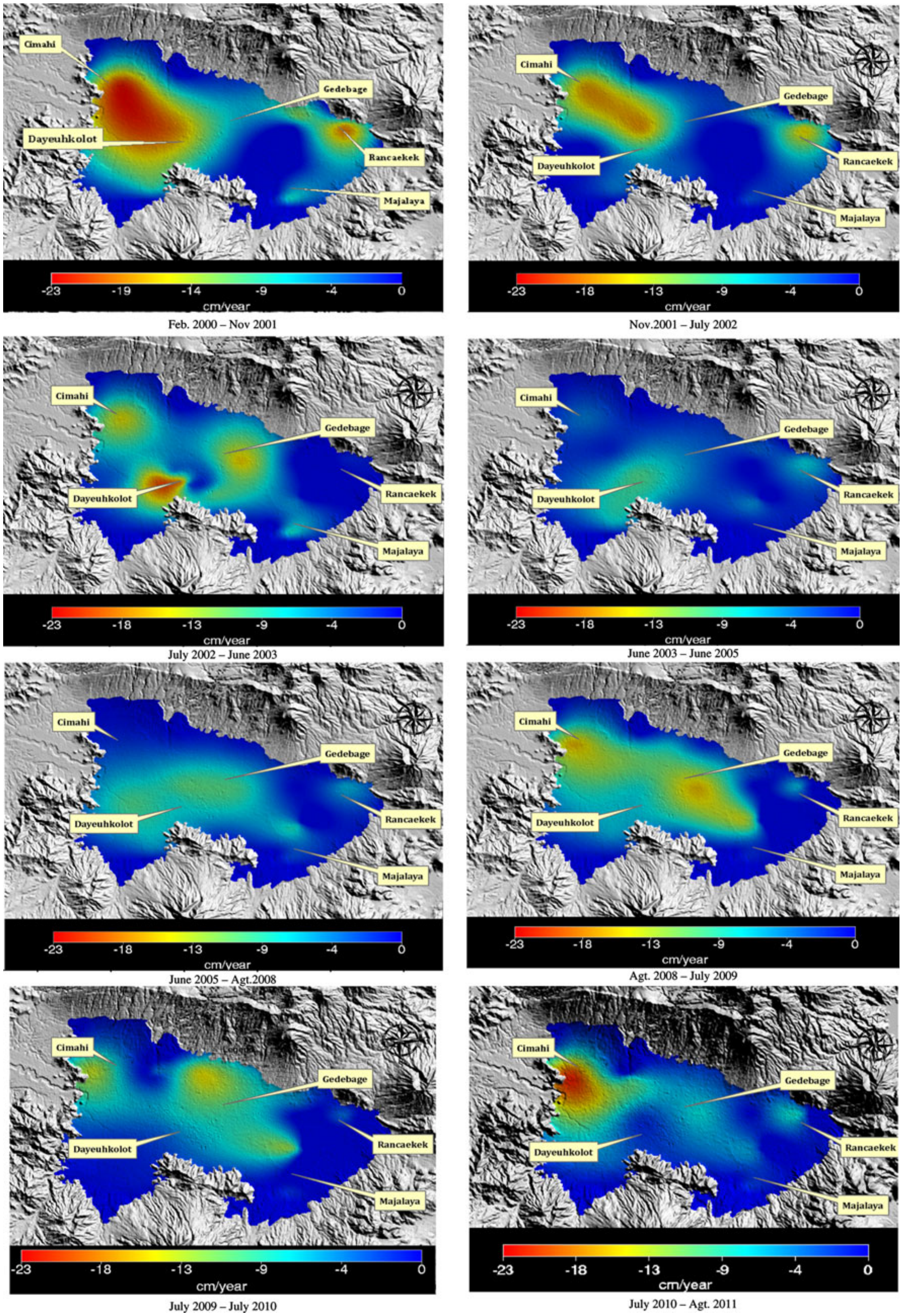

Fig. 3 Temporal and spatial variation of GPS-derived subsidence rates (cm/year) in the Bandung Basin during the period February 2000 to August 2011

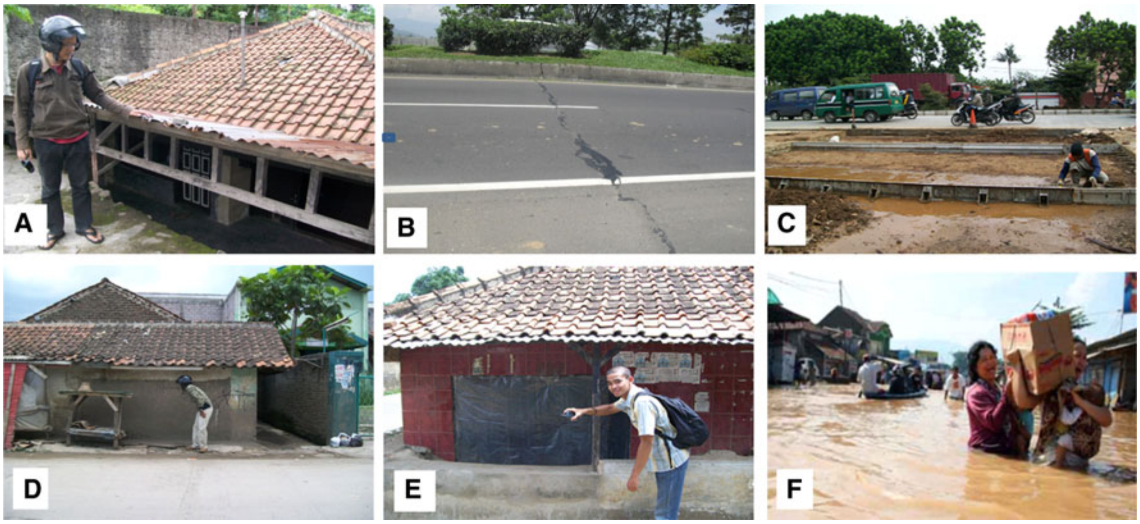

Fig. 4 Examples of recent subsidence features in the Bandung Basin. Photos taken by Irwan Gumilar in 2010. **a** Subsided house in the Dayeuh Kolot area (around DHYK GPS stations); **b** highway cracking in the southern Cimahi area (around CMHI GPS station); **c** uplifting of the road due to subsidence in the Gedebage area (around GDBG GPS station); **d** subsided house in the Gedebage area (around GDBG GPS station); **e** subsided house in the southern Cimahi area (around CMHI GPS station); **f** flooding in Dayeuh Kolot area (around DHYK GPS station)

GPS stations CMHI, BM18L and BM19L (Abidin et al. 2008, Sumantyo et al. 2012).

Impacts of land subsidence in Bandung Basin

In general, the impacts of land subsidence in Bandung Basin could be seen in several forms, such as cracking of permanent constructions and roads, changes in river canal and drain flow systems, wider expansion of flooding areas and malfunction of drainage system. Figure 4 shows some representation in the field caused by land subsidence phenomena from several years ago and recent times.

Ground thruthing surveys have been conducted to find and locate the impact features of land subsidence in the Bandung area. Figure 5 shows the distribution of land subsidence impacts in 2011, overlapped with the average GPS-derived subsidence from 2000 to 2011. From this map, it can be seen that the numbers of buildings, houses and other infrastructure affected by land subsidence phenomena are also numerous, exhibiting cracking, tilting or general damage. Figure 5 also shows that most damages occurred in the areas showing high subsidence and also those which spatially have differential subsidence.

The tangible and intangible impacts of land subsidence cannot be underestimated. The primary environmental and economic effects of land subsidence phenomena can vary from negligible to severe depending on the present land-use nature of the affected area and the subsidence magnitude and coverage. The indirect effects of subsidence through aggravation of other hazards already present in the area are frequently more severe than the direct effects (Viets 2010). In the case of Bandung Basin, the increase in flooding coverage caused by continuing subsidence introduces more problems compared to other indirect effects of land subsidence. Flooding mainly occurred in the areas along the Citarum River and its tributaries and subsidence in these areas worsen it. Flooding can also occur in the other areas during the rainy season due to the poor drainage system. Land subsidence in these areas, besides lowering the ground elevation, can also change the water flow direction in the drainage system and in turn also worsen the flooding phenomena.

The economic losses caused by land subsidence in Bandung are potentially enormous, as many buildings and infrastructure were severely affected by land subsidence, and its collateral flooding disaster also frequently affected economic activities in the southern Bandung region (Gumilar et al. 2012). Many houses, public utilities and a large part of the populations are also exposed to this silent disaster. The corresponding maintenance cost is increasing every year, and the living conditions of the affected population are deteriorating. The quality of their social and economic activity is consequently decreasing as well.

Causes of land subsidence in the Bandung Basin

Land subsidence in the Bandung Basin can be caused by excessive groundwater extraction, load of man-made constructions (i.e., settlement of highly compressible soil), natural consolidation of alluvium soil and tectonic

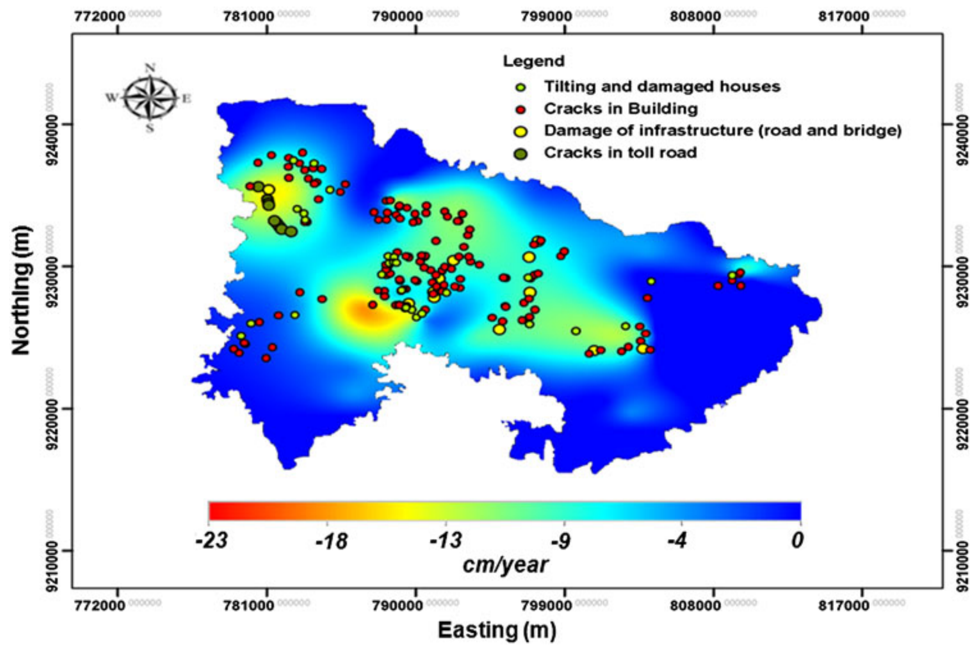

Fig. 5 Example of distribution of land subsidence impacts in Bandung, overlapped with the average GPS-derived subsidence rates from 2000 to 2011

activities. However, the elaborate characteristics and mechanisms of land subsidence in Bandung are yet only partly known.

A hypothesis has been proposed by several studies (Soetrisno 1991; Braadbaart and Braadbaart 1997; IGES 2006; Abidin et al. 2009) that land subsidence observed in several locations in the Bandung Basin has been caused by excessive groundwater extraction. The increase in both population and industrial activity in turn increased the degree of groundwater withdrawal from the aquifers in the Bandung Basin, as illustrated in Fig. 6. According to Wirakusumah (2006), about 60 % of the total clean water required in the Greater Bandung area (i.e., about 512 million cubic meters) are supplied by groundwater and the industry relies nearly 100 % on groundwater resources. The two primary categories of groundwater withdrawers in the basin are shallow well pumps and deep well pumps. The majority of shallow wells are used for domestic purposes, while deep wells are operated by the regional water company or by private firms such as textile industries, manufacturing companies and hotels (Braadbaart and Braadbaart 1997).

Data from the Industry and Trade Agency in Bandung City and Regency show that in 2003 there were 577 large and medium-scale industries in Bandung Municipality, with a total number of workers of about 103,000, while in Bandung and West Bandung Regencies there were 696 companies employing about 235,000 workers (Wangsaatmaja et al. 2006). Nearly 50 % of these are textile industries which require a large amount of water for their textile processing process. Since many of them are located in the areas with no piping infrastructure, the use of groundwater becomes an inexpensive and attractive solution for these industries.

Increased groundwater extraction has led to a rapid sinking of water tables in the plain (Fig. 7), which in turn can cause land subsidence. During the 1980s, the average annual drop in water tables in the basin was 1 m, and in the most heavily extracted areas annual drops of up to 2.5 m were recorded (Soetrisno 1991). From 1980 to 2004, i.e., over about 24 years, the groundwater level in the Bandung Basin has dropped by about 20–100 m. This drop in groundwater level has both spatial and temporal variations. Increased groundwater extraction also decreases well productivity and has led to drastic changes in the time and direction of travel of underground water (Braadbaart and Braadbaart 1997). Continuous lowering of the groundwater level in the industrial areas has considerably changed the flow characteristics of the groundwater system and vertical downward leakage occurs almost in the entire Bandung Basin (Soetrisno 1996).

Correlation between land subsidence and groundwater extraction can be done by utilizing the registered groundwater extraction volume and the observed groundwater level. In case of correlation with groundwater extraction, Abidin et al. (2006, 2008) have shown that the GPS-derived land subsidence do not always have a positive correlation with the registered volume of groundwater extraction around the corresponding GPS stations (i.e., inside 1-km radius). This fact could imply two things: firstly, the registered groundwater extraction volume does not reflect the real groundwater use; secondly, the amount of land subsidence is also influenced by other factors, such as the different geological structures and soil

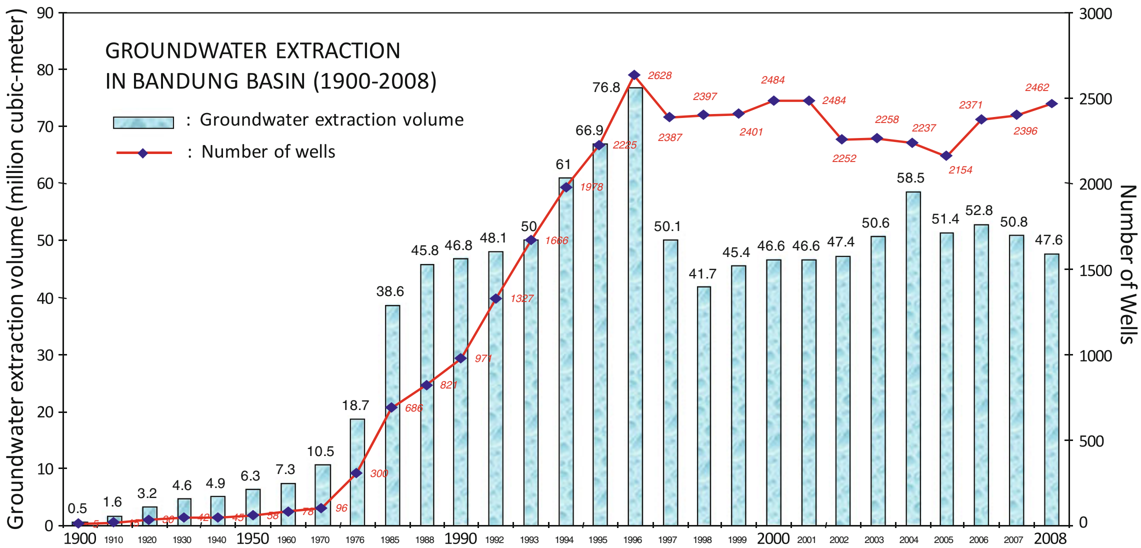

Fig. 6 Registered groundwater extraction in Greater Bandung (1900–2008) from the deep aquifers (40–250 m below the surface): courtesy of the Geological Agency of Indonesia

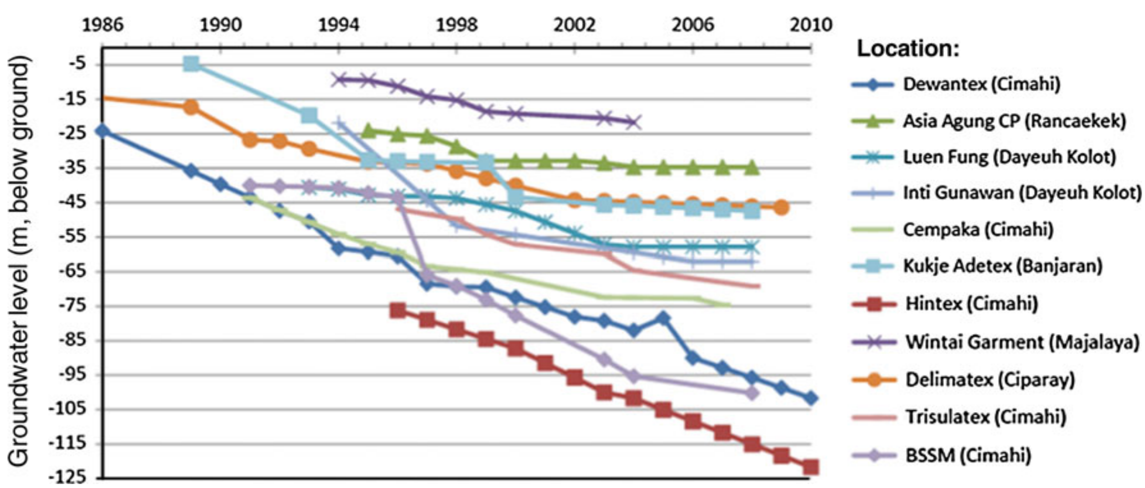

Fig. 7 Lowering of groundwater level in some locations in the Bandung Basin, based on data from the Geological Agency of Indonesia

compressibility at the observed locations. In the case of the Bandung Basin, both reasons may be valid. According to Hutasoit (2008), the registered groundwater extraction volume is just about 30 % of the actual amount. In 1995, the illegal extraction of groundwater was estimated to be 120 % of the registered volume (Soetrisno 1996). Moreover, besides evidence found in the field, the significant GPS-observed subsidence shown in previous Fig. 3 is located in the textile industry area. It is known that the textile industry usually extracts very large volumes of groundwater.

Excessive groundwater extraction will generally lower the groundwater level in the corresponding area. In general, groundwater level inside Bandung Basin has been significantly lowered compared to its level before the 1980s. Theoretically, it can be expected that the subsidence of certain areas will have a positive correlation with the lowering of groundwater level. Abidin et al. (2009) shows that indeed there is a strong correlation between the rates of groundwater level lowering with the GPS-derived rates of land subsidence in certain locations in Bandung Basin, in which considering the maximum groundwater lowering rates, correlation up to 0.92 is obtained. Figure 8 shows an example of this correlation between land subsidence and lowering of the groundwater level in four locations in Bandung Basin, namely Cimahi (CMHI), Dayeuh Kolot (DYHK), Banjaran (BNJR) and Rancaekek (RCK2), which are located in areas with many textile industries. The InSAR technique also detected that significant subsidence occurred in the textile industry area, where very large volumes of groundwater are usually extracted (Abidin et al. 2008, Sumantyo et al. 2012). This InSAR result supports

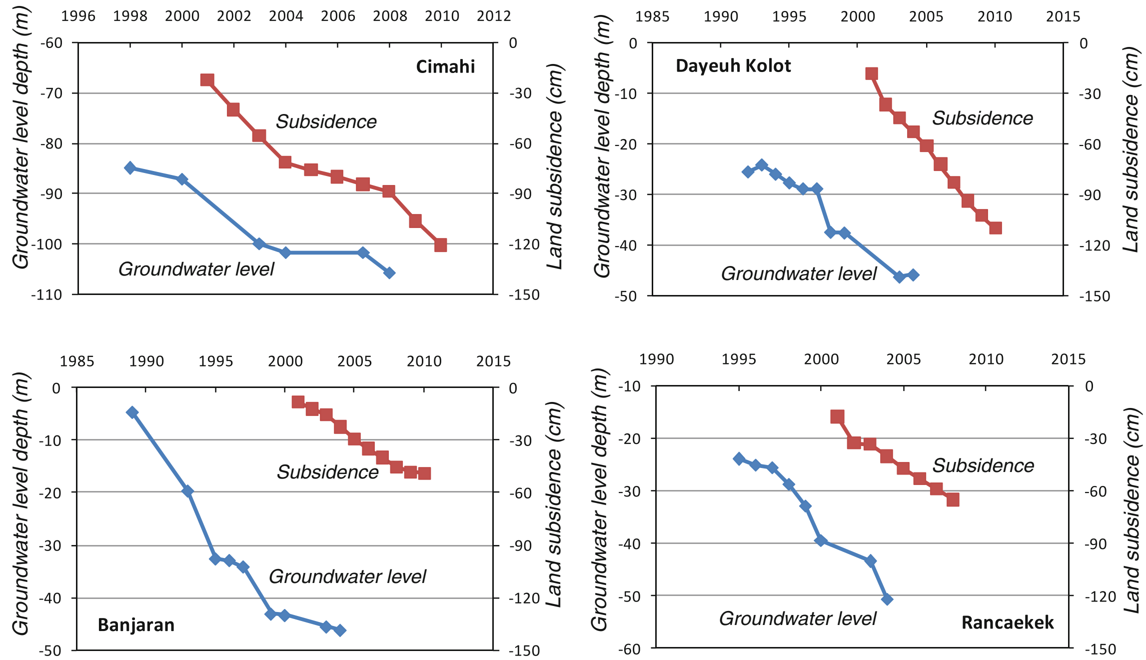

Fig. 8 Correlation between land subsidence and lowering of the groundwater level in some locations in Bandung. Groundwater level depth data were from the Geological Agency of Indonesia

the hypothesis that excessive groundwater extraction has led to subsidence in the corresponding area.

However, as these correlations are only performed at several locations in Bandung Basin, further research is needed to clarify the real correlation pattern between land subsidence, groundwater extraction volume and groundwater level in the Bandung Basin. More geodetic and hydrogeological data are needed to gain greater insight into land subsidence and groundwater characteristics in the Bandung Basin.

Conclusions

Land subsidence is an ongoing phenomenon in the Bandung Basin. Based on the results of nine GPS surveys conducted in 2000 up to 2011, it was shown that several locations in the Bandung Basin have experienced land subsidence, with an average rate of about −8 cm/year and can go up to about −23 cm/year in certain locations. The observed subsidence rates have spatial and temporal variations, and in general the observation stations around the textile industrial areas have relatively high subsidence rates, indicating the effects of excessive groundwater extraction on observed land subsidence.

Land subsidence in Bandung has a strong linkage with the urban development process. The urban development in Bandung Basin and its surrounding areas has grown very rapidly in the sectors of industry, trade, transportation, real estate and many others. This exponential increase in urban development has introduced several environmental problems, such as (1) extensive conversion of prime agricultural areas into residential and industrial areas, (2) significant disturbance to the main ecological function of the surrounding upland areas of Bandung Basin as a water recharge area for Bandung City, and (3) increase in groundwater extraction due to the development of industrial activities and the high population increase. These negative impacts will contribute to the lowering of groundwater level inside the Bandung Basin and in turn can introduce the occurence of land subsidence phenomena in several places in Bandung Basin.

Besides excessive groundwater extraction, land subsidence in the Bandung Basin may also be partly caused by natural consolidation of alluvium soil, load of man-made constructions (i.e., settlement of highly compressible soil) and tectonic activities. Therefore, further research is still needed to clarify the real mechanism and pattern of land subsidence in the Bandung Basin. In this regard, besides carefully considering all possible factors influencing subsidence in the Bandung Basin, the GPS-derived results should also be integrated with results obtained by other monitoring techniques such as InSAR, absolute microgravity, leveling and automatic water level recorders.

The impact of land subsidence in Bandung can be seen in several forms, mainly the cracking and damage of houses, buildings and infrastructure, and also it aggravates flooding in the Bandung Basin. In general, the direct and indirect losses caused by land subsidence in Bandung Basin are quite significant, in terms of financial, environmental and social costs. Elaborate and systematic study is therefore needed to estimate these direct and indirect losses due to land subsidence phenomena in the Bandung Basin.

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