Study on Causes and Impacts of Land Subsidence in Bandung Basin, Indonesia

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Key words: Bandung; land subsidence; groundwater; flooding, GPS; InSAR

SUMMARY

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 2300 km2, is a highland plateau at approximately 650–700 m above sea level and is surrounded by up to 2400 m high Late Tertiary and Quaternary volcanic terrain. Based on the results of 8 GPS surveys conducted since 2000 up to 2010 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 similar rate of subsidence was also detected by the InSAR (Interferometric Synthetic Aperture Radar) technique.

Land subsidence in the Bandung basin can be caused by excessive groundwater extraction, load of manmade constructions (i.e. settlement of highly compressible soil), natural consolidation of alluvium soil, and tectonic activities. However, the elaborate characteristics and mechanisms of land subsidence in Bandung are still partly known. 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, with a correlation coefficient of up to about 0.92. The GPS and InSAR results in this study detected significant subsidence in the textile industry area, where very large volumes of groundwater are usually extracted. Land subsidence also aggravates the flooding in Bandung Basin, which has brought huge economic losses and deteriorates quality of life and environment in affected areas. This paper analyzes and discusses the causes and impacts of land subsidence phenomena in Bandung basin.

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1. INTRODUCTION

Bandung Basin is a large intra-montane basin surrounded by volcanic highlands, located in West Java province, Indonesia (Figure 1). The central part of the basin has an altitude of about 665 m and is surrounded by up to 2400 m high Late Tertiary and Quaternary volcanic terrain [*Dam et al.*, 1996]. The catchment area of the basin and surrounding mountains covers approximately 2300 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 6147 million cubic meters [*Wangsaatmaja*, 2004]. Mean annual temperature in the basin is about 23.7°C, with mean annual precipitation amounts to about 1700 mm [*Iwaco-Waseco*, 1991]. Deposits in the basin comprise of coarse volcaniclastics, fluvial sediments and notably a thick series of lacustrine deposits.

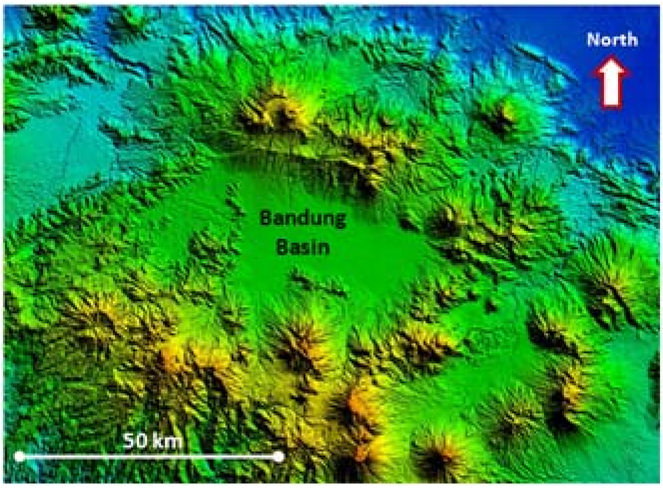

Figure 1. Bandung basin and its location in West Java, Indonesia

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 metres to around 40 m below the surface) and *deep aquifers* (more than 40 m to 250 m below the surface). These aquifers are composed of *volcanic products* from the volcanic complexes that bordered this basin, and *lake 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 2300 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 two and half million by 1995. The population in Bandung basin itself was about 3.4 million in 1986, became about 4.4 million in 1994, and in 2003 the population is about 5.9 million peoples. In addition, with expansion of manufacturing and textile industries in the Bandung Basin, urbanisation increased and in 2005 more than 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 manmade constructions (i.e. settlement of highly compressible soil), subsidence caused by natural consolidation of alluvium soil, and geotectonic subsidence.

Since 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 levelling surveys, GPS surveys and InSAR (Interferometric Synthetic Aperture Radar) [*Massonnet & Feigl*, 1998; *Sneed et al.,* 2001; *Bell et al.,* 2002; *Ge et al.,* 2007]. Subsidence phenomena in Bandung Basin has been studied since 2000 using GPS surveys [*Abidin et al.,* 2006] and also using InSAR since 2006 [*Abidin et al.,* 2008]. This paper analyzes and discusses the causes and impacts of land subsidence phenomena in Bandung basin.

2. ESTIMATING LAND SUBSIDENCE IN BANDUNG BASIN

Subsidence phenomena in Bandung Basin has been studied since 2000 using GPS surveys method [*Abidin et al.,* 2006] and also using InSAR since 2006 [*Abidin et al.,* 2008]. 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.

In order to study the land subsidence phenomena in the Bandung Basin, eight GPS surveys have been conducted in February 2000, November 2001, July 2002, June 2003, June 2005, August 2008, July 2009 and July 2010. The surveys at all stations were carried out using dualfrequency geodetic-type GPS receivers. In this case the PSCA station located inside the Institute of Technology 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 to 12 hours. In the first GPS survey the length of sessions was about 5–6 hours. The data were collected with a 30-second interval, and the elevation mask was set to 15° for all stations. The surveys were carried out by the Geodesy Research Division of ITB. Location of GPS stations used for studying land subsidence in Bandung Basin is shown in Figure 2.

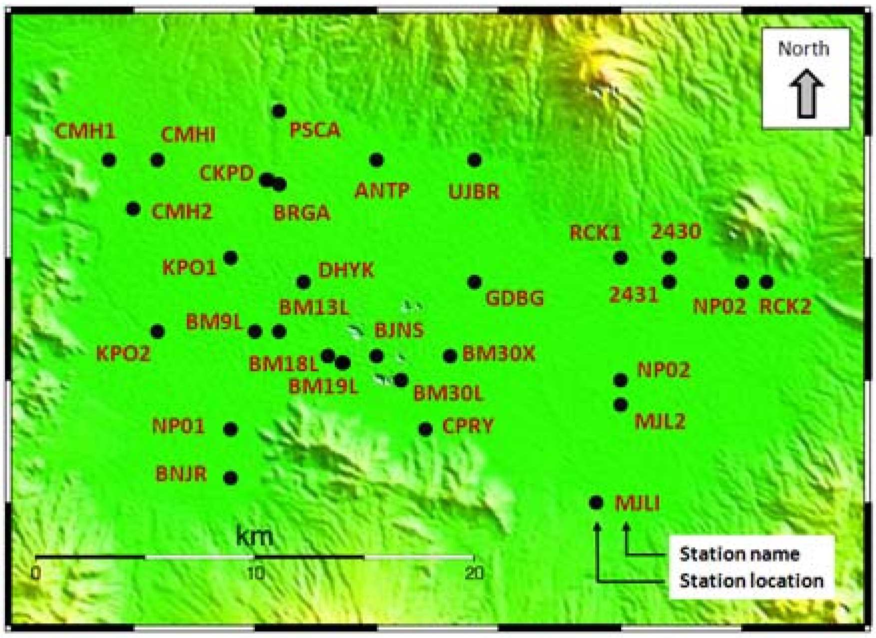

Figure 2. Distribution of GPS points for studying land subsidence in the Bandung Basin. The PSCA reference station is the northern most point in the figure.

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].

Results from GPS show that land subsidence in Bandung has both temporal and spatial variations as indicated by Figure 3. In general, rates of subsidence have a mean of about –8 cm/year, which can go up to about –23 cm/year at certain location and certain time period. Several stations, e.g. CMHI, DYHK, RCK2, GDBG, BM9L and BM18L (see Figure 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 Figure 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 (Interferometric Synthetic Aperture Radar) using ALOS/ PALSAR data also show that subsidence of over 12 cm occurred during the period

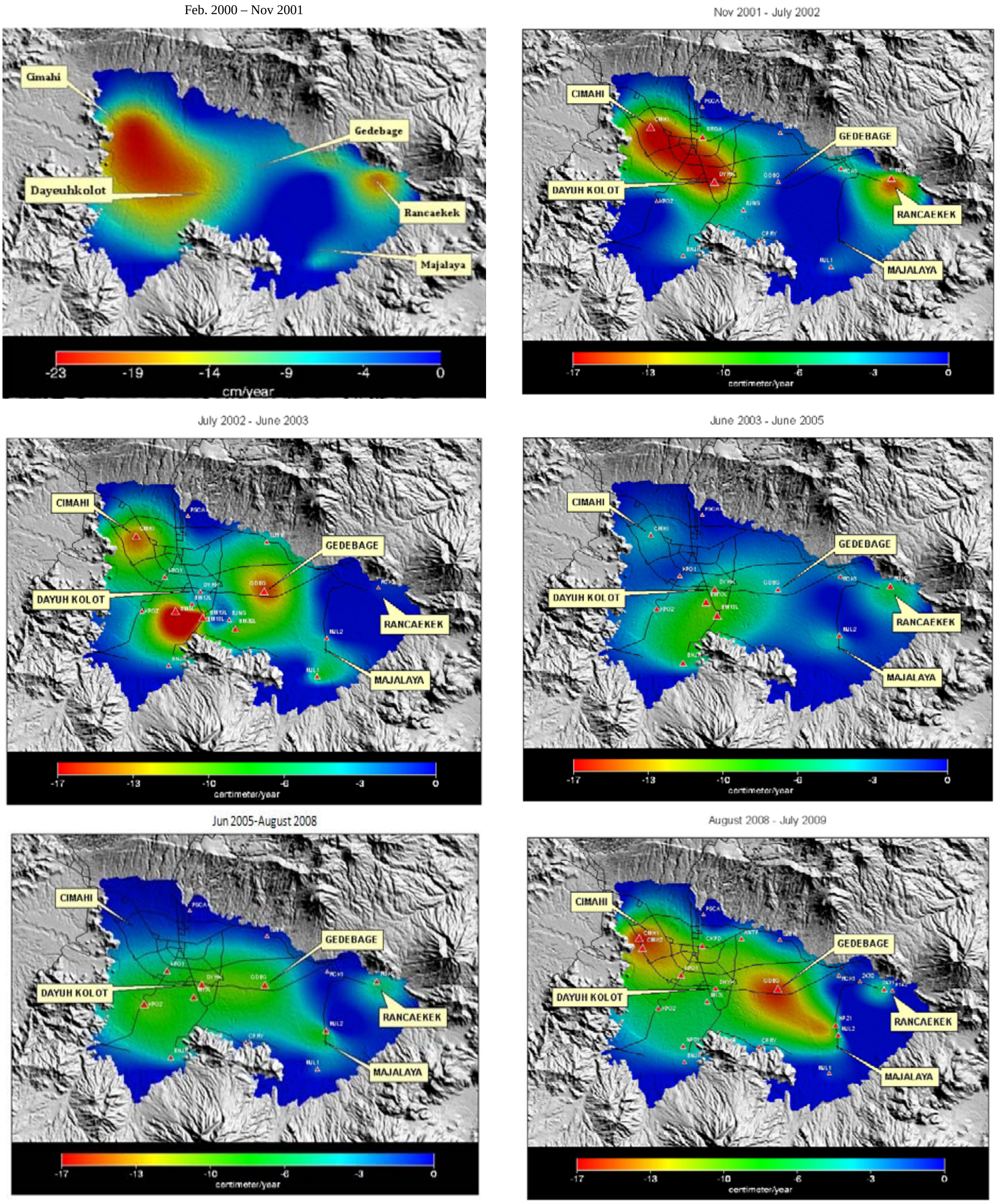

Figure 3. Temporal and spatial variation of GPS derived subsidence rates (cm/year) in the Bandung Basin during the period of February 2000 to July 2009.

between June 2006 and March 2007, near GPS stations CMHI, BM18L and BM19L (Abidin *et al.*, 2008), as shown in Figure 4. From this image, it can be concluded that around the CMHI station, the phase anomalies imply land subsidence during the 276 days that is equivalent to 15 cm (around 20 cm/year) in the look direction of the SAR sensor. If a conversion of look direction into ellipsoidal normal is made, then this rate of subsidence around the CMHI station is in agreement with the previous rates obtained from GPS surveys. During the period of January to December 2009, the same nature of subsidence also detected by InSAR, as shown in Figure 5.

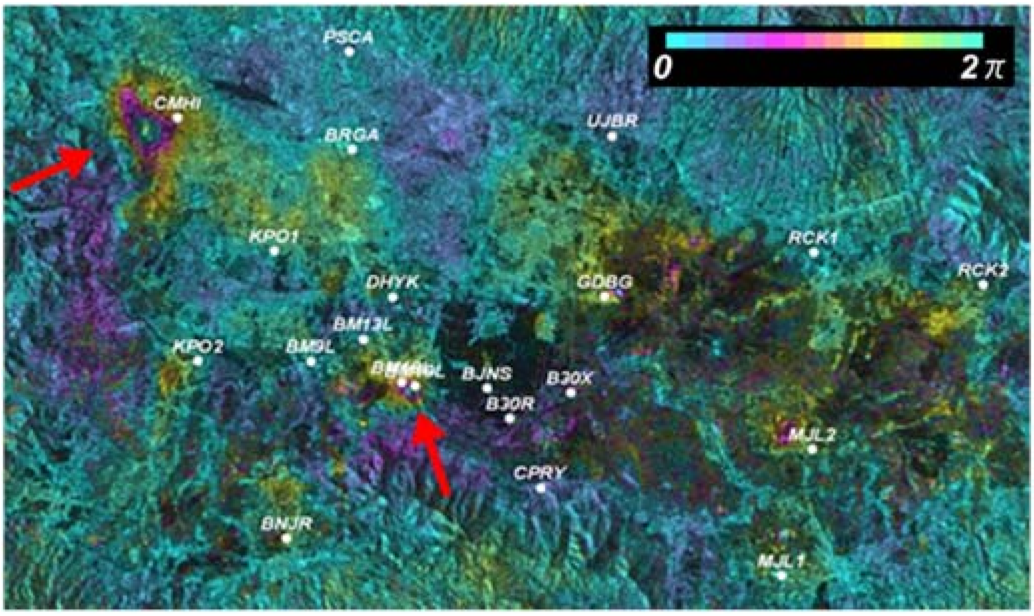

Figure 4. InSAR-derived subsidence in Bandung Basin from June 2006 to March 2007, [*Abidin et al.*, 2008]. One cycle of phase (2π) is about 11.8 cm (half the wavelength of the L-band).

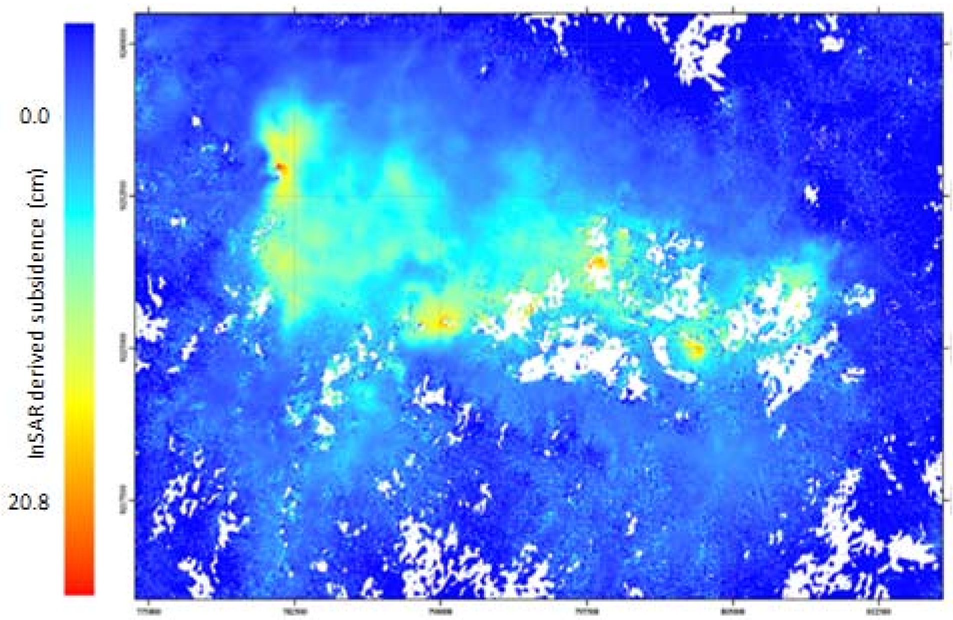

Figure 5. ALOS InSAR-derived subsidence in Bandung basin from January to December 2009.

The above GPS and InSAR results 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, building load, sediment compaction, and tectonic activities.

3. 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. Figures 6 and 7 shows some representation in the field caused by land subsidence phenomena from several years ago and recent times.

Figure 6. Examples of subsidence features in Bandung basin, adapted from *Ruchijat* (2006). In this Figure A: Ground lowering in the Rancaekek area (around RCK2 GPS stations); B and F: Hanging wall and structural cracking in the Leuwigajah area (around CMHI GPS station); C: Ground lowering in the Ujungberung area (around UJBR GPS station); D: Differential subsidence in the Gedebage area (around GDBG GPS station); E: Structural cracking around DYHK GPS station.

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 introduce more problems compared to other indirect effects of land subsidence. The flooding mainly occurred in the areas along the Citarum River and its tributaries; and subsidence in these areas will worsen it. Flooding can also occur in the other areas during the rainy season due to 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.

Figure 7. Examples of recent subsidence features in Bandung basin. Photos taken by Irwan Gumilar in 2010. In this Figure G: Subsided house in the Dayeuh Kolot area (around DHYK GPS stations); H: Highway cracking in the southern Cimahi area (around CMHI GPS station); I: Uplifting of the road due to subsidence in the Gedebage area (around GDBG GPS station); J: Subsided house in the Gedebage area (around GDBG GPS station); K: Subsided house in the southern Cimahi area (around CMHI GPS station); L: Flooding in Dayeuh Kolot area (around DHYK GPS station).

Flooding in the areas with has relatively large subsidence in Bandung basin is shown in Figure 8, namely in the areas of Gedebage, Majalaya, Rancaekek, and Dayeuh Kolot. If referred to Figure 9 that shows the flooded areas in 2010 in comparison with their land subsidence rates; Gedebage is closed to GPS station of GDBG; Majalaya is closed to GPS stations of MJL2 and NP02; Rancaekek is closed to GPS stations of RCK1 and 2430; and Dayeuh Kolot is closed to GPS station of GDBG.

Gede Bage

Majalaya

Rancaekek *Dayeuh Kolot*

Figure 8. Flooding in the areas with has relatively large subsidence in Bandung basin.

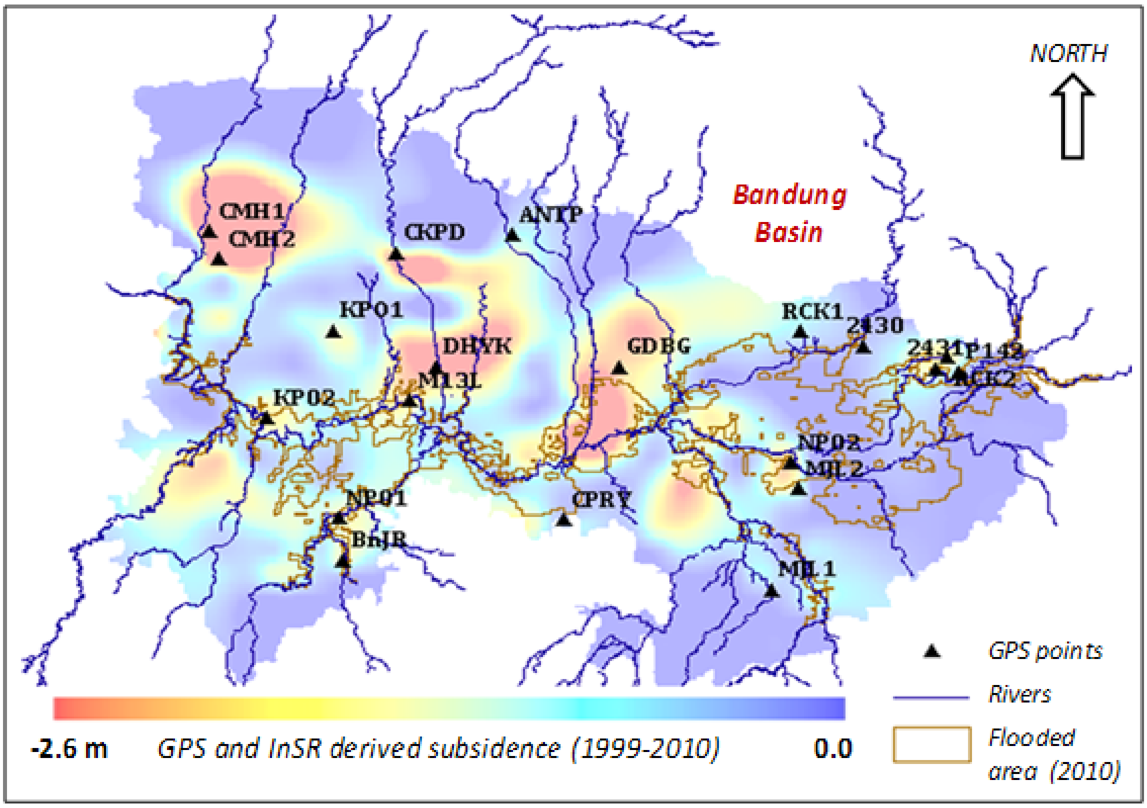

Figure 9. The flooded areas in 2010 and their land subsidence rates.

4. CAUSES OF LAND SUBSIDENCE IN BANDUNG BASIN

Land subsidence in the Bandung Basin can be caused by excessive groundwater extraction, load of manmade constructions (i.e. settlement of highly compressible soil), natural consolidation of alluvium soil, and tectonic activities. However, the elaborate characteristics and mechanisms of land subsidence in Bandung are still 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 Figure 10. According to [*Wirakusumah*,2006], about 60 % of the total clean water required in the Greater Bandung area (i.e. about 512 million cubic metres) 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].

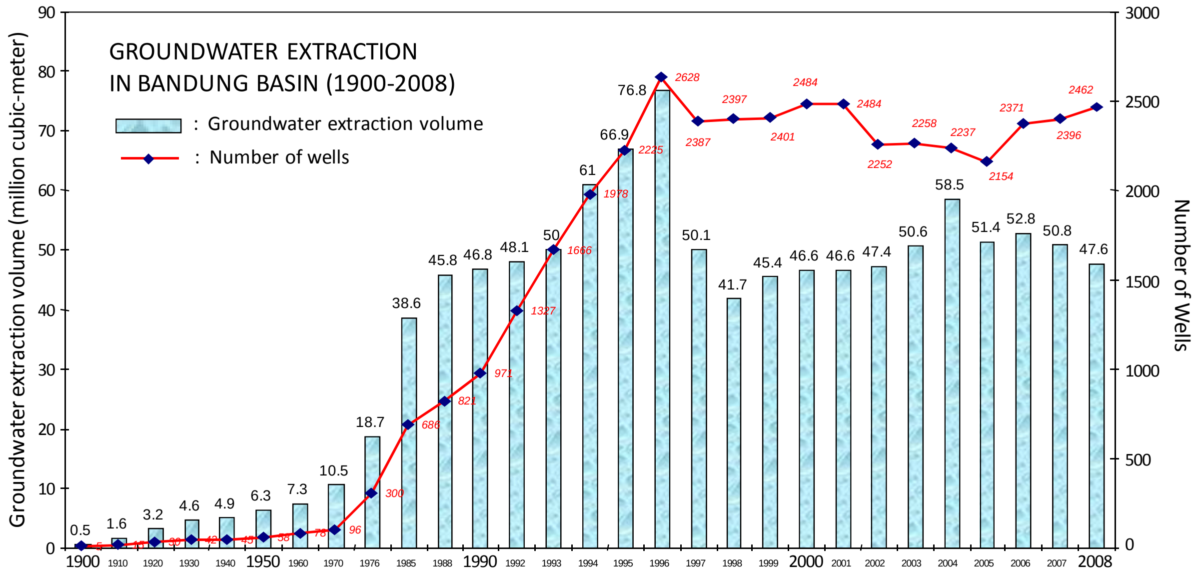

Figure 10. Registered groundwater extraction in Greater Bandung (1900 - 2008)
from the deep aquifers (40-250 m) below the surface); courtesy of Geological Agency of Indonesia.

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 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 percent of these industries are the textile industries which require 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 a cheap and attractive solution for these industries.

Increased groundwater extraction has led to a rapid sinking of water tables on the plain (Table 1), which in turn can cause land subsidence. During the 1980s, the average annual drop in water tables in the basin was one metre, and in the most heavily extracted areas annual drops of up to 2.5 metres 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 to 100 m. This drop in groundwater level has both spatial and temporal variations. Increased groundwater extraction will also decrease 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, in which 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 the 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, and secondly the amount of land subsidence is also influenced by other factors, such as the different geological structures and soil 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, from evidence found in the field, the significant InSAR-observed subsidence shown in previous Figure 8 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 significantly lowered compared to its level before the 1980s. Theoretically, it can be expected that subsidence of certain areas will have a positive correlation with the lowering of the 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 location in Bandung basin, as shown in Figure 11. If the maximum groundwater lowering rates are considered, then correlation up to 0.92 is obtained.

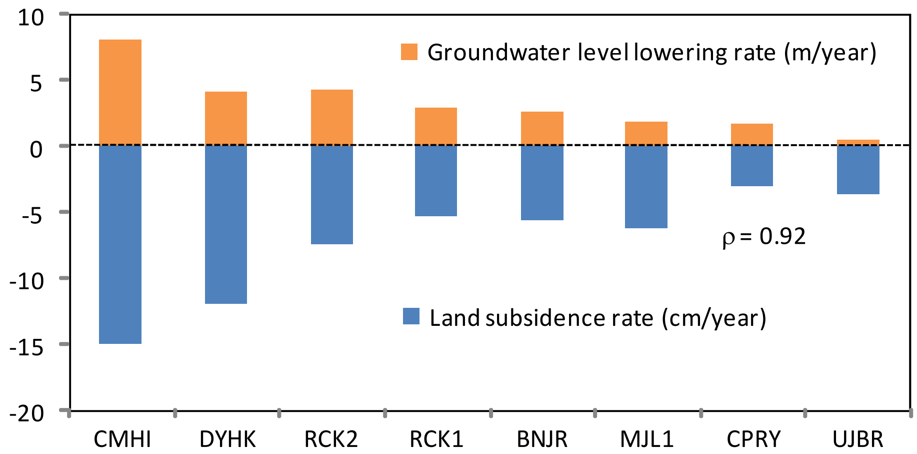

Figure 11. Correlation between the maximum groundwater level lowering rates and land subsidence rates in several locations in Bandung basin, after *Abidin et al.* (2009).

The InSAR technique did also detected that significant subsidence occurred in the textile industry area, where very large volumes of groundwater are usually extracted. This InSAR result supports the hypothesis that excessive ground water extraction has led to subsidence in the corresponding area. Figure 12 shows an example that the GPS stations with large subsidence rates, e.g. CMHI, DYHK, MJL2 and RCK2, are located in the areas with many textile industries, where the huge volume of groundwater are expected to be withdrawn.

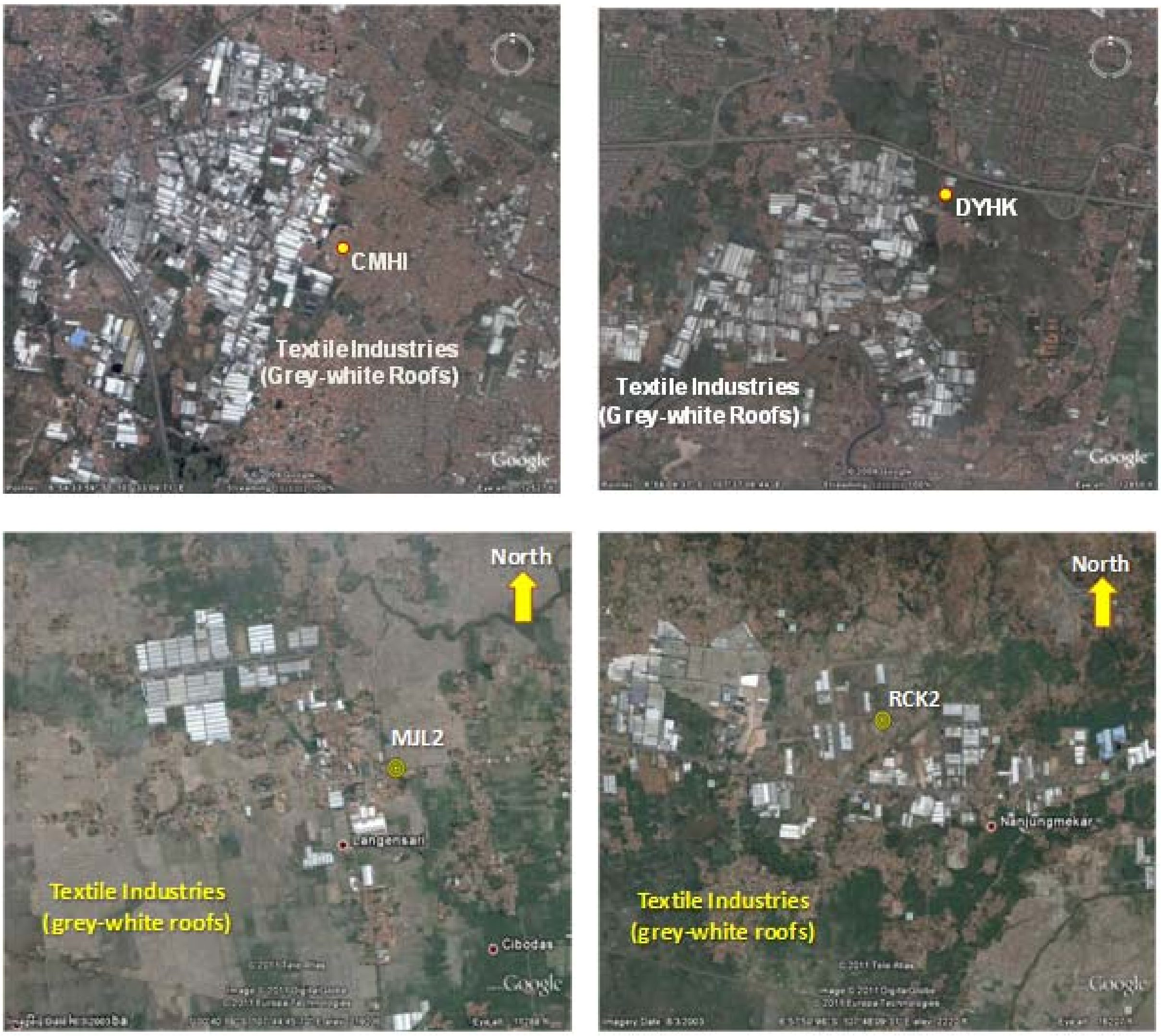

Figure 12. Location of GPS stations CMHI (Cimahi), DYHK (Dayeuh Kolot), MJL2 (Majalaya), and RCK2 (Rancaekek) in the areas of textile industries.

However, since 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 in order to gain greater insight into land subsidence and groundwater characteristics in the Bandung Basin.

Natural consolidation of alluvium soil can also contribute to land subsidence phenomena in certain location in Bandung basin. Information in Figures 3 and 13 shows that several areas with relatively large observed subsidence occurred inside the Kosambi formation in the middle of the basin which mainly composed by relatively young and soft lake sediments, consisting of clay, silt and loose sand [*Dam et al.*, 1996; *Hutasoit*, 2009].

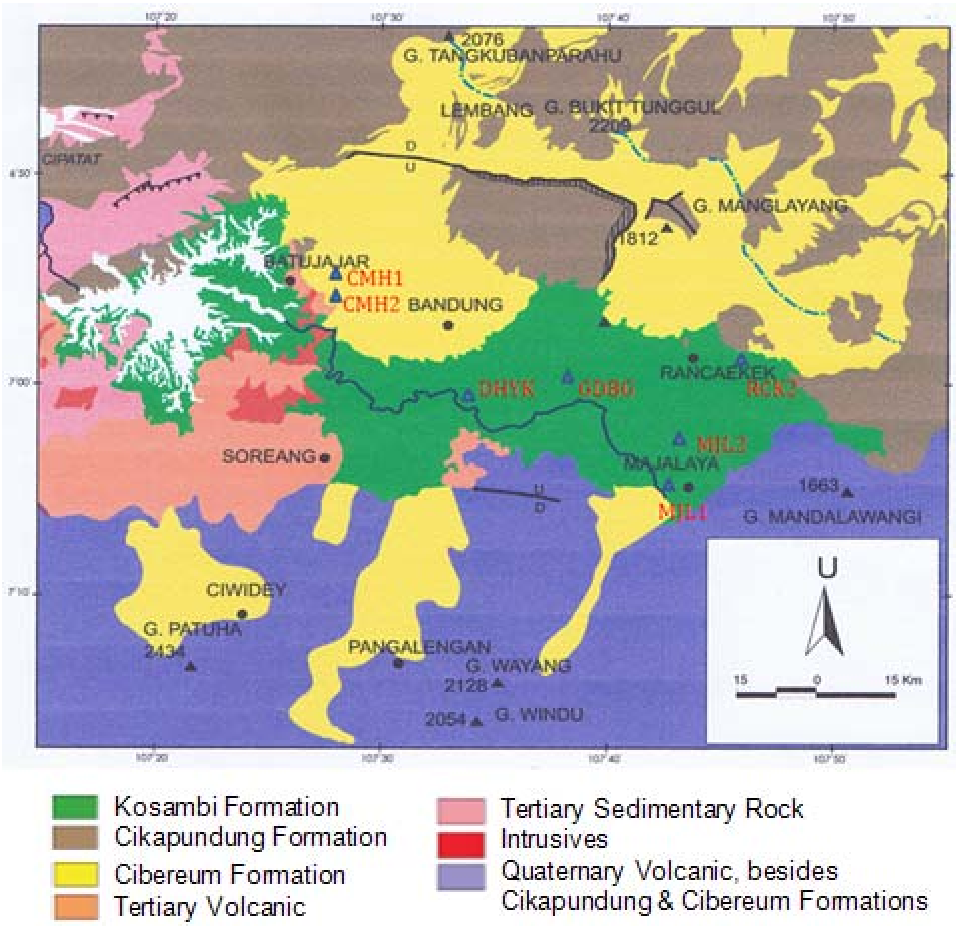

Figure 13. Geological formations in Bandung basin region, adapted from [*Hutasoit*, 2009]. Locations of several GPS stations are plotted and labelled with red color font.

Observed subsidence in some GPS stations located in this geological formation of Kosambi, such as DYHK (Dayeuh Kolot), GDBG (Gedebage), MJL2 (Majalaya), and RCK2 (Rancaekek), may partly came from natural consolidation phenomena besides also caused by excessive groundwater extraction. Figure 14 shows location of GDBG GPS station in Gedebage area. Gedebage is located around the centre of the Kosambi formation (previously covered by old Bandung lake) and probably has the thickest layer of lake sediment. A few textile industries are also operating in this area. Therefore, the observed subsidence in GDBG

GPS station should be at least the combination of natural consolidation of lake sediment and excessive groundwater extraction, with percentages of their contributions are still unknown.

Tectonic activities may also has contribution to observed land subsidence in Bandung basin. The most well known active tectonic around Bandung basin is Lembang fault [*Dam et al.,* 1996]. Lembang fault is topographically and geologically remarkable and runs about 10 km north of Bandung in the EW direction with a total length of around 22 km. Topographically, this fault is a straight scarp facing north with moderately steep slope, with its slopes generally about 50° or steeper, except in the area where young tuff deposits or talus cover the foot slope [*Delinom,* 2009].

Figure 14. Location of GPS station GDBG.

According to *Soehaimi et al*. (2008), there other four possible faults in and around Bandung basin, namely Tanjungsari-Cileunyi fault, Cicalengka fault, Jati fault and Legok Kole fault. No study has been done yet to investigate the contribution of these fault activities on the observed land subsidence phenomena in Bandung basin.

5. CLOSING REMARKS

Land subsidence in the Bandung basin can be caused by excessive groundwater extraction, load of manmade constructions (i.e. settlement of highly compressible soil), natural consolidation of alluvium soil, and tectonic activities. However, the elaborate characteristics and mechanisms of land subsidence in Bandung are still partly known. 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 and InSAR derived results should also be integrated with results obtained by other monitoring techniques such as absolute gravity, leveling and automatic water level recorders.

Land subsidence in Bandung has a strong linkage with 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 exponentially increase urban development introduce several environmental problems, such as (1) extensive conversion of prime agricultural areas into residential and industrial areas, (2) significant disturbance to main ecological function of the surrounding upland areas of Bandung basin as a water recharge area for Bandung city, (3) increase in groundwater extraction due to development of industrial activities and the high population increase. These negative impacts will contribute to the groundwater level lowering inside Bandung basin and in turn can introduce the occurence of land subsidence phenomena in several places in 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. The elaborate and systematic study is therefore needed to estimate these direct and indirect losses due to land subsidence phenomena in Bandung basin.

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BIOGRAPHICAL NOTES

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