Land Subsidence Characteristics of Bandung Basin (Indonesia) between 2000 and 2005 as Estimated from GPS Surveys

Hasanuddin Z. ABIDIN, Heri ANDREAS and M. GAMAL and D. DARMAWAN, Indonesia

SUMMARY

Bandung basin is a large intra-montane basin surrounded by volcanic highlands, inhabited by more than five million people. Based on five GPS (Global Positioning System) surveys conducted on February 2000, November 2002, July 2002 and June 2003, and June 2005, it can be concluded that in the period of 2000 to 2005 several locations in Bandung basin have experienced land subsidence. In this period of about 5 years, land subsidence in a few locations can reach the amount of about 70 cm, with the speed of about 1-2 cm/month.

This paper describes the technical and practical aspects of GPS surveys for land subsidence study in Bandung basin along with the obtained results. The environmental impacts of subsidence on the increase coverage of flood inundation and destruction of utilities and infrastructure will also be discussed. The effects of land use and population changes and groundwater extraction on landslide characteristics are also investigated. Paper will sum up with some conclusions and recommendations.

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1. INTRODUCTION

Bandung is the capital of West Java province, Indonesia (see Figure 1). The city is surrounded by several medium sized towns and all together formed the Greater Bandung; a highland plateau lies in the catchment's area of the upper Citarum river. It is surrounded by range of hills and volcanoes, some of which are still active, and formed the intra-montane basin called as Bandung basin.

It has an area of about 2300 km^2 and encompasses three administrative units, e.g. Bandung municipality, the surrounding Bandung regency and part of Sumedang regency. The central part of the basin, where most of which occupied by urban and industrial areas, is a plain measuring about 40 km East-West and about 30 km North-South, with an altitude of about 650 m to 700 m. In 1995, Bandung municipality has a population about of 2.5 million, and Bandung basin has more than 5 million inhabitants.

Figure 1. Location of Bandung, Indonesia.

There are several types of land subsidence that can be expected to occur in the Bandung basin, namely: subsidence due to groundwater abstraction, subsidence induced by the load of constructions (i.e. settlement of high compressibility soil), subsidence caused by natural consolidation of alluvium soil, and geotectonic subsidence. The detail characteristics and mechanisms of land subsidence are still relatively unknown.

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Since data and information on land subsidence characteristics will be useful for many development and environmental aspects (see Figure 2), systematic and continuous monitoring of land subsidence in Bandung is obviously needed and critical to the welfare of the city. The comprehensive information on the land subsidence characteristics would be important for several tasks, such as spatial-based groundwater abstraction regulation, effective control of flood,
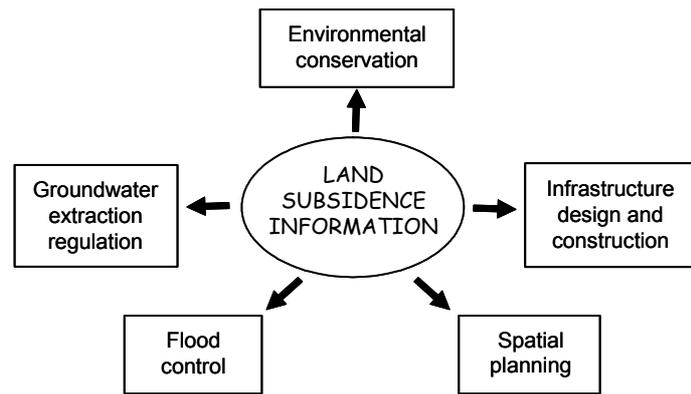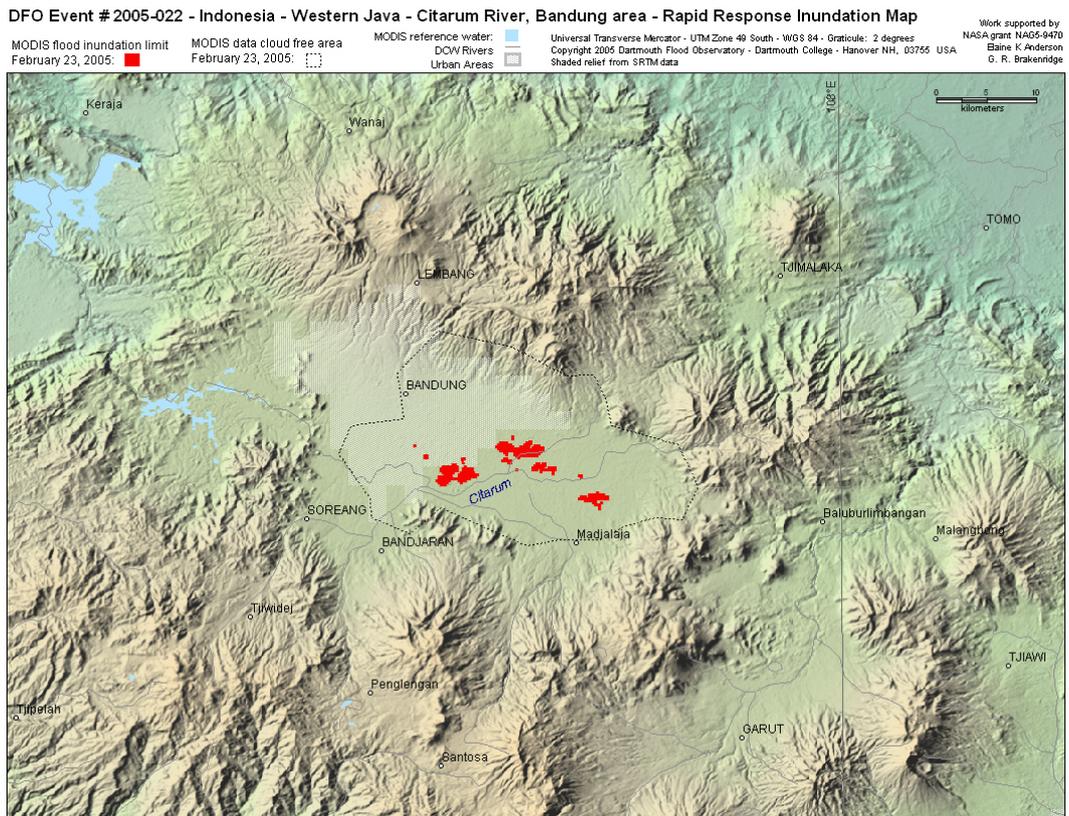

Figure 2. Benefit of land subsidence information

conservation of environment, design and construction of infrastructures, and spatial development planning in general.

In principle, land subsidence phenomenon can be studied using several methods, such as hydrogeology methods, e.g. ground water level observation, extensometer measurement and piezometer measurement; and geodetic methods e.g. leveling surveys, GPS survey and INSAR (Interferometric Synthetic Aperture Radar). In this paper only the use of GPS survey technique for studying land subsidence in Bandung that will be discussed. The discussion will be based on the results obtained from four GPS surveys that have been conducted on February 2000, November 2001, July 2002, June 2003 and June 2005, respectively.

2. BANDUNG BASIN AND ITS HYDROGEOLOGIC FEATURES

Bandung basin is a large intra-montane basin surrounded by volcanic highlands, as shown in Figure 3.. The central part on basin has an altitude of about 665 m and surrounded by up to 2400 m Late Tertiary and Quaternary volcanic terrain [*Dam et al.,* 1996]. The catchment's area of basin and surrounding mountains covers 2300 km^2, and the Citarum River with its tributaries forms the main drainage system of the basin catchment. Deposits in the basin comprise of coarse volcaniclastics, fluvial sediments and notably a thick series of lacustrine deposits. A more detail explanation on geologic and morphologic setting of Bandung basin can be seen in [*Dam et al.,* 1996].

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Figure 3. Bandung basin and its surrounding.

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Bandung basin encompasses three administrative units, e.g. Bandung municipality, an urban area 81 km^2 in size perched against the Northern mountain range, the surrounding Bandung regency, plus part of Sumedang regency [*Braadbaart and Braadbaart,* 1997]. Population of Bandung municipality increased from less than 40,000 in 1906 to nearly one million in 1961 and had expanded to two and half million in 1995. In addition, with expansion of manufacturing and textile industries in Bandung basin, urbanization was increased and in 1995 more than 5 million peoples inhabited the basin. This increases in population and industrial activities in turn increase the groundwater withdrawal from the aquifers in Bandung basin, as illustrated in Figure 4.
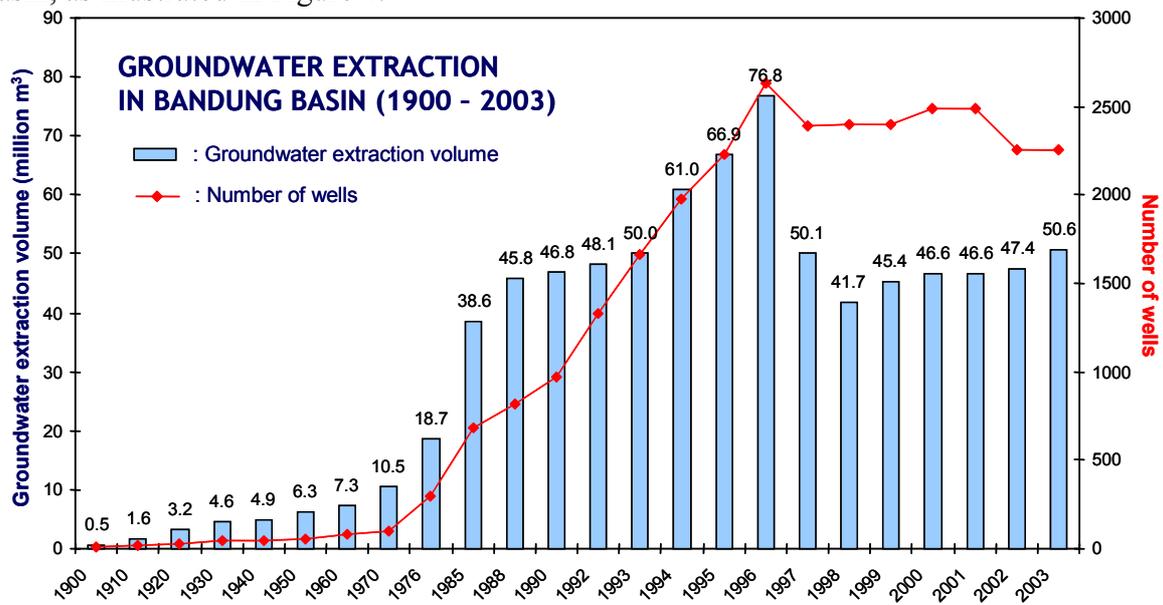

Figure 4. Registered Groundwater Extraction in Greater Bandung (1900 - 2003), adapted from [*Ruchijat,* 2006].

On the basis of its hydraulic characteristic and its depth, the multi layer aquifers 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 m to 250 m below 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.

Increased groundwater abstraction led to a rapid sinking of water tables on the plain and in turn can cause land subsidence, as shown in Table1. During the 1980s, the average annual drop in water tables in the basin was one meter, and in the most heavily abstracted areas annual drops of up to 2.5 meters were recorded [*Sutrisno,* 1991]. From 1980 to 2004, e.g. in about 24 years, the groundwater level in Bandung basin drop

Table 1. Groundwater level decreases in several location in Bandung basin [*Wirakusumah,* 2006].

No.	Location	1980	2004
1.	Cimahi	+ 15 m	- 86 m
2.	Kebon Kawung	+ 22 m	- 36 m
3.	Rancaekek	+ 1 m	- 39 m
4.	Lanud Sulaeman	+ 7 m	- 14 m
5.	Dayeuh Kolot	+ 2 m	- 55 m
6.	Banjaran	+ 2 m	- 20 m
7.	Majalaya	+ 3 m	- 41m

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in about 20 to 100 m as shown in Table 1. This groundwater level decreases have both spatial and temporal variations. Increased groundwater abstraction will also decrease the well productivity and also led to drastic changes in the time and direction of travel of water underground [*Braadbaart and Braadbaart,* 1997].

3. GPS SURVEYS IN BANDUNG BASIN

GPS (Global Positioning System) is a passive, all-weather satellite-based navigation and positioning system, which is designed to provide precise three dimensional position and velocity, as well as time information on a continuous worldwide basis [*Wells et al., 1986*; *Hofmann-Wellenhof, et al.,* 1997; *Abidin,* 2000]. For monitoring land subsidence, in order to monitor the subsidence of even very small magnitude, the ideal positioning accuracy to be achieved is in mm level. In order to achieve that level of accuracy then the GPS static survey method based on phase data should be implemented with stringent measurement and data processing strategies [*Leick,* 1995; *Abidin et al.,* 2002]. Considering the obtainable GPS accuracy and precision which becomes higher and higher, it could be expected that the roles of GPS for monitoring land subsidence would become more and more important in the near future.

The principle of land subsidence monitoring using repeated GPS surveys method is depicted in Figure 5. With this method, several monuments which are placed on the ground covering the area and its surrounding, are accurately positioned using GPS survey relative to a certain reference (stable) point. The precise coordinates of the monuments are periodically determined using repeated GPS surveys with certain time interval. By studying the characteristics and rate of changes of the height component of coordinates from survey to survey, the land subsidence characteristics can be derived.
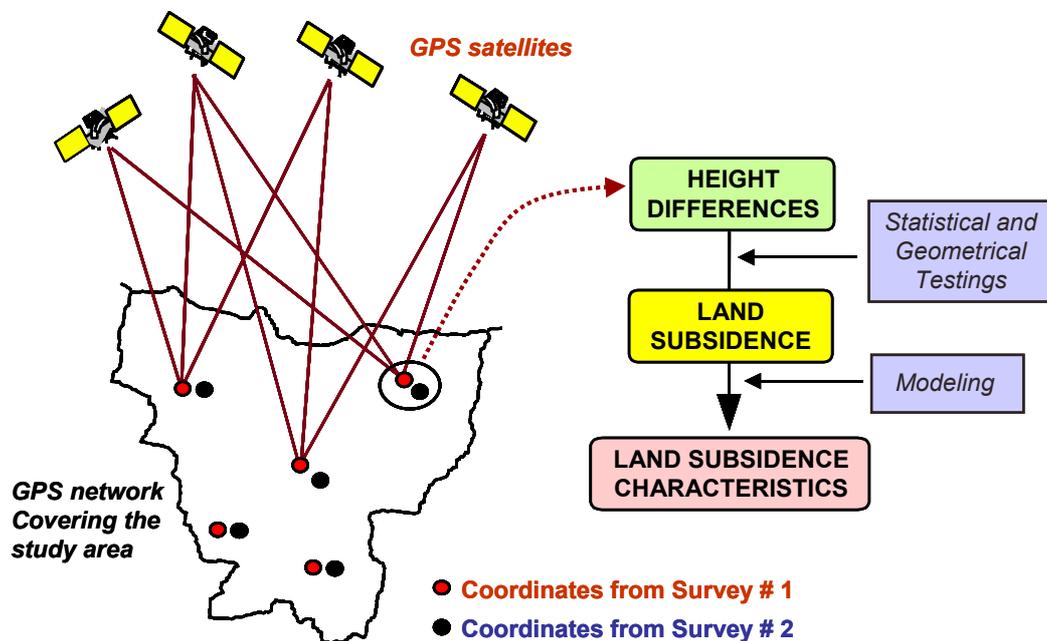

Figure 5. Principle of land subsidence monitoring using repeated GPS survey method.

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In order to study land subsidence phenomena in Bandung basin, five GPS surveys have been conducted, namely on Feb. 2000, Nov. 2001, July 2002, June 2003 and June 2005, as shown in Table 2.

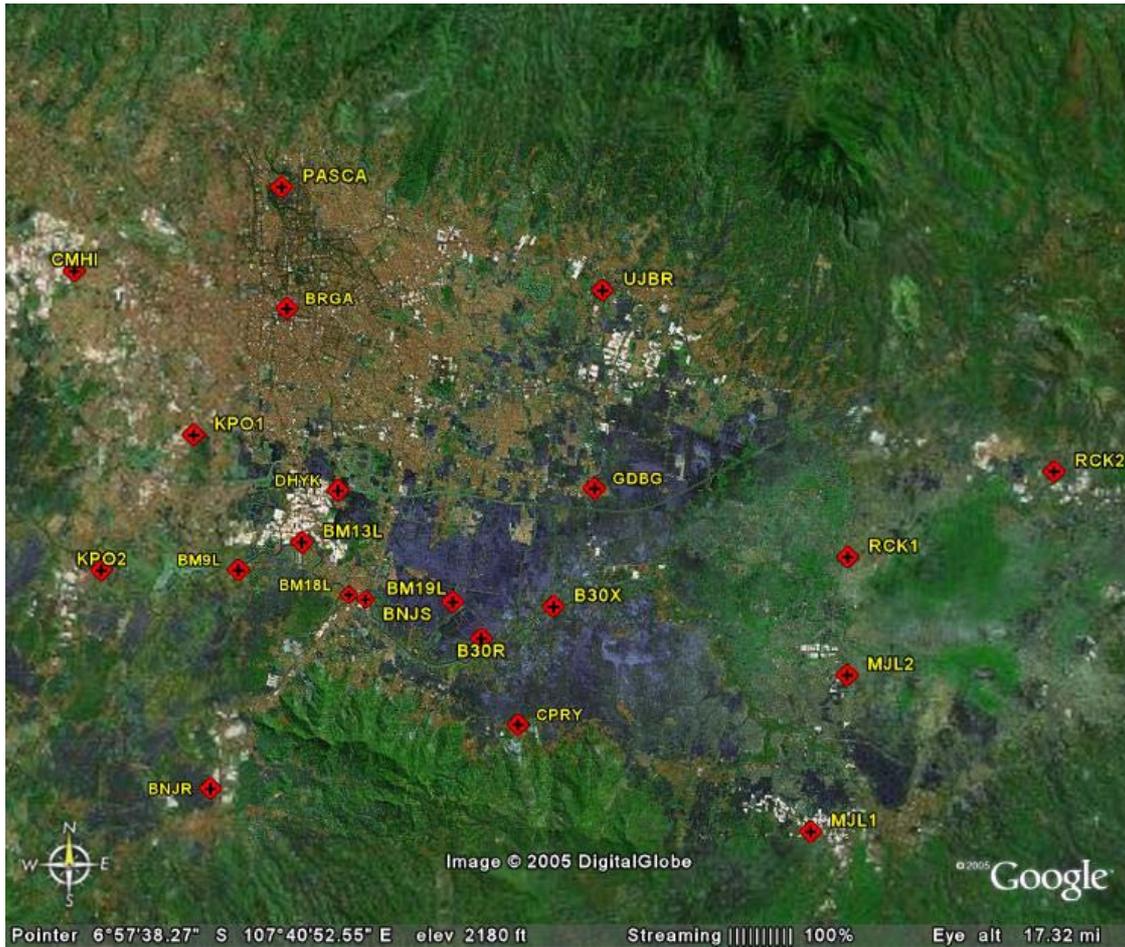**Table 2.** GPS Surveys for land subsidence monitoring in Bandung.

GPS Surveys	Survey Period	Observation Points
Survey-1	21-24 Feb. 2000	PSCA,BNJR,BJNS,CMHI,DYHK,MJL1, RCK1,RCK2,UJBR
Survey-2	21-30 Nov. 2001	PSCA,BRGA,BNJR,BJNS,CMHI,CPRY,DYHK,GDBG, KPO1,KPO2,MJL1,MJL2,RCK1,RCK2,UJBR
Survey-3	11-14 July 2002	PSCA,BRGA,BNJR,BJNS,CMHI,CPRY,DYHK,GDBG, KPO1,KPO2,MJL1,MJL2,RCK1,RCK2,UJBR,BM9L, BM13L,BM18L,BM19L,BM30X,BM30L
Survey-4	1-3 June 2003	Same as on Survey-3, except BRGA (monument was damage)
Survey-5	24-27 June 2005	Same as on Survey-4, except BM9L, BM19L & BM30X (monuments were missing or destroyed)

The GPS surveys at all stations were all carried out using dual-frequency geodetic-type GPS receivers. In this case PSCA station located inside ITB campus is used as the reference (stable) point with known coordinates. For GPS surveys, the length of sessions was between 10 to 12 hours, respectively. The data were collected with a 30 seconds interval, and elevation mask was set at 15° from all stations. The surveys were carried out by the Department of Geodetic Engineering, Institute of Technology Bandung in cooperation with the Directorate of Volcanology and Geological Hazard Mitigation, Ministry of Energy and Mineral Resources. Configuration of the GPS monitoring network is shown in Figure 6.
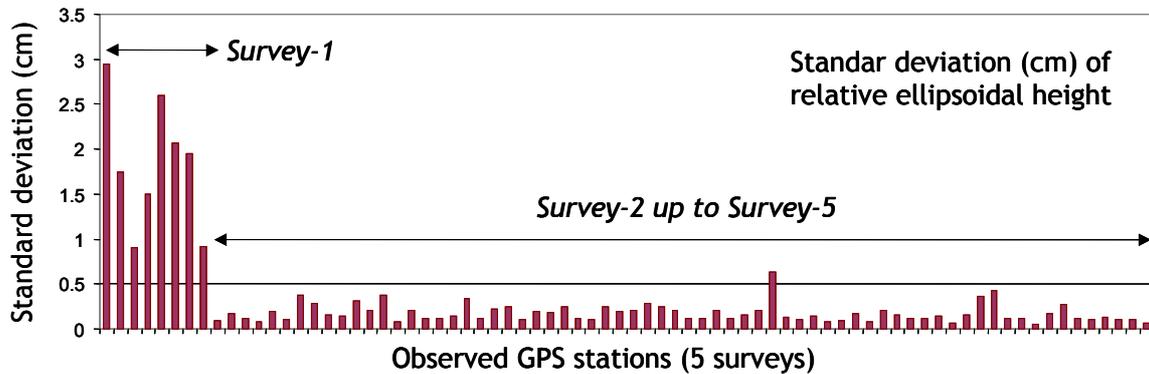
4. GPS SURVEY DATA PROCESSING AND RESULTS

GPS data processing is done using SKIPro commercial software. Processing is done in radial mode from PSCA station. PSCA station is assumed to be stable for the subsidence study, and its coordinates are computed from an Indonesia IGS station located in BAKOSURTANAL area, Cibinong, Bogor. For all computations, precise ephemeris and Saastamoinen tropospheric model are used. The final coordinates are estimated signals using the ionospheric free linear combination signal after fixing the integer ambiguities of L1 and L2 signals.

For land subsidence monitoring only the ellipsoidal height components are used. Standard deviations of GPS derived relative ellipsoidal heights from four surveys that have been conducted in Bandung basin can be depicted in Figure 7. This figure shows that in the first survey the obtained precision level of relative ellipsoidal height is in the level of 1-3 cm, while for the next surveys is in several mm level. The first survey results are slightly worse than the next surveys, due to the lack of observed data caused by shorter session length of the first survey. These results also indicate that GPS data processing has properly done.

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Figure 6. Distribution of GPS points for studying land subsidence in Bandung basin.

Figure 7. Standard deviations of the estimated coordinates of GPS stations from 4 surveys.

5. ESTIMATED LAND SUBSIDENCE RESULTS

Based on the estimated ellipsoidal heights from GPS processing process, the height differences between two consecutive survey epochs can be calculated. The height differences based on five GPS surveys are given in Table 3, along with their standard deviations. In this Table 3, possible subsidence is indicated by negative values of height differences.

Table 3. Ellipsoidal height differences from four GPS surveys.

No.	Station	dh12	σdh12	dh23	σdh23	dh34	σdh34	dh45	σdh45
1.	BNJR	-15.2	2.9	-2.7	0.2	-2.9	0.2	-14.2	0.1
2.	BJNS	-16.1	1.7	-3.0	0.2	-2.6	0.2	-	-
3.	CMHI	-39.9	0.9	-12.5	0.2	-13.7	0.3	-9.0	0.4
4.	DYHK	-32.9	1.5	-12.9	0.2	-3.6	0.2	-16.8	0.2
5.	MJL1	-14.1	2.6	-1.8	0.2	-7.2	0.2	5.9*	0.2
6.	RCK1	-21.1	2.1	-3.8	0.3	13.1*	0.3	-6.6	0.1
7.	RCK2	-31.5	2.0	-10.5	0.4	-0.7	0.2	-14.3	0.1
8.	UJBR	-5.4	1.0	-1.2	0.1	-5.3	0.2	14.3*	0.2
9.	BRGA	-	-	-8.4	0.2	-	-	-	-
10.	CPRY	-	-	-2.1	0.4	9.1*	0.3	3.1*	0.4
11.	GDBG	-	-	-0.8	0.4	-14.7	0.3	-8.2	16.3
12.	KPO1	-	-	0.2*	0.4	-6.1	0.7	-2.7	0.6
13.	KPO2	-	-	-0.1	0.2	-5.3	0.2	-10.5	0.1
14.	MJL2	-	-	3.1*	0.4	-3.0	0.2	-7.6	0.3
15.	BM9L	-	-	-	-	-16.7	0.3	-	-
16.	BM13L	-	-	-	-	-5.0	0.3	-21.2	0.2
17.	BM18L	-	-	-	-	-13.9	0.3	-20.7	0.2
18.	BM19L	-	-	-	-	-4.9	0.3	-	-
19.	BM30X	-	-	-	-	19.8*	0.3	-	-
20.	BM30L	-	-	-	-	-8.9	0.3	3.5	0.2
					* *uplift and not subsidence*				

In order to statistically check the significance of the subsidence values measured by GPS surveys, the congruency test [*Caspary*, 1987] was performed. The null hypothesis of the test is that the relative ellipsoid heights of two consecutive epochs (e.g. i and j) are stable, i.e. there is no subsidence. Therefore :

null hypothesis	H_o :	$dh_{ij} = 0$,	(1)
alternative hypothesis	H_a :	$dh_{ij} \neq 0$.	(2)

The test statistics for this test is :
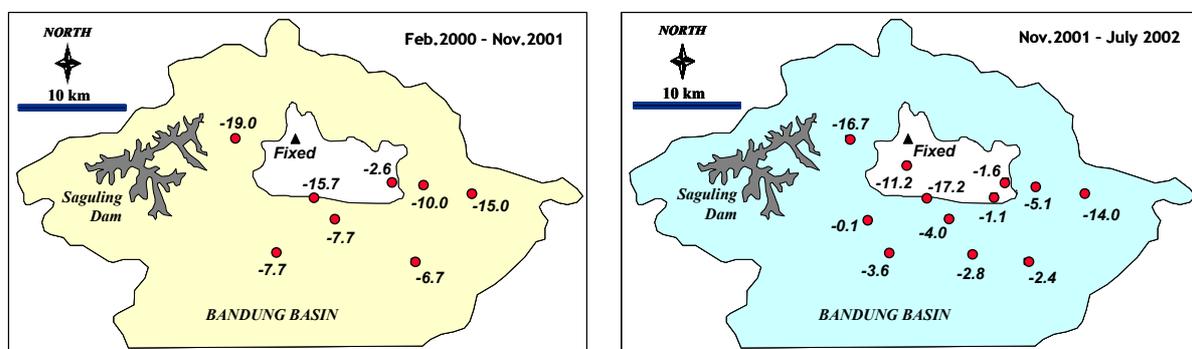
$$T = dh_{ij} / (\sigma \text{ of } dh_{ij}) , \qquad (3)$$
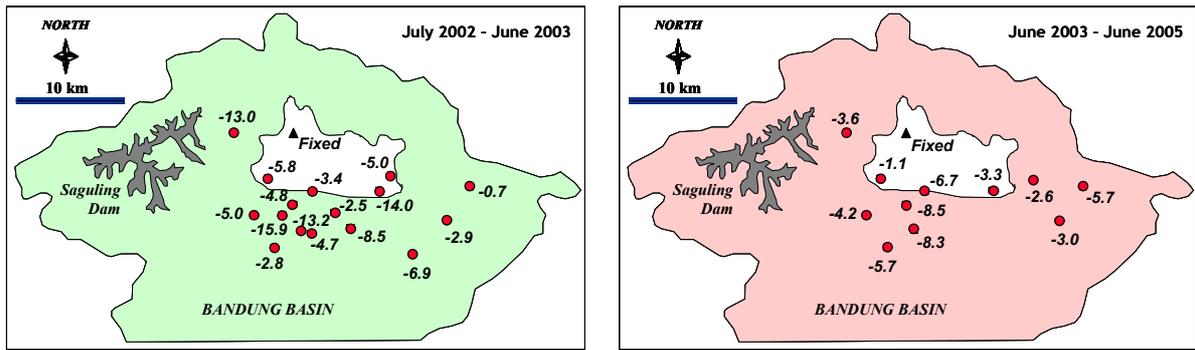
which has a Student's t-distribution if H_o is true. The region where the null hypothesis is rejected is [*Wolf and Gilani*, 1997] :

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$$| \text{T} | > t_{df,\alpha/2} \, , \tag{4}$$

where df is the degrees of freedom and α is the significance level used for the test. In our case, for GPS baselines derived using 10 to 12 hours of GPS data with 30 seconds data interval, then df $\rightarrow \infty$. Please note that a t-distribution with infinite degree of freedom is identical to a normal distribution. If a confidence level of 99% (i.e. α=1%) is used, then the critical value t $_{\infty,0.005}$ ∞ is equal to 2.576 [*Wolf and Gilani*, 1997]. If the values are adopted for the congruency test, then the testing results show that significant subsidence is found in all the stations in all four observed periods, except for stations GDBG and KPO2 in the second observed period (e.g. November 2001 – July 2002), and GDBG in the fourth period. The statistical test only applied to the negative values of height differences. Therefore in the last period, stations MJL1, UJBR and CPRY are not tested.

Based on the testing results, it could be statistically concluded that with 99% confidence level there were subsidence observed by GPS surveys at most of the stations during the four observed periods. Land subsidence in Bandung has both temporal and spatial variations as indicated by Figure 8. In general rates of subsidence about 2-20 mm/month, or 2-24 cm/year. Several stations, e.g. CMHI, DYHK, RCK2, GDBG, BM9L and BM18L, have relatively higher subsidence rates compared to other, namely around 1-2 cm/month or 12-24 cm/year. Stations CMHI, DYHK, RCK2 and GDBG are located in the textile industry areas, where excessive ground water abstraction are expected to occur; while BM9L and BM18L stations are located in the bank of Citarum river. The results in Figure 8 also show that subsidence rates are not always linear. Several stations show a slowing down of subsidence, while the others are not. These results somehow indicate that the mechanism of land subsidence in Bandung basin is not simple and maybe caused by several factors.
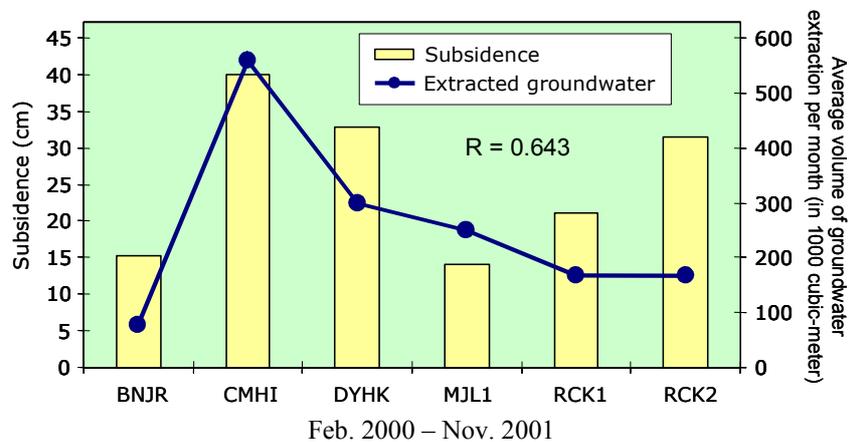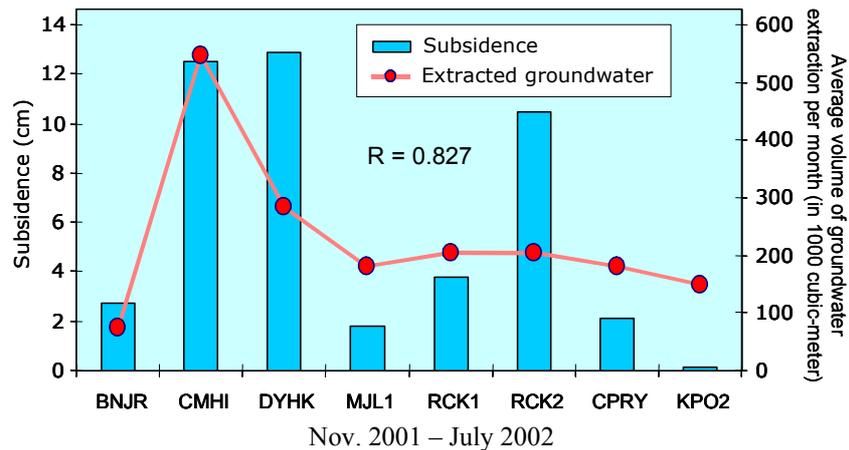
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Figure 8. Temporal and spatial variation of subsidence rates (mm/month) in Bandung basin.

6. LAND SUBSIDENCE AND GROUNDWATER ABSTRACTION

A hypothesis has been proposed that land subsidence observed in several locations in Bandung basin is caused by an excessive groundwater abstraction. The two primary categories of groundwater with-drawers 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].

The above hypothesis is however not always true, as shown in the example shown in Figure 9. This Figure shows the correlation between the observed land subsidence on several GPS points and the registered groundwater abstraction around the corresponding GPS points (e.g. inside 1 km radius). During the two observed periods, only CMHI station shows a good correlation while for the other stations the correlations are not so good.

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Figure 9. Correlation between land subsidence and groundwater abstraction volume
(R is Spearman's rank correlation coefficient).

In order to have more insight into a correlation between those land subsidence and groundwater abstraction variables, their Spearman's rank correlation coefficients (R) are computed for the two observed period using the following relation [*Mulholland and Jones*, 1981] :

$$R = 1 - \frac{6 \sum d^2}{n(n^2 - 1)} \,, \tag{5}$$

where d is the difference between the ranks of both variables and n is the number of pairs being correlated. The computed rank coefficient correlations for the (Feb. 2000 – Nov.2001) and (Nov. 2001 – July 2002) periods are 0.643 and 0.827, respectively.

In order to statistically check the significance of correlation between land subsidence and ground water abstraction, a statistical testing is performed by using a computed rank coefficient R as the test statistic. The hypotheses used for the testing are:

H_0 : there is no correlation between the ranked pairs, and
H_a : ranked pairs are correlated.

The rejection region for null hypothesis is [*Dang and Bui*, 1997] :

$$R \geq R_0(n,\alpha), \tag{6}$$

where α is a significance level used for the testing. The values of $R_0(n,\alpha)$ for $4 < n < 31$ and $\alpha = (0.05, 0.25, 0.01$ and $0.005)$ can be seen in *Dang and Bui* (1997). The results of statistical testing with 99% confidence level being used (i.e. $\alpha = 0.01$) are shown in Table 4.

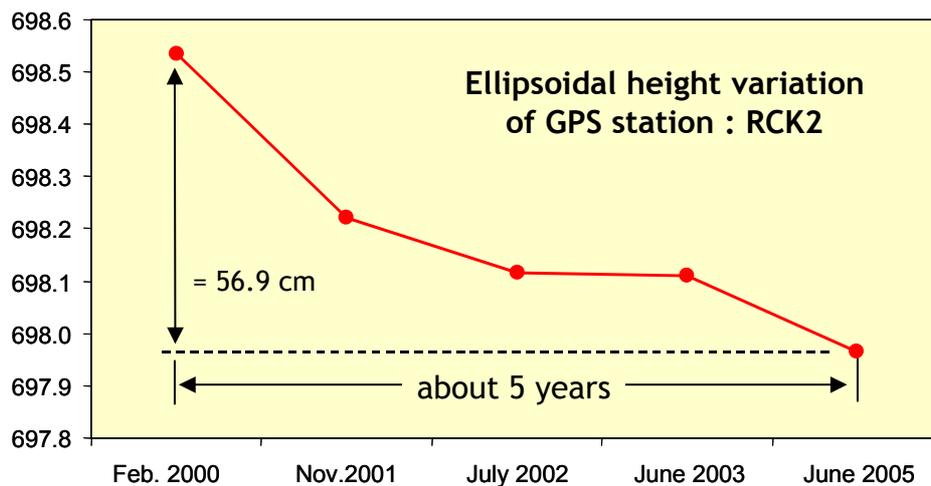**Table 4.** Results of the Spearman's non-parametric test for rank correlation.

Period	R	n	α	$R_0(n,\alpha)$	H_0 is rejected ?
Feb.2000 – Nov.2001	0.643	6	0.01	0.943	no
Nov.2001 – July 2002	0.827	8	0.01	0.833	no

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Based on the above testing results, it could be statistically concluded that with 99% confidence level there were no significant correlation between the GPS observed land subsidence and the registered groundwater abstraction during the period of February 2000 to July 2002

This fact could imply two things; firstly the registered groundwater abstraction volume does not reflect the real groundwater abstraction, and secondly the land subsidence is also governed by other factors, such as the different geological structures and soil compressibility of the corresponding observed locations. In the case of Bandung basin, these two reasons maybe valid.

Excessive groundwater extraction will generally lower the groundwater level in the correponding area. Therefore it can be expected that subsidence of certain area will have a positive correlation with the lowering of groundwater level. Examples given in Figures 10 and 11 show that this correlation is exist in Rancaekek area.
However, further research is needed to clarify the real correlation pattern between land subsidence, ground water abstraction volume and groundwater level in Bandung basin. More geodetic and hydrogeological data and information are still needed in order to gain more insights into subsidence characteristics in Bandung basin.

Figure 10. Subsidence of RCK2 satation located in Rancaekek area.
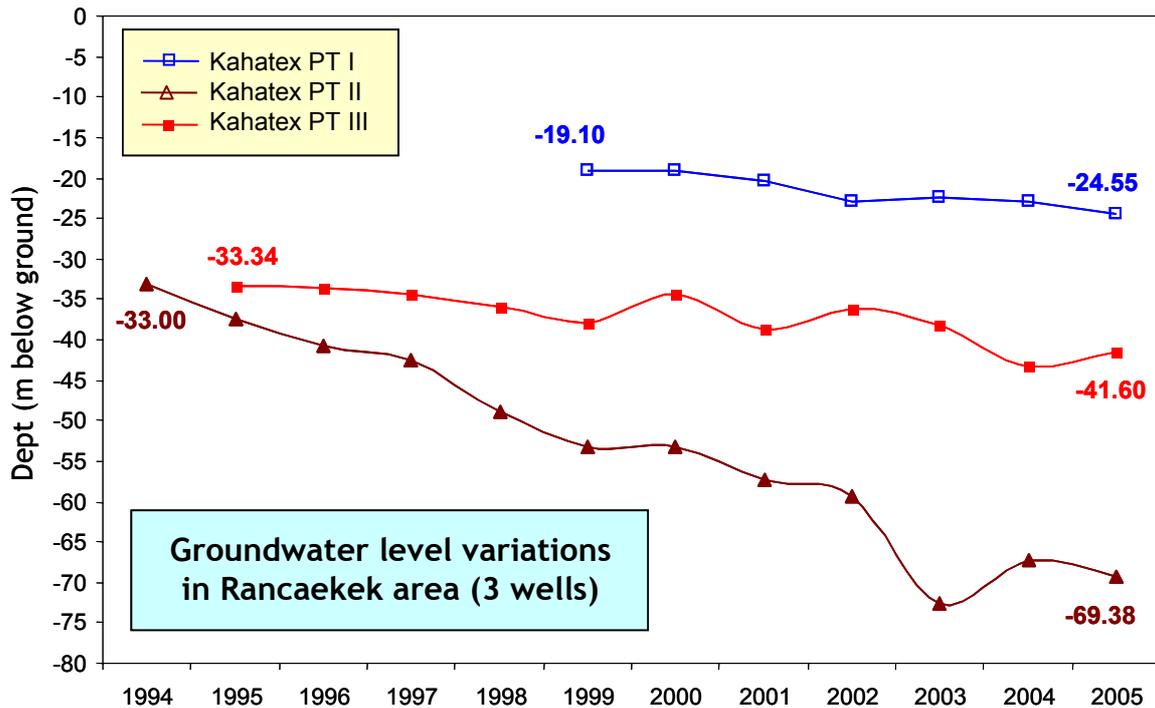
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Figure 11. Indication og groundwater level decreases in Rancaekek area, adapted from *Wirakusumah* (2006).

7. CLOSING REMARKS

Based on the results obtained from land subsidence monitoring in Bandung basin, it can be concluded that GPS survey method is a reliable method for studying and monitoring land subsidence phenomenon. The method is capable of detecting the land subsidence signal that has a relatively small magnitude in the order of a few cm, or even several mm; although achieving this level of accuracy is not an easy task to do. In this case the use of dual frequency geodetic type receivers is compulsory along with good survey planning, stringent observation strategy, and stringent data processing strategy using the scientific software. Considering its relatively high accuracy, all-times weather-independent operational capability, wide spatial coverage, and its user friendliness, the use of repeated GPS surveys for land subsidence monitoring can be expected to gain more popularity in the near future.

In the cases of land subsidence in Bandung basin, excessive groundwater abstraction is hypothesized to be the main cause of land subsidence. The comparison between GPS derived subsidence and the registered groundwater abstraction volume conducted in this study, in the period of February 2000 to July 2002, however show that this hypothesis is not always true for every observed location. This can be caused by the large volume of unregistered groundwater abstraction and also by the facts that land subsidence is may also caused by other factors, such as construction load, natural consolidation and geotectonic phenomena. Therefore, further research is needed to clarify the real mechanism and pattern of land subsidence phenomena in Bandung basin. In this regard, besides carefully considering the

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above factors, the GPS derived results should also be integrated with the results obtained by other monitoring techniques such as leveling, INSAR (Interferometric Synthetic Aperture Radar) [*Massonnet and Feigl*, 1998] and automatic water level recorder.

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