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Land subsidence characteristics of Jakarta between 1997 and 2005, as estimated using GPS surveys

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Abstract Jakarta is the capital city of Indonesia with a population of about 12 million people, inhabiting an area of about 625 km^2. It is well known that several areas in Jakarta are subsiding rapidly. There are four different types of land subsidence that can be expected to occur in the Jakarta basin, namely: subsidence due to groundwater extraction, subsidence induced by the load of constructions (i.e., settlement of high compressibility soil), subsidence caused by natural consolidation of alluvial soil and tectonic subsidence. In addition to the leveling method, Global Positioning System (GPS) survey methods have been used to study land subsidence in Jakarta. In this paper, we characterize subsidence in the Jakarta basin using eight episodic/campaign GPS surveys between 1997 and 2005. The estimated subsidence rates are 1–10 cm/year. The observed subsidence rates in several locations show a positive correlation with known abstraction volumes of groundwater extraction. These basin-wide series of GPS measurements show how this type of measurement can play an important role in multiple public policy decision making in this rapidly growing area.

Keywords Jakarta · Land subsidence · GPS · Groundwater

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Introduction

Jakarta's population is about 10 million people, covering an area of about 650 km^2. Jakarta is centered at about 6°15′S and +106°50′E and located on the lowland of the northern coast of the West Java province, as shown in Fig. 1. The area is relatively flat, with topographical slopes ranging between 0° and 2° in the northern and central parts, and between 0° and 5° in the southern part. The southernmost area of Jakarta has an altitude of about 50 m above mean sea level.

Jakarta is a lowland area with five main landforms (Rimbama and Suparan 1999): (1) alluvial landforms (southern part). (2) Landforms of marine-origin (northern part adjacent to the coastline). (3) Beach ridge landforms (northwest and northeast parts). (4) Swamp and mangrove swamp landforms (coastal fringe). (5) Former channels (perpendicular to the coastline). There are about 13 natural and artificial rivers flowing through Jakarta, of which the main rivers, such as Ciliwung, Sunter, Pesanggrahan, Grogol and their tributaries, form the main drainage system of Jakarta.

Land subsidence is not a new phenomenon for Jakarta. The occurrence of land subsidence was recognized in 1926. Evidence for subsidence was based on repeated leveling measurements conducted in the northern part of Jakarta (Schepers 1926; Suharto 1971). Unfortunately, the investigation of land subsidence using leveling was not repeated for 50 years until 1978. Starting in 1978, the impact of land subsidence in Jakarta could be seen in several ways, such as the cracking of permanent constructions located around the center of the Jakarta area (along Thamrin Street), the wider expansion of flooding areas, the lowering of the groundwater level and increased inland seawater intrusion. According to the Local Mines Agency, over the period of

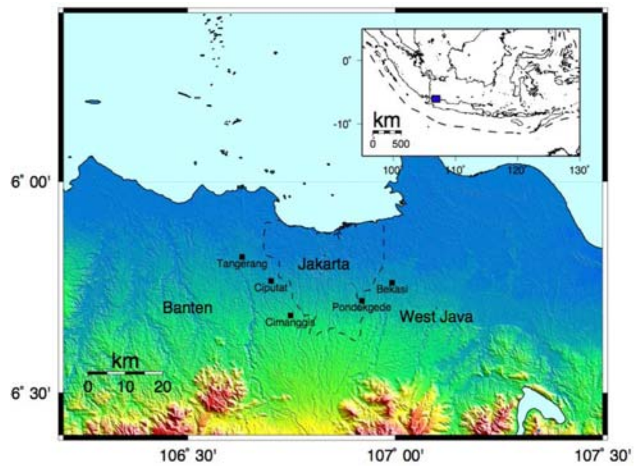

Fig. 1 Jakarta basin

1982–1997, subsidence ranging from 20 to 200 cm is evident in several places in Jakarta. It has been reported for many years that several places are subsiding at different rates (Murdohardono and Tirtomihardjo 1993; Murdohardono and Sudarsono 1998; Rajiyowiryono 1999; Abidin et al. 2001). Considering this significant amount of subsidence and its wide impact on many developmental and environmental aspects, a systematic and continuous monitoring of land subsidence in Jakarta is obviously needed and is critical to the welfare of the city.

In the case of Jakarta, the comprehensive information on the characteristics of land subsidence is important for several tasks (see Fig. 2), such as spatial-based groundwater extraction regulation, effective control of flood and seawater intrusion, conservation of environment, design and construction of infrastructures and spatial development planning.

According to Murdohardono and Sudarsono (1998) and Rismianto and Mak (1993), there are four different types of land subsidence that can be expected to occur in the Jakarta basin, namely, subsidence due to groundwater extraction, subsidence induced by the load of constructions (i.e., settlement of high compressibility soil), subsidence caused by

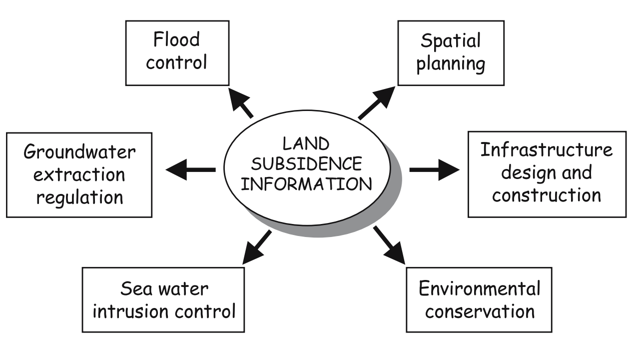

Fig. 2 The importance of land subsidence information

natural consolidation of alluvial soil and geotectonic subsidence. From those types of subsidence, the main spectrum of land subsidence in Jakarta is thought to be caused by groundwater extraction. Excessive groundwater extraction will lead to the deepening of groundwater level (piezometric head), which in turn will cause land subsidence and also seawater intrusion (Soekardi et al. 1986).

Since the early 1980s, land subsidence in several places of Jakarta has been measured using several measurement techniques, e.g., leveling surveys, extensometer measurements, groundwater level observations and Global Positioning System (GPS) surveys (Abidin et al. 2004). The prediction of ground subsidence, based on certain models incorporating geological and hydrological parameters of Jakarta, has also been investigated (Murdohardono and Tirtomihardjo 1993; Yong et al. 1995; Purnomo et al. 1999).

This paper describes the characteristics of land subsidence in Jakarta basin during the period of 1997–2005, as observed by GPS surveys.

GPS surveys for land subsidence study in Jakarta

The use of GPS satellite-based positioning system to systematically establish geodetic control points over the Jakarta area was first conducted in 1994 by the National Land Agency (BPN). This GPS network is aimed at supporting cadastral mapping, and its design was not intended to monitor land subsidence.

Considering the higher cost saving and speed of simultaneous data collection of GPS surveys compared to leveling, the Department of Geodetic Engineering, Institute of Technology Bandung (ITB) decided to establish the new GPS network for monitoring land subsidence in the Jakarta basin, with some stations occupying points of the existing BPN network. The configuration of this GPS monitoring network is shown in Fig. 3. Most of the stations (see Table 1) have reinforced concrete monuments with depths of about 1–2 m below the ground surface and were established between 1993 and 1995.

Station BAKO is the southernmost point in the network and is also the Indonesian zero order geodetic point. It is used as the reference point. BAKO is an IGS [International Global Navigation Satellite Systems (GNSS) Service] station, operated by the National Coordinating Agency for Survey and Mapping (BAKOSURTANAL). Based on IGS daily solutions of BAKO data from 2000 to 2006, as computed by the Jet Propulsion Laboratory (JPL 2007), the global velocities of BAKO during that period are −7.63 ± 0.04 mm/year in latitude, 25.38 ± 0.13 mm/year in longitude and 2.13 ± 0.23 mm/year in height. These velocities represent the global crustal motion of the

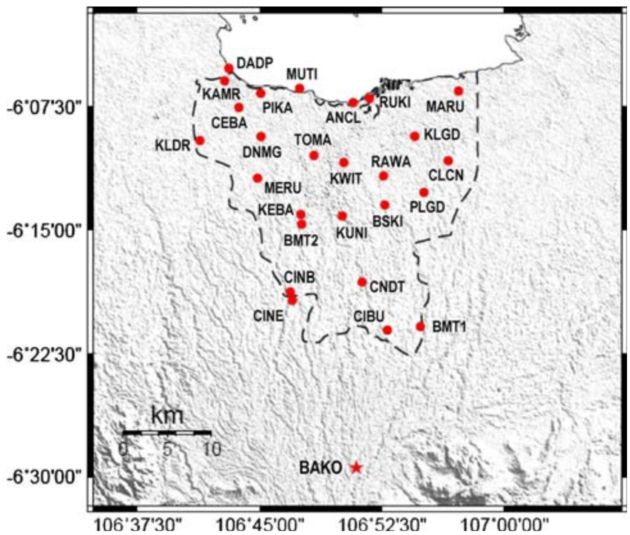

Fig. 3 GPS network for monitoring land subsidence in Jakarta

Sunda Shelf block, where the BAKO station and the Jakarta basin are located. Using yearly GPS campaign data from 1991 to 1997 and 2001, Bock et al. (2003) estimated the horizontal velocity of the block as 6 ± 3 mm/year in SE direction relative to the Eurasian plate. Since BAKO and the Jakarta basin are located in the Sunda Shelf block, all GPS subsidence monitoring stations in the Jakarta basin will experience the same crustal motion velocities. This crustal motion is taking into account when defining the coordinates of BAKO. In this study, ITRF2000 is used as the reference frame for BAKO coordinates. Moreover, since BAKO is located in the southern part of the Jakarta basin, which is geologically located on more stable volcanic deposits (Yong et al. 1995; Rismianto and Mak 1993), it can be safely assumed for the purpose of this subsidence study that it is a relatively stable station. The monument of the BAKO station (see Fig. 4) was built in 1981. It is made of reinforced concrete, 2 m depth, with an underground foundation of about 1.5 × 1.5 m. It is erected 50 cm above the ground with a width of about 40 × 40 cm.

The eight GPS surveys were conducted during December 1997, June 1999, June 2000, June 2001, October 2001, July 2002, December 2002 and September 2005. These surveys did not always occupy the same stations. The first survey started with 13 stations. The network then expanded subsequently to 27 stations. At certain epochs, some stations could not be observed due to the destruction of monuments or severe signal obstruction caused by growing trees and/or new construction.

The GPS surveys exclusively used dual-frequency geodetic-type GPS receivers. The length of the sessions was in general between 9 and 11 h (see Table 1). The data were collected at 30 s intervals using an elevation mask of 15°. The data were processed using the software Bernese 4.2 (Beutler et al. 2001). Since we are mostly interested in the relative heights with respect to a stable point, the radial processing mode was used instead of a network adjustment mode. In this case, the relative ellipsoidal heights of all stations are determined relative to BAKO station.

Considering the length of the baselines of 40–50 km, a 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 the case of the residual ionospheric delay reduction, a local ionospheric modeling is implemented. The algorithms for the tropospheric parameter estimation and local ionospheric modeling can be found in Beutler et al. (2001). In processing baselines, most of the cycle ambiguities of the phase observations were successfully resolved.

The standard deviations of GPS-derived relative ellipsoidal heights from all surveys were in general better than 1 cm (see Fig. 5). A few points have slightly larger standard deviations, due to the lack of observed data caused by the signal obstruction.

GPS-derived land subsidence in Jakarta

In using GPS surveys method, the height change Δdh_{ij} and its rate $v\Delta dh_{ij}$ at each station are derived using the following relation:

$$\Delta dh_{ij} = dh(t_j) - dh(t_i) \quad (1)$$

$$v\Delta dh_{ij} = \Delta dh_{ij} / (t_j - t_i) \quad (2)$$

where $dh(t_i)$ and $dh(t_j)$ are the relative ellipsoidal heights with respect to BAKO, obtained from the ith and jth GPS surveys. Subsidence is represented by a negative value of Δdh_{ij}. All GPS-derived ellipsoidal height changes and their rates, as obtained from GPS data collected by eight GPS surveys, are given in Tables 2 and 3.

In order to statistically check the significance of the subsidence values, we apply the general linear hypothesis test (Leick 2004) to the estimated height parameter. The null hypothesis of the test is that the estimated relative ellipsoid heights at epoch j equal the estimated value of the previous epoch i., i.e., no subsidence has occurred. Therefore,

$$\text{null hypothesis} \quad H_o : \Delta dh_{ij} = 0 \quad (3)$$

$$\text{alternative hypothesis} \quad H_a : \Delta dh_{ij} \neq 0 \quad (4)$$

Table 1 GPS stations and observation times

GPS stations/pillars					Times of observation (h)							
No	Name	A*	B*	C* (m)	S-1**	S-2**	S-3**	S-4**	S-5**	S-6**	S-7**	S-8**
1	BAKO	1981	RC	2	Continuous observation							
2	CIBU	1993	RC	1.5	09.9	09.9	20.6	10.2	10.4	10.0	10.0	09.1
3	CINE	1994	RC	1	20.8	07.8	09.3	n.o.	n.o.	n.o.	n.o.	n.o.
4	KEBA	1994	RC	1	19.8	11.0	10.0	11.3	10.3	10.3	10.2	10.0
5	KUNI	1994	RC	1	10.4	11.4	10.9	10.5	10.0	11.0	10.4	08.6
6	KWIT	1993	RC	1.5	19.2	10.7	10.2	10.6	10.0	09.9	10.1	10.7
7	MARU	1993	RC	1.5	10.2	10.0	10.1	10.1	10.0	09.3	10.0	09.6
8	MERU	1994	RC	1	10.7	11.5	10.2	09.9	10.0	10.1	10.1	10.0
9	MUTI	1994	RC	1	19.6	10.9	10.1	10.7	10.6	10.0	10.2	06.9
10	PIKA	1994	RC	1	10.0	10.0	10.1	09.7	10.3	10.1	10.1	08.8
11	RAWA	1994	RC	1	10.0	10.3	11.0	n.o.	n.o.	n.o.	n.o.	n.o.
12	RUKI	1993	RC	1.5	19.4	10.0.	10.3	11.3	10.3	10.2	10.1	09.7
13	TOMA	1993	RC (on the roof)	0.5	11.1	09.3	10.4	10.3	10.1	10.0	10.8	08.0
14	ANCL	1994	RC	1	n.o.	n.o.	10.3	12.9	10.3	10.0	10.0	10.1
15	BSKI	1994	RC	1	n.o.	n.o.	10.3	10.3	10.4	11.1	10.8	09.5
16	CLCN	1994	RC	1	n.o.	n.o.	11.6	04.8	09.8	12.1	10.4	n.o.
17	CNDT	1993	RC	1.5	n.o.	n.o.	10.2	10.0	09.9	n.o.	n.o.	n.o.
18	DNMG	1994	RC	1	n.o.	n.o.	10.1	09.6	10.0	09.9	10.2	10.8
19	KAMR	1994	RC	1	n.o.	n.o.	10.2	09.6	10.0	10.6	10.3	n.o.
20	KLDR	1994	RC	1	n.o.	n.o.	10.0	10.1	10.0	10.0	10.1	09.8
21	KLGD	1994	RC	1	n.o.	n.o.	10.2	09.9	10.0	10.5	10.2	06.7
22	BMT1	1997	RC	down to bedrock	n.o.	n.o.	n.o.	10.2	13.0	10.5	10.0	10.3
23	BMT2	1997	RC	down to bedrock	n.o.	n.o.	n.o.	11.3	09.6	10.0	10.2	09.0
24	CEBA	1994	RC	1	n.o.	n.o.	n.o.	10.1	10.1	10.0	10.0	09.6
25	DADP	1994	RC	1	n.o.	n.o.	n.o.	10.1	10.0	10.0	10.0	03.6
26	PLGD	1994	RC	1	n.o.	n.o.	n.o.	10.0	10.0	10.0	10.0	09.9
27	CINB	1994	RC	1	n.o.	n.o.	n.o.	10.1	10.1	10.0	10.3	08.3

* A establishment year, B monument type (RC = reinforced concrete), C depth of monument below the surface

** S-1–S-8 denote Survey-1–Survey-8, and they were conducted in the periods 24–26 December 1997, 29 and 30 June 1999, 31 May–3 June 2000, 14–19 June 2001, 26–31 October 2001, 2–7 July 2002, 21–26 December 2002 and 21–25 September 2005, respectively

*** n.o No observation was made

Fig. 4 Monument of BAKO station

The test statistics for this test is

$$t = \frac{\Delta dh_{ij}}{\hat{\sigma}(\Delta dh_{ij})} \tag{5}$$

which has the customary Student's t distribution if H_o is true. The null hypothesis is rejected if

$$|t| > t_{df,\alpha/2} \tag{6}$$

where df is the degrees of freedom and α is the significance level. In our case, the degree of freedom is very large since the GPS baselines were derived using 6–10 h of observa-

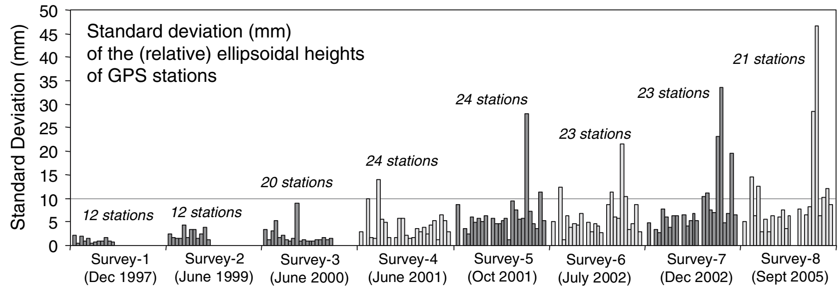

Fig. 5 Standard deviations of GPS-derived relative heights in mm

Table 2 GPS-derived ellipsoidal height changes from eight surveys, in WGS84

No	Station	Δdh_{12}	Δdh_{23}	Δdh_{34}	Δdh_{45}	Δdh_{56}	Δdh_{67}	Δdh_{78}
1	CIBU	–2.4 ± 0.3	–4.6 ± 0.4	–2.3 ± 0.4	–2.9 ± 0.9	–1.3 ± 1.0	–0.2 ± 0.7	–9.6 ± 0.7
2	CINE	–3.5 ± 0.2	–0.6 ± 0.2					
3	KEBA	–6.9 ± 0.3	–2.2 ± 0.3	–4.4 ± 1.0	–1.5 ± 1.1	u.r.	–10.7 ± 1.3	–19.1 ± 1.5
4	KUNI	–4.7 ± 0.2	–4.0 ± 0.6	–7.9 ± 0.6	–1.6 ± 0.3	0.0 ± 0.3	–0.1 ± 0.3	–10.6 ± 0.7
5	KWIT	–5.7 ± 0.5	–1.0 ± 0.5	–0.9 ± 0.2	–0.6 ± 0.6	–3.0 ± 0.9	–7.6 ± 1.0	–29.9 ± 1.5
6	MARU	–6.4 ± 0.2	–0.4 ± 0.3	–4.3 ± 1.4	–0.1 ± 1.5	–0.8 ± 0.6	–0.2 ± 0.7	–13.2 ± 0.7
7	MERU	–5.8 ± 0.3	–5.9 ± 0.4	–0.3 ± 0.6	–4.6 ± 0.8	–1.4 ± 0.7	–1.1 ± 0.6	–17.2 ± 0.7
8	MUTI	–1.2 ± 0.4	–0.5 ± 0.4	–5.5 ± 0.5	–0.5 ± 0.7	–6.1 ± 0.7	–2.4 ± 0.8	–34.4 ± 0.7
9	PIKA	–6.1 ± 0.2	–17.6 ± 0.2	–0.4 ± 0.2	u.r.	–6.9 ± 0.9	–2.1 ± 0.9	–28.0 ± 0.9
10	RAWA	–3.8 ± 0.3	–4.2 ± 0.9					
11	RUKI	–16.1 ± 0.4	–0.4 ± 0.4	–8.5 ± 0.2	–1.4 ± 0.6	0.0 ± 0.8	0.3 ± 0.8	–13.4 ± 0.9
12	TOMA	–1.2 ± 0.1	–1.1 ± 0.2	–2.9 ± 0.6	–0.5 ± 0.7	–4.4 ± 0.5	–3.4 ± 0.5	–29.6 ± 0.9
13	ANCL			–3.4 ± 0.6	–0.3 ± 0.7	–2.3 ± 0.7	–3.2 ± 0.7	–17.8 ± 0.6
14	BSKI			–1.5 ± 0.2	–3.6 ± 0.6	–3.9 ± 0.7	0.0 ± 0.8	–15.1 ± 0.9
15	CLCN			–8.1 ± 0.2	–0.2 ± 0.6	0.2 ± 0.6	–4.7 ± 0.6	
16	CNDT			u.r.	–0.3 ± 0.2			
17	DNMG			–25.8 ± 0.4	–8.5 ± 1.0	–1.8 ± 1.3	–1.0 ± 1.4	–28.7 ± 1.3
18	KAMR			–9.4 ± 0.3	–1.6 ± 0.8	–2.9 ± 1.4	0.0 ± 1.6	
19	KLDR			–13.0 ± 0.4	–2.8 ± 0.7	–0.4 ± 0.8	–2.6 ± 1.0	–14.6 ± 1.0
20	KLGD			–1.4 ± 0.3	–3.3 ± 0.6	–6.7 ± 0.8	–0.1 ± 0.9	–16.4 ± 1.1
21	BMT1				–9.2 ± 2.8	–1.4 ± 3.5	0.3 ± 3.2	4.2 ± 3.7
22	BMT2				–2.3 ± 0.9	–9.8 ± 1.3	u.r	u.r.
23	CEBA				–1.1 ± 0.5	–8.3 ± 0.6	–2.8 ± 0.6	–36.6 ± 0.8
24	DADP				–5.4 ± 0.8	–0.7 ± 0.6	–0.4 ± 0.8	–21.3 ± 1.2
25	PLGD				–5.8 ± 1.3	–6.1 ± 1.4	–34.9 ± 2.1	2.9 ± 2.3
26	CINB				–1.2 ± 0.6	–0.5 ± 0.6	–4.3 ± 0.7	–16.6 ± 1.1

The unit is (cm)

u.r. Indicates unreliable result caused by severe signal obstruction and too many cycle slips in the data

tions at 30 s intervals. A t distribution with infinite degree of freedom is identical to a normal distribution. At a confidence level of 99% (i.e., $\alpha = 1\%$), the critical value is $t_{\infty,0.005} = 2.576$

Examples of GPS-derived land subsidence at several observing stations are shown in Figs. 6 and 7. In about seven years, i.e., December 1997–September 2005, the accumulated subsidence at several GPS stations is about 25–50 cm (see Fig. 6). At other stations the subsidence ranges from 25 to 70 cm in five years, i.e., June 2001–September 2005 (see Fig. 7). Based on the results shown in Figs. 6 and 7, it can be concluded that land subsidence rates in the Jakarta basin have both a spatial and a temporal variation. This indicates that the sources of land subsidence in Jakarta also differ spatially.

The estimated subsidence rates during the time December1997–September 2005 are 1–10 cm/year and reach 15–20 cm/year, as shown in Fig. 8. The highest rates of land

Table 3 GPS-derived rates of ellipsoidal height changes from eight surveys, in WGS84

No	Station	$v\Delta dh_{12}$	$v\Delta dh_{23}$	$v\Delta dh_{34}$	$v\Delta dh_{45}$	$v\Delta dh_{56}$	$v\Delta dh_{67}$	$v\Delta dh_{78}$
1	CIBU	–1.6 ± 0.2	–5.0 ± 0.5	–2.2 ± 0.4	–7.7 ± 2.5	–2.0 ± 1.5	–0.4 ± 1.4	–3.5 ± 0.3
2	CINE	–2.3 ± 0.1	–0.7 ± 0.2					
3	KEBA	–4.6 ± 0.2	–2.4 ± 0.4	–4.2 ± 1.0	–4.1 ± 2.8	u.r.	–21.4 ± 2.6	–6.9 ± 0.5
4	KUNI	–3.1 ± 0.1	–4.3 ± 0.6	–7.6 ± 0.5	–4.2 ± 0.8	0.0 ± 0.4	–0.1 ± 0.6	–3.8 ± 0.3
5	KWIT	–3.8 ± 0.3	–1.1 ± 0.5	–0.8 ± 0.2	–1.6 ± 1.6	–4.5 ± 1.3	–15.2 ± 2.0	–10.9 ± 0.5
6	MARU	–4.3 ± 0.1	–0.5 ± 0.3	–4.1 ± 1.4	–0.3 ± 3.9	–1.2 ± 0.9	–0.4 ± 1.4	–4.8 ± 0.2
7	MERU	–3.9 ± 0.2	–6.5 ± 0.4	–0.3 ± 0.6	–12.2 ± 2.2	–2.0 ± 1.1	–2.1 ± 1.2	–6.3 ± 0.2
8	MUTI	–0.8 ± 0.2	–0.5 ± 0.4	–5.3 ± 0.5	–1.2 ± 1.9	–9.2 ± 1.0	–4.9 ± 1.5	–12.5 ± 0.2
9	PIKA	–4.1 ± 0.1	–19.2 ± 0.2	–0.4 ± 0.2	u.r.	–10.3 ± 1.4	–4.1 ± 1.9	–10.2 ± 0.3
10	RAWA	–2.5 ± 0.2	–4.6 ± 1.0					
11	RUKI	–10.8 ± 0.3	–0.4 ± 0.4	–8.2 ± 0.2	–3.8 ± 1.6	0.0 ± 1.1	0.6 ± 1.6	–4.9 ± 0.3
12	TOMA	–0.8 ± 0.1	–1.2 ± 0.2	–2.8 ± 0.6	–1.4 ± 2.0	–6.6 ± 0.8	–6.7 ± 1.0	–10.8 ± 0.3
13	ANCL			–3.3 ± 0.6	–0.7 ± 2.0	–3.5 ± 1.0	–6.3 ± 1.4	–6.5 ± 0.2
14	BSKI			–1.5 ± 0.2	–9.5 ± 1.5	–5.9 ± 1.0	–0.1 ± 1.6	–5.5 ± 0.3
15	CLCN			–7.7 ± 0.2	–0.6 ± 1.6	0.3 ± 1.0	–9.5 ± 1.2	
16	CNDT			u.r.	–0.7 ± 0.5			
17	DNMG			–24.8 ± 0.4	–22.6 ± 2.7	–2.7 ± 1.9	–1.9 ± 2.7	–10.4 ± 0.5
18	KAMR			–9.0 ± 0.3	–4.3 ± 2.2	–4.3 ± 2.0	0.0 ± 3.2	
19	KLDR			–12.4 ± 0.4	–7.6 ± 1.8	–0.6 ± 1.2	–5.2 ± 1.9	–5.3 ± 0.4
20	KLGD			–1.3 ± 0.3	–8.8 ± 1.6	–10.0 ± 1.2	–0.1 ± 1.8	–6.0 ± 0.4
21	BMT1				–24.6 ± 7.5	–2.2 ± 5.3	0.6 ± 6.4	1.5 ± 1.3
22	BMT2				–6.2 ± 2.4	–14.8 ± 1.9	u.r.	u.r.
23	CEBA				–3.0 ± 1.3	–12.4 ± 0.8	–5.7 ± 1.2	–13.3 ± 0.3
24	DADP				–14.4 ± 2.0	–1.1 ± 0.9	–0.8 ± 1.6	–7.8 ± 0.4
25	PLGD				–15.4 ± 3.3	–9.2 ± 2.1	–69.8 ± 4.3	1.0 ± 0.8
26	CINB				–3.1 ± 1.6	–0.8 ± 0.9	–8.6 ± 1.4	–6.0 ± 0.4

The unit is (cm/year)

u.r. indicates unreliable result caused by severe signal obstruction and too many cycle slips in the data

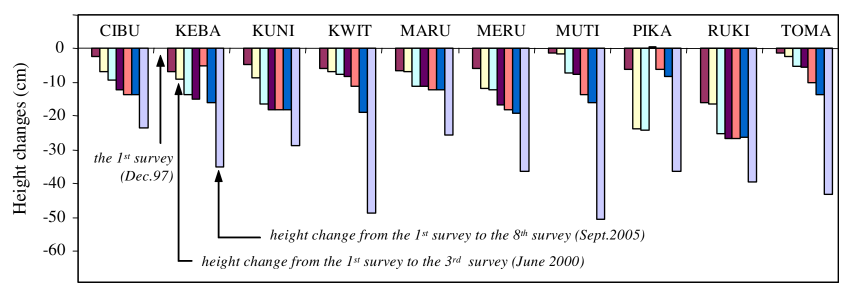

Fig. 6 Accumulated GPS-derived subsidence (cm) during the period of December 1997–September 2005

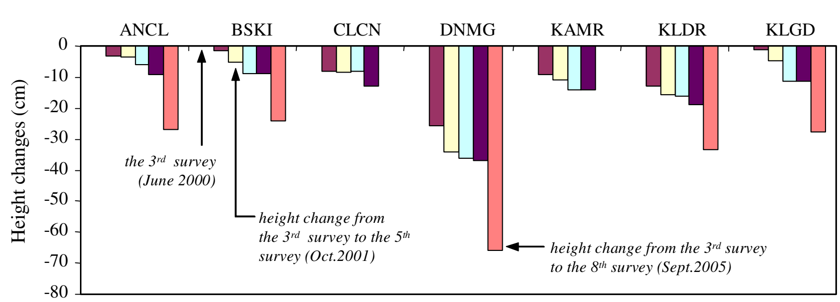

Fig. 7 Accumulated GPS-derived subsidence (cm) during the period of June 2001–September 2005

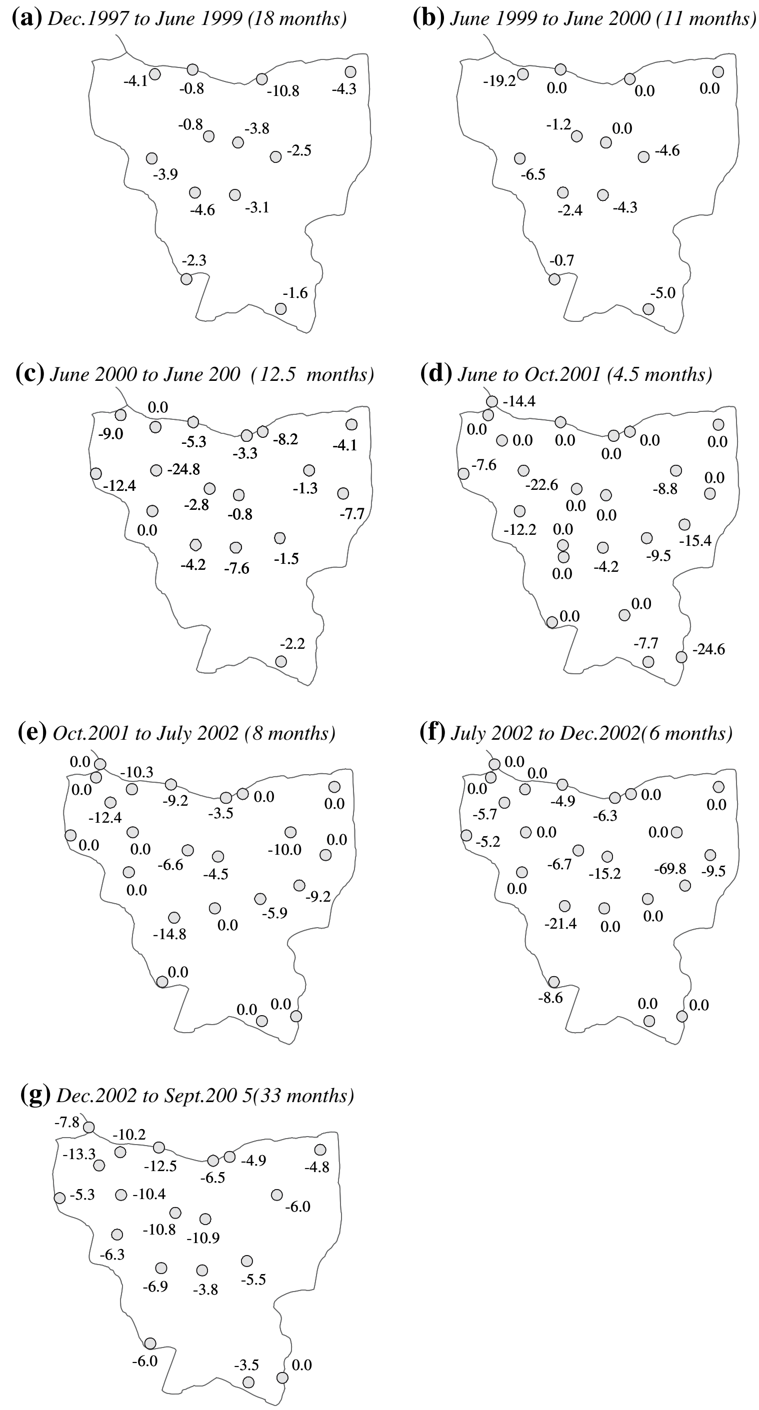

Fig. 8 Rates of land subsidence (cm/year) in several places in Jakarta basin, as estimated by GPS surveys. The statistically insignificant rates (with a confidence level of 99%) are denoted with the values of 0.0 cm/year

subsidence occur in northwestern Jakarta. The central and northeastern parts sometimes also show quite high rates of subsidence. Figure 8 shows more clearly the nature of spatial and temporal variation of land subsidence rates in the basin. These vertical temporal variations, however, may still be contaminated by annual/semiannual signal bias that plagues all GPS temporal measurements. Joint contributions from surface mass redistribution (atmosphere, ocean, snow and soil moisture) are the primary causes of the observed annual vertical variations of GPS-derived site positions (Dong et al. 2002; Blewitt and Lavallee 2002). By using long-term (~5 years) time-series of daily GPS solutions at eight stations, Ding et al. (2005) obtained the annual and semi-annual variations in height components with the weighted means of amplitudes of about 3.6 and 2.0 mm, respectively.

Figures 6, 7 and 8 suggest that the subsidence rates of stations over a certain observation period can slow down, accelerate or be relatively steady in comparison with the rates from the previous period. It indicates that the subsidence in the Jakarta basin is not homogeneous. The variability is due to a number of causal mechanisms, including excessive groundwater extraction, building load, sediment compaction and tectonic activities. Our data set does not allow us to identify which of these causal mechanisms is most important or determine their spatial relationship across the basin.

Land subsidence and groundwater extraction

The GPS surveys show that land subsidence in Jakarta exhibits spatial and temporal variations. Excessive groundwater extraction from the middle and lower aquifers of the Jakarta basin by individuals and by industry is hypothesized to be the main factor that causes land subsidence. In this hypothesis, the spatial and temporal variations of land subsidence will strongly depend on the corresponding variations of groundwater extraction, coupled with the characteristics of sedimentary layers and building loads above it. However, the detail and relation between land subsidence and excessive groundwater extraction in the whole Jakarta basin is not yet understood.

In the context of groundwater extraction, it should be noted that three aquifers are recognized inside a 250 m thick sequence of quaternary sediment of the Jakarta basin, namely, (Hadipurwo 1999) the upper aquifer, an unconfined aquifer, which occurs at a depth of less than 40 m; the middle aquifer, which is a confined aquifer and occurs at a depth between 40 and 140 m; and the lower aquifer, which is confined and occurs at a depth between 140 and 250 m. Inside these aquifers, the groundwater generally flows from south to the north. An aquifer was also found in the tertiary sediment below a depth of 250 m.

The groundwater extraction in Jakarta can be categorized into shallow (<40 m) and deep (>40 m) extraction. Shallow extraction is via dug or driven wells, operated with buckets, hand pumps or small electrical pumps; whereas, deep extraction is mostly from drilled wells. Shallow extraction is mostly done by individuals and the wells are generally evenly distributed across the basin and their extraction rate per well is relatively low. Deep extraction is usually conducted by industry and is localized and has a high extraction rate. The land subsidence observed in the coastal, west and northeastern parts of Jakarta are thought to be caused by this deep groundwater extraction, which reduces the water pressure in the aquifer (piezometric level) (Rismianto and Mak 1993). According to Soetrisno et al. (1997), the piezometric level in north Jakarta has changed from 12.5 m above sea level in 1910 to about sea level in the 1970s, and then deepened significantly to 30–50 m below sea level in the 1990s. Figure 9 shows the piezometric levels inside the middle and lower aquifers in 1992.

The measured subsidence rates established using GPS is closely related to the rate of piezometric water level (head) deepening in the middle and lower aquifers. According to Hadipurwo (1999), the maximum depth of the piezometric head inside the middle and lower aquifers tends to deepen with time. An example is shown in Fig. 10. The increase in population and industry in Jakarta, which requires a lot of groundwater, could explain the declining trend of the piezometric heads. The deepening of piezometric heads in turn contributes to land subsidence in the basin.

Figure 9 shows the piezometric water level contours in 1992. If this figure is compared with the GPS-derived land subsidence rates between 1997 and 2005 shown in Fig. 8, the correlation between land subsidence and excessive groundwater extraction can be seen, especially in northwestern Jakarta.

More data and further investigation are required to understand the complete relationship between land subsidence and excessive groundwater extraction in the basin. Additional causes of subsidence, e.g., load of buildings, natural consolidation of alluvial soil and tectonic movements, should also be investigated and taken into account.

Closing remarks

GPS surveys are a robust method for studying and monitoring land subsidence in Jakarta. There are several advantages of using GPS: (1) GPS provides a three-

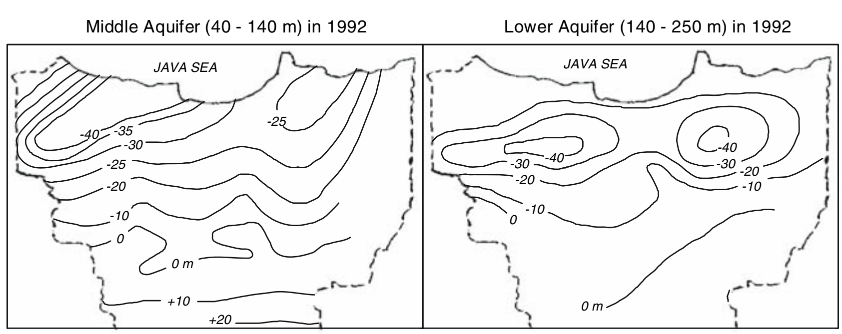

Fig. 9 Piezometric water level contours (in mm) inside middle and lower aquifers of Jakarta in 1992, adapted from (Murdohardono and Tirtomihardjo 1993)

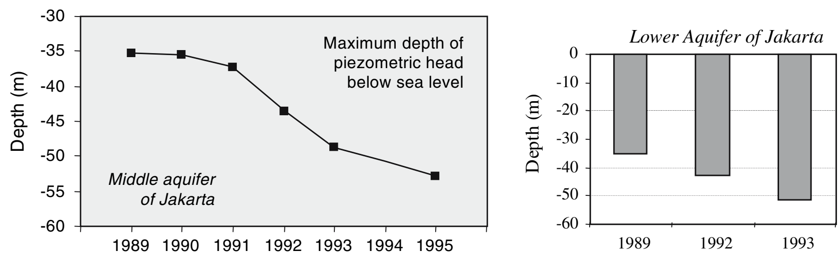

Fig. 10 Example of the deepening of the piezometric head inside the middle and lower aquifers of Jakarta, drawn from the data given in Hadipurwo (1999)

dimensional displacement vector with two horizontal and one vertical component; so it provides not only land subsidence information, but also horizontal motions. (2) GPS provides the displacement vectors in a well-defined coordinate reference system, which makes it possible to effectively monitor land subsidence over large areas. (3) GPS can yield displacement vectors with a precision of several millimeters in the temporal and spatial domain. (4) GPS is available continuously, day and night, and independent of weather conditions. This makes field operations flexible.

Based on our experience, the main constraint for using GPS in studying land subsidence in a large city like Jakarta is signal obstruction and multipath caused by high rise buildings, trees, billboards, etc. For this reason, GPS stations cannot always be established in a desired location. Another problem is due to active development activities inside urban areas, which sometimes destroy or alter observation monuments. It should also be noted that the detection of land subsidence at the level of a couple of millimeters requires dual-frequency geodetic type receivers, good project planning, stringent observation strategy and data processing strategy available only in scientific software. Expertise in GPS data acquisition and precise data processing is therefore required.

Implementing a continuously operating GPS network in the Jakarta basin may be useful, because of the possibly large temporal variations in the rates of subsidence. These temporal variations may be difficult to observe with episodic GPS measurements. A fundamental limitation of GPS methods is that the measurements are limited to specific points with no spatial continuity. To overcome this limitation, the Interferometric Synthetic Aperture Radar (InSAR) technique (Massonnet and Feigl 1998) should be considered. InSAR provides complete spatial coverage, but is only a relative technique that requires a tie to GPS to transform it to an absolute one.

In order to achieve an even better understanding and modeling of land subsidence in the Jakarta basin, the variations derived from GPS surveys should be integrated with land subsidence information obtained from leveling and INSAR, and also with information from geohydrological and geotechnical measurements (e.g., using automatic water level recorder, piezometer, extensometer, drilling, etc.).

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