

Land subsidence of Jakarta (Indonesia) and its relation with urban development

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Abstract Jakarta is the capital city of Indonesia with a population of about 9.6 million people, inhabiting an area of about 660 square-km. In the last three decades, urban development of Jakarta has grown very rapidly in the sectors of industry, trade, transportation, real estate, and many others. This exponentially increased urban development introduces several environmental problems. Land subsidence is one of them. The resulted land subsidence will also then affect the urban development plan and process. It has been reported for many years that several places in Jakarta are subsiding at different rates. The leveling surveys, GPS survey methods, and InSAR measurements have been used to study land subsidence in Jakarta, over the period of 1982–2010. In general, it was found that the land subsidence exhibits spatial and temporal variations, with the rates of about 1–15 cm/year. A few locations can have the subsidence rates up to about 20–28 cm/year. 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. It was found that the spatial and temporal variations of land subsidence depend on the corresponding variations of groundwater extraction, coupled with the characteristics of sedimentary layers and building loads above it. In general, there is strong relation between land subsidence and urban development activities in Jakarta.

Keywords Jakarta · Land subsidence · Urban development · Leveling · GPS · InSAR

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1 Introduction

The city of Jakarta has a population of about 9.6 million people in 2010 with total households of about 2.2 million (BPS 2011), inhabiting an area of about 661.52 km². Jakarta is centered at the coordinates of about $-6^{\circ}15'$ (latitude) and $+106^{\circ}50'$ (longitude) and located on the lowland of the northern coast of the West Java province, as shown in Fig. 1. Region consisting of Jakarta and its surrounding areas of Bogor, Tangerang, and Bekasi are usually termed Jakarta Metropolitan Region (JMR), covering an area of approximately 7,500 km² with total population of 27.9 million people in 2010.

The area is relatively flat, with the 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 (MSL). Regionally speaking, Jakarta is a lowland area which has five main landforms, namely (Rimbaman and Suparan 1999; Sampurno 2001) : (1) volcanic alluvial fan landforms, which are located in the southern part; (2) landforms of marine-origin, which are found in the northern part adjacent to the coastline; (3) beach ridge landforms, which are located in the northwest and northeast parts; (4) swamp and mangrove-swamp landforms, which are encountered in the coastal fringe; and (5) former river channels, which run perpendicular to the coastline. It should also be noted that 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.

In the last three decades, urban development of Jakarta and its surrounding areas has grown very rapidly in the sectors of industry, trade, transportation, real estate, and many others. This exponentially increased urban development introduces several environmental problems. According to (Firman and Dharmapatni 1994), this rapid urban development has caused several negative externalities, namely : (1) extensive conversion of prime agricultural areas into residential and industrial areas, (2) significant disturbance to main ecological function of the upland of Jakarta area as a water recharge area for Jakarta city, (3) increase in groundwater extraction due to development of industrial activities and the high population increase, (4) high concentrations of BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand) in most of the rivers flowing through the Jakarta

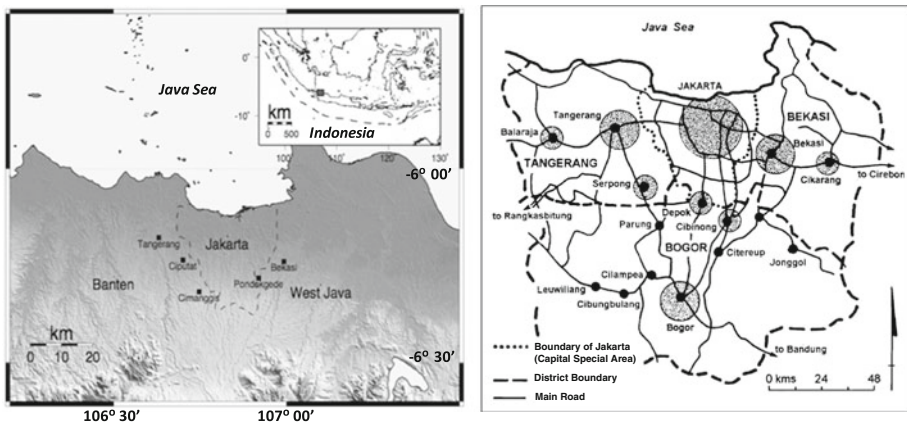


Fig. 1 Jakarta and its surrounding areas. Jakarta Metropolitan Region (JMR) shown on the right is adapted from Firman (1999)

area as a result of domestic, agricultural, and industrial waste disposal, (5) solid waste disposal is now felt as a pressing problem, and (6) the air pollution in Jakarta city has reached a critical point reflected in more evident acid rain. The first three negative impacts will contribute to land subsidence phenomena in several places in Jakarta. The resulted land subsidence will also then affect the urban development plan and process.

Land subsidence resulted as side effects of urban development have also been reported for several cities, such as Bangkok (Phien-wej 2006), Calcutta (Chatterjee et al. 2006), Taipei (Chen et al. 2007), Shanghai (Xue et al. 2005), Semarang (Marfai and King 2007; Abidin et al. 2010b), and Bandung (Abidin et al. 2008a). This paper presents and discusses the characteristics of land subsidence in Jakarta as observed by the geodetics methods (i.e., leveling surveys, GPS survey methods, and InSAR measurements) and its relation to urban development activities in Jakarta.

2 Measurements of land subsidence in Jakarta

Land subsidence is not a new phenomenon for Jakarta, the capital city of Indonesia. It has been reported for many years that several places in Jakarta are subsiding at different rates (Murdohardono and Tirtomihardjo 1993; Murdohardono and Sudarsono 1998; Rajiyowiryono 1999). The impact of land subsidence in Jakarta 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 (inland and coastal) flooding areas, malfunction of drainage system, and increased inland sea water.

Based on several studies (Murdohardono and Sudarsono 1998; Rismianto and Mak 1993; Harsolumakso 2001; Hutasoit 2001), 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 alluvium soil, and geotectonic subsidence. The first three are thought to be the dominant types of land subsidence in Jakarta basin.

In the case of Jakarta, the comprehensive information on the characteristics of land subsidence is important for several tasks, 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. Considering the importance of land subsidence information for supporting the development activities in Jakarta area, monitoring and studying the characteristics of subsidence phenomena become necessary. Since 1982, land subsidence in several places of Jakarta has been measured using three geodetic techniques, e.g., leveling surveys, GPS surveys, and InSAR technique (Abidin 2005; Abidin et al. 2001, 2004, 2008b). 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).

The first reliable information about subsidence in Jakarta came from results of differential leveling surveys (Abidin et al. 2001). The systematic leveling surveys covering much of the Jakarta area were conducted in 1978, 1982, 1991, 1993, and 1997. Except for the last survey, which was performed by the Local Mines Agency of Jakarta, the leveling surveys were done by the Local Surveying and Mapping Agency of Jakarta. The leveling surveys were done using Wild N3, Zeiss Ni002, and Wild NAK precise leveling instruments. Each leveling line was measured in double-standing (double-run) mode, and each

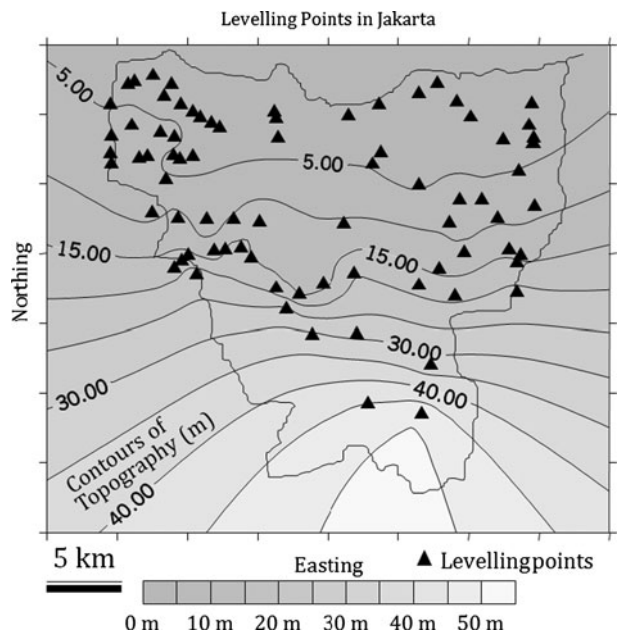
leveling session was measured forward and backward to provide survey closure and to verify accuracy (NGS 2011). The leveling line for each session is about 1 km in length. The tolerance for the difference between the forward and backward height-difference measurements is set to be $4\sqrt{D}$ mm, where D is the length of leveling line in km.

After applying quality assurance criteria related to the standards and requirements for geodetic leveling (NGS 2011), only three surveys were considered sufficiently accurate for investigating the land subsidence in Jakarta; those conducted in 1982, 1991, and 1997. Moreover, only the results from specific leveling points in the network, which are considered the most reliable, are used for investigating land subsidence. In this case, repeatability of the heights obtained from different surveys and different loops and stability of the monument with respect to its local environment are used as the main criteria for selecting the points. The magnitude of land subsidence was estimated using 45 selected points from the leveling networks of 1982, 1991, and 1997 (see Fig. 2).

Besides using leveling surveys, land subsidence in Jakarta has also been studied using GPS survey methods (Leick 2003). The GPS-based land-subsidence study has been conducted by the Geodesy Research Division of ITB since December 1997. Up to now, 13 GPS surveys have been conducted, namely on: December 24–26, 1997, June 29–30, 1999, May 31–June 3, 2000, June 14–19, 2001, October 26–31, 2001, July 2–7, 2002, December 21–26, 2002, September 21–25, 2005, July 10–14, 2006, September 3–7, 2007, August 22–31, 2008, July 15–20, 2009, and May 9–21, 2010.

The configuration of this GPS monitoring network is shown in Fig. 3. These surveys did not always occupy the same stations. The first survey started with 13 stations, and the network then expanded subsequently to 27 stations in 2008, 50 stations in 2009, and 65 stations in 2010. At certain observation period, some stations could not be observed due to the destruction of monuments, or severe signal obstruction caused by growing trees and/or new construction. 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. In this case, the

Fig. 2 Leveling network in Jakarta



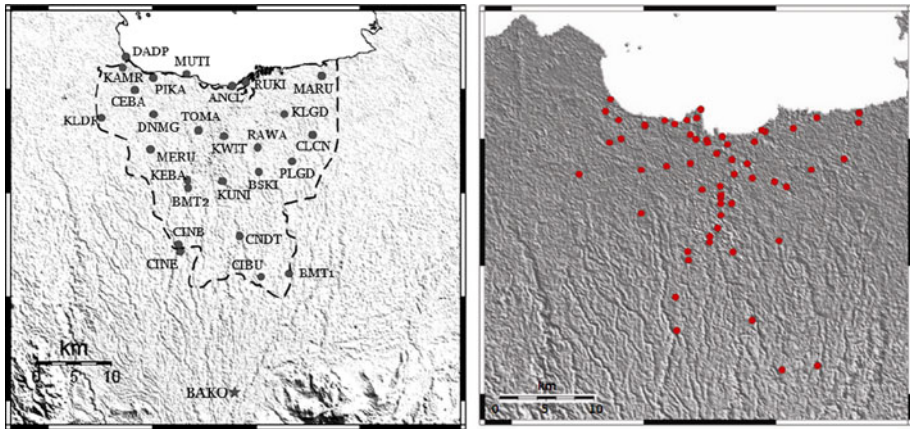


Fig. 3 GPS network for monitoring subsidence in Jakarta for 2008 (*left*) and 2010 (*right*)

relative ellipsoidal heights of all stations are determined relative to BAKO station. BAKO is an IGS station, operated by BAKOSURTANAL which is the Indonesian acronym for the National Coordinating Agency for Survey and Mapping of Indonesia.

The GPS surveys exclusively used dual-frequency geodetic-type GPS receivers. The length of surveying sessions was in general between 9 and 11 h. The data were collected with a 30s interval using an elevation mask of 15° . The data were processed using the software Bernese 4.2 and 5.0 (Beutler et al. 2001, 2007). Since we are mostly interested with the relative heights with respect to a stable point, the radial processing mode was used instead of network adjustment mode.

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, 2007). In processing baselines, most of the cycle ambiguities of the phase observations were successfully resolved. The estimated standard deviations of GPS-derived relative ellipsoidal heights from all surveys were in general better than 1 cm (Abidin et al. 2008b).

Since 2004, subsidence phenomena in Jakarta also have been studied using InSAR (Interferometric Synthetic Aperture Radar) techniques (Schreier 1993; Massonnet and Feigl 1998). The initial results are provided in Abidin et al. (2004). Recently, InSAR techniques were applied to study land subsidence in the Jakarta area using data from the ALOS/PALSAR satellite, which was launched in January 2006 as a successor of JERS-1/SAR. The SAR data observed during June 2006 and February 2007 were used. They were acquired in Fine Beam Single Polarization mode (HH polarization) with off-nadir angle of 41.5 degrees. InSAR processing has been performed using Level 1.1 products (SLC: Single Look Complex) distributed to the public by ERSDAC (Earth Remote Sensing Data Analysis Center) in Japan. The processing software for InSAR was developed by Deguchi (2005) and Deguchi et al. (2006).

3 Characteristics of land subsidence in Jakarta

The results obtained from leveling surveys, GPS surveys, and InSAR technique over the period between 1982 and 2010 show that land subsidence in Jakarta has spatial and temporal variations. This indicates that the sources of land subsidence in Jakarta also differ spatially. Land subsidence only affected several regions of Jakarta, and in general, the observed subsidence rates are about 1–15 cm/year, and can be up to 20–28 cm/year at certain location and certain period. The summary of subsidence rates in Jakarta is given in Table 1.

From leveling surveys, it was found that the maximum subsidence during the period of 1982–1991 is about 80 cm, while for the period of 1991–97 is about 160 cm (see Fig. 4). In general, the subsidence rates in Jakarta area during this period are about 1–5 cm/year and can reach 25 cm/year at several locations. During the period between 1982 and 1991, the maximum rate of subsidence is about 9 cm/year, while during the period between 1991 and 1997 it is about 25 cm/year. More comprehensive results on leveling-based subsidence in Jakarta can be seen in Abidin et al. (2001).

In general, the GPS observed subsidence rates during the period between December 1997 and May 2010 are about 1–28 cm/year. Examples of GPS-derived land subsidence at several observing stations are shown in Figs. 5 and 6. On Fig. 5, the first measurement at each point established the baseline elevation for that site and, therefore, is shown as zero elevation change. The different color codes for the individual bars in these figures indicate that they were estimated from different GPS surveys. In about 10 years, i.e., Dec. 1997 to Sept. 2007, the accumulated subsidence at several GPS stations can reach about 80–90 cm.

Table 1 Observed subsidence rates in Jakarta; the rates vary both spatially and temporally

Method	Period	Subsidence rates (cm/year)
Leveling surveys	1982–1991	1–9
	1991–1997	1–25
GPS surveys	1997–2010	1–28
InSAR	2006–2007	1–12

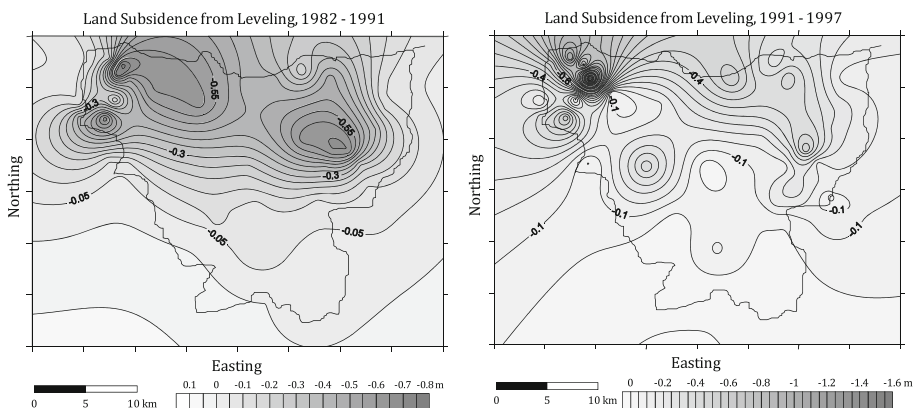


Fig. 4 Land subsidence in Jakarta measured from leveling surveys (in meters), over the periods of 1982–1991 (*left*) and 1991–1997 (*right*); from Abidin et al. (2001). Kriging method was used for interpolating the data

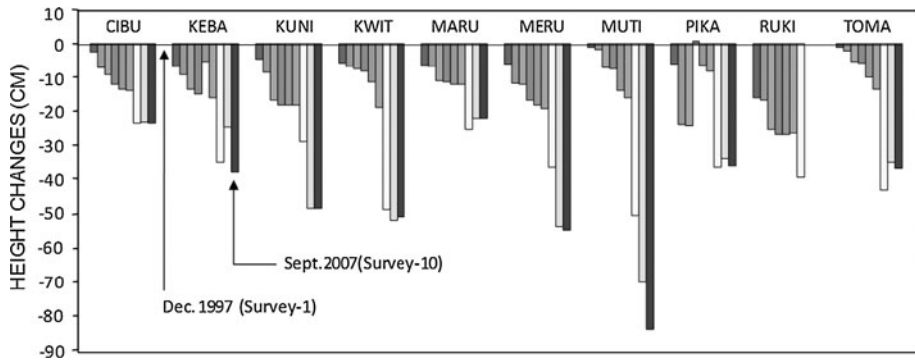


Fig. 5 Accumulated GPS-derived subsidence (cm) during the period of Dec. 1997 to Sept. 2007. The baseline elevations are those from GPS Survey-1 (Dec.1997)

A more comprehensive review of GPS-derived land subsidence in Jakarta during the period of 1997–2005 can be seen in Abidin et al. (2008a). The subsidence rates during the periods of 2007–2008, 2008–2009, and 2009–2010 are shown in Fig. 6, with the maximum rates of about -28, -14, and -16 cm/year, respectively.

Example of InSAR-derived land subsidence in northern part of Jakarta, over the period of June 2006 to February 2007, is shown in Fig. 7. In this figure, subsidence is calculated by multiplying the number of color fringes by 11.8 cm. This figure shows that subsidence along the coastal zone of Jakarta has a spatial variation. After correlation with GPS results, it was found that the maximum InSAR-derived subsidence rates for the 8 month period between InSAR measurements reached about 12 cm/year. This subsidence rate is comparable with the rate observed by the GPS and leveling surveys in the same period.

Please note in Fig. 7, that of the area showing the largest land subsidence in this (2006–2007) period is located in Pantai Mutiara housing complex. The GPS station MUTI is located in this area and, as shown in previous Fig. 5, this station also experienced large subsidence, i.e., about 80–90 cm during the period of December 1997 and September 2007.

4 Urban development and land subsidence

Land subsidence in Jakarta can be caused by four factors, namely: excessive groundwater extraction, load of buildings and constructions, natural consolidation of alluvium soil, and tectonic activities. Up to now, there is no information yet about the contribution of each factor on the subsidence at each location and their spatial (contribution) variation. In case of Jakarta, tectonic activities seem to be the least dominant factor, while excessive groundwater extraction is considered to be one of dominant factor. Tectonic causes were excluded in this case, since at this time, there is no strong evidence on the existence of active (normal or thrust) faults in Jakarta region (Harsolumakso 2001). The first three factors will have close relation with urban development activities in Jakarta and its surrounding areas.

4.1 Increase in population and built-up areas

Urban development in Jakarta is going-on rapidly. According to (Firman and Dharmapatni 1994), Jakarta has been the most attractive area in Indonesia for domestic and direct

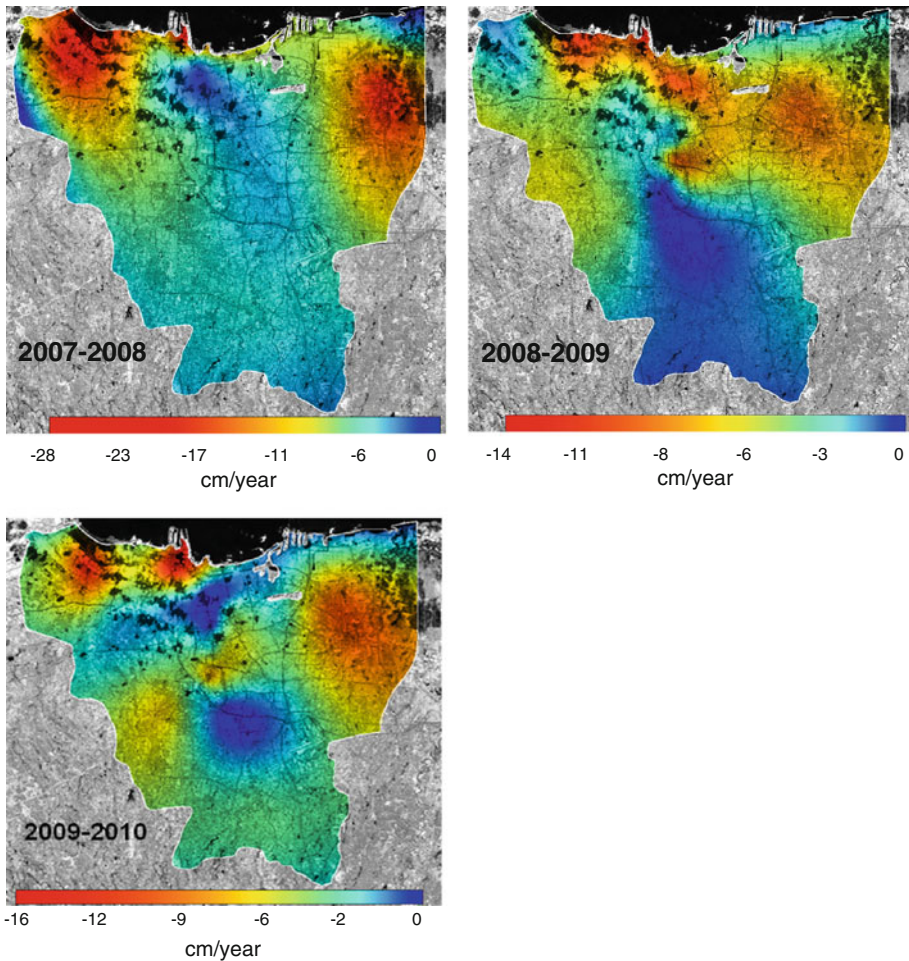
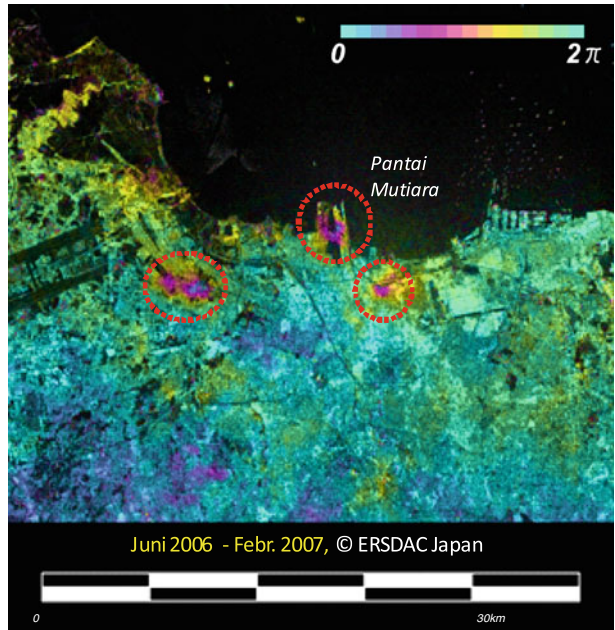


Fig. 6 GPS-derived land subsidence rates in Jakarta, during the periods of 2007–2008 (*upper left*), 2008–2009 (*upper right*), and 2009–2010 (*lower left*). Kriging method was used for interpolating the data

foreign investment because of its better infrastructure, high concentration and access to mass markets, pool of skilled labor and entrepreneurs, and high access to the decision makers. The economic activities in the region have grown very rapidly, especially in industry, trade, transportation, real estate, and many other sectors and have also spilled over into the adjacent areas of Jakarta Metropolitan Region (JMR), such as Bogor, Tangerang, Depok, and Bekasi. Nowadays, JMR is the largest concentration of urban population and economic activities in Indonesia, consisting of about 80% urban population and 20% rural population (Firman 2004). It then increases the urbanization rates into Jakarta and surrounding areas and population of Jakarta growth rapidly. Consequently, coverage of the built-up areas is increased and the green areas are decreased. Built-up areas of Jakarta in 2008 cover about 90% of the region.

According to (Lo Fu-chen and Yue-man Yeung [Eds] 1995), in 1948, the population of Jakarta was about 2 million, with a built-up area of 20,000 ha (about 30%), including

Fig. 7 InSAR-derived subsidence in the northern part of Jakarta using ALOS PALSAR data



Kebayoran Baru, a new town in the south. In 1965, the population of Jakarta was about 4 million, with a built-up area of 35,000 ha (about 53%). By 1980, Jakarta has a population of 6.5 million, and it was by this time that the influence of the city on the region (rather than simply on its fringes) was clearly demonstrated. In 2010, the population of Jakarta and JMR has already reached 9.6 and 27.9 millions, respectively. The population growth of Jakarta and JMR is shown in Table 2.

The increase in population and urban development activities in Jakarta lead to increase in built-up areas and decrease in green areas. New residential areas, industries, condominiums, malls, hotels, commercials, and office buildings have proliferated in Jakarta in

Table 2 Population growth of Jakarta and JMR (Lo Fu-chen and Yue-man Yeung [Eds] 1995; BPS 2011)

Jakarta (special capital territory of Jakarta) with area about 660 km ²			Jakarta metropolitan region, JMR (Jakarta, Bogor, Tangerang, and Bekasi) with area about 7,500 km ²		
Year	Population ('000)	Mean density ('000/km ²)	Year	Population ('000)	Mean density ('000/km ²)
1948	≈2,000	3.0	1971	8,374	1.1
1961	2,973	4.5	1980	11,485	1.5
1971	4,579	6.9	1990	17,105	2.3
1980	6,503	9.9	2000	20,438	2.7
1990	8,259	12.5	2010	27,940	3.7
1995	9,113	13.8			
2000	8,389	12.7			
2005	8,864	13.4			
2010	9,588	14.5			

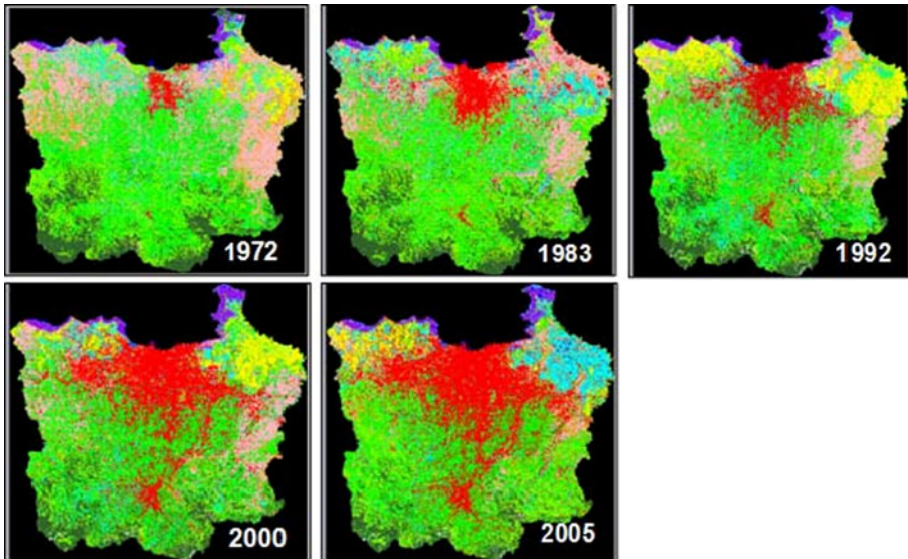


Fig. 8 Expansion of built-up areas in Jakarta and its surrounding areas. (Djakapermana 2008). Red color indicates the built-up areas

the last three decades. In 2006, there are already 306 hotels, in which 135 are star (classified) hotels, and 1955 large and medium manufacturing companies in Jakarta (BPS Jakarta 2007). In 2004, Jakarta already had 73 large shopping malls, besides some 116 department stores, 125 super markets and 151 traditional markets (Steinberg 2007). The areas of shopping malls in Jakarta have significantly increased from 1.4 million m² in 2000 to 2.4 million m² in 2005 (Firman 2009).

Unfortunately, these developments mostly occupied the available green areas in Jakarta. In 1965, the green areas made up more than 35 percent of the Jakarta's area and currently account for only 9.3 percent of the area (Rukmana 2008). Several new towns have also been developed along the perimeter of Jakarta and its surrounding areas which also increase the coverage of built-up areas in the region. Figure 8 shows the sharp increase in coverage of built-up areas in Jakarta since 1972–2005.

This increase in built-up areas directly affects the water recharge areas and rechargeability of withdrawn groundwater in Jakarta and its surrounding areas. Coupled with the increase consumption of groundwater due to increase in population and economic and industrial activities, the (ground and surface) water system in Jakarta and its surrounding areas are severely affected. In turn, it will contribute to occurrence of land subsidence phenomena in several locations inside Jakarta, as depicted by Fig. 9.

4.2 Excessive use of groundwater

The population growth and increase in economic activities in Jakarta and its surrounding region lead to the increase in water need. Unfortunately, about 64% of water need in Jakarta is fulfilled by groundwater extraction (Ali 2011), either because piped treated surface water supplies were inadequate or because it was substantially cheaper to do so (Colbran 2009). For the same reason, this over discharging of groundwater would deepen

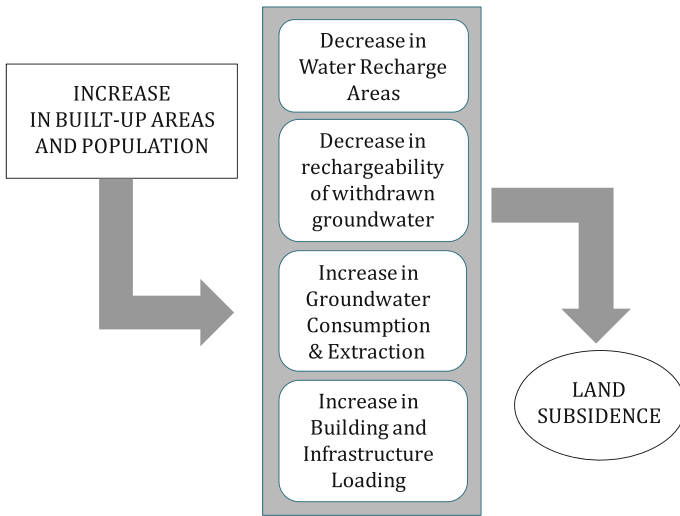


Fig. 9 Relation between the increase in built-up areas and population with land subsidence

the piezometric water level inside the aquifers and in turn would cause land subsidence above it.

Three aquifers are recognized within the 250 m thick sequence of Quaternary sediment of the Jakarta basin, namely: the Upper Aquifer, an unconfined aquifer, occurs at a depth of less than 40 m; the Middle Aquifer, a confined aquifer, occurs at a depth between 40 and 140 m; and the Lower Aquifer, a confined aquifer, occurs at a depth between 140 and 250 m (Soetrisno et al. 1997; Hadipurwo 1999). The geologic materials confining these aquifers are silt and clay. Inside those aquifers, the groundwater generally flows from south to the north (Lubis et al. 2008). Below a depth of 250 m, an aquifer in the Tertiary sediments also has been identified. But according to Murdohardono and Tirtomihardjo (1993), it is less productive and its water quality is relatively poor.

The groundwater extraction in Jakarta could be categorized into shallow (<40 m) and deep (>40 m) extraction. Shallow extraction is through dug wells or driven wells, operated with buckets, hand pumps, or small electrical pumps; whereas the deep extraction is mostly from drilled wells. Shallow extraction is mostly done by the population. It is well spread over the area, but its extraction rate per well is relatively low. Deep extraction is usually conducted by industry. It is usually more concentrated and has a relatively high extraction rate per well. The number of registered drilled wells in Jakarta was about 3,700 wells in 2007 (see Fig. 10). Based on the studies done by Murdohardono and Tirtomihardjo (1993), from the sample of 197 drilled wells in Jakarta, out of 2,800 registered drilled wells at that time, 156 wells (79%) are extracting groundwater from depths between 40 and 140 m, and 41 wells (21%) are extracting from depths between 140 and 250 m.

The registered groundwater extraction in Jakarta varies from just 3 Qabs (million m³) in 1,879 up to maximum of 34 Qabs in 1994, down to 17 Qabs in 1998 after the Indonesian economic crisis of 1997, and then go up again to about 22 Qabs in 2007 (see Fig. 10). It should be pointed out here that these numbers may not reflect the real groundwater extraction in Jakarta basin. According to Soetrisno et al. (1997), the unregistered deep groundwater extraction in Jakarta can be as high as 50% or even more. This excessive groundwater pumping will usually lead to the deepening of the piezometric water level

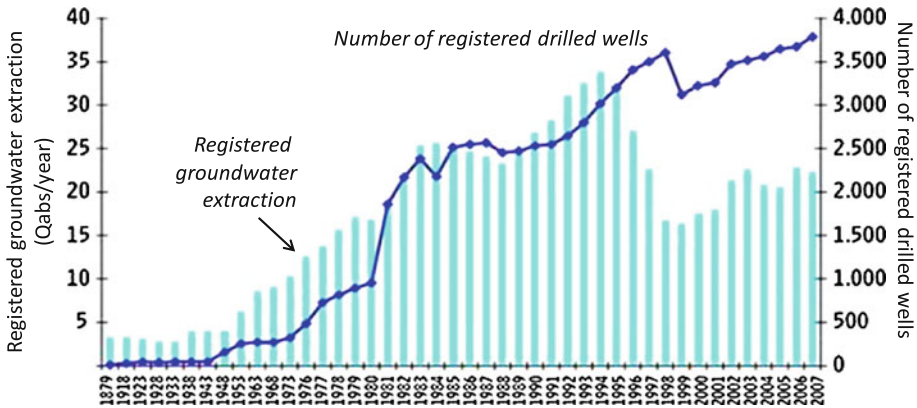


Fig. 10 Groundwater extraction in Jakarta from 1879 to 2007; adapted from Kompas (2010)

inside the middle and lower aquifers. 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 1970s and then deepened significantly to 30–50 m below sea level in 1990s.

The subsidence rate is closely related to the rate of piezometric water level (head) deepening in the middle and lower aquifers. In the case of Jakarta, the increases in both population and industry, which require a lot of groundwater, could explain the above declining trend of piezometric heads, as shown in Fig. 11.

The correlation between land subsidence and excessive groundwater taking in Jakarta can be illustrated using the subsidence results obtained from leveling surveys. Previous Fig. 4 shows the observed land subsidence during the period of 1982–1991 and 1991–1997. If we compare Figs. 11 and 4, it can be realized that the cones of piezometric level depressions inside the middle and lower aquifers more or less coincide with the cones of largest land subsidence measured by the leveling. It should also be noted here that in those areas of subsidence cones, due to their high soil compressibility, the situation could be worse with the settlement caused by the load of constructions.

The groundwater level inside the middle and lower aquifers at several locations in Jakarta continue to decline. Table 3 shows that the groundwater levels are decreasing with

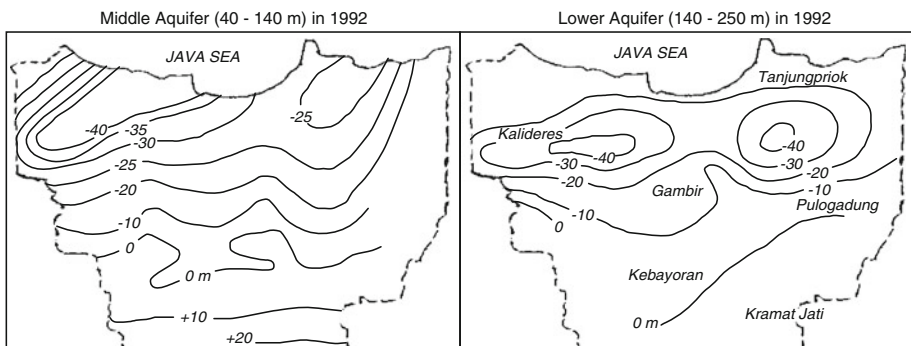


Fig. 11 Piezometric water-level contours (in meters) inside Middle and Lower Aquifers of Jakarta in 1992; adapted from [Murdohardono and Tirtomihardjo 1993]

Table 3 Groundwater level changes and GPS-derived subsidences at several locations in Jakarta

Groundwater level changes				GPS-derived subsidence		
Location	Aquifer	Rates (m/year)	Period	Closest station	Rates (cm/year)	Period
Cilincing (KBN)	Middle	-0.57	2002–2007	MARU	-4.8	2002–2005
Kamal muara	Lower	-0.71	2002–2005	KAMR	-4.3	2001–2002
Kapuk	Middle	-0.75	2002–2007	PIKA	-10.2	2002–2005
					-11.7	2007–2010
Sunter-3	Middle	-0.34	2002–2007	KLGD	-5.3	2002–2007
Sunter-1	Lower	-1.44	2002–2007		-10.1	2007–2010
Tegal Alur	Middle	-0.45	2002–2007	KLDR	-5.3	2002–2005
Tongkol-5	Upper	0.13	2002–2006	RUKI	-4.9	2002–2005
Tongkol-9	Middle	0.52	2002–2007	RUKI	-4.5	2007–2010
Tongkol-8	Lower	-0.87	2002–2007	TNKL	-7.8	2009–2010
Joglo	Middle	-1.73	2002–2007	MERU	-7.8	2002–2007
Parkir Gd. Jaya	Lower	-1.01	2002–2007	CKNI	-5.4	2007–2010
Atrium, Senen	Middle	-1.26	2002–2007	KWIT	-6.0	2002–2007
Bapedalda Kngn	Upper	-0.14	2002–2007	KUNI	-6.8	2002–2007
Dharmawangsa	Middle	-0.31	2002–2007	KEBA	-4.2	2002–2007
PT. Yamaha M-2	Middle	-1.92	2002–2007	PLGD	-12.3	2001–2002

rates of about 0.1–1.9 m/year over the period of 2002–2007. In comparison with GPS-derived subsidences, it can be seen that the large subsidences are usually associated with the relatively high rates of groundwater level change rates. However, the relation between land subsidence and localized groundwater level decrease will not always be a direct and simple relation. A more detail explanation on GPS-derived subsidence and its relation with groundwater extraction is given in Abidin et al. (2010a).

It should be realized, however, that in the shorter time scale, the groundwater level changes inside the Jakarta aquifers are quite dynamic (Abidin et al. 2010a). These groundwater levels can go up and down up from several decimeters to a few meters in a year. The effect of this short-term variation in groundwater level inside the aquifers on the long-term subsidence phenomena in the Jakarta area and its spatial variations are not yet fully understood. More research is needed to study and clarify this matter.

4.3 Coastal development

Coastal area of Jakarta has also experienced extensive urban development. Many establishments take place in this coastal region, such as sea port, coastal resort, golf course, residential areas, industries, condominiums, malls, hotels, and commercial and office buildings (see Fig. 12). Some areas have also been reclaimed to accommodate more coastal development initiatives. It should be pointed out that the observed land subsidences along the coastal areas of Jakarta are relatively have larger rates, as indicated in previous Figs. 4 to 7.

GPS-derived subsidence rates for the coastal station of MUBA, MUTI, and PIKA (shown in Fig. 12) in the period of 2008–2009 are -14, -10, and -11 cm/year, respectively. In the period of 2007–2008, the rates are even larger, i.e., -28, -15, and



Fig. 12 Part of coastal areas of Jakarta, courtesy of Google Earth. In this figure, MUBA, MUTI, and PIKA are GPS stations with relatively large subsidence rates

–18 cm/year, respectively. In the latest observation period of 2009–2010, the rates are –15, –8, and –7 cm/year, respectively. Relatively large subsidence in the coastal areas will certainly affect the coastal development of Jakarta.

Considering the sea-level rise phenomena, coastal subsidence in Jakarta will certainly affect coastal development in Jakarta (Abidin et al. 2010a). Considering the relatively flat nature (i.e., 0–2 m above MSL) of most coastal areas of Jakarta, this combined effect of land subsidence and sea-level rise will certainly have disastrous consequences for habitation, industry, and fresh groundwater supplies from coastal aquifers. During high tides, tidal flooding is already affecting some of these coastal areas, as shown in Fig. 13. The extent and magnitude of subsidence-related flooding will worsen with the likely continuation of sea-level rise along the coastal area of Jakarta, which has the rate of about 4–5 mm/year (Nurmaulia et al. 2010).

4.4 Impacts of subsidence to urban development

Impacts caused by land subsidence to urban development in Jakarta can be seen in several forms. The differential subsidence nature in Jakarta basin may introduce the cracking and damage in buildings and infrastructure and may change the flow pattern of surface water. Subsidence may also enlarge the (tidal) flooding inundation areas, and in general will deteriorate their environmental quality. Subsidence along several coastal areas of Jakarta also makes them more vulnerable toward sea-level rise phenomena. Figure 14 shows several indications of land subsidence phenomena in Jakarta.

In case of Jakarta, which is actually prone toward flooding, subsidence phenomena has to be fully understood for flood management system. Land subsidence will decrease elevation of the dikes and drainage system. It will reduce the function of city drainage system in the subsidence affected areas and may introduce flooding during the rainy season. During the period between 1993 and 2007, at least there are four big floods in Jakarta, namely on January 9–10, 1993, February 1996, January 26–February 1, 2002, and February



Fig. 13 Flooding in the coastal areas of Jakarta; around PIKA GPS station (above) and around MUBA GPS station (below)

4–14, 2007 (Texier 2008). Figure 15 shows in general the flood inundation areas of the 2002–2007 flooding.

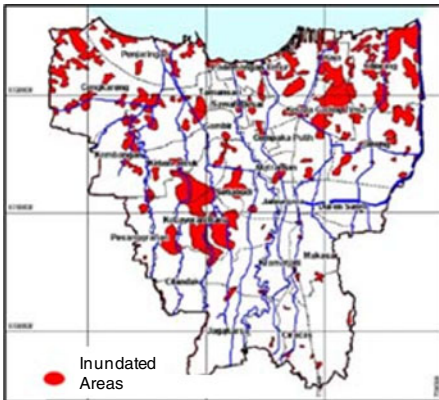
If the flooding inundation areas in Fig. 15 are compared with the previous subsidence information as derived by Leveling, GPS, and InSAR techniques; the correlation between land subsidence and flooding inundation can be seen in the western and eastern parts of North Jakarta region. In other areas, however, the correlation is quite weak, and in this case, the inundation areas are mainly located along the flooded rivers.

5 Closing remarks

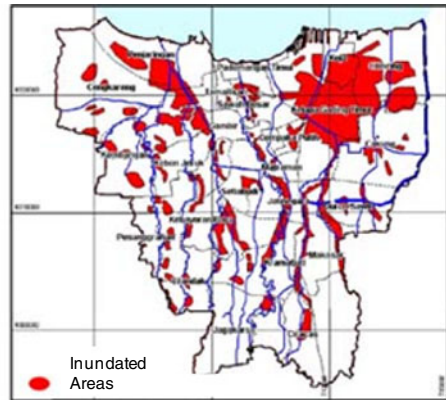
The results obtained from leveling surveys, GPS surveys, and InSAR technique over the period between 1982 and 2010 show that land subsidence in Jakarta has spatial and temporal variations. In the areas affected by land subsidence, in general, the observed subsidence rates are about 1–15 cm/year and can be up to 20–28 cm/year at certain location and certain period. There is a strong indication that land subsidence in Jakarta area is governed by the excessive groundwater extraction from the middle and lower aquifers, besides also by building/construction load and natural consolidation of sedimentary layers. The excessive groundwater extraction causes the rapid decrease in groundwater level inside the aquifers and in turn causes the land subsidence above it. However, the relation between land subsidence and groundwater level decrease inside the aquifers in certain location will not always be a direct and simple relation.



Fig. 14 Several indication and impact of land subsidence in Jakarta (Wirakusumah 2008). **a** and **b** are locations in Kamal Muara; **c** and **d** are locations along the highway to the airport (Cengkareng)



Flooding of 2002, courtesy of LAPAN



Flooding of 2007, courtesy of Kompas (10 Feb. 2007)

Fig. 15 Flooding inundation areas in Jakarta

Land subsidence in Jakarta has a strong linkage with urban development process. Urban development in Jakarta causes increases in built-up areas, population, economic and industrial activities, and also groundwater extraction. These increases can then lead to land subsidence phenomena. In other side, the existing land subsidence phenomena will affect and should be considered in urban development process itself. In this case, land use

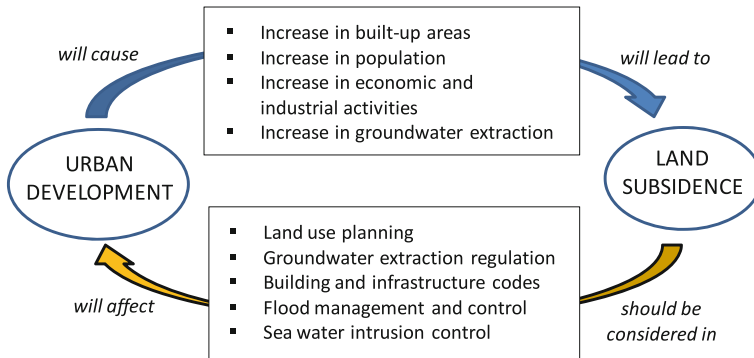


Fig. 16 Urban development and land subsidence relation in Jakarta

planning, groundwater extraction regulation, building and infrastructure codes, flood management and control, and seawater intrusion control are examples of several urban development aspects that will be related with land subsidence phenomena. In general, relation between urban development and land subsidence in Jakarta can be illustrated by Fig. 16.

Finally, it can be concluded that more data and further investigation are required to understand the detail and comprehensive relationship between land subsidence and urban development in the Jakarta basin. Additional causes of subsidence, e.g., load of buildings and construction, natural consolidation of alluvium soil, and tectonic movements, should also be investigated and taken into account. Further research on the impacts of land subsidence in Jakarta should also be systematically conducted, especially in relation with the flooding inundation areas and also with the coastal flooding in relation with sea-level rise phenomena. Several areas along the coast of Jakarta already have experienced tidal flooding during high tide periods. The adaptation measures to reduce the impacts of this phenomenon, therefore, should be developed as soon as possible.

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