Land Subsidence and Urban Development in Jakarta (Indonesia)

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Key words: Jakarta, Land Subsidence, Urban Development, Leveling, GPS, InSAR

SUMMARY

Jakarta is the capital city of Indonesia with a population of about 9 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 increase urban development introduce 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. Over the period of 1982–1997, subsidence ranging from 20 to 200 cm is evident in several places in Jakarta. In general the land subsidence exhibits spatial and temporal variations, with the rates of about 1 to 15 cm/year. A few locations can have the subsidence rates up to about 20-25 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. This paper discusses the relation between land subsidence and urban development activities in Jakarta.

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1. INTRODUCTION

The city of Jakarta has a population of about 9 million people [*BPS Jakarta,* 2007], inhabiting an area of about 661.52 km2. During the day, the population can increase to about 13 million. Jakarta is centered at the coordinates of about -6°15' (latitude) and +106°50' (longitude) and, located on the lowland of the northern coast of the West Java province, as shown in Figure 1. 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).

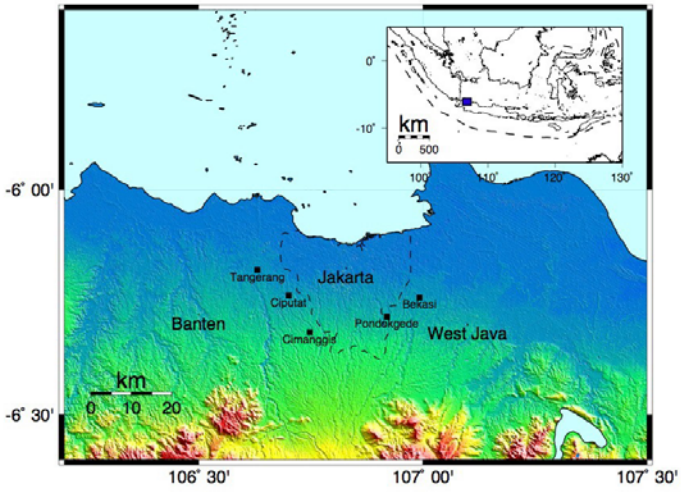


Figure 1. Jakarta and its surrounding areas

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 channels, which run perpendicular to the coastline. There also 13 natural and artificial rivers flowing through Jakarta, namely Cisadane, Citarum, Ciliung, Angke, Krukut, Sunter, Bekasi, Cakung, Karawang, Cikarang, Ciranjang, Cimancuri and Cidurian.

In terms of geological and hydrological settings, according to *Yong et al.* (1995), the Jakarta basin consists of a 200 to 300 m thick sequence of Quaternary deposits which overlies Tertiary sediments. The top sequence is thought to be the base of the groundwater basin. The Quaternary sequence can be further subdivided into three major units, which, in ascending order are: a sequence of Pleistocene marine and non-marine sediments, a late Pleistocene volcanic fan deposit, and Holocene marine and floodplain deposits. Three aquifers are recognized inside a 250 m thick sequence of quaternary sediment of the Jakarta basin, namely [*Soetrisno et al.*,1997; *Hadipurwo,*1999] : 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. 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 sediment was also found. But according to *Murdohardono and Tirtomihardjo* (1993), it is less productive and its water quality is relatively poor.

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 increase urban development introduce 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 and COD in most of the rivers flowing through the Jakarta 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. Figure 2 illustrates the possible relation between land subsidence and urban development in Jakarta.

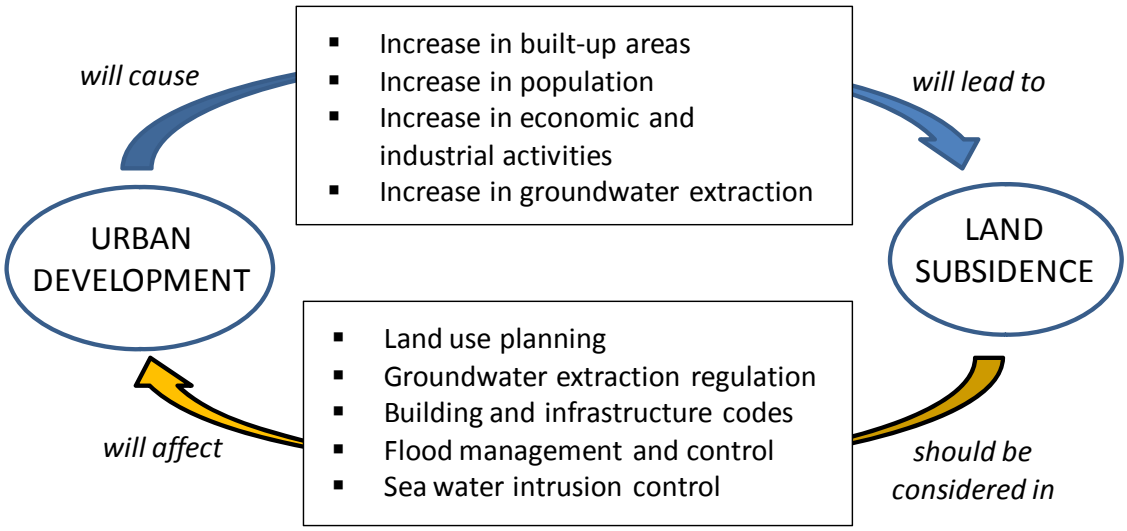


Figure 2. Urban development and land subsidence relation in Jakarta

Land subsidence is a real phenomenon in Jakarta. Over the period of 1982–1997, subsidence ranging from 20 to 200 cm is evident in several places in Jakarta. In general the land subsidence exhibits spatial and temporal variations, with the rates of about 1 to 15 cm/year. A few locations can have the subsidence rates up to about 20-25 cm/year. 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 the following sub-chapters, the relation between land subsidence and urban development activities in Jakarta will be discussed and analyzed.

2. 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 & Tirtomihardjo,* 1993; *Murdohardono & 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 flooding areas, malfunction of drainage system, increased inland sea water intrusion and increased tidal flooding coverage.

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 (see Figure 3), 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 becomes necessary.

Since the early 1980's, the land subsidence in several places of Jakarta has been measured using several measurement techniques, e.g. leveling surveys, extensometer measurements, ground water level observations, GPS surveys, and InSAR technique [*Abidin,* 2005; *Abidin et al.,* 2001, 2004, 2008a, 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 results obtained from leveling surveys, GPS surveys and InSAR technique over the period between 1982 and 2008 show that land subsidence in Jakarta has spatial and temporal variations. In general the observed subsidence rates are about 1 to 15 cm/year, and can be up to 20-25 cm/year at certain location and certain period. The summary of subsidence rates in Jakarta is given in Table 1. The more comprehensive results can be seen in *Abidin et al.* (2001, 2008a, 2008b).

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

Method	Period	Subsidence Rates (cm/year)
Leveling surveys	1982-1991	0 - 9
	1991-1997	0 - 25
GPS surveys	1997 - 2008	0 - 25
InSAR	2006 - 2007	0 - 12

3. 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. The first three factors will have close relation with urban development activities in Jakarta and its surrounding areas.

3.1 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 foreign investment because of its better infrastructure, high concentration and access to mass markets, pool of skilled labour 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, such as Bogor, Tangerang, Depok and Bekasi. 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. Nowadays, most areas of Jakarta are built-up areas, as shown in Figure 3.

Figure 3. Built-up areas of Jakarta in 2008, which cover about 90% of the region.

According to [*Lo and Yeung,* 1995], in 1948 the population of Jakarta was about 2 million, with a built-up area of 20,000 ha, including 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. By 1980, Jakarta occupied 65,400 ha with 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. The 1990 Population Census showed that Jakarta had 8.2 million inhabitants. The population growth of Jakarta is shown in Table 2. In 2006, the population density has reached about 13,500 peoples/km^2, which make Jakarta the densest region in Indonesia.

Table 2. Population growth of Jakarta [*Lo and Yeung,* 1995; *BPS Jakarta,* 2007]

Year	Population ('000)	Year	Population ('000)
1948	≈ 2,000	2002	8,379
1961	2,973	2003	8,603
1971	4,579	2004	8,725
1980	6,503	2005	8,864
1990	8,259	2006	8,961

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 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].

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 4 shows the sharp increase in coverage of built-up areas in Jakarta since 1972 to 2005.

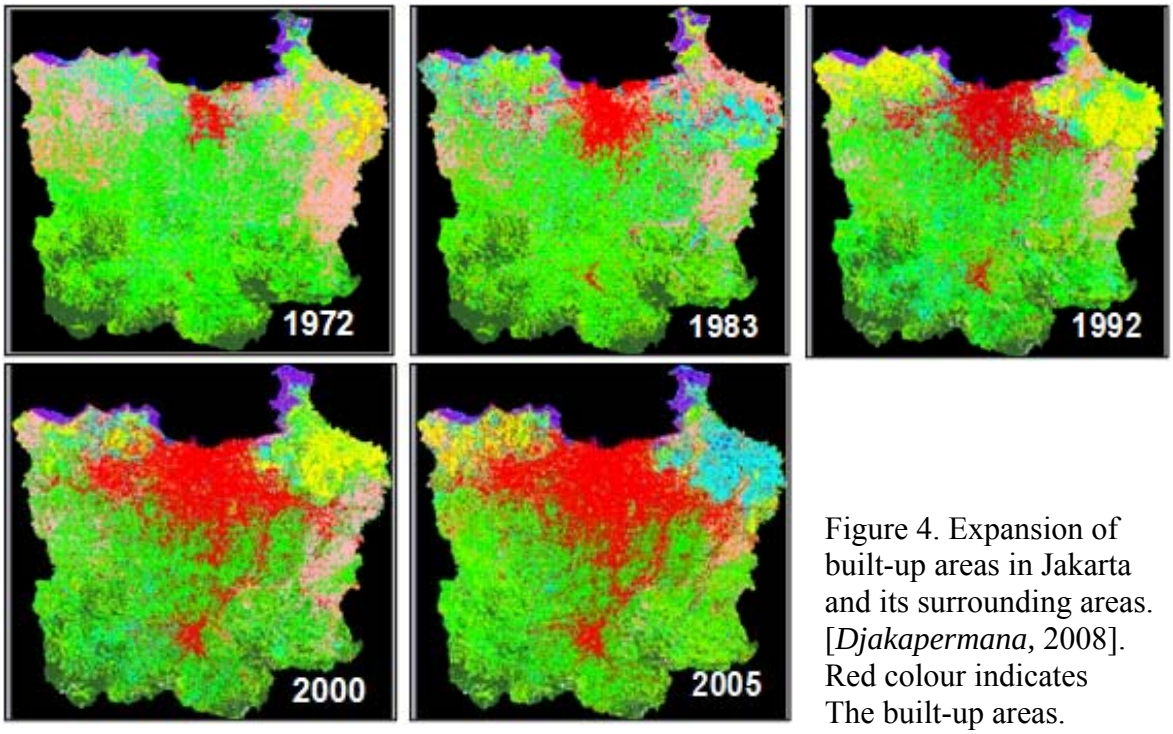


Figure 4. Expansion of built-up areas in Jakarta and its surrounding areas. [*Djakapermana*, 2008]. Red colour indicates The built-up areas.

This increase in built-up areas directly affect 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 contributes to occurance of land subsidence phenomena in several locations inside Jakarta, as will be explained in the following section.

3.2. 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 most of water consumption in Jakarta is fulfilled by groundwater extraction. This over discharging of groundwater would deepen the piezometric water level inside the middle and lower aquifers and in turn would cause land subsidence above it.

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. According to *Sudibyo* (1999), the number of registered drilled wells in Jakarta was 3626 wells in 1998. Based on the studies done by *Murdohardono and Tirtomihardjo* (1993), from the

sample of 197-drilled wells in Jakarta, out of 2800 registered drilled wells at that time, 156 wells (79%) are extracting groundwater from depths between 40 m and 140 m, and 41 wells (21%) are extracting from depths between 140 m and 250 m.

The registered groundwater extraction in Jakarta varies from just 3 Qabs (million m^3) in 1900 up to maximum of 33.8 Qabs in 1994, and then down to 16.9 Qabs in 1998. It should pointed out here that, these numbers may not reflect the real groundwater extraction in Jakarta basin. According to *Soetrisno* (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 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 1970's, and then deepened significantly to 30-50 m below sea level in 1990's.

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 Figure 5.

The corelation between land subsidence and excessive groundwater taking in Jakarta can be illustrated using the subsidence results obtained from leveling surveys. Figure 9 shows the observed land subsidence during the period of 1982-1991 and 1991-97. Maximum subsidence during the period of 1982-1991 is about 80 cm, while for the period of 1991-97 is about 160 cm. In general the subsidence rates in Jakarta area during this period is about 1-5 cm/year and can reach 26 cm/year at several locations. During the period between 1982 and 1991, the maximum rate of subsidence is about -8 cm/year, while during the period between 1991 and 1997 it is about -26 cm/year. More comprehensive results on leveling-based subsidence in Jakarta can be seen in *Abidin et al.* (2001).

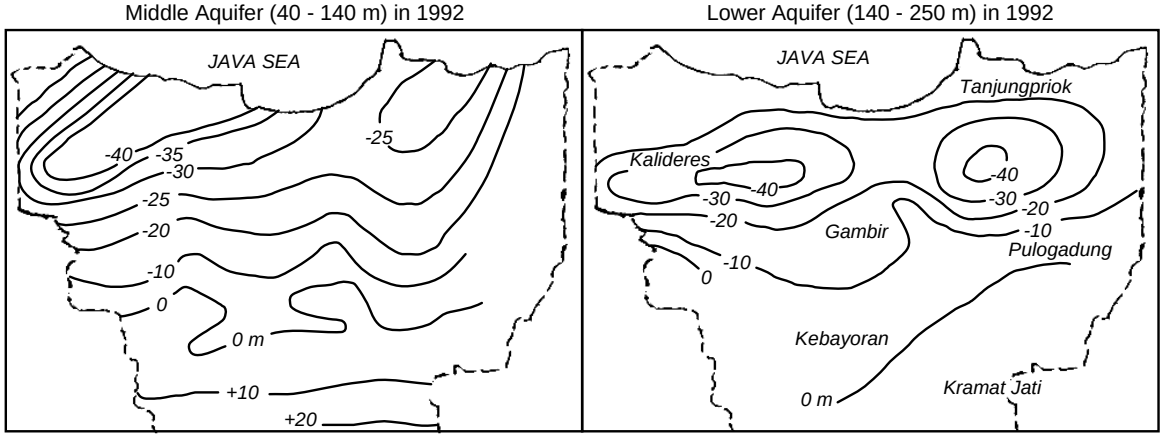


Figure 5. Piezometric water level contours (in metres) inside Middle and Lower Aquifers of Jakarta in 1992; adapted from [*Murdohardono and Tirtomihardjo,* 1993].

If we compare Figures 5 and 6 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.

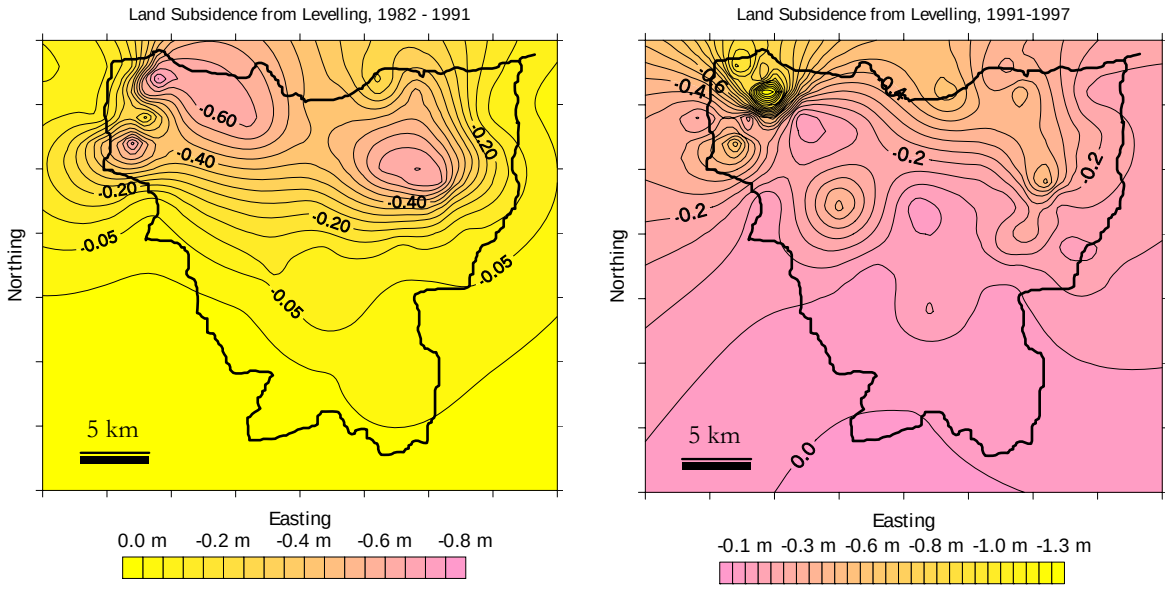


Figure 6. Land subsidence in Jakarta measured from leveling surveys (in metres), Over the periods of 1982 – 1991 (left) and 1991 – 1997 (right) [Abidin et al, 2001].

The groundwater level inside the middle and lower at several locations in Jakarta are seems still decreasing up to now. The groundwater level are decreasing with the rates of about 0.2 to 2 m/year over the period of 2002 to 2007 [*Abidin et al.*, 2008b]. In comparison with GPS-derived subsidences, it can be seen that the large subsidences are usually associated with the realtively high rates of groundwater level change rates. A more detail explanation on GPS-derived subsidence and its relation with groundwater extraction is given in [*Abidin et al,* 2008a; 2008b].

3.3 Coastal Development

Coastal area of Jakarta has also experienced extensive urban development. Many establishments take places in this coastal region, such as sea port, coastal resort, golf course, residential areas, industries, condominiums, malls, hotels, and commercials and office buildings. Some areas haev also been reclaimed to accomodate 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. Therefore it will somehow affect the coastal development of Jakarta.

Figure 8 shows land subsidence in northern part of Jakarta detected by InSAR over the period of June 2006 to February 2007. This Figure shows that subsidence along the coastal zone of Jakarta has a spatial variation, with subsidence rates can reach about 12 cm/year. Please note in this Figure, that one cone of deepest subsidence is located in Pantai Mutiara housing complex, which is actually a land reclamation area.

The GPS derived subsidence result (see Figure 9) also show the relatively higher subsidence rates in the western and central parts of Jakarta coastal areas, during the period of Sept. 2007 to August 2008.

Figure 7. Part of coastal areas of Jakarta.

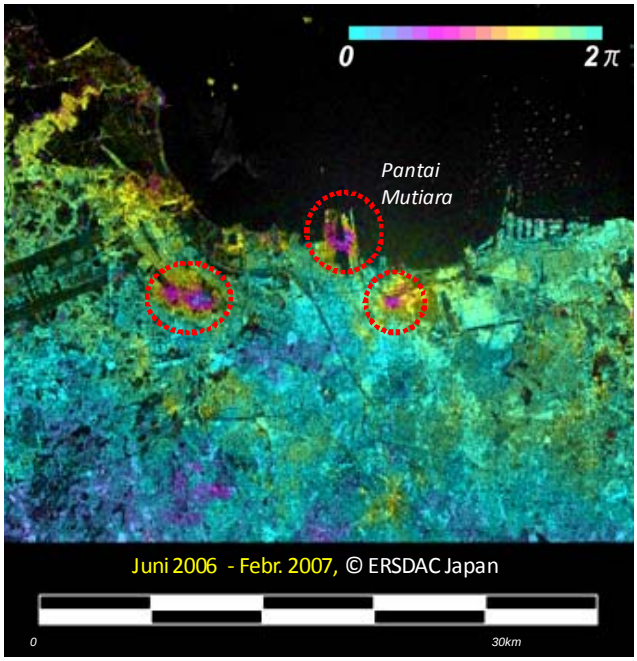


Figure 8. InSAR-derived subsidence in the northern part of Jakarta using ALOS PALSAR data.

Considering the sea level rise phenomena, coastal subsidence in Jakarta will certainly affect coastal development in Jakarta. Considering the relatively flat nature (i.e. 0-2 m above MSL) of most coastal areas of in Jakarta, this combined effect of land subsidence and sea level rise will certainly be have disastrous consequences for habitation, industry, and fresh groundwater supplies from costal aquifers. During high tides, tidal flooding is already affecting some of these coastal areas. 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 is bordered by the Java sea.

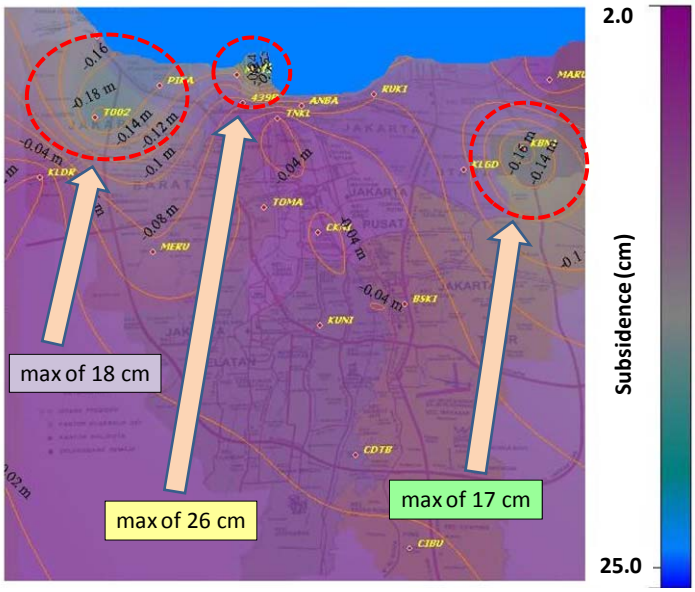
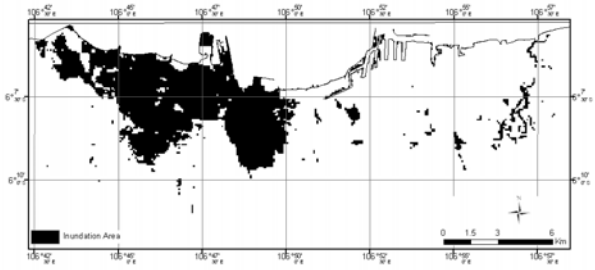
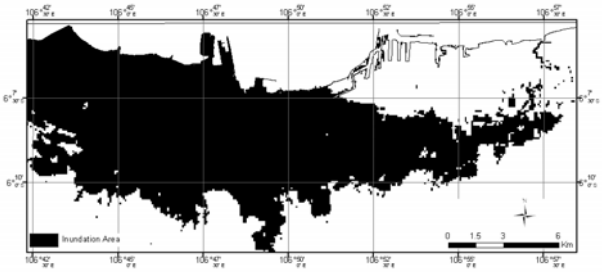


Figure 9. GPS derived subsidence during the period of Sept. 2007 to August 2008.

By utilizing the InSAR derived subsidence as shown in Figure 8 and the sea level rise rate of 2 mm/year [*Gornitz,* 1995; *IPCC,* 2007], the possible inundated areas can be estimated as shown in Figure 10.



Inundation areas in 2020 (in black); covering about 5,146.80 hectares



Inundation areas in 2050 (in black); covering about 16,237.87 hectares

Figure 10. Possible inundation areas in the coastal areas of Jakarta; with the assumption of spatially different subsidence rates along the coast and sea level rise rate of 2 mm/year.

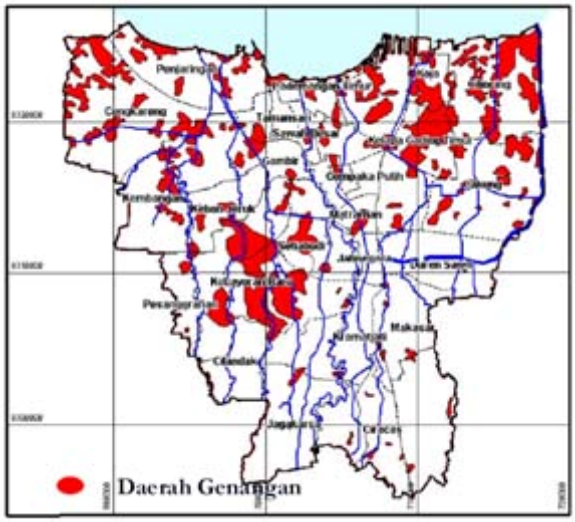
3.4 Impacts of Subsidence to Urban Development

Impacts caused by land subsidence to urban development in Jakarta can be seen in several forms. The differential subsidence nature in Jakarta basin my 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

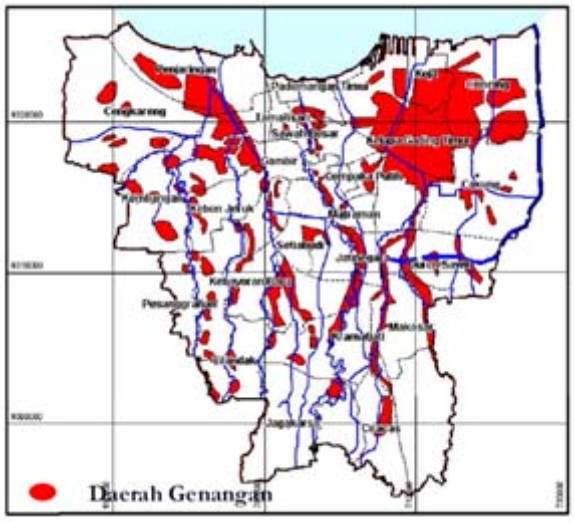
makes them more vulnerable toward sea level rise phenomena. Figure 11 shows several indications of land subsidence phenomena in Jakarta.

Figure 11. 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).

In case of Jakarta, which is actually prone toward flooding, subsidence phenomena has to be fully understood for flood management system. During the period between 1993 and 2007, at least there are four big floods in Jakarta, namely on 9-10 January 1993, February 1996, 26 January - 1 February 2002, and 4 – 14 February 2007. Figure 12 shows in general the flood inundation areas of the 2002 and 2007 flooding.



Flooding of 2002, courtesy of LAPAN



Flooding of 2007, courtesy of Kompas (10 February)

Figure 12. Flooding inundation areas in Jakarta.

If the flooding inundation areas in Figure 12 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.

4. CLOSING REMARKS

The results obtained from leveling surveys, GPS surveys and InSAR technique over the period between 1982 and 2008 show that land subsidence in Jakarta has spatial and temporal variations. In general the observed subsidence rates are about 1 to 15 cm/year, and can be up to 20-25 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 cause the land subsidence above it. However, the relation between land subsidence and groundwater level decrease inside the acquifers in certain location will not always be a direct and simple relation.

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 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.

Finally it can be concluded that more data and further investigation is 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 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.

ACKNOWLEDGEMENTS

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