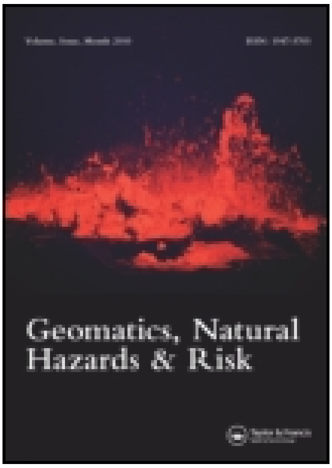

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H.Z. Abidin [a] , H. Andreas [a] , I. Gumilar [a] , T.P. Sidiq [a] & Y. Fukuda [b]

[a] Geodesy Research Group , Institute of Technology Bandung (ITB) Jl. Ganesha 10 , Bandung , Indonesia

[b] Graduate School of Science , Kyoto University , Kyoto , Japan

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Land subsidence in coastal city of Semarang (Indonesia): characteristics, impacts and causes

H.Z. ABIDIN†, H. ANDREAS†, I. GUMILAR†, T.P. SIDIQ† and Y. FUKUDA‡

†Geodesy Research Group, Institute of Technology Bandung (ITB) Jl. Ganesha 10, Bandung, Indonesia

‡Graduate School of Science, Kyoto University, Kyoto, Japan

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Semarang is the capital of Central Java province, located in the northern coast of Java island, Indonesia. Land subsidence in Semarang has been widely reported and its impacts can be seen already in daily life. Based on the estimation from Levelling, Interferometric Synthetic Aperture Radar (InSAR), Microgravity and Global Positioning System (GPS) survey methods, land subsidence with rates of up to about 19 cm/year were observed during the period of 1999 up to 2011. Results derived from GPS since 2008 up to 2011 show that land subsidence in Semarang has spatial and temporal variations, with spatial average rates of about 6 to 7 cm/year and maximum rates that can go up to 14–19 cm/year at certain locations. The northern region of Semarang along the coast exhibits higher rates of subsidence compared to its southern region, and this subsidence is believed to be caused by the combination of natural consolidation of young alluvium soil, groundwater extraction and load of buildings and constructions. The impact of land subsidence in Semarang can be seen in several forms, mainly the wider expansion of (coastal) flooding areas, cracking and damage of buildings and infrastructure, and increased inland sea water intrusion.

1. Introduction

Semarang is the capital city of Central Java province, located in the northern coast of Java island, Indonesia (see figure 1). It is centred at the coordinates of about $-6^\circ 58'$ (latitude) and $+110^\circ 25'$ (longitude), and covers an area of about 37,367 hectares or 374 km^2, with a population of about 1.55 million people in 2010 (BPS 2011).

Topographically, Semarang consists of two major landscapes, namely lowlands and coastal areas in the north and hilly regions in the south. The northern part, comprising the city centre, harbour, airport and railway stations, is relatively flat with topographical slopes ranging between 0° and 2°, and altitude between 0 and 3.5 m. The southern part includes slopes up to 45° and altitude up to about 350 m above sea level. The northern part has relatively higher population density and also has more industrial and business areas compared to the southern part. The land use of the southern part consists of residential housing, offices, retail, public use and

*Corresponding author. Email: hzabidin@gd.itb.ac.id

open space areas. Two rivers run through the city, one on the east side and another on the west which essentially divides the city into three parts.

Geologically, Semarang has three main lithologies, namely, volcanic rock, sedimentary rock and alluvial deposits. According to Sukhyar (2003), the basement of Semarang consists of Tertiary Claystone of the Kalibiuk Formation. Overlying this Formation is the Notopuro Formation which consists of Quaternary volcanic material. The two formations crop out in the southern part of the Semarang area. The northern part of the Semarang area is covered by Kali Garang deltaic alluvium up to a depth of 80 to 100 m in the coastal area. Aquifers are found at depths ranging from 30 to 80 m in this alluvium. The northern part of Semarang is composed of very young alluvium with high compressibility. According to Barry (2001) and Geological Research and Development Centre of Indonesia (GRDC 1996), the alluvial deposits found in coastal areas of Semarang consist of beach, floodplain, tidal, near-shore, and alluvial fan deposits, as illustrated in figure 2. Several studies (Van Bemmelen 1949, Marfai *et al.* 2008) have reported that in the

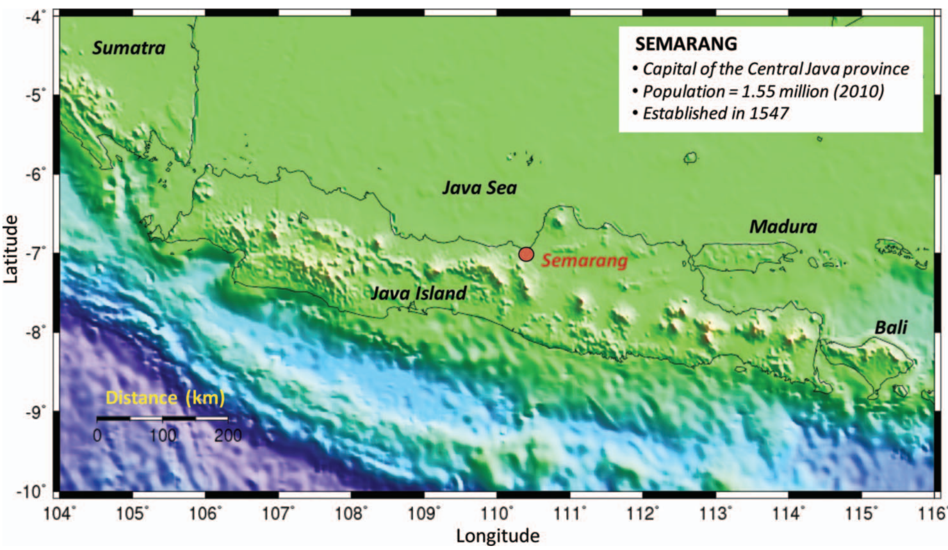

Figure 1. Geographical location of Semarang.

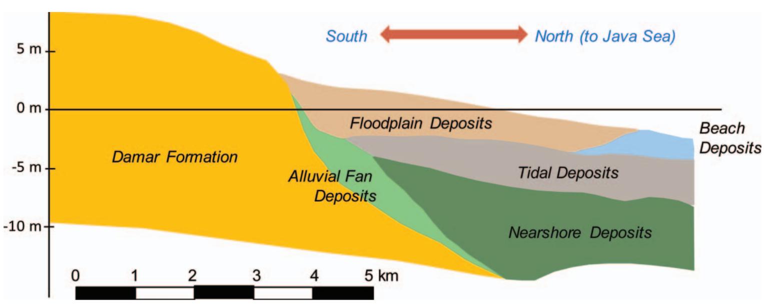

Figure 2. Quaternary geological section east of Kaliwungu, Semarang, after GRDC (1996). The location of this north-south cross section is about 1 to 2 km west of GPS station 1303 shown in Figure 3.

period of 1695 to 1991, the shoreline of Semarang progressed relatively quick towards the sea, namely about 2 km in 2.5 centuries or about 8 m/year in average. Therefore, it can be expected that a natural consolidation process is still occurring until now, causing land subsidence in the northern part of Semarang. Increases in the population and urban development in the area have accelerated land subsidence through excessive groundwater extraction, and load from buildings and structures.

Land subsidence is not a new phenomenon for Semarang, which has experienced it for more than 100 years. The impact of land subsidence in Semarang can be seen in several forms, such as the wider expansion of (coastal) flooding areas, cracking of buildings and infrastructure, and increased inland sea water intrusion. It also badly influences the quality and amenity of the living environment and life (e.g. health and sanitation condition) in the affected areas. In the case of Semarang, comprehensive information on the characteristics of land subsidence is applicable to several important planning and mitigation efforts, such as effective control of coastal flood and seawater intrusion, spatial-based groundwater extraction regulation, environmental conservation, design and construction of infrastructure, and spatial development planning.

Considering the importance of land subsidence information in support of development activities in the Semarang area, monitoring and study of the characteristics of this subsidence phenomenon should necessarily be conducted in systematic manner.

2. Study of land subsidence in Semarang

Some subsidence studies have been conducted in Semarang city using several geodetic methods, such as Levelling (Sutanta *et al.* 2005, Marfai and King 2007), Global Positioning System (GPS) surveys, Gravity (Sarkowi *et al.* 2005, Fukuda *et al.* 2008) and Interferometric Synthetic Aperture Radar (InSAR) (BGR 2009, Kuehn *et al.* 2009, Murdohardono *et al.* 2009, Lubis *et al.* 2011).

Based on the levelling surveys conducted by the Centre of Environmental Geology from 1999 to 2003, it was found that relatively large subsidence was detected around Semarang Harbour, Pondok Hasanuddin, Bandar Harjo and around Semarang Tawang Railway station, with the rates ranging from 1 to 17 cm/year (Tobing and Murdohardono 2004, Murdohardono *et al.* 2007). Levelling-derived subsidence zones in Semarang shows that the northern coastal areas of Semarang are subsiding with the rates larger than 8 cm/year. These areas are generally composed of swamp deposits of soft clay soil.

The estimation based on the Permanent Scatterer (PS) InSAR technique also revealed that the areas close to the shoreline have subsidence rates of more than 8 cm/year (Kuehn *et al.* 2009, Murdohardono *et al.* 2009). The result is based on the PS InSAR based velocity data derived from 28 ERS-2 and ENVISAT-ASAR radar scenes recorded between 27 November 2002 and 23 August 2006. In another study, after processing 22 ascending ALOS-SAR images from January 2007 to January 2009 plus 2 descending SAR images acquired on 6 June 2006 and 17 June 2007, Lubis *et al.* (2011) found maximum subsidence rates of about 8 cm/year in the northern region of Semarang.

Subsidence in Semarang has also been studied using the microgravity method since 2002 by the research group from the Department of Geophysics at ITB (Institute of Technology Bandung). Based on this method, it is found that from

September 2002 to November 2005, a maximum subsidence of about 48 cm occurred in the northern region of Semarang. It corresponds to a maximum rate of about 15 cm/year.

Since 2008, the Geodesy Research Group of ITB began to study land subsidence in Semarang by using GPS surveys and InSAR methods. The GPS derived results are presented in the following section.

3. GPS-derived land subsidence in Semarang

Global positioning system is a passive, all-weather, satellite-based navigation and positioning system, which is designed to provide precise three-dimensional position and velocity, as well as time information on a continuous worldwide basis (Wells *et al*. 1986, Abidin 2007, Hofmann-Wellenhof *et al*. 2007). Using the GPS survey method, several monuments were placed on the ground covering the city of Semarang and its surroundings, and accurately positioned relative to specific stable reference points. The precise coordinates of the monuments are periodically determined using repeated GPS surveys at certain time intervals. By studying the characteristics and rate of change in the height components of the coordinates from survey to survey, the land subsidence characteristics can be derived. For monitoring land subsidence, when the expected subsidence is of very small magnitude, the ideal positioning accuracy to be achieved is at the mm level. In order to achieve this level of accuracy, the GPS static survey method based on dual-frequency carrier phase data processing should be implemented, with stringent measurement and data processing strategies (Leick 2004, Abidin *et al*. 2011).

Global positioning system surveys for studying land subsidence in Semarang have been conducted at 44 GPS points in yearly basis since 2008; namely on 7–13 July 2008, 5–11 June 2009, 21–24 July 2010 and 21–26 June 2011. The location and distribution of the points are shown in figure 3. Station SMG1 is the southernmost point in the network and considering its relatively stable location is used as the reference point for this subsidence.

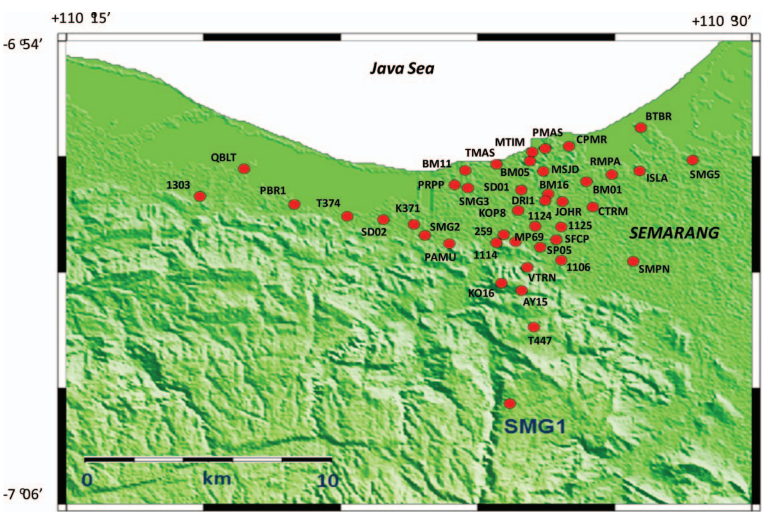

Figure 3. Distribution of GPS stations for studying land subsidence in Semarang.

The GPS surveys used exclusively dual-frequency geodetic-type GPS receivers. The length of surveying sessions was in general between 9 h and 11 h. The data were collected with a 30 s interval using an elevation mask of 15°. The surveys were mainly carried out by the staff and students from the Department of Geodesy and Geomatics Engineering of ITB. An example of some GPS stations is shown in figure 4.

The data were processed using the software Bernese 5.0 (Beutler *et al*. 2007). Since this study is mostly interested in the relative heights with respect to a stable point, the radial processing mode was used instead of a network adjustment mode, with baselines ranging from about 4 to 16 km in length. In this case, the relative ellipsoidal heights of all stations are determined relative to SMG1 station (southernmost station in figure 3). For data processing, 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. The algorithms for the tropospheric parameter estimation can be found in Beutler *et al*. (2007). 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 1–2 mm (figure 5). A few points have slightly larger standard deviations, due to the lack of observed data caused by the signal obstruction.

Figure 4. Example of GPS stations for monitoring land subsidence in Semarang.

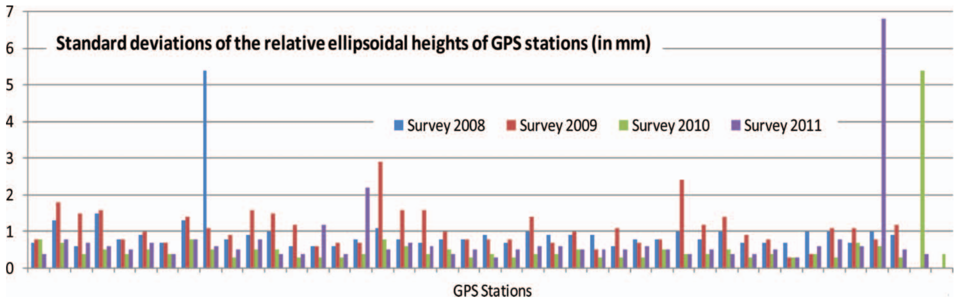

Figure 5. Standard deviations of GPS-derived relative heights in mm.

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

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

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

where $dh(t_i)$ and $dh(t_j)$ are the relative ellipsoidal heights with respect to SMG1, obtained at two consecutive observation epochs t_i and t_j, related to the ith and jth GPS surveys, respectively. Subsidence is represented by a negative value of Δdh_{ij}.

In order to statistically check the significance of the estimated 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 height at epoch j equals the estimated value of the previous epoch i, i.e. no subsidence has occurred. Therefore,

$$\text{null hypothesis} \qquad \mathrm{H}_0: \qquad \Delta dh_{ij} = 0 \tag{3}$$

$$\text{alternative hypothesis} \qquad \mathrm{H}_a: \qquad \Delta dh_{ij} \neq 0 \tag{4}$$

The test statistics for this test is

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

where $\sigma(\Delta dh_{ij})$ is the standard deviation of Δdh_{ij}. The statistics has the customary Student's t-distribution if H_0 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 9 to 11 h of observations at 30 s interval. 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 $t_{\infty,0.005}$ is $= 2.576$. The GPS-derived ellipsoidal height changes and their rates that have passed the statistical testing are shown in table 1.

Table 1. GPS-derived subsidence results in Semarang, based on GPS surveys (2008–2011).

GPS stations	Subsidence in cm (2008–2009)		Subsidence in cm (2009–2010)		Subsidence in cm (2010–2011)	
	Δdh_{12}	$\sigma(\Delta dh_{12})$	Δdh_{23}	$\sigma(\Delta dh_{23})$	Δdh_{34}	$\sigma(\Delta dh_{34})$
259	−1.00	0.10	−1.64	0.11	−2.92	0.09
1106	−6.20	0.20	−2.21	0.19	−2.67	0.11
1114	−4.80	0.20	−0.44	0.16	−0.60	0.08
1124	−3.40	0.20	−5.23	0.17	−8.51	0.08
1125	−4.10	0.10	−5.60	0.09	−4.02	0.06
1303	−0.80	0.10	No subsidence		−1.12	0.09
AY15	−2.00	0.10	−1.01	0.08	−1.09	0.06
BM01	−12.40	0.20	−10.49	0.16	−10.45	0.11
BM05	−4.50	0.60	−7.67	0.12	−5.44	0.08
BM11	−3.50	0.10	−10.66	0.09	−3.30	0.06
BM16	−9.40	0.20	−3.48	0.17	−3.50	0.09
BM30	−1.50	0.20	No subsidence		No observation data	
BTBR	−8.00	0.10	−8.79	0.12	−8.58	0.05
CTRM	−6.10	0.10	−20.37	0.07	−7.00	0.05
ISLA	−11.30	0.10	−10.56	0.08	−5.76	0.12
JOHR	−4.40	0.10	−19.29	0.08	−8.70	0.06
K371	−3.00	0.30	No subsidence		No subsidence	
KO16	−1.80	0.20	−0.89	0.17	No subsidence	
MP69	−4.70	0.20	−1.82	0.16	−0.47	0.08
MSJD	−7.90	0.10	−8.07	0.11	−5.77	0.08
MTIM	−8.60	0.10	−10.54	0.09	−5.92	0.05
PMAS	−4.90	0.10	−12.39	0.09	−7.67	0.06
PRPP	−8.30	0.10	−15.02	0.09	−10.30	0.04
SD01	−7.30	0.20	−5.76	0.15	−7.83	0.06
SD02	−3.90	0.10	No subsidence		No subsidence	
SFCP	−3.60	0.10	−7.46	0.11	−3.69	0.08
SMG2	−1.20	0.10	No subsidence		−8.04	0.06
SMG3	−10.10	0.10	−10.80	0.11	−9.90	0.06
SMG5	−5.20	0.10	−14.80	0.08	−8.81	0.06
SMPN	−4.80	0.10	−8.65	0.09	−5.09	0.08
SP05	−10.40	0.30	−6.14	0.24	−4.80	0.06
T447	−2.80	0.10	−0.86	0.13	No subsidence	
VTRN	−6.20	0.20	−0.93	0.15	−0.27	0.07
SMKN	No observation data		−8.99	0.09	No observation data	
T374	No observation data		No subsidence		No subsidence	
CPMR	No observation data		−9.25	0.04	−3.50	0.05
RMPA	No observation data		−11.02	0.06	−9.80	0.06
DRI1	No observation data		−4.95	0.00	−5.28	0.04
K370	No observation data		−12.70	0.13	−8.20	0.09
KOP8	No observation data		−7.67	0.13	−10.69	0.10
PAMU	No observation data		−0.73	0.09	No subsidence	
PBR1	No observation data		No subsidence		−2.58	0.87
QBLT	No observation data		−1.49	0.04	−3.42	0.06

Results derived from GPS in table 1 show that land subsidence in Semarang has spatial and temporal variations. In general, subsidence rates in Semarang have an average rate of about 6 to 7 cm/year, with maximum rates that can go up to 14–19 cm/year at certain locations (figure 6). The spatial and temporal variations of subsidence rates in Semarang are better shown by the three interpolated maps in

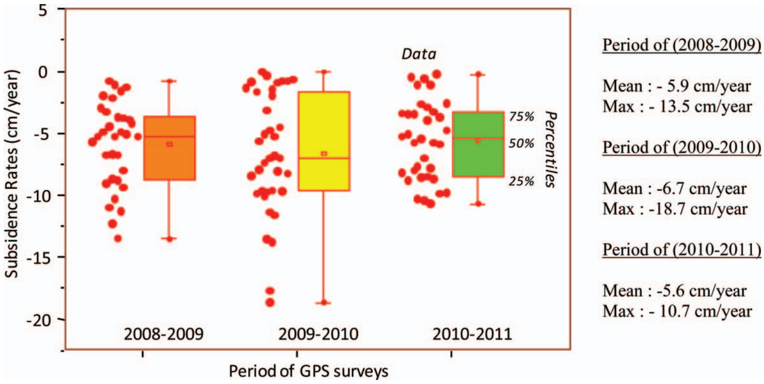

Figure 6. Box-and-Whisker plots of GPS-derived subsidence rates in Semarang.

figure 7, where the northern region of Semarang along the coast exhibits higher rates of subsidence compared to its southern region. These maps were interpolated using Kriging method based on the subsidence rates given in table 1, and then plotted using the Surfer software. Considering the distribution of GPS points shown in figure 7, these interpolated maps should be considered just as the indicative rather than final land subsidence maps of Semarang area. In this case, the interpolated and extrapolated values for the areas located several kilometres away from the GPS stations may be misleading and may alter the interpretation of the maps.

The GPS derived subsidence results show more or less the same rates and pattern of subsidence as derived by levelling, PS InSAR and microgravity methods. Global positioning system results also indicate that subsidence is still on-going until recently (i.e. June 2011) in Semarang.

4. Impact of land subsidence in Semarang

Land subsidence in Semarang has been widely reported and its impacts can be seen already in daily life. It can be seen in the form of coastal flooding (it is called *rob* by the locals) and its coverage tends to enlarge over time. Figure 8 shows the severity of coastal flooding in coastal areas of Semarang. This frequent and severe *rob* not only deteriorates housing, buildings and other infrastructures, but also badly affects the quality of the living environment (e.g. health and sanitation condition) and (social and economic) life in the affected areas (figure 9). Cracking and damage of housing, buildings and infrastructure, malfunction of drainage systems, changes in river canal and drain flow systems and increased inland sea water intrusion, are also other impacts of land subsidence. Therefore, land subsidence increases the maintenance and rehabilitation costs for the affected environment, buildings and infrastructure.

Ground thruthing surveys have been conducted to find and locate the impact features of land subsidence in Semarang area. Figure 10 shows the distribution of land subsidence impacts in 2011, overlapped with the average GPS-derived subsidence rates from 2008 to 2011. From this map it can be seen that coastal flooding (rob) has already affected the areas up to 2–3 km from the coast. The numbers of building, houses and other infrastructure affected by land subsidence phenomena are also numerous exhibiting either cracking, tilting, general damage and some have been abandoned. Figure 10 also shows that most damages occurred in the

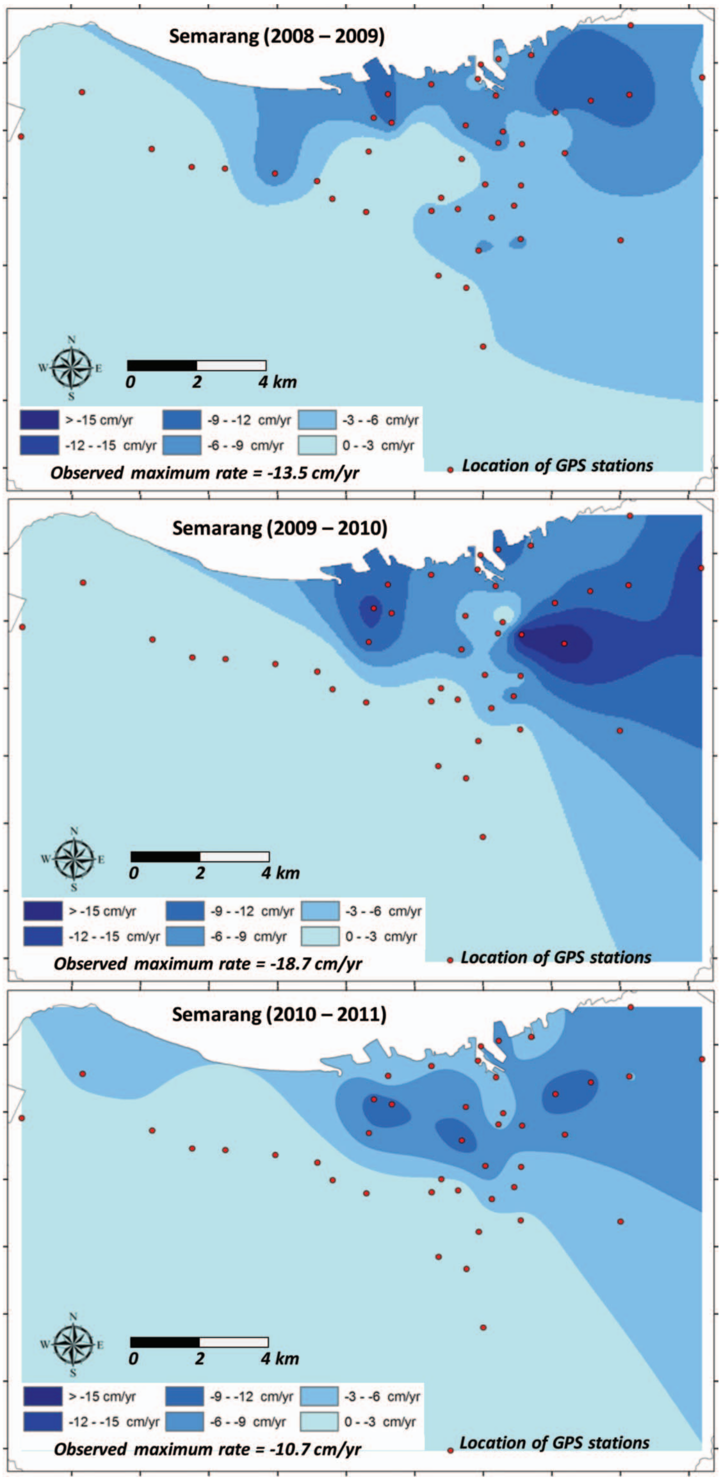

Figure 7. GPS derived subsidence rates in Semarang in the periods of 2008–2009 (upper), 2009–2010 (middle) and 2010–2011 (lower).

Figure 8. Coastal flooding in Semarang on mid April 2009; courtesy of Kompas photo, 2 July 2009.

Figure 9. Examples of subsidence impacts in Semarang.

areas showing high subsidence rates, and also in the areas which spatially have differential subsidence.

The economic losses caused by land subsidence in Semarang are enormous; since many buildings and infrastructure severely affected by land subsidence and its collateral coastal flooding disasters are located in the industrial zone of Semarang. Many houses, public utilities and a large number of populations are also exposed to this silent disaster. The corresponding maintenance cost is increasing every year. Provincial government and communities are required to frequently raise the ground surface to keep roads and buildings dry. The living conditions of the affected

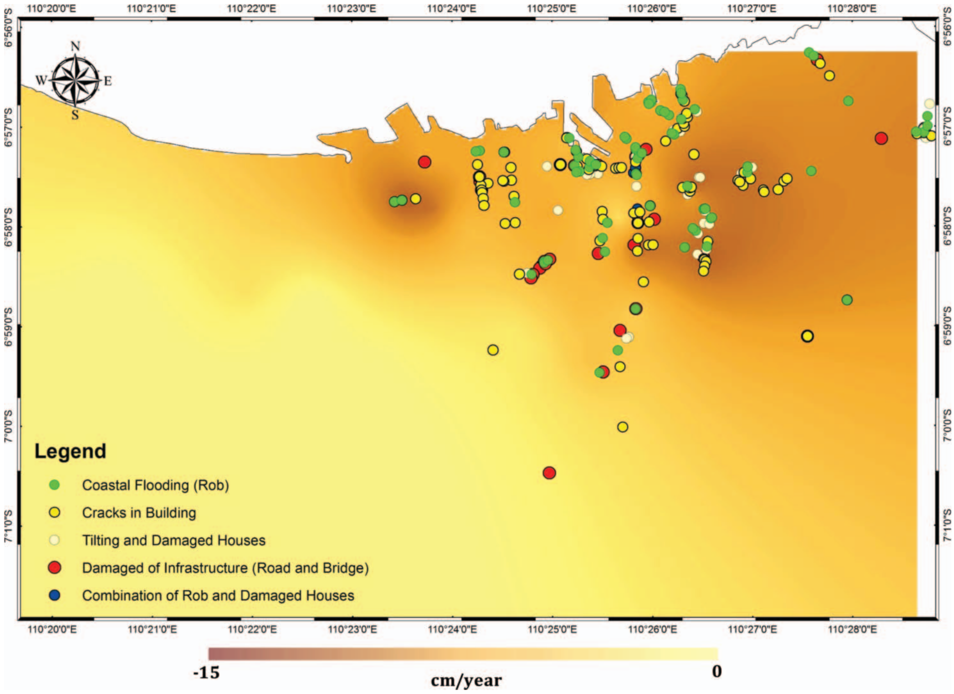

Figure 10. Example of distribution of land subsidence impacts in Semarang, overlapped with the average GPS-derived subsidence rates from 2008 to 2011.

population are deteriorating. The quality of their social and economic activity is consequently decreasing as well.

5. Causes of land subsidence in Semarang

Land subsidence in the northern part of Semarang is believed to be caused by the combination of natural consolidation of young alluvium soil, groundwater extraction and load of buildings and structure. Due to this coastal land subsidence, part of the north coast area of Semarang city has been showing a growth of sea water inundation (figure 8) since most of the last three decades.

In the coastal areas around Semarang harbour, the coastal seaward progression is quite fast with rates of about 4 to 16 m/year in the period of 1695 to 1991 (table 2). Since 1695 up to now, the coastline progression has reached up to about 2–3 km in certain locations. According to van Bemmelen (1949), muddy sedimentation in the coastal areas of Semarang occurred at least 500 years ago. Therefore, it can be expected that the coastal natural consolidation of young alluvium soil will have significant contribution on the relatively large observed subsidence in the coastal areas of Semarang.

Besides natural consolidation of relatively young alluvium soil, land subsidence in Semarang may also partly be caused by excessive groundwater extraction. Groundwater extraction in Semarang city is increasing sharply since early the 1990s, especially in industrial areas (figure 11). According to Marsudi (2001), the number of registered wells in 1900 was 16; it increased to 94 wells in 1974, 178 wells

Table 2. Coastline progression rates in Semarang from 1695 to 1991 (Van Bemmelen 1949, Marfai *et al.* 2008).

Period	Coastline progression (m)	Average rate (m/year)
1695–1719	100	4.2
1719–1847	700	5.5
1847–1892	700	15.6
1892–1921	300	10.3
1921–1940	200	10.5
1940–1991	303	5.9

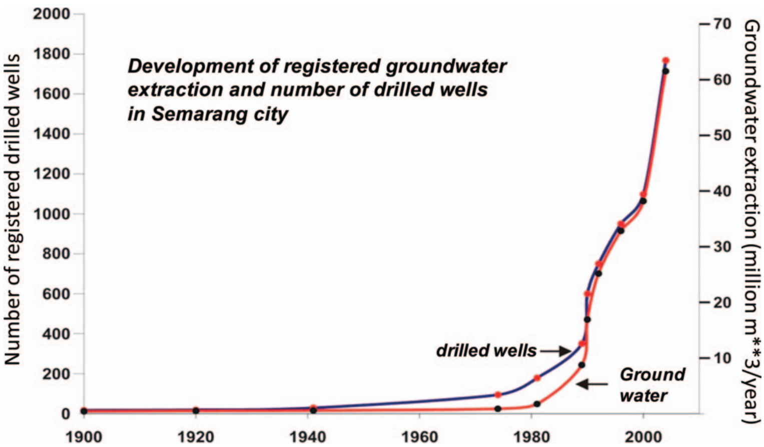

Figure 11. Development of ground water extraction and registered drilled wells in Semarang, after (Murdohardono *et al.* 2007).

in 1981, 350 wells in 1989, 600 wells in 1990, 950 wells in 1996 and 1050 wells in 2000. The registered groundwater extraction increased from about 0.4 million m^3/year in 1900 to 0.9 million m^3/year in 1974, 1.8 million m^3/year in 1981, 8.8 million m^3/year in 1989, 16.9 million m^3/year in 1990, 32.8 million m^3/year in 1996 and 38 million m^3/year in 2000. Due to excessive groundwater extraction, the groundwater level in Semarang during the period of 1980 and 1996 lowered with rates of about 1.2 to 2.2 m/year (Marsudi 2001). This will then introduce land subsidence on the surface.

Based on GPS surveys since 2008, it was found that relatively significant subsidence rates (i.e. 7 to 11 cm/year) were observed at stations in the coastal region where soil is mainly composed of alluvial deposits, and close to industrial facilities which usually extract a lot of groundwater for their activities. Figure 12 illustrates this situation. Load of buildings and structures in the area can be expected to also have a contribution in the observed subsidence rates. However, more data and further investigations is required to understand the intricacies of the relationship between land subsidence with natural consolidation, groundwater extraction and load of buildings and construction in the Semarang area. Additional cause related to tectonic movements in the southern part of Semarang should also be investigated and considered.

6. Closing remarks

Land subsidence is an on-going phenomenon in Semarang. Based on the estimation from levelling, InSAR, microgravity and GPS Survey methods, land subsidence with rates of up to about 19 cm/year were observed during the period of 1999 up to 2011 (table 3). The observed subsidence rates have spatial and temporal variations, and in general the northern region of Semarang along the coast exhibits higher rates of subsidence compared to its southern region. The observation stations around the industrial areas also have relatively high subsidence rates, indicating the effects of excessive groundwater extraction on observed land subsidence.

Land subsidence in Semarang has been widely reported and its impacts can be seen already in daily life. The subsidence impacts are both tangible and intangible, and the related damage and loss has been enormous and significant.

Finally, it should be noted that in the coastal areas of Semarang, the combined effects of land subsidence and sea level rise will worsen the tidal flooding phenomena already experienced by Semarang during the high tide periods. Adaptation measures to reduce the impacts of this hazard therefore should be developed as soon as possible.

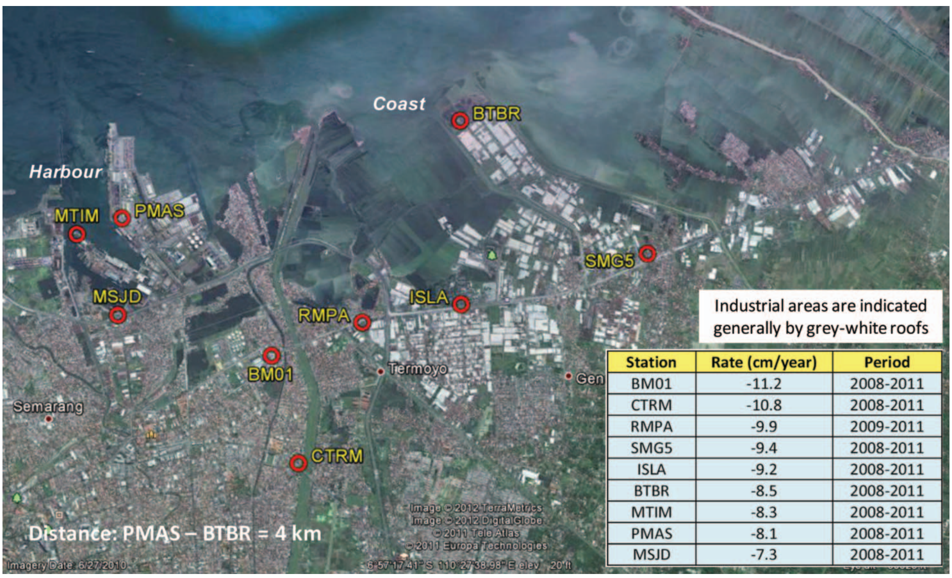

Figure 12. Location of several GPS stations and their estimated land subsidence rates.

Table 3. Land subsidence rates in Semarang as observed from several geodetic methods (Murdohardono *et al.* 2007, Supriyadi 2008, Kuehn *et al.* 2009, Abidin *et al.* 2010).

No.	Method	Subsidence rates (cm/year)	Observation period
1	Levelling	0–17	1999–2003
2	GPS Surveys	0–19	2008–2011
3	PS InSAR	> 8	2002–2006
4	Microgravity	0–15	2002–2005

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