Environ Geol (2007) 53:651–659
DOI 10.1007/s00254-007-0680-3

ORIGINAL ARTICLE

Monitoring land subsidence in Semarang, Indonesia

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Received: 10 August 2006 / Accepted: 7 February 2007 / Published online: 24 February 2007

Abstract Semarang is one of the biggest cities in Indonesia and nowadays suffering from extended land subsidence, which is due to groundwater withdrawal, to natural consolidation of alluvium soil and to the load of constructions. Land subsidence causes damages to infrastructure, buildings, and results in tides moving into low-lying areas. Up to the present, there has been no comprehensive information about the land subsidence and its monitoring in Semarang. This paper examines digital elevation model (DEM) and benchmark data in Geographic Information System (GIS) raster operation for the monitoring of the land subsidence in Semarang. This method will predict and quantify the extent of subsidence in future years. The future land subsidence prediction is generated from the expected future DEM in GIS environment using ILWIS package. The procedure is useful especially in areas with scarce data. The resulting maps designate the area of land subsidence that increases rapidly and it is predicted that in 2020, an area of 27.5 ha will be situated 1.5–2.0 m below sea level. This calculation is based on the assumption that the rate of land subsidence is linear and no action is taken to protect the area from subsidence.

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Keywords Land subsidence · Monitoring · Digital elevation model · ILWIS · Semarang · Indonesia

Introduction

Land subsidence, as a movement of a surface downwards relative to a datum such as sea level, is a major constraint to the development in many regions all over the world. It can damage existing buildings, roads, bridges, industrial estates, and result in loss of homes, even cause injury or loss of life. There are many factors causing land subsidence; it can occur naturally or by human activity. Natural subsidence may occur by collapses, for instance mine and limestone collapses (e.g. Hasan 1996). It also commonly occurs over man-made voids, such as tunnels, wells and covered quarries. Subsidence is also possible by faulting (e.g. Rathje et al. 2003; Gutiérrez 2004), in the foot wall of normal geological faults. Furthermore, subsidence may occur by thermal contraction of the lithosphere (e.g. Hamdani et al. 1994). It may also be caused by extraction of natural gas (e.g. Cassiani and Zoccatelli 2000). However, the most phenomenal causing of land subsidence is extreme groundwater withdrawal (e.g. Sun et al. 1999; Mousavi et al. 2001; Bhattacharya et al. 2004; Chai et al. 2004; Lamont-Black et al. 2005). Groundwater withdrawal results in fluid-pressure change in the layers, especially in sedimentary and clay materials. Excessive pumping of such aquifer systems, which contain rich clay materials, may cause permanent compaction that cannot be recovered after stress and leads to land subsidence. When large amounts of water are pumped out, the subsoil compacts, thus reduces the size and number of the open pore spaces in the soil that previously hold water. This can result in a permanent reduction in the total storage capacity of the aquifer system as well. This phenomenon is common on coastal regions and urban areas with dense housing, buildings and industrial estates all over the world.

Many urban areas in Indonesia, like Jakarta, Bandung, and Semarang suffer from land subsidence. Excessive groundwater withdrawal is probably the main factor causing land subsidence in urban areas of Indonesia. According to Abidin (2005), several areas of Jakarta have been subsiding at annual rates ranging from 20 to 200 cm over the years. The impact of subsidence in Jakarta appeared for the first time in 1978 in the form of cracking on permanent constructions, expansion of flooding areas, lowering of groundwater level and increased inland–seawater intrusion. Land subsidence in Bandung is caused by rapid sinking of water tables due to the increasing population and industry since the 1990s. Meanwhile, in Semarang land subsidence is mainly due to excessive groundwater withdrawal and natural consolidation of alluvium soil. Therefore, monitoring land subsidence in suspected cities is required for groundwater withdrawal regulation, effective control of floods and seawater intrusion, conservation of the environment, construction of infrastructure, and spatial development planning.

Investigations for the prediction and modelling of land subsidence in Semarang have been done by various researchers using various methods and approaches, e.g., based on models incorporating geological and hydrological parameters (Tobing et al. 1999), levelling and Global Positioning System (GPS) survey (Abidin et al. 2001; Sutanta 2002; Abidin 2005). This paper will concentrate on monitoring land subsidence in Semarang using digital elevation model (DEM) data in a Geographic Information System (GIS) environment. Future land subsidence prediction based on raster operation will be generated in GIS environment using the Integrated Land and Water Information System (ILWIS) package (ILWIS 2000). A high point map, which was created from photogrammetry high spot is used to generate DEM using a moving average interpolation system. Superimpose benchmark data and DEM data is processed in raster operation to generate the prediction of elevation models, which indicate future land subsidence for the years 2010, 2015, and 2020, respectively. The total area of subsidence in certain levels has been calculated using histogram analysis for each prediction year. This study has benefited from benchmark data issued by the Public Work Department of Semarang (PWD 2000).

Description of Semarang

Semarang is a coastal urban area situated on Java Island in Indonesia. It is located at the northern coast of Java and about 500 km East of Jakarta (the capital city of Indonesia). Semarang is positioned at the coordinates of about at 6°58′S and 110°25′E. Figure 1 shows the location of Semarang city. The city whose main activities are industrial estate, trade, education, and tourism covers an area of approximately

Fig. 1 Location of Semarang city

373.7 km^2. Most of commercial and industrial areas are built on the flat coastal plain with elevations ranging from 0 to 10 m. Semarang had a population of more than 1.5 million in 2004, and has been projected to be about 2 million in 2025 (Sutanta 2002). The landuse pattern and physical environment in Semarang have been changing rapidly. Changes in landuse in Semarang have become uncontrollable both in the upland and in the lowland areas. In this process the environmental capacity of the system is often neglected. The residential growth, industrial expansion, and agriculture in the lowland area contribute to the land subsidence and the affected areas increase every year. Table 1 gives the description of landuse in Semarang.

From a geological point of view, Semarang has three main lithologies, namely, volcanic rock, sedimentary rock, which is marine in origin, and alluvial deposits. Volcanic rock consists of volcanic breccias, lava flows, tuff, sandstone, and clay stone. This area is located on the Southern part of Semarang. Sedimentary rock originated from marine consists of clay stone and dominated by sandstone in between. Alluvial sediment consists of beach deposits formed by clay and sand with a thickness of more than 80 m with the age of the Holocene period. It is on these deposits (Marin sediment and alluvial sediment) where the land subsidence is occurring.

Groundwater, as water which may be flowing within aquifers below the water table, is among the most important natural resources in Semarang. It provides drinking water for the communities, supports irrigation and industry, and sustains the flow of streams and rivers. Semarang has a high potency of groundwater, especially along the alluvial plain. Excessive groundwater withdrawal has taken place since 1900 in line with the population growth (Fig. 2). In the area of Semarang, withdrawal rates increased rapidly after 1982 and have lowered the groundwater table to more than 20 m below sea level (Sofner and Schmidt 2002).

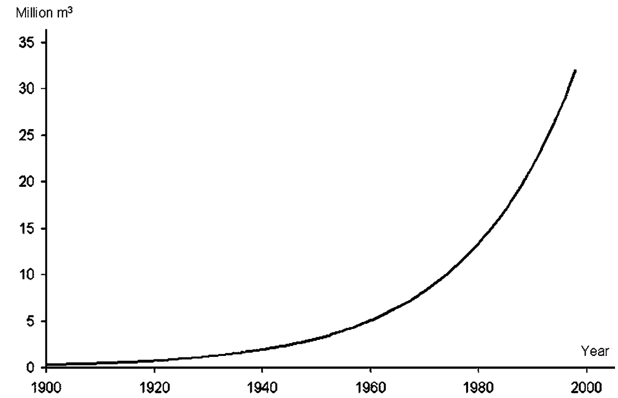


Fig. 2 Groundwater withdrawal in million m^3/year

Nowadays, the sustainability of groundwater resources in Semarang is at risk from overuse and induces natural hazards such as subsidence and tidal inundation (Sutanta 2002; Marfai 2004). Without adequate recharge, the sediments become increasingly compressed causing the land to settle or subside.

In general, Semarang can be divided into two major landscapes, namely, lowland and coastal area on the northern part and hill area on the southern part (Fig. 3). The city centre is situated on the lowland area and is growing rapidly in line with the increasing population. The landuse also changes rapidly from agriculture and cultivation purposes to industrial estates and houses. The materials of the lowland area are composed of the alluvial and coastal deposits which are susceptible from land subsidence triggered by extreme groundwater withdrawal.

Table 1 Description of landuse in Semarang

No.	Types of landuse	Area (km^2)
1	Residential area	123.6
2	Dry land farming	68.8
3	Agriculture field	43.6
4	Homestead garden	51.4
5	Plantation	8.7
6	Open pit mining	1.4
7	Industry and tourism	10.2
8	Transportation	4.8
9	Forest	13.8
10	Bare land	4.1
11	Fisheries	17.8
12	Miscellaneous	25.5

Source Development Planning Board of Semarang (DPB 2002)

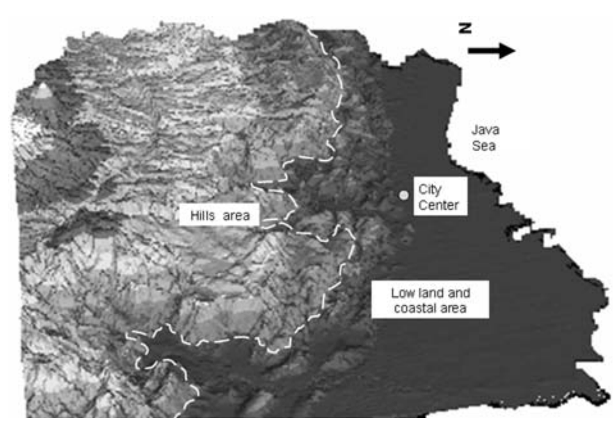


Fig. 3 Landscape in Semarang, in general is divided into hills and lowland area

Land subsidence in Semarang

Land subsidence may occur due to building loads (residential houses and industrial buildings) and groundwater pumping, particularly on the clayey sediments layer, by then the ground will be lowered from previous elevation. Therefore, land subsidence is more likely to be a problem in areas underlain by clay-bearing layers such as in the coastal area of Semarang. On this area subsidence occurs gradually and spreads widely. Since the 1980s the land subsidence in several places of Semarang has been measured using several measurement techniques, e.g., benchmark and field surveys, Dutch cone soundings, consolidation tests, standard penetration tests, and groundwater level studies (PWD 2000).

Since 1983 government agencies have monitored the subsidence and implemented several measures to mitigate the problem. Benchmark, as a point of reference for a measurement, have been installed by the city government in the Semarang areas, both on the hilly and coastal areas with the serial number "DTK", "JP", and "TTG". In 1996/1997 the Mining Department of Semarang also installed some benchmarks to establish the elevation of nearby points with the serial numbers "BM". About 70 points were installed and distributed across Semarang, but unfortunately not all the points provided good data. After checking the number of collected points between the survey only 38 points are used in this study. In this case, stability of the benchmark with respect to its local environment and repeatability of the heights obtained from benchmark

Table 2 Land subsidence and its rate in Semarang, measured from benchmark data

No.	BM no.	Year	Elevation (m)	Elevation in 1996 (m)	Elevation in May 2000 (m)	Differences (cm)	Subsidence (cm/year)
1	BM 1	Oct 1997	0.593	–	0.415	–17.8	7.1
2	BM 2A	Oct 1997	2.026	–	1.614	–41.2	16.5
3	BM 14	Oct 1997	0.892	–	0.874	–1.8	0.7
4	BM 16	Oct 1997	5.023	–	4.955	–6.8	2.7
5	BM 17A	Oct 1997	2.543	–	2.431	–11.2	4.5
6	BM 19	Oct 1997	2.687	–	2.548	–13.9	5.6
7	BM 20	Oct 1997	3.460	–	3.422	–3.8	1.5
8	BM 21	Oct 1997	4.495	–	4.453	–4.2	1.7
9	BM 22	Oct 1997	7.497	–	7.425	–7.2	2.9
10	BM 23A	Oct 1997	7.017	–	6.982	–3.5	1.4
11	BM 27	Oct 1997	2.387	–	2.248	–13.9	5.6
12	BM 28	Oct 1997	1.549	–	1.370	–17.9	7.1
13	BM 29A	Oct 1997	2.547	–	2.471	–7.6	3.1
14	BM 30	Oct 1997	7.02	–	6.920	–10.8	4.3
15	DTK 000	1991	5.494	5.421	–	–7.3	1.5
16	DTK 008A	1991	20.777	20.743	–	–3.4	0.7
17	DTK 009	1991	7.906	7.860	–	–4.6	0.9
18	DTK 013	1991	5.222	5.117	–	–10.5	2.1
19	DTK 135	1993	3.305	3.232	–	–7.3	2.4
20	DTK 136	1993	1.409	1.288	–	–12.1	4.0
21	DTK 218	1993	1.016	0.915	–	–10.1	3.4
22	DTK 221	1993	1.148	1.002	–	V14.6	4.9
23	DTK 222	1993	1.532	1.358	–	–17.4	5.8
24	DTK 223	1993	2.010	1.834	–	–17.6	5.9
25	DTK 224	1993	2.228	2.085	–	–14.3	4.8
26	JP 1	Oct 1997	0.922	–	0.633	–28.9	11.6
27	JP 2	Oct 1997	1.015	–	0.859	–15.6	6.2
28	JP 3	Oct 1997	0.926	–	0.658	–27.0	10.8
29	JP 4	Oct 1997	0.744	–	0.509	–23.5	9.4
30	JP 5	Oct 1997	2.999	–	2.792	–20.7	8.3
31	JP 6	Oct 1997	0.986	–	0.864	–12.2	4.9
32	JP 8	Oct 1997	2.864	–	2.766	–9.8	3.9
33	JP 10	Oct 1997	7.980	–	7.900	–8.0	3.2
34	TTG-442	Oct 1997	6.338	–	6.283	–5.5	2.2
35	TTG-443	Oct 1997	4.137	–	4.096	–4.1	1.6
36	TTG-446	Oct 1997	4.362	–	4.256	–10.6	4.2
37	TTG-926	1984	1.612	0.640	–	–97.2	8.1
38	TTG-927	Oct 1997	3.234	–	3.039	–19.5	7.8

Source PWD (2000)

point are used as the main criteria for selecting the points. After the installation and distribution not all the benchmarks provide time series data and even some of them are damage due to unstable condition and other environmental disturbance. Thirty-eight points are considered the most reliable with minimum two times series and the points are situated on the lowland area of Semarang. Almost all the benchmarks installed in coastal areas and surroundings are affected by land subsidence to some extent (Table 2). Spatial distribution of the benchmark data is shown in Fig. 4.

From Table 2 and Fig. 4 can be seen that even all observed points are located on the lowland and coastal area of Semarang, they vary both spatially and temporally. If these values of land subsidence are plotted with respect to their elevations (Fig. 5), it shows that land subsidence mostly occurred at the points with elevations lower than 5 m above mean sea level, and that the rate of subsidence mostly ranges from 2 up to 10 cm per year. The maximum land subsidence observed by benchmark data during the period of 1997–2000 is about 16 cm per year and occurs on the point with *elevations* of about a few meter, i.e., relatively close to the shore.

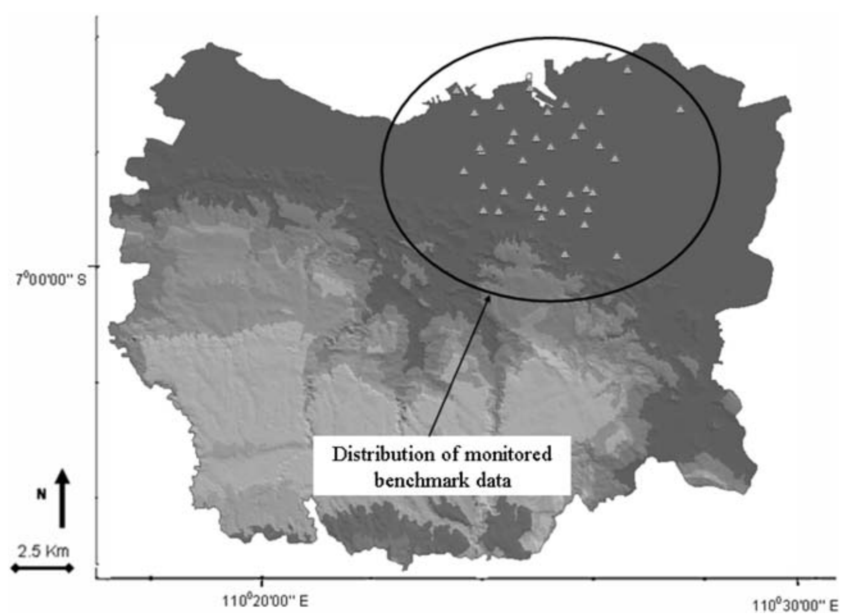
Three major causes of land subsidence in Semarang are groundwater withdrawal, by natural consolidation of alluvium soil, and subsidence induced by the load of constructions (i.e., settlement on high compressibility soil). Compaction of soils in some aquifer systems accompanied by excessive ground-water pumping is the largest cause of subsidence. Land subsidence causes many problems in Semarang (Fig. 6). Among them are (1) damage to infrastructure such as roads, drains, canals, railroads, sanitary sewers; (2) damage to public and private buildings such as industrial buildings, school buildings, government offices, and houses; (3) changes in elevation and slope of streams, canals, and drains; (4) extra costs of pumping storm water and sewage out to flood canal; (5) subsidence also has resulted in tides moving into low-lying areas that were previously above high-tide level.

There are other less visible slow-onset problems that can be expected change of drainage system. Field and channel drainage can submerge because of higher water level in estuaries and river mouths. Submersion reduces then the drainage capacity and may cause problems of water logging and salinisation.

Monitoring the future of land subsidence in Semarang

Monitoring future land subsidence in Semarang has been done using raster data operation of the DEM in GIS environment. A digital representation of relief of Semarang area was generated from a point map which contains elevation data. Several factors play an important role for the quality of DEM-derived products, among them are, terrain roughness, sampling density (elevation data collection method), grid resolution or pixel size, and interpolation method. In this study, the point map has high consistency and variety of the elevation data which indicates a high-quality of terrain roughness both on the hilly and lowland area. The elevation data were obtained from a photogrammetry high spot based on an aerial photo. It has spot heights at 100 m distance in the undulating and hilly

Fig. 4 Spatial distribution of the benchmark data



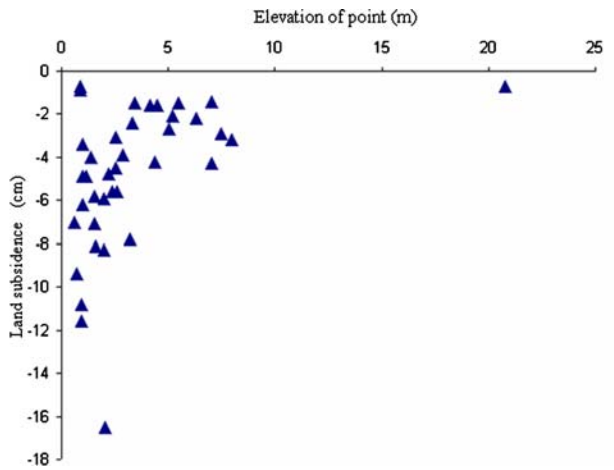


Fig. 5 Land subsidence in Semarang measured from benchmark data

area, and 200 m intervals on the lowland and flat area. The last update of the elevation data was made using geodetic technique by Amhar (2001 after Sutanta 2002), using Global Positioning System (GPS) by Sutanta et al. (2003), and through field checking based on the benchmark data from PWD by Marfai (2003). The DEM has been created in the ILWIS software using moving average interpolation method. Point interpolation performs an interpolation on randomly or regularly distributed point values and returns regularly distributed point values which are represented on the raster map. Moving average assigns to pixels weighted averaged point values. Values of points which are close to an output pixel are thus of greater importance to this output pixel value than the values of points which are farther away. Therefore, with regards to the previous processes that have been made, the DEM data on the study area is advantageous and reliable for this research.

Using 38 points of benchmarks data, a map of the subsidence rate was created. In order to generate the elevation model which indicates future land subsidence on the study area, the map of rate of subsidence was applied to the DEM. Algorithm (Eq. 1) has been performed and applied on the raster operation to produce an expected DEM in a given year. Sources for this operation should be in a raster data. A raster data are a data file or structure representing a general rectangular grid of pixels, and in this case contains value data.

$$X_1 = X_0 - (Y/100 * (t_n - t_0)) \quad (1)$$

where X_1 is the expected DEM in the given year, as a result maps with resolution in meter; X_0 is the recent DEM data with resolution in meter; Y is a map of rate of subsidence in centimeter; t_n is a given year; and t_0 is the year 2003, where the last update for DEM data has been made. From that operation, the result maps which are expected DEM for 2010, 2015, and 2020 have been generated and are shown in Fig. 7.

However, the calculation of land subsidence in a given year requires an assumption that the rate of land subsidence remains the same as the benchmarks data and no action is taken to protect the area from subsidence. A simplification has been made to find the most likely scenario of land subsidence in the entire area for different years. In the reality some

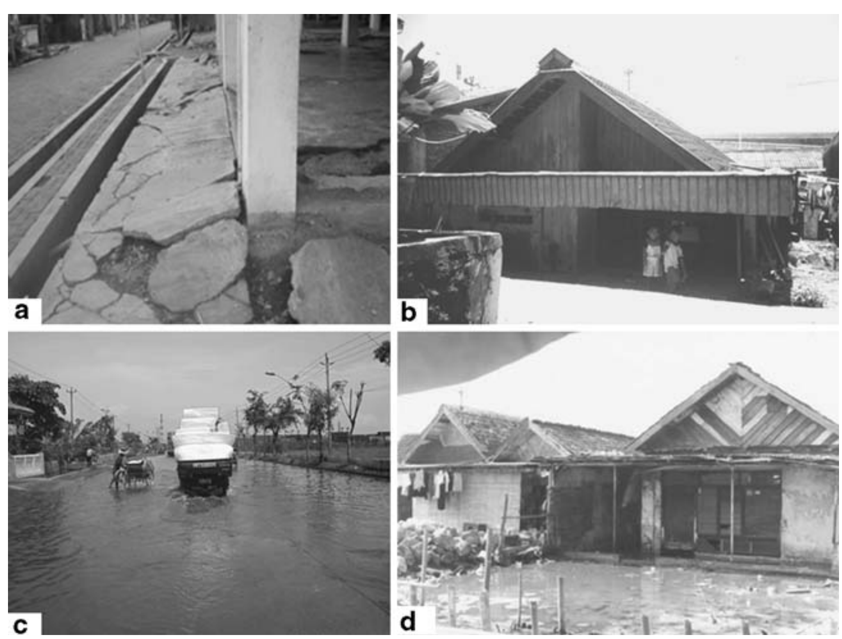


Fig. 6 Examples of problems due to land subsidence in Semarang, **a** building damage (Kobayashi 2003). **b** The remaining dwelling unit after several fillings in the yard (Arbriyakto and Kardyanto 2002). **c** Tidal inundation in main road (Kobayashi 2003). **d** Tidal inundation in front of house leading to health problem as e.g. malaria and yellow fever (Marfai et al. 2005)

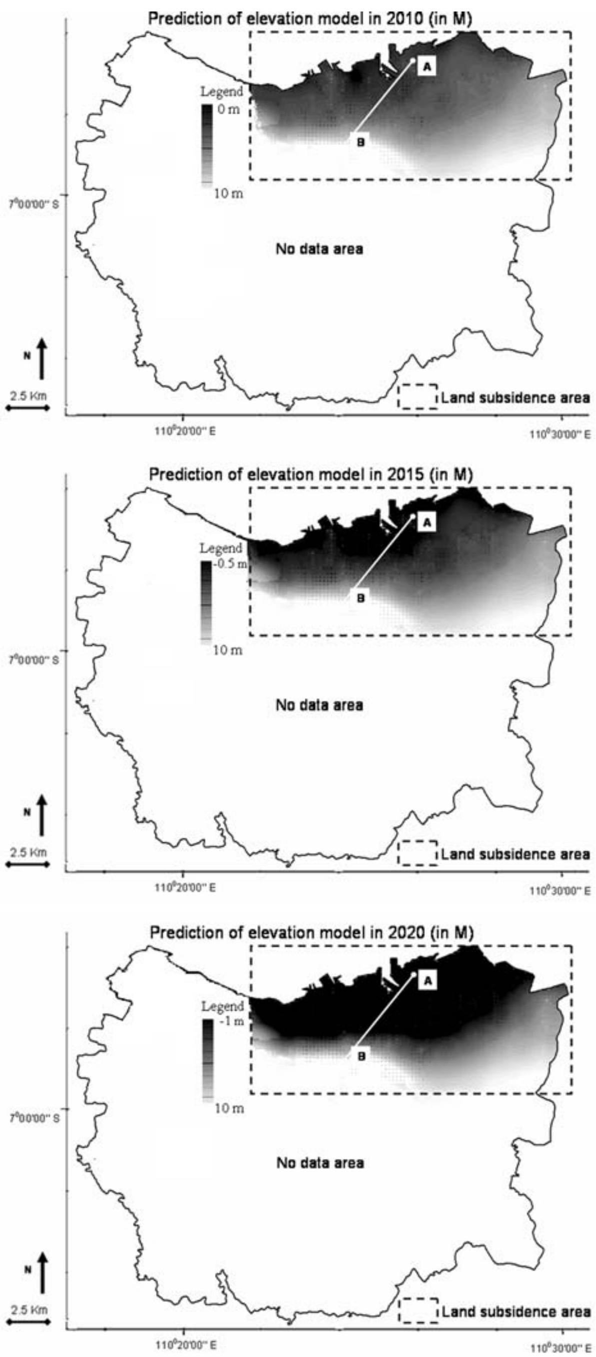


Fig. 7 Expected DEM of the subsidence is in years 2010, 2015 and 2020

factors control the rate and amount of subsidence together (e.g. amount of withdrawal of groundwater, degree of compaction or consolidation of alluvium soil, etc.). Therefore, temporal distribution of these parameters should be considered for more realistic prediction of amount of future subsidence. For this realistic prediction, however, at least three measurements on the points of benchmark are needed between setup time and end time, and then the time-subsidence model can be obtained for each point. Due to lack of the data series on the points of benchmark than it is not possible to generate time-subsidence-dependent model for data points and only linear model accepted. The expected DEM has some negative pixel values which indicate the surface situated below 0 m leading to subsidence process. The expected DEM as a result indicates that more area will be situated below sea level, especially on the lowland and coastal area. Cross-section AB on top of the DEM data has been made to observe the development of the land subsidence in the lowland and coastal area in the future years. The illustration (Fig. 8) clearly indicates the increase of the land subsidence in the next future. It can be seen that the land subsidence occurs on the coastal area of Semarang. This area is considered as industrial with high-density settlements which consume a lot of groundwater. However, it should also be noted that high soil compressibility (Holocene clay and sand with a thickness of more than 80 m) may worsen subsidence by the load of constructions.

The large area located below sea level can be calculated from the map of the expected DEM using the histogram analysis and slicing operation of the raster map. A histogram, as a graphical display of tabulated frequencies provides the non-overlapping value of the pixel on the entire area. Therefore, using these pixels in slicing operation, the total area of subsidence in every subsidence class can be calculated using specified group domain. A group domain is designed to permanently classify values of result maps. A group domain for this operation was created and presented as elevations of 1.5–2 m, 1–1.5 m, 0.5–1 m, and 0–0.5 m below sea level. From the histogram and slicing operation the number of pixels and the areas were calculated and presented in Table 3.

From Table 3 can be seen that the area of subsidence will increase in the future. With an extending size of the urban area on the coastal plane and a growing population, the impact is predicted to be even more severe. When no action is taken against land subsidence, parts of the coastline will be lost and become permanently inundated by seawater. More inundation areas due to tidal flood overflow will be another negative effect.

Conclusions

The occurrence of land subsidence due to excessive groundwater withdrawal and natural consolidation of

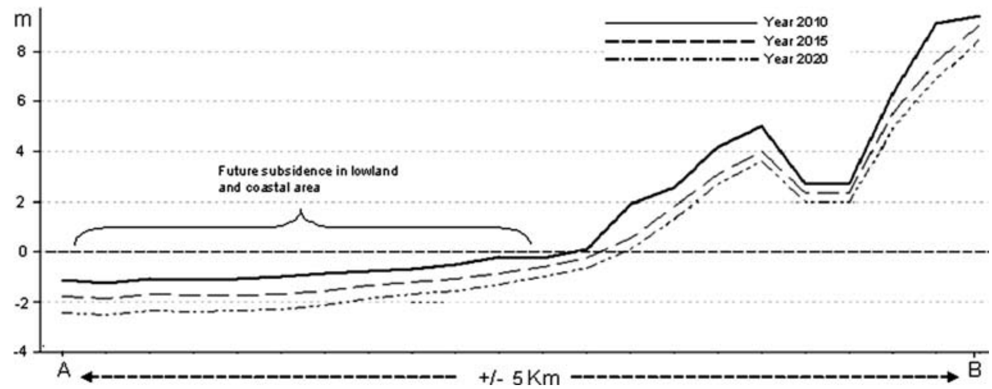


Fig. 8 Cross section AB from the expected DEM in 2010, 2015 and 2020

Table 3 Expected area 0–2 m below sea level in Semarang

Elevation (m) below sea level	2010		2015		2020	
	Number of pixels	Area (m^2)	Number of pixels	Area (m^2)	Number of pixels	Area (m^2)
1.5–2.0	–	–	14	35,000	110	275,000
1.0–1.5	8	20,000	101	252,500	511	1,277,500
0.5–1.0	126	315,000	748	1,870,000	2,427	6,067,500
0.0–0.5	1,314	3,285,000	4,648	11,620,000	5,858	14,645,000

alluvium soil is seldom as obvious as it is in the case of mine collapses, limestone collapses, or catastrophic sinkholes. Where groundwater withdrawal and drainage of clay soils are involved, subsidence is typically gradual and widespread, and hard to detect and evaluate. The detection of regional-scale subsidence originates in the discovery that key benchmark have moved. Once unstable benchmarks are discovered, and truly stable benchmark have been established, subsidence can be mapped. Once subsidence is identified and mapped, subsidence-monitoring programs can be implemented and future subsidence rates can also be calculated.

In the case of Semarang City, subsidence is widespread and gradual. This process takes a long time and land-subsidence related problems hardly become evidence immediately; therefore the need for subsidence monitoring and preventive action is difficult to demonstrate. However, land subsidence in Semarang has now become evidence. Field observations demonstrate that there are a lot of damage on settlement, structures and buildings and even tidal inundation occurs due to land subsidence.

Land subsidence in Semarang has been monitored using DEM data accompanied by subsidence data in order to know the subsidence trend. The elevation below sea level is expected to increase in the future, as e.g. the area between 1.5 m up to 2.0 m below sea level will reach 275,000 m^2 in the year 2020. The prediction and calculation the area of specific landuse types that fall within a certain elevation class for the year 2010, 2015, and 2020, respectively, will be necessary.

The monitoring of the land subsidence through DEM data analysis using the GIS technology provides valuable data for the prediction of the future subsidence (rate and the spatial distribution) since there are limited data from other techniques, i.e., leveling and GPS survey. However, leveling techniques and GPS surveys are considered as good and reliable for measuring and detecting subsidence in Semarang. Subsidence monitoring and mapping programs are crucial for scientific understanding as well as for the management of land and water resources by government agencies, planners, regulators, and administrators in-order to manage and to protect the coastal resources.

Acknowledgments This article derives from research in progress by M. A. Marfai on Risk assessment of tidal inundation under the scenarios of sea level rise and land subsidence at the Justus-Liebig-University Giessen, Germany, supported by The German Academic Exchange Service (DAAD). The authors express their gratitude to Mr. Rosyid (Semarang Public Work Department) for providing valuable benchmark data and the reviewers for their helpful advice.

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