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MAPPING OF LAND SUBSIDENCE INDUCED BY GROUNDWATER EXTRACTION IN URBAN AREAS AS BASIC DATA FOR SUSTAINABILITY COUNTERMEASURES

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ABSTRACT

Estimation of land subsidence induced by groundwater extraction has been observed by some researchers using field instrumentation as well as a spatial mapping technique. Among six Asian cities previously studied (Bangkok, Jakarta, Manila, Osaka, Seoul, Taipei, and Tokyo), the rate of land subsidence in Jakarta is the highest in the period from 1900–2010. In order to improve the applicable monitoring system and obtain comprehensive results for subsidence measurement, tools for raising the government's and society's awareness of subsidence are needed. This paper aimed to determine a benchmark and perform an analysis of sustainable counter measures for land subsidence induced by groundwater extraction in the urban areas of Jakarta city, using a continuous monitoring system and integrated data management system. Land subsidence was measured using field monitoring techniques, such as an extensometer, a leveling survey (global positioning system,GPS; geodetic measurements), and observation wells; this was conducted in some locations in north Jakarta from 1990–2016. The results from the visual observation identified an average land subsidence rate of 1.65 cm/year, while the GPS geodetic measurements ranged from 0–12 cm/year. Monitoring from seven extensometer sensors installed in different borehole elevations revealed subsidence of 0.66 cm on average. Meanwhile, the groundwater surface level ranged from 0.6 m to 44 m from the surface, with the deepest being in the area of Bintaro, South Tangerang. Data analysis was conducted using a computer simulation to investigate the inter-connection between land subsidence and groundwater extraction. Consequently, land subsidence was found to have a strong association with groundwater extraction. Integrated data management systems, including data sharing, are needed to improve the appropriate monitoring system of land subsidence in Jakarta.

Keywords: Continuous monitoring system; Groundwater extraction; Land subsidence measurement

1. INTRODUCTION

Jakarta is the capital city of Indonesia, and has a very dense population. BPS Provincial Capital Data (2016) states that, in 2016, the number of people in Jakarta reached 10.277 million in 2016, the population growth rate per year was 1.07%, and the population density per km^2 was 15.518. This will certainly have had an impact on the carrying capacity of settlement areas, including ondomestic and industrial water consumption.

In the last three decades, the urban development of Jakarta has grown very rapidly in the sectors

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of industry, trade, transportation, real estate, and many others. This exponentially increased urban development has introduced several environmental problems. Land subsidence is one of them. Obviously, with such a large number of people, the extraction of groundwater for the needs of homes and industry is increasing, especially extraction using deep wells. Excessive groundwater extraction will cause an increase in the inter-granular pressure in unconsolidated aquifers and other underground materials. This could result in vertical movement of the land's surface (land subsidence), based on a particular geodetic datum. If the subsidence continues at a significant rate, it will certainly have an impact on the stability of the environment and environmental hazards such as flooding.

Based on the previous research, the factors that cause land subsidence, among others, are excessive groundwater (Djaja et al., 2004), the load of the building (Delinom et al., 2009), the natural consolidation of soil (Teatini et al., 2006), tectonic movement (Coudert et al., 1995), oil and gas extraction (Gurevich & Chilingarian, 1993; Ketelaar, 2009), under ground mining (Ng et al., 2010), broken plates of the earth (Bertrand et al., 2011). Despite all these factors, groundwater extraction is the major factor that causes land subsidence in urban areas.

Learning from the largest urbanized city, Tokyo in Japan, the impact of human activities and urbanization on the groundwater environment has provoked serious environmental problems, such as land subsidence (Hayashi et al., 2009). Groundwater extraction wells can cause the lowering of the groundwater level. An aquifer can induce the consolidation of a clay layer, which can cause land subsidence.

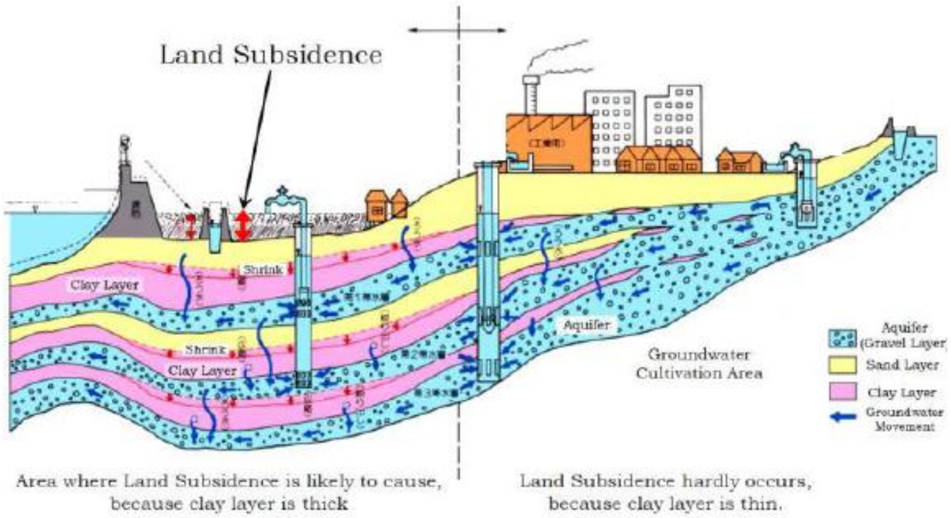

Figure 1 The mechanism of land subsidence in Tokyo, Japan (Hayashi et al., 2009)

Table 1 Groundwater extraction from 2013–2015

Area	Total number of deep wells			Groundwater extraction (m^3)		
	2013	2014	2015	2013	2014	2015
Central Jakarta	641	678	676	817,255	902,159	1,069,829
West Jakarta	745	735	736	1,088,695	1,113,293	1,217,673
South Jakarta	1,613	1672	1680	3,833,332	4,886,166	5,182,929
East Jakarta	981	960	956	1,500,107	1,385,193	1,247,004
North Jakarta	426	428	427	518,727	562,977	426,049
TOTAL	4,406	4,473	4,475	7,758,116	8,849,788	9,143,484

Source: Ministry of Public Works, DKI Jakarta Province (2016)

By 2015, the number of deep wells used for groundwater extraction in Jakarta had approached 4,475, and it still keeps increasing. The amount of groundwater extracted has reached 9,143,484 m^3 per day based on data from the Ministry of Public Works DKI Jakarta Province (2016) for the last three years (2013–2015), as shown in the Table 1.

It is reported that several places in Jakarta have been subsiding at different rates from 1900–2010. Some locations in the Jakarta area have surface levels that have lowered by about 20–28 cm every year (Abidin et al., 2011). West Jakarta and north Jakarta are major areas of land subsidence. The Research Center for Geotechnology at the Indonesian Institute of Sciences (*Lembaga Ilmu Pengetahuan Indonesia*, LIPI) published research analysis on the subsurface conditions in Jakarta and Semarang, which will change efforts and further groundwater policy (Delinom, 2008; Akio, 2014). Among the six Asian cities studied (Bangkok, Jakarta, Manila, Osaka, Seoul, Taipei, and Tokyo), the rate of land subsidence in Jakarta from 1990–2010 is higher compared to others in this period. From Figure 2, it can be seen that, for the other cities, the subsidence already reached a constant level at some point in time during the measurement, while in Jakarta it is still in decline. This might be related to the hydrological cycle of groundwater recharge, which balances the groundwater extraction; this needs further research. Thus, it is very important to determine a benchmark and perform an analysis of the sustainable progressiveness of land subsidence induced by groundwater extraction.

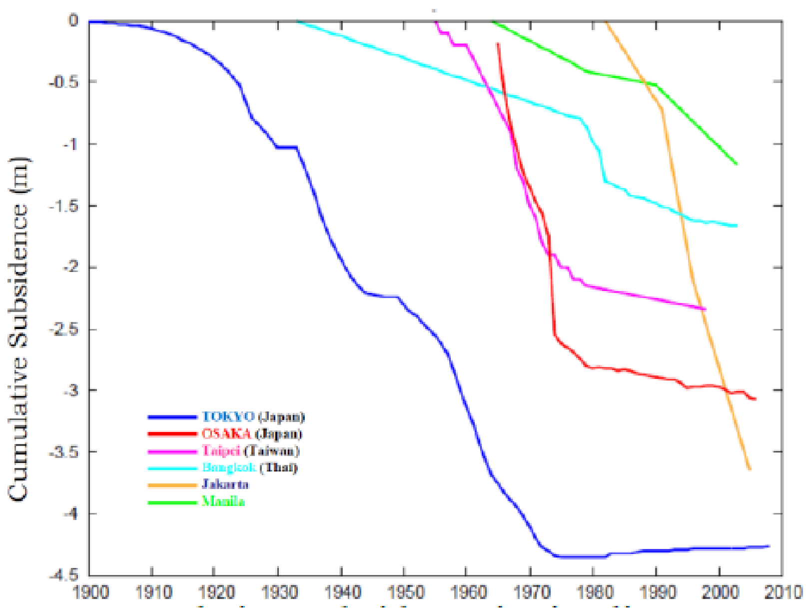

Figure 2 Cumulative subsidence for the time period from1900–2010 (Kaneko & Toyota, 2011)

Essentially, land subsidence is a process of land settlement in which the level of the ground is lowered from its previous level (Marfai & King, 2006), based on a specific geodetic datum, which involves a multitude of variables of a one-dimensional (1D) consolidation process (Terzaghi, 1943). Many of the transient subsurface flow problems that must be analyzed do not involve changes in the total stress. Under these circumstances, if the fluid pressure increases, the effective stress decreases by an equal amount, and if the fluid pressure decreases, the effective stress increases by an equal amount. In a case where the total stress does not change with time, the effective stress at any point in the system, and the resulting volumetric deformations, are controlled by the fluid pressure at that point. If groundwater over pumping is considered to be the only factor that is causing land subsidence, the dewatering of aquifers due to pum page results in decreased pore water pressure and increased effective stress, which causes consolidation and, subsequently, land subsidence. The general three-dimensional (3D) governing equation for groundwater flow for a saturated aquifer is as follows:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial \Delta h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial \Delta h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial \Delta h}{\partial z}\right)=-S_s\frac{\partial \Delta h}{\partial t}-S \quad (1)$$

where K_x, K_y and K_z are the components of hydraulic conductivity, Δh is the drawdown with a positive value denoting a decrease in hydraulic head, t is the time, S_s is the specific storage, and S is the sink/subsidence.

It should be noted that the consolidation equation is derived based on the elastic body theorem, which is more significant when the soil is very soft or the subsurface layer is thick. It is clear from this equation that the complex input of soil and hydraulics parameters need to be taken into account in predicting subsidence caused by groundwater extraction. From Prakoso's (2013a; 2013b) previous research, natural consolidation, groundwater extraction, and land-development-related loads are identified as the major factors causing subsidence.

2. METHODOLGY

Generally, the variable dominant cause of decline in the surface of the land is determined based on the calculation of the amount of the decline in soil that has been recognized and judged to be significant. The subsidence of the ground's surface is shown through changes in the vertical position of the ground level, starting from the predetermined reference plane. In this case, the author utilized the secondary data from the Indonesian Center for Groundwater and Environmental Geology, the Indonesian Research Center for Water Resources, and the Indonesian Research Center for Water Resources, Ministry of Public Works, and the Ministry of Industry and Energy; this data is from observations of continuous land subsidence using field instrumentation and a spatial mapping technique to determine the land subsidence occurring in North Jakarta. The next step was conducting data analysis using a computerized simulation.

2.1. Groundwater-level Monitoring Method

The research area is in the Jakarta groundwater basin, which covers the three provinces of Jakarta, Banten, and West Java. Groundwater extraction in an unconfined groundwater system creates two separate effects on the water-bearing strata: (1) a change in pore water pressure (normally a reduction) leading to an increase of effective stress; and (2) an increase in the volume of air in the soil mass and the void ratio. For unconfined aquifers, this increase is the result of a loss of buoyancy of solid particles in the zone dewatered by the falling water table. For confined aquifers, increases in inter-granular pressure are caused by decreases in the upward hydraulic pressure against the bottom of the upper confining layer, due to a drop in piezometric surface (Bouwer, 1977). The Indonesian Center for Groundwater and Environmental Geology has implemented groundwater level monitoring using 153 observation wells. For confined aquifers, this consists of 46 observation wells and 22 production wells, and for unconfined aquifers, this consists of 57 shallow wells and 28 dug wells. Looking at the groundwater control mechanism in the Jakarta basin, licensing is still considered to be the main tool for controlling groundwater extraction.

2.2. Land-subsidence Monitoring Method

The most important thing in resolving the issue of land subsidence induced by groundwater extraction is conducting monitoring in the field using instrumentation. For land-subsidence measurements, the effective methodologies are using: (1) GPS geodetic measurements; (2) an extensometer; and (3) visual monitoring. However, for the groundwater level, the monitoring is done using: (1) monitoring wells; (2) production wells; (3) shallow wells; and (4) dug well. The Jakarta groundwater basin covers three provinces, which are Jakarta, Banten, and West Java.

The western area borders the Serang-Tangerang groundwater basin, the southern area borders the Bogor groundwater basin, and the eastern area borders the Karawang-Bekasi groundwater basin. Based on the previous research (Soekardi Poespowardoyo, 1986) the hydro geological conditions in the Jakarta area generally consists of extensive productive aquifers and extensive moderately productive aquifers. The regional geology of the Jakarta area needed to be determined.

2.2.1. Using GPS geodetic measurements

The locations at which the GPS geodetic measurements were taken were six benchmark stations, which are Budi Muaratex (BM) Kamal Muara, BM Tongkol, BM Priok, BM Marunda, BM Taman Langsat, and BM Pondok Rangon. These measurements were conducted by the Ministry of Industry and Energy in the period from 2013–2014. The data obtained was compared with data from 13 stations that was obtained by the Indonesian Center for Groundwater and Environmental Geology in the period from 2011–2012.

2.2.2. Using extensometer sensor

Extensometer sensors were applied to the boreholes located in north Jakarta at different elevations, which are 25 m, 45 m, 75 m, 135 m, 200 m, 230 m, and 300 m. Data was recorded for the period from 1999–2003.

2.2.2. Using a visual observation benchmark

The visual observation benchmark for the land subsidence monitoring was taken in the Muara area of North Jakarta for the period from 1990–2016.

2.3. Estimation of Land Subsidence using Geotechnical Data

The field and laboratory soil parameters, including their statistical properties, were evaluated compared to the recent geotechnical data compiled for the port of Sunda Kelapa and West Ancol, which were collected from the library of the Soil Mechanics Laboratory of Universitas Indonesia. The estimation of land-development-induced settlement was performed using the classic Terzaghi's 1D consolidation and secondary compression theories, coupled with the Monte Carlo approach, which was used to analyze the variability of the soil parameters.

3. RESULTS AND DISCUSSION

Land subsidence associated with groundwater extraction has been observed for many years. Subsidence has been reported for some well-documented groundwater extractions in the Jakarta. The cone of groundwater depression has expanded; in 1995 it was only located in Teluk naga and Penjaringan, while by 2013 it had extended to the Pulogadung, Bekasi Utara, Cengkareng, and Tambora areas (Figure 3).

The Indonesian Research Center for Water Resources has developed models for the subsidence of groundwater aquifers in Jakarta for usual groundwater, which shows a decrease of 0.3 m/year, and extreme groundwater, which shows a decrease of 1.5 m/year, as seen in Figure 4.

It is clear that a higher level of groundwater extraction will further amplify the land subsidence occurring in the red zone. The results of the analysis demonstrate that the decrease in the groundwater level of between 0.3 m/year and 1.5 m/year clearly has a strong correlation with the increase in land subsidence in the red zone around the north Jakarta.

The regional geology of the Jakarta area is composed of seven formation units (Ng, Ge et al. 2012), which are (1) alluvial (= Qa); (2) shallow marine sediment (= Qnd); (3) beach ridge deposit (= Qbr); (4) alluvial fan (= Qav); (5) young volcanic (=Qv); (6) Banten tuff (= Qtvb); (7) Serpong formation (= Tpss). The standard penetration test results from the boring log show the lithology of the Jakarta area, is shown in Figure 6.

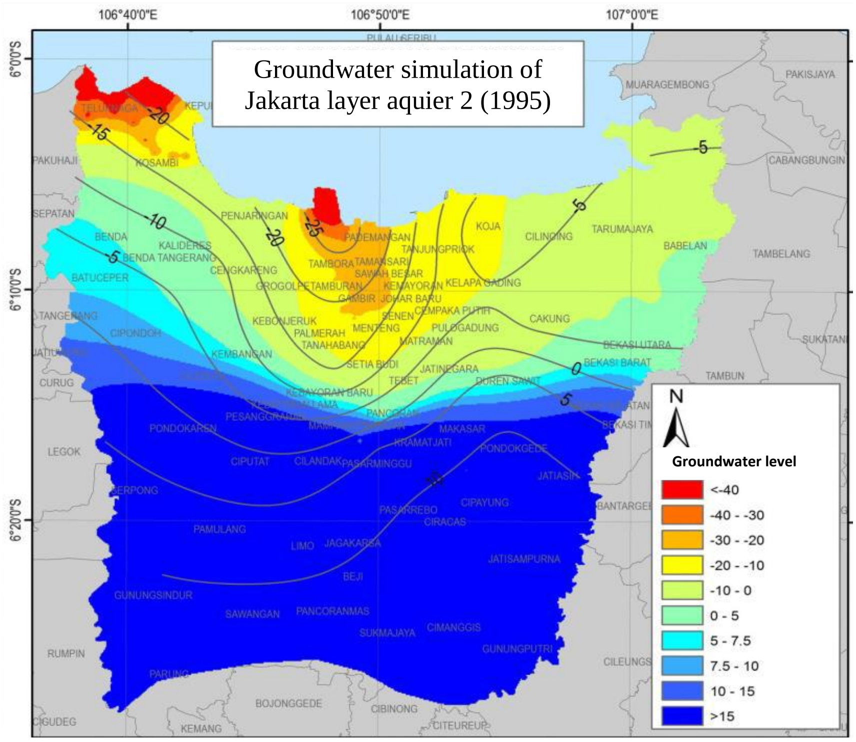

Figure 3 Simulation of the groundwater table of the Jakarta basin in 1995
(Source: Indonesia Research Center for Water Resources, 2017)

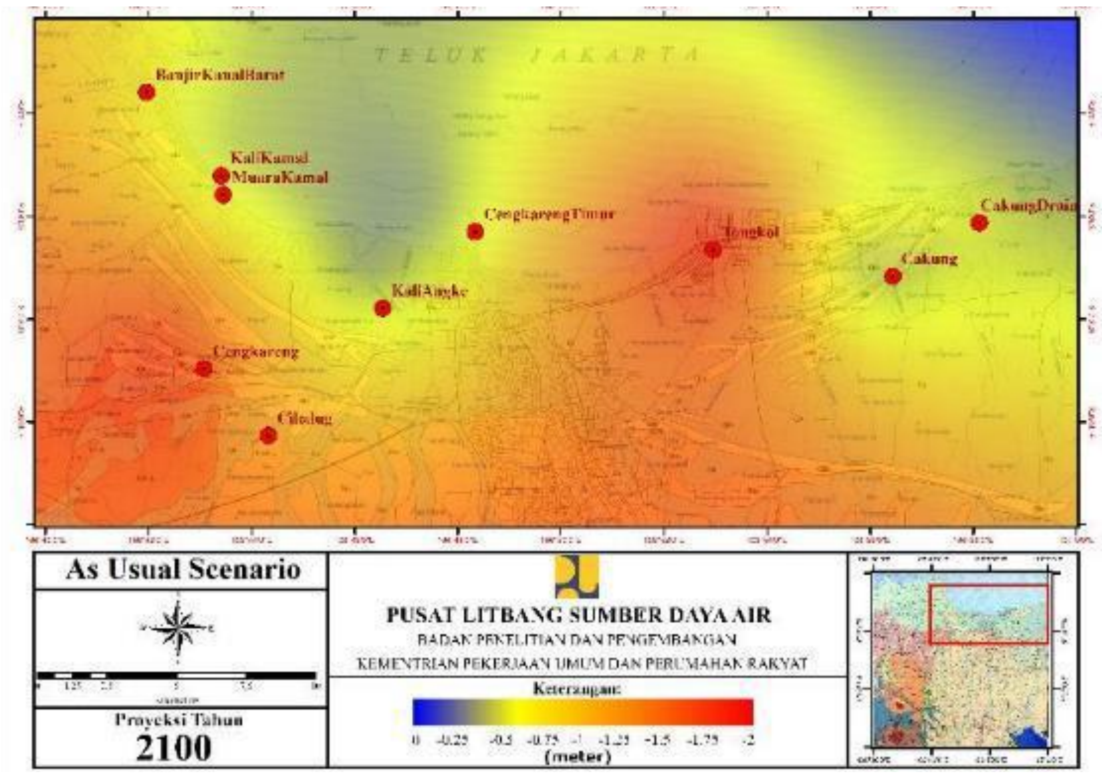

Figure 4 Subsidence modeling result for groundwater decrease 0.3 m/year
(Source: Indonesia Research Center for Water Resources, 2017)

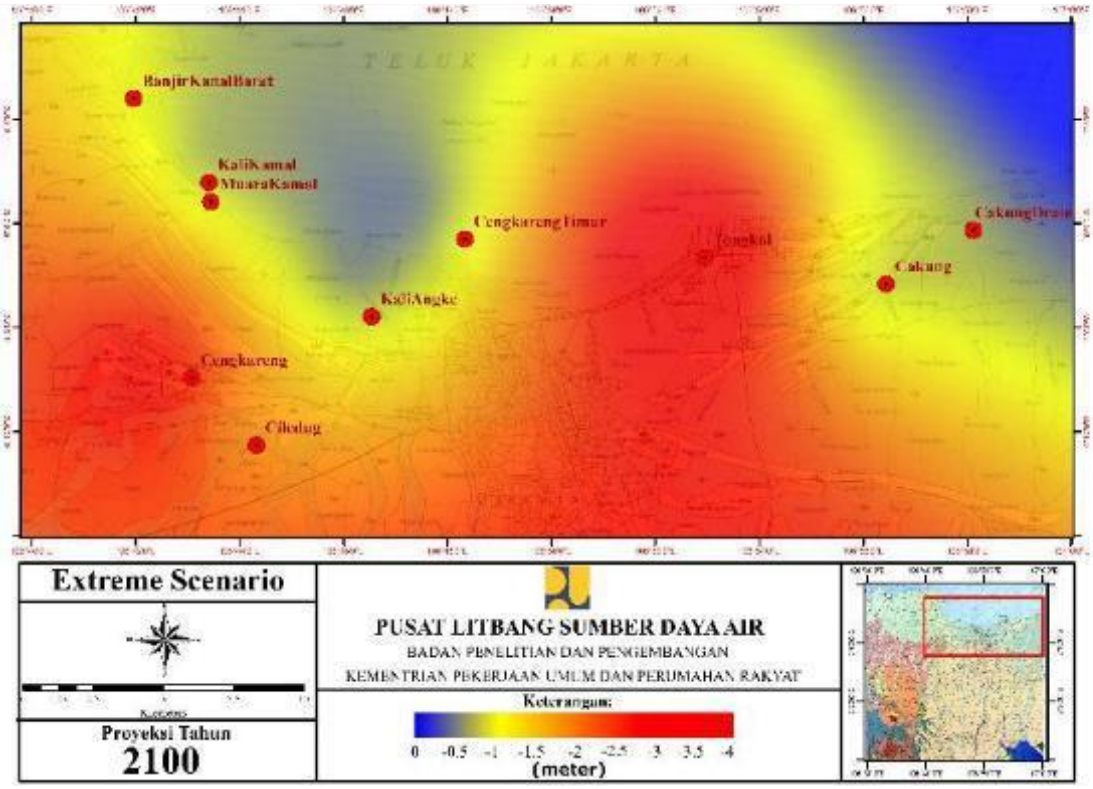

Figure 5 Subsidence modeling result for groundwater decrease 1.5 m/year
(Source: Indonesia Research Center for Water Resources, 2017)

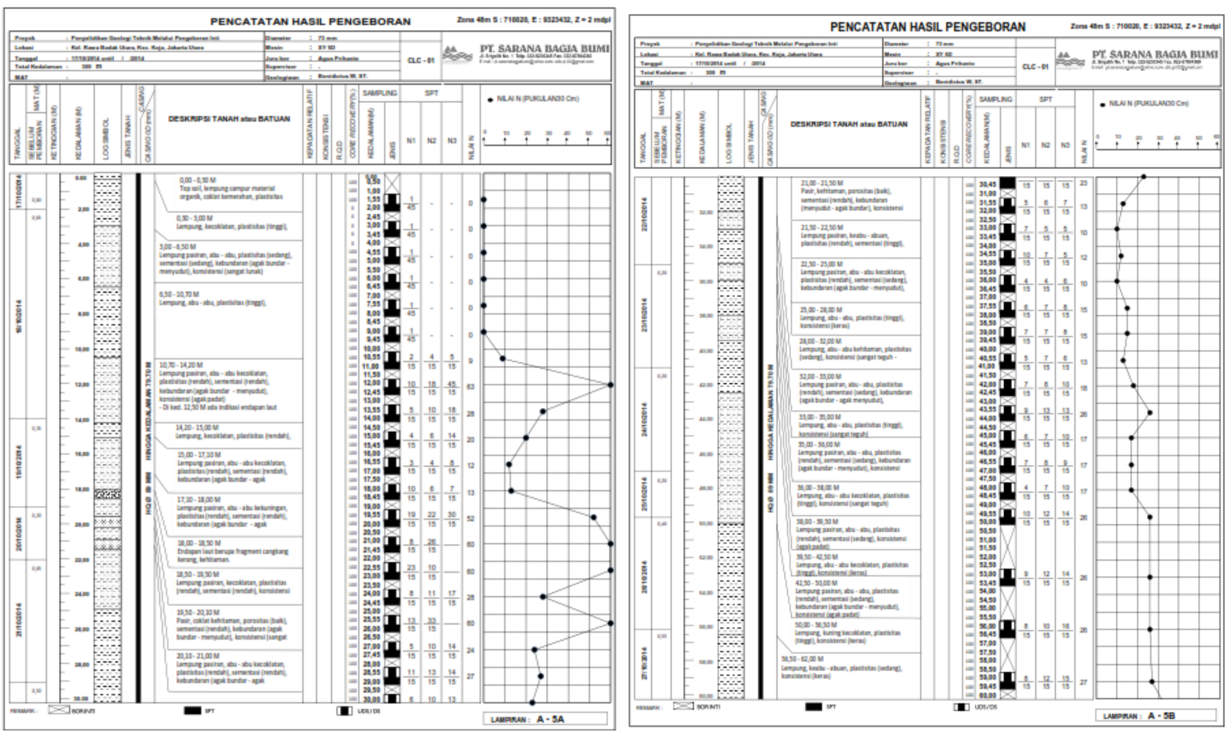

Figure 6 Standard Penetration Test result from 0–62m borehole
(Source: Indonesian Center for Groundwater and Environmental Geology, 2017)

3.1. Results from GPS Geodetic Measurements

The GPS geodetic measurements from 2013–2014 reveal that land subsidence in Jakarta ranges from 0–12 cm/year (Figure 7), which is an increased compared to the 2011–2012 land-subsidence measurements, which ranged from 0–9 cm/year (Figure 8).

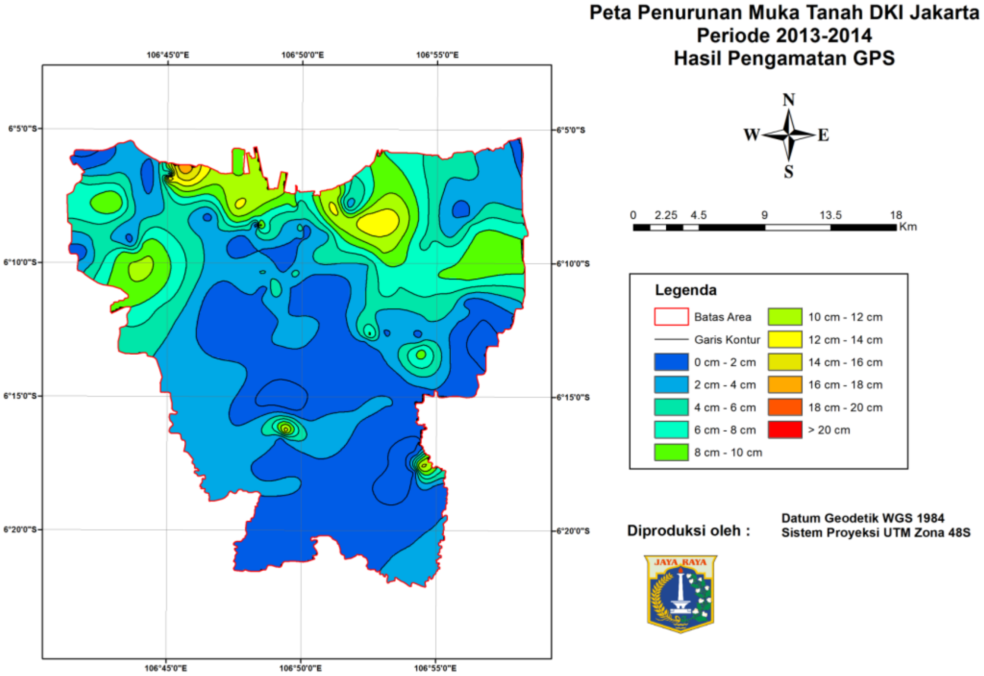

Figure 7 Land-subsidence in period 2013–2014 from geodetic measurements (Source: Indonesian Industrial Services and Energy, 2017)

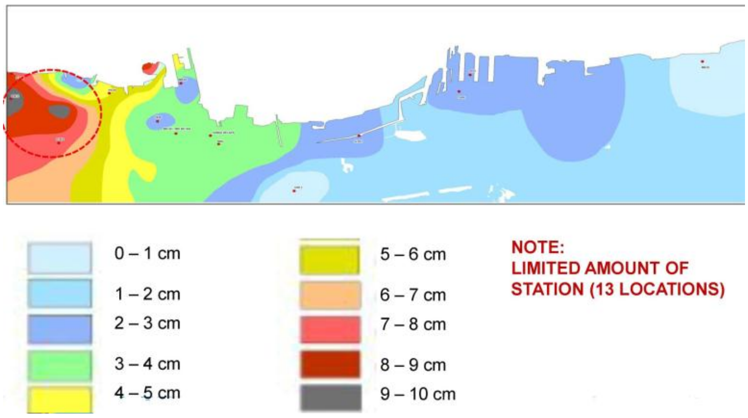

Figure 8 Land-subsidence measurements in period 2011–2012 from geodetic measurements (Source: Indonesia Center for Groundwater and Environmental Geology, 2017)

3.2. Results from Extensometer Sensors

The monitoring from seven extensor meter sensors installed in different borehole elevations in north Jakarta, from which measurements were taken from 1999–2013, gives an average subsidence measurement of 0.66 cm.

Table 2 reveals anomalous result data for the sensors at elevations of 75 m and 230 m, which mean that subsidence did not occur, but instead there was land uplift in that layer. This condition needs further research to identify the factors that influenced this. In a porous aquifer system, the compression and uplift in the layer is related to the compressibility of different soil strata and the distance from the aquifer.

Table 2 Land-subsidence measurements from extensometers for 1999–2003

Depth (m)	Settlement measured (cm)	Settlement in each layer (cm)	Accumulative settlement (cm/m)
e7 → 25	1.72	1.72	0.0688
e6 → 45	2.13	0.41	0.0205
e5 → 75	1.81	-0.32	-0.0107
e4 → 135	3.35	1.54	0.0257
e3 → 200	4.86	1.51	0.0232
e2 → 230	4.61	-0.26	-0.0087
e1 → 300	4.63	0.02	0.0003

(Source: Indonesian Center for Groundwater and Environmental Geology, 2003)

3.3. Results from Visual Observation Benchmark

Frequent measurements were taken from stations at specific locations that were installed by the Indonesian Center for Groundwater and Environmental Geology. Some locations in North Jakarta in the period from 1990–2016 reached an average land subsidence rate of 1.65 cm/year from visual observations (Figure 9).

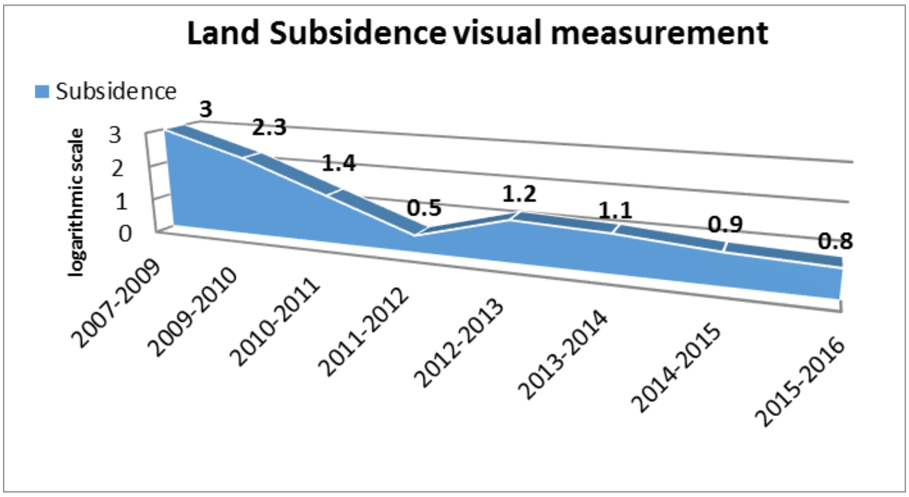

Figure 9 Land subsidence measurement from visual observation
(Source: Indonesian Center for Groundwater and Environmental Geology, 2017)

3.4. Results from the Observation Wells for the Groundwater Table

Based on the groundwater flow pattern results for the Jakarta basin, groundwater generally flows from south to north, in both unconfined and confined systems. However, in the middle and north basin there is a conical pattern, in the form of a draw down cone, which indicates excessive groundwater extraction.

3.5. Results from the Geotechnical Estimation

As the Monte Carlo simulation approach was adopted, 1,000 random numbers were used for each variable, and the analysis was performed using MS Excel™. The mean and standard deviation values for the final settlement were 1.6 m and 0.7 m, respectively. For the period between years 1 and 5, the mean and standard deviation values for the subsidence rate were 0.22 m/year and 0.16 m/year, respectively. Land subsidence in north Jakarta is primarily due to the consolidation of the soft soil layers, which is induced by the land development of the areas. However, all the field result measurements need to be validated to take into account the multitude of variables of the 1D consolidation process caused by groundwater extraction. Further research is needed to obtain the appropriate variables to optimize the measurements for land subsidence. This needs to consider the specific clay layers and particular aquifers that are causing land subsidence, in spite of the occurrence of the process for the natural consolidation of the soil, which is caused by the load of the building on the subsurface.

4. CONCLUSION

For the time period from 1925–2015 land subsidence in Jakarta has been monitored by the Indonesian Research Center for Water Resources and the Indonesian Center for Goundwater and Environmental Geology. Using field monitoring techniques, such as extensometer, leveling survey (GPS geodetic measurements), and observation wells, land subsidence measurements were taken, which have provided various results. The recorded land-subsidence measurements from the field instrumentation reached 1.65 cm/year, and varied from 0–12 cm/year in the GPS geodetic measurements. Based on the data for 2015, the groundwater surface level ranged from 0.6 m to 44 m from the surface, with the deepest being in the Bintaro-South Tangerang area .It is clear that land subsidence has a strong association with groundwater extraction, but the complexity of the geological conditions and the hydrological conditions of the aquifers still need to be considered. Further research is needed to consider how specific clay layers and particular aquifers are causing land subsidence, in spite of the occurrence of the process for the natural consolidation of the soil, which is caused by the load of the building on the subsurface.

In order to improve the applicable monitoring system, monitoring of land subsidence in Jakarta needs an integrated data management system, including data sharing to overcome issue such as: (1) monitoring procedure (who, when, and what for); (2) monitoring methodology (how); (3) database and data management (monitoring, compiling, and evaluation); and (4) data sharing (monitoring data and results, for sharing and publishing). Under such circumstances, the related ministries, agencies, and organizations, using a continuous monitoring system and an integrated data management system, should implement monitoring to gain the optimal results for various purposes, such as urban development master plans and the reduction of any environmental problems in the future.

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