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Land subsidence hazard in Indonesia: Present research and challenges ahead

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ABSTRACT Land subsidence has become a significant silent hazard in the big cities across Indonesia that aggravates future sustainable development. Land subsidence hazards hard-hit Java as the most densely populated island. This paper reviews Indonesia's land subsidence hazards, particularly subsidence cases across the big cities on Java Island, Jakarta, Semarang, and Bandung. Generally, land subsidence research in Indonesia can be categorized into two broad focuses: monitoring subsidence rate and investigating land subsidence mechanism. This paper aims to present a comprehensive summary of the current status of land subsidence research in Indonesia and discusses the challenging issues encountered in research and mitigation measures. A qualitative literature review was used in this study for reviewed articles in the Google Scholar database published in Indonesian and English up to 2020. Land subsidence in Jakarta, Bandung, and Semarang is still ongoing at a high rate. Its mechanism is highly influenced by excessive groundwater withdrawal, although other natural and anthropogenic factors also play a part. This review proposes recommendations to alleviate the impacts of land subsidence hazards in Indonesia and for further research.

INTRODUCTION

According to the USGS, land subsidence is defined as the gradual or sudden sinking of the earth's surface due to the downward movement of the subsurface materials (Galloway et al., 2008). Sudden subsidence is commonly associated with subsidence in karst terrain and underground mining, while a gradual one occurs more widely. The slow-paced land subsidence has occurred in at least 150 locations worldwide, mainly in coastal areas, industrial complexes, and densely populated areas (Barends et al., 1995). In Asia, land subsidence has affected industrialized and urban areas like Tokyo, Bangkok, Hanoi, Ho Chi Minh city, and more. In Tokyo, land subsidence started around 1910-1970 and was primarily due to groundwater extraction (Sato et al., 2006). Bangkok started to experience land subsidence in the 1970s and escalated to its most critical subsidence in the 1980s (Phien-wej et al., 2006). In Hanoi and Ho-Chi Minh cities, land subsidence commences in the 1990s with rapid urban economic development (Thoang and Giao, 2015; Dang et al., 2014). As our country continues to develop, Indonesia is inevitably affected by land subsidence hazards. The land subsidence problem in Indonesia has been recognized since the early 1980s, corresponding to the onset of rapid physical development.

In Indonesia, land subsidence cases mainly occur in the lowland and coastal areas and other areas underlain by soft compressible subsurface. For example, the land subsidence problems on the north coast of Java (Sarah and Soebowo, 2018), subsidence of the lake sediment in the Bandung basin (Gumilar, 2013; Taufiq, 2010), and subsidence in the peat lowlands in Sumatra (Khasanah and van Noordwijk, 2019). Geodetic monitoring has shown that high land subsidence has occurred in densely populated cities in Java islands, such as Jakarta, Bandung, Semarang, and Surabaya. Land subsidence can occur due to natural and anthropogenic causes or combining both. In general, land subsidence research in Indonesia is divided into two major groups: monitoring land subsidence rate and research on land subsidence mechanisms (leading causes and contribution). The author aims to review the key features of land subsidence cases in Indonesia, such as the mechanism, rate of subsidence, and remedial works. Typical cases that represent the significant hazard are reviewed, such as the land subsidence in Jakarta, Bandung, and Semarang.

METHODS

The locus of this study is focused on the three most studied land subsidence cases in Jakarta, Bandung, and Semarang. A brief explanation of the study location and its geology is explained.

Jakarta is located on the northern coast of West Java, centered at coordinates 6°15'S and 106°50'E. Jakarta comprises the lowland morphology in the north and undulating hills in the southern part. The lowland consists of beach deposits, beach ridges, and alluvial deposits. Meanwhile, the southern hills were formed by Quaternary Bogor alluvial fans, volcanic deposits, and Tertiary sedimentary rock (Turkandi et al., 1992).

Jakarta lies on top of a groundwater basin of Quaternary sediment with Tertiary sedimentary rock as its base. Asseggaf (1998) divided the Jakarta groundwater basin into eight aquifers separated by clay as the aquitard layers. Lubis (2018) noted that the Jakarta groundwater basin has suffered from anthropogenic disturbances, resulting in the decline in groundwater level and the expansion of the groundwater depression area.

Bandung is a plateau located +768 m above mean sea level, centered at coordinates -6° 55' S and 107° 37' E. The morphology of the Bandung basin consists of a flat plain at the center surrounded by volcanic mountains, forming a basin. Geologically, the Bandung basin is composed of, from old to young succession, Tertiary volcanic and sedimentary rocks, other Quaternary volcanic rocks, Cikapundung Formation, Cibereum Formation, and Kosambi Formation (Silitonga, 1973). The hydrogeology of the Bandung basin consists of a multi aquifer-aquitard system with Cibereum Formation as the principal aquifer and Kosambi Formation as the aquitard (Hutasoit, 2009). The Cikapundung Formation and other older rocks form the basement of the groundwater basin. Taufiq et al. (2018) divided the groundwater system of the Bandung basin into shallow and deep aquifer systems. The shallow aquifer system is the unconfined aquifer system that can be accessed by dug holes with a depth of 10-20 m. The deep system consists of semi-confined and confined aquifers, usually tapped by boreholes from a depth of 80-150 m. Excessive groundwater pumping due to industrialization and population growth has caused problems of groundwater level drawdown and pollution (Taufiq et al., 2018; Wangsaatmaja et al., 2006).

Semarang is located on the north coast of Central Java, centered at coordinates -6° 58' S and 110° 26' E. Semarang city comprises a coastal lowland area in the north and a hilly area in the southern part. The subsurface of north Semarang comprises an alluvial deposit (Qa) that sits unconformably on top of the Damar Formation (QTd) and Quaternary volcanic rock (QTd) and Tertiary rock at the south hills (Thaden et al., 1996). The hydrogeology of Semarang consists of unconfined and confined aquifer systems (Taufiq Nz, 2009). The unconfined aquifer is found near the surface, consisting of sandy silt, sand, and gravel, with water tables fluctuating to seasonal changes. The confined aquifer system comprises the Garang delta aquifer, the Quaternary marine deposit aquifer, and the Damar Formation aquifer. Groundwater exploitation mostly involved two aquifers having freshwater quality, the Garang delta aquifer and the Damar Formation aquifer. Putranto and Rude (2016) noted that the number of registered deep wells rose sharply from 300 wells in 1995 to 1100 wells in 2010, with a total abstraction of more than 30 million m^3/year in 2010.

A narrative qualitative literature review synthesizes the principal features of land subsidence cases in Indonesia. This study focuses on land subsidence in Jakarta, Bandung, and Semarang. The literature used was identified from the Google Scholar database for reviewed articles published in Indonesian and English up to 2020. The objective of this qualitative review was to identify critical concepts, findings, and research gaps in land subsidence cases and to propose and inform remediation for practical sectors and policymakers.

RESULTS AND DISCUSSION

Land Subsidence in Jakarta

Jakarta resides on the north coast of West Java, and its surficial geology belongs to the North Java alluvial plain. As the largest and most populated city, also the country's capital, Jakarta is undoubtedly prone to land subsidence. Evidence of land subsidence, such as building settlements, is spread out in Jakarta's northern part, such as in Tongkol, Ancol, Pantai Mutiara, and Marunda (Abidin et al., 2008), and regular coastal flooding (Budiyono et al., 2015). Abidin et al. (2008) observed that the land subsidence rate in Jakarta closely resembled the pattern of groundwater drawdown, indicating a strong causal relation.

The land subsidence problem in Jakarta has been recognized since 1978 and actively measured since 1982 (Abidin et al., 2001). Earlier subsidence monitoring had been carried out using the systematic leveling method by the Provincial Government of Jakarta from 1982 to 1991 (Abidin et al., 2001). Further land subsidence monitoring was carried out using GPS and SAR interferometry methods (Abidin et al., 2015; Ng et al., 2012; Abidin et al., 2011).

The author compiled land subsidence monitoring results by geodetic methods: leveling, GPS, and SAR-interferometry, and ground-based monitoring using a stable benchmark (Table 1). The stable benchmark utilizes a metal rod with a steel casing cemented at depth, preferably at a stable rock formation (non-consolidating strata). When subsidence occurs, the rod remains firm while the casing slides downward with the consolidating stratum. The stable benchmark result shows the total factual subsidence that has taken place since it was first installed. A stable benchmark has been installed in the Tongkol site, North Jakarta since 1990 (Hendarto and Standing, 2019). Table 1 and Figure 1 show that spatially varied land subsidence rate occurs across the north Jakarta plain during certain monitoring period intervals. Figure 1 represents the most vulnerable areas experiencing land subsidence with the comparison of several monitoring points from InSAR (Ng et al., 2012) and GPS (Abidin et al., 2011) methods.

Table 1. Compilation of land subsidence monitoring in Jakarta using various methods.

Method	Monitoring period	Subsidence rate (cm/year)	Location	Reference
Leveling	1982-1991	1-9	whole Jakarta city	(Abidin et al., 2001)
	1991-1997	1-5	whole Jakarta city	(Abidin et al., 2001)
	1982-1997	3-8	Cengkareng	(Murdohardono, 2000)
GPS	1997-2000	1-20	whole Jakarta city	(Abidin et al., 2001)
	2001-2010	1-28	whole Jakarta city	(Abidin et al., 2011)
SAR interferometry	2007-2011	1-12	whole Jakarta city	(Ng et al., 2012)
	2007-2009	21.6-21.8	Pantai Mutiara and Cengkareng	(Chaussard et al., 2013)
	2014-2017	1.35	Tongkol	(Yuen, 2018)
	2010-2012	8.5-10.5	Pantai Mutiara	(Putri et al., 2013)
		10.0-17.5	Cengkareng	
		7.5-9.5	Cakung	
Stable benchmark	1990-2007	1.8	Tongkol	(Hendarto and Standing, 2019)
	2009-2010	2.1-2.3	Tongkol	
	2011-2017	1.0	Tongkol	

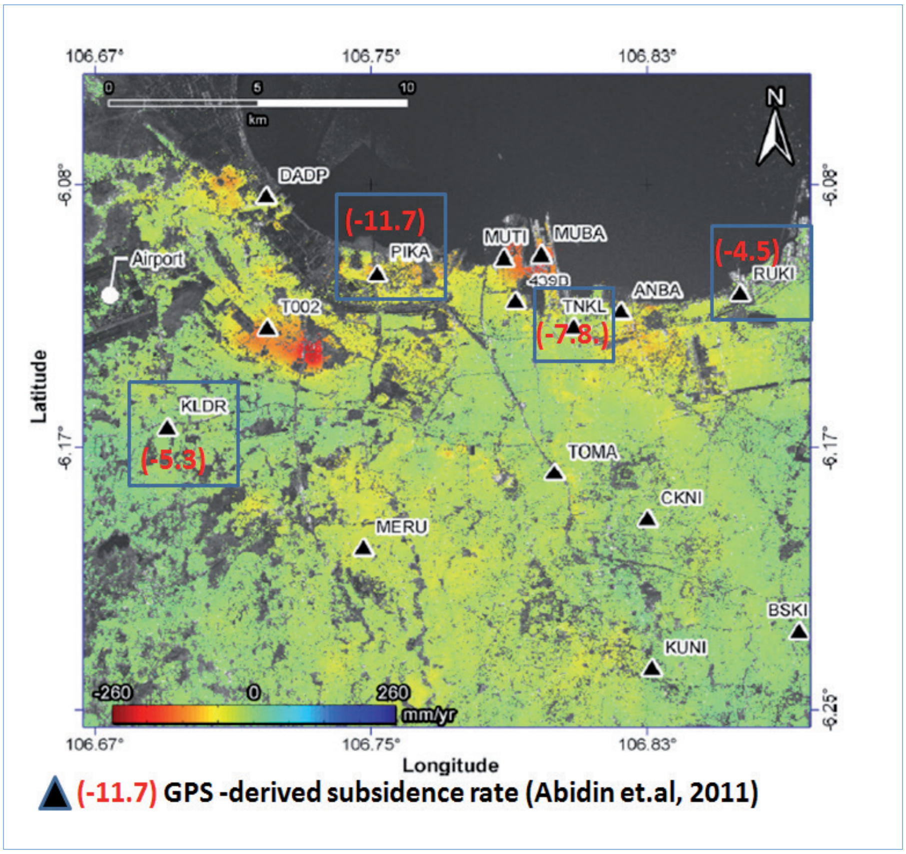

Figure 1. Land subsidence rate in Jakarta as derived from InSAR interferometry (Ng et al., 2012) superimposed by GPS-derived land subsidence rate (Abidin et al., 2011).

Despite the wide variety of observed land subsidence rates in Table 1 and Figure 1, all monitoring results agree that the areas worst affected by the land subsidence hazard are adjacent to the coasts, such as the north coast, northwest, and northeast parts of Jakarta. Several sites in the northwest and northeast Jakarta are experiencing land subsidence at a high rate, such as Cengkareng, Penjaringan, Pantai Mutiara, Pantai Indah Kapuk, Ancol, Cilincing, and Cakung. Table 1 shows that generally, from all geodetic methods, leveling resulted in the most conservative subsidence rates, followed by InSAR interferometry and GPS method. SAR interferometry alone sometimes resulted in differing values; for example, in Pantai Mutiara, the subsidence rates are 21.8 cm/year (2007-2009), 8.5-10.5 cm/year (2010-2012); in Cengkareng, the subsidence rates are 21.6 cm/year (2007-2009), 10.0-17.5 cm/year (2010-2012), 13 cm/year (2007-2010). Comparing the geodetic methods with ground-based monitoring using the stable benchmark shows that the geodetic methods result in more pessimistic values. From Table 1 and Figure 1, the subsidence rate at the Tongkol site from a stable benchmark is 1.0-2.3 cm/year (1990-2017), from InSAR methods are 1.35 cm/year (2014-2017) (Yuen, 2018), 3.3 cm/year (2007-2010) (Ng et al., 2012), and from GPS 7.8 cm/year (2001-2010) (Abidin et al., 2011). In SAR-derived subsidence rate from Yuen (2018) is the subsidence rate closest to the factual subsidence in Tongkol. A graph depicting subsidence rate versus time was constructed from Table 1 to obtain a thorough perspective of the land subsidence rate in Jakarta (Figure 2).

Figure 2. Subsidence rates in Jakarta over 1982-2007 compiled from several monitoring methods in Table 1.

The bold yellow dashed line in Figure 2 shows that for the typical pattern of Jakarta, land subsidence rates derived from various methods experienced a fluctuating rate from 1980 to 2011. From 1982 to 1991, Jakarta subsided fast and slowed down from 1991 to 1997. The subsidence increased from 1998 to 2010, with the fastest rate observed from 2000 to 2010. From 2010 to 2011, the subsidence seemed to slow, albeit still at a high rate. Figure 2 shows that, in Cengkareng and Pantai Mutiara, the subsidence rates from 1982 to 2012 followed a similar pattern to that of the typical Jakarta. Figure 2 also shows that the subsidence rates in Tongkol were the lowest and followed a distinct pattern of Jakarta city The subsidence rate was relatively low at about 2 cm/year from 1990 to 2010 and decreased to 1 cm/year from 2011-2017.

Land subsidence in Jakarta has always been related to the over-exploitation of groundwater. Hendarto and Standing (2019) showed that the groundwater level at the lower confined aquifer in North Jakarta had dropped at least 22–25 meters above sea level (a.s.l.) in 2014 from the previously artesian level in 1914. Bakr (2015) modeled the effect of groundwater drawdown on land subsidence in Daan Mogot (DNMG) site using four groundwater level scenarios. It was found that returning the groundwater level to the 1995 level would reduce the residual subsidence for 2010- 2100 by 41-49%. Pranantya et al. (2017) modeled groundwater head drop on land subsidence in the Sunter site. Four models of linear groundwater continued drawdown were considered, with a maximum of -62 m assumed. This paper revealed that continued drawdown of the groundwater level contributes little to the total subsidence compared to the groundwater level of 2015.

Analyzing the borehole data from Pranantya et al. (2017), the author considers that it is possibly related to the lithology of the Sunter site. The lithological log in Pranantya et al. (2017) suggests that the highly compressible layers possibly occur until the depth of 90 m; below that lay the Tertiary Formations that are compact. Further drawdown of the lower aquifer head did not result in higher subsidence because the upper, more compressible layers had already been drained. Slower dissipation of pore pressure is expected at deeper strata due to the Tertiary Formations' low permeability and stiffer nature. Marylin (2012) conducted a comprehensive study in Rawa Buaya, West Jakarta. Marilyn (2012) modeled the land subsidence mechanism in Rawa Buaya based on data from a 300 m borehole core. She revealed that the land subsidence in Rawa Buaya occurred primarily due to natural sediment consolidation (65%) and groundwater level drawdown (19%). The remaining 16% is attributed to the combined effects of surface loading of buildings and possibly tectonics. Marilyn (2012) also highlighted the hydro-compaction factor common in organic-rich deposits undergoing subsidence.

Land Subsidence in Bandung basin

The Bandung basin is located within an intra-montane basin surrounded by volcanic terrains at 665 m above sea level in West Java. The surficial geology of the Bandung basin consists of Late Quaternary coarse volcaniclastics, fluvial sediments, and a thick series of lacustrine deposits (Dam et al.,1996). Understanding the near-surface geology of the Bandung basin, it is evident that this area is prone to land subsidence hazards due to the presence of highly compressible deposits. The Bandung basin covers an area of approximately 2.300 km^2 with a population of 8.5 million people, which serves as the capital of West Java Province and the center of education and industries. Increasing anthropogenic activities in the area pressurize the subsurface conditions manifested in the surface as land subsidence. Gumilar (2013) extensively studied the evidence of land subsidence in the Bandung basin, such as settlements of houses, cracks in houses, roads, and floods. Settlements and cracks were widely observed in Cimahi, Dayeuhkolot, Majalaya, Kopo Katapang, Rancaekek, Gedebage, and Banjaran. Meanwhile, floods regularly occur in Dayeuhkolot and Rancaekek. A strong correlation between groundwater level drops and land subsidence rates indicated that groundwater exploitation is the leading cause of subsidence in Bandung (Abidin et al., 2009).

Land subsidence in the Bandung basin has only been monitored since 2000 using the GPS method (Abidin et al., 2013). Several researchers have also applied InSAR interferometry after the GPS survey (Ge et al. (2014); Khakim et al. (2014); Sumantyo et al. (2012)). In addition, several places in the Bandung basin have been recognized to suffer from land subsidence, such as Cimahi, Dayeuhkolot, Banjaran, Gedebage, and Rancaekek. Recently, ground-based subsidence monitoring, such as stable benchmark and extensometer, is unavailable in the Bandung basin. Figure 3 and Table 2 summarize the past land subsidence monitoring results using geodetic methods.

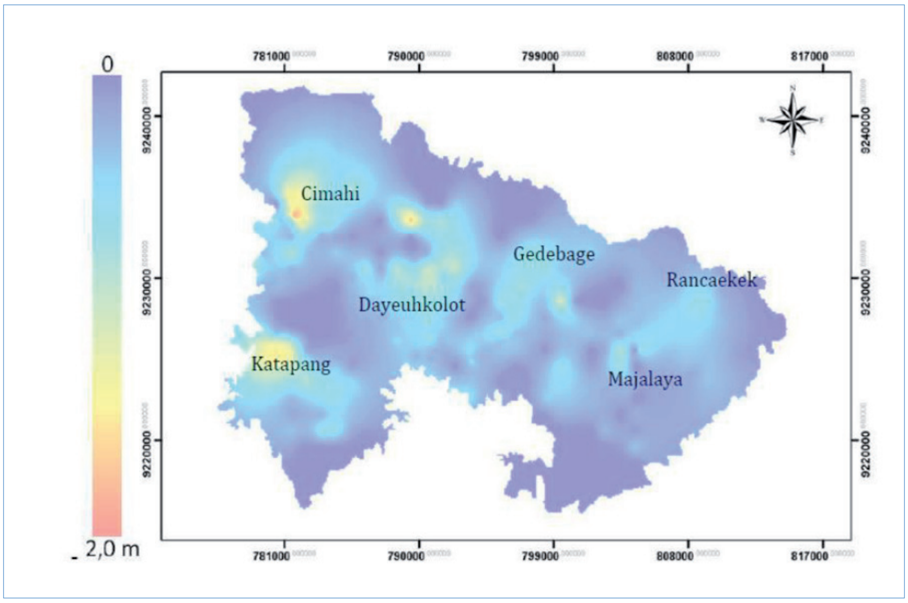

Figure 3. Land subsidence in the Bandung basin derived from GPS and InSAR (Gumilar et al., 2015).

Table 2. Land subsidence rates in Bandung basin as monitored by SAR-interferometry and GPS methods.

Location	Method	Monitoring period	Subsidence rate (cm/year)	Reference
Cimahi	SAR interferometry	2004-2006	12.07	(Chatterjee et al., 2013)
		2005-2006	15.81	
		2007-2008	18.0	
		2007-2008	5.0	(Sumantyo et al., 2012)
		2007-2011	11.9	(Khakim et al., 2014)
		2007-2011	20.0	(Ge et al., 2014)
	GPS	2001-2010	11.67	(Abidin et al., 2013)
Dayeuh kolot	SAR interferometry	2004-2006	10.56	(Chatterjee et al., 2013)
		2005-2006	12.84	
		2007-2008	14.10	
		2007-2008	2.7	(Sumantyo et al., 2012)
		2007-2011	15.0	(Ge et al., 2014)
		2007-2011	8.6	(Khakim et al., 2014)
	GPS	2001-2010	10.55	(Abidin et al., 2013)
Banjaran	SAR interferometry	2007-2008	0.6	(Sumantyo et al., 2012)
		2007-2011	5.0	(Ge et al., 2014)
	GPS	2001-2010	5.0	(Abidin et al., 2013)
Rancaekek	SAR interferometry	2007-2011	6.1	(Khakim et al., 2014)
		2007-2011	5.0	(Ge et al., 2014)
	GPS	2001-2010	5.56	(Abidin et al., 2013)
Gedebage	SAR interferometry	2007-2008	3.3	(Sumantyo et al., 2012)
		2007-2011	10.0	(Ge et al., 2014)
	GPS	2010-2011	5.0 - 6.0	(Abidin et al., 2013)

Table 2 shows that subsidence rates derived from SAR interferometry and GPS monitoring in the Bandung basin vary spatially and periodically. Table 2 suggests that for the same period, different rates can be obtained from the same method (SAR interferometry); for example, in Cimahi, during 2007- 2008, the land subsidence rate was 5 cm/year (Sumantyo et al., 2012) and 18.0 cm (Chatterjee et al., 2013); in Dayeuhkolot, during the year 2007 – 2011, the subsidence rate was 8.6 cm/year (Khakim et al., 2014) and 15.0 cm/year (Ge et al., 2014). Results from Sumantyo et al. (2012) are the most conservative of all SAR interferometry results. Comparison of interferometry results with GPS measurement shows a wide variation, only measurements in Rancaekek seem to agree. It is difficult to obtain the factual land subsidence rates in the Bandung basin since no ground-based monitoring is available. A complete view of land subsidence in the Bandung basin is obtained in Figure 4, constructed using data from Table 2.

Figure 4. Subsidence rates in Bandung over 2001-2011 compiled from several monitoring methods in Table 2.

Figure 4 shows that the highest rate of land subsidence is in Cimahi, followed by Dayeuhkolot, Rancaekek, Gedebage, and Banjaran. During the 2001-2011 period, most subsidence rates were relatively stable at a high rate, some experienced acceleration, and no deceleration was observed. Previous studies relate land subsidence in the Bandung basin with excessive groundwater extraction. Subsidence zones in Table 2 are related to textile and manufacturing industries' locations, which inevitably require water (groundwater) for their businesses. According to Wangsaatmaja et al. (2006), groundwater in the subsidence zones has been exploited intensively, causing declines in piezometric pressures. For example, in Dayeuhkolot, the groundwater level was artesian (+4 m above ground level) in 1920 and continued to drop, reaching 40-80 m below ground level in the 1990s; similar conditions are found in Cimahi and Rancaekek (Wangsaatmaja et al., 2006). Abidin et al. (2013) found a positive correlation between GPS-derived land subsidence rates and piezometric declines in industrial complexes. The mechanism of land subsidence in the Bandung basin is quite complex, resulting from at least four factors, groundwater level decline, the addition of building loads, natural consolidation of young sediment, and tectonics.

Taufiq (2010) modeled the mechanism of land subsidence in three sites, namely Cimahi, Dayeuhkolot, and Rancaekek, using a finite element numerical model and calibrated the results to GPS measurements from the year 2000 to 2008. Modeling results revealed that the contribution of groundwater factor to land subsidence in Dayeuhkolot is between 30-70%, in Rancaekek is 37-47%, and in Cimahi is 79-91%. The building loads contributed 8%, 50%, and 4% to land subsidence in Dayeuhkolot, Rancaekek, and Cimahi, respectively. Taufiq (2010) noted a 2-63% discrepancy between the model and GPS monitoring results, attributed to other factors such as tectonics and natural consolidation.

Land Subsidence in Semarang

Semarang city is the capital of Central Java province, located on the north coast of Java Island. Semarang city consists of the lowland in the north and the highland in the south; the north lowland serves as the center of local government, business, and industrial areas. The population of Semarang city was 1.83 million in 2019, and it primarily resides in the northern lowland. Land subsidence has existed since the late 1980s (Marsudi, 2001) that continues until the present. Land subsidence is a ubiquitous phenomenon in the north Semarang coastal area. Abidin et al. (2013) conducted an extensive survey to map the evidence of land subsidence in Semarang. Severe coastal flooding often deteriorates housing, buildings, and other infrastructures and affects health, sanitary, and social-economic conditions. Other impacts of land subsidence in Semarang are cracking and damage of housing, buildings, and infrastructure, malfunction of drainage systems, changes in river canal and drain flow systems, and inland seawater intrusion. Marsudi (2001) related the causation of land subsidence in Semarang to groundwater and increased loads from reclamation and buildings.

Land subsidence in Semarang city is one of the cases in Indonesia that have been studied extensively from many aspects. Land subsidence in Semarang city has been monitored using various geodetic and non-geodetic methods. Leveling survey was conducted in Semarang from 1983 to 2001, followed by GPS and InSAR measurements. Non-space geodetic monitoring includes stable benchmarks in several locations and a geophysical method of microgravity that measures the groundwater deficit and the corresponding subsidence. The compilation of previous land subsidence geodetic and geophysical monitoring results is presented in Table 3.

Table 3. Monitoring of land subsidence rates in Semarang city using various methods.

Method	Monitoring period	Subsidence rate (cm/year)	Reference
Levelling	1996-2000	0-15.81	(Marfai and King, 2007)
	1999-2003	0-12.07	(Murdohardono et al., 2007)
GPS	2008-2011	0-19	(Abidin et al., 2013)
SAR interferometry	2002-2006	0-8	(Kuehn et al., 2009)
	2007-2008	0-8	(Lubis et al., 2011)
	2007-2008	0-12	(Chaussard et al., 2013)
	2017-2019	0-12.7	(Widada et al., 2020)
Microgravity	2002-2005	0-15	(Supriyadi, 2008)

Table 3 shows that the rate of land subsidence from geodetic and geophysical monitoring ranges from 0-15.81 cm/year. A time serial graph of Table 3 is presented in Figure 5 to understand the evolution of land subsidence rates in Semarang. Figure 5 shows that generally, the subsidence rates fluctuated from 1996 to 2006, increased to the highest rate in 2011 and slightly decelerated up to 2019.

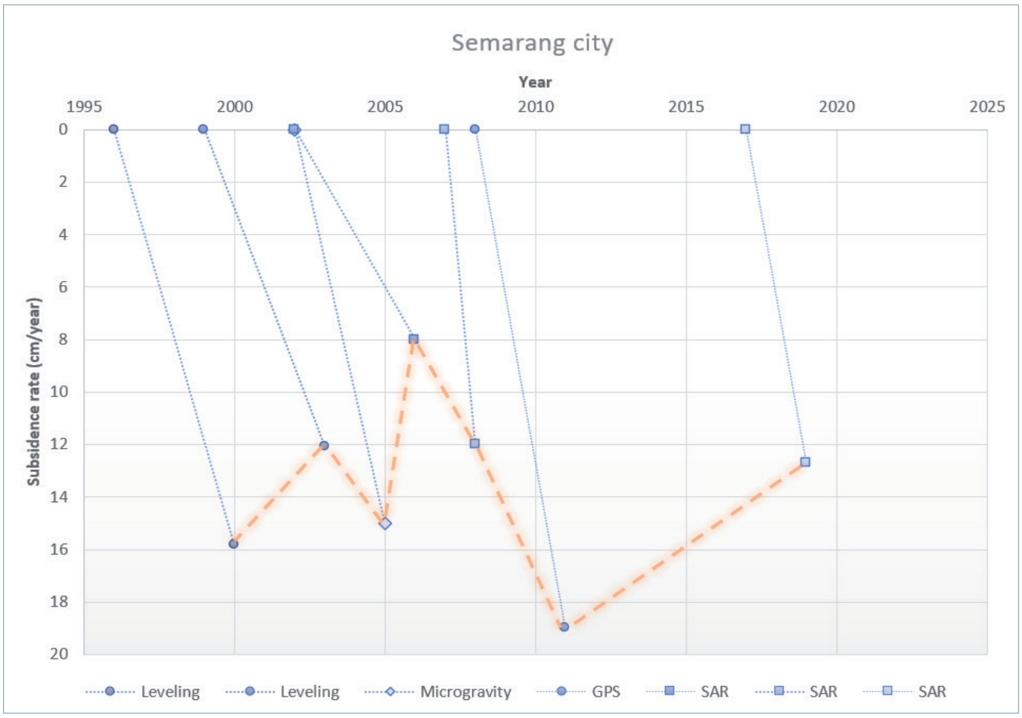

Figure 5. Subsidence rates in Semarang over 1996-2019 compiled from several monitoring methods in Table 2.

Despite the different monitoring periods, all results in Table 3 are consistent, showing that land subsidence occurs in the north part of Semarang city and no subsidence occurs in the south side, as depicted in Figure 6. Figure 6 also shows that the areas near the coast are undergoing the highest rate of land subsidence.

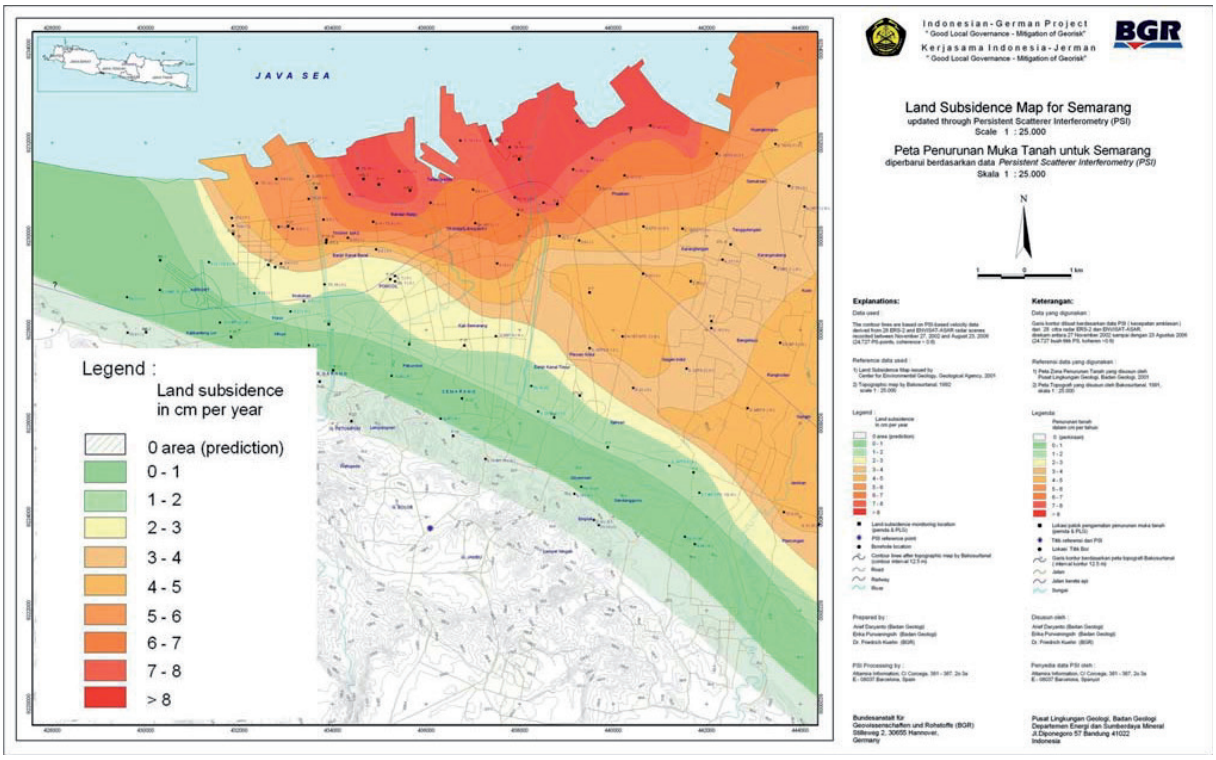

Figure 6. Land subsidence map of Semarang city released by the Indonesian Geological Agency as derived from SAR interferometry (Kuehn et al., 2009).

The Indonesian Geological Agency (Badan Geologi) installed stable benchmarks to monitor the land subsidence in Semarang, similar to the one installed in Tongkol, Jakarta. The stable benchmarks or static extensometers in Kaligawe and Madukoro, Semarang city, were firmly anchored in a firm stratum of the Damar Formation. Results of subsidence monitoring and numerical modeling carried out by a joint team from Badan Geologi dan LIPI in Kaligawe and Madukoro can be found in Sarah et al. (2021). This paper compares the stable benchmark monitoring results with the corresponding geodetic monitoring results from Widada et al. (2020). Figure 4 shows the distribution of GPS and InSAR (Sentinel) monitoring points across the Semarang alluvial plain (InSAR results taken from Widada et al., 2020 and GPS results from Abidin et al., 2013) and the locations of stable benchmarks in Madukoro and Kaligawe. Comparisons were made between GPS and InSAR results to the stable benchmark monitoring results. GPS and InSAR measurement points adjacent to the benchmarks were taken for comparison, as marked by the red boxes in Figure 7.

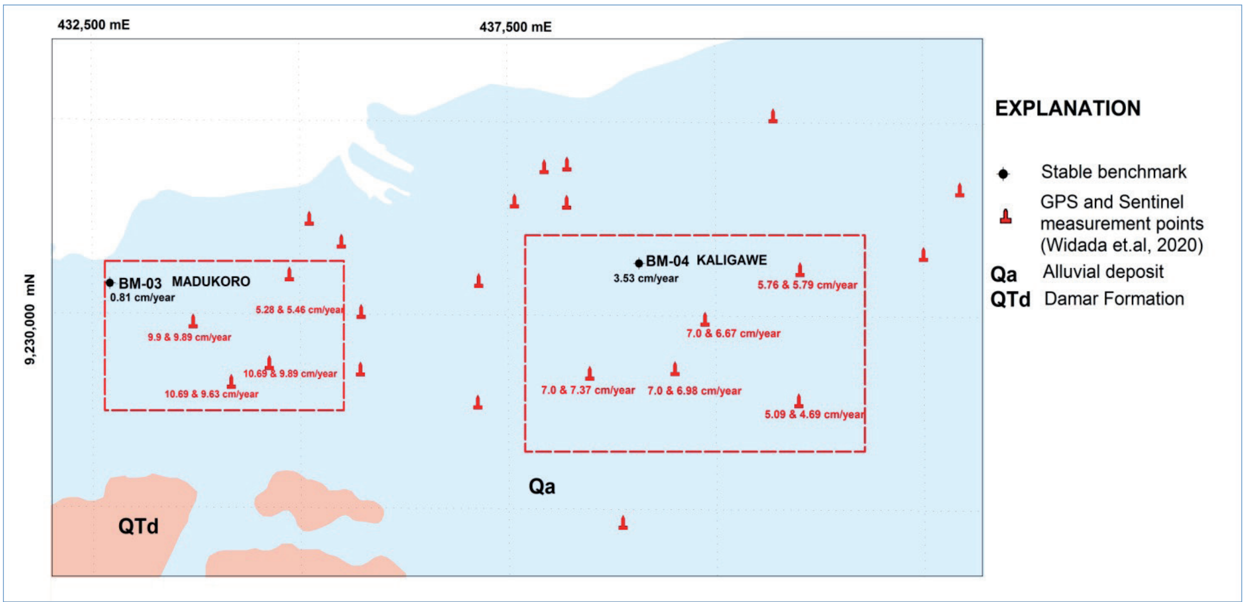

Figure 7. Distribution of geodetic monitoring points (GPS and InSAR) (Widada et al., 2020) and stable benchmark locations.

Figure 7 shows that geodetic points near Madukoro and Kaligawe benchmarks have spatially variable rates; all rates exceed the ground-based monitoring results. The stable benchmark monitoring has been carried out in Madukoro and Kaligawe since 2012. For comparison with the ground-based results, we use the GPS results from 2008-2011 and the latest InSAR results from 2017-2019. The lowest rates from adjacent geodetic points are taken for the assessment (Table 4). Table 4 shows that although the monitoring years overlap between the geodetic and stable benchmarks, all monitoring results show that Madukoro and Kaligawe are subjected to ongoing land subsidence. Despite the different periods, the subsidence rate derived from GPS and InSAR shows similar results (Figure 7 and Table 4).

Table 4. Comparison of geodetic monitoring results and stable benchmark.

Method	Monitoring Period	Subsidence rate in Madukoro (cm/year)	Subsidence rate in Kaligawe (cm/year)
GPS	2008-2011	5.28	5.76
InSAR	2017-2019	5.46	5.79
Stable benchmark	2012-2017	0.81	3.53

Table 4 shows that the GPS and InSAR results in Madukoro and Kaligawe sites are almost similar, while the benchmark results show that Kaligawe subsides a lot faster than Madukoro. The survey on damages caused by land subsidence showed that the subsidence damages in Kaligawe are more intensive than Madukoro in the west (Abidin et al., 2013), indicating a higher subsidence rate in Kaligawe. Table 4 also pointed out that the geodetic subsidence rates exceed the ground-based monitoring results at 6.5 times in Madukoro and 1.6 times in Kaligawe. This difference is possibly due to the spatial variation of the compressible deposit in the subsurface, the difference in local groundwater level, external loads, and others.

Based on groundwater exploitation data and spatial land use, Marfai and King (2007) highlighted that the high subsidence rate in North Semarang is related to excessive groundwater extraction and increased development in the coastal areas for economic and tourism, residential, industrial and commercial purposes. Sarah et al. (2011) analyzed the contribution of anthropogenic factors of groundwater level drawdown and surface loads of reclamation and building load to the land subsidence rates in Tanah Mas and Pelabuhan sites of Semarang. The paper resulted in 75% of groundwater factor and the remaining 25% of surface load factor to the subsidence rates. A comparison of modeling derived subsidence rate to the geodetic subsidence rate showed that the subsidence rates derived from modeling the anthropogenic drivers could only account for 79% of the geodetic monitoring. Sarah et al. (2021) further analyzed the land subsidence mechanism in Madukoro and Kaligawe using numerical modeling and stable benchmark monitoring data as the model validation. The modeling results show that the contribution of groundwater level decrease accounts for 74-82% of the total subsidence, while the remaining 18-26% is attributed to a load of buildings. Comparing the modeling results with ground-based monitoring shows an excellent agreement for the Madukoro site. For the Kaligawe site, the modeling result is slightly lower than the stable benchmark monitoring, possibly due to model parameters that use the older groundwater level data (1980-2010), while there is a possibility that the groundwater level in the industrial estate of Kaligawe has decreased further after 2010 (Sarah et al., 2021).

Apart from anthropogenic factors, land subsidence is also caused by natural drivers, such as tectonics and natural compaction. For example, Sarah et al. (2020) analyzed the contribution of natural compaction of Recent sediments in Semarang City and Demak Regency, the natural compaction rate of less than 0.8 cm/year in Semarang City and more than 0.8 cm/year in Demak Regency. According to Sarah et al. (2020), the subsidence in Semarang City is mainly due to anthropogenic causes (91 - 100%), while natural compaction only accounts for a small part (1 - 9%). The mechanism of the fast subsidence rate in Semarang city is influenced by the occurrence of saline clay layers in the subsurface that compress much faster than the freshwater clays, whereas, in North Semarang city, the upper clays are mostly saline (Sarah et al., 2018).

Remediation of Land Subsidence Hazard and Future Challenges

Jakarta, Bandung, and Semarang are prime examples of land subsidence cases in Indonesia. However, despite the different accuracy of each monitoring method, all land subsidence monitoring results agreed that those areas experience relatively high subsidence rates. The enormous economic and associated loss to the built and natural environment due to land subsidence requires further steps. Adaptation and mitigation measures to this silent disaster must begin with a comprehensive understanding of its motions and mechanisms.

The vertical motion of land subsidence has been analyzed using several geodetic and non-geodetic methods. For the Jakarta case, the result of stable benchmark monitoring is in agreement with geodetic monitoring (InSAR) (Yuen, 2018). For the Semarang case, the discrepancy between geodetic and stable benchmark monitoring is quite large (about 1.5- 6.5 times). As for Bandung city, a comparison between space-geodetic and ground-based methods cannot be made as no stable benchmark has been installed.

Tables 1 to 4 show that land subsidence rates from geodetic monitoring results vary widely over different methods, namely leveling, GPS, and InSAR. Tables 1 and 3 show that subsidence rates derived from leveling are relatively conservative than in GPS and InSAR results. With increasing land development, leveling has become more challenging because of the limited space caused by dense land use, surveying time length, and costly labor. GPS campaigns and InSAR interferometry are alternative methods to cover larger areas within a shorter survey time. For example, land subsidence rates derived from GPS and InSAR in Jakarta, Bandung, and Semarang (Table 1 to 4) show higher rates from GPS compared to InSAR. These findings align with the resolutions of each monitoring method as outlined by Galloway et al. (2000). The land subsidence rates derived from leveling are the most conservative, followed by InSAR and GPS. According to Galloway et al. (2000), the highest resolution for measuring land subsidence rate is by borehole extensometer. The only drawback of this method is the spatial scale of the point element, and building many points in a large spatial area would be very costly. The stable benchmark is a borehole extensometer that measures the total land subsidence rate. The stable benchmark results in Jakarta and Semarang show factual subsidence rates similar to the realistic conditions in the field.

One of the visible impacts of land subsidence is the tilting of buildings due to differential settlement. In Jakarta, Bandung, and Semarang, the sinking and tilting of low-rise buildings, mainly housing, are widely seen in subsidence areas. When differential settlement of the foundation occurs, the building will be distorted or tilted, causing structural damage like cracking of the walls. Tilting of the low-rise building is typically noticed when it is in the region of 1/250 to 1/200; at 1/100, remedial action must be taken, and at 1/50, the building is reaching the dangerous limit that remedial action must be taken immediately or the building shall be demolished (Charles and Skinner, 2004). If we take an average value of 4 m length of the house foundation, when tilting begins to be recognized by the naked eye, the settlement (or subsidence) of 1.6 -2.0 cm has occurred. When the settlement continues to undermine the house, 4 cm of subsidence has occurred, and the house is in danger or inhabitable when 8 cm of subsidence has happened. Applying the approach from Charles and Skinner (2004) to the land subsidence case in Semarang city is comparable to stable benchmark monitoring results. For example, in the Madukoro site, the building settlement is quite visible to threatening; however, the building is still liveable. While in Kaligawe, the observed building settlement is primarily threatening, with some inhabitable.

Understanding spatial land subsidence is significant for remedial and mitigation measures. Geodetic methods are powerful in obtaining the spatiotemporal variation of land subsidence rates. Future studies in geodetic monitoring of land subsidence in Jakarta, Bandung, Semarang, and other Indonesian sites must account for the existing ground-based monitoring results and the visible impacts on buildings and infrastructure. Remediation measures in land subsidence can be divided into two categories: (1) physical measure and (2) administrative regulation measure. Studies on the mechanism of land subsidence assist in decision-making for these remediation measures. For example, when it is understood that anthropogenic factors dominate the land subsidence process, remedial measures must focus on those factors. Likewise, when the natural factors govern the land subsidence factor, remediation measures must be directed to limit land use in subsidence areas or apply ground improvement techniques to stabilize the subsided ground.

Based on previous studies, the land subsidence in Jakarta is caused by several factors that vary spatially, are overexploitation of groundwater, building loads, and hydrocompaction of organic-rich deposits. Studies by Bakr (2015), Hendarto and Standing (2019), and Pranantya et al. (2017) suggested that the groundwater factor is predominant in North Jakarta, furthermore Bakr (2015) suggested that if the groundwater level returns to the 1995 level, the land subsidence rate will reduce by 41-49%. The spatial distribution of the factors causing land subsidence in Jakarta is unclear; therefore, it must be further researched. Also, the characterization and contribution of the hydrocompaction need to be studied in more detail, as hydrocompaction can generate a high subsidence rate.

For the Bandung subsidence case, groundwater and building loads are the factors causing land subsidence. Taufiq (2010) identified three areas, Dayeuhkolot, Rancaekek, and Cimahi, where the groundwater factor accounts for about 30-70 % of the land subsidence, while the rest is attributed to building loads and unknown factors. Taufiq (2010) also recognized a 2- 63% discrepancy between the land subsidence model and GPS monitoring results. As a stable benchmark or other extensometer has yet to be available, it is difficult to compare the modeling results to the factual subsidence. Therefore, building ground-based monitoring is essential, such as a stable benchmark in several land subsidence sites in Bandung. While the previous study only focused on three locations in the Bandung basin, other sites' mechanisms still need to be discovered. Previous studies in Semarang city reveal that groundwater exploitation is the primary driver of land subsidence, followed by building loads due to municipal development. Understanding the mechanism and the current situation of land subsidence rate allow geoscientists and decision-makers to formulate remedial actions to mitigate this silent hazard. Finally, we propose a combination of structural and non-structural (administrative/regulative) methods for land subsidence mitigation, like the following:

1. Coastal flood prevention structures, such as flood-resistant walls and pump and polder systems to mitigate the immediate effect of land subsidence
2. Increasing surface water supply and controlling groundwater withdrawal
3. Establishing a monitoring network to observe groundwater level fluctuations and land subsidence rate using a combination of groundwater monitoring wells, extensometer, and geodetic surveys
4. Groundwater artificial recharge program to replenish the exploited aquifers
5. Hydrogeologic and engineering geologic investigations to understand the spatial subsurface conditions and update the subsurface subsidence model
6. Building regulation for spatial planning in the land subsidence area
7. Law enforcement for illegal groundwater withdrawal

Land subsidence mitigation involving groundwater withdrawal control has received sustainable success in cases of high subsidence rates, such as in Tokyo, Osaka, Bangkok, and the USA. In Tokyo and Osaka, strict groundwater pumping regulation has successfully slowed and reversed the land subsidence rate (Endo, 2011; Sato et al., 2006). Groundwater management in Japan involves regulating groundwater extraction, construction of industrial water supply works to provide an alternate water supply to replace groundwater, and subsidies and favorable tax treatment for applying water-saving technologies (Kataoka, 2006). Specifically, Sato (2006) explained that the restrictions on groundwater pumping are targeted to the pumping facilities' structural design, i.e., target area, depth of pumping, strainer position, and output volume. The groundwater well installation requirements are stringent; building a new well is almost impossible (Endo, 2011). In Bangkok, measures to control groundwater abstraction involve groundwater zoning and charge system and providing waterworks for an alternative water source (Lorphensri et al., 2011). A comprehensive approach to mitigating land subsidence in Coachella Valley, California, USA, includes groundwater substitution, conservation, and managed aquifer recharge (MAR) (Sneed and Brandt, 2020). Water consumption for non-drinking purposes uses the surface water from the Coachella canal and pipes. Conservation measures include the implementation of water-saving technologies and tiered-cost for groundwater usage. Sneed and Brandt (2020) show that the slowing down of subsidence rate and groundwater recovery coincides with the implementation of the groundwater charge, an increase in surface water supply, and artificial aquifer recharge. Learning from the best practices in other countries and combining all options will work best to slow down land subsidence. Endo (2011) argued that the most effective solution to combat land subsidence is replacing groundwater demand with surface water delivered by waterworks.

Land subsidence is a continuous hazard we must carry out long-term mitigation measures. The current mitigation method in Indonesia involves zoning groundwater utilization by assigning the groundwater conservation zones as mandated by the Ministerial Decree ESDM no. 31 (ESDM, 2018). Implementation of this zoning or deep groundwater system faces difficulties due to the lack of deep monitoring wells. Hence, the effectiveness of this zoning is hard to assess. The success of any mitigation method is to be proven by land subsidence monitoring. Regarding the shortcomings in spatial resolution and accuracy of all monitoring methods (ground-based and geodetic), each method complements the others. GPS and InSAR results shall be calibrated against stable benchmark results to obtain a consistent spatial land subsidence rate. Future research on land subsidence in Indonesia is still highly required, particularly regarding its spatial distribution, rates, and mechanism. Another subsidence type still needs more scientific information in Indonesia is peat subsidence in lowland areas. Peat subsidence can produce land subsidence at a substantial rate; in this case, the information on the hydro-geo-mechanical characterization of the peat subsidence, modeling, and monitoring still needs to be discovered.

CONCLUSIONS

Rapid development in many regions in Indonesia has resulted in hidden, silent land subsidence hazards. Regional development is going on at a high pace and is expected to continue across the archipelago. Substantial land subsidence in Jakarta, Bandung, and Semarang has been reviewed. Time series monitoring from 1996 to 2019 shows that land subsidence in Jakarta peaked in 2011 and slowed until 2019, although the subsidence rate is still relatively high, reaching 10 cm/year or more. A similar trend is also observed in Semarang. The subsidence rate in Bandung varies spatially from 0.6 to more than 10 cm/year, where the subsidence centers occur in industrial areas. Land subsidence in Jakarta and Semarang occurs in the alluvial deposit of the north Java coastal area. While in Bandung, the subsidence happens in the lake deposit of the Bandung basin.

Moreover, land subsidence is likely to occur in many other areas underlain by soft, compressible deposits, such as the North Coast of Java, East Sumatra, and Kalimantan. Due to the rapid development, groundwater resources will also be pressured to meet the increasing demands. Case studies in Japan, the USA, and Thailand show that the combination of technology and regulation has successfully mitigated the land subsidence hazard. Finally, prevention and mitigation measures have been proposed that combine the physical method and administrative regulation.

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