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Corresponding author:
santika.tristi@universitaspertamina.ac.id
santikatristi97@gmail.com

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Land Subsidence due to Groundwater Extraction and Natural Consolidation in the Bandung Basin, West Java, Indonesia

Santika T. Maryudhaningrum[1], Wira Cakrabuana[2], Latif Marthakusuma[3], Dwi Sarah[2], Imam A. Sadisun[3], Astyka Pamumpuni[3], Eko Soebowo[2]

[1]Pertamina University, Jl. Teuku Nyak Arief, Jakarta Selatan, DKI Jakarta, 12220, Indonesia
[2]National Research and Innovation Agency, Tangerang Selatan, 15314, Indonesia
[3]Institut Teknologi Bandung, Jl. Ganesha No. 10, Bandung, Jawa Barat, 40132, Indonesia

Abstract

Based on GPS and InSAR data, it is known that there is land subsidence in the Bandung Basin of 1.1 - 16.9 cm/year (GPS) and 0.9 - 1.7 cm/year (InSAR). Several types of land subsidence can be expected to occur in the Bandung Basin. However, the detailed characteristics and exact mechanism of land subsidence from a geological perspective in the Bandung Basin are still unknown. Two factors that can cause land subsidence are groundwater extraction and natural consolidation. It is known that there has been a significant decrease in groundwater levels in Bandung since the 1970s due to the very high intensity of groundwater extraction. It is also known that the Bandung Basin comprises one of them, the Kosambi Formation, which consists of organic clays with very high compressibility and undergoes a natural consolidation. Based on these facts, we determine the distribution of land subsidence rates due to groundwater extraction and natural consolidation, along with the percentage of their respective contributions in the Bandung Basin. Research materials include groundwater level depth data and organic clay consolidation data from previous studies. The results showed that the average land subsidence rate due to groundwater extraction was 1.85 cm/year, with a contribution percentage of 44.30%. In comparison, the average land subsidence rate due to natural consolidation was 0.92 cm/year, with a contribution percentage of 15.76%.

1. Introduction

Land subsidence is a geological hazard characterized by gradually lowering the ground surface, potentially resulting in serious disasters. It could occur as a result of human activities and also due to natural geological actions (Sarah et al., 2011). The average land subsidence rate in the Bandung Basin based on GPS data in the period 2000-2012 was 1.1 - 16.9 cm/year, while based on InSAR data in the period 2006-2010 was 0.9 - 1.7 cm/year (Gumilar et al., 2014). Some of the factors that cause land subsidence that has been commonly known from the results of previous studies are groundwater extraction, natural consolidation, building loading, and tectonic activity (Tzampoglou et al., 2023; Cao et al., 2024; El Magd et al., 2024; Villaseñor-Reyes et al., 2024). Research on land subsidence in the Bandung Basin using geodetic methods, including GPS and InSAR, has already been conducted. Several types of land subsidence can be expected to occur in the Bandung Basin, namely land subsidence due to groundwater extraction, land subsidence caused by artificial construction loads, and land subsidence caused by natural consolidation of sediments that have not been consolidated. The detailed characteristics and exact mechanism of land subsidence in the Bandung Basin are still unknown (Abidin et al., 2013).

As one of Indonesia's textile industry centers, Bandung has experienced a significant settlement in groundwater table (GWT) due to groundwater extraction for industrial purposes for 40 years (starting in the 1970s). Intensive groundwater extraction is one of the anthropogenic factors that can cause land subsidence in Indonesia (Abidin et al., 2009; Sarah et al., 2011; Gumilar et al., 2014; Sarah and Soebowo, 2018; Hendarto, 2019; Sarah et al., 2020). Increasing anthropogenic activities in the area pressurize the subsurface conditions, manifested on the surface as land subsidence (Sarah, 2022).

The Bandung Basin, partly composed of lake deposits (organic clay) that are quite thick, can cause natural land subsidence. Organic clay has a characteristic behavior, namely very high primary compressibility and secondary compressibility in creeping, which allows the settlement to continue even though the loading has stopped (Santagata et al., 2008). This phenomenon is natural consolidation/compaction (Gambolati and Teatini, 1998; Kooi and de Vries, 1998). Consolidation is when air and water are forced out of the soil's solid structure (Syahbana and Sarah, 2013).

This study aims to determine the distribution of land subsidence rates due to groundwater extraction and natural consolidation, along with the percentage of their respective contributions. The research was carried out within the scope of the Bandung geomorphological basin (Figure 1). The assumption used in this study is that the rate of land subsidence is derived from the average magnitude of land subsidence from year to year, and the subsurface conditions are considered continuous, homogeneous, isotropic, and linear elastic.

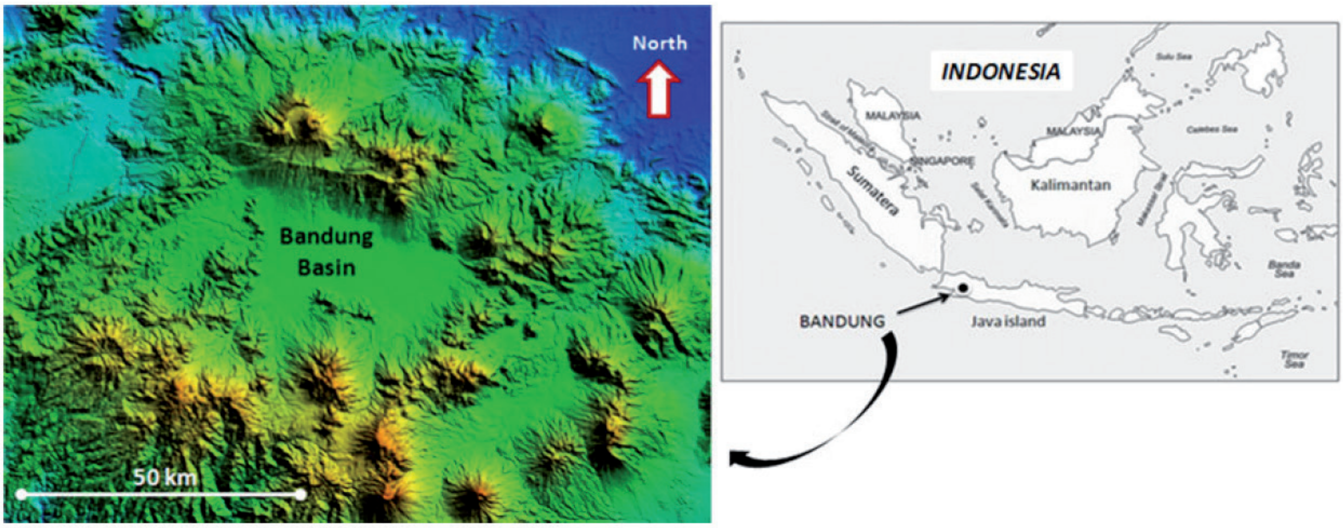

Figure 1. The location map of Bandung Basin (Abidin et al., 2006).

Several studies on land subsidence in Bandung have been conducted. Most studies have focused on investigating the land subsidence occurring in the Bandung Basin using geodetic methods and estimating the possible factors contributing to the subsidence (Table 1). Previous studies have not yet quantitatively determined (in terms of magnitude and rate) which factors are responsible for land subsidence in the Bandung Basin, nor have they identified which factor has the most significant influence on the observed subsidence. A study on the contribution of natural consolidation to land subsidence was conducted by Maryudhaningrum (2019). Of these studies, no one has discussed how much a factor contributes to land subsidence in the Bandung Basin.

Table 1. Previous works on land subsidence in the Bandung Basin.

Year	Author	Title
2021	Gumilar et al.	Extensive Investigation of the Land Subsidence Impressions on Gedebage District, Bandung, Indonesia
2018	Du et al.	Correlating the subsidence pattern and land use in Bandung, Indonesia with both Sentinel-1/2 and ALOS-2 satellite images
2015	Setyawan et al.	Detecting Land Subsidence Using Gravity Method in Jakarta and Bandung Area, Indonesia
2015	Gumilar et al.	Land subsidence in Bandung Basin and its possible caused factors
2014	Ge et al.	Land subsidence characteristics of Bandung Basin as revealed by ENVISAT ASAR and ALOS PALSAR interferometry
2014	Gumilar et al.	Land Subsidence, Groundwater Extraction, and Flooding in Bandung Basin (Indonesia)
2014	Khakim et al.	Lithology-controlled subsidence and seasonal aquifer response in the Bandung basin, Indonesia, observed by synthetic aperture radar interferometry
2012	Abidin et al.	On causes and impacts of land subsidence in Bandung Basin, Indonesia
2009	Abidin et al.	Land subsidence and groundwater extraction in Bandung Basin, Indonesia
2009	Hutasoit	Kondisi Permukaan Air Tanah Dengan dan Tanpa Peresapan Buatan di Daerah Bandung: Hasil Simulasi Numerik
2006	Abidin et al.	Studying Land Subsidence of Bandung Basin (Indonesia) Using GPS Survey Technique

2. Geologic setting

From old to young, the Bandung Basin comprises the Cikapundung Formation, the Cibeureum Formation, and the Kosambi Formation (Silitonga, 1973). The Cikapundung Formation is the oldest rock formation in the Bandung Basin, consisting of compact conglomerates, breccias, tuff, and andesite lava. The compactness of the constituting lithologies of this formation can be used as a basis to determine the role of this formation as bedrock in the research area. Other formations that form bedrock are Quaternary volcanic rocks (except for the Cibeureum Formation and the Cikapundung Formation), Tertiary volcanic rocks, Tertiary sedimentary rocks, and intrusive rocks.

The Cibeureum Formation has a fan-shaped distribution sourced from Mount Tangkubanparahu (Silitonga, 1973). Several other fans are sourced from Mount Malabar and the Wayang Mountain Complex in the southern part. Based on the similarity to the Cibeureum Formation, the lithology that makes up these fans is included as part of the same formation. The Kosambi Formation has an expanse from the south to the northernmost in Margahayu–Kopo. The Kosambi Formation is estimated to have been formed by sediment deposition from all directions in the Bandung Basin due to the Citarum River's damming and Lake Bandung's forming. The regional geological map of the Bandung Basin can be seen in Figure 2.

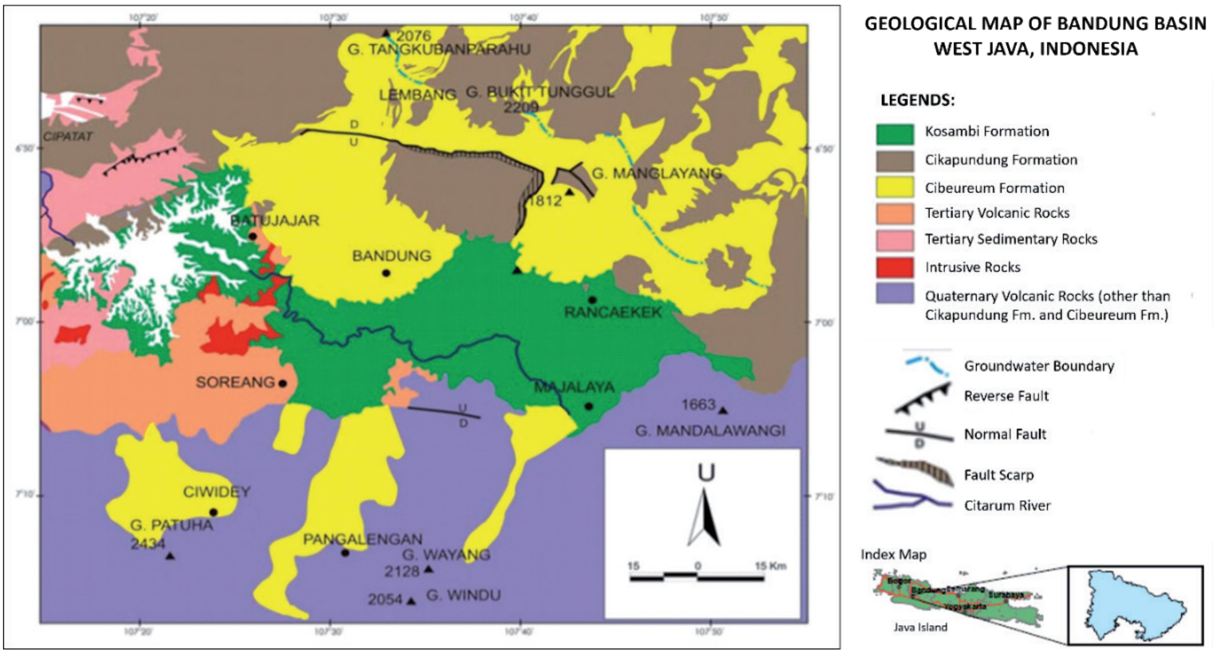

Figure 2. Regional geological map of the Bandung Basin (compiled and modified from Silitonga, 1973; Koesoemadinata and Hartono, 1981; Iwaco-Waseco and the Departemen Pekerjaan Umum, 1990; Alzwar et al., 1992; Kusmono et al., 1996; and Sujatmiko, 2003).

In the hydrogeological system in the Bandung Basin (Figure 3), the Kosambi Formation plays the role of an aquitard, and the Cibeureum Formation plays the role of an aquifer. The Kosambi formation on the surface is spread in the central part. Its lithology mainly consists of claystone, siltstone, and sandstone, which have not yet been compacted. The Cibeureum Formation is spread across the northern and southern parts of the research area. In the central region, the Cibeureum Formation lies beneath the exposed Kosambi Formation on the surface, forming a confined aquifer system. In this study, groundwater and organic soil data that will be used to calculate land subsidence are taken at the interval of the Kosambi Formation.

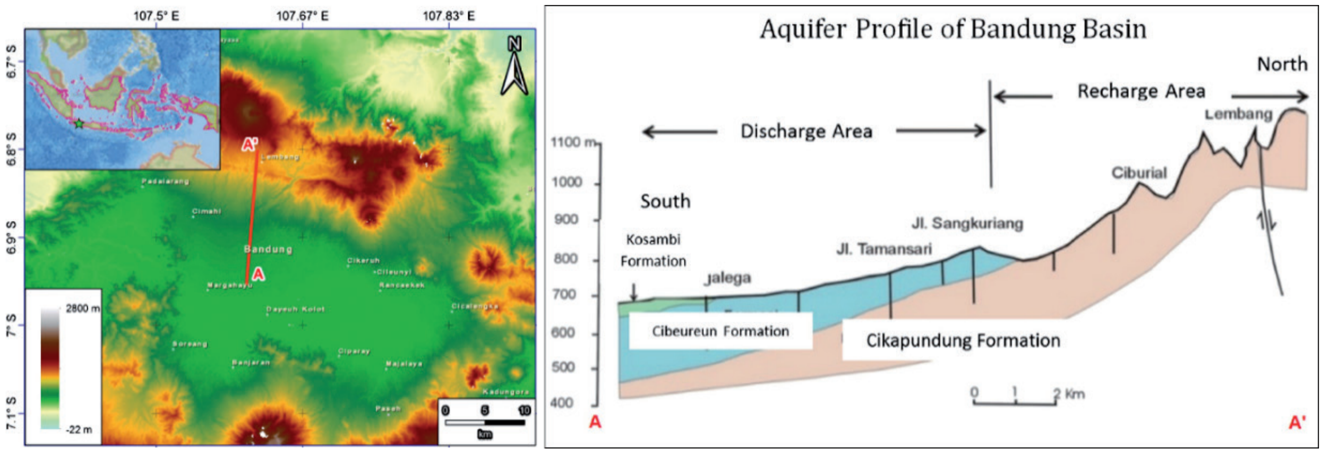

Figure 3. Profile of aquifers in the Bandung Basin (after Ge et al., 2014 and Wirakusumah, 2006).

3. Data and methods

The data on GWT depletion used in this study is sourced from Gumilar (2013), whereas the organic soil consolidation data is from Maryudhaningrum (2019). The GWT depletion data from Gumilar (2013) consists of the name of the well, coordinates, and the depth of the GWT from the 1980s to the 2000s. The data is then processed to become data on the GWT depletion in a certain period. An example of a table of GWT depletion data is listed in Table 2.

Table 2. Example of a GWT depletion data table (Gumilar, 2013).

Well	X (m)	Y (m)	Subsidence (m)	Time (year)
Cigentur	808500	9223100	0.11	24
PT Daese Garmin	791000	9234100	0.62	12
CV Timbul Jaya II	809350	9224000	0.38	11

Organic soil consolidation data from Maryudhaningrum (2019) consists of engineering borehole data, Cone Penetration Test with pore water pressure measurement (CPTu), X-Ray Diffraction Analysis (XRD), and Loss on Ignition test (LOI). The data is then processed to produce the magnitude of land subsidence due to natural consolidation. An example of a data table on land subsidence due to natural consolidation is listed in Table 3.

Table 3. An example of a data table shows the magnitude of land subsidence due to natural consolidation (Maryudhaningrum, 2019).

CPTu and Borehole	X (m)	Y (m)	Subsidence (m)	Time (year)
CPTu 3 2015	800430	9226404	0.05	74.5
CPTu 7 2017	786784	9229924	0.31	172.6
CPTu 15 2017	789753	9229953	0.60	200.2

We used the Terzaghi 1-D consolidation formula to model the land subsidence due to natural consolidation. A one-dimensional consolidation analytical model calculated the land subsidence value and maximum time (Das, 2010). The calculation of primary consolidation can be done by Equation 1 as follows:

$$Sp = \frac{C_c H}{1 + e_0} \log \left(\frac{p_0 + \Delta p}{p_0}\right)$$ **Equation 1**

Where:
Sp = settlement due to primary consolidation (m)
C_c = compression index
H = clay thickness (m)
e_0 = initial void ratio
p_0 = effective stress (kPa)
Δp = vertical stress over clay layer (kPa)

The GWT depletion data is further processed in such a way as to produce the value of land subsidence due to groundwater extraction using Equation 2 (Freeze and Cherry, 1979). After obtaining the magnitude of land subsidence in a certain period, the rate of land subsidence due to groundwater extraction can be calculated. Meanwhile, since the magnitude of land subsidence due to natural consolidation in a certain period is also known, the rate of land subsidence can also be calculated.

$$db = -\alpha b \, d\sigma_e = -\alpha b \, \rho g \, dh$$ **Equation 2**

Where:
db = magnitude of land subsidence (m)
α = compressibility of aquifer (Pa^{-1})
b = initial thickness of aquifer (m)
ρ = density (kg/m^3)
g = gravitational acceleration (m/s^2)
dh = magnitude of GWT depletion (m)

After the rates of the two types of land subsidence are known, a map of the distribution of land subsidence rates within the boundaries of the Bandung Basin is made. Furthermore, it was analyzed how much contribution groundwater extraction and natural consolidation had on total land subsidence observed through GPS data (Abidin et al., 2012). The research flow chart can be seen in Figure 4.

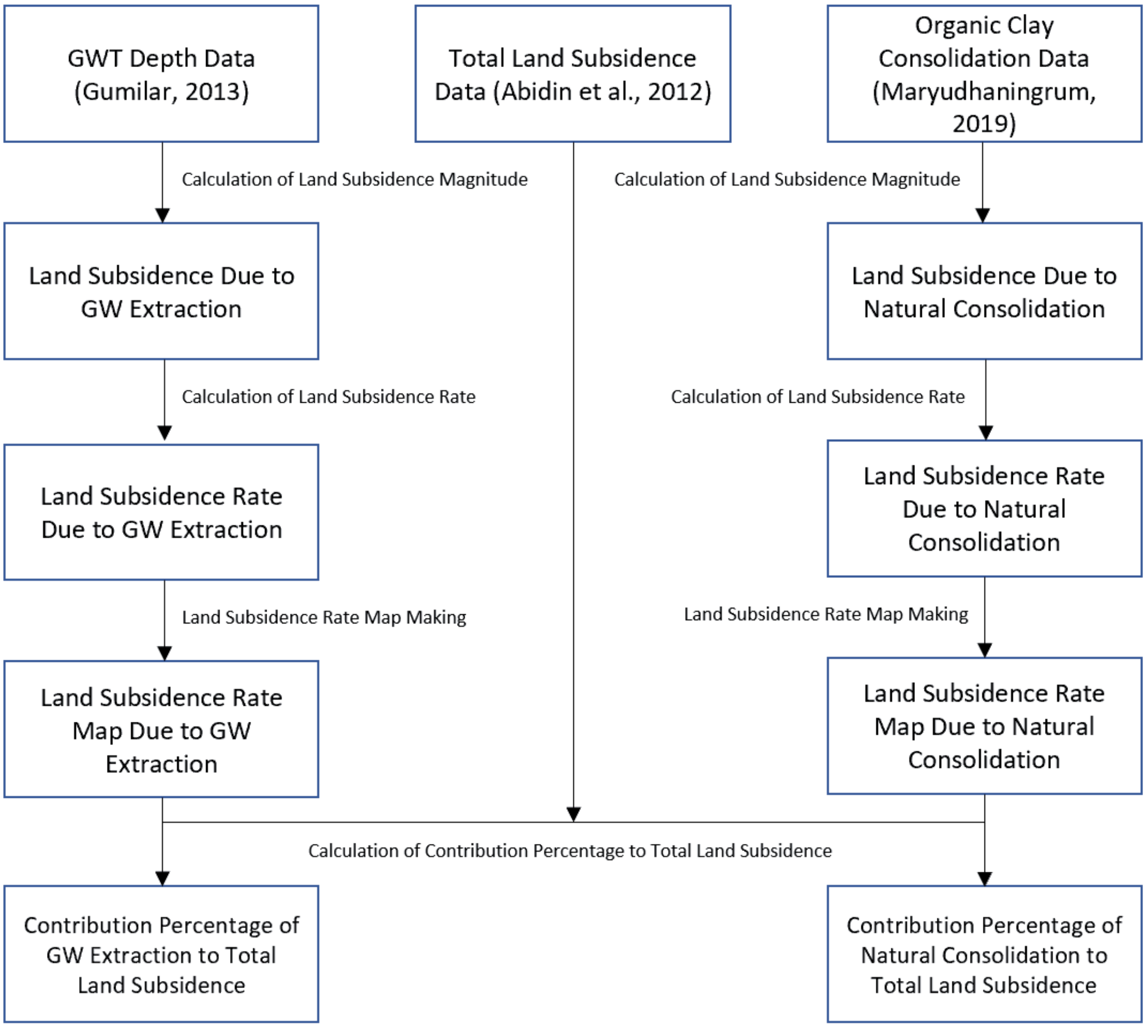

Figure 4. Research flow chart.

4. Results

The land subsidence due to natural consolidation is calculated using Equation 1. Using Equation 2, GWT depletion data is processed into land subsidence data due to groundwater extraction. The compressibility of the aquifer (in this case, the Kosambi Formation composed of loose clay) is $10^{-6} – 10^{-8}$ Pa^{-1} (Table 4). The initial thickness of the aquifer was obtained by thickness reconstruction based on the rate of land subsidence due to natural consolidation in nearby wells (Table 5). The data on land subsidence rate due to natural consolidation in Maryudhaningrum (2019) can be referred to because it is also carried out in the Kosambi Formation. The density of groundwater is assumed to be 1000 kg/m3. The gravitational acceleration is considered to be 9.8 m/s^2. The calculation example of land subsidence due to groundwater extraction is listed in Table 6.

Table 4. The compressibility value of some hydrogeological media and water in general (Freeze and Cherry, 1979).

Material	Compressibility (Pa^{-1})
Clay	$10^{-6} – 10^{-8}$
Sand	$10^{-7} – 10^{-9}$
Gravel	$10^{-8} – 10^{-10}$
Jointed rock	$10^{-8} – 10^{-10}$
Water	4.4×10^{-10}

Table 5. Example of calculating the initial thickness value of the aquifer. Abbreviation: v (subsidence rate), b_t (final thickness), dt (time), b_0 (initial thickness).

Well	X (m)	Y (m)	Closest CPTu/ Borehole	v (cm/yr)	Year of b_t	b_t (m)	Year of b_0	dt (yr)	b_o (m)
BPP Selokan Jeruk	803450	9223850	DH 2 2016	1.47	2016	33	1997	19	33.28
Kp. Gingalaya	801700	9223000	CPTu 8 2015	0.59	2015	44.8	1997	18	44.91
Kp. Manirancan	803650	9221900	CPTu 8 2015	0.59	2015	44.8	1979	36	45.01

Table 6. An example of calculating land subsidence due to groundwater extraction. Abbreviation: α_{min} (minimum compressibility), α_{max} (maximum compressibility), b_0 (initial thickness), ρ_w (density of water), g (gravitational acceleration), dh (subsidence), db_{min} (minimum thickness change), db_{max} (maximum thickness change).

Well	X (m)	Y (m)	Lithol-ogy	α_{min} (Pa^{-1})	α_{max} (Pa^{-1})	b_0 (m)	ρ_w (kg/m^3)	g (m/s^2)	dh (m)	db_{min} (m)	db_{max} (m)
BPP Selokan Jeruk	803450	9223850	Clay	10^{-8}	10^{-6}	33.28	10^3	9.8	-0.24	-0.0008	-0.0770
Kp. Gingalaya	801700	9223000	Clay	10^{-8}	10^{-6}	44.91	10^3	9.8	-0.18	-0.0008	-0.0778
Kp. Manirancan	803650	9221900	Clay	10^{-8}	10^{-6}	45.01	10^3	9.8	-0.20	-0.0009	-0.0893

Based on the data on land subsidence magnitude and the known period, the rate of land subsidence due to groundwater extraction and natural consolidation can be determined. In the case of groundwater extraction, the rate to be used is the average rate. The results were obtained that the rate of land subsidence due to groundwater extraction ranged from 0.01 to 51.75 cm/year with an average of 1.85 cm/year. Meanwhile, the rate of land subsidence due to natural consolidation ranges from 0.02 to 10.59 cm/year, with an average of 0.92 cm/year. An example of calculating the rate of land subsidence due to groundwater extraction is listed in Table 7. An example of calculating the rate of land subsidence due to natural consolidation is listed in Table 8.

Table 7. An example of calculating the rate of land subsidence due to groundwater extraction. Abbreviation: db_{min} (minimum thickness change), db_{max} (maximum thickness change), dt (time), v_{min} (minimum subsidence rate), v_{max} (maximum subsidence rate), v_{avg} (average subsidence rate).

Well	X (m)	Y (m)	db_{min} (m)	db_{max} (m)	dt (yr)	v_{min} (cm/yr)	v_{max} (cm/yr)	v_{avg} (cm/yr)
BPP Selokan Jeruk	803450	9223850	-0.0008	-0.0770	7	0.0110	1.10	0.56
Kp. Gingalaya	801700	9223000	-0.0008	-0.0778	7	0.0111	1.11	0.56
Kp. Manirancan	803650	9221900	-0.0009	-0.0893	5	0.0036	0.36	0.18

Table 8. An example of calculating the rate of land subsidence due to natural consolidation.

CPTu and Borehole	X (m)	Y (m)	Subsidence (m)	Time (year)	Subsidence Rate (cm/yr)
CPTu 3 2015	800430	9226404	0.05	74.5	0.0671
CPTu 7 2017	786784	9229924	0.31	172.6	0.1796
CPTu 15 2017	789753	9229953	0.60	200.2	0.2997

The value of the land subsidence rate of the two factors is then mapped in the boundary of the Bandung Basin. Based on the value range, the rate of land subsidence is divided into 10 classes. The mapping algorithm used is inverse distance weight (IDW). The map of land subsidence rate due to groundwater extraction and natural consolidation can be seen in Figures 5 and 6. The largest rate of land subsidence due to groundwater extraction is in the Rancaekek area, while the largest rate of land subsidence due to natural consolidation is in the Bojongsoang area.

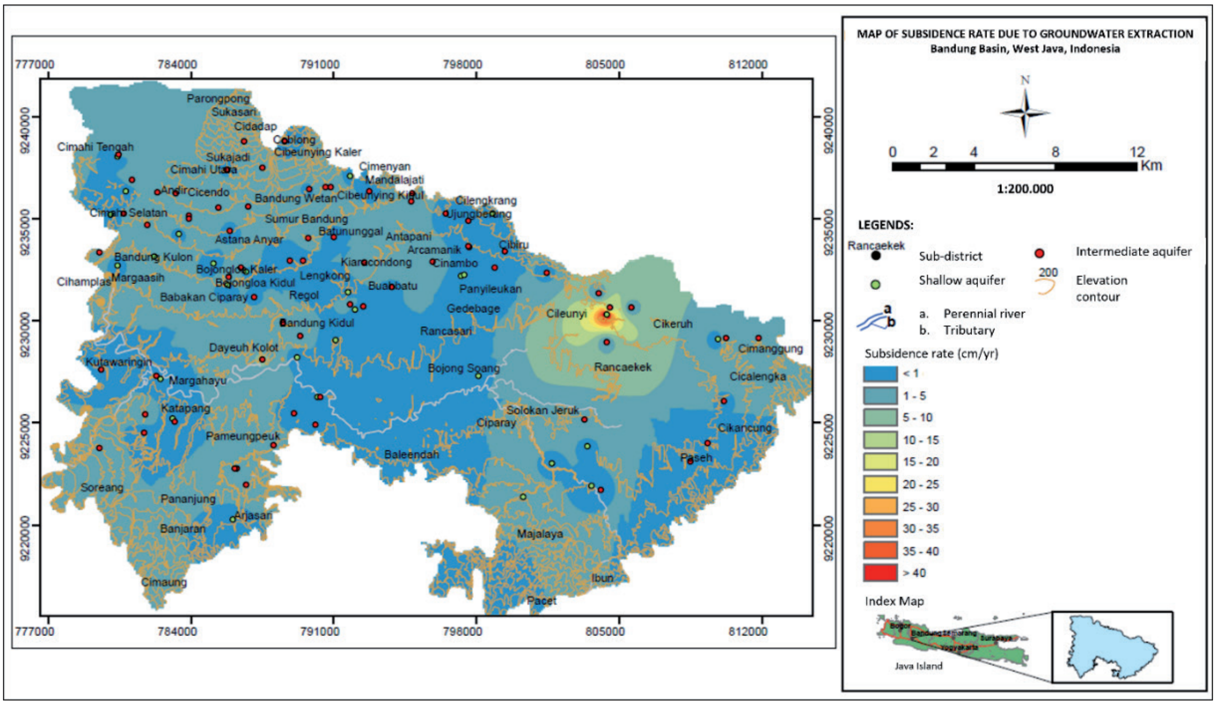

Figure 5. Map of the rate of land subsidence due to groundwater extraction.

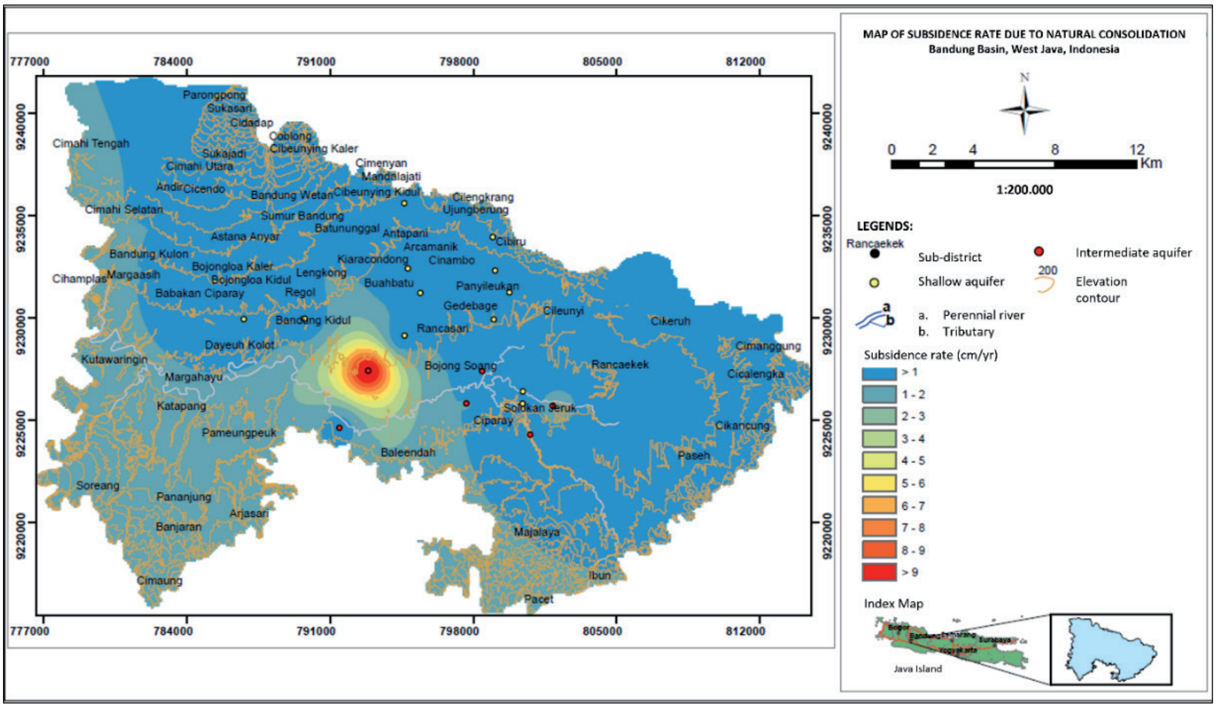

Figure 6. Map of the rate of land subsidence due to natural consolidation.

GPS-based research conducted by Abidin (2012) indicated that several locations within the Bandung Basin have experienced land subsidence, namely Cimahi, Dayeuhkolot, Banjaran, and Rancaekek. Based on this analysis, fairly significant subsidence was also observed in the Rancaekek and Dayeuhkolot areas. Generally, these locations, situated around textile industrial areas, exhibit relatively high subsidence rates, suggesting the impact of excessive groundwater extraction on the observed land subsidence. Furthermore, besides the groundwater extraction factor, the Dayeuhkolot area, located in the central part of the basin with thick clay layers, also experiences substantial natural consolidation.

To calculate the contribution percentage, the land subsidence rates due to groundwater extraction and natural consolidation were compared to the total land subsidence rate obtained from GPS data (Figure 7). The comparison was carried out by plotting the well points in Figure 7, and then the total land subsidence rate at the well points was recorded. Furthermore, the value of the land subsidence rate due to these two factors is determined as a percentage of the total land subsidence rate. The results were obtained: the effect of groundwater extraction was 44.30%, and the impact of natural consolidation was 15.76%. Examples of calculating the contribution percentage are listed in Tables 9 and 10.

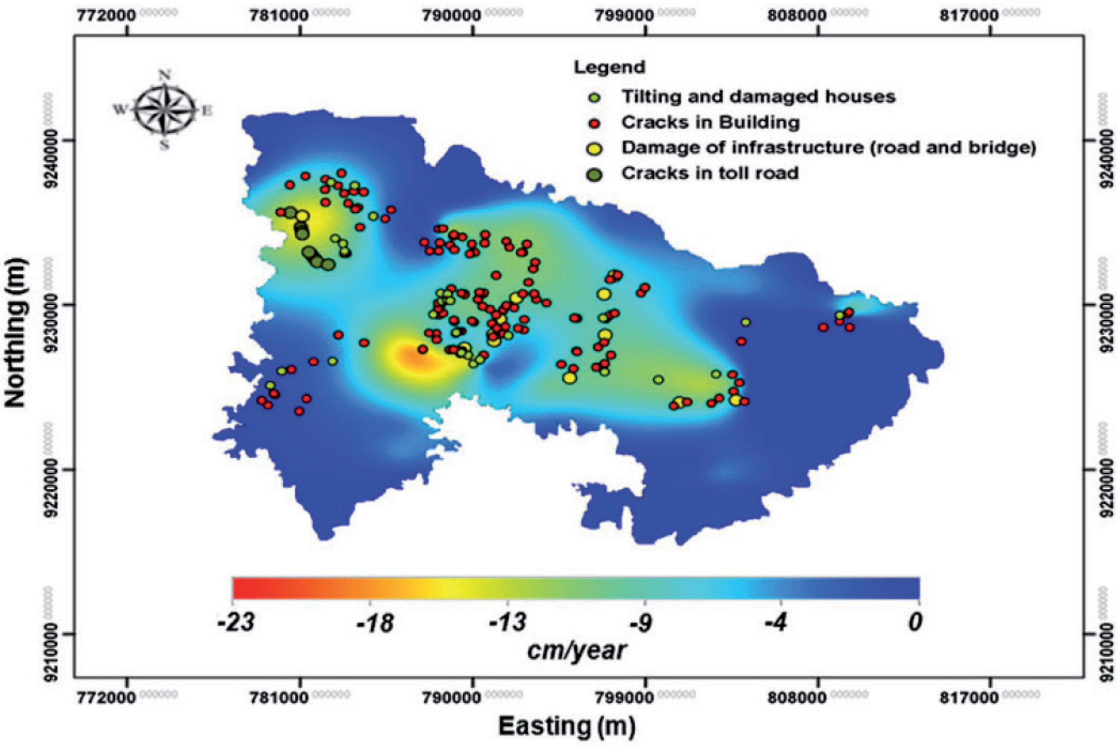

Figure 7. Map of total land subsidence rate based on GPS data (Abidin et al., 2012).

Table 9. Example of calculating the contribution percentage of groundwater extraction on total land subsidence.

Well	Subsidence Rate – Groundwater Extraction (cm/yr)	Total Subsidence Rate (cm/yr)	Contribution Percentage (%)
BPP Selokan Jeruk	0.56	9	6.22
Kp. Gingalaya	0.56	7	8.00
Kp. Manirancan	0.18	3	6.00

Table 10. Example of calculating the contribution percentage of natural consolidation on total land subsidence.

CPTu and Borehole	Subsidence Rate – Natural Consolidation (cm/yr)	Total Subsidence Rate (cm/yr)	Contribution Percentage (%)
CPTu 3 2015	0.07	12	0.56
CPTu 7 2017	0.18	8	2.25
CPTu 15 2017	0.30	12	2.50

5. Discussion

Subsidence due to groundwater extraction with the highest rate occurs in the Rancaekek area, while subsidence due to natural consolidation with the highest rate occurs in the Bojongsoang area. This is because the Rancaekek area is a textile industry center where groundwater extraction is carried out intensively, and the Bojongsoang area has a thick and highly compressible clay layer. In this study, many assumptions and simplifications were still made. It is necessary to obtain additional data related to the details of the analyzed aquifer and the thickness of its layer from time to time to make the calculations more accurate and reliable.

6. Conclusions

Based on this study, in the Bandung Basin, the rate of land subsidence due to groundwater extraction ranges from 0.01 to 51.75 cm/year with an average of 1.85 cm/year. Meanwhile, the rate of land subsidence due to natural consolidation ranges from 0.02 to 10.59 cm/year, with an average of 0.92 cm/year. The largest rate of land subsidence due to groundwater extraction was in the Rancaekek area, while the largest rate of land subsidence due to natural consolidation was in the Bojongsoang area. Based on the comparison of the total land subsidence rate in the Bandung Basin, the percentage of groundwater extraction is 44.30%, while the percentage of natural consolidation is 15.76%. Thus, the other 39.94% was influenced by different factors (building loading, tectonic activity).

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