

LITHOLOGICAL CHARACTERISTICS OF LAND SUBSIDENCE-AFFECTED AREAS BASED ON VERTICAL ELECTRICAL SOUNDING METHOD IN KENDAL REGENCY, CENTRAL JAWA.

**Damar Sayyidina Zulfi^{1*}, Boy Yoseph Cahya Sunan Sakti Syah Alam¹,
Muhammad Kurniawan Alfadli¹**

¹ Geological Engineering Undergraduate Program, Faculty of Geological Engineering, Universitas Padjadjaran, Jatinangor, Sumedang Regency, West Java, Indonesia

*Corresponding author: damar22003@mail.unpad.ac.id

ABSTRACT

Land subsidence along the coastal areas of Kendal Regency, Central Java, is occurring at a rate of up to – 100 mm/year, with the most significant impacts observed in the subdistricts of Kaliwungu, Brangsong, and Patebon. In 2024, groundwater extraction in Kendal reached 40.42 million m³, the highest in Central Java. The decline in the groundwater table is closely linked to the acceleration of land subsidence. The aim of this study is to determine the subsurface lithology affected by subsidence based on electrical resistivity values. The Vertical Electrical Sounding (VES) method, using a Schlumberger configuration, was applied at 25 data collection sites. Inversion results indicate the dominance of alluvial deposits, consisting of clay (0–14 Ω m) and sandy clay (14–30 Ω m), which account for more than 95% of the subsurface model. In contrast, the Damar Formation (comprising sandstone at 30–300 Ω m and breccia at >300 Ω m) occurs only locally. The low-resistivity zone (0–22 Ω m) directly corresponds to the highest rates of land subsidence. In conclusion, the sandy clay layer, which functions as an aquifer, is the primary factor driving land subsidence triggered by intensive groundwater extraction. The resulting geological model serves as a foundational framework for risk mitigation and geologically-based land-use planning.

Keywords: Alluvium, Damar Formation, Kendal, Land Subsidence, Resistivity, VES

INTRODUCTION

Land subsidence is a phenomenon characterized by the gradual or sudden descent of the ground surface in a specific area, triggered by both natural and anthropogenic factors (Galloway and Burbey, 2011; Huning et al., 2024). In Indonesia, this problem generally affects low-lying coastal plains and areas composed of soft, easily compressible soil. Consequently, land subsidence is frequently observed along the northern coast of Java (Sarah and Soebowo, 2018; Sarah, 2022).

The Kedungsepur metropolitan area—which comprises the regencies of Kendal, Demak, Ungaran, Semarang, and Purwodadi—is a coastal region of Java that has experienced rapid urban and economic development. Population growth and structural economic shifts have increased the demand for land, which has ultimately driven the conversion of

land use from the agricultural sector to the non-agricultural sector (Al-Vatia & Djojomartono, 2019; Adiyaksa, 2020). This conversion into residential and industrial areas is a common trend in the outskirts of metropolitan regions across Indonesia (Iqbal, 2007; Syafitri & Santosa, 2020; Adiyaksa, 2020). As part of the Kedungsepur region, Kendal Regency directly reflects these development dynamics.

The industrial sector in Kendal Regency has grown significantly, in line with government policies promoting the development of industrial zones. Kendal has been designated as the Kendal Industrial Zone, covering an area of approximately 2,700 hectares, part of which was converted from underutilized agricultural land (Ministry of Industry, 2016). As a National Strategic Project, the development of the Kendal Industrial Zone is accompanied by the acceleration of macro-

and micro-infrastructure projects to support industrial operations.

Furthermore, in 2019, the Kendal Industrial Park (KIK) was officially transformed into a Special Economic Zone (SEZ) through Government Regulation No. 85 of 2019, further solidifying Kendal's role as a major economic and industrial hub along the North Coast (Pantura) route in Central Java. From a geological perspective, Kendal Regency consists of young Quaternary formations characterized by alluvial deposits (Qa), which comprise unconsolidated materials such as sand, silt, clay, and gravel deposited through fluvial and marine processes in the north, along with young volcanic deposits in the south (Condon et al., 1996; Thanden et al., 1996). Hydrogeological conditions in this study area further increase its structurally vulnerable nature. The aquifer system in the northern coastal plain of Kendal consists of young alluvial deposits that form a highly productive intergranular aquifer. This aquifer system serves as the primary source of groundwater for residential, agricultural, and industrial activities (Thanden et al., 1996; Condon et al., 1996). However, intensive groundwater extraction can lower the water table and trigger land subsidence. A drop in the water table reduces pore water pressure, thereby increasing effective stress and accelerating consolidation. This mechanism is often observed in unconsolidated Quaternary alluvial deposits, where long-term groundwater extraction causes progressive soil deformation. This relationship between groundwater extraction and land subsidence has been extensively documented in industrialized and densely populated urban centers in Indonesia (Maryudhaningrum et al., 2025; Iskandar et al., 2025).

The aims of this study are to identify subsurface geological and geophysical conditions, specifically focusing on areas affected by land subsidence in Kendal Regency. The specific objectives include: (1) Identifying and determining subsurface geological characteristics based on resistivity data obtained using the 1-D electrical resistivity method with a Schlumberger configuration; (2) Performing lithological interpretations and identifying compressible layers from model optimization results; (3) Analyzing spatial patterns of land subsidence distribution using InSAR land subsidence maps; (4) Correlating geoelectrical data, InSAR maps, geological conditions, hydrogeology, and land-use data to understand the mechanisms of land subsidence; (5) Compiling and establishing the lithology that most significantly influences

land subsidence events while identifying its driving factors.

Research Area

This study focuses on Kendal Regency, one of 35 regencies and cities in Central Java Province, which covers an area of 1,002.23 km² divided into 20 subdistricts, 266 villages, and 20 urban villages. Geographically, the regency is located between 109°40' – 110°18' E and 6°32' – 7°24' S, bordered by the Java Sea to the north, Temanggung and Semarang regencies to the south, the city of Semarang to the east, and Batang Regency to the west.

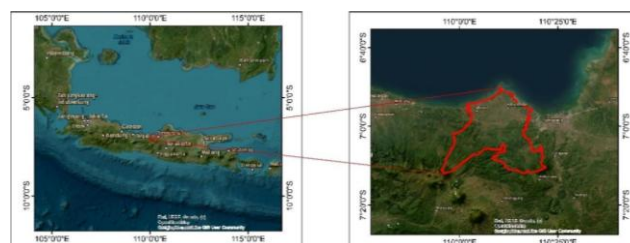


Figure 1. Research Area Map with the Red Line Representing Kendal, Central Java Province (Map Source:ESRI).

The physiographic characteristics of Kendal Regency show a sharp contrast in terrain, ranging from flat coastal plains in the north to steep mountainous landscapes in the south (van Bemmelen, 1949 in Sutarto et al., 2020).

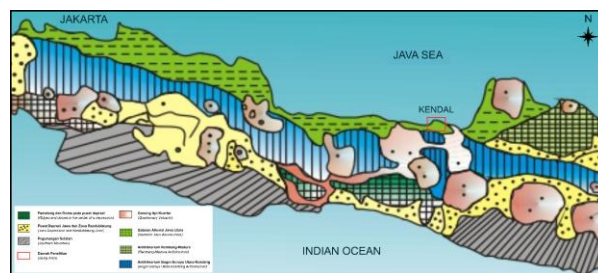


Figure 2. Regional Physiographic Map of Java Island (Modified from van Bemmelen, 1949 in Sutarto et al., 2020).

Based on the Magelang and Semarang Geological Maps (Thanden et al., 1996), the lithology of Kendal Regency is highly varied due to a complex geological history involving sedimentation, volcanic activity, and tectonics. The regional stratigraphy can be simplified as follows:

1. The Kerek Formation (Tmk): This Miocene formation consists of alternating layers of marl, clay, tuff/coralline sandstone, and turbiditic volcanic sediments.
2. Penyatan Formation (Otp): This Miocene–Pliocene formation consists of sandstone, clay, and marl

interspersed with thin lenses of limestone and volcanic breccia.

3. Damar Formation (QTd): This Pliocene–Pleistocene formation is dominated by a combination of tuffaceous sandstone, conglomerate, and volcanic breccia.
4. Kaligetas Formation (Qpkg): This Pleistocene formation consists of volcanic breccia and lahars interspersed with lava flows and tuff.
5. Pleistocene Volcanic Formation: Consists of the Jembatan (Qjmf).

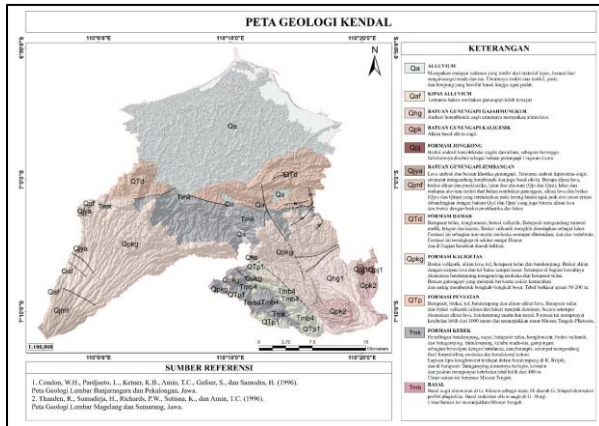


Figure 3. Geological Conditions of Kendal Based on the Systematic Geological Map of Indonesia at a 1:100,000 Scale (Modified from Condon et al. and Thanden et al., 1996).

Based on the land subsidence rate map, it can be observed that Kendal Regency experiences subsidence rates varying between 26–50 mm/year, 51–75 mm/year, and 76–100 mm/year.

Based on their flow media, the aquifer systems in Kendal Regency can be simplified into two main categories (Putranto et al., 2020):

- **Intergranular Flow Aquifer (North & Coastal):** Distributed across the northern alluvial plain (Qa), this system exhibits extensive lateral continuity and high productivity due to shallow groundwater, with potential well yields exceeding 10 L/s and some areas ranging from 5 L/s.
- **Fractured and Intergranular Flow Aquifer (Central & Southern):** Found within volcanic and sedimentary rocks in central and southern Kendal. Its productivity is more localized and variable compared to the alluvial plains, with well yields ranging from just under to just over 5–10 L/s, often limited to fracture zones or weathered rock layers.

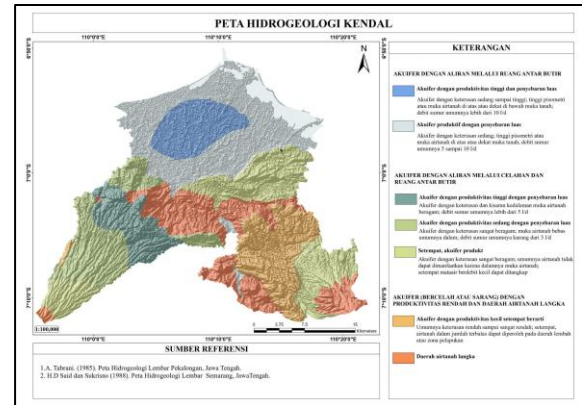


Figure 4. Hydrogeological Conditions of the Kendal Area Based on the Hydrogeological Map of Indonesia at a 1:250,000 Scale (Modified from Tabrani, 1985; Said & Sukrisno, 1988).

Land-use dynamics in Kendal Regency are strongly influenced by demographics, economic growth, and land-use policies (Wijaya & Tjahjono, 2024). Based on Landsat satellite image classification, there are seven main land-use types. Forests and agricultural land dominate the highland areas in the south, while residential areas and built-up land are densely concentrated in the north, adjacent to the Pantura highway and the Kendal Industrial Zone (Wijaya & Tjahjono, 2024).

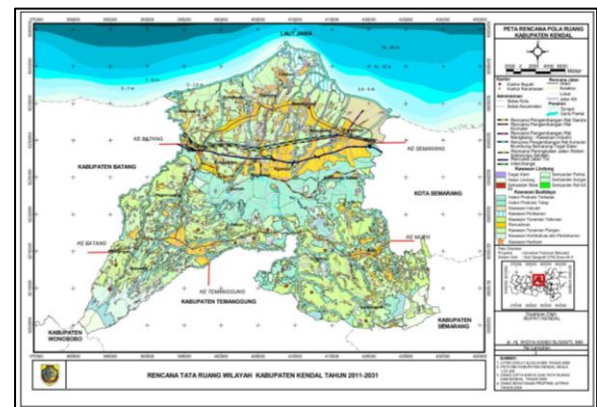


Figure 5. Land Use Plan (RTRW) Map of Kendal Regency 2011–2031, Based on Kendal Regional Regulation (Perda), 2011.

According to the Kendal Regency Spatial Planning Map (RTRW), the development of new residential areas and strategic industrial zones is systematically directed toward northern Kendal to optimize access to the Pantura logistics corridor.

RESEARCH METHOD

This study employed a one-dimensional (1D) geoelectric survey method using a Schlumberger electrode configuration, which was chosen for its efficiency in identifying

vertical variations in the resistivity of subsurface rocks. Field measurements were conducted at 25 observation points distributed primarily in the northern part of Kendal Regency. The collected data were divided into primary and secondary data; primary data were obtained directly through geoelectric measurements at the study sites. Secondary data consisted of existing records and documents, including regional geological maps, regional hydrogeological maps, land subsidence maps, and land cover maps. Electrical resistivity data processing was performed using IP12Win software to analyze the true resistivity and thickness of individual layers at specific depths through curve-fitting techniques. The obtained resistivity values were then correlated with surface geological data and field observations to categorize resistivity ranges corresponding to specific lithological units. The next step is to create lateral iso-resistivity maps and construct vertical geoelectric cross-sections. Finally, all processed datasets are integrated to build a

three-dimensional (3D) subsurface lithological model based on the correlation of geoelectric and geological data.

RESULT

Land Subsidence in Kendal

Land subsidence in Kendal (Figure 6) is primarily concentrated in the northern sector, with minor occurrences in the south. The highest subsidence rate of 100–76 mm/year is found in the northwestern part of Kaliwungu Subdistrict, which is the most severely affected area. Some parts of Brangsong and Patebon Subdistricts also exhibit similarly high subsidence rates in specific areas. Moderate subsidence rates of 75–51 mm/year cover most of the northern subdistricts, including Kaliwungu, Brangsong, Patebon, and the northwestern part of Kendal. Meanwhile, the zone with low subsidence rates of 50–26 mm/year covers the largest area, approximately 25% of the total area of Kendal Regency.

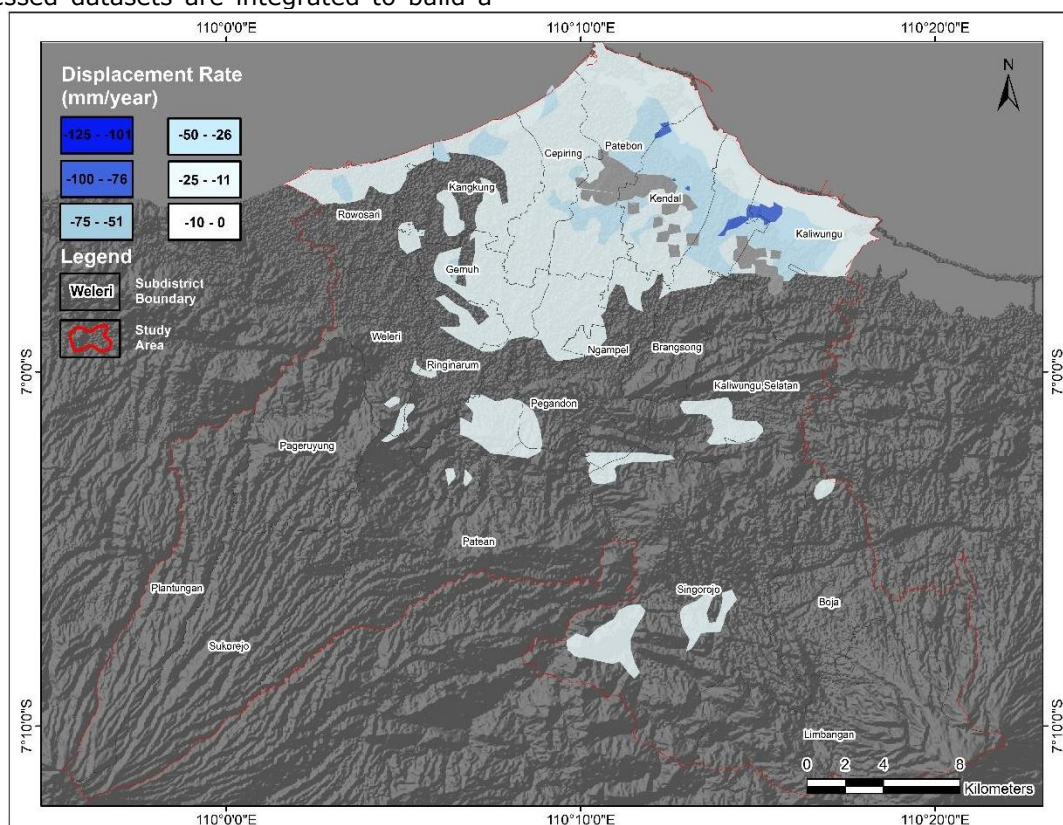


Figure 6. Land Subsidence Map Showing the Varying Subsidence Rate Zones in Kendal.

Groundwater Extraction in Kendal

In a regional context, the 40.42 million m³ of groundwater extracted in 2024 makes Kendal the region with the highest groundwater consumption in Central Java Province. By comparison, Kudus Regency (a major center for tobacco and industry) recorded 16.71 million m³, Jepara Regency recorded 17.23 million m³, Semarang City recorded 13.95

million m³, and Demak Regency recorded 14.27 million m³, based on data from the Central Java Provincial BPS's 2025 Groundwater Extraction report.

The historical trend in groundwater extraction volume in Kendal Regency (Table 1) is summarized as follows:

Table 1. Groundwater Extraction Trends in Kendal Regency 2021–2025

Year	Extraction Volume (m ³)
2021	20.903.000
2022	16.796.000
2023	12.770.000
2024	40.422.000
2025	20.801.000

The correlation between groundwater level decline and land subsidence is clearly evident in monitoring data from the SMK1 observation well (Figure 7) in Semarang (Aditiya & Ito, 2023). As the groundwater level dropped from a depth of 0.25 to 3.0 meters between January 2020 and May 2021, InSAR measurements recorded an acceleration in the rate of land subsidence between 10–50 mm (Aditiya & Ito, 2023).

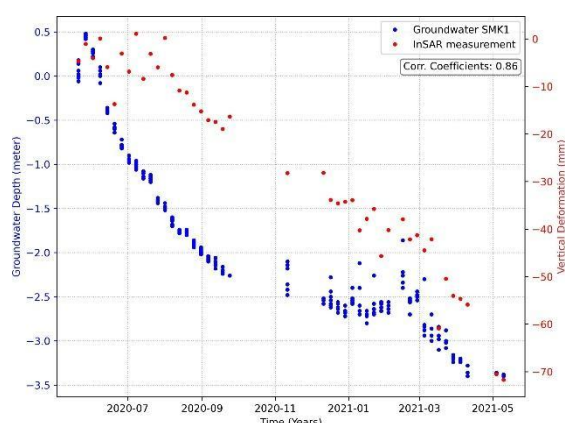


Figure 7. Correlation Between Groundwater Level Decline and Surface Subsidence at the SMK1 Station, Semarang. (Aditiya & Ito, 2023.).

Land-Use Dynamics

Geospatial land use and land cover data (Figure 8) show that most of Kendal Regency is used for agriculture and forests. Built-up areas are densely concentrated in the northern part, which serves as Kendal's administrative and economic center. It is evident that northern subdistricts such as Kangkung, Gemuh, Cepiring, and Ngampel are predominantly used for agriculture. Meanwhile, subdistricts such as Kaliwungu, Kendal, and Patebon are experiencing expansion of built-up areas, including residential, industrial, and supporting infrastructure. On the other hand, the southern part remains dominated by extensive forests, including the subdistricts of

Limbangan, Singorojo, Sukorejo, and Plantungan.

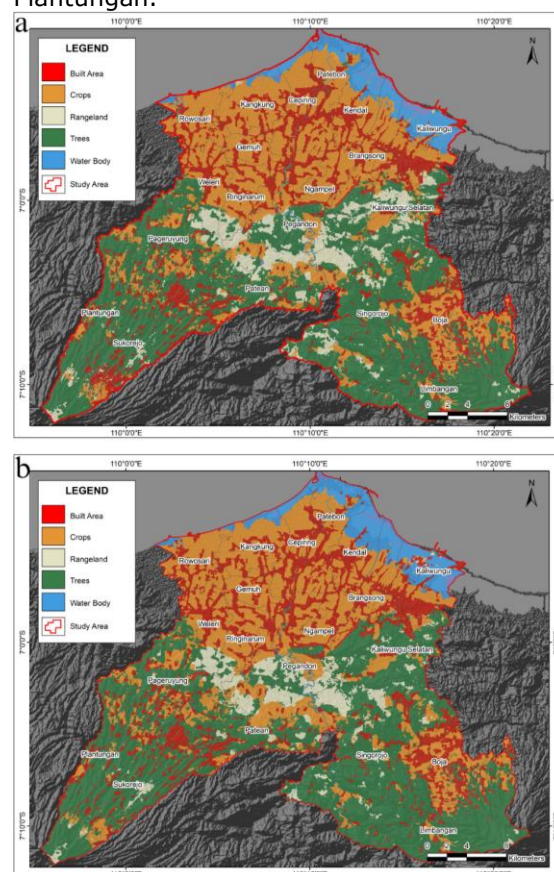


Figure 8. Land Cover Maps of Kendal Regency Illustrating Land-Use Changes from (a) 2017 to (b) 2022 (Map Source: ESRI Land Use Land Cover).

Based on the regional development plan, which refers to the Land Use Planning Map (Figure 5), Kaliwungu has been designated as the main industrial center, while subdistricts such as Kendal, Brangsong, Ngampel, and Kangkung are targeted for large-scale residential expansion. This confirms that the northern plains have been heavily allocated by the local government as the administrative, demographic, and economic core of the regency. In contrast, the southern highlands are primarily utilized for production forests, crop plantations, and small settlements such as those in Patean and Boja.

Geoelectrical

A. Geoelectrical Acquisition Location

This study utilized Vertical Electrical Sounding (VES) geoelectric data acquisition using the Schlumberger configuration at 25 distributed data acquisition stations, most of which were concentrated in the northern part of Kendal Regency (Figure 9).

Table 2. Geoelectrical Acquisition Locations Data in the UTM Zonse 49 S Projection

Station	Easting (m)	Northing (m)	Elevation (masl)	Total Depth (m)
GL-01	410658.943	9238671.251	5.49	133
GL-02	403669.385	9232407.460	11.28	133
GL-03	408287.349	9226623.124	15.24	133
GL-04	399652.282	9235275.400	5.49	133
GL-05	409631.387	9235815.339	4.27	133
GL-06	413616.530	9231092.426	4.57	133
GL-07	415060.870	9226058.947	115.52	133
GL-08	413107.310	9227876.698	33.22	133
GL-09	418850.897	9223700.222	88.09	133
GL-10	402923.919	9229462.131	16.46	133
GL-11	414862.271	9235141.015	1.83	133
GL-12	405764.650	9235716.789	8.23	133
GL-13	409027.094	9231577.419	7.92	133
GL-14	408186.348	9240849.846	1.52	133
GL-15	412475.833	9240355.677	5.18	133
GL-16	418493.404	9220814.150	238.96	133
GL-17	412370.889	9222747.155	83.21	133
GL-18	408762.615	9224374.410	82.6	133
GL-19	407220.582	9224663.546	75.59	133
GL-20	401921.639	9222995.389	44.2	133
GL-21	396469.061	9221737.183	427.63	133
GL-22	392361.201	9222065.642	459.03	133
GL-23	391928.292	9228088.875	121.31	133
GL-24	392624.174	9232159.134	7.01	133
GL-25	422355.713	9223064.379	163.98	133

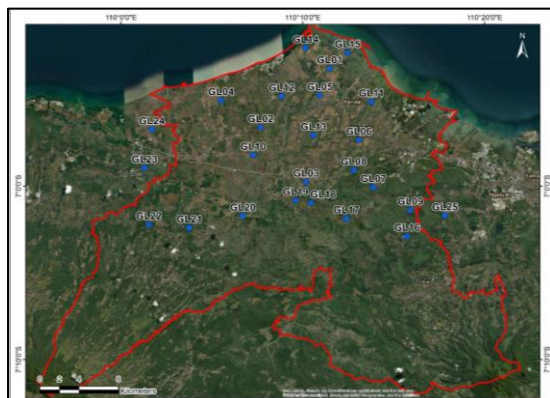


Figure 9. Spatial Distribution of 25 1-D Geoelectrical Acquisition Stations Marked with Blue Dots.

B. Correlation of Geological Conditions with Resistivity Values

Surface geological data from regional maps were used as a baseline for interpreting subsurface conditions by correlating it with geoelectric acquisition at nearby locations. Based on the regional geology of the study area, station GL-14 is located in Quaternary alluvium (Qa), which formed by loose gravel, sand, and clay. The inversion results show a sequence of five layers (Figure 10). The uppermost layer has a very low resistivity of 0.821 Ω , which is directly associated with clay deposits along the northern coast of Kendal at an elevation of 1.52 masl.

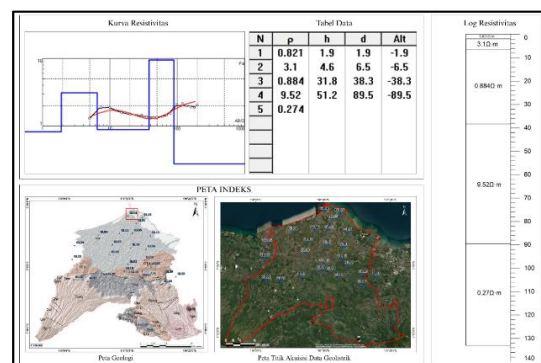


Figure 10. Correlation of Acquisition Station GL-14 with the Quarter Alluvium (Qa).

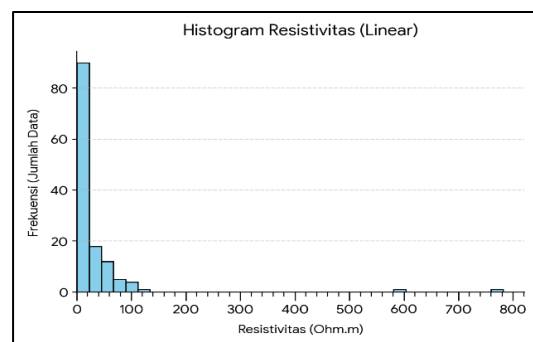


Figure 11. Histogram of Subsurface Resistivity Values from Geoelectrical Acquisition.

The statistical distribution of all inverted resistivity data is shown in the histogram (Figure 11). This distribution is heavily dominated by low resistivity values ranging from 0 to 10 Ω . Values between 30 and 100 Ω

occur less frequently. Distinct high-resistivity anomalies appear at 589 and 782.0 Ω . Based on this range, resistivity classifications and lithological categories have been established (Table 2).

Table 3. Subsurface Lithological Resistivity Range in Kendal

Resistivity	Lithology
0-14 Ω m	Clay
14-30 Ω m	Sandy Clay
30-300 Ω m	Sandstone
>300 Ω m	Breccia

Subsurface Resistivity Modelling

Subsurface characterization is done by analysing the distribution of lateral and vertical resistance, which allows for an integrated assessment of layer changes with depth and variations across different zones.

A. Lateral Resistivity Distribution

The maximum depth that can be penetrated by a geoelectric sounding is 133 meters. Isoresistivity maps are generated at specific intervals to determine lateral distribution: from the surface down to depths of 10, 25, 50, 75, and 100 meters.

1. Surface to 10 Meters

On the surface, the resistivity map shows a pattern varying from pink to blue, with values ranging from 0 to 22 Ω , covering the northern coastal zone. The southern section shows values ranging from 53 to 306 Ω , displayed in green. At a depth of 10 meters, a similarity pattern is observed with values of 9–22 Ω extending from north to south, indicating consistency with surface geology (Figure 3).

2. 25 - 50 meters

At depths of 25–50 m, the northern coastal area showed very low values between 0–4 Ω , which constituted the northern coastal section of the study area at a depth of 25 m. Meanwhile, the southern highlands range from 22–127 Ω at a depth of 50 meters; the northern plains show values in the 4–22 Ω range that are widely distributed, while parts of the northern sector exceed 53–127 Ω .

3. 75 - 100 meter

Throughout the 75–100 depth interval, the northern coastal zone is consistently characterized by low resistivity values of 0–22 Ω , while the southern region exhibits high values ranging from 53 to 306 Ω , shown in green.

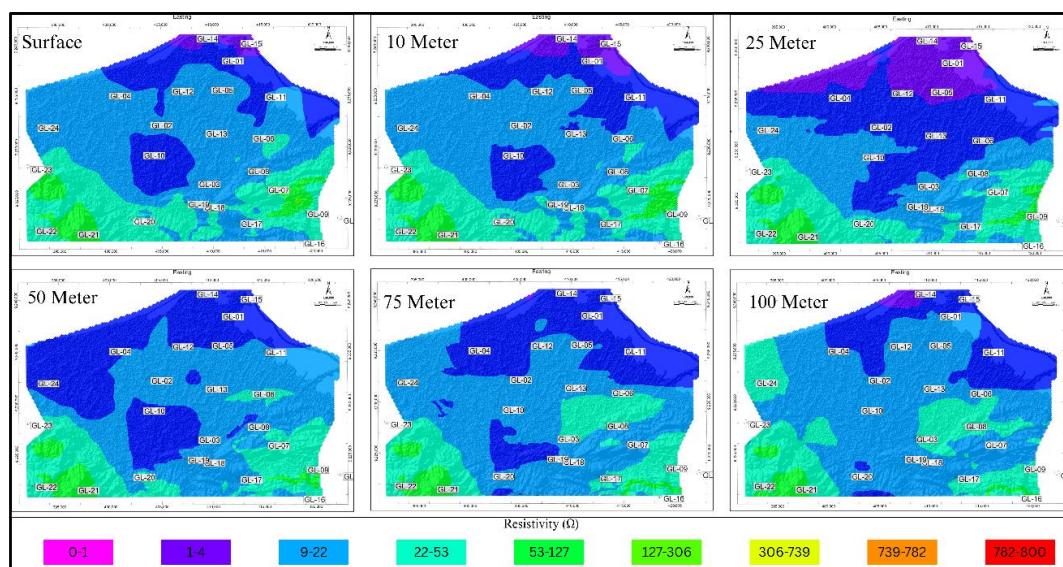


Figure 12. Isoresistivity Maps of the Lateral Subsurface Resistivity Distribution in Kendal.

B. Vertical Resistivity Distribution

To visualize the vertical distribution, two cross-sections were established: one oriented southwest–northeast and one oriented west–east.

1. Resistivity Cross-Section B

Cross-sectional profiles from GL-17 and GL-8 on the left to GL-15 on the right (Figure 13) showing resistivity values between 9–53

Ω in the south which decreased significantly to the right, reaching 0–4 Ω at GL-6, GL-11, and GL-15, indicating a softer subsurface material toward the north coastal area.

2. Resistivity Cross-Section C

Covers the west–east profile in the southern highlands from GL-22 to GL-16 (figure 13).

Higher values of 22–127 Ω dominant in the west and east highland (GL-22, GL-21, GL-20), followed by a central depression with lower values of 9–53 Ω from GL-19 to GL-16, indicating the presence of a sediment-filled basin.

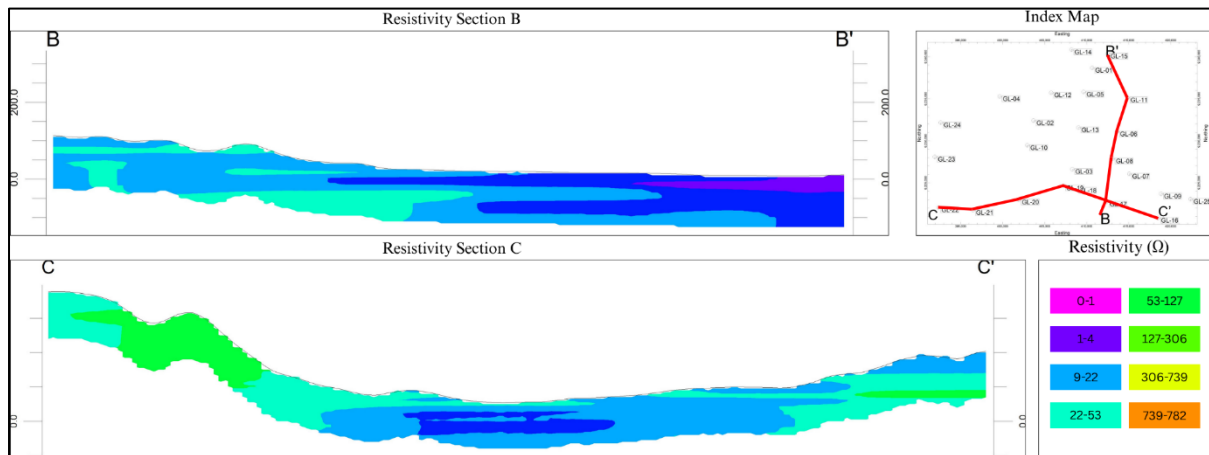


Figure 13. Cross-Sections of the Vertical Subsurface Resistivity Distribution in Kendal.

C. 3-Dimensional Resistivity Model

3D spatial visualization was constructed with a vertical exaggeration of 10 and a fence plot (Figure 14). This model combines all acquisition stations to provide a

comprehensive view of subsurface lithological variations and spatial distribution across various depth layers.

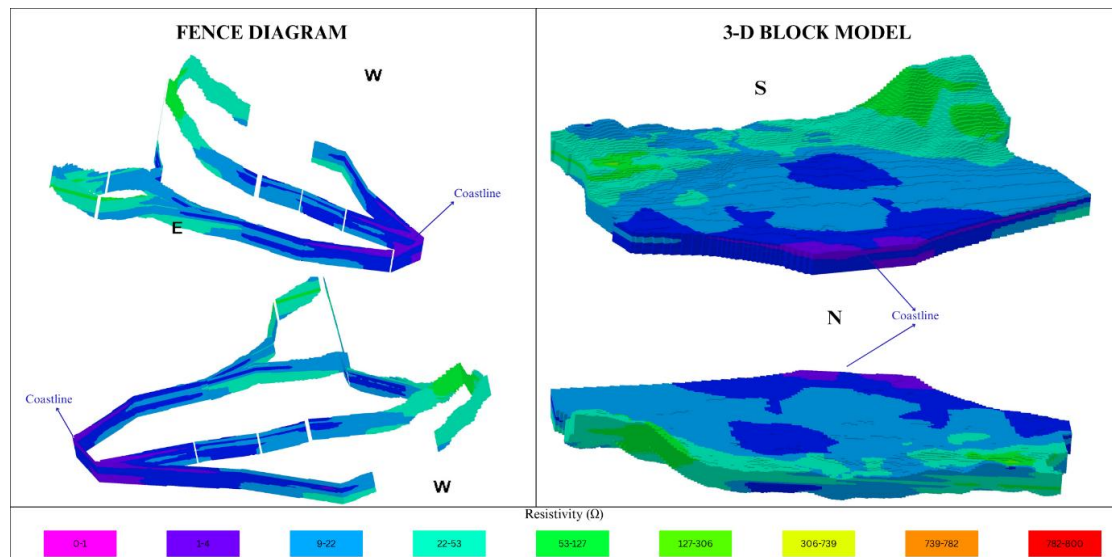


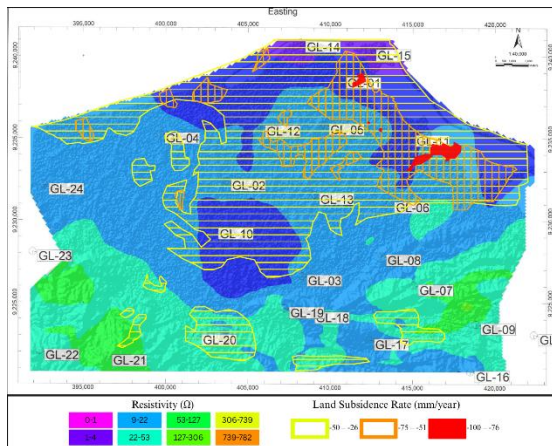
Figure 14. Fence Diagram and 3-Dimensional Block Model of the Subsurface Resistivity Values of Kendal.

Surface Resistivity Distribution and Land Subsidence Rates

At the surface area (Figure 15), the highest rate of land subsidence occurred in the area with a resistivity varying between 1 and 22 Ω .

Subsurface Lithology Based on Resistivity Values

DISCUSSION



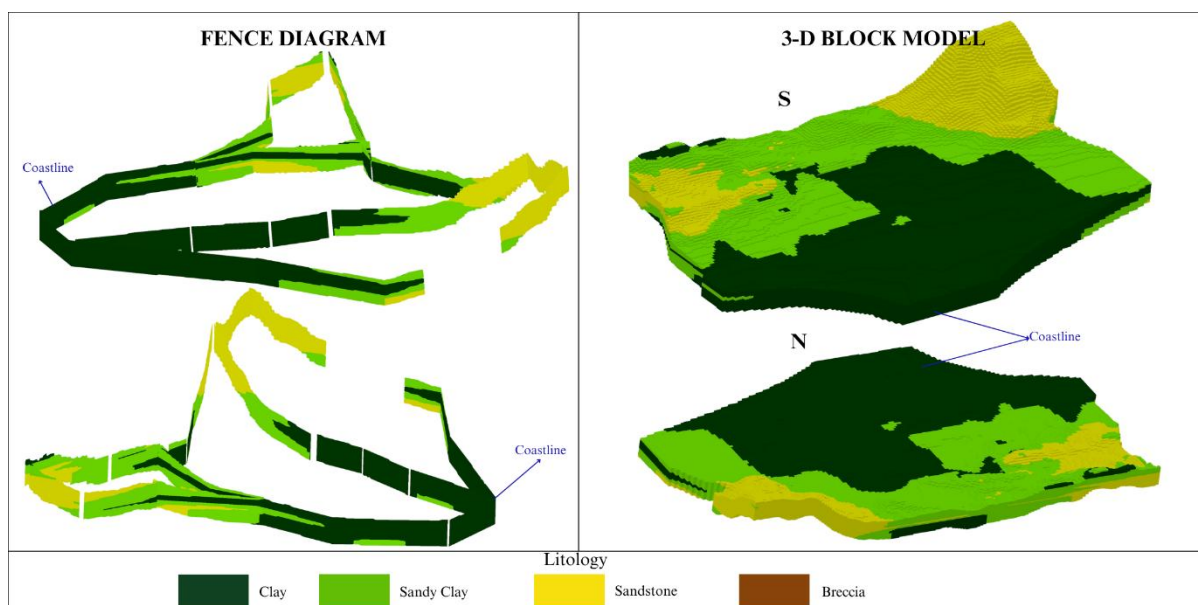


Figure 17. Fence Diagram and 3-Dimensional Block Model of the Subsurface Lithology of Kendal.

CONCLUSION

According to surface geology and integrated interpretation, the following conclusions were obtained:

1. **Resistivity Profile.**
The subsurface profile of the study area is dominated by low resistivity ($\leq 30 \Omega m$), which covers 71.9% of the area. The low resistivity area extends extensively both laterally and vertically along the northern coast to a depth of 100 meters, reflecting alluvial deposits composed of clay and sandy clay. In contrast, higher resistivity values ranging from 30 to 300 Ωm are primarily distributed in the northern part of the study area.
2. **Subsurface Lithology**
Subsurface materials are characterized as clay (0–14 Ωm), sandy clay (14–30 Ωm), and sandstone (10–30 Ωm), which serve as a more compact layer and an serve as a aquifer.
3. **Subsidence Spatial Distribution**
Land subsidence is concentrated along the northern plain. The highest rates (-100 to -76 mm/year) are centered in the northwest of Kaliwungu and parts of Brangsong and Patebon. Moderate rates (-75 to -51 mm/year) span the northern corridor, while low-rate subsidence covers approximately 25% of the total regency area.
4. **Anthropogenic Driving Factors**
The rapid expansion of built-up areas and industrial zones has led to increased groundwater extraction from sandy clay aquifers, adding an

anthropogenic component that accelerates natural consolidation. The development of areas with high land subsidence without strict technical regulations will accelerate structural failure.

5. **Primary Geological Controller**
The leading cause of land subsidence in Kendal is found in the presence of thick, unconsolidated layers of sandy clay and Quaternary clay. Intensive extraction of groundwater from the sandy clay aquifer creates a severe fluid pressure deficit in the rock pores, leading to irreversible volume reduction and compaction of the loose material.

ACKNOWLEDGEMENT

The author expresses their deepest gratitude to their beloved father and mother, whose continuous prayers, moral support, and endless guidance accompanied the author throughout the completion of this research. Warmest thanks are also extended to the author's sister and brother for their constant affection and heartwarming support as siblings.

The author dedicates their highest appreciation to the Geological Engineering Faculty, Padjadjaran University, for providing all the necessary facilities for the academic processes and this research activity. Furthermore, the author would like to thank the *Balai Air Tanah* (Groundwater Management Agency) for providing the research data and valuable technical guidance during the data acquisition and processing stages.

REFERENCES

- Aditiya, A., & Ito, T. (2023). Land Subsidence Monitoring in Northern Coast of Central Java, Indonesia, using Sentinel-1 SAR Interferometry. *Journal of Applied Geophysics*, 215, Article 105121.
- Adiyaksa, M. S. (2020). Analisis Perubahan Penggunaan Lahan Pertanian Menjadi Lahan Non-Pertanian di Kabupaten Kendal. *Jurnal Pengembangan Kota*, 8(2), 145–154.
- Al-Vatia, & Djojmartono. (2019). Analisis Alih Fungsi Lahan Pertanian dan Dampaknya terhadap Pola Ruang Wilayah.
- Badan Pusat Statistik Provinsi Jawa Tengah. (2025). Nilai perolehan air tanah dan volume pengambilan air tanah dari badan usaha menurut kabupaten/kota di Provinsi Jawa Tengah, 2024.
- Condon, W. H., Pardyanto, L., Ketner, K. B., Amin, T. C., Gafoer, S., & Samodra, H. (1996). Peta Geologi Lembar Banjarnegara dan Pekalongan, Jawa (Skala 1:100.000). Pusat Penelitian dan Pengembangan Geologi.
- Galloway, D. L., & Burbey, T. J. (2011). Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeology Journal*, 19(8), 1459–1486.
- Iqbal, M. (2007). Analisis Alih Fungsi Lahan Pertanian dan Faktor Pendorongnya di Kawasan Metropolitan.
- Iskandar, M., et al. (2025). Dampak Ekstraksi Air Tanah terhadap Amblesan Lahan di Kawasan Industri Indonesia.
- Kementerian Perindustrian. (2016). Kawasan Industri Kendal (KIK) sebagai Proyek Strategis Nasional. Kementerian Perindustrian Republik Indonesia.
- Lowrie, W. (2007). *Fundamentals of Geophysics* (2nd ed.). Cambridge University Press.
- Maryudhaningrum, P., et al. (2025). Korelasi Spasial Pengambilan Air Bawah Tanah dan Land Subsidence di Pesisir Utara Jawa.
- Mous, M., Ischak, S., & Hasan, M. (2023). InSAR Analysis of Land Subsidence in Semarang and Demak, Central Java. *Remote Sensing Applications: Society and Environment*, 30, Article 100951.
- Peraturan Pemerintah Republik Indonesia Nomor 85 Tahun 2019 tentang Kawasan Ekonomi Khusus Kendal.
- Putranto, T. T., Widiarso, D. A., & Sasi, G. (2020). Analisis Hidrogeologi dan Karakteristik Akuifer di Kabupaten Kendal, Jawa Tengah. *Jurnal Geosains dan Teknologi*, 3(1), 15–24.
- Said, H. D., & Sukrisno. (1988). Peta Hidrogeologi Indonesia Lembar Semarang (IX), Jawa Tengah (Skala 1:250.000). Direktorat Geologi Tata Lingkungan.
- Sarah, D. (2022). Land Subsidence in Indonesia: A Review of its Status, Challenges, and Future Directions. *IOP Conference Series: Earth and Environmental Science*, 1065, Article 012001.
- Sarah, D., & Soebowo, E. (2018). Land Subsidence Vulnerability of the Coastal Alluvium in Semarang City, Indonesia. *Bulletin of the Geological Society of Malaysia*, 66, 63–69.
- Sutarto, Soesilo, J., Triwibowo, B., & Hamdalah, H. (2020). Atlas Batuan Pegunungan Jiwo Bayat, Kabupaten Klaten Jawa Tengah. LPPM UPN "Veteran" Yogyakarta.
- Tabrani, A. (1985). Peta Hidrogeologi Indonesia Lembar Pekalongan (VIII), Jawa Tengah (Skala 1:250.000). Direktorat Geologi Tata Lingkungan.
- Telford, W. M., Geldart, L. P., Sheriff, R. E., & Keys, D. A. (1990). *Applied Geophysics* (2nd ed.). Cambridge University Press.
- Thanden, R. E., Sumadirdja, H., Richards, P. W., Sutisna, K., & Amin, T. C. (1996). Peta Geologi Lembar Magelang dan Semarang, Jawa (Skala 1:100.000). Pusat Penelitian dan Pengembangan Geologi.
- Van Bemmelen, R. W. (1949). *The Geology of Indonesia: Vol. IA. General Geology of Indonesia and Adjacent Archipelagoes*. Government Printing Office.
- Wijaya, A. K., & Tjahjono, B. (2024). Analisis Dinamika Perubahan Tutupan Lahan di Kabupaten Kendal Berbasis Citra Satelit Landsat. *Jurnal Geografi*, 16(1), 32–41.