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Subsurface Characterization using Electrical Resistivity Tomography (ERT) for Sponge City Planning in Nusantara Capital City (IKN), Indonesia

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Abstract

Clay shale dominates the lithology along access roads in the IKN development area. Its impermeable nature poses challenges to implementing the Sponge City concept, which relies on enhanced rainwater absorption to reduce surface runoff. This study aims to map the spatial distribution of clay shale and assess its implications for Sponge City planning. The geoelectrical resistivity method was applied at three sites, each consisting of one long section and three cross sections. Resistivity contrasts were used to delineate subsurface lithology, producing two- and three-dimensional models. The results reveal three main lithological units: topsoil, clay shale, and sandy clay. Topsoil shows heterogeneous resistivity values with thicknesses ranging from <1 m to 5 m. Clay shale exhibits resistivity values below 50 Ωm and thicknesses of <5–30 m, while sandy clay exceeds 50 Ωm with variable thicknesses up to 30 m. The thick, low-resistivity clay shale indicates poor permeability, which limits infiltration and groundwater storage. These findings suggest that the IKN area is less suitable for a natural sponge system. Therefore, stormwater management should prioritize engineered solutions such as green roofs, retention ponds, and bioretention facilities to control runoff and support sustainable urban development.

Keywords: Clay Shale; Nusantara Capital City; Resistivity; Sponge City.

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Introduction

With the advancement of instrumentation and software technologies, geophysical methods have been extensively applied, particularly in developed countries, for geotechnical and environmental surveys. In Indonesia, research and applications of geophysics in the geotechnical field are relatively new but are expected to expand in line with the growing demand for subsurface characterization.

The planned development of a Sponge City in the prospective Nusantara Capital City (IKN) area of East Kalimantan is one of the projects requiring geophysical investigation. The dominant lithology in this region is clay shale. According to Bachtiar (2022), the geology of the study area consists of marine clay sediments belonging to the Pamaluan Formation of Late Oligocene age, deposited in a middle-shelf facies environment (Figure 1).

Alamsyah et al. (2024) reported that clay shale is not only exposed along the IKN access roads but also occurs in the subsurface, as confirmed by Seismic Refraction Tomography (SRT). In civil engineering, clay shale is classified as an intermediate rock containing montmorillonite clay minerals, characterized by low durability due to weathering and high swelling potential, which pose significant challenges for construction (Ohlmacher, 2000; Wahidah et al., 2024). Higher clay content typically reduces both effective porosity and hydraulic conductivity (K) (Orozco et al., 2022). Furthermore, clay shale has inherently low permeability (Ningtyas et al., 2020), limiting its ability to transmit water. Low permeability reduces infiltration capacity, leading to soil saturation. Prolonged rainfall may cause waterlogged soils to swell and exert pressure on soil particles, potentially triggering mass movement (Bachtiar, 2022). These properties are unfavorable for the Sponge City concept, which aims to mitigate flooding by maximizing rainwater infiltration and minimizing surface runoff (Qiu, 2015; An et al., 2015; Liu et al., 2021; Li et al., 2022).

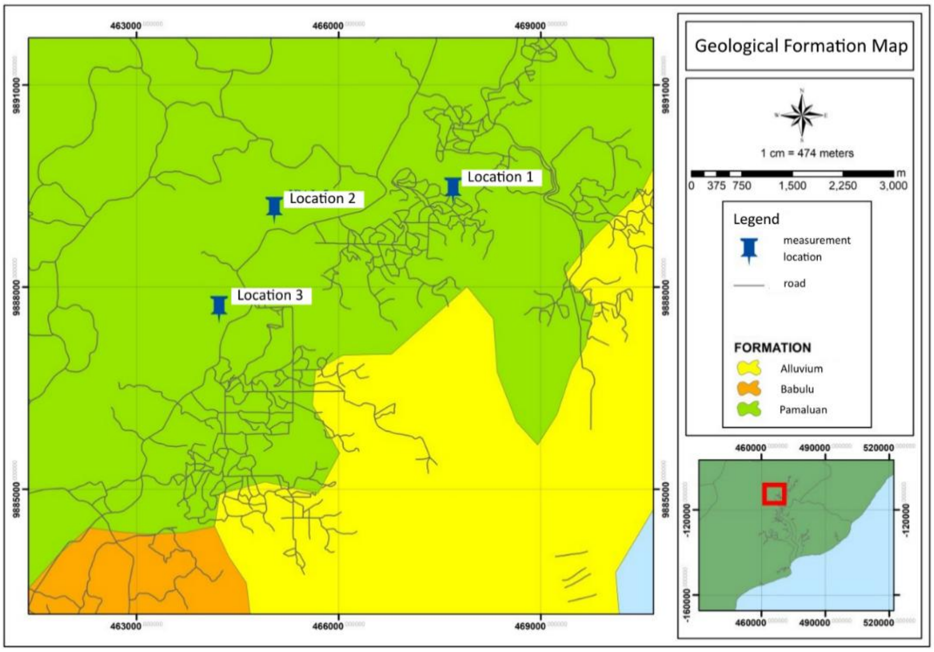


Figure 1. Geological formation map.

Since the 1980s, Chinese scholars have studied the Sponge City concept from various perspectives, including urban stormwater control, land use, and ecological construction. Several studies (Huang et al., 2018; Su et al., 2023; Liu et al., 2025) evaluated Sponge City suitability using Analytic Hierarchy Process (AHP) based on regional geology and hydrogeological conditions. Ye et al. (2018) provided recommendations for stormwater management facilities suited to different zones based on geological suitability assessments, while Wang et al. (2019) analyzed sponge characteristics such as vegetation cover, slope topography, vadose zone, and aquifers, and proposed a geological suitability evaluation framework for Sponge City planning.

Su et al. (2023) highlighted geology as a primary factor influencing Sponge City development, including lithology, vadose zone characteristics, aquifer thickness and composition, slope gradient, and groundwater abundance. Primary indicators include surface characteristics, vadose zone properties, and aquifer conditions, while secondary indicators consist of lithology, slope gradient, vadose zone thickness, and groundwater availability. Areas classified as suitable for Sponge City development typically support infiltration, vadose zone transport, and aquifer storage, enabling sustainable urban hydrological cycles when combined with surface water storage and drainage infrastructure. Conversely, less suitable areas require emphasis on engineered stormwater management strategies, such as green roofs, retention ponds, and bioretention facilities, supported by geotechnical measures.

To evaluate the suitability of the Sponge City concept in IKN, comprehensive and multidisciplinary subsurface investigations are essential. The geoelectrical resistivity method represents a promising approach, as it exploits resistivity contrasts to delineate lithology and subsurface geological structures. This method offers a non-invasive and cost-effective alternative for mapping subsurface conditions (Bichet et al., 2016; Adeyemo et al., 2017; Feng et al., 2017; Hu et al., 2019; Tagoe et al., 2025), and it has been effectively applied to image clay-pan distributions (Jeřábek et al., 2017; Mathis et al., 2018) and to monitor seasonal water-content variations in clay (Genelle et al., 2012; Chrétien et al., 2014).

Therefore, this study aims to map clay shale distribution using the Electrical Resistivity Tomography (ERT) method, addressing the lack of previous research in the IKN area related to the Sponge City concept, and to assess its implications for the planned Sponge City. The results are expected to provide a clearer understanding of how clay shale affects groundwater infiltration and storage, offering valuable input for the Sponge City design in IKN.

Materials and Methods

The study area is located within the planned Nusantara Capital City (IKN), specifically in Sepaku District, Penajam Paser Utara Regency, East Kalimantan, as shown in Figure 1–4.

The geoelectrical survey was conducted in an area covered by the regional geological map of East Kalimantan (Figure 1). The three survey sites are situated within the Pamaluan Formation (Tomp), which is predominantly composed of claystone and shale with intercalations of marl, sandstone, and limestone.

The research workflow consisted of three main stages: (i) data acquisition using geoelectrical equipment, (ii) data processing to generate subsurface models, and (iii) data analysis and interpretation.

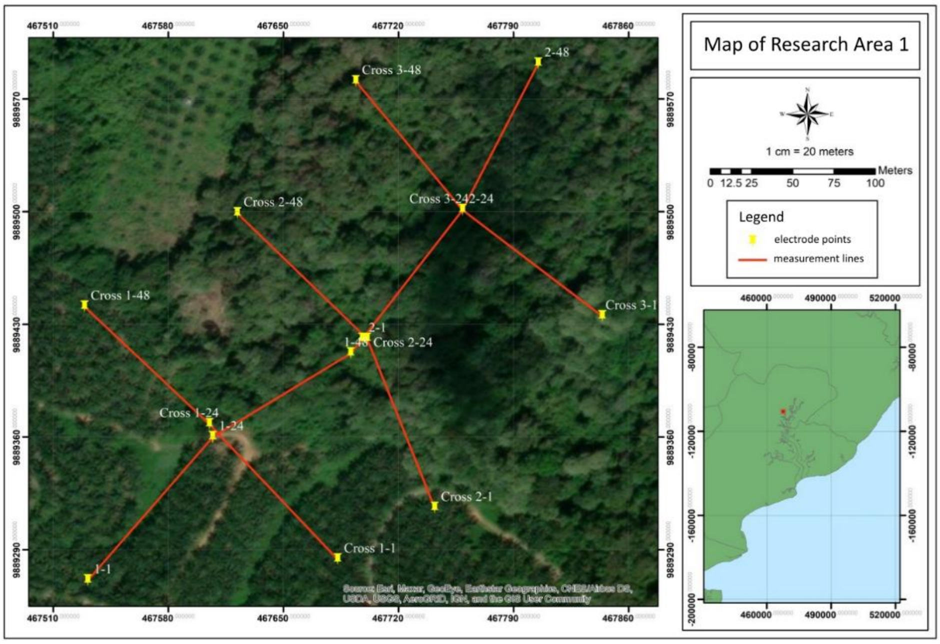


Figure 2. Research Area 1.

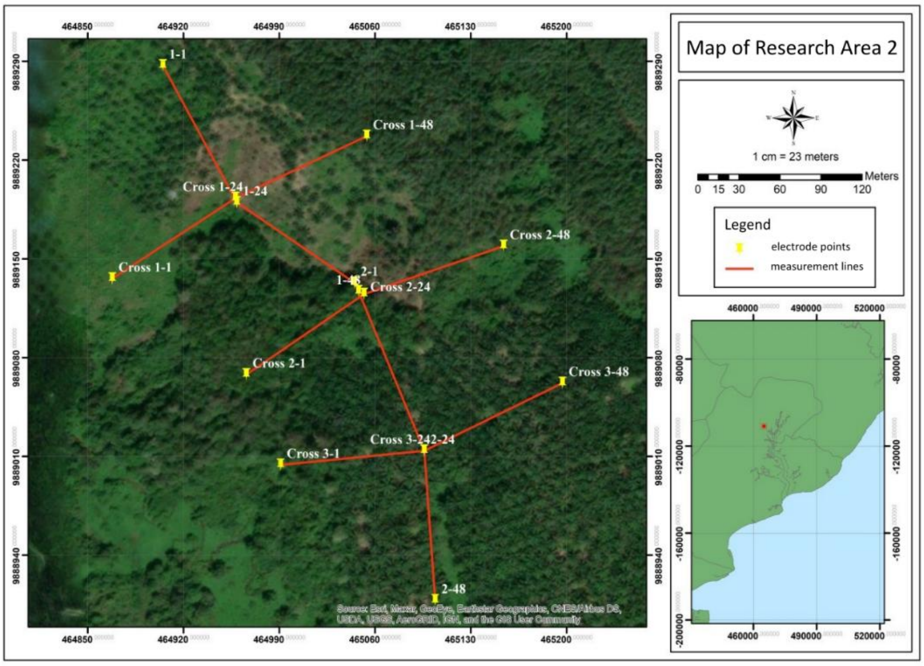


Figure 3. Research Area 2.

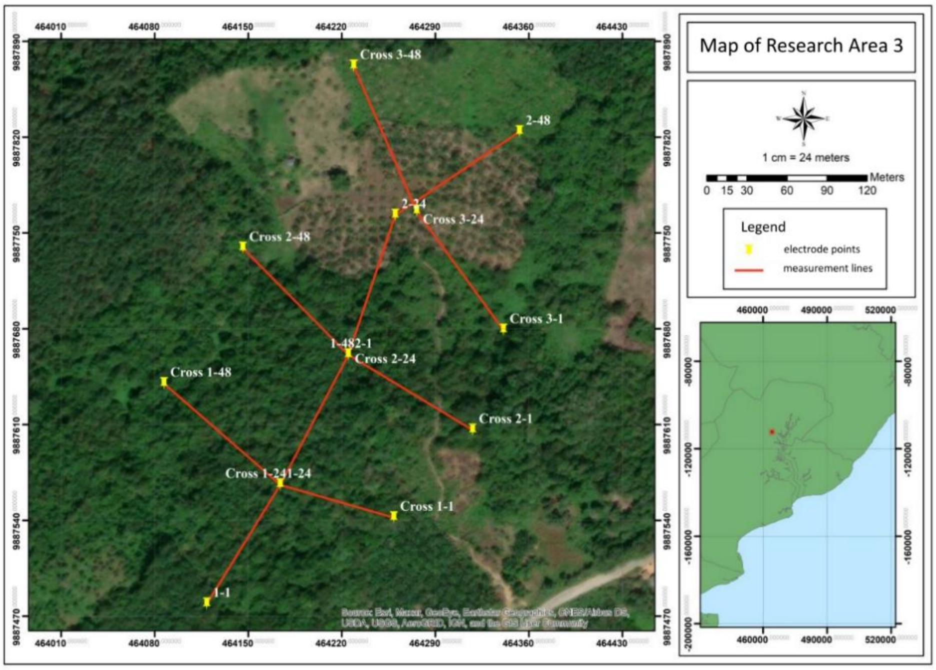


Figure 4. Research Area 3.

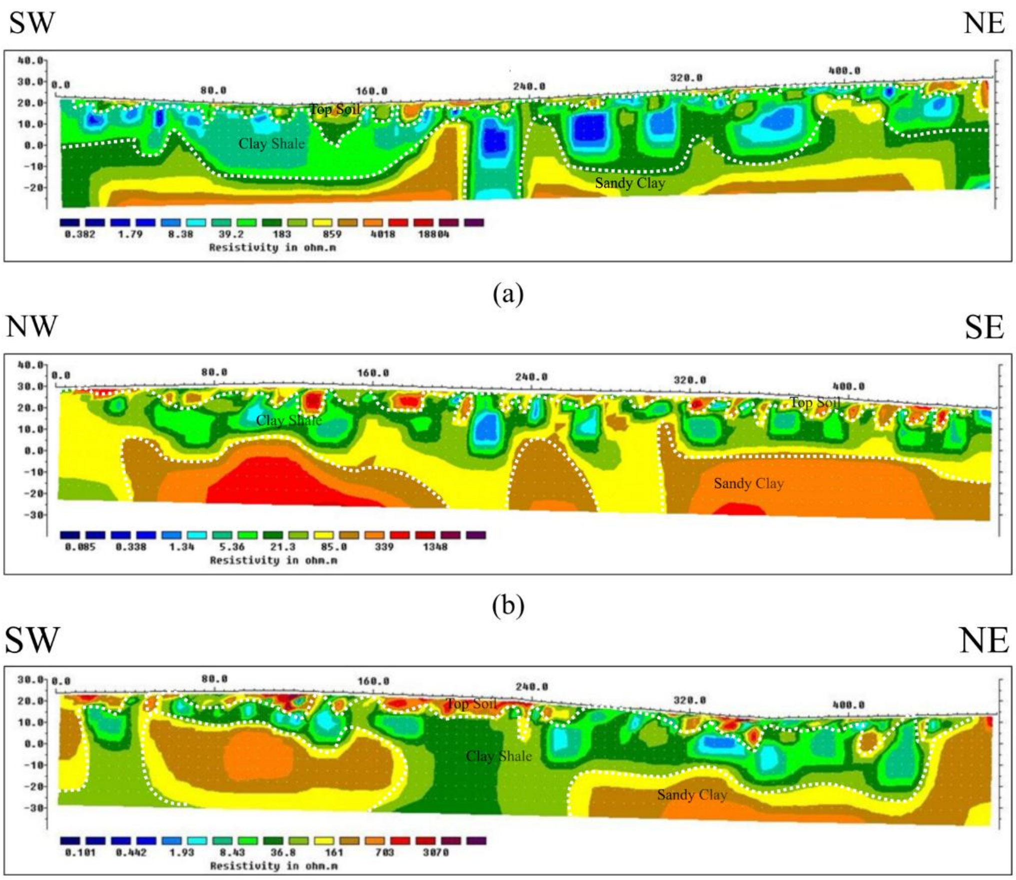
In the acquisition stage, measurements were performed at three survey sites (Figure 2–4) using a set of MAE Multi-Channel Resistivity and IP Meter equipment. The geoelectrical survey was conducted using the dipole-dipole configuration. Before data collection, survey configurations and field parameters, including electrode spacing, survey line length, and the number of profiles, were carefully determined. At each site, four survey lines were deployed: one main line and three cross-lines, resulting in a total of 12 profiles. Figure 2–4 illustrate the layout of the survey lines. The main survey line was 470 m long, whereas each cross-line measured 235 m.

After the data acquisition stage, the next step is data processing. In this phase, the recorded current values, potential measurements, and electrode spacing are entered and processed using geoelectrical software to generate a two-dimensional (2D) resistivity model. Subsequently, a three-dimensional (3D) modeling process is performed to visualize the spatial distribution of clay shale.

The resulting 2D resistivity sections and 3D clay shale models were subsequently analyzed and interpreted by comparing measured resistivity and chargeability values with published reference tables. Geological validation, which involved the regional geological map, was performed to ensure consistency between interpretation results and the actual subsurface conditions at the study site. As a working hypothesis, lithologies characterized by low resistivity values are interpreted as clay shale, which correlates with low permeability. Consequently, areas within IKN dominated by low-permeability lithology are considered less suitable for the implementation of the Sponge City concept.

Result and Discussion

The geoelectrical survey results are presented as resistivity sections. Each site comprises four survey lines (one long section and three cross-sections), yielding a total of twelve sections across the three investigated sites. For each site, the 2D long-section model was selected as the representative profile (Figure 5), as it most clearly illustrates the spatial distribution trend of clay shale. In contrast, the cross-section models are utilized in the 3D correlation to highlight the lateral continuity between sections.



(c)

Figure 5. Geoelectrical Resistivity Longsection Profiles: (a) Location 1, (b) Location 2, (c) Location 3.

Figure 5 illustrates three main lithological units identified from the resistivity profiles: topsoil, clay shale, and sandy clay. The topsoil layer is relatively thin (<1 – 5 m), underlain by clay shale with resistivity values below 50 Ωm and thicknesses ranging from less than 5 m to over 30 m. The deepest unit is sandy clay, which shows resistivity values above 50 Ωm.

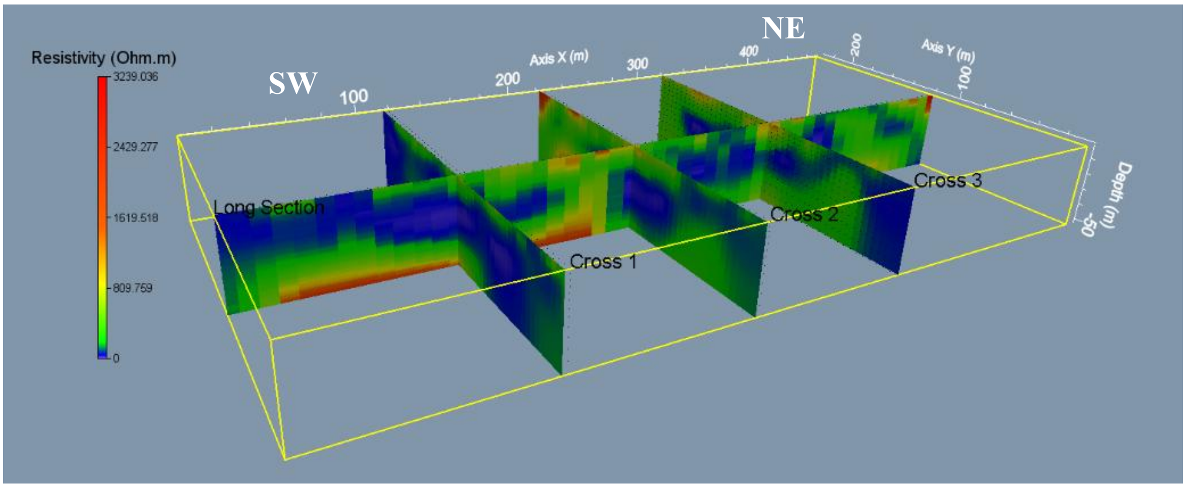
The profiles show clear spatial variations. At Location 1 (Figure 5a), the clay shale layer thickens toward the southwest, while the sandy clay unit becomes thinner in the same direction. Location 2 (Figure 5b), which trends northwest to southeast, exhibits a relatively thick sandy clay layer reaching up to 30 meters with a nearly horizontal stratification. At Location 3 (Figure 5c), oriented southwest to northeast, clay shale is the dominant lithology, with only a thin sandy clay layer observed at the base.

Overall, the presence of clay shale is significant, indicating high fluid saturation and low permeability. According to Fallah-safari et al. (2010), clay materials generally exhibit either higher water content or higher air-void ratios; in this study, the clay shale corresponds to the former, characterized by low resistivity (<50 Ωm) and high ionic fluid saturation.

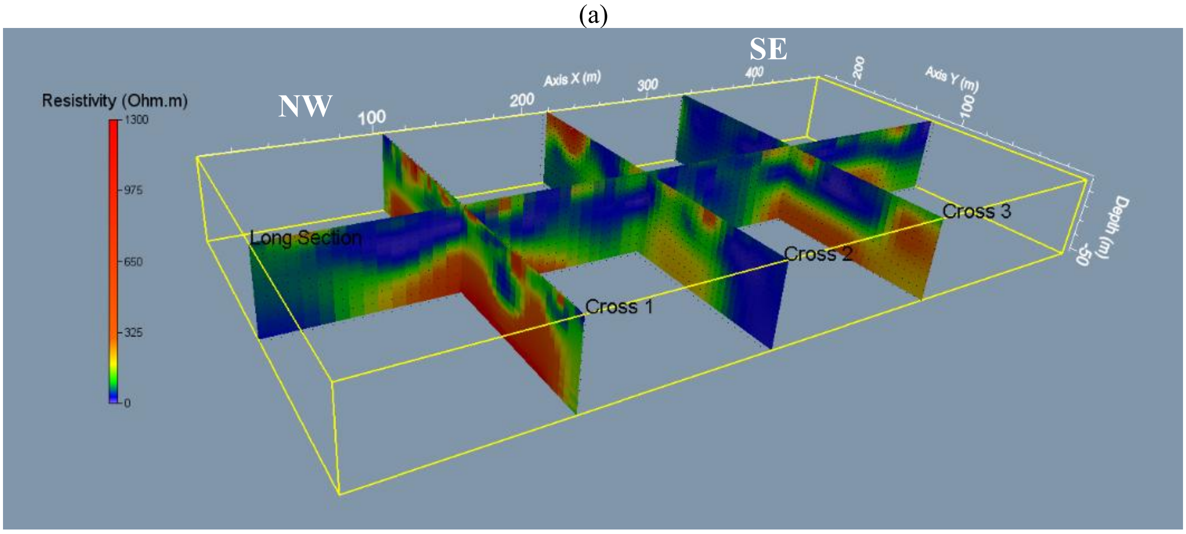
The interpretation of the geoelectrical section indicates the presence of a hard soil layer, identified at the contact boundary between the topsoil and clay shale. Based on Figures 5 and 6, the hard layer occurs at a depth of approximately 2–4 meters, corresponding to the relatively thin topsoil observed in the section. From a hydrogeological perspective, the topsoil acts as an infiltration zone, where rainwater initially enters the ground through soil pores. This layer is also part of the vadose zone or the unsaturated zone, where pores contain both air and water, allowing downward water movement through gravity and capillary action. Beneath it lies an impermeable clay shale layer that serves as the lower boundary of the vadose zone, restricting vertical infiltration and impeding percolation into deeper layers. The underlying sandy clay layer exhibits higher permeability compared to the clay shale and potentially functions as a shallow confined aquifer, capable of storing infiltrated water from the upper layers.

Integration of the geoelectrical section and the 3D resistivity model (Figures 5 and 6) reveals that the clay shale forms a continuous low-resistivity layer (<50 Ωm) thickening toward the northeast. This thickening trend is consistent with the regional geological pattern, where the study area lies within the Pamaluan Formation (depicted in green on the geological map in Figure 1), composed predominantly of alternating claystone and shale. The clay shale distribution follows a southwest–northeast orientation, indicating agreement between the geoelectrical results and regional stratigraphic structures. In contrast, higher-resistivity zones in the southern and southwestern parts indicate the presence of sandy clay correlated with deposits of the Bebulu Formation and younger alluvium. Integration of the 3D resistivity model, geoelectrical cross-section, and regional geological map strengthens the interpretation that the clay shale of the Pamaluan Formation functions as an impermeable layer that controls infiltration processes and defines the position and thickness of the vadose zone, while the underlying sandy clay may serve as a limited shallow aquifer in the study area.

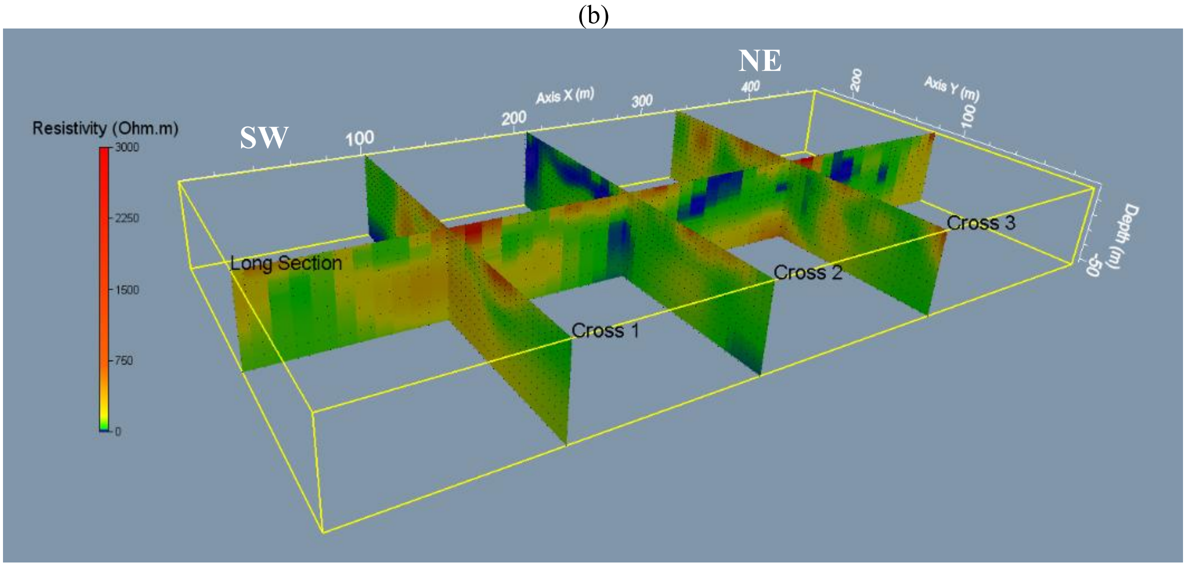
According to Filho et al. (2017), a decrease in resistivity values is generally caused by increased clay content and soil compaction. This finding aligns with Ningtyas et al. (2020), who reported that low resistivity correlates with low permeability. Therefore, clay shale with low resistivity values indicates poor water conductivity and impermeable characteristics. In relation to porosity, lower permeability in a lithologic unit result in reduced water absorption, causing water to remain within the soil and increasing saturation levels. Saturated soils tend to expand during prolonged or intense rainfall, which may increase pore pressure and trigger slope instability, particularly in areas dominated by clay-rich materials.



(a)



(b)



(c)

Figure 6. 3D Model of Geoelectrical Resistivity Sections at (a) Location 1, (b) Location 2, and (c) Location 3.

The geological conditions in the IKN region, dominated by thick, low-permeability clay shale, suggest that surface infiltration, water transport within the vadose zone, and natural aquifer storage are not well developed. Consequently, implementing the Sponge City concept that relies solely on natural recharge into deep aquifers would be ineffective in this region. The results of this study highlight the need for a hybrid approach that integrates natural and engineered systems. Water management strategies in IKN should emphasize surface retention and stormwater management, such as green roofs, retention ponds, and bioretention facilities, while also considering artificial recharge to replenish the deeper sandy clay aquifer. Further studies are recommended to determine the depth of the water table in order to delineate the lower limit of the vadose zone and evaluate the potential of the shallow aquifer.

In addition to its implications for Sponge City implementation, the presence of low-resistivity clay shale also has geotechnical and geotectonic consequences. The low resistivity of this layer likely reflects the presence of clay minerals such as illite or montmorillonite. Ohlmacher (2000) stated that clay shale containing illite and montmorillonite exhibits low shear strength and high swelling potential with increasing water content. Such lithologies are more prone to deformation and landslides than clay shale dominated by kaolinite or chlorite minerals. Therefore, the presence of clay shale should be considered a major factor in infrastructure design and slope stability mitigation across the IKN area.

Conclusion

The geoelectrical survey successfully mapped the distribution of clay shale in the IKN area, revealing a relatively thick layer (up to 30 meters) with low resistivity values (<50 Ωm), indicative of low permeability. This lithological characteristic restricts surface infiltration and groundwater recharge, suggesting that the natural implementation of the Sponge City concept would be less effective under such geological conditions. Therefore, the study concludes that a hybrid water management approach, integrating both natural and engineered systems, is essential to achieve sustainable stormwater control and effectively support the Sponge City framework in IKN.

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Author Contribution

Wahidah: Conceptualization, Writing - Review & Editing, Visualization, and Project administration. **Piter Lepong:** Writing – Original Draft, Supervision, Validation, and Investigation. **Supriyanto and Djayus:** Methodology and Formal Analysis. **Muhamad Akmal Firdaus dan Dwi Azisyarlina:** Data Curation and Software.

Conflict of Interest

The authors declare no conflict of interest.

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