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Literature Review: Analysis of the Ecological Phenomenon of Land Subsidence in Urban Areas of Indonesia

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ABSTRACT

Land subsidence is one of the increasingly serious environmental problems in various urban areas of Indonesia. This phenomenon occurs due to a combination of natural factors and human activities, particularly excessive groundwater extraction, the burden of infrastructure development, soft soil consolidation, and changes in land use. Major cities such as Jakarta, Bekasi, Bandung, Semarang, and Surabaya experience different rates of land subsidence, with significant impacts on the environment and community life. These impacts include increased flood risk, infrastructure damage, seawater intrusion, and declining urban environmental quality. This study uses a literature review method to examine the causes, characteristics, ecological impacts, and mitigation efforts related to land subsidence in Indonesian urban areas. The findings indicate that groundwater exploitation is the dominant factor accelerating land subsidence, especially in coastal cities. Therefore, sustainable water resource management, improved piped water services, stricter development control, and adaptive spatial planning policies are needed to reduce future risks.

Keywords: Ecological Impact; Groundwater Extraction; Indonesia; Land Subsidence; Mitigation; Urban Areas

Contribution/Originality:
This article synthesizes environmental engineering literature on land subsidence across major Indonesian cities and links the phenomenon to ecological degradation, urban risk, groundwater governance, monitoring technology, and integrated mitigation planning.

1. INTRODUCTION

Indonesia is a developing country experiencing continuous urban growth and rapid socio-economic transformation. The expansion of urban populations has increased the demand for land, clean water, housing, transportation systems, industrial areas, and other urban infrastructure. This condition has placed significant pressure on the physical environment, especially in large cities where land use changes occur intensively. One of the most serious environmental problems resulting from this pressure is land subsidence, which refers to the downward movement of the land surface due to natural geological processes and human activities (Chaussard et al., 2013; Arabamaeri et al., 2021).

Land subsidence has become an important issue in several major Indonesian cities, including Jakarta, Bekasi, Bandung, Semarang, and Surabaya. These cities have experienced different rates and patterns of subsidence depending on their geological characteristics, groundwater use, urban density, and infrastructure development. In many cases, subsidence occurs slowly and is not immediately visible, but its long-term impacts can be severe for urban sustainability, environmental quality, and community safety (Abidin et al., 2011; Abidin et al., 2015; Marfai, 2021).

One of the main causes of land subsidence in Indonesian urban areas is excessive groundwater extraction. The increasing need for clean water in households, industries, commercial buildings, and public facilities has encouraged intensive groundwater use, especially in areas where piped water services are still limited. Continuous groundwater extraction reduces pore-water pressure in aquifer layers, causing soil compaction and a decline in land elevation. This process is particularly significant in urban areas formed by soft alluvial deposits, where clay, silt, and sand layers are vulnerable to consolidation (Iskandar et al., 2025; Ministry of Public Works and Housing of the Republic of Indonesia, 2023; DGTL Ministry of Energy and Mineral Resources, 2023).

In addition to groundwater extraction, infrastructure development also contributes to land subsidence. High-rise buildings, road networks, industrial estates, ports, and commercial centers impose heavy loads on the land surface. When these structures are built on soft soil layers, the pressure can accelerate soil consolidation and increase subsidence risk. This condition is evident in dense metropolitan areas where urban development often exceeds the natural carrying capacity of the environment (Chairani et al., 2024; Rumbyarso, 2024; Ardiansyah & Murti, 2025).

Land-use change is another factor that intensifies subsidence in urban areas. The conversion of open land, wetlands, rice fields, and coastal zones into built-up areas reduces natural water infiltration and weakens the hydrological balance of the subsurface environment. In Java, rapid population growth and urban expansion have contributed to ecological overshoot, in which environmental pressure exceeds the ability of natural systems to recover. This situation increases the vulnerability of urban land to degradation, flooding, and subsidence-related hazards (Rusli et al., 2010; Bappenas, 2022).

Jakarta is one of the most widely studied examples of land subsidence in Indonesia. Previous research has shown that subsidence in Jakarta is closely related to urban development, groundwater extraction, and the concentration of population and economic activities. In coastal areas of North Jakarta, subsidence interacts with tidal flooding and sea-level rise, creating serious risks for settlements, infrastructure, and public services. Studies on Jalan R.E. Martadinata and other coastal zones also show that land movement has direct implications for road stability and coastal safety (Abidin et al., 2011; Ramadhan et al., 2023; Sofieyanti & Sirodj, 2024).

Semarang also faces serious land subsidence problems, particularly in its northern coastal area. The combination of soft coastal sediment, groundwater extraction, and sea-level rise has increased the frequency and intensity of tidal flooding. Research on Semarang shows that land subsidence has contributed to the physical lowering of coastal land, making settlements and infrastructure more vulnerable to inundation. In the long term, coastal cities such as Jakarta and Semarang may experience changes in coastal land area due to the combined effects of sea-level rise and land subsidence (Abidin et al., 2015; BMKG, 2024; Fauziyah et al., 2026).

Land subsidence is not only a physical or geotechnical problem but also an ecological and socio-economic issue. The lowering of land elevation can increase flood risk, reduce drainage capacity, trigger seawater intrusion, damage infrastructure, and disturb coastal ecosystems. In legal and spatial terms, changes in coastline and sea-level conditions may also affect coastal boundaries and navigation. Therefore, land subsidence must be understood as a multidimensional environmental problem involving ecological balance, urban planning, public safety, and economic resilience (Narwati et al., 2022; IPCC, 2023; Putri et al., 2025).

Monitoring land subsidence is essential for understanding its spatial distribution, rate, and long-term trends. Modern technologies such as Global Navigation Satellite System (GNSS), Interferometric Synthetic Aperture Radar (InSAR), Differential InSAR (DInSAR), and geodetic measurements have been widely used to detect land surface deformation. These methods are important because they allow researchers and policymakers to identify vulnerable areas and design more accurate mitigation strategies. Several studies in Bandung, Pekalongan, and other Indonesian cities demonstrate the usefulness of satellite-based monitoring for detecting subsidence patterns over time (Andreas et al., 2020; Nusantara & Sari, 2022; Muharam & Sari, 2024; Rizki & Basyid, 2024).

Based on these conditions, this article aims to review the causes, spatial characteristics, ecological impacts, socio-economic consequences, monitoring approaches, and mitigation efforts related to land subsidence in Indonesian urban areas. The main research question is: how do groundwater extraction, infrastructure development, land-use change, and geological conditions contribute to ecological land subsidence risks in major Indonesian cities, and what mitigation strategies are most relevant for sustainable urban management? By reviewing previous studies, this article is expected to provide a clearer understanding of land subsidence as an urban ecological phenomenon and support more adaptive policies for sustainable city development.

2. METHOD

This study applies a qualitative literature review method. The review was conducted by collecting and analyzing scientific articles, government reports, and institutional documents related to land subsidence, groundwater extraction, urban ecology, coastal flooding, spatial planning, and monitoring technology in Indonesia. The reviewed materials focus mainly on urban areas that have been repeatedly reported as vulnerable to subsidence, including Jakarta, Bekasi, Bandung, Semarang, and Surabaya.

The analysis was organized by identifying major themes from the literature: the basic concept of land subsidence, dominant causal factors, ecological and socio-economic impacts, city-specific characteristics, mitigation and adaptation efforts, and monitoring methods. The information was then synthesized descriptively to explain the relationship between physical processes and urban environmental consequences. Because this article is a literature review, it does not involve field sampling, laboratory testing, or statistical hypothesis testing. The strength of the method lies in integrating findings from different cities to support a broader understanding of subsidence as an ecological and urban-management problem.

3. FINDINGS AND DISCUSSION

Land subsidence can be understood as a geological and environmental phenomenon in which the elevation of the land surface decreases relative to a reference plane. In an urban ecological context, it can be categorized as a form of land degradation because it changes the capacity of land to support settlements, infrastructure, drainage systems, and groundwater functions. The process may occur gradually through sediment compaction or more suddenly when subsurface layers fail to support the pressure above them (Arabamaeri et al., 2021). In Indonesian cities, gradual compaction is the most common pattern because it is reinforced by urban water demand and construction pressure.

The most dominant cause identified in the literature is excessive groundwater exploitation. Dense urban populations and large industrial areas require large quantities of water, while piped-water coverage is often insufficient. As a result, groundwater abstraction becomes the practical option for households, factories, hotels, and commercial buildings. Continuous extraction lowers pore-water pressure and allows aquifer layers to compact. This mechanism explains why coastal and industrial areas often show faster subsidence than less developed zones (Sofieyanti & Sirodj, 2024; Rumbyarso, 2024).

The second important driver is the physical burden of urban infrastructure. Multi-storey buildings, toll roads, industrial estates, shopping centers, ports, and reclaimed areas produce persistent loads on soft soil layers. In cities with thick alluvial deposits, such as the northern coast of Java, these loads accelerate consolidation. The transformation of open land, wetlands, and agricultural fields into impermeable built-up surfaces further reduces groundwater recharge and disrupts the urban hydrological balance (Chairani et al., 2024; Rusli et al., 2010).

The ecological and socio-economic impacts are multidimensional. Subsidence reduces land elevation, weakens drainage performance, and increases the frequency of flooding and tidal inundation. In coastal areas, the lowering of land relative to sea level allows seawater to penetrate further into settlements and aquifers, decreasing groundwater quality and threatening freshwater availability. The phenomenon can also disturb wetlands, mangrove areas, and coastal ecosystems. At the same time, infrastructure damage, road deformation, cracked buildings, and repeated house elevation create economic burdens for communities and local governments (Narwati et al., 2022; Putri et al., 2025).

Table 1. Comparative overview of land subsidence issues in selected Indonesian cities

Urban area	Main pressure	Reported tendency	Main impacts	Mitigation focus
Jakarta	Groundwater extraction, dense buildings, coastal lowland conditions	Some northern areas have been reported at very high rates, reaching 10-25 cm per year in previous studies	Tidal flooding, drainage failure, infrastructure damage, seawater intrusion	Groundwater control, piped-water expansion, coastal protection, adaptive planning
Bekasi	Industrial estates, housing expansion, deep aquifer use	Generally about 1-4 cm per year, with higher rates in critical industrial and northern zones	Reduced recharge, soil compaction, increasing flood vulnerability	Industrial water regulation, recharge conservation, spatial control
Bandung	Groundwater use and basin sediment conditions	DInSAR studies reported significant subsidence in the Bandung Basin, including high values around Cileunyi	Surface deformation, infrastructure vulnerability, basin hydrology pressure	Satellite monitoring, groundwater management, land-use control
Semarang	Coastal alluvium, groundwater extraction, sea-level interaction	Coastal northern areas have been reported to experience rapid cumulative subsidence	Rob flooding, permanent inundation risk, building adaptation costs	Building adaptation, coastal drainage, groundwater restriction, monitoring
Surabaya	Soft alluvial clay, port and urban infrastructure loads, groundwater use	Generally lower to moderate rates, with higher tendencies in coastal and reclaimed zones	Salinity intrusion, port-area deformation, drainage stress	Coastal ecosystem protection, structural control, water-resource management

The comparative overview shows that each city has a specific combination of physical setting and development pressure. Jakarta and Semarang represent coastal-risk cases where land subsidence interacts strongly with tidal flooding and seawater intrusion. Bekasi illustrates the pressure of industrial expansion and deep groundwater use, while Bandung shows the vulnerability of basin areas where groundwater and sediment conditions interact. Surabaya has relatively moderate general rates, but port, reclamation, and coastal zones remain vulnerable because of soft soil and hydrological pressure.

Monitoring methods are essential because subsidence is often slow, cumulative, and spatially uneven. Geodetic GPS can measure vertical displacement accurately at selected points, while Interferometric Synthetic Aperture Radar (InSAR) uses satellite imagery to detect broad spatial patterns of surface deformation. Conventional levelling remains useful for checking elevation changes along infrastructure corridors, and groundwater-level monitoring helps identify whether aquifer pressure is declining. The combination of these methods can support early warning, zoning decisions, and evaluation of mitigation policies (Andreas et al., 2020; Nusantara & Sari, 2022).

Mitigation requires integrated management rather than isolated engineering responses. Reducing groundwater use is the most urgent step, especially through restrictions on deep wells, inspection of industrial extraction, and expansion of reliable piped-water services. Urban planning must also protect recharge zones, limit construction in highly vulnerable areas, and integrate green infrastructure such as infiltration wells, biopores, open spaces, and mangrove restoration in coastal environments. Technical measures such as sea walls and drainage improvements may reduce immediate flood risk, but they will not solve the root causes if groundwater extraction and land conversion continue (DGTL Ministry of Energy and Mineral Resources, 2023; Ministry of Public Works and Housing, 2023).

Community adaptation is also part of the response. Residents in subsiding coastal areas often elevate house floors, raise roads, or modify drainage channels to remain in place. These actions show local resilience, but they also transfer costs to households and may not be sustainable for low-income communities. Therefore, mitigation should combine technical infrastructure, ecological restoration, water governance, social protection, and clear spatial policies. Without integrated action, subsidence will continue to increase the ecological and economic vulnerability of Indonesian urban areas.

4. CONCLUSION

Land subsidence is a serious environmental challenge for Indonesian urban areas. The reviewed literature shows that excessive groundwater extraction is the most dominant accelerating factor, while infrastructure load, soft alluvial geology, and land-use conversion intensify the process. The impacts include higher flood and tidal-inundation risk, seawater intrusion, declining groundwater quality, infrastructure damage, and disruption of urban and coastal ecosystems. The most relevant response is an integrated mitigation strategy that combines sustainable groundwater management, expanded piped-water supply, strict supervision of deep wells, conservation of recharge areas, adaptive spatial planning, coastal ecosystem restoration, and continuous monitoring using GPS, InSAR, levelling, and groundwater observation. These measures are necessary to reduce future risk and support more resilient urban development in Indonesia.

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