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Research article

Anthropogenic and Natural Drivers of Land Subsidence

Rochmad Wahyudi[1*], Kismartini[2], Mochamad Arief Budihardjo[3], Annisa Sila Puspita[4], Marah Ammar[5,6]

[1] Master of Environmental Sciences, Universitas Diponegoro, Jalan Prof. Soedarto, Tembalang, Semarang, Indonesia 50275
[2] Department of Public Administration, Faculty of Social and Political Sciences (FISIP), Universitas Diponegoro, Jalan Prof. Soedarto, Tembalang, Semarang, Indonesia 50275
[3] Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Jalan Prof. Soedarto, Tembalang, Semarang, Indonesia 50275
[4] Environmental Sustainability Research Group, Departement of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Jalan Prof. Soedarto, Tembalang, Semarang, Indonesia 50275
[5] Doctoral student in Faculty of Civil Engineering, Universitas Diponegoro, Jalan Prof. Soedarto, Tembalang, Semarang, Indonesia 50275
[6] Department of Civil Engineering, Faculty of Engineering, Latakia University, Suriah, GRC5+Q2V, Syria
*Corresponding Author, email: rezayd.227@gmail.com

Abstract

This review is the first attempt to integrate natural and anthropogenic drivers of coastal subsidence, the evolution of monitoring techniques, and geo-environmental impacts, with a focus on coupled human-environment systems. This review compares traditional geodetic techniques (levelling, GNSS) with other satellite and geophysical methods (InSAR, LiDAR, microgravity, and seismic survey) and assesses subsidence monitoring under different geo-environmental conditions. Empirical evidence from the northern coastline of Java, in particular Semarang, shows that subsidence has occurred at an annual rate of 2–10 + cm, which is directly linked to groundwater exploitation, alteration of land use, and coastal construction, which exacerbates tidal flooding, coastal recession, saltwater encroachment, ecosystem destruction, infrastructure deterioration, and social impacts. The findings suggest that subsidence is a unique geophysical phenomenon and not a result of anthropogenic interactions with natural systems involving water, land use, coasts, and public administration frameworks. This type of integration is essential for improved risk assessment, resilience, and sustainable development.

Keywords: Anthropogenic drivers; coastal subsidence; coastal vulnerability; land deformation; natural processes

1. Introduction

Worldwide, low-lying and rapidly urbanizing deltaic and estuarine environments are also experiencing geohazards, such as coastal subsidence. Coastal regions worldwide undergo significant environmental and human-induced changes, resulting in a decline in land surface. Areas of land along coastlines are experiencing rapid climate changes, such as tectonic adjustments and sediment compaction. The land elevation along coastlines is declining at a rate as fast as, and even faster than, the rate of rise of the planet's sea level (Hammond et al., 2021; Tay et al., 2022). Human activities, such as urbanization and population growth, have compromised subsurface coastal systems and solid sediment assemblies (Esteban et al., 2021; Zhang & Ouyang, 2019). Coastal cities, such as Jakarta, Pekalongan, Semarang, and Surabaya, have subsidence patterns as fast as 2–20 cm yr – 1, leaving them vulnerable to tidal flooding and coastal hazards (Figure 1). Coastal regions are changing rapidly over time and space.

Numerous fields in science, such as hydrogeology, coastal geomorphology, engineering geology, and geodesy, have addressed subsidence in their literature. The subsidence phenomenon has a variety of causes, including sediment compaction, crust deformation, and human activities such as groundwater extraction, drainage alteration, and surface load (Chen et al., 2018; Higgins, 2016). Remote sensing innovations, such as LiDAR, PS-InSAR, DInSAR, and GNSS, have recently enhanced detection capabilities (Ma, 2021; Xu et al., 2022). However, the literature remains largely fragmented. Individual mechanisms or a single monitoring strategy are typically the focus of most studies. This fragmented literature provides little synthesis in the physical, environmental, or social realms. In turn, policy and management responses to subsidence are fragmented, which hinders the formation of integrated strategies for coastal adaptation. This research focuses on the natural and anthropogenic drivers and geoe-environmental consequences of subsidence to improve existing research gaps. Some previous reviews on subsidence have examined it as a geophysical problem or as an engineering concern. However, this article situates subsidence within a coupled human–environment system, specifically, land use, groundwater, crustal, and climatic systems (Grabowski et al., 2022; Silva et al., 2016). The northern coast of Java is presented as a case study on spatio–temporal urban subsidence and the varying degree of hazard caused by urban expansion and groundwater extraction.

This review aims to improve the understanding of risk, evidence-based policy, and adaptive management framework in coastal zones to promote the sustainable development of subsiding coasts. The study attempts to achieve the above objectives by examining monitoring methods for coastal subsidence, evaluating the natural and anthropogenic causes of coastal subsidence, and studying the consequences of subsidence on the coastal environment and society.

2. Review of literature

Over the past few decades, researchers have focused on the environmental and hydrological aspects of coastal subsidence. Early studies concentrated on natural subsidence attributed to sedimentation and compaction of the field in delta regions, post-glacial isostatic adjustment, and tectonic deformation (Simms et al., 2022; Zhang et al., 2019). These studies illustrate that, in the long term, the natural geological processes that occur in the subsurface, which gradually lower the surface of the earth, will make coastal plains and estuaries increasingly susceptible to relative sea-level rise. More recent studies have focused on sediment supply deficits, or the reduced sediment supply due to upstream damming and altered channels, which has led to increased compaction of sediment in mega-deltas such as the Mississippi, Nile, and Mekong (Simms et al., 2022; Zhang et al., 2019).

Simultaneously, there is a vast amount of literature on the anthropogenic drivers of subsidence risk in coastal zones. From various types of human impact, groundwater retrieval has the most subsidence of over 10 cm year during peak periods of extraction in Jakarta, Bangkok, Shanghai, and Mexico City (Huang et al. 2023; Khatri & Tyagi, 2015). Urban loading, drainage structures, peatland oxidation, and engineered coastal works facilitate land depression in cities (de Oliveira et al. 2022; Seifollahi-Aghmiuni et al. 2022). More recent studies have focused on coupled effects, the interaction of natural compactions, reduced recharge, and high urbanization, which lead to complex and nonlinear subsidence (Luo et al., 2025; Yang et al., 2022). Indeed, the advancement of subsidence research has been largely a result of technological advancement.

Survey methods from history, such as leveling, GNSS, and borehole extensometers, allowed for the understanding of areas with vertical displacements, even though the spatial coverage of the elements was not the most extensive (Gholinia et al., 2022). Elements, such as satellite geodesy and more recently developed technologies like InSAR, persistent scatterer interferometry (PS-InSAR), and LiDAR, have allowed for detailed analyses of subsidence (Lafortezza & Giannico, 2019; Letsios et al., 2023; Lin et al., 2020). Using remote sensing data, the subsidence process has been spatially heterogeneous. Locations that are classified as “hotspot zones” of fast sinking are usually situated around areas of industrial activity, centers of aquifer depletion, or areas of land that have been previously reclaimed (Duan et al., 2022; X. Yang et al., 2024). Many studies have been conducted on monitoring subsidence processes; however, monitoring has remained limited. The literature has reported monitoring limitations, including signal decorrelation in vegetated wetlands, the absence of continual data from a temporal perspective, and the necessity for ground verification of the data.

The effects of coastal subsidence are a growing area of study. Some researchers have attributed subsidence to increased tidal flooding, permanent flooding, wetland collapse, salinity of groundwater, and damage to structures (Mastrocicco & Colombani, 2021; Thompson et al., 2021). Studies conducted in cities like Jakarta, Semarang, Bangkok, and Tokyo Bay, found that in some areas, the subsidence of the coastal land proves to be even more detrimental than the relative rise in sea level on the wetlands, resulting in the flooding of the land and the rapid loss of the land. (Mastrocicco & Colombani, 2021; Thompson et al., 2021). From the perspective of social science and policy research, subsidence is not only a physical assault but also a social and environmental crisis (Calvário et al., 2017; Long & Steel, 2020). However, most of the literature is in the form of fragmented pieces, specifically pertaining to integrated assessments that combine geophysical monitoring, land use change, hydrology, and socio-economics in a cohesive framework of risk assessment.

3. Review Methodology

This study aimed to unpack and critique the literature pertaining to coastal subsidence and the monitoring, triggers, and geoe-environmental impacts of coastal subsidence. For this purpose, the author conducted a literature search across three platforms (Scopus, Web of Science, and Google Scholar) and restricted the search to peer-reviewed studies from 2020 to 2024. The terms “ coastal subsidence,” “land subsidence,” “InSAR,” “PS-InSAR,” “GNSS,” “groundwater extraction,” “urban subsidence,” “deltaic coasts,” “coastal flooding,” and various Boolean operators were used to identify pertinent literature. Relevant studies were those that (i) addressed subsidence of either the coastal or deltaic regions, (ii) utilized any of the geodetic, remote sensing, or geophysical monitoring techniques, and (iii) described either the natural or man-made causes and effects (including socio-environmental) of subsidence. Studies related to non-coastal subsidence, those that were not peer-reviewed, and those with vague approaches were omitted. The resulting literature was analyzed thematically, focusing on monitoring methods, natural causes, man-made causes, and geo-environmental effects. This research aimed to identify basic patterns, associations, and cumulative effects. It examined the human–environment interface that interweaves natural (sediment compaction and crustal alterations) and human-induced (groundwater extraction, urban sprawl, and coastal engineering) subsidence processes. This study relies exclusively on subsidence data extracted from the reviewed literature, including InSAR (e.g., Sentinel-1 and ALOS-2) and GNSS monitoring networks, with due citations to the data owners. It depends solely on subsidence data from the reviewed literature, including subsidence rates from InSAR (e.g., Sentinel-1 and ALOS-2) and GNSS monitoring networks, with all datasets properly credited to the original authors. Files and maps that have been redrawn or altered from previous works and Google Earth images include complete metadata in the captions that identify the owner and year of acquisition, and the spatial resolution, to comply with academic fair use of copyright materials.

4. Monitoring Techniques for Coastal Subsidence

Coastal waters require subsidence monitoring strategies capable of detecting vertical deformation over multiple and varying temporal and spatial scales. Traditionally, observation systems were based on grounded systems; however, they have transitioned to more sophisticated and remote-sensing geodetic systems that can map land motion and urban, industrial, and deltaic landscapes at finer resolution. When assessing hazards over time, the methods used together have varying sensitivities, consistency, and limitations.

4.1. Traditional Survey Methods (Leveling, GNSS, Inclinometers)

Classic geodetic techniques were the first developed comprehensive techniques to monitor changes in the elevation of land. By placing precision at the level of the leveling solution, vertical precision (millimeter) is achievable and has been widely used in engineering and hydrology (Kuchmister et al., 2020; Shafi et al., 2019). Because of its repeatability, vertical precision is useful for long-term deformation detection; however, the process is laborious and has spatial restrictions. Global Navigation Satellite System (GNSS) observations have increased the time flexibility for observations to be continuous or for measurements to be taken at intervals, with centimeter accuracy (Jin et al., 2024). These observations complement borehole inclinometers and extensometers for subsurface compaction at specific depths of interest, and the latter are useful for investigating groundwater extraction. Thus, these approaches are limited in their spatial coverage and maintenance and have no applications in large systems that cover local networks and do not incorporate satellite mapping at the local scale.

4.2. Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) is commonly used for the characterization of the subsurface with respect to shallow stratigraphy, buried infrastructure, and layers of sediment compaction. GPR transmits electromagnetic energy into the ground and captures reflections from the boundary surfaces of materials with varying dielectric properties (Ling et al., 2022). For subsidence studies, GPR is used to identify the presence of voids, near-surface compaction, and subsurface collapse attributed to the removal of groundwater or urban loading. The resolution of GPR is limited under certain environmental conditions, particularly in the presence of salts and clays, which are rich in moisture and conductive soils, as these significantly attenuate the penetrating signal and limit GPR use in coastal wetlands and estuaries.

4.3. Seismic and Geophysical Methods

The analysis of lithological layering and fluid saturation under sinking coastlines is being enhanced using seismic refraction, electrical resistivity tomography (ERT), and magnetotellurics (Meqbel et al., 2016). Seismic surveys indicate the presence of compaction, fault lines, and sediment consolidation, whereas resistivity measurements indicate the presence of saline entry and aquifer channels. Although geophysical models help understand what drives subsidence under deep compaction and groundwater withdrawal, the models draw on specialized instruments, extensive field campaigns, and highly skilled interpretations, which only result in occasional monitoring.

4.4. Geodetic Monitoring Networks (Continuous GNSS)

For short- or long-term periods, continuous networks of global navigation satellite systems (GNSS) can track crustal deformation or urban subsidence. By utilizing stable reference lines (or stable reference points), one can capture high-resolution vertical and horizontal shifts and determine if there are seasonal patterns of groundwater fluctuations or storm surges (Schneider et al., 2017). Several large cities, including Jakarta, Bangkok, and Tokyo, are using continuous GNSS to measure and evaluate subsidence, with the aim of studying and implementing response mechanisms (Kubo et al., 2020). This method is effective in maintaining a singular dimension of time; however, to capture multiple dimensions (i.e., multiple time intervals and multiple locations), there is a need for a significant increase in the quantity and, therefore, the cost and logistical complexity of the measurement systems.

4.5. InSAR / DInSAR / PS-InSAR

Differential Interferometric Synthetic Aperture Radar (DInSAR) has certain limitations. Despite the fact that DInSAR has redefined the field of subsidence monitoring by enabling researchers to monitor remote subsidence above and below the centimeter and millimeter levels over vast areas, it is limited. In urbanized coastal zones, where subsidence is associated with aquifer depletion, infrastructure loading, and reclaimed land, DInSAR is useful for detecting subsidence at varying spatial levels. In DInSAR, signal decorrelation is caused by vegetated wetlands, loss of coherence due to the presence of open water bodies, and atmospheric noise. To alleviate these issues, researchers often use empirical models that incorporate datasets from other measurement techniques, particularly Global Navigation Satellite System (GNSS) measurements.

Table 1. Comparative summary of key monitoring methods for coastal subsidence

Method	Spatial Coverage	Temporal Resolution	Vertical Accuracy	Strengths	Limitations
Leveling	Local	Periodic	mm	High precision	Labor-intensive, sparse coverage
GNSS (campaign)	Local–regional	Periodic	cm–mm	Repeatable, cost-effective	Limited density
Continuous GNSS	Local networks	High/real-time	cm–mm	Time-series monitoring	Expensive network
Borehole instruments	Point-based	Continuous	mm	Measures subsurface compaction	No spatial extent
GPR	Site-specific	Event-based	decimeter-meter	Subsurface imaging	Sensitive to water/clay
Seismic/ERT	Site-specific	Campaign	meter–decimeter	Deep mechanism analysis	Costly, complex
InSAR / PS-InSAR	Regional–metropolitan	Weeks–days	mm	Broad coverage, hotspot mapping	Noise, wetland decorrelation
LiDAR	Regional	Event-based	cm–dm	High-resolution topography	Costly acquisition
Aerial/Satellite imagery	Regional–global	Varies	meter–sub-meter	Historical change analysis	Indirect subsidence inference

4.6. Microgravity Surveys

Microgravity methods can detect variations in the subsurface density of materials resulting from the removal of fluids or the compaction of materials. These types of surveys detect the mechanisms of aquifer depletion and subsurface–surface displacement (Othman et al. 2018). Microgravity methods in conjunction with geodetic measurements have been used to detect mass loss at groundwater reservoirs in Jakarta and Mexico City. However, the presence of anthropogenic structures and vibrations, as well as atmospheric conditions, requires correction and/or significant adjustments.

4.7. Aerial Photography and Satellite Imagery

Aerial photographs and multispectral satellite images enable indirect subsidence analysis subsidence analysis, along with aerial photographs and multispectral satellite images, which enables the analysis of land use change, shoreline retreat, historical flooding, surface deformation, and subsurface deformation (Babaee et al., 2024). While modern imaging, in particular high-resolution images from Sentinel-2 and WorldView, can detect surface collapses or damage to infrastructure, archival images can aid in the reconstruction the evolution of coastlines. However, because these images do not measure deformation directly, they must be integrated with certain geodetic methods (for example, GNSS or InSAR) to perform quantitative subsidence analysis.

4.8. Anthropogenic Drivers of Coastal Subsidence

In many coastal regions, especially rapidly urbanizing deltas, subsidence dynamics are increasingly shaped by anthropogenic impacts, including groundwater extraction, coastal development, and altered shoreline construction, which changes sediment trapping and hydrological regulation, and shifts sediment (Babaee et al., 2024). These dynamics, combined with the presence of alluvium, estuarine clays, and reclaimed materials, are further complicated not only by sediment consolidation, but also by prolonged reduction in vertical elevation. Urban–coastal engineering and aquifer depletion are two of the dominant anthropogenic processes.

4.9. Groundwater Withdrawal and Subsurface Hydrological Alteration

Groundwater withdrawal is the most documented anthropogenic cause of land subsidence. Pumping leads to the depressurization of the aquifer system, which then causes the fine-grained sediment to compact and the subsurface to consolidate irreversibly. During periods of heavy industrial and residential groundwater use, subsidence has been documented at major Asian delta centers, including Jakarta, Bangkok, and Ho Chi Minh City. In addition to the large volume abstracted, subsidence is further aggravated by changes in the hydrological recharge system. Urbanization decreases aquifer recharge steps in several ways. In addition, the application of pavement decreases infiltration, drainage channelization controls the flow, and embankments of the river limit the natural recharge of the aquifer (Ertan & Çelik, 2021; Öztürk et al., 2024). In this way, consolidation can still be prolonged even after extraction is reduced to a minimum. One of these cities is Semarang, where this is especially evident in the port districts, industrial estates, and densely urbanized corridors; decades-long groundwater dependence has led to large areas of aquifer depletion and subsequent subsidence. The subsidence signal monitored through geodetic techniques illustrates the strong relationship between groundwater abstraction and hydrological mechanisms.

4.10. Urban Development, Surface Loading, and Coastal Engineering Activities

Urban development impacts fragile sediment layers and increases vertical stress on them. Construction activities, such as port operation buildings, industrial and commercial buildings, and land reclamation operations, increase consolidation times for soils, including soft marine clay. The reclamation fill adds pressure on the seabed sediment, which is compressible, further exacerbating the issue and prolonging the time it takes for the sediments to settle and laterally shift. Coastal engineering structures, such as seawalls, tidal gates, retention basins, and elevated roads, add another anthropogenic pressure on the stability of the landscape. The sedimentation subsidence that these structures control is likely aggravated by load, drainage changes, and modifications to the active sedimentation processes. Semarang is a typical case for this example. The integrated sea dike and toll road, which have been constructed to manage the impacts of tidal flooding and subsidence, have been designed to manage the infrastructure of the city. They control tidal intrusion, allow for a road, and the retention basins manage flooding and runoff. Figure 6 describes the engineering blueprint for the program as a system and thus outlines the complexity of the protective features overlaying subsidence-prone coastal zones.

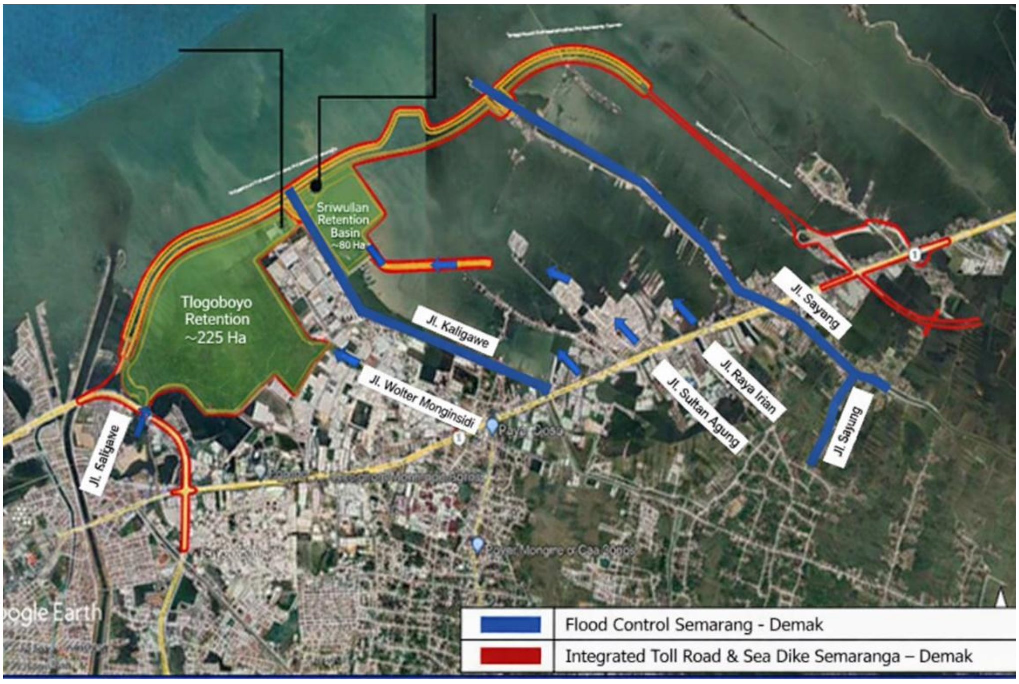

Figure 1. Integrated sea dike and toll road system (Semarang–Demak) as a coastal engineering response to subsidence, erosion, and tidal flooding in Semarang, Indonesia.

Although this infrastructure represents a defensive measure, the additional structural load on soft deltaic sediments necessitates continuous monitoring and adaptive maintenance strategies. Subsidence persists beneath reclaimed land and engineered coastal defenses; therefore, protection requires ongoing reinforcement rather than one-time construction. This case underscores the paradox of coastal engineering in subsiding environments, in which structures designed to reduce hazard exposure may simultaneously add loading pressure that accelerates settlement.

5. Geo-Environmental Impacts of Coastal Subsidence

5.1. Coastal Flooding and Permanent Inundation

Expanding subsidence caused by lowering land surfaces results in rising sea levels, leading to more frequent and longer flooding, as well as permanent inundation of previously dry land. In rapidly sinking cities, such as Semarang, Jakarta, and Bangkok, formerly land and farmed areas have been converted into tidal flats or open water. Although sea dikes and pumping systems can lessen flooding, the impacts of subsidence cannot be fully mitigated when subsidence exceeds the defendable adjustable limits. Loss of coastal land, displaced populations, and increased dependence on artificially flood control systems to adjust cities to liveable levels are potential consequences of subsidence.

5.2. Saltwater Intrusion into Groundwater Systems

As land surface elevations decrease and the pressure within aquifers drops, seawater is able to move further inland and invade the freshwater lenses that provide water to domestic, industrial, and agricultural users. Subsidence accelerates the invasion of freshwater lenses by further reducing the thickness of the confining layers of the aquifer, thereby contaminating aquifer systems and reducing their recoverability. In deltaic cities, such as Semarang, seawater has invaded both shallow and deep aquifers; if treating water is not an option, this problem only increases the cost of water. Once salinization of an aquifer occurs, it is nearly impossible to reverse, and the only solution may involve the expensive option of cutting off surface water supplies to the system to increase the flow of water into the salinized aquifer.

Table 2. Key geo-environmental impacts of coastal subsidence

Impact Dimension	Mechanism	Resulting Effects
Coastal flooding & permanent inundation	Land surface lowering relative to sea level	Increased tidal flooding, land loss, reliance on seawalls/pump systems
Saltwater intrusion	Aquifer pressure decline and hydraulic gradient reversal	Groundwater salinization, reduced water supply quality

5.3. Land Loss and Coastal Erosion Acceleration

Deltaic conditions accelerate coastal subsidence and submergence, resulting in the permanent loss of land. Wherever land subsides, tidal limits are pushed inward, creating new erosion and transforming previously land-based agricultural areas into water bodies, including tidal flats and open water. A similar trend has been observed in several Southeast Asian cities, where subsidence-driven flooding outpaces sediment supply and coastal margins collapse and retreat (Duy et al., 2018; Zhang & Hou, 2020). Lower sediment supplies due to upstream damming, alterations to ports, and loss of mangroves, results in increased erosion and limits the natural recovery processes. A comparison of shoreline geospatial shifts (1985–2020) indicated that recession was accompanied by the loss of land and the permanent flooding of adjacent coastal areas. Comparison of shoreline geospatial shifts (1985-2020) indicated the recession was accompanied by loss of land and the permanent flooding of adjacent coastal areas. This exemplifies the rapid loss of defensible land due to subsidence and the rising costs of coastal flooding protection measures, such as sea dikes, retention basins, and land reclamation. This exemplifies the rapid loss of defensible land due to subsidence, and the rising costs of coastal flooding protection measures, such as sea dikes, retention basins, and land reclamation. Erosion will be enhanced for urbanized deltas which are sinking, experiencing storm surges and a reduced sediment supply, if there is no monitoring and active adaptive management (Kochskämper et al., 2021).

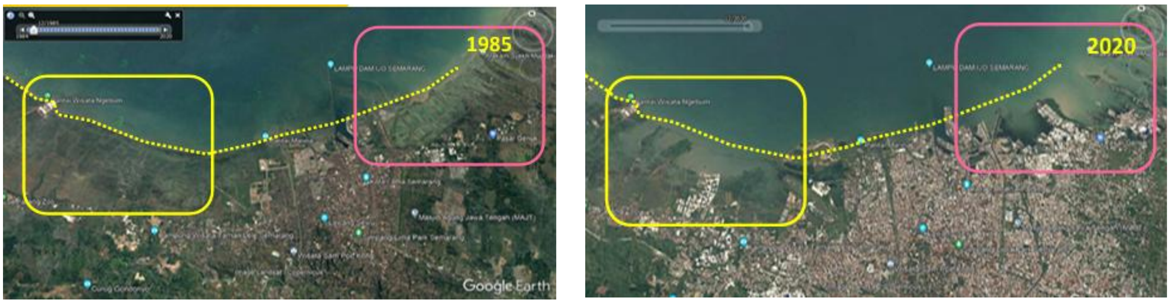

Figure 2. Evidence of coastline regression associated with coastal subsidence in Semarang, Indonesia. (a) Shoreline conditions in 1985 and (b) shoreline conditions in 2020 derived from Google Earth time-series imagery, illustrating the inland migration of tidal boundaries and permanent land loss linked to subsidence and flood-driven coastal erosion.

5.4. Ecosystem Degradation (Wetlands, Mangroves, Estuaries)

Subsidence has a multifaceted impact on coastal wetlands. It alters wetland hydrology, increases inundation stress, and decreases ecological function. Mangroves, wetlands, estuaries, and tidal flats are extremely vulnerable, as their existence relies on a fragile balance between elevation and mean sea level. Subsidence increases the depth and duration of tidal inundation, which can drown vegetation and weaken the sediment necessary for biotic stabilization and carbon sequestration (Gracia et al., 2018; Uzarski et al., 2017). Estuarine and mangrove vegetation dies back rapidly when inundation becomes excessive or when salinity becomes a stress factor. Subsiding coastal wetlands reduce their productivity and are eventually converted into open water or less productive mudflats with a reduced capacity for supporting life and sequestering carbon. Subsidence-induced tidal incursions in the Semarang and other deltas on the northern coast of Indonesia are the cause of mangrove erosion, loss of fishery resources, and fragmentation of ecosystems, which can only be restored through rehabilitation and the strategic placement of sediment to restore ecological functions.

Table 3. Summary of ecosystem impacts associated with coastal subsidence

Ecosystem Type	Mechanism of Degradation	Observed/Expected Effects
Mangroves	Prolonged tidal submergence; salinity stress	Root suffocation, vegetation dieback, habitat collapse
Tidal Wetlands	Elevation deficit relative to sea level	Conversion to mudflat or open water; carbon loss
Estuaries	Altered sediment and hydrology balance	Fish nursery loss, reduced productivity, habitat shift
Coastal Lagoons/Marshes	Landward migration blocked by urbanization	Ecological squeeze and fragmentation

5.5. Impacts on Buildings, Ports, and Critical Infrastructure

Subsidence is particularly relevant in coastal cities with large populations because the built environment, including buildings, port activities, transport corridors, and service utilities, relies on the land remaining at a constant elevation. In differential settlement, the soil remains uneven, resulting in surface cracking, drainage failure, and building tilting. Port and industrial complexes are also at risk of sinking deltas. In these cases, quay walls, container, and storage tank yards, and embankments built on reclaimed or compressible sediments will deform under the imposed pressure (Gracia et al., 2018; Uzarski et al., 2017). These system problems can be aggravated by floods. When the land sets lower than the surrounding sea, urban drainage systems lose their slopes, thereby making gravity drainage inoperative, and expensive pumping systems are required. Arterial roads, toll roads, and railways are also built at these lower levels, affecting the movement of people, the transport of goods, and the provision of emergency services. This situation is particularly true for Semarang, where subsidence-related tidal flooding primarily affects commercial areas, port activities, and main road arteries, such as Simpang Lima, in the middle of the city's business and tourist area. Continuous flooding in Semarang affects its commercial and institutional main roads (See Semarang's commercial and institutional main Roads); flooding due to subsidence, flooding causes and hinders human movement, causes damage to properties, reduces the utility of a building, and economically threatens the building. Continuous tidal flooding causes the erosion of the roadway, the destruction of a building's structural system, the acceleration of the corrosion of embedded metal, and the exposure of the roadway to flood, which causes a financial burden to the owner of the roadway to provide maintenance on a regular basis. Subsidence of the quay, including ports and cargo terminals, should be alleviated by elevating and changing the operational activities of the ports and cargo terminals. This indicates that subsidence is not just a geophysical phenomenon but a perpetual infrastructural crisis that requires elevating, adaptive, continuous pumping, and policy modifications to ensure the operational continuity of exposed coastal markets and the livelihood of the affected coastal markets (Gracia et al., 2018; Uzarski et al., 2017). As it is shown in Figure 3, repeated inundation affecting roads, commercial areas, heritage zones, and business districts. These also illustrate disruptions to transportation services, building functionality, and mobility due to persistent land subsidence and inadequate drainage.

Figure 3. Chronic urban flooding as a manifestation of subsidence impacts infrastructure in Semarang, Indonesia.

5.6. Socioeconomic Impacts and Community Vulnerability

Subsidence intensifies socioeconomic vulnerability by destroying socioeconomic stability through the loss of livelihoods and economic burdens, and widening inequalities, especially in coastal and low-income communities. The loss of habitable land, cyclical flooding due to rising tides, and worsening infrastructure increase household costs for maintenance, relocation, access to water, and medical care. Overall, flooding events cause lower productivity for businesses in the subsiding zone, lower property values, higher insurance costs, and sporadic business closures, all of which reduce economic activity in urban areas. In port cities such as Semarang, subsidence will mean losing key economic activities, such as logistics, commercial trade, fishing, and tourism. Flooding limits the poor's access to job markets, hospitals, schools, and markets, thus diminishing their social resilience and upward mobility. Informal settlements nearest to subsidence hotspots are more vulnerable to environmental degradation due to the presence of inadequate structures and drainage systems and poor social protection systems. As numerous studies have indicated, being impacted by space wastage, environmental disturbance, and forced eviction, and leading to the psychological toll and health risks related to stagnant water and to community environmental deterioration, disproportionately impacts the disadvantaged and increases urban inequity (Ni and Wei, 2024, Nygren 2018, Wei et al, 2024). Local authorities are thus compelled to invest disproportionately in pumping, levee strengthening, and relocations, ignoring other development needs, to deal with the subsidence that creates social and civil order vulnerabilities. The regions most at risk absorbing continued hazards and socioeconomic marginalization (Ni and Wei, 2024, Nygren 2018, Wei et al, 2024).

6. Discussion

Given the monitoring, anthropogenic influences and effects, and researched impacts, the phenomenon of coastal subsidence has been articulated not exclusively as a geological process but as a social and environmental complexity that involves human activity, as well as a blend of geomorphological sensitivities and political/legal boundaries. Subsidence has, historically, been a relatively discrete phenomenon. Hydrogeologists focus on aquifer depletion, coastal engineers on structural deformation, and urban planners on the deconstruction of systems. However, the delta cities of Semarang, Jakarta, Bangkok, Ho Chi Minh City, and New Orleans have taught us that subsidence must be viewed as multidisciplinary and multi-phased. As a result, research must be interdisciplinary in order to provide the underpinning balance with respect to policy frameworks. One lesson that can be learned is that the methods implemented in monitoring subsidence define the level of understanding and the responsiveness to the situation. Ground-based tools such as leveling, global navigation satellite systems (GNSS) receivers, and borehole measurements can provide small, precise data; and large deformation satellite measurements such as Persistent Scatter-to-InSAR (Ps-InSAR) and LiDAR are limited in providing clarifying data about the relationship of surface changes to their underlying causes and the social impacts that result therefrom. Consequently, there is a need for the uniform integration of geodetic monitoring, hydrology, infrastructure, and social vulnerability. In the Semarang case studies, with groundwater withdrawal, coastal constructions, and land reclamations, practitioners work outside stable geologic boundaries and yet the consequences, especially the impacts, are limited. Furthermore, protective infrastructures such as sea dikes and retention ponds designed to prevent flooding increase the overtopping weight to hasten the settlement of the reclamation area. This paradox shows the competing objectives for engineers the rapid development of overtopping and the long-term stability of the land and aquifers (Minderhoud et al., 2018; IPCC, 2021). Therefore, for mitigation to be sustainable, it should move beyond structural defenses to include improved placed groundwater control or recharge, nature-based coastal buffer & sediment mitigation, and elevated adaptive measures. Subsidence alters not only the physical environment but also the life-support systems, adaptive resilient infrastructure, ecosystems, and governance frameworks. These cascading effects clearly demonstrate that risk reduction must be multisectoral. The loose ends on a hyper-complex system of interlinked hydrology, spatial planning, engineering, and social systems, when left unaddressed, deepens vulnerabilities, and potentially facilitates the deteriorating consequences of unequal futures and irreversible losses.

7. Conclusion

Delta cities face systemic risks due to the combined natural and anthropogenic causes of subsiding coasts. These include groundwater extraction, urban weight, land reclamation, and coastal activities. Recent studies have shown that most fast-urbanizing coastal regions, subsiding areas, and urbanization contribute to flooding and are far more significant than the growing eustatic sea level. This increases the rate of decline of the natural environment and increases the socioeconomic risks. The north coast of Indonesia, especially Semarang, is groundwater-dependent. This causes urban weight subsidence to create variable subsidence across the landscape, worsening chronic flooding, land loss, saltwater intrusion, and the decline of ecosystems and vulnerable infrastructure. This review shows that coastal subsidence should be viewed more as a coupled human and natural phenomenon, rather than a purely physical process. This work aims to critically synthesize the most recent progress (2021–2024) in GNSS monitoring, InSAR, and other geophysical methods to integrate recent work and provide a unified framework to explain the relationship between detection, causation, and risk from subsidence to coastal environments. This combined conceptual approach demonstrates that the relationships between technologies, engineering, and policies need to be considered together. The findings from this study suggest that management should consider subsidence mitigation to be effective from a management standpoint. This means that subsidence mitigation should focus more on actions, such as (i) developing hybrid monitoring systems that allow early detection and trend analysis by integrating satellite-based InSAR and GNSS, (ii) developing regulatory and contractual grounds under which groundwater abstraction can be controlled, supplemented by artificial recharge and alternative supply-of-water measures, (iii) designing subsidence-informed infrastructure and coastal defense works, where the design of the structure provides for a long-term settlement of the structure, rather than the elevation of the structure remaining static, and (iv) subsidence risk being included as a consideration in the spatial plans and design documents, along with the integration of other measures, such as nature-based solutions to sediment management and restoration of coastal ecosystems. Out of such integrated approaches, the adaptation costs will continue to increase, and so too will the inequities related to the exposure and the resilience of the affected population. Although there have been advancements in methodologies, there continue to be fundamental gaps in research. Future research should focus on integrated hydro-geo-mechanical models, long-term multi-source monitoring databases, as well as social vulnerability and governance in conjunction with subsidence risk assessment. It is critical that these gaps be resolved to facilitate empirically driven policy initiatives and to provide a basis for the development of urban design strategies that are both sustainable and resilient to subsidence in coastal cities.

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Declaration of Generative AI and AI-assisted technologies in the writing process

The author(s) used Chat GPT-3.0 to improve readability and language understanding during the preparation of this work. After utilizing this AI technology, the author(s) meticulously reviewed and amended the content as required to ensure its accuracy and completeness. The author(s) assumes complete accountability for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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The authors of this article did not perform any studies with human participants.

CRediT Author Statement

Rochmad Wahyudi: Conceptualization, Data Curation. **Kismartini:** Formal Analysis, Investigation, Methodology. **Mochamad Arief Budihardjo**: Resources, Software. **Annisa Sila Puspita**: Writing Review and Editing, Formal Analysis, Project Administration, Resources, Supervision. **Marah Ammar**: Project Administration, Resources.

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