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Vertical Land Motion and Coastal Cities: Bridging Global Science and Policy for Resilient Communities

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Abstract

Vertical land motion (VLM) is an underrecognized hazard in susceptible coastal cities, especially those experiencing rapid urbanization. Human-induced VLM often causes elevation loss (subsidence) at rates that exceed, sometimes by an order of magnitude or more, those of climate-driven sea-level rise. Local land subsidence (LLS) also damages infrastructure, disrupts drainage, and alters flood dynamics, yet its broader impacts remain poorly quantified and systematically assessed. This review synthesizes the scientific, technical, and policy dimensions of VLM, with particular focus on LLS, highlighting how natural processes and human activities interact to amplify coastal hazards. We examine the geophysical drivers of VLM, advances in monitoring and modeling, and their integration into hazard assessment frameworks. We consider socioeconomic and infrastructural vulnerabilities of city residents, especially where limited observational capacity and governance gaps intensify risk. VLM acts as both a physical amplifier and a socio-institutional blind spot within coastal adaptation planning, requiring real-time data integration, scenario testing, and inclusive policy development. Finally, we identify key research frontiers—including subsidence mitigation strategies, dynamic VLM projections, and equitable, high-resolution risk assessment—to support more resilient, adaptive, and just coastal futures.

- Tectonics, sediment compaction, groundwater extraction, and urban loading combine to produce complex, nonlinear patterns of vertical land motion that shape local hazard dynamics.
- Local land subsidence, often exceeding the rate of global sea-level rise, is the dominant and least understood driver of coastal flooding and infrastructure risk in many urban regions worldwide.
- Subsidence disproportionately affects marginalized communities, exacerbating social inequities, driving displacement, and eroding cultural heritage, underscoring the need for inclusive, justice-centered adaptation frameworks.
- Closing critical data and policy gaps through coordinated vertical land motion observation, open-access standards, and equitable governance is essential to safeguard coastal populations and sustain long-term urban resilience.

1. INTRODUCTION

1.1. Coastal Cities and the Challenge of Relative Sea-Level Rise

Relative sea-level rise (RSLR), the combined effect of climate-driven sea-level rise (SLR) and vertical land motion (VLM), is a primary driver of hazards in many coastal cities across the globe (Gregory et al. 2019). Here we define a coastal city as any human settlement with a dense population located in coastal areas with an elevation below 10 m and whose infrastructure, economy, or environment is significantly influenced by its interaction with the adjacent ocean, sea, or other large body of saltwater. By this definition, there are ∼3,350 coastal cities worldwide (UN-Habitat 2020).

While SLR, primarily resulting from glacier and ice sheet mass loss and ocean thermal expansion (Solomon et al. 2009), establishes the background hazard trend, RSLR captures the localized coastal conditions and is essential to inform risk assessment and adaptation planning (Nicholls et al. 2021a). Within coastal cities, RSLR has numerous effects, including permanent inundation, amplification of flood risk, saltwater intrusion, and shoreline erosion (Nicholls & Cazenave 2010).

1.2. The Role of Vertical Land Motion

VLM can cause structural damage, impair infrastructure performance, and amplify localized hazards. Local land subsidence (LLS) or negative VLM (positive VLM is called uplift), defined as the gradual or sudden sinking of Earth's surface, amplifies the impacts of SLR and is a widespread phenomenon in susceptible coastal cities, primarily due to human-made activities such as groundwater extraction and land drainage (Erkens et al. 2015).

While sinking coastal cities account for less than 1% of the world's coastal length (Nicholls et al. 2021a), they experience elevated risks due to the high concentration of population and assets. In many coastal cities, LLS rates can exceed global oceanic SLR by up to several orders of magnitude, thereby greatly amplifying local hazards (Erkens et al. 2015, Nicholls et al. 2021a, Shirzaei et al. 2021). LLS is driven by both natural [e.g., tectonics, glacial isostatic adjustment (GIA), sediment compaction] and more importantly anthropogenic (e.g., groundwater withdrawal, oil and gas extraction, farmland drainage) processes, with deformation rates ranging from a few millimeters to several tens of centimeters per year. Except for the VLM caused abruptly by earthquakes, the fastest rates of land subsidence are generally attributed to anthropogenic processes, particularly groundwater pumping (Shirzaei et al. 2021).

1.3. Interacting Climate and Human Drivers

RSLR is exacerbated by other climate factors and, more importantly, by other human interventions across different scales, primarily influencing hazard, exposure, and vulnerability (Nicholls 2018, Nicholls & Ballesteros 2025). Climate-driven processes are expected to accelerate VLM in coastal regions (Huning et al. 2024), for instance, by increasing groundwater demand that drives aquifer compaction, thereby increasing the rate of RSLR, leading to more frequent and prolonged flood hazards throughout the twenty-first century. This impact is often exacerbated in coastal cities, where compound flooding from multiple sources (e.g., fluvial, pluvial, and coastal) interacts with LLS (Moftakhari et al. 2017), affecting densely populated areas and assets.

1.4. Population Growth and Exposure in Coastal Zones

Currently, around 2.15 billion people reside within 100 km of the shore and at elevations of less than 100 m above sea level (Reimann et al. 2023). This means that 9% of the global land area accommodates 23% of the global population (Small & Nicholls 2003). Of these, approximately

900 million people live within the low-elevation coastal zone, areas with elevations less than 10 m above sea level, making them particularly vulnerable to coastal hazards. These numbers are projected to grow to up to 2.9 billion and 1.2 billion, respectively, by 2100, depending on the development pathway considered (Reimann et al. 2023).

The growing concentration of already dense population and assets in coastal regions drives the exposure to RSLR-related hazards, making it an issue of global significance (Barnard et al. 2025, Cigna & Tapete 2021, Hallegatte et al. 2013, Ohenhen & Shirzaei 2022, Ohenhen et al. 2024b). The continued expansion of coastal cities within floodplains and hazard-prone zones reflects a pattern of human settlement that increasingly drives risk (Devitt et al. 2023, Hauer et al. 2020, Rentschler et al. 2023, Shirzaei et al. 2025).

1.5. Knowledge Gaps and Unequal Observational Capacity

Despite RSLR's critical importance, most global coastal hazard assessments rely primarily on SLR projections derived from sparse tide gauge networks and satellite altimetry, often neglecting the contribution of LLS (Fox-Kemper et al. 2021). This omission is especially problematic in low-income and developing regions, where many rapidly subsiding coastal cities lack the necessary observational infrastructure (Avornyo et al. 2023).

Access to high-resolution VLM data remains uneven and fragmented, reflecting broader disparities in data availability and scientific capacity. Coastal communities in the Global South are disproportionately affected due to the scarcity of long-term VLM and SLR observation records, limited technical expertise, lack of open-data policies for noncommercial purposes, and high costs associated with proprietary software and data processing tools (Becker et al. 2024). These challenges contribute to a significant knowledge gap, leaving many communities unaware of their subsidence risk with uncertainty and likely bias in RSLR projections (Kopp et al. 2023; Nicholls et al. 2021a,b).

Democratizing access to VLM tools, investing in capacity building, and supporting open-access data platforms are essential steps toward understanding risk and enhancing resilience. Without these efforts, the risks faced by coastal populations remain underestimated and poorly addressed.

1.6. Scope of This Review

In this review, we synthesize current VLM science and its implications for hazard management in coastal cities. We establish the geophysical basis of VLM and its interaction with human activities; assess monitoring, modeling, and projection capabilities, highlighting advances and gaps; examine direct and indirect impacts of VLM on populations, infrastructure, and ecosystems; evaluate governance and equity challenges, showing how subsidence management often reinforces inequalities; and identify research frontiers where Earth system science, engineering, data integration, and social science can converge to support equitable adaptation. This review goes beyond technical synthesis by framing VLM as a cross-cutting factor that reshapes hazards through both physical processes and socio-institutional pathways.

2. SCIENTIFIC FOUNDATION OF EARTH SYSTEM PROCESSES FOR VERTICAL LAND MOTION

2.1. Defining Vertical Land Motion

VLM is defined as the upward (positive) or downward (negative) movement of Earth's surface relative to a fixed reference, where downward movement is referred to as subsidence and upward movement is called uplift. While some studies (e.g., Törnqvist & Blum 2024) distinguish between

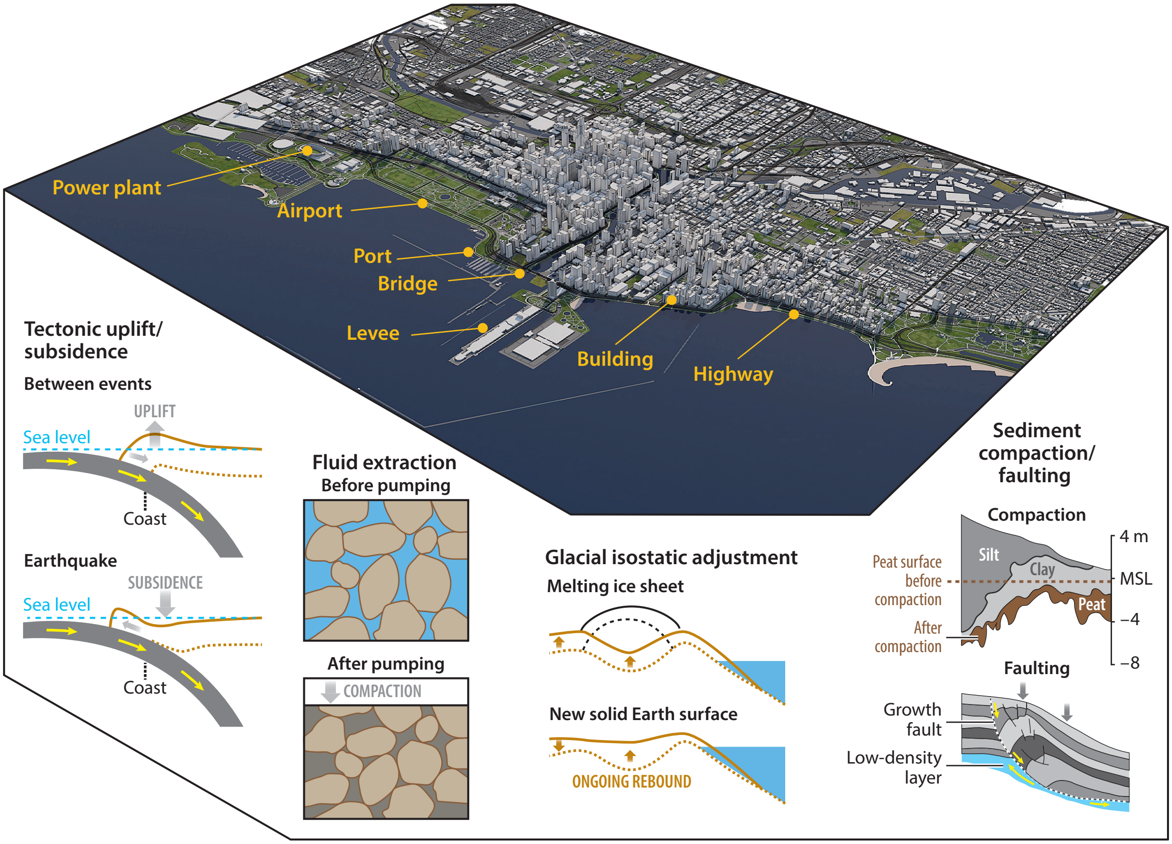

Figure 1

Drivers of VLM affecting coastal city infrastructure. (*Top*) A hypothetical coastal city with critical infrastructure highlighted. (*Bottom*) Various drivers of VLM from left to right, including tectonic processes during earthquake cycles along subduction zones, fluid extraction such as groundwater withdrawal, isostatic response of solid Earth to the decay of late Pleistocene ice sheets, removal or addition of sediment loads, changes in total water storage (noting that added load from ice or sediment produces an equal but opposite response to removal), and natural compaction of sediments and growth faulting in deltaic and coastal plains. Together, these processes influence relative sea-level change and the stability of coastal urban infrastructure. Abbreviations: MSL, mean sea level; VLM, vertical land motion. Figure adapted from Shirzaei et al. (2021).

sediment accretion or erosion, VLM, and surface elevation change, particularly in the context of wetlands and deltaic environments, for simplicity, we define VLM here as any process that results in vertical displacement of the land surface.

2.2. Natural and Anthropogenic Drivers

VLM results from a complex interplay of natural and anthropogenic processes, often operating simultaneously across varying spatial and temporal scales (**Figure 1**). Natural drivers include tectonic deformation, isostatic adjustments, sediment compaction, peat oxidation, soil organic carbon decomposition, and hydrological surface loading (Erkens et al. 2015, Shirzaei et al. 2021). Anthropogenic contributors include groundwater extraction, hydrocarbon and geothermal production, mining, tunneling, urban loading, drainage of soils rich in organic matter, dam impoundment, and engineered subsurface activities such as wastewater injection and underground energy storage (Galloway & Burbey 2011, Shirzaei et al. 2021). Unlike natural drivers that cause uplift and subsidence, anthropogenic contributors overwhelmingly cause subsidence.

2.3. Naturally Induced Subsidence

Tectonic and sometimes volcanic activities drive long-term VLM through crustal shortening, extension, and strike-slip movement (Segall 2010). In subduction zones, interseismic coupling on the subduction interface produces broad uplift and subsidence bands (**Figure 1**). Coseismic slip causes sudden seaward motion and produces uplift and subsidence zones opposite to that of motion during the interseismic period (**Figure 1**). Post-seismic relaxation can persist for decades, causing additional vertical displacement (Hu et al. 2016).

Isostatic adjustments, including glacial, sedimentary, and hydrologic, result from mass redistribution due to ice melt, sediment loading, or sea-level change (Argus et al. 2014, Kuchar et al. 2018, Whitehouse 2018). These processes produce VLM rates ranging from ∼0.1 to 20 mm/year, with regional variation depending on mantle and crust viscosity and surface load history.

Sediment compaction is a long-term process in deltas and basins where overburden load expels pore fluids, leading to consolidation and gradual land lowering (Teatini et al. 2011, Van Asselen et al. 2009). For instance, in the San Francisco Bay area, localized subsidence rates of up to 10 mm/year have been observed over regions underlain by landfill and fine-grained sediments (Shirzaei & Bürgmann 2018).

2.4. Human-Induced Subsidence

Groundwater extraction is the most widespread human-induced cause of land subsidence (Galloway & Burbey 2011). In confined aquifers, sustained pumping reduces pore pressure, increases effective stress, and causes elastic or permanent compaction, sometimes exceeding tens of centimeters per year in extreme cases (Ghobadi-Far et al. 2023, Ojha et al. 2018), with profound implications for flood risk and infrastructure stability (Miller & Shirzaei 2019, Ohenhen et al. 2024a, Sherpa & Shirzaei 2022).

Similarly, hydrocarbon production induces VLM through reservoir compaction and, in some cases, fault reactivation, as seen in Long Beach, California, and the Gulf Coast region (Mayuga & Allen 1969, Morton et al. 2006). Geothermal operations contribute via fluid extraction, reinjection, and thermal contraction (Massonnet et al. 1997). Urban loading imposes vertical stress on soft sediments; examples include San Francisco, New York, Hanoi, and Rome (Dang et al. 2014, Parsons 2021, Parsons et al. 2023). Reclaimed lands and peat soils are particularly prone to settlement (Wang et al. 2024, Zanello et al. 2011).

2.5. Superposition of Multiple Vertical Land Motion Processes

In many regions, the net VLM reflects the superposition of multiple VLM processes. For example, in the Mississippi Delta, groundwater extraction and hydrocarbon production, combined with natural sediment compaction, result in subsidence rates of up to tens of millimeters per year (Frederick et al. 2019). Along the northeast US East Coast, GIA-induced uplift is offset by extensive subsidence due to groundwater pumping, but GIA amplifies RSLR further south, where it induces subsidence (Ohenhen et al. 2024a,b).

2.6. Challenges of Attribution and Monitoring

Accurately attributing VLM sources is crucial for modeling and projecting RSLR (Section 3), managing infrastructure risk (Section 4), and designing targeted mitigation strategies (Sections 7 and 8). Challenges to accurately attribute VLM sources include overlapping temporal signatures, spatial heterogeneity, and nonlinear deformation behaviors. Disentangling these contributions can be aided by geodetic time series decomposition through signal processing techniques, such as wavelet multi-resolution analysis (Shirzaei et al. 2013) and independent component analysis (Li et al. 2025a), as well as integrating various data types (Section 3) and forward multi-modeling of known physical processes (Verbene et al. 2025).

Interdisciplinary collaboration and sustained geodetic monitoring are crucial for resolving VLM processes and ensuring proactive planning in coastal urban environments. Without a comprehensive understanding of the individual and combined VLM drivers, risk mitigation efforts may remain incomplete or misdirected.

3. MONITORING, MODELING, AND PROJECTING VERTICAL LAND MOTION

Monitoring coastal VLM at high spatial and temporal resolution is fundamental for characterizing underlying processes, associated hazards, and informing management.

3.1. Ground-Based Techniques

Ground-based techniques, such as the Global Navigation Satellite System (GNSS), leveling, extensometers, and tide gauges, provide precise point measurements over extended periods. Leveling and tide gauges have provided multi-decadal data with millimeter accuracy, while extensometers and GNSS have been invaluable in groundwater compaction studies, as seen in the Santa Clara Valley and the Houston-Galveston region (Ghobadi-Far et al. 2023, Hammond et al. 2021, Zervas et al. 2013). However, these tools are labor intensive and have spatial limitations.

3.2. Satellite-Based Observations

Satellite-based observations, particularly interferometric synthetic aperture radar (InSAR), have revolutionized subsidence monitoring over the past three decades (Fiaschi et al. 2025, Wu et al. 2022) (**Figure 2**). InSAR provides spatially extensive, accurate, high-resolution maps of ground deformation, independent of daylight or weather conditions.

Complementary to InSAR, GNSS offers 3D displacement vectors and long-term stability, enabling the production of robust deformation models referenced to a global datum (Ohenhen et al. 2024b, Shirzaei & Bürgmann 2018).

3.3. Emerging Technologies

Emerging technologies are further enhancing subsidence monitoring. For instance, distributed fiber optic sensing is increasingly applied to measure aquifer compaction and structural deformation with high precision (Gu et al. 2018). Though their spatial coverage is limited, optical fiber sensors are cost-effective and particularly useful for infrastructure-scale applications.

3.4. Need for Vertical Land Motion Modeling

Modeling VLM is crucial for understanding its causes, predicting its future behavior, and evaluating its impacts on infrastructure, ecosystems, and communities (Nicholls & Shirzaei 2024). However, despite advances in monitoring VLM, modeling individual processes driving coastal cities' VLM remains a challenge due to the variety of natural and anthropogenic processes involved, which often act simultaneously at a given site, hindering the ability to predict future VLM trends (Section 2). For example, in New York City, it is well-known that VLM is primarily influenced by GIA, resulting in a broad, regional subsidence trend of approximately 1–2 mm/year

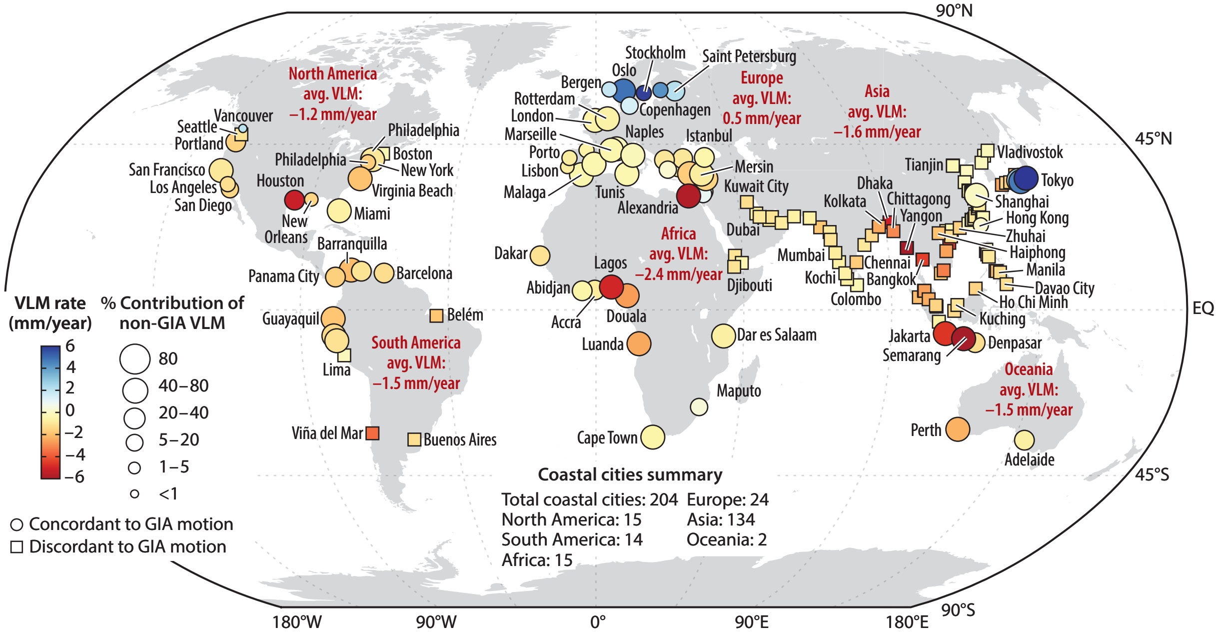

Figure 2

Interferometric synthetic aperture radar (InSAR)-based vertical land motion (VLM) in 204 coastal cities worldwide: 15 cities in North America, 14 in South America, 15 in Africa, 24 in Europe, 134 in Asia, and 2 in Oceania. Each city is color coded by its area-weighted average VLM, derived from multi-temporal processing of the complete Sentinel-1 C-band satellite archive spanning a period smaller than or equal to the interval 2015–2024. Cities where the average VLM sign aligns with the glacial isostatic adjustment (GIA) signal are shown as circles, with circle size indicating the percentage of agreement. Cities with VLM signs opposite to GIA are shown as squares. All results are referenced to the International GNSS (Global Navigation Satellite System) Service 14 (IGS14) reference frame. Data for European cities were obtained from European Ground Motion Service (Costantini et al. 2021).

(Ohenhen et al. 2025). However, certain shoreline areas experience significantly higher subsidence rates of up to 5 mm/year due to factors such as sediment compaction and the loading effect of buildings, while other zones exhibit uplift of up to 3 mm/year, likely associated with fluid injection activities. Accurately modeling the VLM across New York City requires accounting for these overlapping, independent processes, each driven by different physical mechanisms and operating across diverse spatial and temporal scales.

Currently, physics-based and data-driven models offer complementary approaches to understanding and projecting VLM, each with distinct strengths and limitations. Physics-based models rely on governing equations of geodynamics, rock mechanics, and fluid flow, incorporating parameters such as rock viscosity and elasticity, aquifer compressibility, pore pressure, stress history, and boundary conditions to simulate subsurface processes (e.g., Farrell 1972, Galloway & Burbey 2011). These models provide mechanistic insights and are especially useful for process understanding, scenario testing, and projecting VLM. However, they require extensive input data, are computationally intensive, and often suffer from oversimplification and parameter uncertainty.

In contrast, data-driven models, such as machine learning or statistical regression techniques (**Figure 3**), leverage large observational datasets to identify empirical relationships between surface deformation and potential drivers. For instance, Hasan et al. (2023) developed a machine learning framework to investigate the relationship between land subsidence and aquifer dynamics, thereby identifying key drivers of urban subsidence globally.

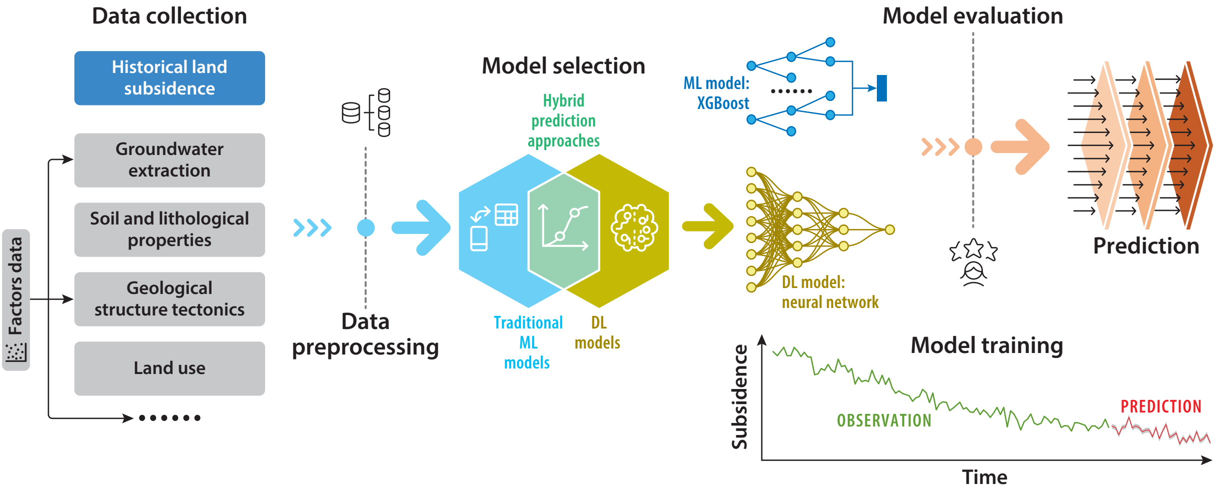

Figure 3

Workflow for predicting future land subsidence in coastal cities using machine learning (ML) approaches. The process begins with data collection, including historical displacement observations [interferometric synthetic aperture radar (InSAR), Global Navigation Satellite System (GNSS)], groundwater extraction, soil and lithological properties, geological structure, and land use. After preprocessing, predictive models are selected from traditional ML approaches [e.g., XGBoost (eXtreme Gradient Boosting)], deep learning (DL) architectures (e.g., neural networks), or hybrid methods, depending on dataset characteristics and process complexity. Models are trained, evaluated, and applied to forecast future subsidence, capturing its spatiotemporal dynamics to support urban risk assessment and resilience planning.

These models excel in capturing complex, nonlinear patterns and are more scalable across large regions. However, they are often opaque, lack physical interpretability, and are limited in their ability to extrapolate beyond the training domain (Zhao et al. 2024). Another challenge is the scarcity of high-quality, labeled datasets for supervised learning, which limits model generalizability across different terrains and sensors (Tiwari & Shirzaei 2024).

Synthetic data and model transferability can partially address issues associated with data-driven models, while explainable artificial intelligence (AI) is emerging to enhance interpretability in critical applications (Zhou et al. 2025). Additionally, hybrid approaches that integrate physics-based and data-driven models are emerging. Utilizing data-driven tools to constrain or inform physics-based models, or vice versa, provides a more robust framework for characterizing and projecting VLM in diverse geological and human-influenced settings (Zhao et al. 2024).

3.5. Toward Integrated Monitoring and Modeling Vertical Land Motion

Advances in monitoring and modeling have revolutionized our understanding of land subsidence, particularly in coastal regions where its interaction with SLR amplifies environmental and infrastructure risks. The integration of high-resolution InSAR, GNSS, Lidar (light detection and ranging), and unmanned aerial vehicle data with hydrological and geomechanical models enables precise detection, quantification, and forecasting of subsidence at multiple scales. Emerging technologies such as NASA and the Indian Space Research Organisation's NISAR satellite and the European Space Agency's (ESA's) ROSE-L mission, together with AI and deep learning and data assimilation frameworks, are ushering in a new era of predictive, data-driven analysis. These innovations not only enhance accuracy and reduce uncertainty in predictions but also facilitate early warning systems and decision-support tools that link physical processes with policy, planning, and management.

4. VERTICAL LAND MOTION AS AN AMPLIFIER OF COASTAL CITY HAZARDS

4.1. Vertical Land Motion and Relative Sea-Level Rise

VLM significantly impacts coastal city resilience by altering RSLR, reshaping socio-ecological systems, and undermining the functional integrity of infrastructure. Subsidence accelerates RSLR, increases the frequency and severity of high-tide and sunny-day flooding, and imposes cumulative economic costs that may exceed those of extreme flood events, despite their often-localized character (Karegar et al. 2017; Moftakhari et al. 2017, 2018).

4.2. Vertical Land Motion and Coastal Ecosystems

Subsidence disrupts wetland hydrology, prolongs inundation, and promotes saltwater intrusion, redox imbalances, and vegetation dieback, contributing to the formation of ghost forests and the loss of natural flood buffers (Kirwan et al. 2025, Miller & Shirzaei 2019, Nienhuis et al. 2020). For coastal cities, this translates into reduced protection from flooding, increased shoreline erosion, and heightened vulnerability of infrastructure and communities to extreme weather events and SLR. Over time, the combined effect accelerates the loss of protective natural barriers, amplifying both the frequency and severity of coastal hazards.

4.3. Impacts on Infrastructure

VLM can compromise coastal infrastructure, including levees, drainage networks, transportation corridors, and water and energy facilities, which are particularly vulnerable to spatially variable deformation (e.g., Fiaschi et al. 2025, Shirzaei et al. 2025).

VLM impacts infrastructure performance through direct structural failure, especially where LLS is accompanied by Earth fissuring, as well as elevation-dependent performance degradation, including gravity-fed drainage failure and cumulative deformation that surpasses operational thresholds. These are compounded by aging infrastructure, poor construction quality, external stressors such as flooding and earthquakes, and insufficient design standards (Shirzaei et al. 2025).

4.4. Uplift and Its Management Challenges

Although uplift can partially offset SLR, it also introduces management challenges. In glacio-isostatic regions (e.g., Gulf of Bothnia), uplift reduces channel depth, increasing dredging demands (Kierulf et al. 2021). Tectonic uplift, as observed along the Peru–Chile Trench, alters river gradients and sediment delivery, thereby increasing flood risk (Pritchard et al. 2009). Earthquakes may cause sudden shoreline shifts, while differential uplift strains infrastructure and elevates maintenance burdens (Hart et al. 2020).

4.5. Nonlinear Vertical Land Motion and Uncertainty in Management

Nonlinear VLM, marked by variable or accelerating deformation, poses particular challenges for resilience planning and management. Unlike steady motion, nonlinear VLM undermines long-term projections and assumptions underlying infrastructure design.

Drivers such as groundwater overdraft, anthropogenic loading, and earthquake cycles can unexpectedly accelerate subsidence, triggering earlier-than-anticipated flooding and infrastructure failure. This undermines levees, utilities, and drainage systems; increases differential settlement; and elevates socioeconomic risk to coastal cities.

Rapid VLM can lead to reclassification of risk zones, higher insurance premiums, restricted financing, and disinvestment, creating a reinforcing socioeconomic feedback loop (Murray et al. 2025, Ohenhen et al. 2024b).

4.6. Case Studies and Current Gaps

Despite increasing awareness, many resilience planning frameworks still overlook the direct geomechanical and operational impacts of VLM. Empirical cases from Jakarta, New Orleans, Houston, and New York City demonstrate the infrastructure instability and flood vulnerability associated with high subsidence rates (Abidin et al. 2011, Buzzanga et al. 2023, Chaussard et al. 2013, Dixon et al. 2006, Parsons et al. 2023).

Current zoning regulations, design codes, and hazard mitigation strategies rarely integrate high-resolution VLM data, and predictive models often fail to capture compound hazards involving flooding, storm surges, and land deformation (Aerts et al. 2014, Erkens et al. 2015).

4.7. Toward Integrated Resilience Planning

Addressing these challenges demands an interdisciplinary approach that couples resilient engineering with continuous geotechnical and geodetic monitoring. InSAR-derived deformation maps, particularly in rapidly urbanizing and data-sparse areas, are critical for characterizing the spatial and temporal complexity of VLM (Buzzanga et al. 2023, Sherpa et al. 2023).

Effective adaptation strategies should incorporate VLM into infrastructure design, permitting, and land-use decisions, supported by investments in resilient materials, modular designs, and updated policy frameworks. Ultimately, long-term resilience requires coordinated technical, financial, and community-based efforts to ensure that coastal cities remain livable and functional amid ongoing and potentially accelerating VLM and climate change (Sections 6 and 7).

5. CLIMATE CHANGE, HYDROLOGY, AND EARTH SYSTEM FEEDBACK

5.1. Climate-Driven Intensification of Vertical Land Motion Drivers

Climate-driven changes in terrestrial water storage, land cover, and land use, coupled with human decision-making, can intensify the drivers of VLM, generate multi-hazards that operate across diverse spatial and temporal scales, and accelerate coastal urban landscape transformation (**Figure 4**). These compounding effects of climate variability and hydrologically induced land deformation complicate long-term management and resilience planning in coastal cities, necessitating integrated, multi-hazard frameworks to address dynamic and nonlinear risks.

5.2. Seasonal and Interannual Variability in Water Storage

Seasonal and interannual variability in terrestrial water storage, resulting from fluctuations in snowpack, soil moisture, and groundwater, directly drives VLM (Argus et al. 2014, Carlson et al. 2022). On seasonal timescales, displacements driven by the loading effect of water mass changes can be as much as tens of millimeters in the vertical direction (e.g., A.M. White et al. 2022).

In Taiwan, GNSS and GRACE (Gravity Recovery and Climate Experiment) data indicate that seasonal changes in water storage, driven by rainfall and infiltration, result in measurable VLM, with groundwater contributions being particularly significant in amplifying these effects (Hsu et al. 2020).

5.3. Groundwater Overdraft and Aquifer Compaction

Overdraft of groundwater, primarily during droughts, induces poro-mechanical deformation of the aquifer system, comprising both elastic and inelastic components, particularly in aquifers

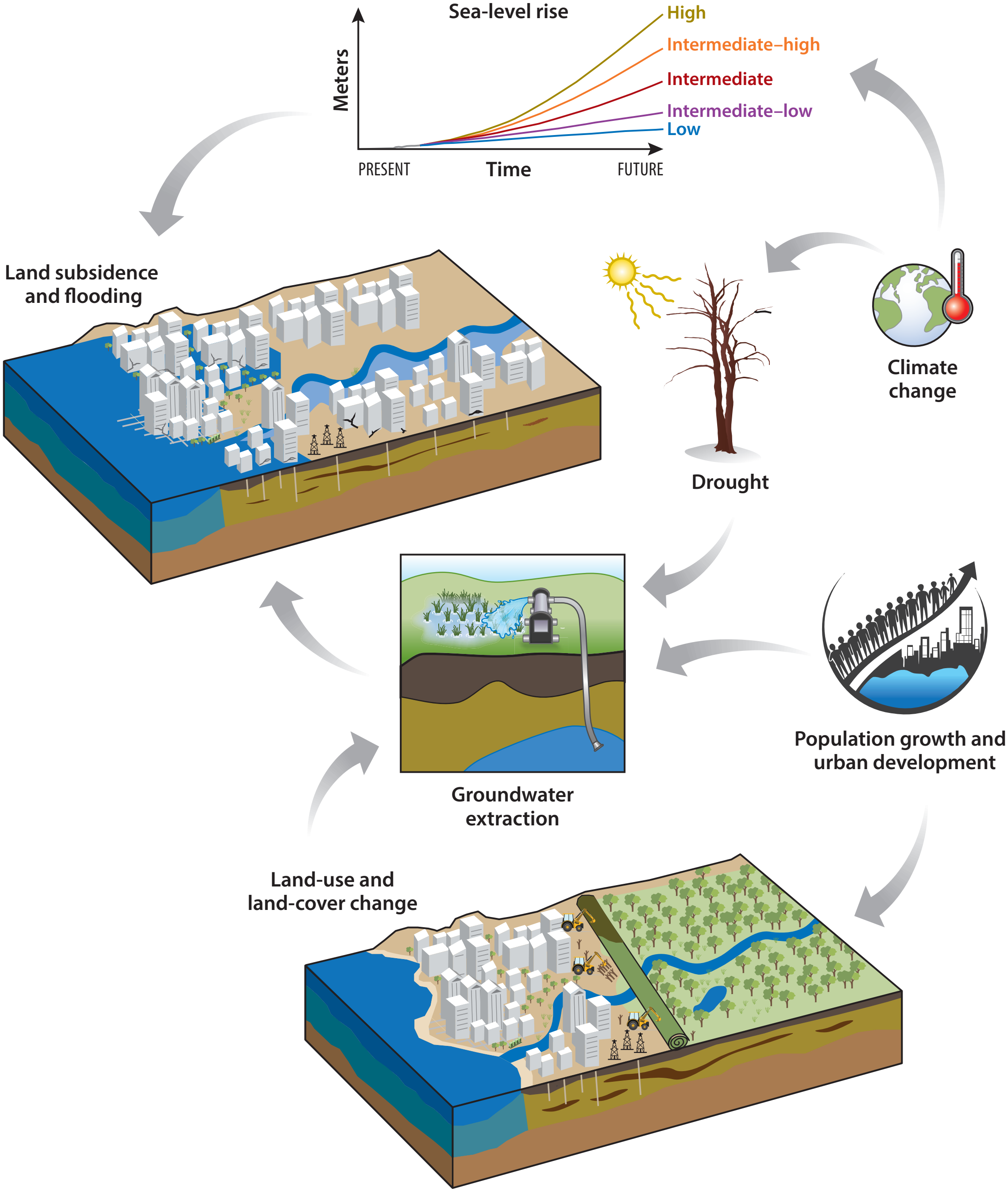

Figure 4

Interactions between climate change, anthropogenic activities, and coastal hazards in urban coastal environments. Climate-driven processes such as sea-level rise, drought, and extreme events combine with human-induced factors, including groundwater extraction, land-use/land-cover change, and rapid urban development, to accelerate land subsidence and flooding. These interconnected drivers amplify hazard exposure, threatening infrastructure, ecosystems, and community resilience in coastal cities.

containing interbedded clay and silt, leading to land surface subsidence (Galloway & Burbey 2011).

In Jakarta, Indonesia, excessive pumping has led to subsidence rates exceeding 200 mm/year, thereby exacerbating flood hazards and increasing the vulnerability of infrastructure (Chaussard et al. 2013). Similarly, in Bangkok, Thailand, intense extraction during the 1970s and 1980s caused subsidence exceeding 1.5 m, with peak rates of 120 mm/year. Although subsequent regulatory interventions reduced extraction and lowered rates to ∼30 mm/year by 2010, residual subsidence persists, where delayed equilibration of pore pressure in thick marine clay leads to continued consolidation despite groundwater recovery in the sandy units (Phien-wej et al. 2006).

5.4. Vertical Land Motion as a Proxy for Hydroclimatic Anomalies

Real-time monitoring of VLM changes in total water storage offers a valuable proxy for detecting hydroclimatic anomalies, such as droughts, floods, or abrupt changes in water resource allocation. These VLM signals offer a crucial tool for water management, particularly in vulnerable regions. However, to ensure accurate interpretation, they must be disentangled from long-term secular trends driven by tectonics or GIA (Section 4). Incorporating delayed aquifer compaction responses into predictive models is crucial for effective land-use and water resource planning in coastal areas.

5.5. Sediment Delivery and Deltaic Subsidence

In addition to local subsidence driven by groundwater extraction, many coastal cities located within or near deltaic systems are affected by upstream water management practices. The construction of large dams and reservoirs significantly reduces downstream sediment delivery, especially to river deltas, where numerous megacities such as New Orleans (Mississippi Delta) (Törnqvist et al. 2008), Venice (Po Delta) (Teatini et al. 2011), and Ho Chi Minh City (Mekong Delta) (Zoccarato et al. 2018) are situated. This sediment starvation limits natural vertical accretion, allowing auto-compaction of deltaic sediments and anthropogenic loading to dominate the VLM signal. Syvitski et al. (2009) reported that more than 70% of the world's major deltas experienced a more than 30% decline in sediment supply during the twentieth century, with reductions exceeding 90% in basins such as the Colorado, Krishna, and Nile, and further declines are expected over the twenty-first century (Dunn et al. 2019).

5.6. Divergent Anthropogenic Influences

Streamflow alterations driven by droughts, monsoon variability, and increased surface water withdrawals compound sediment deficits, thereby accelerating RSLR and heightening risks for densely populated coastal cities situated on delta plains. In contrast, certain anthropogenic disturbances, such as deforestation and land-use change, can increase sediment flux and promote net land gain in select deltas (Nienhuis et al. 2020), temporarily offsetting submergence.

These divergent effects underscore the need for integrated catchment-to-coast sediment management strategies that balance upstream water use and downstream sediment delivery to stabilize land elevations, mitigate subsidence, and enhance the long-term resilience of deltaic coastal cities.

6. SOCIOECONOMIC RISK AND EQUITY

6.1. Disproportionate Burdens of Vertical Land Motion–Related Hazards

VLM-related hazards and inundation caused by RSLR enhance the vulnerability of coastal cities, both directly through their physical impact and indirectly through their disproportionate burden on communities with the fewest resources to adapt, as well as through ecological and cultural impacts and a cycle of risk accumulation that accounts for intergenerational impacts (Minderhoud et al. 2017, Ohenhen et al. 2024b, Schmitt et al. 2021).

While the direct physical impacts of coastal land subsidence and RSLR are increasingly quantified, the social, economic, and ecological costs associated with subsidence exposure and the disproportionate burdens it places on larger coastal communities, and specifically marginalized ones, remain underexplored. Integrating maps of VLM hazards with social vulnerability indicators, such as age, income, education, poverty, infrastructure accessibility, and other place-based attributes like population density, and patterns of historical disinvestment to create spatially explicit, VLM-informed risk maps would enable the identification of risk zones that are underrepresented in conventional hazard assessments (Herrera-García et al. 2021).

6.2. Property, Infrastructure, and Displacement

On the US East Coast, more than 5 million properties and more than 50% of the infrastructure in cities such as New York, Norfolk, and Baltimore are exposed to subsidence rates of 1–2 mm/year (Ohenhen et al. 2023). By 2050, RSLR may endanger up to 171,000 properties across 32 coastal US cities (Hanson et al. 2011, Ohenhen et al. 2024b).

This exposure can contribute to reduced investment (Willemsen et al. 2020), billions in property value loss, and population displacement that destabilizes local economies. Driven by RSLR, some communities, such as Isle de Jean Charles in Louisiana, are almost entirely resettled (Simms 2021), while others, like Newtok in Alaska, are experiencing partial relocation (Ristroph 2021). Indonesia is relocating its capital from Jakarta to Nusantara, primarily due to severe land subsidence in Jakarta, caused by excessive and unregulated groundwater extraction and soil compaction from building weight (Silver 2025).

Urban areas are also experiencing flood-driven changes in population mobility, albeit more gradually and spontaneously, closely linked to the availability of financial mechanisms and programs supporting the move. Globally, 15 of the top 20 coastal cities exposed to coastal flood risk, identified by Hallegatte et al. (2013), are also susceptible to subsidence, which exacerbates the impacts on populated areas and mobility patterns.

6.3. Unequal Exposure and Social Vulnerability

Like most hazards, across coastal cities, land subsidence is not an equal-opportunity hazard, often disproportionately impacting socially vulnerable and marginalized populations. For example, in Los Angeles, non-Hispanic Black and disadvantaged communities face heightened flood exposure within the 100-year floodplain, many of which are also subsiding (Lee & Shirzaei 2023), compounding preexisting socioeconomic inequities (Sanders et al. 2023). Similarly, in New Orleans and Port Arthur, properties in subsiding neighborhoods have median values 18–34% below city averages, reflecting historic disinvestment and limiting residents' ability to recover from recurrent flooding (Ohenhen et al. 2024b). Vulnerable coastal populations often lack access to flood insurance and political representation, which reduces their ability to utilize mitigation resources and reinforces cycles of vulnerability and displacement (Devi & Moisio 2024).

6.4. Ecological and Ecosystem Risks

In coastal cities where land subsidence exacerbates the risks of inundation, shoreline retreat, and ecological degradation, hazards extend far beyond conventional economic loss metrics and are often insufficiently captured in most exposure and risk assessments.

Subsidence-driven flooding submerges wetlands, degrades habitats, and reduces biodiversity, thereby eroding critical ecosystem services, including storm buffering, carbon storage, and water purification (Danielsen et al. 2005, Jankowski et al. 2017, Temmink et al. 2022). This loss is particularly consequential for urban-adjacent coastal ecosystems, which already face intense pressure from land development, altered hydrology, and pollution.

As these ecosystems degrade, nearby coastal cities lose vital natural defenses, increasing their exposure to flooding, storm surge, and water quality deterioration. Despite documented impacts on at least 113 ecological sites globally, environmental consequences of subsidence remain underreported in terms of infrastructure damage or economic costs, reflecting a major blind spot in current resilience frameworks (Dinar et al. 2021).

In Indonesia, rapid coastal subsidence near urban areas is driving shoreline erosion and displacing communities, underscoring the urgent need for integrated planning that accounts for both human and ecological vulnerability (van Bijsterveldt et al. 2023). As subsiding coastal cities continue to expand, failing to incorporate ecosystem risks will undermine long-term sustainability and adaptive capacity.

6.5. Spatial and Intergenerational Injustice

Subsidence also exacerbates spatial injustice, where high-income districts drive VLM in adjacent low-income communities through excessive groundwater extraction, as observed in Jakarta and Manila. On the US East Coast, uniform hazard assessments can obscure localized risks in marginalized areas with degrading levee systems (Ohenhen et al. 2023).

Beyond spatial disparity, subsidence in coastal and deltaic regions generates intergenerational inequity, where current developments impact the prospects of future generations. In Vietnam's Mekong Delta, unsustainable groundwater extraction has intensified subsidence (up to 75%), driving saltwater intrusion, crop failure, and a 12–18% decline in soil fertility per decade, trapping farmers in a feedback loop of land degradation and economic decline (Minderhoud et al. 2017, Schmitt et al. 2021).

These impacts extend beyond rural agriculture, undermining urban water security, infrastructure stability, and livelihoods in coastal cities, which depend on the same subsiding deltaic systems. As such, the legacy of unsustainable resource use in these regions manifests as both an environmental and social debt, disproportionately borne by future urban and rural populations alike. These dynamics underscore the necessity of equitable adaptation strategies that incorporate social vulnerability and long-term impacts into land-use planning to prevent perpetuating an elevation divide (Handwerger et al. 2021).

6.6. Cultural Heritage and Community Identity

Subsidence not only threatens infrastructure and ecosystems but also erodes cultural heritage and community identity. In Aquileia, Italy, differential subsidence has compromised the structural stability of the UNESCO-listed Patriarchal Basilica of Aquileia, a key symbol of early Christian heritage (Alfarè et al. 2014). Venice stands as a classic and globally recognized example, where centuries of subsidence, exacerbated by groundwater extraction and SLR, have imperiled architectural treasures, necessitating costly interventions such as the MOSE (Modulo Sperimentale Elettromeccanico) flood barrier system (Lionello et al. 2021, Umgiesser 2020).

Beyond physical structures, subsidence-driven displacement in coastal and deltaic regions reshapes social landscapes. In Ghana's Volta Delta, where expanding coastal towns and peri-urban settlements face increasing exposure to flooding and subsidence, resettlement has reduced flood exposure but disrupted community cohesion, sense of place, and cultural continuity (Abu et al. 2024). Similar patterns are emerging in other coastal cities built on vulnerable delta plains, where relocation or adaptation policies can unintentionally fracture long-established social networks and exacerbate inequality, underscoring the need for socially inclusive coastal resilience planning.

These cases underscore the urgent need for coastal hazard management frameworks to expand beyond economic and physical metrics, integrating ecological and cultural dimensions of risk and recognizing the profound, inequitable impacts on heritage, identity, and community well-being.

6.7. Insurance, Liability, and Governance

The impacts of climate change are becoming increasingly evident in the insurance sector, with more insurers withdrawing coverage for high-risk areas, particularly those vulnerable to wildfires and floods (Liao et al. 2024). As subsidence amplifies floods and causes additional hazards, complex legal questions arise regarding liability, compensation, and coverage. Commercial liability policies are increasingly incorporating subsidence exclusions, yet courts remain divided on whether these exclusions apply to human-induced or natural causes.

Key questions emerge: Will insurers continue underwriting properties in subsiding zones? Can municipalities be held liable for infrastructure failures linked to unmanaged land motion risks? These issues are growing in importance for urban planning, litigation, and fiscal policy, especially as variable and nonlinear VLM (Section 4) introduces uncertainty that complicates risk assessment and liability determination (Govorcin et al. 2025).

7. GOVERNANCE, POLICY, AND ADAPTATION STRATEGIES

Subsidence presents a polycentric governance challenge, characterized by complex causality, fragmented jurisdictional responses, and contextualized impacts, which may be misaligned with the political goals and policy agendas rooted in the history of the place and local mentality (Candela & Koster 2022, Siriwardane-de Zoysa et al. 2021).

7.1. Subsidence Governance Through National-Scale Systems

Effective subsidence governance relies on robust monitoring and modeling systems (Section 3) that can capture where, how fast, and why VLM occurs, with sufficient spatial and temporal resolution to inform timely decisions (Erkens & Stouthamer 2020, Nicholls & Shirzaei 2024).

Over the past two decades, several subsidence-prone nations have institutionalized VLM monitoring as part of their national geospatial infrastructure, establishing a critical empirical foundation for risk-informed governance (e.g., Thiéblemont et al. 2024). For instance, Japan's Geospatial Information Authority operates a nationwide program that delivers quarterly updates on ground deformation, directly supporting urban planning and infrastructure maintenance in major coastal cities such as Tokyo and Osaka (Geospatial Information Authority of Japan 2025). Italy's special plan for environmental remote sensing maintains a dense InSAR-based monitoring network across all major coastal cities, with established protocols for integrating geodetic data into regional spatial planning frameworks (European Global Ocean Observing System 2025). China has also adopted a national-scale approach to subsidence monitoring and mitigation, combining satellite-based observations with ambitious policy aspirations aimed at integrating VLM into water resource management, land use regulation, and urban planning (Ao et al. 2024, Fang et al. 2022). These systems not only enable early detection and hazard zoning but also provide the scientific basis for designing and enforcing evidence-based policy, ultimately enhancing the resilience of both infrastructure and communities.

7.2. Surveillance Versus Governance: Divergent Pathways

Monitoring infrastructure alone is not enough to address land subsidence; its effectiveness ultimately depends on the institutional capacity and sustained political will to translate early warnings into preventive action.

The divergent governance trajectories of Jakarta, Tokyo, and the Netherlands illustrate that subsidence is not an inherently unmanageable process, but one that demands timely, coordinated policy responses supported by scientific insight (Bucx et al. 2015, Erkens & Stouthamer 2020). Jakarta exemplifies the consequences of a persistent gap between surveillance and governance. Subsidence has been documented since 1926, when Dutch surveyors first recorded vertical displacement through leveling surveys (Abidin et al. 2001). Although a network of leveling benchmarks and GNSS stations was later established, policy responses remained fragmented and reactive, focused on visible impacts rather than root causes such as unregulated groundwater extraction (Cao et al. 2021, Marfai et al. 2015). This failure to act on decades of knowledge contributed to the extreme decision to relocate the administrative capital to another island (Hsiao 2023). By contrast, Tokyo, once among the world's fastest-subsiding cities, successfully halted subsidence by the 1970s through stringent groundwater regulations, investment in alternative water supplies, and integration of VLM data into urban planning (Bucx et al. 2015, Cao et al. 2021). The Netherlands offers another leading example, where subsidence projections are embedded into national infrastructure planning and water management, notably in the Delta Works and polder systems, demonstrating anticipatory governance at scale (Bucx et al. 2015).

These contrasting examples underscore a critical lesson: Even with long-standing knowledge and advanced monitoring, subsidence control hinges on the ability to proactively incorporate scientific signals into institutional frameworks. Effective governance requires early intervention thresholds, cross-sectoral coordination, and a long-term commitment, encompassing not only technical capacity but also the political resolve to act decisively in the face of emerging risks.

7.3. Dual Approach: Mitigation and Adaptation

Figure 5 proposes a framework for addressing land subsidence in coastal cities comprising a dual approach: mitigation of underlying subsidence drivers and adaptation to reduce exposure to resulting hazards (Erkens et al. 2015, Ohenhen et al. 2025).

Unlike externally forced coastal hazards, subsidence is often rooted in local anthropogenic activities (Section 2), demanding stronger local governance and cross-sectoral coordination (Erkens & Stouthamer 2020). Long-term coastal resilience thus depends on integrating VLM monitoring and management across traditionally siloed domains, including land use planning, water resource management, infrastructure design, and climate adaptation.

However, protective measures such as levees, storm surge barriers, and tidal gates are often planned with insufficient consideration of localized, variable, and sometimes accelerating subsidence (Duarte et al. 2013, Ohenhen et al. 2024b, Shirzaei et al. 2025). This oversight can result in premature infrastructure failure, financial losses, and increased vulnerability, outcomes that could be avoided through governance models that incorporate dynamic, site-specific VLM data into all stages of policy, investment, and regulatory decision-making (Dixon et al. 2006, Duarte et al. 2013, Fang et al. 2022, Ohenhen et al. 2024b, Takagi et al. 2017).

7.4. Integrated Strategies and Co-Benefits

Integrated strategies that incorporate VLM offer multiple co-benefits across ecological, social, and economic systems, but only if designed with accurate elevation data and a nuanced understanding of local dynamics and coproduced with stakeholders.

For instance, wetland restoration projects can simultaneously enhance biodiversity, improve water quality, and provide natural buffers against storm surges (Duarte et al. 2013, Kirwan & Megonigal 2013, Narayan et al. 2017). However, their long-term success depends on monitoring spatiotemporal changes in land elevation; in subsiding regions, failure to account for VLM may

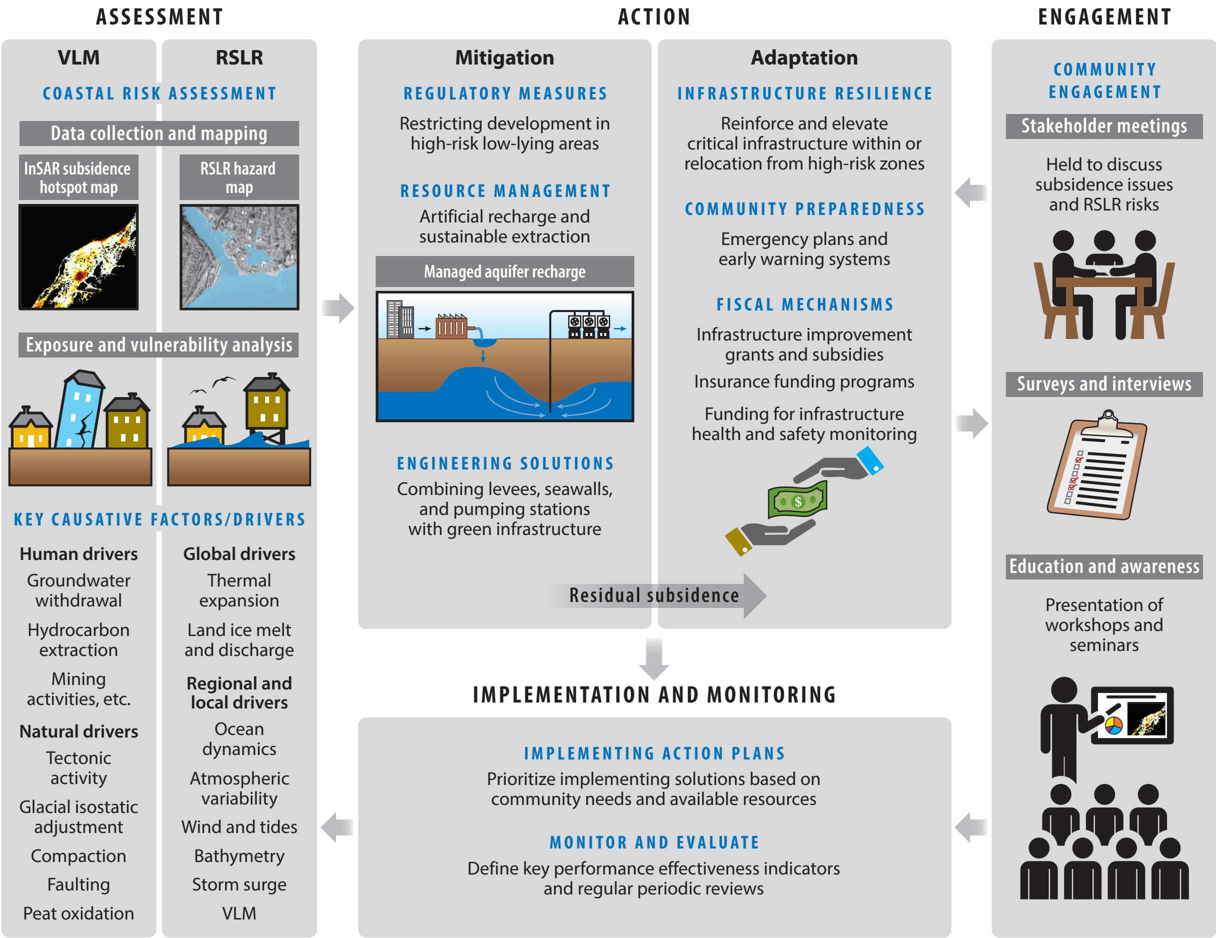

Figure 5

Framework for addressing RSLR and land subsidence in coastal cities. The approach integrates four steps: Assessment: mapping VLM and RSLR, identifying exposure, vulnerability, and key drivers. Action: implementing mitigation measures (e.g., regulatory, resource management, and engineering solutions) and adaptation strategies (e.g., infrastructure resilience, community preparedness, fiscal mechanisms). Engagement: facilitating stakeholder participation, community education, and public awareness. Implementation and monitoring: executing prioritized action plans and tracking performance through continuous evaluation. The framework emphasizes coordinated, inclusive, and adaptive management to reduce hazard exposure and enhance resilience in urban coastal environments. Abbreviations: InSAR, interferometric synthetic aperture radar; RSLR, relative sea-level rise; VLM, vertical land motion. Figure adapted from Ohenhen et al. (2025).

result in ecosystem degradation or permanent inundation (Ohenhen et al. 2023, Watson et al. 2017, E.E. White et al. 2022, Zoccarato et al. 2019).

Subsidence mitigation efforts, such as managed aquifer recharge (MAR), are increasingly employed to counteract groundwater-induced subsidence (Erkens et al. 2015, Parker et al. 2021), while sediment diversion projects in deltaic regions aim to offset elevation loss through targeted land reclamation (Elsey-Quirk et al. 2019).

However, these interventions can generate unintended social consequences. Wetland restoration, for example, has been linked to green gentrification, raising property values and displacing vulnerable populations in areas ranging from the San Francisco Bay to Brooklyn's Gowanus Canal and cities across Africa (Asante et al. 2025, Gould & Lewis 2016, Miller 2016, National Oceanic and Atmospheric Administration 2023). Similarly, MAR programs often prioritize agricultural or industrial zones, potentially neglecting residential communities at equal or greater risk.

7.5. Adaptation and Community Thresholds

To ensure long-term resilience, governance frameworks must integrate geophysical, ecological, and social dimensions, aligning mitigation and adaptation strategies with equity, inclusivity, and place-based needs. This becomes especially important in areas experiencing severe or irreversible subsidence. The viability of adaptation hinges on both the rate and spatial extent of subsidence. When VLM exceeds some threshold (e.g., ∼10–15 mm/year) over extended areas of a coastal city, the financial, technical, and social costs of adaptation may become unsustainable (Abidin et al. 2011, Erkens et al. 2015, Ohenhen et al. 2025). In such cases, adaptive strategies such as elevating infrastructure or installing tidal barriers may only delay, rather than prevent, the eventual need for planned relocation.

In areas experiencing advanced or accelerating subsidence, particularly where it intersects with other hazards, governments must move beyond reactive measures and transition toward proactive adaptation and retreat planning. This includes, for instance, implementing relocation incentives, property buyouts, infrastructure reinforcement, and equitable coastal mobility frameworks designed to protect vulnerable populations. Where subsidence is modest, localized, or potentially reversible, policy should prioritize preventive measures, such as groundwater regulation, land-use planning, and early warning systems.

Despite the urgency, the VLM literature offers limited operational guidance on where the tipping point lies between the feasibility of protect versus retreat. Recent studies emphasize the need for site-specific decision thresholds that incorporate high-resolution deformation data, infrastructure sensitivity, and social vulnerability to inform context-appropriate responses (Buzzanga et al. 2025, Ohenhen et al. 2024b).

7.6. Transboundary and Externality Challenges

Effective subsidence governance must also avoid the balloon effect, where localized mitigation efforts inadvertently transfer the problem to adjacent or less regulated areas. For instance, groundwater extraction limits in one jurisdiction may lead to increased pumping in neighboring regions that lack similar controls. Likewise, restricting development in high-subsidence zones can increase pressure on adjacent areas, some of which have existing vulnerabilities.

Many subsiding systems, such as coastal aquifers and deltas (e.g., the Ganges-Brahmaputra-Meghna and the Rio Grande), span political boundaries, necessitating transboundary coordination. Upstream dams alter sediment delivery, amplifying deltaic subsidence downstream, while transboundary groundwater extraction can drive uneven VLM patterns.

Policy must anticipate externalities and evaluate the broader impacts of interventions (e.g., levees, drainage, or pumping bans) on sediment fluxes, groundwater levels, and land motion beyond local scales.

8. RESEARCH FRONTIERS AND KNOWLEDGE GAPS

8.1. The Digital Twin–Decision Theater Concept for Coastal Cities

To provide real-time monitoring, enable predictive capabilities, improve decision-making, enhance operational efficiency, and support sustainability efforts by creating a virtual replica of natural and built systems, we propose a combined digital twin–decision theater framework tailored for coastal cities (**Figure 6**).

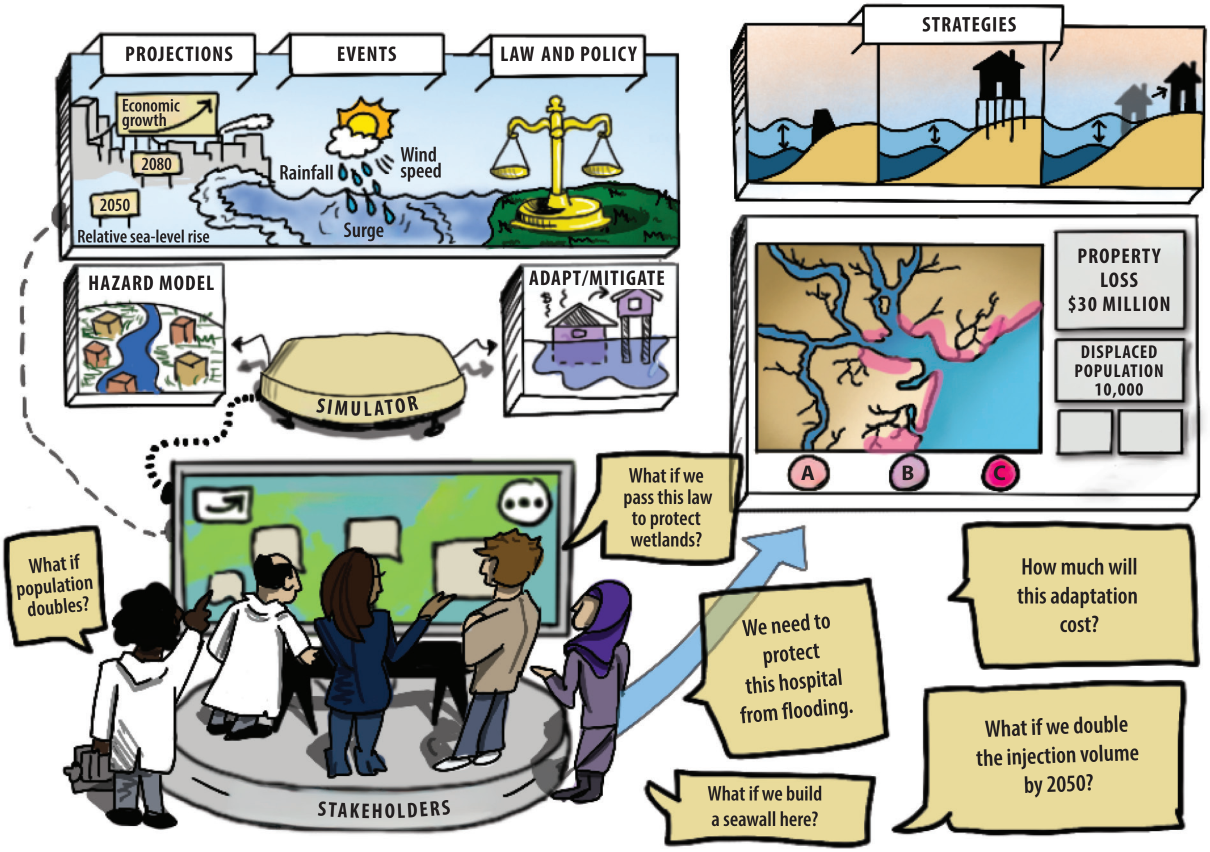

Figure 6

Illustration of a decision theater framework for coastal flood risk management. Projections of relative sea-level rise, economic growth, and extreme events are integrated with hazard models, adaptation and mitigation strategies, and policy considerations. A simulator interface enables stakeholders to explore what-if scenarios, such as population growth, infrastructure protection, and legal measures, assessing trade-offs in cost, property loss, and displacement. This interactive platform supports collaborative, evidence-based decision-making for coastal resilience planning. Modified from FloodAdapt Concept, Deltares.

A digital twin is a dynamic, continuously updated, data-driven model of the urban environment (Jones et al. 2020, Piras et al. 2024) that integrates VLM observations with climate projections, geological data, socioeconomic indicators, infrastructure inventories, and policy parameters. The purpose of digital twins is to monitor, forecast, and assess feedback between humans and built and natural environments (Hazeleger et al. 2024).

For coastal cities, this capability enables simulation of scenarios ranging from gradual RSLR amplification to rapid infrastructure destabilization in subsiding neighborhoods. The digital twin provides a powerful analytical environment for identifying risk hotspots, quantifying trade-offs among adaptation pathways, and stress-testing long-term planning strategies under different socioeconomic and climate scenarios.

8.2. Role of the Decision Theater

When embedded in a decision theater (Edsall & Larson 2006), an immersive and participatory environment that brings together city officials, planners, engineers, community leaders, and stakeholders, the digital twin becomes an interactive decision-support tool. Stakeholders can visualize the otherwise slow-onset nature of subsidence in an intuitive, spatially explicit format; explore the implications of delayed action; and evaluate the effectiveness of adaptation measures such as groundwater management, infrastructure reinforcement, zoning changes, or strategic retreat.

The decision theater setting enables real-time scenario testing, facilitating diverse groups to reach consensus on technically robust, socially just, and politically feasible strategies. This integrated approach is especially valuable for coastal cities where decision timelines are short, budgets are constrained, and multiple hazards interact. By linking advanced modeling capabilities with transparent, collaborative decision-making, the digital twin–decision theater framework can transform fragmented knowledge into coordinated, actionable adaptation plans.

It fosters cross-sector collaboration, supports adaptive governance through continuous data assimilation, and builds public trust by making complex risks tangible. Ultimately, this approach empowers coastal cities to shift from reactive to proactive resilience planning, ensuring long-term sustainability in the face of ongoing land subsidence and SLR.

8.3. Key Requirements for Digital Twin–Decision Theater Implementation

Implementing a digital twin–decision theater for coastal cities requires enhanced data availability, sharing, and monitoring; improved integration and technical interoperability; strengthened modeling capacities; and the removal of economic and institutional barriers. It also demands addressing governance and policy fragmentation, as well as developing advanced decision-support and stakeholder engagement tools.

8.4. Data and Monitoring Gaps

Unlike the extensively studied climate-driven SLR, observations and models of VLM specific to coastal cities, as well as their integration into adaptation and resilience planning, remain scarce. The VLM data available to RSLR scenarios are considered to have low to medium certainty and are a priority for substantial improvement (Slangen et al. 2023). Many urbanized coastal zones, particularly in the Global South, small island states, deltaic megacities, and Arctic settlements, still lack adequate VLM monitoring. These blind spots often coincide with areas of high exposure, dense populations, and limited adaptive capacity. Addressing this gap requires globally coordinated efforts in data collection, standardization, and sharing, coupled with stronger integration of satellite and ground-based observations into urban planning and policy frameworks.

While institutional collaboration on subsidence monitoring is improving, the integration of subsidence monitoring into city-level risk assessments remains uneven. Initiatives such as UNESCO's Land Subsidence International Initiative (LaSII), the International Panel on Land Subsidence (Minderhoud et al. 2024), ESA's Copernicus European Ground Motion Service (EGMS) (Costantini et al. 2021), and NASA's Observational Products for End-Users from Remote Sensing Analysis (Buzzanga et al. 2023) provide open-access displacement datasets.

However, challenges persist in harmonizing data, aligning spatial resolutions with urban-scale needs, and developing technical pipelines to feed VLM products into flood models, zoning ordinances, and infrastructure risk analyses (Govorcin et al. 2025, Pedretti et al. 2024). For example, despite EGMS's high-resolution ground motion data, only a few municipal storm surge or flood models incorporate VLM due to gaps in interdisciplinary coordination and end-user training. An equitable open science framework for urban coastal VLM data, ensuring fair funding, standardized formats, comprehensive metadata, and inclusive participation, is essential to make these datasets actionable for city planners and engineers.

8.5. Model Integration and Coupled Systems

The integration of VLM into coupled hydrodynamic, climate, and land-use models remains an underdeveloped yet urgent frontier for coastal cities. While recent studies have incorporated VLM into SLR and storm surge projections (Govorcin et al. 2025; Kearse et al. 2025; Minderhoud et al. 2025; Ohenhen et al. 2023, 2024b; Wang et al. 2024), most still rely on downsampled data, oversimplified assumptions, and limited feedback between geophysical and human-driven factors that fail to capture the block-by-block variations critical for urban adaptation. This is especially problematic for deltaic megacities and low-lying urban districts, where subsidence interacts with SLR, storm tides, sediment starvation, and rapid development. VLM in these environments can compromise drainage systems, overwhelm flood defenses, and accelerate the loss of wetlands and mangroves, stripping cities of their natural buffers. Advancing toward dynamic, high-resolution modeling platforms that integrate geodetic, hydrological, atmospheric, and socioeconomic data will be essential for supporting long-term, locally tailored adaptation strategies.

8.6. Groundwater–Vertical Land Motion Feedbacks

One critical yet underexplored consequence of sustained subsidence is the permanent loss of aquifer storage capacity due to irreversible compaction of unconsolidated sediments (Hasan et al. 2023, Li et al. 2025b, Ojha et al. 2018). This process reduces pore space and aquifer resilience, particularly in complex coastal and alluvial systems where sediment heterogeneity makes porosity changes difficult to quantify. Current groundwater models supporting coastal cities often overlook the feedback between VLM and hydraulic properties, risking underestimation of future water-supply vulnerability and overestimation of post-recharge recovery. Furthermore, the cumulative impact of episodic subsidence during droughts or intensive pumping remains poorly understood, highlighting the need for integrated modeling frameworks that capture these nonlinear, spatially variable dynamics.

8.7. Projecting Urban Vertical Land Motion and Scenarios

Accurate VLM projections are crucial for developing effective coastal city adaptation and mitigation strategies that mitigate VLM impacts on infrastructure, ecosystems, and communities, particularly in vulnerable coastal regions. Multi-objective models that integrate geophysical drivers, urban land-use patterns, and climate forcing, calibrated with contemporary observations, are needed to forecast future city-specific hazards.

Recently, shared socioeconomic pathways (SSPs) have been developed through iterative community efforts to examine the temporal evolution of global society, economy, and demography over the next century. The SSPs examine how the world evolves under five different scenarios, considering both no climate policy and a range of climate change mitigation actions, describing multiple baseline worlds that depend on economic and population growth, as well as technological advances. Accordingly, SSP-based databases are created that document quantitative projections of various factors, such as population, economic development, land use, and energy use, in relation to SLR (Fox-Kemper et al. 2021). To create future estimates of urban inundation and flooding hazards, in addition to scenario-based projections of SLR, SSP-based projections of urban VLM are required. The SSPs offer an opportunity to integrate city-scale VLM projections into global climate risk assessments, as urban VLM rates will be shaped by evolving human systems: groundwater extraction, infrastructure loads, land-cover changes, and policy responses. These interactions operate at spatial and temporal scales finer than those typically captured in global SLR scenarios, making city-specific modeling indispensable.

8.8. Economic and Legal Dimensions

The economic impacts of land subsidence on coastal cities remain underexamined, mainly due to the absence of standardized, reliable datasets that quantify the costs associated with VLM and RSLR (Kok & Costa 2021). Urban coastal zones face unique economic risks, as subsidence not only drives higher flood protection and infrastructure maintenance costs but also erodes property values, disrupts economic activity, and undermines investor confidence. Standard valuation approaches, such as value transfer, hedonic pricing, and restoration cost estimates, are constrained by inconsistent or incomplete city-level data (Kok & Costa 2021). A coordinated global framework, potentially led by UNESCO's LaSII or the World Bank's Global Facility for Disaster Reduction and Recovery, could harmonize regional datasets, improving consistency in cost modeling for VLM and RSLR in urban contexts.

Most coastal nations lack transparent, accessible systems to track subsidence impacts. This gap impedes integrated risk assessments and cost–benefit analyses for urban adaptation. Legal uncertainties over subsurface ownership and liability, particularly where groundwater extraction contributes to subsidence, further discourage transparent reporting. To address these challenges, national and municipal governments should incentivize coastal cities, utilities, and infrastructure agencies to systematically track and report subsidence-related repair, replacement, and resilience costs.

8.9. Infrastructure Vulnerability and Risk Assessment

In coastal cities, assessing the risk of infrastructure damage due to VLM is complicated by the uneven and spatially variable nature of subsidence. Urban infrastructure, ranging from flood defenses and seawalls to transportation networks and utilities, responds differently to localized vertical motions depending on soil conditions, construction materials, and design standards. Current assessment methods, such as distortion angle metrics, are widely used to classify the risk of building damage (Burland & Wroth 1975, Cigna & Tapete 2021, Ohenhen & Shirzaei 2022). However, these approaches primarily account for cumulative continuous deformation and often overlook nonlinear, discontinuous subsidence (Boscardin & Cording 1989), which is common in densely built coastal environments. This simplification can underestimate actual risk, particularly in reclaimed land, deltaic soils, and other geotechnically complex urban settings.

Improved damage thresholds require experimental and field data that capture the temporal variability and spatial heterogeneity of subsidence in coastal contexts. Strengthening these models is essential for developing predictive tools that can inform targeted adaptation and mitigation strategies for coastal infrastructure resilience.

SUMMARY POINTS

1. Vertical land motion (VLM) is a critical yet underrecognized driver of coastal hazards; human-induced local land subsidence from groundwater extraction, urban loading, and resource withdrawal often surpasses climate-driven sea-level rise (SLR), amplifying relative SLR in many coastal cities.
2. Monitoring and modeling advances, particularly using satellite-based interferometric synthetic aperture radar, the Global Navigation Satellite System, and machine learning, have transformed our ability to detect and analyze VLM, but coverage remains uneven, especially in the Global South.

3. Natural and anthropogenic processes interact, producing complex and nonlinear land motion patterns that challenge current hazard assessments and adaptation planning.
4. Subsidence amplifies multiple hazards, including chronic flooding, infrastructure deformation, salinization, and wetland loss, while also increasing socioeconomic vulnerability, insurance risk, and displacement pressures.
5. Socioeconomic and equity dimensions of subsidence are profound yet poorly understood, and marginalized and low-income communities often face the highest exposure and the least adaptive capacity, perpetuating spatial and intergenerational inequities.
6. Governance and policy fragmentation hinder effective mitigation. Only a few nations (e.g., Japan, the Netherlands, Italy, China) have institutionalized systematic monitoring and integrated VLM into planning frameworks.
7. Integrated frameworks, such as digital twin–decision theater systems, provide a means to fuse geophysical, hydrological, and socioeconomic data to support scenario testing, stakeholder engagement, and coproduction of adaptation strategies.
8. Emerging frontiers include coupling VLM models with hydrodynamic and climate projections, quantifying economic losses, and establishing open, standardized, and equitable global datasets for VLM in coastal cities.
9. Resilient coastal futures require coordinated global efforts that merge Earth observation, data science, and policy innovation to anticipate, rather than react to, the intertwined challenges of subsidence and SLR.

DATA AVAILABILITY

All datasets used in this study, including the VLM data for the 204 coastal cities shown in **Figure 2**, are available here: **https://doi.org/10.7294/31029349**.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTION STATEMENT

M.S. conceptualized and designed the study, made substantial contributions to data acquisition/analysis, and drafted and critically revised the manuscript. L.O. made substantial contributions to the study's conception, design, data acquisition/analysis, and intellectual input, and participated in drafting the manuscript. C.A., G.C., O.D., N.D., M.K., J.L., and S.F.S. made substantial contributions to the study's conception and intellectual input and participated in drafting or critically revising the manuscript. S.A. made substantial contributions to the study's conception and data acquisition/analysis and participated in drafting. G.F., H.J., and M.R. made substantial contributions to the study's data acquisition/analysis and participated in critically revising the manuscript. N.S. made substantial contributions to the study's conception, design, and intellectual input, and participated in critically revising the manuscript. G.Z. made substantial contributions to the study's conception and participated in drafting the manuscript. W.Z. made substantial contributions to the study's design and intellectual input and participated in critically revising the manuscript. C.B. and S.W. made contributions to data acquisition/analysis and participated in critically revising the manuscript. C.W., W.E., I.O.I., N.P.K., F.O., and E.O.O. made contributions to the study's conception and intellectual input and participated in critically revising the manuscript. A.A., A.B., R.B., J.F., N.H., R.J.N., J.O., S.N., P.T., F.V., M.J., and S.W. participated in critically revising the manuscript. All authors approved the final version and accept accountability for the integrity and accuracy of the work.

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