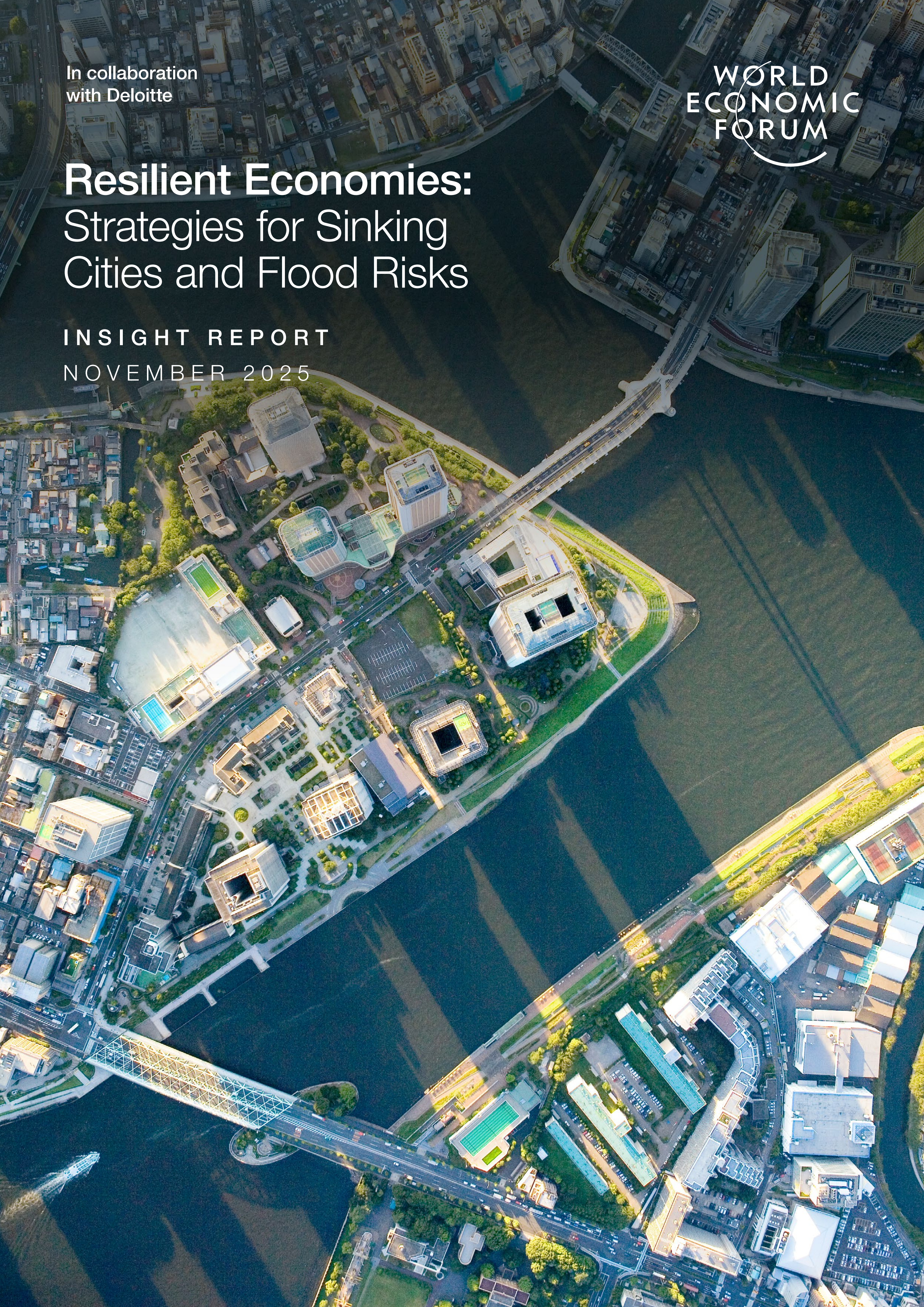
In collaboration with Deloitte

WORLD ECONOMIC FORUM

Resilient Economies: Strategies for Sinking Cities and Flood Risks

INSIGHT REPORT

NOVEMBER 2025



Images: Getty Images and Adobe Stock

Contents

Foreword

Anu Devi
Lead, Strategic Insights, Centre for Urban Transformation, World Economic Forum

Raj Kannan
Leader for Infrastructure and Real Estate, Asia Pacific and Southeast Asia, Deloitte

Cities are at the forefront of transformation. As urbanization accelerates and the climate crisis intensifies, the risks facing urban environments are becoming more complex, interconnected and urgent. Among these, land subsidence, often overlooked due to its gradual onset and localized causes, has emerged as a critical challenge with profound implications for cities worldwide.

This is a decisive moment to address sinking cities. Today, the convergence of sea-level rise, extreme weather events and rapid urban growth is amplifying economic, social and environmental risks in places with land subsidence. The consequences of inaction are already evident: increased flood risk, infrastructure damage, saltwater intrusion, coastal erosion, and threats to people's well-being.

These impacts are not confined to any single region; both coastal and inland cities are affected. Urban transformation in the 21st century must be anchored in prevention and resilience. Integrating proactive, systems-based approaches to address land subsidence within urban planning and development is no longer optional, it is essential.

This report is published at a pivotal moment, as leaders across the public and private sectors are called to move beyond reactive crisis management and embrace holistic and integrated strategies that anticipate, prevent, mitigate, adapt and is resilient to evolving risks. Collaborative action and shared responsibility are essential to building urban resilience and ensuring future readiness.

The insights and recommendations in this report are intended as a foundational resource for decision-makers seeking to future-proof cities and economies against the growing challenge of land subsidence and climate change, while improving quality of life for all. By recognizing subsidence as a core element of the broader urban and climate resilience agenda, stakeholders can unlock new opportunities for sustainable growth, safeguard critical infrastructure and protect livelihoods. Now is the time for bold, coordinated action. Together, we can turn the tide on land subsidence and build thriving, resilient cities for generations to come.

Executive summary

Ignoring sinking cities today means accepting escalating costs, stranded assets and social disruption tomorrow.

Urban land subsidence, commonly referred to as "sinking cities", is an underrecognized global challenge. This report demonstrates that subsidence can threaten the prosperity and liveability of cities worldwide. Subsidence is driven primarily by unsustainable human behaviours from groundwater extraction to rapid urbanization. These pressures can heighten flood risks, infrastructure damage and displacement. When combined with sea-level rise and extreme weather, subsidence can transform manageable risks into existential threats for businesses, governments and communities.

Subsidence often progresses gradually and invisibly, masking its true scale until critical thresholds are crossed. The private sector faces direct risks to assets, supply chains and profitability, while governments must contend with additional costs for infrastructure management. Subsidence undermines buildings, utilities and transport systems, leading to property devaluation, increased maintenance costs and service disruptions.

Beyond economic costs, subsidence threatens societal well-being and environmental systems. Communities face displacement, property loss and public health challenges. Environmental consequences include loss of vital ecosystems that buffer places against storms and erosion. Despite its magnitude, land subsidence remains underrepresented in global urban and climate agendas, hindered by fragmented knowledge and data, a lack of international standards and insufficient investment.

Early, cohesive interventions are essential. Case studies from Tokyo, Shanghai and Rotterdam demonstrate that cities can mitigate and adapt to land subsidence through integrated solutions, while Jakarta is on a trajectory to address its sinking challenges. Key measures include regulatory reforms, sustainable groundwater management, infrastructure investment and nature-based solutions. The experiences of these cities highlight the need to shift from reactive crisis management to proactive, long-term resilience building.

The report identifies several foundational drivers of change for public and private stakeholders:

- **Value land and water as strategic assets**: Manage resources as finite assets essential for economic, social and environmental benefits.
- **Strengthen governance and leadership**: Encourage proactive leadership, regulatory guidance and collaboration to enable systems-based solutions, while empowering communities and businesses as agents of change.
- **Operationalize systems thinking**: Implement holistic strategies to prevent, mitigate, adapt and enable resilience to subsidence and its interplay with climate risks.
- **Commit to evidence-based approaches**: Use reliable data, expert insights and global case studies to inform risk assessments, interventions and investments, and overcome fragmented information.
- **Invest in infrastructure resilience**: Upfront investments in subsidence monitoring, building resilient infrastructure, technology and innovation are essential to reduce the long-term costs of inaction.

Land subsidence can accelerate social, economic and environmental risks. Only by treating subsidence as a core component of urban resilience agendas can economies and societies enable future prosperity and liveability.

Introduction: Sinking cities

Beneath the world's cities, sinking land is undermining urban foundations and accelerating flood and infrastructure risks.

Why should governments and businesses care?

While the world's attention is often drawn to the visible impacts of climate change, another crisis is unfolding beneath our cities. From Jakarta to New Orleans, Bangkok to Mexico City, urban areas are experiencing land subsidence, sinking at rates that, in some cases, outpace global sea-level rise.

Land subsidence – the gradual or rapid downward movement of the Earth's surface – is estimated to affect two billion people worldwide.[1] Commonly referred to as "sinking cities", when applied to urban locations, subsidence is prevalent across continents with impacts observed both in coastal and inland cities. This phenomenon is primarily driven by human action, often resulting from a combination of unsustainable water and land use, rapid urbanization and underlying geological processes.

The implications of sinking cities are far-reaching. Land subsidence alone can amplify flood risks, damage infrastructure and displace businesses and communities, resulting in economic losses. The economic exposure to potential land subsidence is estimated at $8.17 trillion, representing approximately 12% of global gross domestic product (GDP).[2] Annual global economic losses attributable to subsidence are estimated to be in the billions of dollars.[3]

The negative impacts of land subsidence can compound when combined with climate risks, further undermining the stability of cities, communities and economies.[4] The interaction between subsidence, sea-level rise and extreme weather (such as intense rainfall or heatwaves) can create threats, transforming what might have been a manageable or long-term risk into an immediate risk. This combination poses high risks for coastal areas, many of which are experiencing subsidence and are also affected by sea-level rise and extreme weather events.

For instance, subsiding land reduces natural defences against storm surges, while rising sea levels push water inland.[5] Extreme rainfall exacerbates flooding in areas compromised by land subsidence. In California, US, land subsidence relative to sea-level rise is projected to impact 4.3–8.7 million people across coastal communities.[6] Although the root causes of these factors may vary, their impacts are converging, making it essential to integrate subsidence in urban resilience strategies, including flood and infrastructure management.[7]

One of the most striking examples is in Jakarta, Indonesia, where parts of the city are sinking by up to 200mm per year. Land loss and flooding have partly prompted the government's decision to relocate the capital to Nusantara, Borneo Island. In the US, localized areas of New Orleans have subsided by more than 50mm over the past century, with hurricanes and sea-level rise compounding flood threats. Some areas of Mexico City were built on an ancient lakebed, parts of which are sinking at a rate of 350mm per year. These places have consequently experienced land loss, infrastructure damage and service disruptions. These challenges are also mirrored in other cities worldwide, highlighting the need for coordinated action.

For the private sector, the risks are immediate. Industries such as real estate, agriculture and critical infrastructure face operational and supply chain disruptions, threatening profitability and business continuity. Companies with assets in sinking cities can face unaccounted costs, stranded assets and regulatory pressures. Flood damages in subsiding areas, for instance, can drive property devaluation and widen protection gaps in insurance coverage.

Governments, meanwhile, are confronted with unaccounted costs for infrastructure repair, strained public services and the diversion of resources from other priorities. The compounding effects of subsidence, sea-level rise and climate extremes can trigger social disruptions, population displacement and public health challenges. For global leaders, proactive identification of and tackling such risks is essential for ensuring economic, social and environmental resilience and stability.

“ The interaction between subsidence, sea-level rise and extreme weather can create threats, transforming what might have been a manageable or long-term risk into an immediate risk.

What are the economic, social and environmental implications?

The impacts of land subsidence extend far beyond the physical landscape, carrying critical economic, social, health and environmental challenges for governments, businesses and communities.

Economic implications

The absence of standardized international frameworks for assessing and comparing the economic costs of subsidence, particularly when compounded by sea-level rise and extreme weather, complicates effective global risk management. Nevertheless, emerging research and data point to the financial burden.

> **Investing in mitigation is 5–7 times more economically efficient than repairing/rebuilding post-disaster.**
>
> Jonathan Reckford, CEO, Habitat for Humanity

FIGURE 1 **Economic consequences of sinking cities (land subsidence)**

US
Infrastructure related:
Buildings

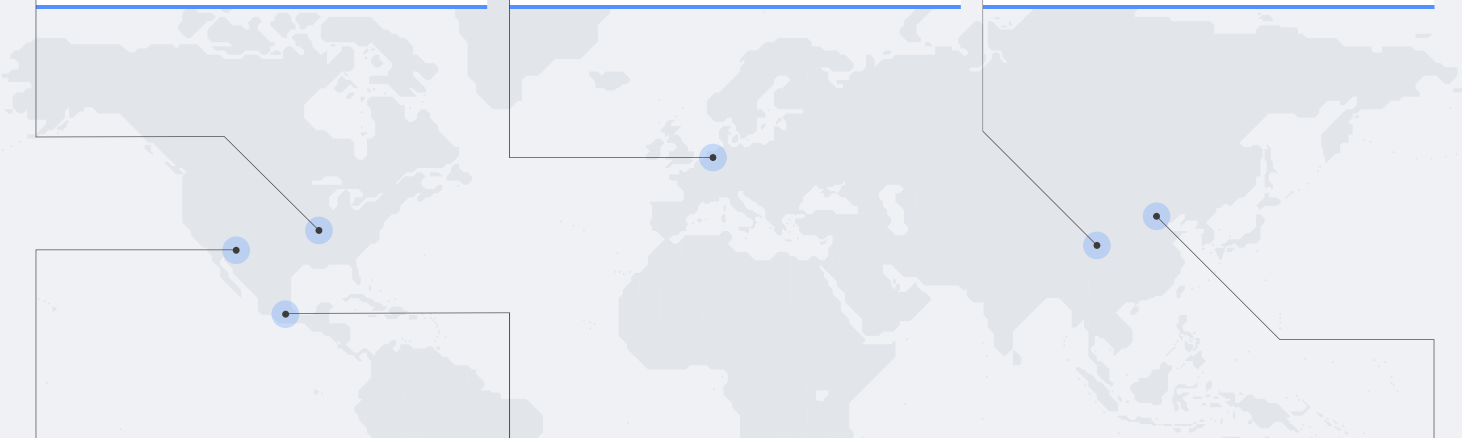
Over 90 flood incidents since 2000 have occurred across eight cities experiencing sinking rates above 3mm per year. In urban areas, 29,000 buildings are located in high and very-high-risk damage areas.[8]

Netherlands
Infrastructure related:
Buildings/other

Damage to buildings and infrastructure from peat and clay soil subsidence is projected to reach €20 billion by 2050, of which €17 billion are in repair costs of structural damage. In Rotterdam and Gouda, property values are expected to decline by 7% and 6%, respectively.[9,10]

China
Infrastructure related:
Structural damages

Total economic loss since 1950 due to subsidence is estimated at CNY 450–500 billion (Chinese yuan); direct losses due to structure and infrastructure damage reach CNY 0.8–1.0 billion per year.[11]



Maricopa County, Arizona, US
Infrastructure related:
Buildings

Modelling from 2004 and 2010 indicates that home value depreciation averages 1.82% (approximately $5,229) in subsidence areas.[12]

Mexico City, Mexico
Infrastructure related:
Metro system

Subsidence has damaged parts of metro infrastructure, which serves four million passengers per day. Impacts include compromised brake safety, rail bending and heightened flood risk.[13]

Beijing–Tianjin, China
Infrastructure related:
Railway

Along the Beijing–Tianjin high-speed railway, subsidence-sensitive areas have been matched to maintenance and repair records, implying increased inspections and potential operational costs.[14]

Global, coastal cities
Without significant mitigation investments, flood risks due to sinking could cost coastal cities an estimated $635 billion per year by 2050.[15,16]

Subsidence generates both direct and indirect impacts. Direct losses encompass damage to critical infrastructure, such as roads, buildings, railways, ports and utilities, resulting in increased maintenance expenditures and declining property values.[17,18] These vulnerabilities risk being exacerbated by ageing infrastructure, much of which was designed for past conditions, and may now be inadequate to withstand current and future climate-related and other shocks. Land loss from subsidence constrains housing availability, economic development and agricultural productivity. Additionally, as coastal land sinks and sea levels rise, saltwater intrusion into freshwater resources intensifies, threatening water security for households, industry and agriculture alike.[19,20,21]

Subsidence alone can increase flood risks, and when combined with rising sea levels and more frequent extreme weather events, the likelihood of flooding and infrastructure failures is significantly amplified. These impacts can strain emergency response systems, disrupt public services and supply chains, and undermine local economies and livelihoods.

The true burden of land subsidence is likely underestimated, as cascading social, health, environmental and economic interdependencies, particularly in the context of the climate crisis, are not yet fully captured. Impacts are likely to be most severe in cities with limited monitoring capabilities and resources to fully assess the issues, carry out risk assessments and implement response measures.

Social and health implications

The social and health ramifications of land subsidence are equally significant, as sinking amplifies vulnerability to flooding and acts as a risk multiplier when combined with sea-level rise or extreme weather.[22,23] In severe cases, flooding can displace residents and businesses, disrupt livelihoods and limit access to essential services. Large-scale displacement places additional pressure on governments and local economies, with marginalized communities often lacking resources for adaptation and relocation.[24]

CASE STUDY 1

Submerged neighbourhood: compounding impacts of subsidence and sea-level rise, Muara Baru, Jakarta, Indonesia

Localized areas of Muara Baru, a low-lying area in northern Jakarta, has been reported to experience subsidence rates of 60mm per year. When combined with sea-level rise, this area has experienced frequent and worsening floods, especially during high tides. Notably, landmarks such as the Waladuna Mosque have submerged over recent decades. Since 2009, rising water levels have rendered parts of neighbourhoods unusable, forcing businesses and residents to relocate.

The challenges have been associated with subsidence, sea-level rise and inadequate water management. The situation in Muara Baru highlights the urgent need for comprehensive resilience strategies to protect communities and local economies from the escalating risks associated with subsidence and the broader climate crisis.

Sources: Bott et al. (2021). Land subsidence in Jakarta and Semarang Bay – The relationship between physical processes, risk perception, and household adaptation. *Ocean & Coastal Management*, vol. 211, no.105775. https://doi.org/10.1016/j.ocecoaman.2021.105775; Kompas. (2022, 28 November). *Menengok Masjid Wal Adhuna, saksi bisu tenggelamnya pesisir Jakarta*. https://megapolitan.kompas.com/read/2022/11/28/18415841/menengok-masjid-wal-adhuna-saksi-bisu-tenggelamnya-pesisir-jakarta?page=1.

The Waladuna Mosque submerged in water due to tidal flooding: Muara Baru, Jakarta, Indonesia

Strong social networks and a resilient social fabric are essential for building community resilience to both acute and chronic shocks.

Health impacts are critical yet often overlooked. Given subsidence is associated with flooding, chronic flooding increases the risk of waterborne diseases (e.g. diarrhoeal diseases) and vector-borne diseases (e.g. malaria).[25,26] Prolonged exposure to damp environments can lead to respiratory illnesses, particularly among vulnerable populations.[27] Flooding can also bring harmful chemicals from underground to the surface, posing toxicological risks.[28]

Beyond physical health, persistent threats of flooding, displacement and property loss can impact mental health. There is a strong correlation between a healthy environment and a healthy population, as highlighted in frameworks such as DIALOG's Community Wellbeing Framework.[29] It recognizes that without meaningful community engagement, efforts to promote well-being are less likely to succeed.

Flooding and related risks also disproportionately affect women and children, especially in places where water accessibility is limited and inequitable. In some countries, these risks can reduce women's participation in household decision-making. For children, these conditions can result in reduced school attendance and an increased risk of child marriage.[30,31]

The 1.1 billion residents of informal settlements and slums also face heightened risks. These communities are often located in high-risk, low-lying areas and face additional vulnerabilities due to inadequate housing, limited access to basic services and insecure tenure. As a result, they bear the brunt of urban disasters yet remain largely invisible in resilience planning and investment.

Furthermore, strong social networks and a resilient social fabric are essential for building community resilience to both acute and chronic shocks (e.g. subsidence and flooding). Community facilities, public spaces, local governance and social agencies all play a vital role in helping communities adapt and recover more effectively.

There is growing recognition of the broader influence of social determinants of health (e.g. housing, income, physical environment and healthcare access). The risks of land subsidence, compounded by climate risks, can undermine these determinants and create public health challenges, ultimately affecting well-being and economic productivity.

Environmental implications

Environmentally, subsidence in coastal areas threatens vital ecosystems such as wetlands, mangroves and estuaries. These habitats are crucial for biodiversity and serve as natural buffers against storm surges and erosion.[32]

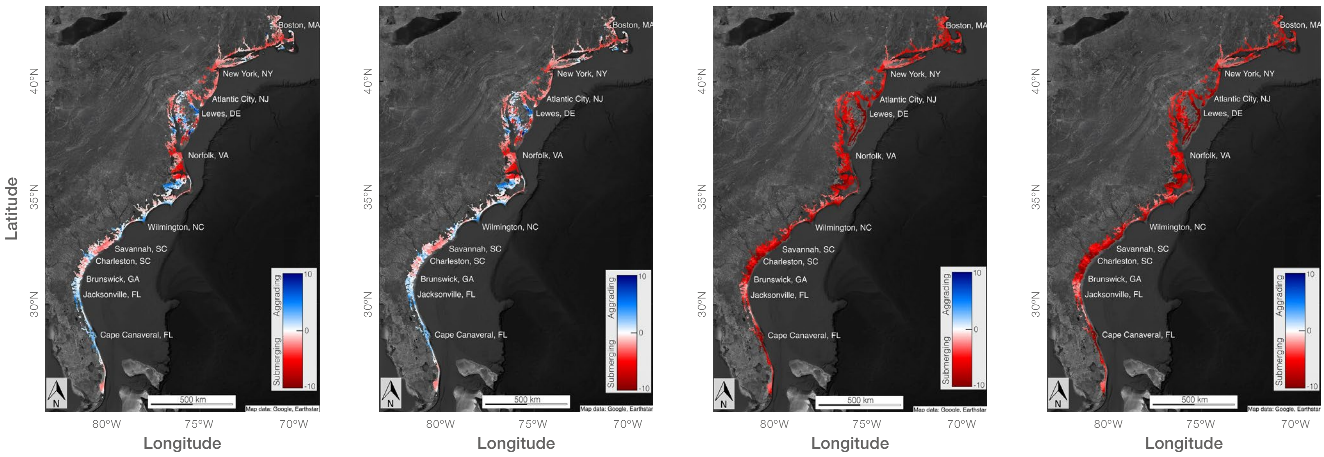
CASE STUDY 2

Habitat vulnerability from subsidence and sea rise, US Atlantic Coast

Satellite data from 2007 and 2020 along 3,500km of the US Atlantic Coast reveal that most areas are sinking by more than 3mm per year, impacting farmlands, wetlands, forests and developed regions. Projections indicate that 58–100% of coastal marshes are losing elevation relative to sea level when accounting for subsidence.[33] This study shows that land sinking plays a major role, it can cause marshes to sink faster than they can keep up, leading to submersion. Any assessment of marsh risk that ignores land sinking will likely underestimate how vulnerable these areas really are.

Source: Ohenhen, L.O., Shirzaei, M., Ojha, C. et al. (2023). Hidden vulnerability of US Atlantic coast to sea-level rise due to vertical land motion. *Nature Communications.* vol. 14, no. 2038. https://doi.org/10.1038/s41467-023-37853-7.

A Low-elevation wetlands (lower bound) | B Low-elevation wetlands (upper bound) | C High-elevation wetlands (lower bound) | D High-elevation wetlands (upper bound)



	A	B	C	D
Total area	725km²	551km²	725km²	551km²
Submerging	57.6%	57.6%	100%	100%
Maintaining	14.4%	12.4%	0%	0%
Aggrading	28.0%	30.0%	0%	0%

Despite mounting evidence, a comprehensive understanding of the full economic, social, health and environmental costs of land subsidence remain fragmented. The risks and costs associated with the interplay between subsidence, sea-level rise and extreme weather are still insufficiently quantified.

Cities that fail to proactively manage these interconnected risks face escalating costs for drainage systems, infrastructure maintenance, urban planning and disaster response. Areas built on soft soils, reclaimed land or with excessive groundwater use, especially those also facing sea-level rise and extreme weather, are most at risk.

While the specifics of subsidence vary by location, land and water use, and governance practices, the overarching trend is clear: without sustainable management, cities, businesses and communities will confront compounding challenges from sinking land and associated threats.

> **The impacts of a sinking city accelerate, like an avalanche, if ignored. It pays to be proactive.**
>
> Antonio Gómez-Palacio, Chair, DIALOG

How to use this report

This report serves as a call to action to strengthen urban resilience in response to the growing challenges of land subsidence and climate-related risks. It aims to raise awareness of land subsidence and its compounding effects when combined with sea-level rise and extreme weather events. Rather than offering technical solutions, the report provides high-level, foundational insights into the issue of sinking cities, presents four illustrative use cases and offers actionable recommendations for public and private sector stakeholders.

By framing land subsidence as a critical factor accelerating the impacts of climate change in urban environments, the report underscores the need for cohesive, coordinated, cross-sector dialogue and long-term resilience planning. Without consensus-driven, decisive and collective action, many of the world's most dynamic coastal and inland cities will face increasing threats to their prosperity and liveability.

- **National and local governments**: Policy-makers can use this report to deepen their understanding of the drivers and impacts of subsidence, draw lessons from the strategies adopted by peer cities and identify opportunities for collaboration with other sectors.
- **Private sector**: Businesses with operations or supply chains in affected areas can use the report to investigate their exposure to subsidence-related risks. They can explore opportunities to address the root causes and develop adaptive solutions across markets in collaboration with relevant stakeholders.

For the purposes of this report, "sinking" refers specifically to land subsidence, the downward movement of the Earth's surface. While many locations may experience sinking due to sea-level rise or other factors, this report relates sinking to subsidence as a standalone phenomenon and its interaction with climate risks such as sea-level rise and extreme weather. Additionally, data is taken from different sources and publications, highlighting the challenge of fragmented information; yet, the findings point to similar outcomes.

1 Sinking landscape

Understanding the scale and drivers of sinking cities can catalyse appropriate mitigation and adaptation strategies.

1.1 How widespread is urban sinking?

Without significant attention, consensus and collective action, portions of several major cities may become uninhabitable in the coming decades.

The scale of sinking cities is immense and uneven in its impacts across continents, countries and local economies. Today, an estimated 6.3 million square kilometres (km^2) of land globally is experiencing subsidence, an area equivalent to the combined size of India, Argentina and Japan – affecting an estimated two billion people worldwide.[34]

Accelerating sea-level rise further compounds this issue. Over the past three decades, the rate of global sea-level rise has more than doubled, now reaching about 3.3mm per year. Projections suggest that levels could reach 16.9cm in the next 30 years.[35,36] Critically, in several coastal cities, land is sinking at rates that exceed the pace of sea-level rise, amplifying flood and other risks.

Subsidence is not a uniform phenomenon; its impacts are concentrated in specific areas.[37] Recent analyses of 99 coastal cities, using data from 2015 and 2020, reveal that 33 cities are subsiding at rates equal to or up to five times faster than global sea-level rise. For example, coastal Shanghai has recorded areas with subsidence rates of up to 10mm per year. The fastest rates are observed in South, South-East and East Asian cities.[38]

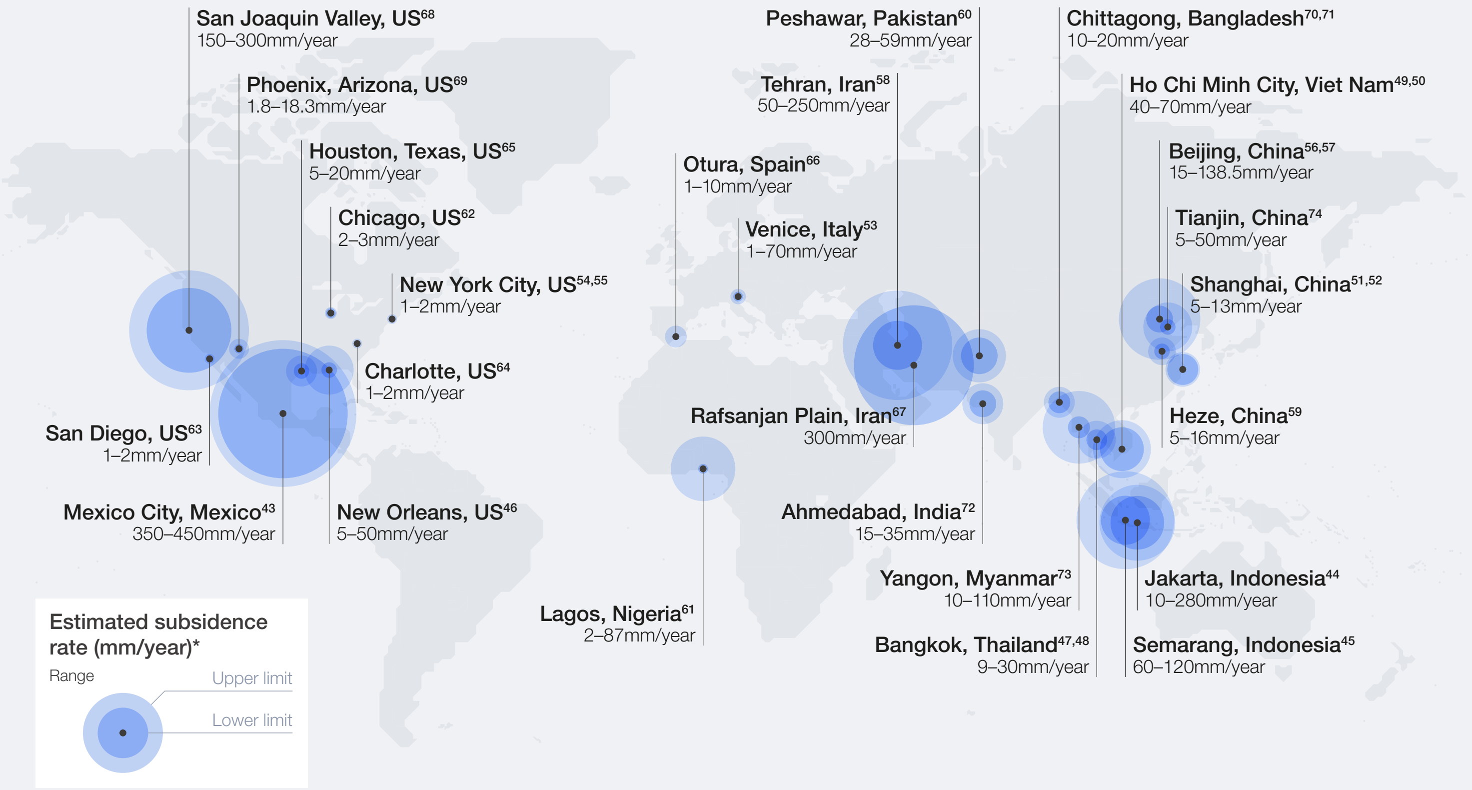
In some cities, localized areas are subsiding at rates 10 to 20 times faster than sea-level rise, with extreme cases documented in cities such as Tianjin, Semarang and Jakarta. Notably, Jakarta's northwest coast has experienced land subsidence of up to 280mm per year. While cities like Jakarta and Shanghai continue to face acute subsidence, targeted policy interventions have slowed rates in some areas, underscoring the critical role of governance and adaptive management.[39]

This challenge is not limited to Asia. In the US, high-resolution satellite data from 2015 to 2021 indicate that 20% of urban areas across 28 cities are experiencing subsidence, potentially affecting 34 million people, approximately 12% of the national population. In 25 of these cities, at least 65% of the examined land area is subsiding, with cities such as Houston, Dallas, Fort Worth, Chicago, New York and Detroit seeing over 70% of their land affected. Since 2000, more than 90 flood incidents have occurred in eight US cities with subsidence rates above 3mm per year. In addition, 29,000 buildings are classified as high or very high risk, stressing the widespread vulnerability to critical infrastructure.[40]

The most affected regions are low-lying, densely populated coastal areas, river deltas and small islands. Importantly, land subsidence affects inland cities, including Mexico City and Tehran, where impacts are compounded by other climate crises, such as heatwaves and drought.[41,42]

These findings highlight the urgent need for ongoing monitoring, a deeper understanding of subsidence dynamics, along with prevention, mitigation and adaptation strategies. Without significant attention, consensus and collective action, portions of several major cities may become uninhabitable in the coming decades due to combined effects of subsidence and the climate crisis.

FIGURE 2 | **Examples of cities with areas experiencing subsidence**



*Multiple sources. The data was gathered from different sources and may vary based on measurement methodologies and time. This highlights the need to collect and update data.

Note: Land subsidence rates can vary spatially within cities, across regions and globally. Thus, reported rates do not indicate uniform sinking risks for an entire city; rather, they highlight that specific areas within a city are experiencing land subsidence, and it varies.

Source: World Economic Forum.

1.2 Why do cities sink?

Land subsidence, the gradual or sudden sinking of the ground, results from a complex interplay of natural geological processes and, increasingly, unsustainable human activities. While factors such as local geology, seasonal groundwater fluctuations and seismic activity contribute to subsidence, mounting evidence indicates that human actions are now the dominant accelerant globally.

Excessive groundwater extraction is the leading anthropogenic driver of urban land subsidence. Over-extraction for domestic, industrial and agricultural use leads to aquifer-system compaction, peat oxidation, uneven soil compression and, in some cases, the formation of sinkholes. This also includes the drainage of land for development purposes, often a factor in coastal and delta-built cities (low-lying landforms with rivers and connection to a larger body of water). Recent studies analysing hundreds of subsidence-prone areas found that approximately 77% of cases were linked to human activity, with around 60% directly attributed to groundwater withdrawal.[75] Another study of 200 locations encountering subsidence revealed that 55% of cases resulted from underground water extraction.[76]

As urban populations expand and water demand rises, groundwater aquifers are depleted beyond their natural replenishment rates, resulting in irreversible soil compaction. The consequences, such as infrastructure damage, increased flood risk and heightened vulnerability to sea-level rise and extreme weather, often remain hidden until critical thresholds are crossed. Once the ground compacts or collapses, recovery can be difficult and costly.

Urbanization is also a driver of land subsidence, particularly when combined with vulnerable geological conditions and rising water demand. The interplay between urban growth, geological factors and historical development practices complicates the challenge.[77,78] The pressure (weight)

12%

of soil compaction is attributed to urbanization.

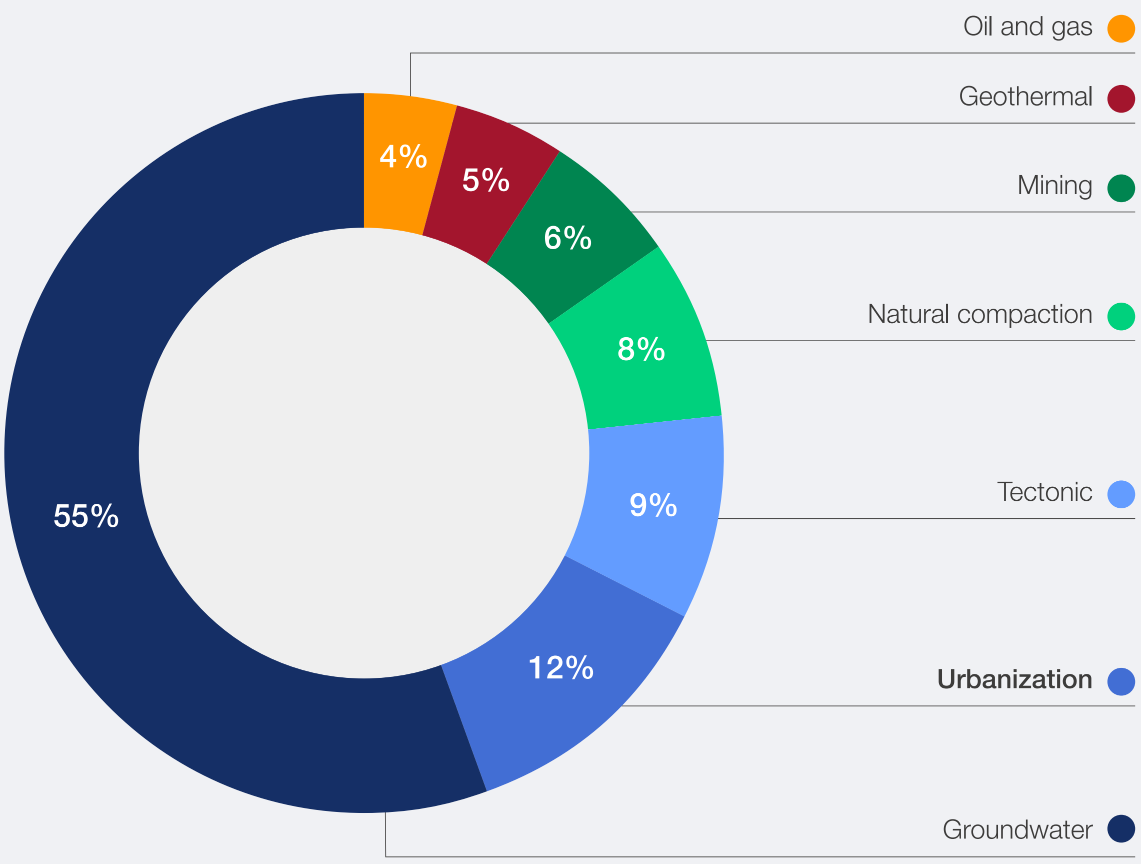
from development and land reclamation can exacerbate subsidence in risk zones.[79] Inadequate urban planning – for example, road developments that block natural groundwater recharge – can also contribute to land subsidence. Globally, it is estimated that 12% of soil compaction is attributed to urbanization.[80] With nearly 58% of the world's population currently living in cities – projected to rise to 68% by 2050 – the long-term implications of urban expansion on land stability warrant attention.

Urbanization also drives increased water consumption for domestic purposes and across sectors. For example, the technology and manufacturing sectors use water for cooling and other uses. In areas prone to subsidence, heightened pressure on groundwater aquifers can intensify risks. Addressing these interconnected challenges requires coordinated approaches that consider both the physical environment, patterns of urban development and natural resource use.

Climate change is a critical compounding factor driving land subsidence. While thermal expansion contributes to sea-level rise, the majority is driven by the melting of glaciers and ice sheets, linked to rising global temperatures from human action. Climate change also disrupts weather patterns, increasing the frequency and severity of tropical cyclones, extreme rainfall and storms, all of which amplify flooding in areas already experiencing land subsidence. Importantly, prolonged heatwaves and droughts can worsen subsidence. This can be due to a lack of rain to replenish underwater aquifers, overextraction of water to compensate for water storage and land erosion that occurs due to climate disruptions. Additional drivers include underground mining of other resources, other than water, hydrocarbon and geothermal extraction, hydro compaction and thawing permafrost. Each of these activities can destabilize subsurface layers, leading to ground instability and increased subsidence risk.

Cities that fail to proactively manage these interconnected risks face escalating costs for drainage systems, infrastructure maintenance, urban planning and disaster response. Areas built on soft soils, reclaimed land or with excessive groundwater use, especially those also facing sea-level rise and extreme weather, are most at risk. While the specifics of subsidence vary by location, land and water use, and governance practices, the overarching trend is clear. Without sustainable management, cities, communities and economies will confront compounding challenges from sinking land and associated threats.

FIGURE 3 **Global land subsidence drivers**



Source: Huning, L. S., Love, C. A., Anjileli, H., et al. (2024). Global Land Subsidence: Impact of Climate Extremes and Human Activities. *Reviews of Geophysics*. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023RG000817.

FIGURE 4 | Key factors driving sinking cities

Groundwater pumping and drainage of organic soil

Overuse for domestic, industrial and agricultural needs, leading to aquifer compaction and soil sinking.[81] Draining wetlands or peatlands causes soil shrinkage and compaction, often linked to groundwater extraction.[82]

Underground mining and hydrocarbon extraction

Removal of minerals, oil or gas, destabilizing subsurface layers. The spatial extent of subsidence depends on exploitation depth, rock mass geo-mechanical conditions and post-mining void reclamation.[84] Hydrocarbon extraction results in reservoir compaction. As fluids are extracted, the pressure within the reservoir decreases, causing the surrounding geological layers to compress.[85]

Hydro-compaction

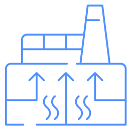
Soil compaction due to wetting of previously dry, loose or low-density soil.

Natural geological compaction and conditions

Gradual settling of soils and sediments due to natural processes.[88]

Urbanization and load pressure (in relation to soil conditions and history)

Dense development and expansion of built areas and assets, increasing pressure on vulnerable soils; depending on geology.[83]



Geothermal extraction

Removal of geothermal fluids leads to subsurface volume loss and thermal contraction of rocks can further worsen subsidence.[86]

Thawing permafrost

Melting of frozen ground can contribute to ground instability and subsidence. Thawing permafrost is primarily driven by climate change, global warming.[87]

Climate change

Extreme drought and heat can increase soil erosion risks and higher groundwater demands. Sea-level rise can increase ecosystem loss and flood risks, causing soil erosion. Extreme weather increases risk of wildfires, rainfall, storms, increasing flood and wind risks, leading to soil erosion and subsidence.

1.3 What are the barriers to action?

While sudden sinking can happen, the slow onset, combined with diverse local drivers, contributes to a lack of urgency in both public and private sector agendas.

Land subsidence represents an urgent yet underrecognized global risk. Often described as a "silent" challenge, its gradual progression obscures its true scale, making detection difficult until critical thresholds are surpassed and consequences become severe. While sudden sinking can happen, the slow onset, combined with diverse local drivers, contributes to a lack of urgency in both public and private sector agendas. Several persistent barriers continue to impede decisive action.

Disconnection from climate agendas: Despite clear links to climate change, land subsidence remains largely absent from mainstream climate policy and discourse. The disconnect limits development of integrated, cross-sectoral solutions and reduces opportunities for alignment with broader urban and climate resilience strategies.

Limited awareness and understanding: The complex interdependences and feedback loops between land subsidence, human activity and their socioeconomic and environmental costs are poorly understood outside academia, government and businesses directly involved. This lack of shared understanding reduces urgency and weakens consensus for collective action.

Data gaps and limited access: Even where awareness exists, the data needed to analyse and respond to subsidence is scattered across institutions and often inaccessible. Without comprehensive, up-to-date information, governments, businesses and communities cannot assess risks or target investments effectively.

Lack of standards and coordination: There is a notable absence of international standards for measuring, monitoring and responding to subsidence, particularly regarding its interaction with sea-level rise and extreme weather. This gap limits benchmarking, accountability and the development and adoption of effective solutions. While initiatives such as the United Nations Educational, Scientific and Cultural Organization (UNESCO) Land Subsidence International Initiative are facilitating global exchange of information, broader engagement across sectors is needed.[89]

Insufficient urgency and investment: The often gradual nature of subsidence can relegate it to a lower priority until disaster strikes. This results in limited public awareness, insufficient funding and a lack of public-private engagement, which can be exacerbated by the challenge of demonstrating immediate financial returns on prevention, mitigation and adaptation measures. The absence of clear attribution between asset damage and land subsidence can further impede action.

These barriers perpetuate a reactive approach, with interventions typically occurring only after significant damage has taken place. In an era of rapid urbanization and climate volatility, economies and societies can no longer afford to treat land subsidence as an isolated or secondary issue.

A fundamental shift is required: from reactive to proactive, strategic resilience building to land subsidence, associated risks and compounding factors. Addressing land subsidence and its interaction with sea-level rise and extreme weather demands a holistic, collaborative approach. Without collective action, the liveability and stability of several cities worldwide are at risk.

2 Case studies and solutions

The sinking journeys of four cities provide a baseline and valuable lessons for the public and private sectors to address sinking cities and associated risks.

2.1 Tokyo's comeback: the first sinking city to stabilize

Population

~37 million

Area

~2,188km^2

Context

In Japan, Tokyo's rapid rise as a global megacity during the 20th century brought significant environmental challenges, most notably severe land subsidence. Driven by unchecked groundwater extraction due to industrialization and growth, ground levels in some areas declined up to 24cm per year by 1968.[90,91]

The combination of land subsidence and extreme weather events, such as Typhoon Kathleen (1947) and Typhoon Kanogawa (1958), exposed Tokyo's infrastructure gaps and led to increased flooding.[92]

Solutions

Recognizing the existential risks, the national government and the Tokyo Metropolitan Government (TMG) implemented strategies over time that combined infrastructure investment, regulatory reform and ecological planning. Their approach reduced subsidence rates drastically over the years and positioned Tokyo as a model for urban resilience for subsidence (see Figure 5).[93]

– **Regulatory innovation**: Groundwater regulation was formulated at the national level, involving inter-ministerial coordination across areas such as water quality and supply, irrigation, river management, industrial water use and pollution control.

Legislation such as the Industrial Water Law (1956) and Building Water Law (1962) imposed strict limits on groundwater use and well construction. It introduced reporting requirements and established penalties for non-compliance – e.g. up to JPY 100,000 (Japanese yen) in fines and imprisonmnt.[94,95,96,97]

The TMG subsequently developed technical regulations and operational guidelines, with implementation led by the Bureau of Environment. Government subsidies and the Multipurpose Dams Act (1957) enabled industry transitions and the development of dam infrastructure for water supply and flood control.[98]

FIGURE 5 | **Groundwater regulation governance in Tokyo**

Central government office

Cross-sector and national-level enforcement and oversight body for national government laws

1 Ministry of Health, Labour and Welfare

Sets policy on water supply and quality

3 Ministry of Economy, Trade and Industry

Sets policy on industrial water use and guidelines

5 Ministry of Land, Infrastructure and Tourism (MLIT) – River Bureau

Regulates on river water maintenance, uses and preservation

2 Ministry of Agriculture, Forestry and Fisheries

Sets policies on agriculture-related resources, measures for subsidence, and observes irrigation water using groundwater

4 Ministry of Environment

Regulates basic environmental law, industrial water law and building law

6 Ministry of Land, Infrastructure and Tourism (MLIT) – Water Resource Bureau

Manages the basics plan for water resource, and provides guideline for prevention of ground subsidence

→

7 Tokyo Metropolitan Government (TMG)

Builds regulation and technical guideline upon national laws

→

8 Bureau of Environment

Operational arm for groundwater management under TMG, enforcing local regulation

Source: Hori, S. (2016). The Structure of Local Groundwater Law for Sustainable Groundwater Policy in Japan. *Laws*, vol. 5, no. 19. https://doi.org/10.3390/laws5020019.

– **Water infrastructure:** Tokyo shifted from groundwater reliance to surface water resources, expanding water treatment plants and distribution networks. Today, some 600 facilities with water purification plants, supply, distribution and pump stations, and source wells provide water.[99] Coupled with demand-side efficiency and leakage reduction, this alleviates pressure on aquifers, addressing a root cause of sinking.

Additionally, investments in drainage systems such as the Metropolitan Area Outer Underground Discharge Channel have prevented over JPY 150 billion in potential flood damages since 2006.[100] Its effectiveness was demonstrated during Typhoon Hagibis in 2019, diverting over 12 million cubic metres (m^3) of floodwater.[101] While the system does not directly prevent subsidence, it reduces erosion and other risks.

– **Nature-based infrastructure**: Since 2001, local ordinances have required green roofs, vertical gardens or vegetation on 20–25% of new and renovated building areas between 1,000 and 5,000 square metres (m^2). As of 2024, over 5,700 new or existing buildings feature 180 hectares of rooftop greenery.[102] Conservation of green areas, rainwater infiltration and reclaimed wastewater initiatives further support groundwater recharge and flood mitigation.[103,104]

– **Technology and data**: Authorities support subsidence and flood management using data from traditional and advanced technologies, in engagement with agencies like the Geographical Survey Institute (GSI) and the Japan Aerospace Exploration Agency (JAXA). Observation wells and surveys, global navigation satellite systems and interferometric synthetic aperture radar (InSAR) provide data to track land subsidence and inform infrastructure planning.

Takeaways

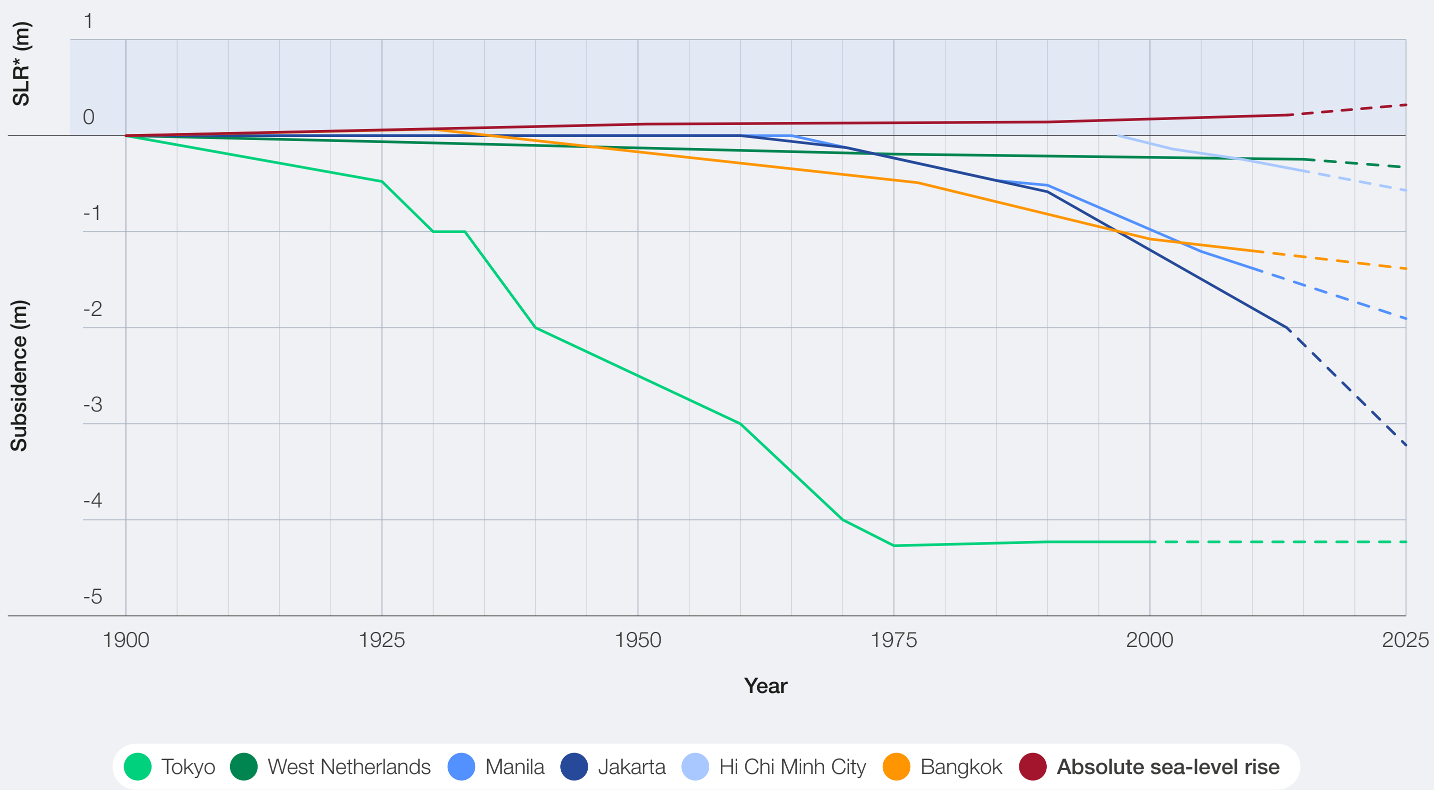
Tokyo's journey from crisis to stability stands as a testament to the power of integrated solutions. Within decades, the city's actions reduced subsidence, with some data indicating rates slowed to 1cm per year.[105] This case provides invaluable lessons for cities and organizations globally confronting similar challenges.

– **Decisive policy action**: Tokyo's transformation began with a clear recognition of the threat, leading to bold regulatory reforms and shifts in water and nature-based infrastructure. For governments, this highlights the importance of policy instruments. For businesses, it underscores the need to innovate in response to changing landscapes.

– **Multiple approaches**: Success in reducing subsidence was not a result of isolated projects but of implementing different solutions. This strategy, where engineering, regulation and nature-based solutions reinforce each other, demonstrates that integrated solutions can support long-term resilience to subsidence.

– **Proactive investment**: Upfront investments in water infrastructure, regulation, and advanced drainage systems have proven effective, protecting Tokyo's economy and population. This highlights the benefits of prioritizing mitigation and adaptation initiatives.

FIGURE 6 **Tokyo's localized sinking experience (cumulative) between 1900 and 2025**



*Sea-level rise

Source: Erkens, G., et al. (2015). Sinking coastal cities. *Proceedings of the International Association of Hydrological Sciences*, vol. 372, pp. 189–198. https://www.researchgate.net/publication/283771445_Sinking_coastal_cities.

2.2 Shanghai's evolution: integrating policy and sponge city

Population	Area
~30 million	~6,340km^2

Context

In China, Shanghai has grappled with localized land subsidence since the 1920s, with some hotspots sinking by more than 2.6m between 1921 and 1965, primarily due to urban expansion and groundwater extraction.[106,107]

The economic consequences have been significant. Between 1950 and 2001, Shanghai's total losses from subsidence reached an estimated CNY 290 billion, with direct damages accounting for CNY 18.9 billion. The challenge extends beyond Shanghai; over 50 cities in China, including Tianjin, Taiyuan, Xi'an, Wuxi and Cangzhou, have areas of more than two metres of subsidence.[108]

Today, Shanghai also faces a compounded risk landscape, as land subsidence can converge with global sea-level rise and intensifying weather patterns. These intersecting threats place immense pressure on flood defences and critical infrastructure, necessitating continuous advanced prevention, mitigation and adaptation strategies.[109,110]

Solutions

Shanghai's response to land subsidence has been defined by a blend of policy innovation, infrastructure investment and nature-based solutions over the decades. While not all solutions are centred on combating land subsidence, they help to minimize sinking by rebalancing the urban water system.

- **Early interventions**: Initial measures included regulating deep wells, pioneering artificial groundwater recharge (e.g. the "winter recharge and summer withdrawal" policy), establishing monitoring networks and relocating factories to suburban areas.[111] These efforts temporarily reduced subsidence, but rapid urban development in the 1990s led to renewed challenges, driven by groundwater pumping to dry out sites for large construction projects, the increased weight of new high-rises and continued reliance on groundwater.[112,113]
- **Regulatory transformation**: In 2013, Shanghai enacted the Regulation of Prevention and Control of Land Subsidence of Shanghai Municipality, recognized for its alignment with strategic environmental assessment principles.[114] It is viewed as a science-based framework integrating groundwater management, robust monitoring and risk-based zoning. Key features include:
  - **Land and water management:** Shanghai set a strict annual subsidence cap of 6mm, enforced by multiple city departments. It also shifted water reliance to surface sources and continued artificial groundwater recharge.

Shanghai's journey highlights that addressing subsidence requires broader consideration of urban development, local soil conditions and climate pressures.

- **Control zones and construction materials**: The regulation implemented a zoning-based risk classification system, requiring geotechnical assessments, continuous monitoring and tailored foundation methods for new developments. High-risk areas were required to use lightweight, high-strength materials and deep-pile foundations, directly linking construction practices to subsidence management.

- **Monitoring and collaboration**: Land subsidence and groundwater detection networks were established, providing critical data to understand, evaluate and supervise groundwater extraction and construction activities. Additionally, formalized cross-department collaboration ensures coordinated action, for instance, related to planning, water management and construction.

- **Nature-based infrastructure**: Since 2016, Shanghai has participated in China's "sponge city" programme, integrating green infrastructure, water conservancy and technological upgrades to restore natural water cycles. Solutions, such as green roofs, permeable pavements, rain gardens and constructed wetlands, collectively absorb and reuse stormwater, reduce flood risks and support groundwater recharge.[115]

  Sixteen districts have renovated spaces into sponge parks. Notable examples include the 54-hectare Starry Sky Park in Lingang, which filters and redirects stormwater into natural channels, a rainwater garden in Nanhui New City, and conservation green spaces with water permeable bricks in Rainbow Bay Park, Hongkou District.[116]

Takeaways

According to the International Journal of Environmental Research and Public Health, Shanghai's average annual subsidence rate has dropped to 5mm. While localized uneven sinking persists, the city's overall approach offers learning opportunities and a model for urban leaders seeking to build resilience against land subsidence and related risks.

- **Decisive prioritization**: Shanghai's progress reflects the importance of recognizing land subsidence as a significant threat and acting proactively to address it before further or catastrophic damage occurs.

- **Integrated planning**: The city's progress was not achieved through isolated measures but through the convergence of regulation, infrastructure investment and active monitoring, demonstrating the value of multistakeholder action.

- **Systems approach**: Shanghai stands out as a city that has recognized the impacts of urbanization on land and water. The city's journey highlights that addressing subsidence requires broader consideration of urban development, local soil conditions and climate pressures. Such an approach can enable the movement towards systems thinking for building resilience.

2.3 Rotterdam's resilience: engineering a future on water

Population

~1 million

Area

~326km^2

Context

Rotterdam, a port city situated in the low-lying delta of the Netherlands, is vulnerable to land subsidence. With significant portions of the city located below sea level, ongoing groundwater management is essential to maintain land for agriculture, industry and urban living. Its location renders subsidence a persistent challenge with surface water playing a key role in reducing sinking risk.[117,118]

Subsidence rates tend to be most pronounced in areas built on reclaimed land and peat soil. These conditions exacerbate flood risks, threaten infrastructure and accelerate saltwater intrusion. In response, Rotterdam has adopted strategies combining engineering, innovative urban design, policy measures and community engagement.

Solutions

The city employs a multi-layer approach to manage water and stabilize land.

– **National programmes**: Rotterdam benefits from the Netherlands' Delta Works Programme, including the Maeslant storm surge barrier, a system of dikes, locks and barriers that provide flood protection and mitigate subsidence.[119] This programme is sustained by a policy foundation and an annual budget of €1.25 billion funded by the national government until 2032. In specific programmes, like the Freshwater Delta Plan, there are cost-sharing responsibilities between different government bodes.

– **Large-scale infrastructure**: The 2013 Rotterdam Climate Change Adaptation Strategy and the Rotterdam Climate Initiative (RCI) have made water resilience central to spatial planning.[120] The city's adaptive network of canals, lakes, retention areas, pumping stations and sewer systems helps to address climate risks. Notable projects include the Museumpark underground water storage (10,000m^3 capacity) and extensive green roof installation (over 185,000m^2) to manage stormwater.[121] These efforts help mitigate the consequences of subsidence.

↑ **A rowing facility in the Eendragtspolder water storage facility for flood prevention:** Rotterdam, the Netherlands

- **Innovative urban planning and design**: Micro-scale innovations such as the Benthemplein water square serves as a flood retention basin during heavy rain and a public plaza. Supported by the RCI and local water boards, agencies collaborate on funding, design and maintenance to ensure the space serves functional and social purposes.[122] While Eendragtspolder, a major water storage site, has been transformed into a recreational area, blending flood management with community amenities.[123,124] These projects ease pressure on traditional sewer systems and reduce surface flooding.[125]

- **Stakeholder collaboration**: The Rotterdam Adaptation Strategy (RAS) and RCI unites public agencies, utilities, research institutions and citizens around shared adaptation goals.[126] Coordination between municipal agencies and regional water boards ensure sustained funding, ongoing maintenance and community involvement. These efforts signal a shift from reactive flood control to proactive, integrated strategies. Moreover, governance has shifted from a top-down model to one that empowers community-led initiatives, supported by tools like the Climate Game and incentives for green infrastructure.[127,128]

- **Knowledge and technology**: A consortium consisting of government agencies, private sector and other stakeholders have developed a programme on subsidence. They focus on advancing measurements to improve understanding, evaluating control measures and developing legal strategies for effective implementation. Outputs include satellite-based monitoring, predictive models and integrated approaches that strengthen the governance, finance and legal capacity.[129]

Takeaways

Rotterdam's experience demonstrates that urban resilience is an ongoing, adaptive process requiring evidence-based knowledge, agility and collaboration. Key lessons for cities and stakeholders worldwide include:

– **Integrated planning**: Addressing flood risks linked to land subsidence and the climate crisis requires adopting and integrating various solutions rather than isolated interventions. Rotterdam demonstrates the value of combining large and small-scale infrastructure, urban planning and design, regulatory and legal frameworks and community engagement for continuous adaptation. Such an approach can create opportunities for multistakeholder collaboration within an interconnected ecosystem.

– **Governance and sustained investment**: For governments, Rotterdam's approach highlights the need for legal frameworks and dedicated budgets. For the private sector, it signals the importance of understanding subsidence and flooding challenges related to urban planning and infrastructure development, management and expansion.

– **Adaptability in a changing climate**: Complete elimination of subsidence and flood risks may not be possible due to unique geological conditions, and especially as climate change accelerates sea-level rise and extreme weather events. Continuous monitoring, scenario analysis and adaptive management are critical. Both governments and businesses should embed flexibility into their strategies to respond to evolving subsidence and climate conditions.

FIGURE 7 **Rotterdam flood risk map, 2100**

Flood risk map – 2100

The risk map depicts the areas where it is expected that water storage deficits will occur in the future, and where unequal subsidence makes the area more vulnerable to the effects of intensive rainfall. These are mainly areas that are built on peat. Furthermore, the map shows the bottlenecks: the sewer system, groundwater and low-lying infrastructure such as tunnels.

Water issues

Current water storage deficit areas (NBW – National Water Agreement)

Subsidence (cm/year) -0.1–0.5 0.5–1 >1

Bottlenecks and vulnerable areas

Bottleneck sewers; Bottleneck flooding due to groundwater; City centre with considerable consumer pressure on the open spaces

Urban area with little open space; Urban area with much open space; Low-lying infrastructure

Source: Rotterdam Climate Initiative. (2013). *Rotterdam Climate Change Adaptation Strategy*. https://www.urbangreenbluegrids.com/uploads/RCI_-RAS_UK_-DEF.pdf

2.4 Jakarta's actions: confronting subsidence and flooding

Population	Area
~10.7 million	~661.5km^2

Context

Jakarta, Indonesia's sprawling megacity, is among the fastest-sinking cities globally. The city's location on a delta plain, intersected by numerous rivers, combined with rapid urbanization, contributes to subsidence. The city has tripled in size in four decades, with the weight of development impacting its highly compressible soil in some areas. In some parts of northern districts, land subsidence has reached up to 280mm per year, primarily due to excessive groundwater extraction for domestic and industrial use.[130]

Accelerating subsidence increases Jakarta's vulnerability to flooding and infrastructure damage, creating major challenges for sustainable urban planning and management. This risk is compounded by extreme weather events, including rainfall, such as the 377mm downpour recorded in a single day in January 2020, which overwhelmed and caused disruptions in some areas of the city.[131]

Solutions

Jakarta city government and national authorities' response is defined by a multi-layered strategy that combines regulatory reforms, water resource management and infrastructure investment to reduce groundwater extraction and flooding risks.

- **Water infrastructure**: The approach spans upstream, midstream and downstream interventions. Upstream, the focus is on expanding retention wells and reservoirs (47 built by the city, 49 by other institutions, 41 planned) to delay runoff and support downstream systems. Midstream, an extensive system of 38 primary and 36 secondary drainage channels is managed jointly by local and national jurisdiction.[132] Downstream, the National Capital Integrated Coastal Development (NCICD) project features a 37.3km sea wall, polder systems and pumping stations.[133] As of 2023, 8.2km of coastal embankments and retention ponds have been completed.[134] The NCICD exemplifies national-level coordination, special task forces and openness to global partnerships.

The transition to piped water requires the assurance of equitable and reliable access to safe drinking water for every household, especially the most vulnerable.

– **Regulatory frameworks**: Jakarta is strengthening regulations to reduce groundwater extraction, particularly in high-risk areas. Jakarta Governor Regulation 93/2021 establishes groundwater-free zones, prohibiting buildings with a gross floor area exceeding 5,000m² from using groundwater where piped water is available.[135] The Zero Delta Q policy mandates stormwater absorption systems in new developments. The Jatiluhur 1 and Karian Serpong water systems aim for 100% piped water coverage by 2030, reducing reliance on deep wells. The effectiveness of these policies depends on aligning the groundwater-free zone with areas most affected by subsidence.

Takeaways

Jakarta is addressing sinking challenges and associated risks. The city has had the potential to exchange information and learnings with peers managing similar issues since the early 1900s, as well as harnessing research, data, technological advancements, partnerships and regulatory reforms to mitigate and adapt.

– **Integrated planning**: No single solution can tackle subsidence and flooding risks alone. The success of the NCICD hinges on national coordination, while piped water infrastructure expansion would be ineffective without widespread public-private sector participation, managing illegal groundwater extraction and ensuring efforts are adequately aligned with high-risk subsidence and flood risk areas.

– **Balancing development and sustainability**: Jakarta's rapid urbanization has also been a driver of subsidence. Their strategies reflect a growing awareness of the need to balance growth with sustainable practices. The shift towards reducing groundwater dependence and investing in surface water and flood defences highlights an evolving understanding that unchecked development can exacerbate urban threats.

– **Compliance, equity and community engagement**: Without curbing illegal groundwater extraction by the public and businesses, success will be undermined. The transition to piped water requires not only knowledge sharing and behavioural change, but also the assurance of equitable and reliable access to safe drinking water for every household, especially the most vulnerable.[136] This highlights the crucial role of governance in making sure policies have a tangible and widespread impact. Community engagement is also essential as millions will depend on these implemented solutions for their safety and livelihoods.

2.5 What solutions are adopted by cities?

Review of the use cases points to adopting an integrated approach where multistakeholder collaboration, proactive investment, policy reform and systems-thinking are essential. A range of solutions exists to address the threat of sinking cities. No single intervention is sufficient; maximum impact can be achieved when multiple measures are implemented in a coordinated, cohesive manner across global, regional and local levels.

FIGURE 8 **Examples of city solutions that help address sinking levels (non-exhaustive)**

Infrastructure updates and development

- Expansion of surface water treatment plans and piped distribution network
- Large-scale drainage infrastructure, to also manage flood risks
- Retention wells and network of reservoirs to capture surface water
- Managed aquifer recharge
- Coastal protection infrastructure
- Nature-based and green infrastructure integration

Policy and regulation

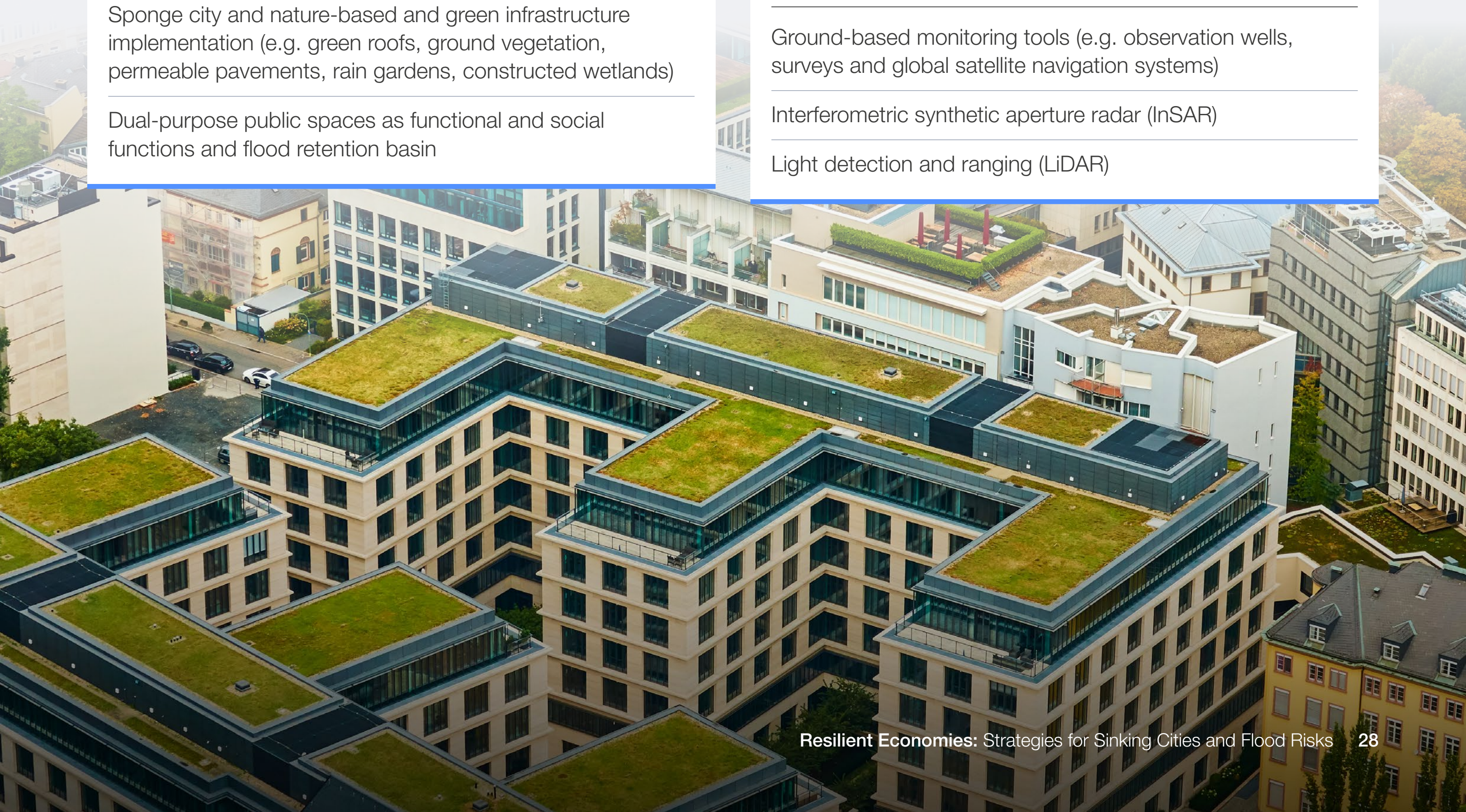
- Prohibition and limitations of groundwater use
- Enabling zoning laws to manage subsidence
- Requirements for building materials and mandatory geotechnical assessments
- Coordinated long-term water systems framework
- Water conservation (e.g. rainwater infiltration and reclaimed wastewater)
- Environmental plans for building owners
- Setting strict maximum allowed subsidence

Urban planning and design

- Sponge city and nature-based and green infrastructure implementation (e.g. green roofs, ground vegetation, permeable pavements, rain gardens, constructed wetlands)
- Dual-purpose public spaces as functional and social functions and flood retention basin

Technology and data

- Ground-based monitoring tools (e.g. observation wells, surveys and global satellite navigation systems)
- Interferometric synthetic aperture radar (InSAR)
- Light detection and ranging (LiDAR)



Stakeholders are encouraged to consider unintended consequences, including the impact of local water and land management on cities, economies and communities.

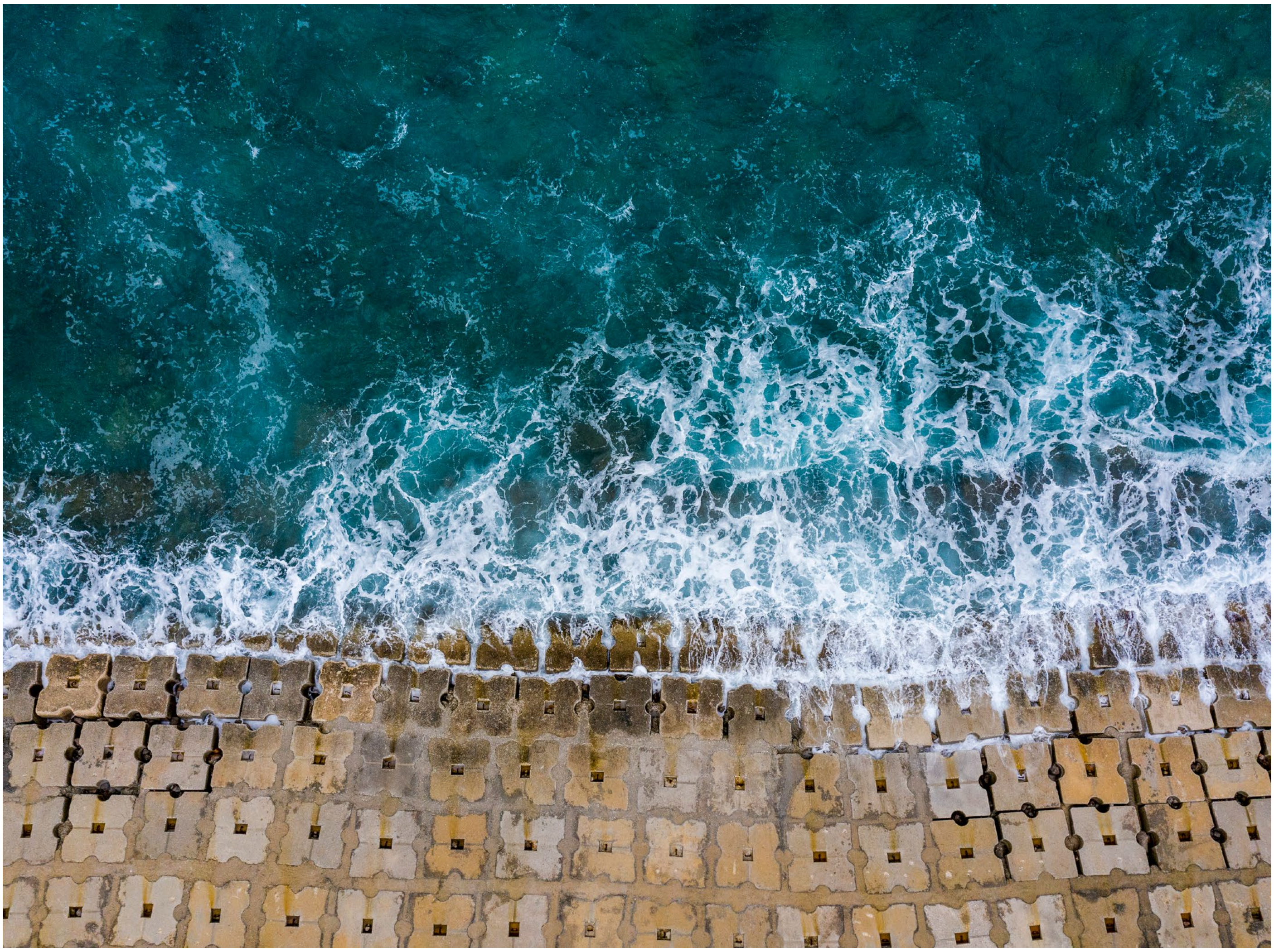
To identify the most suitable and sustainable strategies, each city must assess its unique context, including geographic characteristics, underlying subsidence drivers, development and climate risk factors, fiscal capacity and stakeholder alignment.

Careful evaluation of each solution's benefits, drawbacks, and potential combinations can enable cities to implement context-specific, feasible, and sustainable approaches. In assessing the appropriate solutions, stakeholders are also encouraged to consider unintended consequences, including the impact of water and land management on cities, economies and communities upstream and downstream from their location.

Peer-to-peer exchange and evidence-based learning are critical. By drawing on tried-and-tested solutions, cities and their partners can better understand the benefits, limitations and unintended consequences of solutions, such as:

- Retention infrastructure can support flood control in subsiding areas, but may involve high capital costs, environmental disruption and community displacement.
- Sea walls can protect against tidal floods and storm surges, but can cause land erosion and beach loss by blocking the natural movement of sand, potentially undermining their own effectiveness.[137]
- Dams can potentially disrupt the sediment flow, leading to erosion below the dam. A lack of sediment replenishment in delta areas can also cause the loss of wetlands.[138]
- Underground discharge channels can reduce surface flooding, but can require significant investment and technical requirements for large-scale impact.[139]
- Green roofs can enhance water absorption and reduce runoff, though they require upfront investment and regular maintenance compared to standard roofs. However, long-term savings can offset costs.[140]

Engaging public-private sector experts who understand the interconnections and long-term impacts of these solutions is key preventing current and future risks and costs of subsidence and compounding impacts. Sinking challenges also provide opportunities to harness technologies such as digital twins, satellite, artificial intelligence (AI) or machine learning, and the internet of things (IoT) to obtain reliable, up-to-date data and real-time data to inform decision-making.



3 The way forward

Breaking reactive cycles requires a bold mindset shift, making land and water stewardship central to resilient, prosperous cities.

3.1 Is a mindset shift needed to make progress?

As urban land subsidence intensifies alongside the global climate crisis, the need for collective, multistakeholder action has never been greater. Despite its significant impacts – from increased flooding, infrastructure damage, social displacement and public health concerns – subsidence remains underrepresented in policy agendas and corporate risk frameworks. However,evidence and action taken by several cities such as Tokyo, Shanghai, Jakarta and Rotterdam, as well as insights from leading experts, suggest that meaningful progress is possible when there is clear intent, sustained commitment and informed leadership.

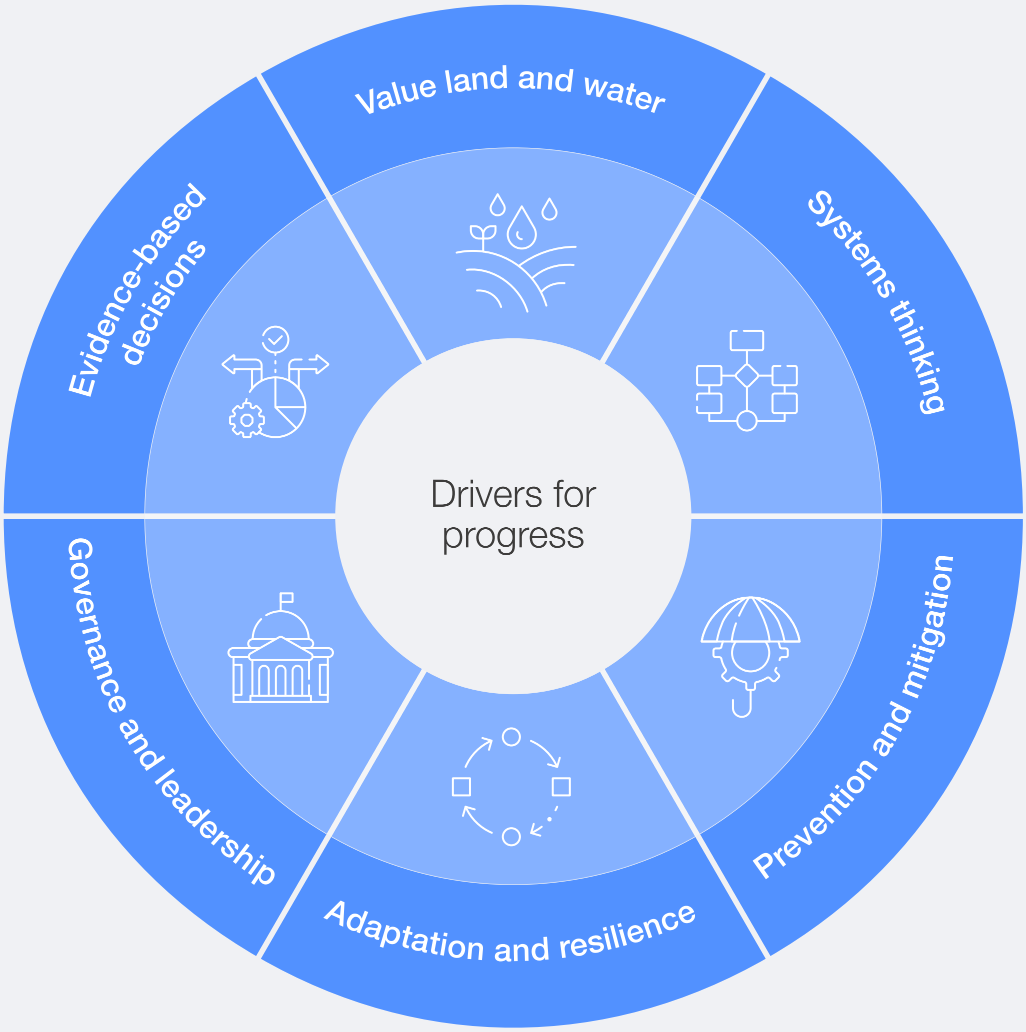
Historically, responses to subsidence have been largely reactive, centred on crisis management rather than building immediate and long-term resilience. To break this cycle, leaders across the public and private sectors must collaborate to develop and implement sustainable, forward-looking strategies. Success will require ongoing dialogue, consensus-building and coordinated, cohesive action among diverse stakeholders.

A fundamental shift in mindset is needed – one that recognizes land, water and other natural resources as central to economic, social and environmental stability and well-being.

We must realize the importance of cooperation and looking at the root cause of issues holistically. Ecosystems are interconnected and a remediation programme may have detrimental impacts to other areas downstream.

Devin Yaung, Senior Vice-President, Group Entreprise IoT Products and Services, NTT

FIGURE 9 **Key drivers for addressing sinking cities and associated risks**



Key drivers explained:

Value land and water as strategic assets: Human activities are the primary drivers of subsidence. Addressing sinking challenges requires a fundamental shift in how land and water are valued and used in urban planning, economic development and sustainability practices. Future growth must prioritize these resources as finite and critical assets, embedding resource-conscious practices to reduce subsidence risks, and compounding risks through its interplay with climate change. By prioritizing the stewardship of these resources, stakeholders can help secure their availability, quality and quantity for current and future generations.

Enable systems thinking: Adopting a systems approach is essential to understand the complex interdependencies, behaviours and feedback loops between human activities, natural assets and their economic, social and environmental impacts. By committing to best practices in systems thinking, leaders can move beyond fragmented policies, data and solutions, enabling the development of integrated and effective strategies.

This perspective can support the design, maintenance and adaptive reuse of built environments to better withstand subsidence and compounding risks. It can also encourage innovation and enable more effective targeting of investments, ensuring that urban development is resilient, resource-efficient and aligned with sustainability goals.

Focus on prevention and mitigation: Proactive strategies must address the root causes of land subsidence and create interventions to reduce risks and costs through a holistic, systems approach. This includes accounting for the interplay between subsidence, sea-level rise and extreme weather, as these factors can amplify risks together. To ensure interventions are comprehensive and sustainable, effective mitigation efforts should be integrated into broader urban and environmental planning frameworks.

Strengthen adaptation and resilience: Building the capacity of cities, economies and communities to anticipate, withstand and adapt to evolving risks is essential. Comprehensive strategies should address the combined effects of subsidence and climate change. By advancing the ability to withstand shocks, stakeholders can minimize risks, enable rapid recovery and enhance the overall resilience of urban systems.

Encourage strong governance and leadership: Effective governance and strong leadership are foundational for building urban resilience in places impacted by subsidence and climate extremes. Demonstrated commitment at national, regional and local levels serves as a catalyst for transformative change, enabling cross-sector and cross-community engagement.

Governance frameworks should be guided by principles of collaboration, sustainability, efficiency, scalability, equity, accountability and transparency. Multistakeholder collaboration is indispensable, as no single actor can address the multifaceted risks of subsidence alone. Given the close link between subsidence and groundwater use, ensuring equitable access to sustainable surface water sources is critical to reducing pressure on groundwater resources and curbing illegal extraction.

Governance should ensure that prevention to resilience plans extend beyond city boundaries, recognizing that activities in one area can have unintended consequences elsewhere. A coordinated, cohesive approach can enable comprehensive resilience planning, establishment of clear benchmarks and facilitation of knowledge-sharing.

Evidence-based decisions: Commit to using evidence to guide decisions on addressing subsidence. Accurate and reliable quantitative and qualitative data can inform policies, best practices and solutions. It can help combat misinformation, enable informed communication and knowledge sharing and build accountability. This approach strengthens the foundation for impactful action and can promote trust across sectors.

“ By committing to best practices in systems thinking, leaders can move beyond fragmented policies, data and solutions, enabling the development of integrated and sustainable strategies.

FIGURE 10 | **How sinking cities arise, its systemic impacts and making progress**

Factors: increases land subsidence and associated risks

Over extraction of underground resource and mining

(e.g. water, oil, gas, geothermal)

Urbanization pressures

(e.g. increased load related to geological conditions, inadequate land use practices)

Climate change

(e.g. sea-level rise, extreme weather: rainfall, storms, heatwaves, drought, wildfires)

Natural conditions and shifts

(e.g. local geology, seasonal groundwater fluctuations seismic activity)

Impacts: direct and indirect threats of land subsidence and compounding risks, particularly when sinking land interacts with climate risks

Environmental

- Flooding
- Coastal and inland habitat loss (e.g. biodiversity, wetlands, marshes, beaches)
- Saltwater intrusion
- Freshwater contamination
- Groundwater aquifer storage reduction
- Land loss, soil erosion, sand and sediment disruptions

Economic

- Infrastructure damages and management disruptions (e.g. buildings, utilities, transport)
- Property devaluation, housing and office space availability
- Business, operational and supply chain disruptions and displacement
- Workforce and job disruptions
- Agricultural risks: food and water stability
- Increased costs and resource disruptions

Social

- Health, well-being and safety risks (e.g. waterborne and vector-borne diseases, respiratory, toxic contaminations, injuries)
- Social displacement and instability
- Socioeconomic disparities, including financial security
- Increased vulnerability to residents of informal settlements and slums
- Reduced workforce and education participation (especially for the most vulnerable groups)[141]

Drivers and enablers: foundational components to address subsidence and compounding risks

- **Land and water as high value and finite strategic assets**
- **Strong governance and leadership**
- **Systems thinking and a holistic approach**
- **Evidence-based approaches and decisions**
- **Prevention and mitigation**
- **Adaptation and resilience**
- **Effective regulation and policy**
- **Building resilient infrastructure**
- **Investment and financial mechanisms**
- **Research, technology and data**
- **Stakeholders and community**

Addressing land subsidence and compounding risks depends on a holistic understanding of the interconnections, behaviours and feedback loops between factors, impacts, drivers and enablers. Effective understanding of these relationships are essential for fostering and sustaining places where people would want to live, work and visit both in the short- and long-term.

3.2 What are the key enablers of positive change?

Research, case studies and expert perspectives highlight several enablers to addressing subsidence, including regulation and policy, infrastructure and investment, community and stakeholder engagement, and technology, data and research.

Regulation and policy

Regulation and policy provide the strategic foundation for addressing land subsidence, translating vision into actionable standards, incentives and compliance mechanisms. Evidence-based policy, developed through multistakeholder consensus, is essential to driving effectiveness.

Policy alone, however, is not sufficient. Success depends on the alignment of legal frameworks with infrastructure readiness and institutional coordination, particularly in rapidly urbanizing or resource-constrained places. Integrated policy and infrastructure interventions, such as Tokyo's Building Water Act, demonstrate how such solutions can halt severe subsidence.[142]

Although there are currently no international standards specific to land subsidence, several existing guidelines and technical standards address aspects of subsidence management within broader themes of engineering practices, groundwater management and disaster risk reduction. Harnessing and harmonizing such guides can support subsidence risk management at local, national and international levels. International frameworks such as the Sendai Framework for Disaster Risk Reduction 2015-2030 and UN-Habitat's New Urban Agenda encourage countries to integrate land-use planning, water management and geophysical risk monitoring into their national strategies.[143,144] Standard bodies focusing on geotechnical monitoring and measurements of soil also provide direction (e.g. ISO 14688).[145]

Infrastructure and investments

Resilient infrastructure and strategic investment are central to preventing, mitigating and adapting to sinking cities and building resilience. Interventions range from protective measures, such as sea levees and aquifer replenishment, to nature-based solutions. Adopting context-specific infrastructure solutions informed by local geological and climate conditions is crucial, as a one-size-fits-all approach can be counterproductive. For instance, a sea wall that is beneficial in one location may cause long-term land erosion elsewhere. Thus, understanding the intended impacts of proposed solutions is critical for managing subsidence-related risks and costs.

> Focus must shift from reactive repairs to anticipatory investments that protect critical assets against subsidence and climate risks.

The focus must shift from reactive repairs to anticipatory investments that protect critical assets (e.g. water systems, utilities, buildings) against subsidence and climate risks. Improving water systems is particularly important, including the following actions:

- **Reduce aquifer dependence**: Implement policies and incentives to transition from over-extraction of groundwater to alternative water sources.
- **Expand surface water supply**: Invest in infrastructure to diversify and expand surface water resources.
- **Adopt circular water use**: Integrate nature-based solutions, such as green roofs, rain gardens and infiltration parks, to enhance water absorption and enable rainwater harvesting and greywater reuse.
- **Promote conservation and education**: Strengthen public understanding of the links between human behaviour, land and water use, and their economic and social consequences.

Investment is fundamental to these strategies. While governments often lead large-scale projects, such as Tokyo's $2.8 billion G-Cans flood project, the limited commercial viability of many interventions calls for innovative funding models. The private sector can play a pivotal role through public-private partnerships, green bonds and land value capture mechanisms.

Cities such as Tokyo, Shanghai and Rotterdam demonstrate the power of integrated approaches over time. Tokyo halted decades of subsidence by expanding its piped water supply and regulating groundwater use, while Rotterdam's water square exemplified multifunctional infrastructure. With regards to commercial incentives, the private sector can fully or co-finance resilience structures, benefitting from development rights or future revenue linked to property valuation. To ensure long-term impact, cities must make use of diverse financial instruments aligned with policy objectives.

❝ **Machine learning/AI-powered predictive models can optimize water resource distribution, drainage management and infrastructure maintenance.**

Empower stakeholders and communities

Active participation from communities, businesses, governments, research institutions, non-profits and residents is essential. These stakeholders are not merely beneficiaries but active agents of positive change. Engagement should move beyond consultation and empower communities with knowledge, tools and agency to steward their built environments.

Miami-Dade County's Resilience Hub Network, which provides climate education and emergency support, exemplifies how direct engagement promotes behavioural shifts and localized resilience. Involving residents and local businesses in strategy development is critical for capturing valuable local knowledge, raising awareness of subsidence risks, and ensuring that mitigation and adaptation efforts are tailored to community needs and economic realities.

The private sector plays a pivotal role in advancing subsidence resilience. Businesses, particularly those in high-water-use industries, such as agriculture, mining, manufacturing and energy and those driving urban expansion, can co-finance resilience projects, innovate and design solutions that can reduce pressure on land and water aquifers. By understanding the feedback loops between their operations, subsidence rates and asset vulnerability, the private sector can proactively manage risks across their value chains.

Effective governance should facilitate these collaborations and support capacity-building initiatives that transform resilience from a technical goal into a shared economic, environmental and social commitment.

Technology, data and research

Technology and data are foundational enablers of urban resilience to land subsidence. Advanced monitoring tools, such as InSAR, can provide large-scale data on land movement and groundwater levels, supporting accurate risk assessments, targeted interventions and verification of impact. Accurate risk projections must also account for spatial variations in subsidence.[146,147]

Beyond monitoring, technology, innovation, continued research (including R&D) and learnings can drive the evolution of intelligent urban systems. Machine learning/AI-powered predictive models can optimize water resource distribution, drainage management and infrastructure maintenance, while digital twins can simulate subsidence impacts and support future-proof urban planning.

Research into resilient building materials and construction techniques can help enhance infrastructure longevity in subsidence-vulnerable areas. Digital platforms can enable rapid scaling of solutions and knowledge exchange among cities and stakeholders.

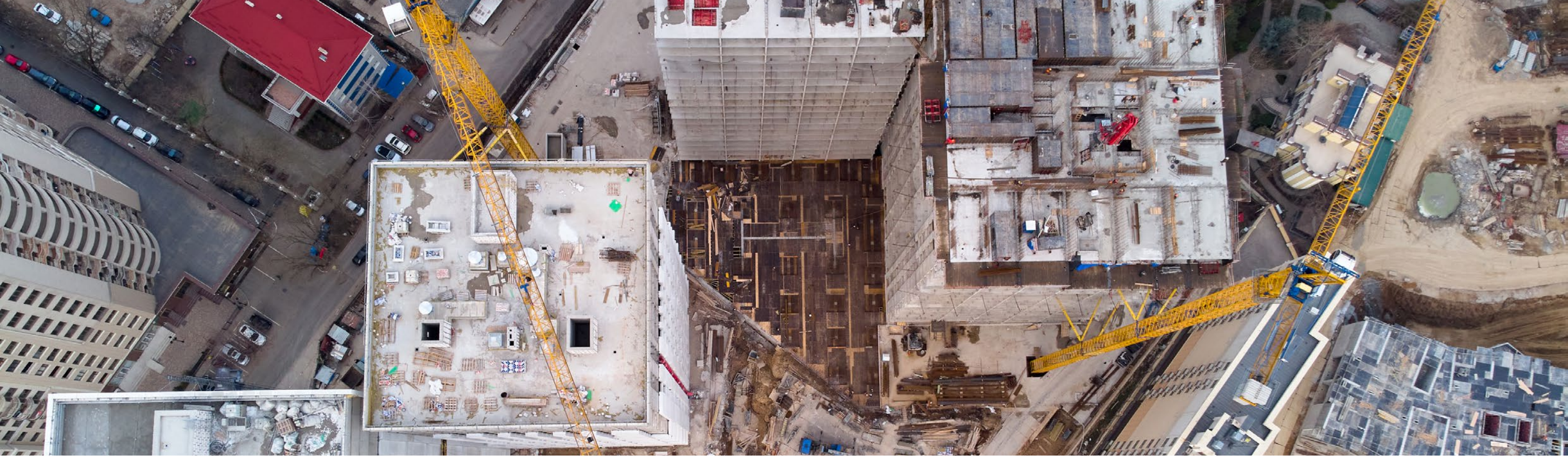
Building networks and ecosystems through partnerships can accelerate the development and deployment of proven solutions for land subsidence and compounding factors.

A collaborative and data-driven approach can help quantify previously under-recognized risks, impact levels and costs, guide investments, optimize resource allocations, enable timely alerts, and ensure urban planning remains agile and responsive to growing and emerging risks.

TABLE 1 | **Key drivers and enablers for addressing sinking cities**

Driver/enabler		Description
Value of natural assets	Land, water and air	Land, water and air are recognized as high value, strategic natural assets, essential for sustaining life and economic activity. Their value is assessed not only in terms of immediate economic and social utility, but also through the lens of preserving quality (reducing pollution) and quantity, while ensuring long-term sustainability.
Overall resilience and preparedness	Prevention	Implement strategies and solutions to identify and address the root causes of land subsidence, particularly those driven by human activity. Early intervention is essential to prevent the onset and escalation of risks.
	Mitigation*	Build targeted interventions that reduce the severity, costs and impacts of land subsidence, as well as the factors that exacerbate these risks.
	Adaptation*	Adjust urban systems and practices in response to actual or anticipated land subsidence and compounding risks, with the aim of avoiding harm.
	Resilience*	Resilience is the capacity of human systems to withstand, respond to and reorganize to subsidence and compounding risks, while maintaining their essential functions, identity and structure, and ability learn and adapt.
Systems thinking and evidence-based decisions	Understand interdependencies with evidence	Comprehend the complex interdependencies, behaviours and feedback loops between human activities, land subsidence, climate risks, and their impacts on the economy, environment and society based on evidence.
	Integrated approaches and solutions	Combine urban planning, policy development, infrastructure, investment, technology, innovation and data, and nature-based solutions, guided by evidence and predictive insights to deliver holistic and sustainable outcomes.
Governance and leadership	Willingness to act	Local and national governments must understand the immediate and long-term risks posed by land subsidence, its interaction with climate change risks and demonstrate strong commitment to address challenges through decisive leadership and sustained action.
	Foundational regulations and policies	Implement evidence-based legal, regulatory and policy frameworks to mandate and guide actions for the prevention, mitigation, adaptation and resilience to subsidence, while aligning with boarder climate resilience objectives.
	Cross-government and institution coordination	Facilitate interagency and multi-level collaboration to ensure coordinated, cohesive and integrated strategies to address subsidence and risks.
Communities and stakeholders	Resident and community engagement	Actively involve residents and communities as key partners in addressing subsidence. Harnessing local knowledge and lived experiences can inform effective strategies and enable the co-creation and delivery of tailored solutions.
	Private sector or non-government engagement	Engage businesses and non-governmental organizations in learnings, strategy development, implementation and investment, including local data collection and sharing of practical experiences.
Resilient infrastructure and investments	Transition from groundwater to surface water	Reduce reliance on groundwater by prioritizing the use of sustainable surface water sources.
	Proactive infrastructure investment	Move beyond reactive repairs through forward-looking infrastructure planning. Prioritize upfront investments to enhance resilience, ensuring critical systems are prepared to withstand future shocks and stresses.
	Nature-based solutions and climate-risk-resilient designs	Integrate natural systems and climate resilience principles (e.g. sponge solutions, wetlands restoration, mangrove protection) into urban planning and development to enhance water absorption, reduce flood risks and protect coastlines.
Technology, data and research	Data-driven actions	Use data from current and emerging technologies, innovation, research insights, including advanced satellite technologies and predictive modelling tools and other reliable sources, to inform decisions.
	Continuous understanding	Facilitate ongoing accurate and reliable qualitative and quantitative research and collaborations with businesses, governments, institutions, academia and civil society to unlock timely information to support measurements, monitoring, assessments, evaluations and predictive analytics for subsidence and its interaction with climate risks.

*Definitions modified and based on: Intergovernmental Panel on Climate Change (IPCC). (2019). Annex I: Glossary. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Edited by P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, et al. https://www.ipcc.ch/site/assets/uploads/2019/11/11_Annex-I-Glossary.pdf.



3.3 What actions can the public and private sectors take?

Effectively addressing land subsidence, alongside the compounding risks associated with sea-level rise and extreme weather events, requires a coordinated, cohesive multistakeholder approach. National and local governments, large corporations, small and medium-sized enterprises (SMEs), technology providers, academia, civil society and local communities each have critical roles to play in advancing urban resilience. The following action areas highlight how diverse stakeholder groups can contribute to addressing subsidence and related challenges.

TABLE 2 **Action areas for public-private sectors and stakeholders to address sinking cities (non-exhaustive)**

Stakeholders	Recommended actions
Governments (national/local)	Develop national-level directives and masterplans on land subsidence intervention and adaptation strategies.
	Establish multistakeholder governance platforms (at basin, national and transboundary levels) to monitor the progress of land subsidence and coordinate water management, data-sharing and investment priorities.
	Facilitate and/or provide funding and financing support to implement national and local initiatives through: – Development of investable projects with clear risk-return profiles – Blended finance mechanisms (e.g. concessional loans, guarantees, and co-investment) – Water-related green bonds, water credits, or payments for ecosystem services to finance groundwater and land subsidence solutions – Innovation-friendly regulatory environments that allow experimentation with emerging technologies
	Identify root causes of land subsidence to inform targeted policies and interventions; use reliable and accurate data from satellite and other sources.
	Regulate and progressively reduce unsustainable groundwater extraction while investing in alternative sources.
	Develop national frameworks to value water's full cost (economic, environmental and social), integrating pricing mechanisms that reflect water quality and quantity, and ecosystem services and align with global initiatives to promote consistency in water valuation and data collection.
	Develop and enforce zoning regulations on high-risk subsidence areas.
	Use nature-based solutions where possible for groundwater retention.
	Engage and provide incentives for businesses, civil society organizations, residents and other stakeholders in land subsidence strategy planning and implementation, while ensuring inclusive governance by including women, Indigenous groups, youth and others.
	Strengthen capacity-building programmes for residents and businesses on land subsidence and water risk management.
	Integrate social protection measures and livelihood support for communities most affected by land subsidence.
	Create multistakeholder innovation platforms linking government, utilities and technology firms (e.g. 50L Home Coalition model), and use these data in planning decisions, including regular monitoring of land subsidence and flooding.

TABLE 2 | **Action areas for public-private sectors and stakeholders to address sinking cities (non-exhaustive) (continued)**

Stakeholders	Recommended actions
Construction and real estate	Carry out geotechnical and subsidence risk surveys.
	Account for construction load in building and foundation design.
	Adopt soil-sensitive construction and stabilization methods.
	Build future-proof structures, such as more-elevated buildings, to account for any land subsidence risks.
	Leverage adaptive reuse of existing structures and brownfield development opportunities where possible, in lieu of new greenfield development.
	Implement water-conscious design and use alternative water sources apart from groundwater.
	Integrate nature-based solutions in building design, such as green roofs and walls.
	Employ district and masterplan development strategies that make use of shared water resources, preserve green and blue spaces, and optimize stormwater management solutions.
	Engage in public-private partnerships for co-financing resilient infrastructure.
Technology providers	Advance real-time monitoring and early warning technologies
	Obtain reliable data and perform data analytics to inform decision-makers on targeted land subsidence solutions and compounding risks.
	Advance IoT and AI to provide real time visibility into issues that cause subsidence, particularly water waste. These can include leak sensors, flow meters and water level meters to gather real time information.
	Advance emerging technologies such as photonics and nanotechnologies to alleviate water stresses (e.g. photonics for data centres, IoT for agriculture and manufacturing, digital twins).
Urban planners	Integrate land subsidence risk and sponge city and green infrastructure principles into spatial planning and urban design.
	Advocate for long-term planning horizons, moving beyond political cycles to ensure sustainability.
Agriculture	Use efficient irrigation and shift to less water-intensive crops where possible.
	Implement regenerative agricultural practices such as cover cropping, composting and crop rotation to maintain soil structure and reduce erosion.
	Strengthen farmer education and do capacity building on groundwater use and land subsidence.
	Use drip irrigation and efficiency rebates.
	Implement managed recharge (e.g. recharge basins and flood irrigation recharge).
	Encourage farmer reservoirs for rainwater storage.
Utilities	Assess and monitor subsidence along pipelines, treatment plants and other assets to understand and address risks.
	Transition from groundwater to surface or recycled water.
	Retrofit or relocate buried infrastructure if needed, considering both short- and long-term implications.
	Develop affordable sustainable water management solutions.
	Enhance rainwater management, including incorporating rainwater harvesting systems that capture, store and release water gradually, promoting soil absorption rather than surface runoff.
Fashion	Adopt regenerative agriculture or agroecology paradigm in practice.
	Implement water recycling within fashion supply chains.
	Apply rain-fed agriculture to reduce freshwater use in fibre production and use rain-fed varieties of crops (e.g. organic cotton).

TABLE 2 | **Action areas for public-private sectors and stakeholders to address sinking cities (non-exhaustive) (continued)**

Stakeholders	Recommended actions
Insurance and finance	Use subsidence data in underwriting and risk-based premiums.
	Partner in public-private risk pooling models.
	Require disclosure of groundwater reliance in high-risk zones.
	Offer premium reductions for structures with mitigation measures.
	Finance adaptive infrastructure and recharge projects.
	Integrate subsidence risk into environmental, social and governance (ESG) due diligence and credit scoring.
Transport	Reroute new infrastructure away from highly compressible soils and use advanced technologies, data and modelling to inform decisions.
	Monitor structural integrity in differential-settling zones.
	Elevate rail beds, roads and bridges while accounting for load (dependent on soil type and conditions).
Mining and gas	Predict and map mining-induced subsidence; adopt mine-design (leave pillars, backfill) and surface-management buffers.
	Compensate and reinforce infrastructure and monitor post-mining settlement.
	Limit large-scale fluid removal without recharge plans; monitor reservoir compaction and surface movement.
	If extraction causes subsidence, require operator mitigation plans and remediation funds.
Manufacturing	Adopt industrial water-reuse and closed-loop cooling systems; reduce groundwater sourcing.
	Participate in water-stewardship and community recharge projects.
Academia and research	Offer data, policy and innovation inputs on subsidence through research and modelling.
	Produce localized risk maps and tools to support policy and innovation.
Civil society	Promote public awareness and behavioural change.
	Monitor policy enforcement and empower local action.
	Develop training modules for capacity building and knowledge sharing for governments and citizens.
	Participate in dialogues and multistakeholder partnerships on water management and land subsidence to strengthen accountability and trust.
Communities and individuals	Shift from groundwater to surface water use, including learning about water conversation best practices.
	Participate in building public awareness of land subsidence and associated risks including its interplay with climate change.
	Understand land subsidence and associated risks when building and buying houses.
	Hold relevant stakeholders accountable for land subsidence and climate risks initiatives.

Note: Given that subsidence levels vary from place to place, these recommendations are more relevant for some cities, sectors and stakeholders compared to others.

CASE STUDY 3

Utilities infrastructure management under sinking conditions

The gas distribution network operator Stedin in the Netherlands is addressing critical infrastructure challenges posed by land subsidence. With a network spanning 23,000km of pipelines, Stedin operates in a region where soft soils are prone to gradual sinking. While most buildings in the area have deep foundations and remain stable, the gas pipelines, embedded in the shifting ground, are susceptible to movement. This differential movement creates stress points, particularly at the connections between pipelines and buildings, increasing the risk of pipeline fractures and service disruptions.

To mitigate these risks, Stedin has embedded subsidence management into its strategic planning. The company employs advanced radar-based monitoring technologies, such as InSAR, to capture high-resolution data on ground movement across its network. This enables the early identification of vulnerable pipeline segments and supports the prioritization of maintenance activities. By integrating subsidence data into asset management and maintenance planning, Stedin exemplifies a shift from reactive repairs to a proactive, risk-based approach. This enables targeted interventions before critical failures occur, thereby enhancing both safety and service reliability. A pilot project near Rotterdam demonstrated the effectiveness of this approach, resulting in a 15–20% improvement in maintenance budget efficiency.

Their experience highlights the value of using technology and data-driven decision-making to strengthen infrastructure resilience in the face of subsidence risks. This model offers insights for utilities and infrastructure operators globally, demonstrating how adoption of such practices can mitigate the impacts of land subsidence, safeguard critical services and optimize investment in infrastructure resilience.[148]

Conclusion

Sinking cities or urban land subsidence, while often gradual and shaped by complex local and geological factors, now stands as a critical global challenge requiring urgent and coordinated action. The convergence of accelerating sea-level rise, intensifying extreme weather events and rapid urbanization signals that the risks facing cities and communities will only intensify and can compound in areas with subsidence. Proactive resilience-building must become the norm, integrated into the fabric of urban planning and development, rather than relying on managing subsidence as reactive crisis management modes.

Recent years have demonstrated the consequences of inaction, including flooding risks and damage to critical infrastructure in areas with land subsidence. Embedding resilience into urban systems is vital to ensure that economies, societies and environmental ecosystems can withstand, adapt to and recover from negative impacts with minimal disruption.

Collective action across the public and private sectors is essential. By adopting a systems approach and employing proven prevention, mitigation, adaptation and resilience strategies, stakeholders can minimize the risks of flooding, infrastructure damage and social disruption from land subsidence and where it is compounded by climate risks. Leadership, robust governance, evidence-based decision-making and multistakeholder collaboration, including the voices of directly affected communities, are vital to drive meaningful progress.

Positioning land subsidence as a core element of climate and urban resilience agendas will empower cities, businesses and societies to secure long-term prosperity and enhance the liveability of urban environments. The moment for decisive, integrated and collaborative action is now.

Contributors

World Economic Forum

Anu Devi
Lead, Strategic Insights,
Centre for Urban Transformation

Jane Tjahjono
Project Fellow,
Centre for Urban Transformation

Deloitte

Risha Ardelia
Analyst, SEA Consulting

Agnes Malau
Analyst, SEA Consulting

Nadia Wijanarko
Consultant, SEA Consulting

Acknowledgements

We thank the following leaders and experts for their contribution, expertise and perspectives.

Hasanuddin Z. Abidin
Professor in Geodesy and Geomatics Engineering, Institute of Technology Bandung

Cipta Aditya
Head, Infrastructure and Environment Subdivision 3, Jakarta Regional Development Planning Agency (Bappeda)

Afan Adriansyah Idris
Assistant, Development and Environment, Regional Secretariat of Jakarta Special Capital Region (DK Jakarta)

Karol Bot
Research Scientist, Arctic Basecamp

Jake Chidester
Vice-President, Strategy and Innovation, Bedrock

Antonio Gómez-Palacio
Chair, Dialog

Devyani Kar
Principal Resilience Scientist, Jacobs

Michael Lake
CEO, Leading Cities

Katherine Lang
Senior Knowledge Lawyer, Real-Estate, Baker McKenzie

Rianne Leitner
Communications Specialist, World Economic Forum

Onoda Masami
Director, International Relations and Research Department, Japan Aerospace Exploration Agency (Jaxa)

Robert Nicholls
Director, Tyndall Centre for Climate Change Research, University of East Anglia

Rebecca Ochong
Director, Government Relations & International Advocacy, Habitat for Humanity International

Jean-Philippe Salcedo
Programme Lead, Economics of Freshwater, World Economic Forum

Nishchal Sardjoe
Head, Urban Resilience and Spatial Transformation, Deltares

Manoochehr Shirzaei
Associate Professor of Geophysics and Remote Sensing, Virginia Tech Corporate Research Center

Taylor Spicer
Executive Director, Engineers & Scientists Acting Locally

Susy Torriente
Global Principal for City Resilience, Jacobs

Gregory Wessel
Founder and President, Geology in the Public Interest

Devin Yaung
Senior Vice-President, Group Enterprise IoT Products and Services, NTT

Production

Phoebe Barker
Designer, Studio Miko

Laurence Denmark
Creative Director, Studio Miko

Blake Elsey
Designer, Studio Miko

Martha Howlett
Editor, Studio Miko

Endnotes

1. Davydzenka, T., Tahmasebi, P., & Shokri, N. (2024). Unveiling the global extent of land subsidence: The sinking crisis. *Geophysical Research Letters*, vol. 51, no. 1, pp. 1–11. https://doi.org/10.1029/2023GL104497.
2. United Nations Office for Disaster Risk Reduction (UNDRR). (n.d.) *Global map shows nineteen percent of the global population may face a high probability of subsidence*. https://www.preventionweb.net/news/global-map-shows-nineteen-percent-global-population-may-face-high-probability-subsidence#:~:text=Eighty%20six%20percent%20of%20the,areas%20and%20guide%20mitigation%20efforts.
3. Kok, S., & Costa, A. L. (2021). New framework for assessing the economic impact of land subsidence. *Natural Hazards*, vol. 106, no. 4, pp. 1931–1949. https://doi.org/10.1007/s11069-021-04520-3.
4. Erkens, G., Bucx, T., Dam, R., de Lange, G., & Lambert, J. (2015). Sinking coastal cities. *Proceedings of the International Association of Hydrological Sciences*, vol. 372, pp. 189–198. https://doi.org/10.5194/piahs-372-189-2015.
5. ClimateCheck. (n.d.). *Coastal Flooding, Subsidence vs Sea Level Rise*. https://climatecheck.com/risks/flood/coastal-flooding-subsidence-sea-level-rise#:~:text=The%20subsidence%20of%20land%20in,Geologic%20Factors%20of%20Subsidence.
6. Blackwell, E. (2020). Tracking California's sinking coast from space: Implications for relative sea-level rise. *Science Advances*, vol. 6, no. 31, eaba4551. https://doi.org/10.1126/sciadv.aba4551.
7. Navarro-Hernández, M. I. (2023). Analysing the impact of land subsidence on flooding risk: Evaluation through InSAR and modelling. *Water Resources Management*, vol. 37, pp. 4363–4383. https://doi.org/10.1007/s11269-023-03561-6.
8. Nature. (2025). Addressing land subsidence impacts. *Nature*, vol. 2, pp. 543–554. https://www.nature.com/articles/s44284-025-00240-y.
9. Willemsen, W. (2020). The effect of land subsidence on real estate values. *Proceedings of the International Association of Hydrological Sciences*, vol. 382, pp. 703–707. https://doi.org/10.5194/piahs-382-703-2020.
10. Ana, L. (2020). Systematic assessment of damage to buildings due to groundwater lowering-induced subsidence: Methodology for large-scale application in the Netherlands. *Proceedings of the International Association of Hydrological Sciences*, vol. 382, pp. 577–582. https://doi.org/10.5194/piahs-382-577-2020.
11. Yin, Y., Zhang, K., & Li, X. (2006). Urbanization and land subsidence in China. In *Proceedings of the IAEG 2006 Conference*. https://media.geolsoc.org.uk/iaeg2006/PAPERS/IAEG_031.PDF.
12. Liao, H., & Chang, H. (2017). The varying impact of land subsidence and earth fissures on residential property values in Maricopa County: A quantile regression approach. *ResearchGate*. https://www.researchgate.net/publication/312161393.
13. Solano-Rojas, D., Wdowinski, S., Cabral-Cano, E. et al. (2024) Geohazard assessment of Mexico City's Metro system derived from SAR interferometry observations. *Scientific Reports*, vol. 14, no. 6035. https://doi.org/10.1038/s41598-024-53525-y.
14. Chen, M. Li, Z., Tomás, R., Herrera, G., et al. (2025). Land subsidence induced damage assessment along Beijing-Tianjin high speed railway from space using high resolution TerraSAR-X data. *Structural Health Monitoring*, vol. 320, no. 114651. https://doi.org/10.1177/14759217251334328.
15. United Nations Office for Disaster Risk Reduction (UNDRR). (2021). *A new framework for assessing the economic impact of land subsidence*. https://www.preventionweb.net/news/new-framework-assessing-economic-impact-land-subsidence.
16. Kok, S., & Costa, A. L. (2021). Framework for economic cost assessment of land subsidence. *Natural Hazards*, vol. 106, no. 4, pp. 1931–1949. https://doi.org/10.1007/s11069-021-04520-3.
17. Tok, X. (2023). *Sinking cities: Cracks in the ground*. CWRRR Opinions. https://cwrrr.org/opinions/sinking-cities-cracks-in-the-ground/.
18. Valley Water. (n.d.) *Subsidence*. https://www.valleywater.org/your-water/groundwater/subsidence#:~:text=What%20problems%20can%20subsidence%20cause,all%20susceptible%20to%20subsidence%20damage.
19. Kok, S., & Costa, A. L. (2021). Framework for economic cost assessment of land subsidence. *Natural Hazards*, vol. 106, no. 4, pp. 1931–1949. https://doi.org/10.1007/s11069-021-04520-3.
20. Saputra, E. (2019). *Land subsidence as a sleeping disaster: Case studies from Indonesia*. https://dspace.library.uu.nl/handle/1874/390878.
21. Yin, Y., Zhang, K., & Li, X. (2006). Urbanization and land subsidence in China. In *Proceedings of the IAEG 2006 Conference*. https://media.geolsoc.org.uk/iaeg2006/PAPERS/IAEG_031.PDF.
22. Navarro-Hernández, M. I. (2023). Analysing the impact of land subsidence on flooding risk: Evaluation through InSAR and modelling. *Water Resources Management*, vol. 37, pp. 4363–4383. https://link.springer.com/content/pdf/10.1007/s11269-023-03561-6.pdf.
23. United Nations Educational, Scientific, and Cultural Organization (UNESCO). (n.d.). *General concepts of land subsidence*. Land Subsidence International Initiative. https://www.landsubsidence-unesco.org/general-concepts/.
24. Mester, B., Frieler, K., Korup, O., Desai, B., et al. (2025). Socioeconomic predictors of vulnerability to flood-induced displacement. *Nature Communications*, vol. 16, no. 8296. https://doi.org/10.1038/s41467-025-64015-8.

25. Acosta-España, J.D., Romero-Alvarez, D., Luna, C. & Rodriguez-Morales, A.J. (2024). Infectious disease outbreaks in the wake of natural flood disasters: global patterns and local implications. *Le Infezioni in Medicina*, no. 4, pp. 451–462. https://pmc.ncbi.nlm.nih.gov/articles/PMC11627491/.
26. Schmidt. C.W. (2015). Delta Subsidence: An Imminent Threat to Coastal Populations. *Environmental Health Perspectives*, vol 123, issue 8. https://pmc.ncbi.nlm.nih.gov/articles/PMC4528996/#:~:text=Apart%20from%20the%20increased%20risk,more%20data%2C%E2%80%9D%20he%20says.
27. Hoppe, K.A., Metwali N., Perry, S.S., Hart, T., et al. (2013, 1 December). Assessment of airborne exposures and health in flooded homes undergoing renovation. *Indoor Air*, vol. 6, pp. 446–456 https://pmc.ncbi.nlm.nih.gov/articles/PMC3484189/.
28. Manke, K. (2023, 20 June). *Rising Groundwater Threatens Thousands of Toxic Sites in the Bay Area*. University of California, Berkeley. https://vcresearch.berkeley.edu/news/rising-groundwater-threatens-thousands-toxic-sites-bay-area.
29. DIALOG. (n.d.). *Community Wellbeing Framework*. https://dialogdesign.ca/community-wellbeing-framework/.
30. Shamsuddoha, M., Akib Jabed, M., Shahnul Islam, M., Sultana, N. et al. (2024). Impacts of climate change-induced natural hazards on women and their human rights implications: A study in the southwest coast of Bangladesh. *Journal of Migration and Health*, vol. 4. https://www.sciencedirect.com/science/article/pii/S2666623524000114.
31. Lowe D., Ebi K.L. & Forsberg B. (2013, 11 December). Factors increasing vulnerability to health effects before, during and after floods. *International Journal of Environmental Research and Public Health*, vol. 10, no. 12, pp. 7015–7067. https://pmc.ncbi.nlm.nih.gov/articles/PMC3881153/.
32. Earth.org. (2024). *Subsidence and Sea Level Rise in California. Earth.org Data Visualization*. https://earth.org/data_visualization/california-subsidence-as-the-water-around-it-rises/.
33. Ohenhen, L.O., Shirzaei, M., Ojha, C. et al. (2023). Hidden vulnerability of US Atlantic coast to sea-level rise due to vertical land motion. *Nature Communications*, vol. 14, no. 2038. https://doi.org/10.1038/s41467-023-37853-7.
34. American Geophysical Union. (2024, 28 February). *First global subsidence map reveals sinking problem for cities*. AGU Newsroom. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023GL104497.
35. Lindsey, R. (2023). *Climate change: Global sea level*. Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level.
36. Physical Oceanography Distributed Active Archive Center. (2025, 5 February). *Data in Action: The rate of global sea level rise doubled during the past three decades*. https://podaac.jpl.nasa.gov/DataAction-2025-02-05-The-rate-of-global-sea-level-rise-doubled-during-past-three-decades.
37. Huning, L. S., Love, C. A., Anjileli, H., et al. (2024). Global Land Subsidence: Impact of Climate Extremes and Human Activities. *Reviews of Geophysics*. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023RG000817.
38. Wu, P-C., Wei, M., & D'Hondt, S. (2022). Subsidence in coastal cities throughout the world observed by InSAR. *Geophysical Research Letters*, vol. 49, no. 6. https://doi.org/10.1029/2022GL098477.
39. Ibid.
40. Nature. (2025). *Addressing land subsidence impacts*. Nature. https://www.nature.com/articles/s44284-025-00240-y.
41. Zapata-Norberto, B., Morales-Casique, E., Contreras-Galván, R., Ramos-Leal, J.A. (2025). Land subsidence in Mexico City: New insights from field data and numerical modeling. *Groundwater for Sustainable Development*, vol. 29, no. 101432. https://www.sciencedirect.com/science/article/pii/S2352801X25000293.
42. Babaee, S. et al. (2024). Spatiotemporal characterization of the subsidence and change detection in Tehran plain (Iran) using InSAR observations and Landsat 8 satellite imagery. *Remote Sensing Applications: Society and Environment*, vol, 36, no 101290. https://www.sciencedirect.com/science/article/pii/S235293852400154X.
43. Khorrami, M., Shirzaei, M., Ghobadi-Far, K., Werth, S., et al. (2023). Groundwater volume loss in Mexico City constrained by InSAR and GRACE observations and mechanical models. *Geophysical Research Letters*, vol. 50, no. 5, e2022GL101962. https://doi.org/10.1029/2022GL101962
44. Abidin, H.Z., Andreas, H., Gumilar, I. et al. (2011). Land subsidence of Jakarta (Indonesia) and its relation with urban development. *Natural Hazards*, vol. 59, pp. 1753–1771. https://doi.org/10.1007/s11069-011-9866-9.
45. Bott, L-M., Schöne, T., Illigner, J., Haghshenas Haghighi, M., et al. (2021). Land subsidence in Jakarta and Semarang Bay – The relationship between physical processes, risk perception, and household adaptation. *Ocean & Coastal Management*, vol. 211, no. 105775. https://doi.org/10.1016/j.ocecoaman.2021.105775.
46. Kooi, H., Salzer, J., Jaimerena, B.A., Stuurman, R. (2023). *Assessment of Land Subsidence in New Orleans*. Deltares. https://nola.gov/nola/media/Stormwater/Assessment-of-Land-Subsidence_20230510.pdf.
47. Ahmed, S., Hiraga, Y., & So, K. (2024). Land subsidence in Bangkok vicinity: Causes and long-term trend analysis using InSAR and machine learning. *Science of the Total Environment*, vol. 946, no. 174285. https://doi.org/10.1016/j.scitotenv.2024.174285.
48. Intergovernmental Panel on Climate Change (IPCC). (2021). *Sixth Assessment Report (AR6)*. https://www.ipcc.ch/assessment-report/ar6/.
49. Nguyen, T.C., Schwarzer, K., & Ricklefs, K. (2023). Water-level changes and subsidence rates along the Saigon-Dong Nai River Estuary and the East Sea coastline of the Mekong Delta. *Estuarine, Coastal and Shelf Science*, vol. 283, no. 108259. https://doi.org/10.1016/j.ecss.2023.108259.

50. Intergovernmental Panel on Climate Change (IPCC). (2021). *Sixth Assessment Report (AR6)*. https://www.ipcc.ch/assessment-report/ar6/.

51. He, X., Yang, T., Shen, S., Xu, Y., & Arulrajah, A. (2019). Land Subsidence Control Zone and Policy for the Environmental Protection of Shanghai. *Environmental Research and Public Health*. https://pmc.ncbi.nlm.nih.gov/articles/PMC6696418/.

52. Ibid.

53. Zanchettin, D. Bruni, S. Raicich, F. Lionello, P. (2020). Review article: Sea-level rise in Venice: historic and future trends. *Natural Hazards and Earth System Sciences*, vol. 21, issue 8. https://nhess.copernicus.org/articles/21/2643/2021/.

54. Younger, S. (2023). *NASA-Led Study Pinpoints Areas of New York City Sinking, Rising*. NASA Jet Propulsion Laboratory (JPL). https://www.jpl.nasa.gov/news/nasa-led-study-pinpoints-areas-of-new-york-city-sinking-rising/.

55. NASA (n.d.). *Climate Impacts in New Yok City: Sea Level Rise and Coastal Floods*. https://www.giss.nasa.gov/edu/icp/research/ppa/2002/impacts/introduction.html.

56. Lyu, M., Li, X., Ke, Y., Jiang, J., et al. (2024). Nonlinear Evolutionary Pattern Recognition of Land Subsidence in the Beijing Plain. *Remote Sensing*, vol. 16, issue 15, no. 2829. https://doi.org/10.3390/rs16152829.

57. Song, X., Zhang, J., AghaKouchak, A., Roy, S.S., et al. (2014). Rapid urbanizationand changes in spatiotemporal characteristics of precipitation in Beijingmetropolitan area. *Journal of Geophysical Research: Atmospheres*, vol. 119, no. 19, pp. 11250–11271, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JD022084.

58. Haghshenas Haghighi, M., & Motagh, M. (2019). Ground surface response to continuous compaction of aquifer system in Tehran, Iran: Results from a long-term multi-sensor InSAR analysis. *Remote Sensing of Environment*, vol. 221, pp. 534–550. https://doi.org/10.1016/j.rse.2018.11.003.

59. Gao, Y., Zhu, C., & Yang, R. (2024). Land subsidence analysis using InSAR along the RiLan high-speed railway in Heze, China. *Survey Review*, vol. 57, issue 402, pp. 273–283. https://doi.org/10.1080/00396265.2024.2421042.

60. Hussain, M.A., Chen, Z., & Khan, J. (2024). Monitoring land subsidence in the Peshawar District, Pakistan, with a multi-track PS-InSAR technique. *Environmental science and pollution research international*, vol. 31, pp. 12271–12287. https://doi.org/10.1007/s11356-024-31995-x.

61. Ikuemonisan, F.E., & Ozebo, V.C. (2020). Characterisation and mapping of land subsidence based on geodetic observations in Lagos, Nigeria. *Geodesy and Geodynamics*, vol. 11, issue 2, pp. 151–162. https://doi.org/10.1016/j.geog.2019.12.006.

62. CBS News. (2025, 8 May). *These 28 major U.S. cities are sinking, new study finds — and researchers say damage may only appear when it's "potentially catastrophic"*. https://www.cbsnews.com/news/cities-are-sinking-new-study-finds-damage/.

63. Ibid.

64. Ibid.

65. Krajick, K. (2025, 8 May). *All of the biggest U.S. cities are sinking*. Columbia Climate School. https://news.climate.columbia.edu/2025/05/08/all-of-the-biggest-u-s-cities-are-sinking/.

66. Sousa, J. J., Ruiz, A. M., Hanssen, R. F., Bastos, L., et al. (2010). PS-InSAR processing methodologies in the detection of field surface deformation—Study of the Granada basin (Central Betic Cordilleras, southern Spain). *Journal of Geodynamics*, vol. 49, issues 3–4, pp. 181–189. https://doi.org/10.1016/j.jog.2009.12.002.

67. Bagheri, M., Dehghani, M., Esmaeily, A., & Akbari, V. (2019). Assessment of land subsidence using interferometric synthetic aperture radar time series analysis and artificial neural network in a geospatial information system: Case study of Rafsanjan Plain. *Journal of Applied Remote Sensing*, vol. 13, issue 4, https://doi.org/10.1117/1.JRS.13.044530.

68. Ojha, C., Werth, S., & Shirzaei, M. (2019). Groundwater loss and aquifer system compaction in San Joaquin Valley during 2012–2015 drought. *Journal of Geophysical Research: Solid Earth*, vol. 124, issue 3, pp. 3127–3143. https://doi.org/10.1029/2018JB016083.

69. Miller, M. M., & Shirzaei, M. (2015). Spatiotemporal characterization of land subsidence and uplift in Phoenix using InSAR time series and wavelet transforms. *Journal of Geophysical Research: Solid Earth*, vol. 120, issue 7, pp. 5822–5842. https://doi.org/10.1002/2015JB012017.

70. Tay, C.W.J., Lindsey, E.O., Chin, S.T., McCaughey, J.W., et al. (2022). Sea-level rise from land subsidence in major coastal cities. *Nanyang Technological University*. https://www3.ntu.edu.sg/CorpComms2/Releases/NR2022/NR_220920_sinkingcities/Sea-level%20rise%20from%20land%20subsidence%20in%20major%20coastal%20cities.pdf.

71. Wu, P-C., Wei, M. (M.), & D'Hondt, S. (2022). Subsidence in coastal cities throughout the world observed by InSAR. *Geophysical Research Letters*, vol. 49, issue 6. https://doi.org/10.1029/2022GL098477.

72. Pandit, A., et al. (2025). Mapping land subsidence in Ahmedabad City, India: Interpreting InSAR-derived land subsidence with auxiliary data. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, X-G-2025, pp. 613–622. https://doi.org/10.5194/isprs-annals-X-G-2025-613-2025.

73. van der Horst, T., Rutten, M.M., van de Giesen, N.C., & Hanssen, R.F. (2018). Monitoring land subsidence in Yangon, Myanmar using Sentinel-1 persistent scatterer interferometry and assessment of driving mechanisms. *Remote Sensing of Environment*, vol. 217, pp. 101–110. https://doi.org/10.1016/j.rse.2018.08.004.

74. Yu, X., Wang, G., Hu, X., Liu, Y., & Bao, Y. (2023). Land Subsidence in Tianjin, China: Before and after the South-to-North Water Diversion. *Remote Sensing*, vol. 15, issue 6, no. 1647. https://doi.org/10.3390/rs15061647.

75. Bagheri-Gavkosh, M., Hosseini, S.M., Sohani, Y., et al. (2021). Land subsidence: A Global Challenge. *Science of the Total Environment*, vol. 778. https://www.sciencedirect.com/science/article/abs/pii/S0048969721012602.

76. Huning, L.S., Love, C.A., Anjileli, H. Vahedihfard, F., et al. Global Land Subsidence: Impact of Climate Extremes and Human Activities. *Advancing Eart and Space Sciences*, vol. 62, issue 4, https://doi.org/10.1029/2023RG000817.

77. Ibid.

78. Parsons, T. (2021). The Weight of Cities: Urbanization Effects on Earth's Subsurface. *Advancing Earth and Space Sciences*, vol. 2, issue 1. https://doi.org/10.1029/2020AV000277.

79. Parsons, T. (2021). The Weight of Cities: Urbanization Effects on Earth's Subsurface. *AGU Advances*, vol. 2, issue 1. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020AV000277.

80. Huning, L.S., Love, C.A., Anjileli, H., et al. (2024). Global Land Subsidence: Impact of Climate Extremes and Human Activities. *Reviews of Geophysics*, vol. 62, issue 4. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023RG000817.

81. Metzger, L. (2018). *Land Subsidence*. USGS Science for a Changing World. https://www.usgs.gov/water-science-school/science/land-subsidence#overview.

82. Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., et al. (2012). Subsidence in drained coastal peatlands in Southeast Asia: Implications for sustainability. *Biogeosciences*, vol. 9, issue 1, pp. 1053–1071. https://www.researchgate.net/publication/228759314_Subsidence_in_drained_coastal_peatlands_in_SE_Asia_Implications_for_sustainability.

83. Zhang, Y., & Guo, H. (2019). Evaluation of the impact of urbanization factors on land subsidence by GWR. 2019 IEEE International Conference on Geoscience and Remote Sensing Symposium (IGARSS). *IEEE*. https://ieeexplore.ieee.org/document/8882441.

84. Guzy, A., & Malinowska, A.A. (2020). Assessment of the Impact of the Spatial Extent of Land Subsidence and Aquifer System Drainage Induced by Underground Mining. *The Department of Mining Surveying and Environmental Engineering, AGH University of Science and Technology*, vol. 12, issue 19. https://www.mdpi.com/2071-1050/12/19/7871?utm.

85. Baù, D., & Ferronato, M. (2020). Subsidence induced by gas extraction: A data assimilation framework to constrain the driving rock compaction process at depth. *Frontiers in Earth Science*, vol. 8, no. 179. https://www.frontiersin.org/articles/10.3389/feart.2020.00179/full.

86. James, R.A., Fowler, S.L., & Tolliver, C.H. (n.d). *Subsidence from Geothermal Operations: Navigating the Regulatory Landscape and Potential Claims*. Pillsbury. https://www.pillsburylaw.com/en/news-and-insights/subsidence-geothermal-operations-regulatory-claims.html.

87. Ohenhen, L.O., Zhai, G., Lucy, J. et al. (2025). Land subsidence risk to infrastructure in US metropolises. *Nature Cities*, vol. 2, pp. 543–55. https://doi.org/10.1038/s44284-025-00240-y.

88. Maryudhaningrum, S.T., Cakrabuana, W., Marthakusuma, L., et al. (2025). Land subsidence due to groundwater extraction and natural consolidation in the Bandung Basin, West Java, Indonesia. *Geological Society of America Bulletin*, vol. 123, issues 9–10, pp. 240–252. https://www.researchgate.net/publication/233543296_Land_Subsidence_due_to_Groundwater_Extraction_and_Natural_Consolidation_in_the_Bandung_Basin_West_Java_Indonesia.

89. United Nations Educational, Scientific and Cultural Organization (UNESCO). (n.d.). *Land Subsidence International Initiative (LaSII)*. https://www.landsubsidence-unesco.org/lasii/.

90. Gotoh, H., Takeawa, M., Maeno, Y., Oshiki, H., et al. (2009). Development and restoration of the urban rivers: examples from old downtown Tokyo, Japan. In *River Basin Management V*. Edited by C.A. Brebbia. Wessex Institute of Technology. https://www.witpress.com/Secure/elibrary/papers/RM09/RM09007FU1.pdf.

91. Sato, C., Haga, M., Nishino, J. (2006). Land Subsidence and Groundwater Management in Tokyo. *International Review for Environmental Strategies*, vol. 6, no. 2, pp. 403–424. https://www.iges.or.jp/system/files/publication_documents/pub/peer/1208/IRES_Vol.6-2_403.pdf.

92. Gotoh, H., Takeawa, M., Maeno, Y., Oshiki, H., et al. (2009). Development and restoration of the urban rivers: examples from old downtown Tokyo, Japan. In *River Basin Management V*. Edited by C.A. Brebbia. Wessex Institute of Technology. https://www.witpress.com/Secure/elibrary/papers/RM09/RM09007FU1.pdf.

93. Sato, C., Haga, M., Nishino, J. (2006). Land Subsidence and Groundwater Management in Tokyo. *International Review for Environmental Strategies*, vol. 6, no. 2, pp. 403–424. https://www.iges.or.jp/system/files/publication_documents/pub/peer/1208/IRES_Vol.6-2_403.pdf.

94. Water Resources Policy Division, Land and Water Bureau. (2006). *Outline of Ground Water Management in Japan*. https://www.narbo.jp/data/01_events/materials/tw03_5_2_1.pdf.

95. Japan International Cooperation Agency (JICA). (2022). *Theme 7 Groundwater Management: Securing Alternative Water Sources along with Regulations*. https://www.jica.go.jp/Resource/english/our_work/thematic_issues/water/fh$_2$q4d000000ruz4-att/theme_07.pdf.

96. World Economic Forum. (2024, 18 September). *Forest conservation is key to safeguarding Japan's underground water. Here's why*. https://www.weforum.org/stories/2024/09/forest-conservation-key-safeguarding-japan-underground-water/.

97. Japanese Law Translation. (n.d.). *Act on the regulation of extraction of groundwater for use in buildings*. https://www.japaneselawtranslation.go.jp/en/laws/view/3367.

98. Japan International Cooperation Agency (JICA). (2022). *Japan's Experience on Water Resources Management*. https://openjicareport.jica.go.jp/pdf/1000047169_01.pdf.

99. Tokyo Water. (n.d.). *Water purification plants*. https://www.tokyowater.co.jp/en/service/plant/.

100. Reuters. (2024). *Tokyo Expands Underground 'Temple' Complex to Counter Climate Change Rains*. https://www.reuters.com/investigates/special-report/climate-change-japan-rain/.

101. Giuroiu, A. (2024). *How Tokyo Built World's Largest Underground Water Tank for Flood Protection*. Architecture Lab. https://www.architecturelab.net/tokyo-has-the-largest-underground-water-tank-in-the-world/.

102. C40 Cities. (n.d.). *Nature Conservation Ordinance is Greening Tokyo's Buildings*. https://www.c40.org/case-studies/nature-conservation-ordinance-is-greening-tokyo-s-buildings/#:~:text=The%20Nature%20Conservation%20Ordinance%2C%20passed%20in%202001%2C,million%20square%20meters%20of%20greenery%20by%202016.

103. Tokyo Metropolitan Government. (2012). *Tokyo Green Action Plan (Version 3)*. https://www.english.metro.tokyo.lg.jp/documents/d/english/green_action_ver3_english.

104. Sato, C., Haga, M., Nishino, J. (2006). Land Subsidence and Groundwater Management in Tokyo. *International Review for Environmental Strategies*, vol. 6, no. 2, pp. 403–424. https://www.iges.or.jp/system/files/publication_documents/pub/peer/1208/IRES_Vol.6-2_403.pdf.

105. Ibid.

106. He, X., Yang, T., Shen, S., Xu, Y., & Arulrajah, A. (2019). Land Subsidence Control Zone and Policy for the Environmental Protection of Shanghai. *Environmental Research and Public Health*, vol. 16, issue 15. https://pmc.ncbi.nlm.nih.gov/articles/PMC6696418/.

107. Zhan, Y., Zhang, Y., Zhang, J. et al. (2025). Risk assessment of land subsidence in Shanghai municipality based on AHP and EWM. *Scientific Reports*, vol. 15, no. 7339. https://doi.org/10.1038/s41598-025-91109-6.

108. Yin, Y., Zhang, K., & Li, X. (2006). Urbanization and land subsidence in China. In *Proceedings of the IAEG 2006 Conference*. https://media.geolsoc.org.uk/iaeg2006/PAPERS/IAEG_031.PDF.

109. Zhan, Y., Zhang, Y., Zhang, J. et al. (2025). Risk assessment of land subsidence in Shanghai municipality based on AHP and EWM. *Scientific Reports*, vol. 15, no. 7339. https://doi.org/10.1038/s41598-025-91109-6.

110. Wang, J., Yi, S., Li, M., Wang, L., & Song, C. (2018). *Effects of sea level rise, land subsidence, bathymetric change and typhoon tracks on storm flooding in the coastal areas of Shanghai*. https://pubmed.ncbi.nlm.nih.gov/29179079/.

111. He, X., Yang, T., Shen, S., Xu, Y., & Arulrajah, A. (2019). Land Subsidence Control Zone and Policy for the Environmental Protection of Shanghai. *Environmental Research and Public Health*. https://pmc.ncbi.nlm.nih.gov/articles/PMC6696418/.

112. Yin, Y., Zhang, K., & Li, X. (2006) Urbanization and land subsidence in China. In *Proceedings of the IAEG 2006 Conference*. https://media.geolsoc.org.uk/iaeg2006/PAPERS/IAEG_031.PDF.

113. He, X., Yang, T., Shen, S., Xu, Y., & Arulrajah, A. (2019). *Land Subsidence Control Zone and Policy for the Environmental Protection of Shanghai. Environmental Research and Public Health*. https://pmc.ncbi.nlm.nih.gov/articles/PMC6696418/.

114. Ibid.

115. Xu, Y. (2016). *Sponge Cities: An Answer to Floods*. CWRRR. https://cwrrr.org/resources/analysis-reviews/sponge-cities-an-answer-to-floods/.

116. Jiayun, K. (2021). *Shanghai banking on sponge parks to become city of ecology*. City News Service. https://www.shine.cn/news/in-focus/2110146376/.

117. Koster, K., Stafleu, J., & Stouthamer, E. (2018). Differential subsidence in the urbanised coastal-deltaic plain of the Netherlands. *Netherlands Journal of Geosciences*, vol. 97, pp. 215–227. https://doi.org/10.1017/njg.2018.11.

118. United Nations Office for Disaster Risk Reduction (UNDRR). (2024, 26 September). *How to save a sinking city*. https://www.preventionweb.net/news/how-save-sinking-city.

119. Rotterdam Climate Initiative. (2013). *Rotterdam Climate Change Adaptation Strategy*. https://www.urbangreenbluegrids.com/uploads/RCI_-RAS_UK_-DEF.pdf.

120. Ibid.

121. C40 Cities. (n.d.). *C40 Good Practice Guides: Rotterdam – Climate Change Adaptation Strategy*. https://www.c40.org/case-studies/c40-good-practice-guides-rotterdam-climate-change-adaptation-strategy/.

122. German Institute of Development and Sustainability (IDOS) Research. (2022). *Resilience through placemaking: Public spaces in Rotterdam's climate adaptation approach*. https://www.idos-research.de/discussion-paper/article/resilience-through-placemaking-public-spaces-in-rotterdams-climate-adaptation-approach/.

123. Urban Green Blue Grids. (2025). *Rotterdam Climate Change Adaptation Strategy*. https://www.urbangreenbluegrids.com/uploads/RCI_-RAS_UK_-DEF.pdf.

124. Mariano, C., Marino, M. (2020). *Sustainable urban project: the role of public spaces in adapting cities to the effects of climate change*. Faculdade de Arquitetura da Universidade de Lisboa. https://upcommons.upc.edu/entities/publication/c38931d2-7d33-447b-9fd4-07503c58401d.

125. Public Space. (2013). *"Water Square" in Benthemplein*. https://www.publicspace.org/works/-/project/h034-water-square-in-benthemplein.

126. United Nations Framework Convention on Climate Change (UNFCCC). (n.d.). *Rotterdam Climate Proof*. https://unfccc.int/files/adaptation/cancun_adaptation_framework/application/pdf/rotterdam_climate_proof.pdf.

127. Climate Adaptation Platform Netherlands. (n.d.). *Climate game*. https://klimaatadaptatienederland.nl/en/tools/all-tools/climate-game/.

128. INTERLACE. (n.d.). *Green Roof Subsidy – Rotterdam*. https://interlace-hub.com/green-roof-subsidy-rotterdam.

129. Stouthamer, E., Erkens, G., Cohen, K., et al. (2020). Dutch national scientific research program on land subsidence: Living on soft soils – subsidence and society. *Proceedings of the International Association of Hydrological Sciences*. https://piahs.copernicus.org/articles/382/815/2020/.

130. Abidin, H.Z., Andreas, H., Gumilar, I. et al. (2011). Land subsidence of Jakarta (Indonesia) and its relation with urban development. *Natural Hazards*, vol. 59, pp. 1753–1771. https://doi.org/10.1007/s11069-011-9866-9.

131. Ramadhan, A., & Galih, B. (2020, 3 January). *BMKG sebut curah hujan di Jakarta awal 2020 paling ekstrem dalam sejarah*. Kompas. https://nasional.kompas.com/read/2020/01/03/10141971/bmkg-sebut-curah-hujan-di-jakarta-awal-2020-paling-ekstrem-dalam-sejarah.

132. Bappeda Jakarta. (2025, 2 May). Interview. (J. Tjahjono, Interviewer).

133. Witteveen + Bos. (n.d.). *NCICD – Jakarta: Coastal protection and urban development*. https://www.witteveenbos.com/projects/ncicd-jakarta.

134. Antara News. (2024). *Jakarta coastal embankment development to be complete in 2024: govt*. https://en.antaranews.com/news/302802/jakarta-coastal-embankment-development-to-be-complete-in-2024-govt.

135. Widodo, J., Trihatmoko, E., Setyaningrum, N., Izumi, Y., et al. (2025). Technical and policy analysis: Time series of land subsidence for the evaluation of the Jakarta groundwater-free zone. *Urban Science*, vol. 9, no 3:67. https://doi.org/10.3390/urbansci9030067.

136. Berita Jakarta. (2024). *Clean Water and Piped Drinking Services in Jakarta Optimistic to Reach 100 Percent in 2030*. https://m.beritajakarta.id/en/read/54302/clean-water-and-piped-drinking-services-in-jakarta-optimistic-to-reach-100-percent-in-2030.

137. Hawai'i Institute of Geophysics and Planetology. (n.d.) *Coastal Erosion and Beach Loss in Hawaii*. https://www.higp.hawaii.edu/~scott/GG170/Lab_reading/Coastal_Processes_reading.pdf.

138. Arora, A. (2024). *Dams: Economic Assets of Ecological Liabailities?* Earth.Org. https://earth.org/dams-economic-assets-or-ecological-liabilities/.

139. Canada Water Portal. (2023, 8 September). *Flood Mitigation: Underground Flood Tunnels*. https://waterportal.ca/underground-flood-tunnels/#:~:text=In%20the%20event%20of%20a,Accessed%202023%2D05%2D01.

140. United States General Services Administration (GSA). (2011). *The Benefits and Challenges of Green Roofs on Public and Commercial Buildings GSA*. https://share.google/jl8u56SETcf9LIj3L.

141. Shand, W. and Ndezi, T. 2025. *Community-led Climate Adaptation in Informal Settlements*. World Bank; UN-Habitat (2018). *Pro-poor climate action in informal settlements: Thematic guide*. United Nations Human Settlements Programme. https://unhabitat.org/sites/default/files/2019/05/pro-poor_climate_action_in_informal_settlements-.pdf.

142. Japan International Cooperation Agency (JICA). (n.d.). *Japan's Experiences on Water Supply Development*, pp. 15–16. https://www.jica.go.jp/english/our_work/thematic_issues/water/c8h0vm0000fgpuk7-att/materials_01_03.pdf.

143. United Nations Office for Disaster Risk Reduction (UNDRR). (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030*. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

144. UN-Habitat. (2016). *New Urban Agenda*. https://habitat3.org/the-new-urban-agenda/.

145. International Organization for Standardization (ISO). (2017). *ISO 14688-1:2017: Geotechnical investigation and testing — Identification and classification of soil*. https://www.iso.org/standard/66345.html.

146. Ohenhen, L.O., Shirzaei, M., Ojha, C. et al. (2024). Disappearing cities on US coasts. *Nature*, vol. 627, https://doi.org/10.1038/s41586-024-07038-3.

147. Wu, P.-C., Wei, M., & D'Hondt, S. (2022). Subsidence in coastal cities throughout the world observed by InSAR. *Geophysical Research Letters*, vol. 49, no. 6. https://doi.org/10.1029/2022GL098477.

148. Maccabiani, J. & Visser. I., (2016). Life expectancy estimation for large pipeline networks based on satellite monitoring. In *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure*. Edited by J. Bakker, D.M. Frangopol & K. Breugel. (pp. 1622–1626). Taylor & Francis Group. https://www.taylorfrancis.com/chapters/edit/10.1201/9781315375175-235/life-expectancy-estimation-large-pipeline-networks-based-satellite-monitoring-maccabiani-visser?context=ubx.

WORLD ECONOMIC FORUM

COMMITTED TO IMPROVING THE STATE OF THE WORLD

The World Economic Forum, committed to improving the state of the world, is the International Organization for Public-Private Cooperation.
The Forum engages the foremost political, business and other leaders of society to shape global, regional and industry agendas.

World Economic Forum
91–93 route de la Capite
CH-1223 Cologny/Geneva
Switzerland
Tel.: +41 (0) 22 869 1212
Fax: +41 (0) 22 786 2744
contact@weforum.org
www.weforum.org