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GOVERNING A SINKING CITY: LAND SUBSIDENCE AND TIDAL FLOODING IN SEMARANG

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ABSTRACT

Coastal cities across South and Southeast Asia are sinking faster than the sea is rising, yet planning instruments in many of them still treat inundation as a flooding problem rather than a subsidence problem. This study examined the evidence on land subsidence and tidal flooding in Semarang, Indonesia, and assessed how far that evidence has been absorbed into the city's spatial and development planning. Published measurements from geodetic, interferometric and machine-learning studies were compiled and compared, alongside recorded inundation extents, and the resulting picture was set against global subsidence surveys and against the governance literature on coastal adaptation. Reported subsidence rates for Semarang vary widely across studies, from two to nineteen centimetres per year, but three independent sources converge on six to eleven centimetres per year in the worst-affected coastal districts, a rate that matches or exceeds contemporaneous measurements for Jakarta. Recorded tidal inundation rose from 292.82 hectares in 2020 to 478.85 hectares in 2022. Nearly forty-four per cent of the coastal zone falls in the two highest vulnerability classes. Despite this evidence, subsidence has not been formally designated as a disaster-prone area category in the city's spatial plan. The study argues that the governance gap, rather than the measurement gap, is now the binding constraint, and that the wide dispersion of published rates is itself an obstacle to designation.

ABSTRAK

Kota-kota pesisir di Asia Selatan dan Tenggara turun lebih cepat daripada laju kenaikan muka air laut, namun instrumen perencanaan di banyak kota masih memperlakukan genangan sebagai persoalan banjir, bukan persoalan penurunan muka tanah. Penelitian ini menelaah bukti mengenai penurunan muka tanah dan banjir rob di Kota Semarang serta menilai sejauh mana bukti tersebut terserap ke dalam perencanaan tata ruang dan pembangunan kota. Hasil pengukuran yang telah dipublikasikan dari studi geodetik, interferometri, dan pembelajaran mesin dihimpun dan diperbandingkan, bersama data luas genangan tercatat, lalu diposisikan terhadap survei penurunan muka tanah global dan literatur tata kelola adaptasi pesisir. Laju penurunan yang dilaporkan untuk Semarang sangat beragam antarstudi, dari dua hingga sembilan belas sentimeter per tahun, tetapi tiga sumber independen bertemu pada kisaran enam sampai sebelas sentimeter per tahun di kecamatan pesisir terparah — laju yang setara atau melampaui pengukuran Jakarta pada periode yang sebanding. Luas genangan rob tercatat naik dari 292,82 hektare pada 2020 menjadi 478,85 hektare pada 2022. Hampir empat puluh empat persen wilayah pesisir berada pada dua kelas kerentanan tertinggi. Meskipun demikian, penurunan muka tanah belum ditetapkan secara formal sebagai kategori kawasan rawan bencana dalam rencana tata ruang kota. Penelitian ini berargumen bahwa kesenjangan tata

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	kelola, bukan kesenjangan pengukuran, kini menjadi kendala pengikat. Kata kunci: penurunan muka tanah; banjir rob; tata kelola pesisir; perencanaan tata ruang; adaptasi iklim

1. INTRODUCTION

For most of the past three decades, coastal inundation has been framed publicly as a consequence of climate change acting through sea-level rise. That framing is incomplete in a way that matters for policy. In many of the world's most exposed cities, the land is descending faster than the ocean is ascending, and the dominant driver is local rather than global.

Nicholls et al. (2021) quantified the discrepancy at global scale. While the global mean rate of relative sea-level rise is approximately 2.6 millimetres per year, coastal populations experience 7.8 to 9.9 millimetres per year — up to four times faster — because people are concentrated in subsiding deltas and reclaimed coastal plains. Wu et al. (2022), measuring 99 coastal cities with satellite interferometry, found that subsidence frequently exceeds the rate of sea-level rise, with South, Southeast and East Asia most severely affected and groundwater extraction the probable dominant cause. Tay et al. (2022), examining 48 coastal cities, reported relative land-level change spanning a range far wider than sea-level rise alone could explain.

The policy consequence is direct. Sea-level rise is a global externality that a city cannot control and can only accommodate. Subsidence driven by groundwater extraction is a local externality that a city can, in principle, regulate. Cities that classify their inundation problem correctly gain access to a policy instrument that cities classifying it as sea-level rise do not.

Semarang, on the north coast of Java, is among the most severely affected cities in this global set, and it has been extensively measured. What is less clear is whether the accumulated measurement has changed how the city is planned. This study therefore asks three questions. First, what do the published measurements actually establish about the rate of subsidence, given that reported values differ by an order of magnitude? Second, how does Semarang compare with other sinking cities internationally? Third, has the evidence been absorbed into the city's statutory planning instruments?

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

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Subsidence as a global urban phenomenon

The comparative literature has converged on the finding that anthropogenic subsidence, principally from groundwater withdrawal, is the dominant component of relative sea-level change in many large coastal cities. Wu et al. (2022) and Tay et al. (2022) established this at the level of global city samples, and Nicholls et al. (2021) established its consequences for population exposure. Taken together these studies establish the phenomenon as general rather than local.

Two features of this literature bear on the present study. First, it is overwhelmingly geophysical: the measurement problem has been solved far more thoroughly than the governance problem. Second, it treats cities as observation units rather than as institutions, so the question of why measurement does or does not translate into regulation is largely left open.

Subsidence governance as a wicked problem

Siriwardane-de Zoysa et al. (2021) address that opening directly, characterising land subsidence governance in urban Southeast Asia as a wicked problem in the technical sense: the causal chain crosses institutional boundaries, the affected population is not the population that benefits from the extraction driving it, and no single authority possesses the instruments required for a solution. Their comparative material covers Jakarta, Metro Manila and Singapore.

The wickedness framing supplies this study's central analytical proposition. If subsidence governance fails primarily because of institutional fragmentation rather than ignorance, then additional measurement will not by itself produce policy change, and the diagnostic question becomes whether existing evidence has been translated into the specific legal categories through which planning operates. Wannewitz et al. (2024), mapping adaptation progress across coastal cities globally, find that documented adaptation remains predominantly incremental and rarely reaches the transformational scale that subsidence would require.

Evidence from Semarang and the Java north coast

Semarang is among the most intensively measured subsiding cities in the region. Susilo et al. (2023) published a continuous GNSS dataset from twenty stations along the north coast of Java covering 2010 to 2021, providing the region's most systematic geodetic baseline. Aditiya

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and Ito (2023) applied time-series interferometry to the city using a small baseline subset technique. Bott et al. (2021) connected physical process to risk perception and household adaptation across Jakarta and Semarang Bay.

On the wider north coast, Widodo et al. (2024) mapped subsidence and land cover for Pekalongan and for the Semarang and Demak area using interferometry with cloud-based processing explicitly for spatial planning assessment. Setyaningsih et al. (2024) mapped the spatial and temporal distribution of tidal flooding and vulnerability levels for coastal Semarang.

On the governance side, On the governance side, however, the literature is markedly thinner than on the measurement side, and no study located examines whether the accumulated measurement has been translated into the statutory planning categories through which land use is actually regulated.

Subsidence as a component of relative sea-level rise

Nicholls et al. (2021) establish the framing that governs this study. Global mean relative sea-level rise is approximately 2.6 millimetres per year, but because coastal settlement concentrates in subsiding areas, coastal populations experience between 7.8 and 9.9 millimetres per year — up to four times the climate-driven rate. Their further observation is the one with policy content: anthropogenic subsidence driven by groundwater extraction is, unlike climate-driven sea-level rise, rapidly reversible through policy.

Tay et al. (2022), applying satellite radar interferometry across 48 major coastal cities housing roughly a fifth of the global urban population, measure subsidence velocities between −16.2 and 1.1 millimetres per year, far exceeding the range used in climate assessment, with Asian cities subsiding fastest. Wu et al. (2022), analysing 99 coastal cities from 2015 to 2020 using persistent scatterer interferometry, find that in most cities part of the land subsides faster than sea level rises, with the pattern concentrated in South, Southeast and East Asia and attributed primarily to groundwater extraction.

Measurement and the groundwater driver

Aditiya and Ito (2023) supply the closest independent measurement to the present study. Using time-series interferometry on Sentinel-1 data from 2015 to 2022 with atmospheric correction, they report maximum subsidence of 100 to 120 millimetres per year in the northern and eastern parts of the city and its neighbouring regency, affecting approximately

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twenty per cent of the city's land area, with an adjacent regency subsiding at 50 millimetres per year. They report a correlation coefficient of 0.86 between groundwater conditions and deformation.

Bott et al. (2021) combine interferometric measurement with household survey in the same bay, reporting subsidence up to approximately 100 millimetres per year locally against regional sea-level rise of 2.1 millimetres per year measured by radar altimetry since 1993. Their social finding is the more unexpected one: slow-onset subsidence becomes normalised in residents' perception, so that exposure predicts adaptation behaviour better than risk awareness does, and residents resist relocation even where they understand the hazard.

Two studies establish the causal attribution more firmly than local correlation alone permits. Sajjad et al. (2023), using persistent scatterer interferometry in a large inland city, find subsidence accelerating from 27 to 106 millimetres per year while groundwater levels declined at 0.49 metres per year over seventeen years, with a significant correlation between depletion and subsidence. Sun et al. (2023) demonstrate the alternative mechanism, finding maximum subsidence of 74.9 millimetres per year in a reclaimed bay area driven by reclamation and construction loading and correlating with Quaternary marine sediment thickness of ten to twenty metres.

What adaptation costs and what it buys

Pratiwi et al. (2023) provide the cost analysis for this specific coastal system, and their result is unusually favourable. All three mitigation strategies examined return benefit-cost ratios above unity; a piped water system supplying 1,000 litres per second reaches a ratio of 51.4 under low demand, while a 2,000 litre per second system reaches 13.4 under high demand and proves most robust across scenarios, with benefits of 80.6 trillion rupiah against costs of 2.86 trillion rupiah in present value terms over a century. Avoided land loss dominates the benefit side.

Nature-based options have measurable but bounded protective value. Zhang et al. (2022), surveying a six-year-old planted mangrove forest after a severe typhoon, record a 77 per cent reduction in wave height across 100 metres of forest width despite heavy defoliation. Xu et al. (2024) qualify the global outlook, finding a 25 per cent decrease in a mangrove coastal protection index between 2007 and 2019 driven principally by loss of height and biomass rather than of area, which fell only two per cent — so protective capacity has declined far faster than maps of extent suggest.

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Arifanti et al. (2022) report the Indonesian position, with approximately 3.3 million hectares of mangrove of which some 637,000 hectares, between ten and thirty-three per cent, has been degraded or converted in recent decades, and identify integrated ecosystem approaches, stronger enforcement and coastal community engagement as requirements. Sengupta et al. (2023) model the underlying choice formally through an agent-based framework in which a planning authority selects between building coastal defences and relocating exposed areas inland under rising sea level and extreme events.

Two further findings bear on whether protection resolves the problem. Wu et al. (2022b) find coastal urban land expanding at 6.51 per cent annually across all protection levels and at 9.40 per cent annually in the least protected counties, indicating that protection status does not restrain development of flood-prone land and may accelerate it. Jatmiko (2018), evaluating flood control performance in one district of the city examined here, works from a local subsidence rate of four centimetres per year and finds combined rainfall and tidal loading exceeding the design basis of existing infrastructure.

Research gap

The literature reviewed contains no study that places Semarang's governance response within a cross-regional comparative frame. Siriwardane-de Zoysa et al. (2021) compare governance but confine the comparison to Southeast Asia; Tay et al. (2022) and Wu et al. (2022) compare cities globally but on geophysical rather than institutional variables. A second and more immediately practical gap is that no study reconciles the widely divergent subsidence rates reported for Semarang, even though that divergence has direct consequences for regulatory designation. This study addresses both.

3. METHOD

The study combines a structured review of published measurements with documentary analysis of planning instruments. It generates no new geophysical observations; its contribution lies in reconciling existing measurements and in relating them to the regulatory record.

Compilation and comparison of published rates

Reported subsidence rates for Semarang were compiled from peer-reviewed studies published between 2023 and 2026, and recorded for each source together with the measurement technique, observation period, and spatial unit. Because these three attributes

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differ across studies, reported values are not directly comparable, and the comparison is presented as a range with attribution rather than as a pooled estimate. Convergence across independent techniques is treated as the criterion for a defensible working figure.

Inundation and vulnerability data

Annual tidal flood inundation extents and coastal vulnerability classifications were taken from Setyaningsih et al. (2024), which provides the most complete published series for the city. Comparative international figures were taken from the global surveys cited above.

Documentary analysis of planning instruments

The treatment of subsidence in the city's spatial plan and medium-term development plan was assessed against the regulatory framework for disaster-prone area designation under national spatial planning regulation, by examining whether subsidence appears as a designated hazard category and what consequences attach to it. All sources are publicly available; no confidential material was used.

The principal limitation of this design is that the documentary assessment covers the presence or absence of a hazard category rather than a full content analysis of planning provisions. This is stated explicitly here and revisited in the limitations section.

4. RESULTS AND DISCUSSION

Reconciling the reported subsidence rates

Published rates for Semarang span an order of magnitude. The lowest values, two to three centimetres per year, come from satellite interferometry over 2015 to 2020 as reported in Susilo et al. (2023); the highest, fourteen to nineteen centimetres per year, come from campaign geodesy over 1999 to 2011 reported in the same source. Between these extremes sit a cluster of independent measurements.

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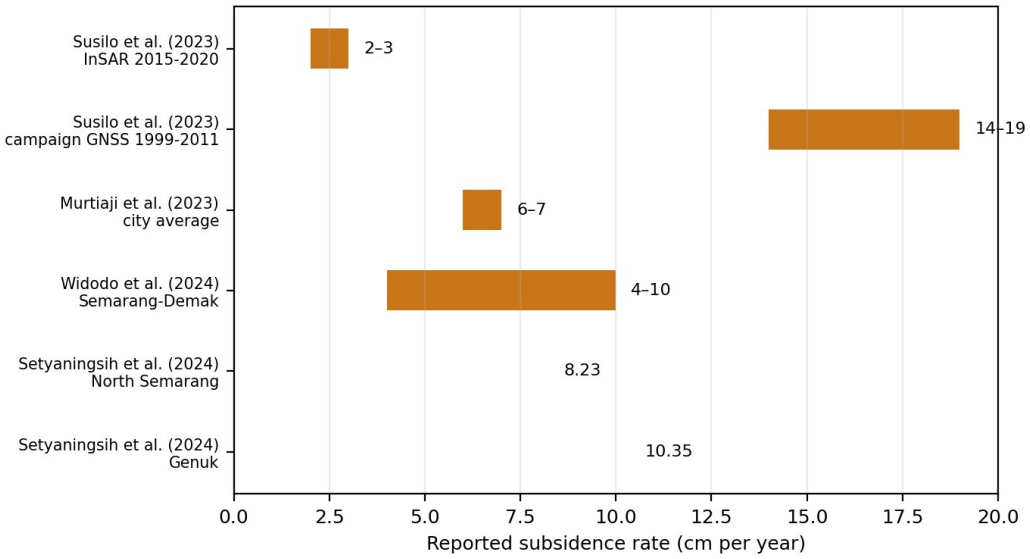


Figure 1. Subsidence rates reported for Semarang across published studies, by source and location (source: compiled by the authors from the studies cited)

Independent sources using different techniques converge on the range of roughly six to eleven centimetres per year for the worst-affected coastal districts. Setyaningsih et al. (2024) report 10.35 centimetres per year for Genuk, 8.31 for Pedurungan and 8.23 for North Semarang. Murtiaji et al. (2023) report a city average of six to seven centimetres per year with specific locations considerably higher. Widodo et al. (2024) place the Semarang and Demak area at four to ten centimetres per year. This convergence, obtained from different methods and periods, provides the most defensible working figure.

The extreme values require care. The low interferometric values cover a specific and relatively short window and a different spatial averaging, while the high campaign-geodesy values cover an earlier period during which extraction rates may have differed. A sustained rate near ten centimetres per year over three decades would imply accumulated displacement on the order of three metres in the worst-affected zones, consistent with the depth of chronic inundation now observed there.

The dispersion is not merely a technical inconvenience. Designation of a disaster-prone area under spatial planning regulation requires a defensible quantitative threshold. Where the published evidence base spans an order of magnitude, any proposed designation is exposed to challenge on the ground that the rate is contested. Reconciling the measurements is therefore a precondition for regulatory action, not merely an academic exercise — which is why the convergence identified above matters practically.

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Tidal inundation and vulnerability

Recorded tidal flood inundation in Semarang rose from 292.82 hectares in 2020 to 349.59 hectares in 2021 and 478.85 hectares in 2022, before falling to 381.38 hectares in 2023 and 166.67 hectares in 2024.

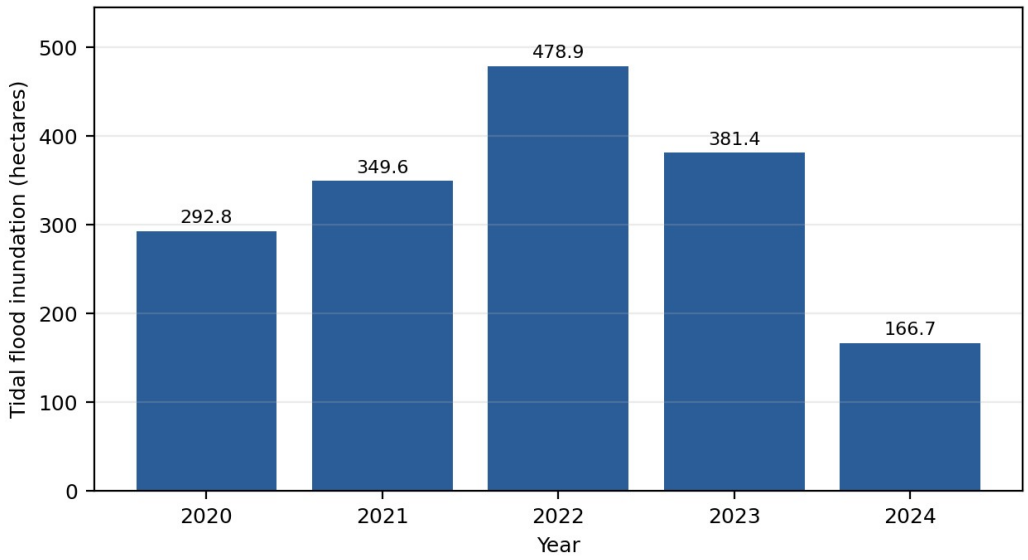


Figure 2. Recorded tidal flood inundation extent in Semarang, 2020–2024 (source: Setyaningsih et al., 2024)

The decline in the final two years should not be read as evidence that the problem is receding. Annual inundation extent is strongly conditioned by tidal maxima, rainfall coincidence and the operational state of pumping and embankment infrastructure, none of which reverses subsidence. The underlying land-level trend is monotonic and downward; annual inundation is the noisy surface expression of it. Confusing the two is precisely the analytical error that a subsidence framing is meant to prevent.

Table 1. Coastal vulnerability classification, Semarang

Vulnerability class	Area (hectares)	Share of coastal zone (%)
Very high	481.40	3.9
High	4,988.65	40.0
Moderate	4,080.01	33.0
Low	2,802.22	23.0
Very low	10.39	0.1

Source: Setyaningsih et al. (2024). Most affected sub-districts: Genuk, Tugu, West Semarang, North Semarang, Gayamsari and East Semarang.

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Approximately 43.9 per cent of the coastal zone falls within the two highest vulnerability classes. This is not a marginal exposure at the city's edge but a condition affecting a substantial share of its coastal territory, including established industrial and residential districts.

Semarang in international perspective

Placing these figures against the international record establishes the severity of the case. Susilo et al. (2023), citing earlier work, report Jakarta at one to twenty-eight centimetres per year for campaign GNSS over 1982 to 2010 and one to approximately eleven centimetres per year for Sentinel-1 interferometry over 2014 to 2020. Semarang's convergent estimate of six to eleven centimetres per year in its worst districts therefore matches or exceeds contemporaneous Jakarta measurements.

The comparison is significant because Jakarta's subsidence has attracted national policy attention commensurate with a capital city, including a relocation decision of the national capital. Semarang exhibits a comparable physical process without comparable institutional response. Nor is the north coast problem confined to Semarang: Widodo et al. (2024) report ten to nineteen centimetres per year for Pekalongan, and Widodo et al. (2024) report the Semarang and Demak area at four to ten centimetres per year, with 60.9 per cent of observation points subsiding and cumulative displacement reaching one metre over 2014 to 2022. The phenomenon is regional and crosses administrative boundaries, which is itself a governance problem, since no single municipal authority has jurisdiction over the aquifer system driving it.

Table 2. Semarang in comparative context

Location	Reported rate (cm/year)	Method and period	Source
Semarang (worst districts)	6–11	Multiple, 2014–2023	Convergence of three studies
Jakarta	1–28	Campaign GNSS, 1982–2010	Cited in Susilo et al. (2023)
Jakarta	1–11	InSAR, 2014–2020	Cited in Susilo et al. (2023)
Pekalongan	10–19	PS-InSAR, 2014–2022	Widodo et al. (2024)
Rapidly subsiding cities globally	> 2 (i.e. > 20 mm/yr)	InSAR, 2015–2020	Wu et al. (2022)

Source: compiled by the authors. Rates are not directly comparable across methods and periods and are presented with attribution rather than pooled.

The causal mechanism and why it matters for policy

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The attribution of subsidence to groundwater extraction is what makes the phenomenon governable, and it is therefore worth stating precisely. Wu et al. (2022), surveying 99 coastal cities, identify groundwater withdrawal as the probable dominant driver of the rapid subsidence observed in South, Southeast and East Asia. The mechanism is compaction: extraction reduces pore pressure in unconsolidated sediments, the sediment column compacts, and the surface descends. Where compaction occurs in clay layers it is largely irreversible, so subsidence does not recover when extraction ceases; it only stops accumulating.

Two policy consequences follow. First, the irreversibility means that delay is uniquely costly. Every year of continued extraction converts into a permanent loss of elevation that no subsequent measure can restore, which distinguishes subsidence from most environmental problems where remediation is possible in principle. Second, because the mechanism is local and anthropogenic, it is regulable in a way that sea-level rise is not. A city that correctly attributes its inundation to extraction has an available instrument; a city that attributes it to climate change has only accommodation.

This is why the framing question posed in the introduction is not semantic. The choice between describing Semarang's problem as tidal flooding and describing it as subsidence-driven relative sea-level rise determines which authority is responsible, which legal regime applies, and whether a preventive instrument exists at all.

The governance gap

Against this evidence, the central governance finding is stark. examination of the city's spatial and development planning documents indicates that land subsidence has not been formally established as a disaster-prone area category within them. The city plans for flooding; it does not plan for the process that is causing the flooding to worsen.

The consequence is not rhetorical. Designation as a disaster-prone area triggers specific legal effects under spatial planning regulation: constraints on permitted land uses, requirements in permit issuance, and eligibility criteria for particular categories of public investment. Without designation, those instruments remain unavailable, and the city's response is confined to engineering works — embankments, pumps, polders — that mitigate the symptom while the causal process continues.

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This is Siriwardane-de Zoysa et al.'s (2021) wickedness in concrete form. Groundwater extraction driving subsidence is regulated under a different legal regime from spatial planning, licensed by a different authority, and monitored by a different agency. The costs fall on coastal residents while the benefits accrue to extractors who are frequently located elsewhere in the metropolitan area. No single authority holds the full instrument set, and the aquifer crosses municipal boundaries in any case.

The finding also connects to Wannewitz et al. (2024), whose global mapping shows adaptation remaining predominantly incremental. Semarang's response fits that pattern precisely: substantial and continuing investment in protective infrastructure, and no transformational measure addressing extraction. The engineering response is not misconceived — it buys time — but it is not a subsidence policy, and describing it as one obscures the absence of the latter.

What designation would require

Because designation is identified here as the highest-value regulatory step, it is worth specifying what it would concretely demand. Three elements are necessary. The first is a delineated zone: a mapped boundary of the area to which the designation applies, derived from measured subsidence rates and defensible against challenge. The convergent range established above supplies the rate basis, and the sub-district-level measurements reported by Setyaningsih et al. (2024) supply spatial resolution sufficient for an initial delineation.

The second is a threshold rule stating the rate above which land falls within the designated zone. This is where the dispersion in published rates becomes an operational obstacle rather than an academic one, since a threshold expressed in centimetres per year is only administrable if the measurement standard is specified alongside it — technique, observation period, and spatial averaging. A designation that specifies a threshold without specifying the measurement protocol invites disputes that will be resolved by whichever study a party finds most favourable.

The third is the schedule of consequences: which land uses are restricted, what conditions attach to permits within the zone, and what obligations fall on existing users. Without this schedule the designation is declaratory. With it, the designation becomes the instrument through which subsidence enters land-use decisions that are currently taken as though the land were stable.

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Implications

Three implications follow. First, formal designation of subsidence-affected zones within the spatial plan is the single highest-value regulatory step available, because it unlocks instruments that no amount of additional protective infrastructure can substitute for. The convergent rate range identified above provides the evidentiary basis such a designation requires.

Second, because the aquifer system crosses municipal boundaries, groundwater regulation belongs at provincial rather than municipal level. The regional pattern documented across Semarang, Demak and Pekalongan implies that a municipal instrument, however well designed, addresses only part of the extraction driving subsidence in any one city.

Third, monitoring should report land-level trend separately from annual inundation extent. The 2023 and 2024 reduction in inundation illustrates the risk of conflating them: a favourable year in the surface indicator can coexist with continued deterioration in the underlying condition, and an indicator set that reports only inundation will periodically produce false reassurance.

Regional coordination and the boundary problem

A finding that recurs across the north-coast studies is that the affected area does not respect administrative boundaries. Widodo et al. (2024) document both Pekalongan and the Semarang and Demak area within a single interferometric assessment, finding sustained subsidence across the corridor. These are separate autonomous jurisdictions drawing on a shared aquifer system.

The mismatch between the hydrological unit and the administrative unit is a classic collective action problem. Extraction in one jurisdiction produces subsidence in another; each jurisdiction bears the full economic benefit of its own extraction while sharing the physical cost across the corridor. Under these conditions no municipality has an adequate incentive to restrict extraction unilaterally, and a municipality that did so would bear the cost while its neighbours captured the benefit.

This supplies a determinate institutional conclusion. Groundwater extraction licensing for the north-coast aquifer belongs at provincial level, not because provinces are administratively superior, but because the province is the smallest unit whose boundary encloses the resource. Municipal spatial planning designation and provincial extraction

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licensing are complements rather than alternatives: the first governs what is built on subsiding land, the second governs whether the land continues to subside.

A practical corollary concerns monitoring. Because the resource is shared, a monitoring network organised municipality by municipality will produce datasets that cannot be compared, measured over different periods with different techniques — which is, in part, how the order-of-magnitude dispersion documented earlier in this study arose. A corridor-level monitoring protocol, specifying common technique, common reporting period, and common spatial units, would resolve both the coordination problem and the evidentiary problem with a single instrument.

One further asymmetry is worth naming. Jakarta and Semarang share a physical process, but they differ in the political salience attached to it. Jakarta's subsidence entered national debate because it coincided with a capital relocation decision that gave the problem a constitutional dimension. Semarang has no comparable forcing event, and its subsidence has therefore remained a technical matter handled through public works budgets. The comparison suggests that in the absence of an external trigger, evidence alone has not proved sufficient to move a subsidence problem from the engineering agenda to the regulatory one — which is precisely the translation failure that the wicked-problem framing predicts.

One further finding bears on where the exposed population will be. Arifin et al. (2023), modelling peri-urban land conversion around an Indonesian coastal city, project built-up land reaching 67.27 per cent of their study area for a population of approximately two million, and recommend modifying coastal development strategy to preserve open space and enforce zoning. Where subsidence is concentrated in low-lying northern districts and conversion continues in the same zone, the exposed population grows through settlement decisions taken independently of the subsidence record — which means an inundation projection built on present population understates future exposure even if the physical projection is exact.

Limitations

Four limitations qualify this study. First, it generates no primary geophysical measurement and depends entirely on published values whose underlying data it cannot independently verify. Second, the assessment of planning documents addresses the presence of a hazard category rather than the full content of provisions. Third, reported rates differ in technique,

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period and spatial unit, so the convergent range should be treated as a defensible working figure rather than a precise estimate. Fourth, the international comparison is confined to published rate figures and does not extend to systematic comparison of governance arrangements across cities — the gap identified in the literature review, which this study documents but does not close.

5. CONCLUSION

Semarang is sinking at a rate that matches or exceeds Jakarta's, across a coastal zone of which nearly forty-four per cent falls in the two highest vulnerability classes. The published measurement base is extensive, and although reported rates span an order of magnitude, independent studies converge on six to eleven centimetres per year in the worst-affected districts. The measurement problem, in other words, is substantially solved.

The governance problem is not. Subsidence has not been established as a disaster-prone area category in the city's statutory planning instruments, which means the regulatory consequences of designation remain unavailable and the response stays confined to protective engineering. This is not a failure of knowledge but a failure of translation, and it exemplifies the institutional fragmentation that the wicked-problem literature anticipates: the authority that plans land use, the authority that licenses groundwater extraction, and the population that bears the consequences are three different sets of actors operating under three different legal regimes.

For the comparative literature on sinking cities, the Semarang case indicates that the binding constraint has shifted. Where the field's centre of gravity remains geophysical, the evidence assembled here suggests that in intensively measured cities the marginal return to further measurement is now low and the marginal return to institutional analysis is high. Systematic cross-city comparison of subsidence governance arrangements — as distinct from subsidence rates — is the research programme this case calls for.

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DECLARATIONS

Author contributions (CRediT)

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Muhammad Kenny Nastution: conceptualisation; methodology; formal analysis; writing - original draft; writing - review and editing.

Conflict of interest

The authors declare that they have no competing interests.

Data availability

All data supporting the findings of this study are available within the article and from the publicly accessible sources cited therein.

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Declaration on the use of artificial intelligence

No generative artificial intelligence tool was used in the preparation of this manuscript.

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