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LAND SUBSIDENCE AND TIDAL FLOODING ON CENTRAL JAVA'S NORTH COAST: A STRUCTURED NARRATIVE REVIEW

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ABSTRACT

The north coast of Central Java is sinking faster than the sea is rising, and tidal (rob) flooding now disrupts Semarang, Demak and Pekalongan in ordinary weather. This structured narrative review collates subsidence rates measured by interferometric synthetic aperture radar (InSAR), Global Navigation Satellite System (GNSS) surveys and levelling, the drivers identified for them, and the engineering and planning responses in place or planned as of 2026. Searches of Crossref and the open web on 8 October 2026 returned 289 records; 44 were assessed in detail and 40 studies were included, 19 of which report measured rates. Published maxima range from about 10 cm/year (2002–2006) to 100–120 mm/year (2015–2022) and 144–146 mm/year (2020–2023) in Semarang–Demak, and from 3 cm/year to more than 20 cm/year in Pekalongan, where a continuous GNSS station records −107.0 mm/year. The spread reflects differences in statistic, reference frame, geometry, period and benchmark depth more than disagreement about the phenomenon. Groundwater abstraction dominates in Semarang and Pekalongan, whereas natural compaction contributes 0.9–2.2 cm/year in Demak. The review argues that sea dikes and polders without enforced groundwater control are a wasting asset, and proposes conditions for making coastal defence durable.

1. Introduction

The alluvial lowlands of the north coast of Java (*Pantai Utara Jawa*, abbreviated Pantura) carry the island's main transport corridor, large ports and a dense belt of industry and housing. They are also subsiding. A global assessment concluded that in many coastal and delta cities land subsidence now exceeds absolute sea-level rise by up to a factor of ten [1], and that, because people live preferentially where the ground is sinking, coastal residents experience an average relative sea-level rise of 7.8 to 9.9 mm/year against a global mean of 2.6 mm/year over the past two decades [2]. Satellite surveys of the world's coastal cities reach the same conclusion: across 99 cities observed between 2015 and 2020, land in most of them is sinking faster than the sea is rising, with the fastest rates in South, Southeast and East Asia [3], and across the 48 largest coastal cities relative local land subsidence spans −16.2 to 1.1 mm/year when expressed as a city-scale statistic [4].

Central Java's north coast sits at the upper end of that distribution. Continuous GNSS stations operated by the Geospatial Information Agency of Indonesia show that Jakarta, Pekalongan, Semarang and Demak subside at least about nine times faster than the present rate of global sea-level rise [5]. Geodetic work summarised for the European Geosciences Union in 2022

describes typical rates of 3–10 cm/year at several locations along the coast, including Semarang, Demak and Pekalongan [6]. The consequence is tidal flooding, known locally as *rob*, which no longer requires a storm: by 2018 it was already reported to occur at regular tides in some areas [7]. In the Semarang–Demak plain the inundated share of the coastal plain grew from 7.04% in 2014 to 15.17% in 2021 [8]; in Sayung, Demak, the coastline has retreated by up to 5 km in places and more than 300 families have moved inland [9]. During the flood of late October 2025, the Semarang disaster management agency counted 63,450 people affected in five sub-districts, with traffic queues of up to 10 km on the Semarang–Demak road [10].

The state's answer has been overwhelmingly structural. Section 1 of the Semarang–Demak toll road is being built as a combined expressway and sea dike with retention ponds and pumping stations [11], [12]; Pekalongan has built a sea wall [13]; and in June 2025 a presidential regulation created a national authority to plan and build coastal protection for the whole of northern Java, popularly called the Giant Sea Wall [14]. The Semarang–Demak section alone is reported at Rp 10.9 trillion [15], and public estimates for the north Java programme range from about USD 80 billion [16] to USD 100 billion [17].

Whether such investments are durable depends on a quantity that is surprisingly hard to pin down: how fast the ground is actually sinking, where, and why. Published rates for the same city differ by an order of magnitude. For Semarang, a global Sentinel-1 survey gives 2 to 3 cm/year for 2015–2020 while earlier GNSS campaigns gave 14 to 19 cm/year for 1999–2011, as one data paper pointedly notes [5]. For Pekalongan the literature spans 3 cm/year [18] to more than 20 cm/year [19]. A designer choosing a crest level, or a planner deciding whether a polder will still drain in twenty years, cannot use numbers that vary this much without knowing what each one measures.

A systematic review published in 2021 covered two decades of work on Semarang City and concluded that monitoring had advanced technically but was poorly connected to mitigation [20]. Since then the evidence base has changed in three ways. First, a second generation of Sentinel-1 time-series studies with GNSS validation has appeared [21], [22], [23]. Second, continuous GNSS and deep-pipe records have become available for Pekalongan, which the earlier review did not cover [5], [24], [25]. Third, the policy setting has shifted: the combined toll road and sea dike has passed half of its physical progress [12], the provincial groundwater regulation of 2018 was replaced at the end of 2025 [26], and the national coastal authority is drafting its master plan [27].

This article therefore asks three questions. What subsidence rates have actually been measured in Semarang, Demak and Pekalongan, by which method and over which period, and why do they differ? What does the literature identify as the drivers, and how does their mix vary along the coast? And, given those answers, are the engineering and planning responses now under way likely to last? The thesis argued here is that hard coastal defence without effective groundwater control is not a durable response on this coast: it buys a decade or two of protection at a recurring cost, and it does so by converting a gravity-drained coast into a pumped one whose dependence on machinery grows every year the ground continues to sink. The corollary is not that dikes are a mistake. In Demak, where a large share of subsidence is

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natural, defence or managed retreat is unavoidable. The argument is that defence must be conditional on, and sequenced with, measures that reduce the controllable part of subsidence.

The contribution is threefold: a matrix of the published rates with their method, period and statistic; an account of why the estimates diverge, written for engineers who must choose a design value; and a simple durability criterion linking measured rates to the service life of a defence line.

2. Review Method

2.1 Design and search protocol

This study is a structured narrative review rather than a full systematic review. Searches were conducted on one date and screened in a single pass; no formal risk-of-bias tool was applied, and Scopus, Web of Science and Garuda were not queried. Four additional database queries failed because of rate limits and were not repeated. The method is reported as performed, and the results should therefore be read as a structured synthesis of accessible evidence rather than an exhaustive census of all relevant studies.

All searches were carried out on 8 October 2026. Two sources were used. The first was the Crossref REST interface, queried with the bibliographic strings “land subsidence Semarang” (publication years 2000–2026) and “land subsidence Demak Sayung”; the first 60 and the first 40 records respectively, ranked by relevance, were screened by title. Two further Crossref queries (“land subsidence Pekalongan” and a query on sea dikes and polders in Semarang) and two OpenAlex queries failed because the services returned rate-limit errors, and they were not repeated. The second source was general web search, which indexes Google Scholar-visible journal pages, the Directory of Open Access Journals, Indonesian journal portals and institutional repositories. Twenty literature queries were run. They combined the place names Semarang, Demak, Sayung and Pekalongan with the terms land subsidence, InSAR, Sentinel-1, GNSS, GPS, levelling, groundwater abstraction, consolidation, polder, sea dike and tidal flooding, and included known-item searches for studies cited in the papers already retrieved (backward snowballing). A further twelve web queries were directed at official documents and news reports on regulations and projects. OpenAlex was subsequently used only to retrieve abstracts of items already identified.

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2.2 Eligibility criteria

Records were eligible if they (a) concerned Semarang City, Demak Regency, Pekalongan City or Pekalongan Regency, alone or within a wider study of Java's north coast; (b) reported a measured or modelled subsidence rate, analysed its causes, or assessed a flood-defence, drainage or groundwater response; (c) were published between 2000 and October 2026 in English or Indonesian; and (d) had accessible full text or an abstract with complete bibliographic information. Journal articles, conference papers, conference abstracts with a DOI and one preprint were admitted because relevant geodetic evidence is also reported in these formats. Abstract-only items were retained only when the information available was sufficient to identify the study and the claim attributed to it; they were not treated as equivalent in evidential detail to full-text studies. Records were excluded if subsidence was incidental to the study, if the rate, method or observation period could not be established from the accessible material, or if they duplicated another included record.

2.3 Screening and included studies

The two Crossref queries returned 100 records in total, while the 20 literature web queries produced 189 result links; the latter can include repeated links or duplicate records. Their sum (289) is therefore an initial search yield, not a verified count of unique bibliographic records. Forty-four items were opened and assessed. Four were excluded at that stage: two radar studies whose abstracts or observation periods could not be retrieved, one conference-series paper for which no rate was accessible, and one journal version that duplicated an included article. Forty studies were included (Table 1). Nineteen report measured rates and form the matrix in Table 2; the others address drivers, modelling, impacts or responses. Because a complete deduplication log was not available for all web-search links, the screening flow is reported transparently without claiming that all 289 initial results were unique records.

For each included study, the location, technique, sensor or instrument, observation period and reported rate were extracted as published, along with the statistic represented (maximum, mean, range or single-station value). Units are retained as reported in the source, so centimetres and millimetres per year both appear. Rates were not recalculated to a common reference frame or statistic. Where only an abstract was accessible, this is identified in the relevant table notes; such estimates should be interpreted with the corresponding limitation in mind.

Policy and project information was taken from primary legal texts on official legal-documentation portals and, for construction progress and planning announcements that have no other public record, from ministry releases and national news reports dated between November 2024 and July 2026. Three international studies were added by targeted look-up to provide context; they are not counted in the corpus.

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Table 1. Search and screening summary (searches run on 8 October 2026)

Step	Source	Initial yield / items
Identification	Crossref, “land subsidence Semarang”, 2000–2026, first 60 by relevance	60
Identification	Crossref, “land subsidence Demak Sayung”, first 40 by relevance	40
Identification	Web search, 20 literature queries (result links, duplicates included)	189
Screened at title level	All of the above	289
Opened and assessed (abstract or full text)	—	44
Excluded after assessment	Rate, period or abstract not retrievable (3); duplicate version (1)	4
Included in the review	Studies of Semarang, Demak and Pekalongan	40
Of which report measured rates	Table 2	19

Source: Authors’ search log.

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3. Results

3.1 Profile of the evidence

The included studies fall into three generations. The first, up to about 2013, rests on levelling benchmarks, campaign Global Positioning System (GPS) surveys, microgravity and early radar interferometry, and is almost entirely about Semarang City [28], [29], [30], [31], [32]. The second, from 2015, exploits the free Sentinel-1 archive, first with two-image differential interferometry and then with persistent-scatterer and small-baseline time series, and extends eastwards into Demak [33], [34], [35], [36], [21]. The third, since 2023, adds continuous GNSS, corridor-scale radar processing with decomposition into vertical and horizontal components, and subsurface instruments, and brings Pekalongan into view [5], [22], [24], [25]. Geographically the evidence remains uneven: of the 19 rate-reporting studies, 12 concern Semarang, Demak or both, six concern mainly Pekalongan, and one covers the whole corridor.

3.2 Measured rates in Semarang

The reference study for the first generation combined levelling, InSAR, microgravity and GPS surveys and estimated subsidence of up to about 19 cm/year for 1999–2011. Its GPS results for 2008–2011 give average rates of roughly 6 to 7 cm/year, with maxima of 14 to 19 cm/year at certain locations, higher along the coast than in the south of the city [31]. A radar study using the stable points network technique on 35 images acquired between 2002 and 2006 found rates from fractions of 1 mm/year up to about 10 cm/year, with mainly stable ground in the south and increasing subsidence towards the coast [30]. An L-band survey of western Indonesia identified Semarang and Pekalongan among nine subsiding areas whose rates reach up to 22 cm/year, the maximum being a regional figure rather than one attributed to either city [32].

Repeated GPS surveys in 2008, 2009, 2010, 2012, 2016 and 2017 gave typical rates of about 3 to 10 cm/year and, importantly, a change of behaviour: roughly linear subsidence from 2008 to 2012 followed by acceleration from 2012 to 2017, strongest in the north-eastern coastal area [37]. Persistent-scatterer processing of Sentinel-1 data for 2015–2018 returned 0 to 6.753 cm/year across the city [34]. Ascending Sentinel-1A data for November 2014 to October 2017 showed up to about 120 mm/year in the coastal city and around 60 mm/year in Kendal and Demak, while the GNSS station at the Semarang tide gauge recorded about 100 mm/year; the same paper notes that sparse points measured between 1991 and 1996 had shown at most 81 mm/year [36]. A multi-sensor study spanning 2003 to 2017 [35] could be read only as a bibliographic record, so its rates are not reproduced here.

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The most thoroughly corrected radar estimate applies a new small-baseline subset technique to C-band data for 2015–2022 with atmospheric correction, and finds maximum rates of 100–120 mm/year in northern and eastern Semarang and Demak, about 50 mm/year in Kendal, and about 20% of Semarang's land affected; GNSS data support the result [21]. Later studies report higher maxima: 144.34 mm/year in Semarang City for 2020–2023 from a 2.5-dimensional decomposition of ascending and descending tracks [22], up to 15 cm/year for 2015–2025 [23], rates exceeding 120 mm/year in the urbanised Semarang–Demak plain [38], and a maximum of 0.23 m/year for 2020–2024 in the northern coastal zone [39]. At the other extreme, the global Sentinel-1 survey of coastal cities gives Semarang 2 to 3 cm/year for 2015–2020 [3], as summarised in [5], and the national continuous GNSS station in Semarang (CSEM) records a vertical velocity of only −0.8 mm/year [5].

3.3 Measured rates in Demak

Demak has been measured mostly as the eastern edge of Semarang scenes. The one campaign record specific to it comes from GNSS surveys in May 2015, April 2016, April 2017 and May 2018 in Sayung District, which give station rates between 0.8 and 17.91 cm/year, highest in the middle of the district, alongside two-image Sentinel-1 interferograms showing an average of 9.3 cm of subsidence for the 2015–2016 pair. The authors caution that the two data sets differ in temporal and spatial coverage, that radar coherence is low and that the results still need validation by precise levelling [33]. Corridor-scale processing for 2020–2023 puts Demak Regency highest of all the districts analysed at 146.45 mm/year [22]. A Landsat-based rapid assessment of Sayung reports an average of about 6 cm/year, although the derivation of that figure is not transparent in the accessible text [40], and an earlier radar compilation cited in a regional policy analysis gives 0 to 3 cm/year for the north-east Demak coast against 3 to 9 cm/year for the Semarang north coast [8]. The most recent study processes Sentinel-1A data from November 2014 to April 2025, locates the high-subsidence zones in the villages of Bedono, Gemulak and Sriwulan and estimates that potential land loss could reach 1,787 ha [41].

3.4 Measured rates in Pekalongan

Pekalongan entered the literature later and with the widest spread. Time-series interferometry on twelve ALOS scenes from 2008–2009 gave an average of 3 cm/year for Pekalongan City, concentrated in the west [18]. A two-image Sentinel-1 analysis for February 2017 to July 2020 gave 20.58 to 23.49 cm/year across four coastal sub-districts of Pekalongan Regency [19]. Persistent-scatterer analysis finds the fastest rates, above 10 cm/year, in unconsolidated coastal units and a close correspondence between the subsidence pattern, geology and the density of human activity [42]. Corridor-scale processing gives 137.94 mm/year for Pekalongan Regency in 2020–2023 [22].

Pekalongan is the only one of the three areas with a published continuous GNSS velocity inside the subsiding zone. Station CPKL records −107.0 mm/year with a formal uncertainty of 0.202 mm/year in a network solution covering 2010–2021, by far the fastest of the 20 stations along the coast [5]; an independent analysis of continuous GNSS data for 2015–2019 gives −122.54 mm/year for Pekalongan and −11.04 mm/year for Tegal [24]. Subsurface instruments tell a slower story. A deep pile benchmark installed about 500 m from CPKL recorded about 80 ± 1

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mm of subsidence between 6 April 2021 and 2 October 2022 [5], and nine conventional deep pipe monitoring sites observed between 2021 and 2025 give maxima of −3.89 cm/year at Wonokerto and −3.24 cm/year at Tirto, the fastest sites coinciding with the thickest clay [25].

Table 2. Matrix of reviewed studies

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reporting measured subsidence rates (rates as published)

Study	Location	Method and sensor	Observation period	Reported rate	Statistic and notes
Kuehn et al. [30]	Semarang	Stable points network InSAR, 35 SAR images	2002–2006	Fractions of 1 mm/year to about 10 cm/year	Range; field checks in 2007
Abidin et al. [31]	Semarang	Levelling, InSAR, microgravity, GPS	1999–2011	Up to about 19 cm/year	Maximum
Abidin et al. [31]	Semarang	Campaign GPS	2008–2011	About 6–7 cm/year; 14–19 cm/year at some sites	Spatial average; local maxima
Andreas et al. [37]	Semarang	Campaign GPS (six epochs)	2008–2017	About 3–10 cm/year	Typical; acceleration after 2012
Azeriansyah et al. [34]	Semarang	PS-InSAR, Sentinel-1	2015–2018	0–6.753 cm/year	Range; abstract only
Bott et al. [36]	Semarang, Kendal, Demak	Sentinel-1A InSAR, ascending; GNSS at tide gauge	Nov 2014–Oct 2017		

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Up to about 120 mm/year; about 60 mm/year in Kendal and Demak; GNSS about 100 mm/year
Maximum; single station
Wu et al. [3]
Semarang
PS-InSAR, Sentinel-1
2015–2020
2–3 cm/year
As summarised in [5]
Aditiya and Ito [21]
Semarang, Demak, Kendal
New small-baseline InSAR, C-band, atmospheric correction, GNSS check
2015–2022
100–120 mm/year; about 50 mm/year in Kendal
Maximum; abstract only
Janur et al. [22]
Semarang City
2.5D small-baseline InSAR, Sentinel-1 ascending and descending
2020–2023
144.34 mm/year
Vertical component; abstract only
Janur et al. [22]
Demak Regency
As above
2020–2023
146.45 mm/year
Highest of the corridor
Janur et al. [22]
Pekalongan Regency
As above
2020–2023
137.94 mm/year
Validation: vertical root-mean-square error 8.8 mm at 12 stations
Kusumawardani et al. [39]
North Semarang
InSAR with site reconnaissance
2020–2024
0.23 m/year
Maximum; abstract only
Azeriansyah et al. [38]
Semarang–Demak plain
Small-baseline InSAR
Not stated in abstract
Exceeding 120 mm/year
Abstract only
Fahrudin et al. [23]
Semarang towards Demak
Small-baseline InSAR, Sentinel-1
2015–2025
Up to 15 cm/year

Maximum; abstract only
Yuwono et al. [33]
Sayung, Demak
Campaign GNSS (four epochs)
May 2015–May 2018
0.8–17.91 cm/year
Range across stations
Yuwono et al. [33]
Sayung, Demak
Two-image DInSAR, Sentinel-1
Nov 2015–Nov 2016
Average 9.3 cm (1.0–19.5 cm)
Displacement over the pair
Sutrisno et al. [40]
Sayung, Demak
Landsat change analysis with GNSS and tide data
1997–2024
About 6 cm/year (±0.8)
Derivation unclear
Nashrrullah et al. [18]
Pekalongan City
Time-series DInSAR, ALOS, 12 scenes
2008–2009
3 cm/year
City average
Zainuri et al. [19]
Pekalongan Regency (coastal)
Two-image DInSAR, Sentinel-1
Feb 2017–Jul 2020
20.58–23.49 cm/year
Sub-district averages
Mous et al. [42]
Pekalongan; Semarang–Demak
PS-InSAR
Not stated in abstract
More than 10 cm/year in coastal units
Preprint, abstract only
Susilo et al. [5]
Pekalongan (CPKL)
Continuous GNSS
Network 2010–2021
−107.0 ± 0.202 mm/year
Single station
Susilo et al. [5]
Semarang (CSEM)
Continuous GNSS
Network 2010–2021
−0.8 ± 0.038 mm/year
Single station
Susilo et al. [5]

Pekalongan
Deep pile benchmark
6 Apr 2021–2 Oct 2022
About 80 ± 1 mm in total
Cumulative, about 1.5 years
Mumtaz et al. [24]
Pekalongan
Continuous GNSS
2015–2019
−122.54 mm/year
Single station
Yuwana et al. [25]
Pekalongan and surroundings
Deep pipe monitoring, nine sites
2021–2025
−3.89 cm/year (Wonokerto); −3.24 cm/year (Tirto)
Site maxima
Source: Compiled by the authors from the studies cited in the first column.

3.5 Why the estimates differ

Read without context, Table 2 suggests a very wide spread in reported subsidence rates. The values range across studies from fractions of a millimetre per year to about 23 cm/year in the entries summarised there, while a separate North Semarang study reports a maximum of 0.23 m/year for 2020–2024 [39]. These figures must not be treated as a single interchangeable estimate for an entire city: they refer to different locations, observation periods, instruments and statistics. Six principal sources of difference help explain the spread.

The first is the statistic. A maximum, a spatial mean, a "typical" range and a single-station velocity are different quantities. The same GPS network that yields a maximum of 14 to 19 cm/year yields a spatial average of 6 to 7 cm/year [31]. City-scale statistics used in global comparisons are lower still, because they average over stable ground: the cities in the 48-city study span only −16.2 to 1.1 mm/year on that basis [4]. Most of the recent papers in Table 2 report maxima, which describe the worst hotspot and not the ground beneath any particular structure.

The second is the reference. Radar interferometry measures displacement relative to a point assumed stable, and the choice matters. The GNSS data paper observes that one location on Jakarta's coast subsides about seven times faster in one global Sentinel-1 study than in another and suggests that different reference points may explain the gap; it argues that GNSS is needed to tie radar results to a global frame [5]. The low Semarang figure in the global survey [3] should be read in that light. The near-zero velocity at station CSEM is not a contradiction either: it suggests that the national reference station in Semarang does not sample the subsiding plain, which is why a rapid assessment that drew on CSEM data to characterise neighbouring Sayung [40] should be treated with caution.

The third is geometry. A single-track radar measurement is a line-of-sight change that mixes vertical and horizontal motion. Studies that combine ascending and descending tracks to isolate the vertical component [22] are not directly comparable with single-track results such

as [36], and three-dimensional analysis of the Semarang–Demak plain indicates that horizontal motion and tilt are significant near infrastructure [38].

The fourth is time. Subsidence here is not steady. The GPS record indicates acceleration after 2012 [37], and a review of two decades of monitoring found maximum coastal rates relatively steady in 2008–2010 and rising afterwards [20]. A 2002–2006 maximum of about 10 cm/year [30], a 2015–2022 maximum of 100–120 mm/year [21] and a 2020–2023 maximum of 144 mm/year [22] may therefore all be right for their periods. Short windows add noise: two-image interferograms over a pair of dates carry the full atmospheric and seasonal signal, which probably contributes to the very high Pekalongan values in [19] and to the scatter in the Sayung pairs [33].

The fifth is sampling. Radar loses coherence over fishponds, mangrove and flooded land, so the fastest-sinking, already-inundated margin is under-sampled and estimates are biased towards built-up ground; the Semarang review notes that InSAR can both overestimate subsidence and show a "no-subsidence" bias in low-coherence areas [20]. Campaign GNSS and levelling, conversely, sample a few dozen points chosen for access. A modelling study that assembled the ground record found levelling and GPS data at 137 locations measured intermittently between 1991 and 2019 by agencies that did not coordinate, so that the record at each point is short [43].

The sixth is depth. A GNSS antenna on a shallow-founded building, a radar scatterer on a roof, a pile-founded benchmark and a deep pipe do not record the same thing. The surface instruments capture compaction of the whole sediment column, including the soft upper clay under the weight of fill and buildings; an instrument anchored at depth records only what happens below its anchor or within its measured interval. This is a plausible reading of the Pekalongan data, in which continuous GNSS gives 107 to 123 mm/year [5], [24], a deep pile benchmark about 500 m away gives roughly 80 mm in a year and a half, and deep pipes give at most 3.89 cm/year [5], [25]. The authors of the GNSS paper themselves decline a one-to-one comparison because the sites and periods differ [5]; the pattern is nevertheless what a depth-partitioned compaction profile would produce, and it matters for design because a dike founded on improved ground and a house on fill will not settle at the same rate.

Taken together, the available measurements support three cautious conclusions. First, hotspot rates of the order of 10 cm/year or more have been reported along parts of the Semarang–Demak coast over multiple observation periods, including recent studies. Second, published Pekalongan estimates include surface or station rates around 10 cm/year or higher, alongside slower values from subsurface instruments; the instruments do not measure identical depth intervals or locations. Third, the studies reviewed here do not establish a sustained, coast-wide deceleration. This is not proof that rates cannot decline; it means that the available records do not demonstrate a sustained decline across all three areas.

3.6 Drivers

The literature has named the same three drivers since the first benchmark studies: groundwater withdrawal, natural consolidation of young alluvium and the load of

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construction [28], [31]. Where the studies differ is in the weight given to each, and here the evidence points to a spatial gradient, not a single answer.

For Semarang City the case for groundwater abstraction is strong. Piezometric levels in monitoring wells fell by 0.81 to 1.2 m/year at the port well and by 0.29 to 1.02 m/year at two others across the periods 1977–2010, producing depression cones 15–30 m below mean sea level by 2010, while registered abstraction rose by 3.37 million m^3/year over 1990–2006, after which no abstraction records exist [8]. The radar deformation field correlates with groundwater change with a coefficient of 0.86 [21]. A coupled groundwater-flow and subsidence model calibrated against levelling, GPS and InSAR reproduces the pattern with a greatest simulated rate of 36.8 mm/year in Genuk District and indicates that the proposed groundwater management could cut the subsidence rate by up to 59% and the affected area by up to 76% [43]. That simulated maximum is well below the observed radar maxima, which implies either that abstraction is under-recorded or that shallow processes not represented in a deep-aquifer model add to the total; a separate numerical analysis for two Semarang sub-districts computes consolidation of 12.4 to 12.5 cm/year without pumping and 33.8 to 38.8 cm/year with pumping [44], figures that are themselves model-dependent but point the same way. The demand side explains the persistence: in 2013 the municipal utility supplied 59% of Semarang's clean-water demand and the Demak utility under 31% of Demak's, and by 2019 the piped network covered 61% of the Semarang service area and 44% of Demak's [8]. Industry in the Genuk area alone abstracts about 250 L/s, in a zone that subsided 8.5–10 cm/year in 2008–2011 [45].

For Demak the natural component cannot be dismissed. Modelling of delayed dissipation of measured overpressure gives natural compaction below 0.8 cm/year in Semarang City but 0.9–2.2 cm/year in Demak, where the clay is thick, recently deposited and underconsolidated; natural processes account for 48–92% of total subsidence in the eastern plain when compared with the geodetic rates available to that study [46]. The soft clay is 11–25.5 m thick in Demak against 0–16 m in Semarang [8]. The comparison was made against geodetic totals lower than the recent radar maxima, so the natural share at today's hotspots is probably smaller than 48–92%; the absolute natural rate, however, is a floor that no regulation can remove.

For Pekalongan a review of the subsurface identifies 30–70 m of compressible alluvial deposits and attributes subsidence to natural compaction, over-exploitation of confined groundwater from the deltaic and Damar Formation aquifers and the growth of built-up areas, with tectonics judged negligible [47]. The deep-pipe data tie the fastest rates to the thickest clay, 43.3 m at Wonokerto [25], and the radar pattern follows both geology and the intensity of human activity [42]. Fault-related vertical motion was tested with continuous GNSS and found statistically significant only at Semarang, not at Pekalongan or Tegal [24]; a recent radar study nonetheless argues that buried structures in the deep aquifer shape the subsidence zones in Semarang [23], and a tectonic component of 3–5 mm/year has been cited for 2011–2017 [43].

Loading is the least quantified driver and probably the most under-rated at the scale of individual structures. Constructed area in the Semarang–Demak study area grew from 11.61 km^2 in 1984 to 131.02 km^2 in 2021 [8]. Residents typically raise their houses every five to ten years, each lift adding fill to compressible ground [36], [20]. A national review concludes that

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groundwater withdrawal is the principal cause in Indonesia's subsiding cities while other natural and human factors contribute [48]. The practical summary is that the controllable share of subsidence is large in Semarang and Pekalongan and smaller, though not negligible, in Demak.

3.7 Engineering and planning responses

Combined toll road and sea dike. Section 1 of the Semarang–Demak toll road (Kaligawe–Sayung) is 10.64 km long and is built in three packages: an elevated road, a sea dike integrated with the carriageway, and retention ponds with pump houses; it is financed 15% from the state budget and 85% from a Chinese loan and was targeted for operation in 2027 [11]. Physical progress was 32.67% in February 2025 [11] and 52.27% on 1 September 2025, when the dike was reported to be fully connected [12]. The Terboyo retention pond has a 6.55 km embankment, six pumps of 5 m^3/s and two of 500 L/s and serves 189 ha; the Sriwulan pond has a 2.10 km embankment, four pumps of 5 m^3/s and two of 500 L/s and serves 28 ha [12]. The geotechnical problem is severe. The embankment is designed at 6 m above mean sea level on soft soil up to 40 m thick with an undrained shear strength of about 6.5 kPa, which could carry only about 3 m of fill untreated; the solution combines bamboo mattresses, high-strength geotextile, prefabricated vertical drains and staged preloading, with computed safety factors of 1.25 during construction and 1.55 in the long term [49]. On the land section, settlement predicted by the Asaoka and Terzaghi methods has been compared with settlement-plate readings [50]. These analyses concern consolidation induced by the structure itself; neither accessible abstract treats regional subsidence as a separate, continuing load case.

Polders and pumping. The dike only keeps the sea out; rainfall and river water behind it must be stored and lifted. The Tenggang–Sringin system in eastern Semarang comprises six pump houses with a total capacity of 81 m^3/s and 10.53 km of river embankment, intended to reduce flooding over 4,429 ha and protect 254,546 people [12]. An operational study of the Sringin polder judged the system not yet adequate in capacity [51]. In Pekalongan, modelling of the Banger Lama drainage system proposes embankments, flap gates and gravity drainage but warns that these may lose effectiveness where subsidence is significant [52]. The October 2025 flood struck exactly the sub-districts that these systems serve [10].

Pekalongan sea wall. Two modelling studies bracket what the wall can do. One finds that an embankment reduces the tidal-flood area in 2020 from 783.99 ha to 1.68 ha, but that by 2035 some 1,686.62 ha would be inundated even with the embankment, against 7,578.94 ha without it [19]. The other, written after construction, reports 94.830 ha flooded in 2021 and none in 2022, then predicts 249.494 ha by 2050, and concludes that subsidence, more than a sea-level rise of 4.05 mm/year, controls the outcome [13]. According to a planning-ministry official, an embankment built in Pekalongan in 2019 was already submerged by 2022 [53].

Water supply and groundwater regulation. Substitution of surface water is the precondition for any reduction in pumping. The Jatibarang dam was completed in 2015 [8], and the West Semarang water supply system, inaugurated on 23 January 2024, adds 1,000 L/s for 70,000 household connections, or about 350,000 people [54]. A cost comparison for the Genuk industrial area recommends treating polluted surface water for industrial use in the short term as a substitute for groundwater [45]. On the regulatory side, the Central Java regional regulation on groundwater management (*Peraturan Daerah Provinsi Jawa Tengah Nomor 3 Tahun 2018 tentang Pengelolaan Air Tanah*) required a permit for non-commercial abstraction above 9 m^3/day (Pasal 33 ayat (2)) and made unpermitted use an offence (Pasal

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59) [55]; analysts read it as banning abstraction in the red zone of the north coast [8]. It was revoked and replaced on 31 December 2025 by the regional regulation on water resources management (*Peraturan Daerah Provinsi Jawa Tengah Nomor 14 Tahun 2025 tentang Pengelolaan Sumber Daya Air*) [26], which gives priority to surface water (Pasal 4 ayat (1)) and provides that in critical zones new abstraction is limited and existing use gradually reduced, while in damaged zones new abstraction is prohibited and existing use gradually reduced (Pasal 51) [26]. At national level, the ministerial regulation on groundwater business licences and use approvals (*Peraturan Menteri Energi dan Sumber Daya Mineral Nomor 14 Tahun 2024 tentang Penyelenggaraan Izin Pengusahaan Air Tanah dan Persetujuan Penggunaan Air Tanah*) ties licences to groundwater conservation zones (Pasal 3 ayat (1)), caps abstraction in critical zones at 10 m^3/day and bars new licences in damaged zones (Pasal 20 ayat (1)) [56]. The instruments therefore exist. What the literature documents is weak monitoring and enforcement [36], the absence of abstraction records after 2006 [8], the discontinuation of government subsidence monitoring in 2000 and of a donor-supported programme begun in 2013, and the continued drilling of public deep wells [20].

The north Java coastal protection programme. Presidential Regulation No. 77 of 2025 (*Peraturan Presiden Nomor 77 Tahun 2025 tentang Badan Otorita Pengelola Pantai Utara Jawa*), enacted on 24 June 2025, establishes a non-structural authority reporting to the President (Pasal 2) with the task of preparing, planning, constructing and developing the north Java coast (Pasal 3) under an integrated master plan (Pasal 1) [14]. Table 3 traces the programme's public record. The reported dimensions are not consistent: about 500 km and USD 80 billion in May 2026 [16], 500–700 km and USD 100 billion in April 2026 [17], and 575 km in 15 segments in July 2026 [27]. As of July 2026 the head of the authority described the project as still at master-plan stage with financing, locations and construction stages undecided [27]. The updated government work plan for 2025, as reported, lists six pillars for the north coast, among them control of sea-water damage, raw and drinking water supply and land subsidence monitoring [57]. Monitoring is on the list; groundwater demand management is not named as a pillar. In March 2026 the public works minister stated that the Semarang–Demak structure would be upgraded and integrated into the programme, that the dike is planned to supply raw water, and that a regional regulation may prohibit groundwater extraction [15].

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Table 3. Timeline of principal responses, 2015–2026

Date	Event	Source
2015	Jatibarang dam completed (surface-water source for Semarang)	[8]
23 March 2018	Central Java Regional Regulation No. 3 of 2018 on groundwater management enacted	[55]
5 March 2021	Assessment and roadmap on land subsidence for Central Java Province issued (nine strategies)	[58]
23 January 2024	West Semarang water supply system inaugurated, 1,000 L/s	[54]
2 December 2024	Ministerial Regulation No. 14 of 2024 on groundwater licences and approvals enacted	[56]
19 February 2025	Semarang–Demak toll road Section 1 at 32.67% physical progress	[11]
24 June 2025	Presidential Regulation No. 77 of 2025 establishes the north Java coastal authority	[14]
1 September 2025	Section 1 at 52.27%; sea dike reported fully connected	[12]
29 October 2025	63,450 people affected by flooding in eastern and northern Semarang	

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[10]
31 December 2025
Central Java Regional Regulation No. 14 of 2025 on water resources management replaces the 2018 regulation
[26]
1 March 2026
Minister announces integration of the Semarang–Demak structure into the north Java programme
[15]
13 July 2026
Authority states the programme is still at master-plan stage; 575 km in 15 segments
[27]
Source: Compiled by the authors from the documents cited in the third column.

4. Discussion

4.1 A durability criterion

The engineering case against defence without subsidence control can be stated in one line. If a defence line has a freeboard above the design water level, its crest sinks at a rate and mean sea level rises at a rate , the time until the freeboard is consumed is

Equation (1) excludes wave overtopping, settlement caused by the structure's own weight, changes in tidal range, storm surge, drainage performance and maintenance; these factors can reduce actual performance, so the equation is an illustrative screening calculation, not a design or service-life prediction. Published sea-level trends cited for this coast are 3.8 mm/year for 1993–2018 [19] and 4.05 mm/year for 1993–2024 [13]. For illustration only, if relative sea-level rise is assumed to be 4 mm/year and crest subsidence is assumed to be 100 mm/year, a nominal 1 m of freeboard would be consumed in about 9.6 years under the simplified constant-rate assumption. The 100 mm/year value is a scenario close to some hotspot rates in Table 2, not a measured rate for every dike segment. At an assumed subsidence rate of 10 mm/year, the same 1 m would last about 71 years with a 4 mm/year sea-level contribution; at the natural compaction rates modelled for Demak, 9–22 mm/year [46], it would last approximately 38–77 years. These calculations are arithmetic illustrations only. They do not establish the service life of the Semarang–Demak structure, because its design freeboard and site-specific crest settlement rate were not established in the sources reviewed. The calculations indicate why reducing the controllable component of subsidence can materially improve durability, but the required design values must be measured at the structure and checked by qualified engineers.

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Because the design freeboard and a structure-specific long-term crest-settlement rate for the Semarang–Demak defence were not established in the sources reviewed, Equation (1) is not applied to that project as a prediction. It is used only to show the relationship among freeboard, subsidence and relative sea-level rise; actual design requires site-specific geotechnical, hydrodynamic and operational analysis.

4.2 The polder trap

The second half of the argument concerns what happens behind the dike. Closing the coast converts the hinterland into a polder. Every cubic metre of rain and river water must then be stored and pumped over a sea level that, relative to the land, rises by the sum of subsidence and sea-level rise. Pump head, energy use and the consequences of a pump failure all grow with time, and the land surface inside the polder continues to drop below the water outside it. Raising dikes makes inland drainage harder, not easier [7]; structural sea defences under high subsidence trap water from the hinterland [36]; and gravity outlets and flap gates lose their function as the ground sinks [52]. The floods of October 2025 in Genuk, Gayamsari and Pedurungan, inside the area served by 81 m^3/s of installed pump capacity, illustrate the residual risk [10], [12]. The Pekalongan simulations make the same point quantitatively: the sea wall nearly eliminates tidal flooding in the first years and then progressively loses ground, to 1,686.62 ha by 2035 in one model and 249.494 ha by 2050 in another [19], [13]. The two projections differ by almost an order of magnitude, which is itself a measure of how sensitive the outcome is to the subsidence rate assumed.

A completed dike also signals that the problem is solved. The Semarang review found that subsidence was “overlooked” by both public and government [20], and if the pillars of the national programme as reported [57] are carried into the master plan, monitoring will be funded while the reduction of abstraction is left to instruments outside the programme.

4.3 Why groundwater control is necessary but not sufficient

International experience shows that the controllable component responds to policy. Tokyo restricted groundwater extraction in the early 1960s and subsidence stopped about ten years after groundwater levels began to recover; Bangkok’s regulation from 1977 and charges from 1985 reduced subsidence in most urban areas to about 1 cm/year [1]. The Semarang model suggests reductions of up to 59% in rate from management measures [43]. A provincial roadmap valued the avoided losses of a scenario in which subsidence is cut to a quarter of its current rate at more than Rp 78 trillion by 2040 for Semarang and Demak, and described elevation and embankments as adaptation whose effectiveness wanes over time [58].

Three qualifications keep this from being a simple prescription. First, the response is delayed: compaction of thick clay continues for years after heads recover, as the ten-year lag in Tokyo shows, so defence built now will have to ride out a period of continued subsidence whatever is decided about wells. Second, in Demak a natural component of 0.9–2.2 cm/year [46] sets a floor; groundwater control there slows the loss without stopping it, and for the villages of Sayung already at or below tide level the choice is between a defended polder and retreat. Third, groundwater cannot be withdrawn from users who have no alternative. With piped coverage at 61% of the Semarang network area and 44% of Demak’s in 2019 [8], a prohibition

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in the damaged zone is enforceable only as fast as surface-water supply expands. The 1,000 L/s added in West Semarang in 2024 [54] is a real step, but it serves the west of the city, whereas the fastest subsidence and the heaviest industrial abstraction lie in the east and north-east [37], [45].

The position taken here is therefore conditional. Hard defence is justified on this coast, and in parts of Demak unavoidable. Hard defence without groundwater control is not durable in Semarang and Pekalongan, where the dominant driver is controllable, because the structure's service life is then set by a rate that policy has chosen not to reduce. The durable configuration is a defence line designed for the residual rate and paired with an enforced reduction of abstraction.

4.4 Implications for engineering and planning

Four implications follow.

Design values should be taken from measurements that match the structure. For a dike crest, the relevant quantity is the vertical movement of the ground and foundation supporting that crest, measured over an appropriate period and tied to a stable reference frame. Maximum line-of-sight radar rates and city-wide averages are not automatically suitable design values. Table 2 shows that continuous GNSS, a deep benchmark and deep pipes have been studied within a few kilometres of one another in Pekalongan [5], [25], although they differ in site, period and depth sensitivity. Comparable co-located monitoring along the Semarang–Demak dike alignment and inside polders—continuous GNSS, extensometers, piezometers and repeat levelling tied to radar time series—would support annual estimates of crest movement and groundwater conditions. The provincial roadmap lists a GNSS-based monitoring system among its nine strategies [58].

Defence investment should be made conditional on abstraction targets. The regional regulation of 2025 prohibits new abstraction in damaged zones and requires gradual reduction of existing use [26], and the ministerial regulation of 2024 caps licences in critical zones at 10 m^3/day [56]. Neither has effect without zone maps, metering and a public register of wells, none of which could be found for the period after 2006 [8]. Linking the release of funds for each segment of the north Java programme to a published abstraction baseline and a reduction schedule for the groundwater basin behind it would give the master plan the element that the reported pillars lack.

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Spatial planning should stop adding load and exposure to the zones with the least remaining freeboard. The tenfold growth of constructed area since 1984 [8] and the projected loss of 1,787 ha in coastal Demak [41] argue for limits on new fill and heavy construction on the thickest clay, and for an explicit decision, segment by segment, between defence and managed retreat where natural compaction dominates.

5. Limitations

This review has limitations that affect how its conclusions should be used. The search was conducted on one day by a single screening pass and relied on Crossref and open-web searches; Scopus, Web of Science and Garuda were not queried, and four additional database queries failed and were not repeated. The 289 initial yield combines 100 Crossref records with 189 web-search result links, including possible duplicates, and must not be interpreted as 289 unique records. Relevant studies may have been missed. Some included studies were accessible only as abstracts, limiting verification of reference points, uncertainty and validation; this particularly affects some recent high subsidence maxima. One included item is a preprint and two are conference abstracts, and one statement about a submerged embankment in Pekalongan rests on an official's remark. Rates were not recalculated or harmonised to a common statistic, reference frame or depth interval, and no meta-analysis was attempted. Explanations for differences in Section 3.5 are interpretations of the published information; the depth-partitioning explanation for Pekalongan remains a hypothesis, not a conclusion asserted by the original authors. Equation (1) is an illustrative constant-rate calculation, not a design method. Project and programme information from ministry releases and news reports reflects statements made between November 2024 and July 2026 and may have been superseded; cost and length figures for the north Java programme are inconsistent across sources and are not final. Legal provisions should be checked against the promulgated official texts before being relied upon for legal or regulatory decisions.

6. Conclusion

Measured subsidence on the north coast of Central Java is substantial in several coastal hotspots, but the reported rates differ because studies observe different locations, periods, reference frames, geometries, statistics and depth intervals. In Semarang and Demak, published hotspot estimates include about 10 cm/year for 2002–2006, 100–120 mm/year for 2015–2022, 144.34–146.45 mm/year for 2020–2023, and up to 0.23 m/year for northern Semarang in 2020–2024 [21], [22], [39]. In Pekalongan, reported values range from 3 cm/year to more than 20 cm/year; continuous GNSS station CPKL records −107.0 mm/year for 2010–2021, while another analysis reports −122.54 mm/year for 2015–2019 [5], [19], [24]. These are published study-specific results and should not be read as uniform rates for each region. The evidence identifies groundwater abstraction as an important controllable driver in Semarang and Pekalongan, natural compaction of young clay as a substantial contributor in Demak, and construction loading as an additional factor. The relative contribution of each driver varies by site and cannot be inferred from subsidence rate alone.

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Coastal dikes and polders must therefore be planned together with ongoing ground deformation, drainage capacity, groundwater conditions, foundation behaviour and maintenance. Under the simplified assumptions in Equation (1), a 1 m freeboard would be consumed in about 9.6 years at an assumed subsidence rate of 100 mm/year plus a 4 mm/year relative sea-level contribution; at the reported maximum of 0.23 m/year, the arithmetic would be much shorter, but neither calculation is a prediction of actual project performance. The combined toll road and sea dike, the Pekalongan sea wall and the wider north Java programme should be evaluated using site-specific crest and foundation measurements rather than regional maxima alone. Priority actions are to maintain monitoring tied to stable reference frames, reduce groundwater abstraction where evidence shows it is a material driver, expand alternative water supply so reductions are feasible, and set clear local thresholds for inspection, pumping, maintenance and crest raising. Natural compaction means that groundwater control will not eliminate subsidence everywhere; in those locations, adaptation choices must also consider the residual risk and the feasibility of continued defence.

Declarations

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