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ORIGINAL ARTICLE OPEN ACCESS

Flood Insurance in Dutch Unembanked Areas: Quantifying the Interplay Between Climate Change, Urban Development, and Adaptation Strategies

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ABSTRACT

Many coastal and riverine communities lack dedicated flood protection and face growing flood risk from climate change and urban development. In such areas, flood insurance is one of few mechanisms to manage financial exposure, yet how adaptation measures, participation structures, and infrastructure policy jointly shape long-term insurability is poorly understood. We develop an integrated framework that combines hydrodynamic modelling, damage assessments, and premium estimates to quantify flood risk and insurance viability under coupled climate and socioeconomic change. Applied to unembanked areas in the Rotterdam Metropolitan Region, the Netherlands, we evaluate sea-level rise scenarios (0–2 m), urban development projections and adaptation strategies. Currently, flood insurance is unavailable for unembanked residents in the Netherlands. We therefore investigate whether such a scheme could be viable, what premiums it would imply, and how adaptation would shape its long-term sustainability. Under full participation, risk-based annual premiums covering expected damages and cost of capital would average approximately €50 per household today, but without adaptation could rise to nearly €3000 under high sea-level rise. Beyond 1.0 m sea level rise, the dominant risk driver is no longer gradual climate change itself but its second-order effect on infrastructure policy: storm surge barrier closure thresholds that must rise with the sea. We find that building-level adaptation reduces aggregate damages by up to 60%, but under risk-based participation structures increases individual premiums by shrinking the pool faster than it reduces losses. Our results indicate that flood insurance for unembanked areas could be viable under current conditions, though sustaining manageable premiums over time depends on combining building-level and regional adaptation with risk transfer mechanisms before climate impacts accelerate. The framework is transferable to other coastal and riverine settings facing similar challenges, though flood risk and premium trajectories will vary with local hydrodynamic conditions and how flood damages are allocated among insurers, governments, and households.

1 | Introduction

Globally, many coastal and riverine communities face growing flood risk from urban development and climate change without the protection of large-scale flood defenses. For these areas, insurance is one of few mechanisms available to manage households' financial exposure to flooding. Beyond protecting household wealth and accelerating post-flood recovery, well-designed insurance systems can distribute losses across time and space while incentivizing risk-reducing adaptations through premium structures (Botzen and van den Bergh 2008; Hudson et al. 2016; Surminski 2014). Yet the same forces that

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increase flood risk also challenge the long-term viability of flood insurance, and whether insurance remains affordable depends on how climate change, adaptation measures, and institutional design interact over time.

Flood insurance systems worldwide illustrate this challenge. The United States' National Flood Insurance Program faces recurring financial crises, European markets contend with widening coverage gaps after events such as the 2021 floods across Germany, Belgium, and the Netherlands (Mohr et al. 2023), and rising reinsurance costs signal that the current equilibrium between risk and affordability is under strain. Jarzabkowski et al. (2023) argue that disaster insurability requires dynamic equilibrium across three paradoxes—knowledge, responsibility, and control—implying that the mechanisms shaping insurance viability cannot be assessed in isolation. Yet existing studies typically examine them in isolation or at national to continental scales that average across heterogeneous local conditions (Aerts and Botzen 2011; Hudson et al. 2019; de Ruig et al. 2022). How these drivers interact to determine long-term insurability at the local scale, where threshold effects and building-level exposure shape outcomes, remains poorly quantified.

The Netherlands exemplifies these challenges. Its flood insurance system differentiates coverage by flood source: damage from rainfall and failures of regional flood defenses is insurable, while flooding from the coast, major rivers, and in unembanked areas is excluded from standard property insurance. This exclusion has sparked recurring debate since the North Sea Flood of 1953, most recently after the July 2021 floods across Germany, Belgium, and the Netherlands, which caused at least 220 deaths and an estimated €46 billion in damages across the region (Mohr et al. 2023). In the Netherlands alone, approximately €500 million in damages occurred, of which €220 million was insured and €100 million compensated through the Calamity Compensation Act (Kok et al. 2023; Engelhard et al. 2024). Within this system, unembanked areas represent a particularly instructive case for studying flood insurance viability under changing conditions.

In the Netherlands, "unembanked" is a juridical designation under Dutch water law: unlike embanked zones, which benefit from primary flood defenses with legally enforced safety standards, unembanked areas carry no governmental flood protection standard and residents bear responsibility for their own flood risk. These areas have a distinctive risk profile: high-probability but low-depth flooding, contrasting with the low-probability, high-depth risks of embanked zones. This combination of frequent but manageable losses, growing urban development pressure, and dependence on a threshold-based infrastructure system (the Maeslant storm surge barrier) makes unembanked areas well-suited for examining how adaptation, insurance design, and infrastructure policy interact under climate change.

Flood insurance is currently unavailable for unembanked residents in the Netherlands, constituting a protection gap in the sense of Jarzabkowski et al. (2023) that is driven in part by the absence of quantified flood risk estimates for these areas. Existing Dutch flood insurance research has focused on embanked regions (Aerts and Botzen 2011; Kok et al. 2002; Jongejan and Barrieu 2008) or examined unembanked areas without considering the interplay between sea level rise, urban development, and adaptation strategies (Ermolieva et al. 2017). No study addresses how these drivers, together with infrastructure policy decisions such as storm surge barrier closure thresholds, shape long-term premium trajectories in unembanked areas.

This study develops an integrated framework combining hydrodynamic modelling, damage assessment, and premium estimation to quantify flood risk and insurance viability for unembanked areas under coupled climate and socioeconomic change. Applied to the Rotterdam Metropolitan Region, we quantify how sea level rise, urban development patterns, adaptation strategies, and insurance scheme designs interact to determine premium trajectories through 2100. We make three contributions. First, we assess the role of infrastructure policy decisions, specifically storm surge barrier closure thresholds, as a driver of flood risk relative to gradual climate change. Second, we quantify how building-level adaptation interacts with participation structure to shape premium trajectories. Third, we analyze local-scale threshold dynamics where flood levels approach building elevations, producing non-linear damage responses invisible in assessments that average across heterogeneous building stocks.

Our research question is: how do the physical drivers of flood risk, adaptation strategies, and insurance participation schemes interact to determine the long-term insurability of unembanked areas under climate change and urban development?

The paper proceeds as follows: Section 2 reviews international flood insurance models and Dutch compensation mechanisms. Section 3 details the assessment method. Section 4 presents flood risk trajectories and premium estimates under various climate, development, and adaptation scenarios. Section 5 discusses implications for insurance design and connects findings to the international debate on flood insurability, and Section 6 concludes.

2 | International and Dutch Context of Flood Damage and Compensation

Flood insurance approaches for risk management differ widely across countries. We first review international flood insurance models, then examine Dutch flood damage compensation arrangements.

2.1 | International Flood Insurance Models

Flood insurance is an important component of flood risk management in many developed nations, often involving partnerships between public and private sectors to address challenges of risk assessment, affordability and market penetration (Table 1). European and US systems follow three structural models: entirely private (private organizations serve as both insurers and reinsurers), entirely public (government handles both insurance and reinsurance), and hybrid systems combining public and private roles. These models reflect different approaches to

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TABLE 1 | Comparative analysis of flood insurance arrangements across European countries (adjusted from Crawford and Mangalmurti 2025).

	Market structure				Policy characteristics		
Country	Sales distribution	Claims processing	Reinsurance provider	Government backstop	(In)direct premium subsidy	Mandatory coverage	Risk mitigation incentives
Belgium	Private	Private	Private	Yes, above €280 M	Yes	Yes	Yes
Germany	Private	Private	Private	Ad hoc only	No	No	No
Switzerland	Mixed	Mixed	Public	Yes, joint fund	Yes	Partial	Yes
United Kingdom	Private	Private	Public	Yes, with £250 M loss limit	Yes	Partial	Yes
France	Private	Private	Public	Yes	Yes	Yes	Yes
Spain	Private	Public	Primary insurer[a]	Yes	No	Yes	No
United States	Public	Public	Private	Yes	Yes	Partial	Yes

[a]The government pays citizens directly, while public reinsurers reimburse private insurers.

risk sharing between insurers, reinsurers, governments and individuals.

Belgium, Germany, and some Swiss cantons operate entirely private models where both insurance and reinsurance are managed privately. These systems differ in whether insurance is mandatory or optional and whether pricing is risk-based or flat-rate, affecting market penetration. Belgium mandates flood insurance bundled with fire insurance, which banks require for mortgages (Mees et al. 2016). Government-set premium thresholds maintain affordability, while federal intervention prevents insurer insolvency when damages exceed €280 million. Regional funds provide additional support: Flanders' Disaster Fund covers particularly rare or intense disasters exceeding €30 million (Crawford and Mangalmurti 2025), while Wallonia caps an individual insurer's annual damages at €320 million. This threshold was passed in 2021 when floods caused €2.5 billion in damages, requiring €590 million in insurance payouts plus government intervention (Milliman 2022). Germany relies on voluntary flood insurance as a fire insurance add-on. Despite uptake rising from 19% (2002) to 54% (2023), many properties remain uninsured (Gesamtverband der Versicherer 2024). The 2021 floods caused €33 billion in largely uninsured losses (Mohr et al. 2023).

France and the United Kingdom use private flood insurance with public reinsurance to maintain affordability. The UK's Flood Re keeps average premiums at €390 annually for 250,000 high-risk properties, half the unsubsidised rate of €780 (Bank of England 2024). To avoid subsidising new development in flood-prone areas, Flood Re excludes properties built after January 2009 (Fan and Davlasheridze 2016; de Koning et al. 2019; Tesselaar et al. 2023). France's Cat Nat program bundles flood coverage with other natural disasters, requiring all property owners to pay a 20% surcharge that creates a collective reinsurance pool. A mandatory €380 deductible and exclusion of uninsured victims from government aid maintain risk incentives. The pressure on Cat Nat is rising: average annual costs doubled from €1.2 billion between 1982 and 2016 to €2.5 billion between 2016 and 2022 (Keucheyan 2023).

Public insurance systems in Spain, most Swiss cantons, and the United States represent comprehensive state-managed approaches where flooding is the costliest disaster category. These systems prioritize solidarity over risk-based pricing. Spain's Consorcio de Compensación de Seguros faced severe testing during the 2024 Valencia floods, which generated €3.5 billion in insurance claims alongside €6 billion in uninsured damages (Galvez-Hernandez et al. 2025). The United States' National Flood Insurance Program (NFIP), operational since 1968, demonstrates the challenges of maintaining long-term financial sustainability in federally backed schemes, with major flood events creating significant debt that necessitated reforms toward risk-based pricing while addressing affordability concerns.

These diverse arrangements reflect different responses to the same underlying challenge: balancing the paradoxes of knowledge, responsibility, and control that Jarzabkowski et al. (2023) identify as central to disaster insurability. Private systems like Germany's prioritize individual responsibility but leave large coverage gaps, while public systems like Spain's Consorcio emphasize collective risk sharing but face fiscal strain under extreme events. Hybrid systems such as Flood Re and Cat Nat attempt to balance both, yet remain sensitive to shifts in any one paradox, as rising risk knowledge enables more precise pricing that can push high-risk households out of the collective pool.

2.2 | Financial Arrangements for Flood Damage in the Netherlands

The Netherlands combines selective private insurance with government compensation. Standard home insurance covers local rainfall, sewage overflow, regional surface water flooding and failures of regional flood defenses (15,000 km along canals and small rivers), but excludes groundwater flooding, unembanked

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areas and primary flood defenses failures (3500 km along sea and major rivers).

The exclusion of primary flood defenses from insurance coverage traces back to the 1953 North Sea Flood (Table 2). In response to this disaster, the Dutch Insurers Union issued a binding decree in 1955 prohibiting members from insuring such risks (Seifert et al. 2013). Unlike typical pooled risks, such failures would cause catastrophic losses exceeding reinsurance capacity (currently around €5–€7 billion), while low market demand further undermines viability. The "Neerlandse" flood insurance policy, launched in 2012 with €75,000 coverage, was terminated in 2020 due to insufficient uptake (van Rijswick et al. 2015). Insurance coverage has expanded since the late 1990s, with standardized pluvial insurance introduced in 2001 and regional defense coverage gradually extended, particularly after 2018 industry recommendations.

For uninsurable risks, the Calamity Compensation Act (WTS) provides disaster relief, compensating 90% of eligible damages for declared disasters (Table 3). However, the system faces growing complexity as the boundary between insurable and uninsurable risks evolves. The 2021 Limburg floods exemplified this challenge: despite the rainfall-driven flooding being insurable, the government activated the WTS to provide broader compensation beyond what private insurance would cover. While providing welcome relief to flood-affected residents, this decision also exposed fundamental tensions within the WTS framework (Engelhard et al. 2024).

3 | Method

3.1 | Study Area

This study examines the unembanked areas in the Rotterdam Metropolitan Region of the Netherlands, extending from the Hollandsche IJssel to the Haringvliet sluices and eastward from the coast to the Biesbosch (Figure 1). Located behind the Maeslant barrier, this region contains approximately 46,000 homes and 5000 businesses (Kadaster 2024), with 23,000 additional unembanked homes planned for development (Gemeente Rotterdam 2024).

While other unembanked areas exist in the Netherlands, including sites along the Meuse in Limburg and IJburg near

TABLE 2 | Evolution of private flood insurance availability for Dutch households by flood source type.

Flood source	Status	Historical context and key changes
Primary flood defense failures (sea and major rivers)	Not insurable	1953 flood led to permanent industry exclusion
Regional flood defense failures (local rivers and canals)	Insurable	Gradual inclusion since 2000; expanded after 2018 industry recommendations
Heavy rainfall	Widely insurable	Introduced in 2000, now standard in most policies
Groundwater	Selectively insurable	Limited coverage; varies by insurer and specific circumstances
Unembanked	Not insurable	Only tailor-made insurance for companies and industry

TABLE 3 | Flood events and financial impacts in the Netherlands, 1953–2021 (Jak and Kok 2000; Kok et al. 2002; Aerts and Botzen 2011; Bisschop et al. 2013; Kok et al. 2023; Engelhard et al. 2024).

		Total damage		Insured damage		Government compensation
Year	Event	Original	2025	Original	2025	(in 2025 prices)
1953	North Sea Flood (Watersnoodramp)	680	5800	0	0	Full compensation
1993	Meuse river flood	250	230	0	0	Full compensation
1995	Meuse river flood	165	140	0	0	Full compensation
1998	Nationwide heavy rainfall	400	740	0	0	430 via WTS (two claims)
2003	Meuse flooding	4	7	0	0	6 via WTS
2003	Wilnis dike failure	16	25	8	13	3 via WTS
2011	Meuse flooding	1	1	0	0	1 via WTS
2021	Severe Flooding in Limburg (Geul, Gulp, Meuse areas)	500	590	210	230	100 via WTS

Note: Values in million EUR. For 2003 and 2011 the total damage is estimated based on the WTS pay-out, assuming this amounted to 90% of the total damage.

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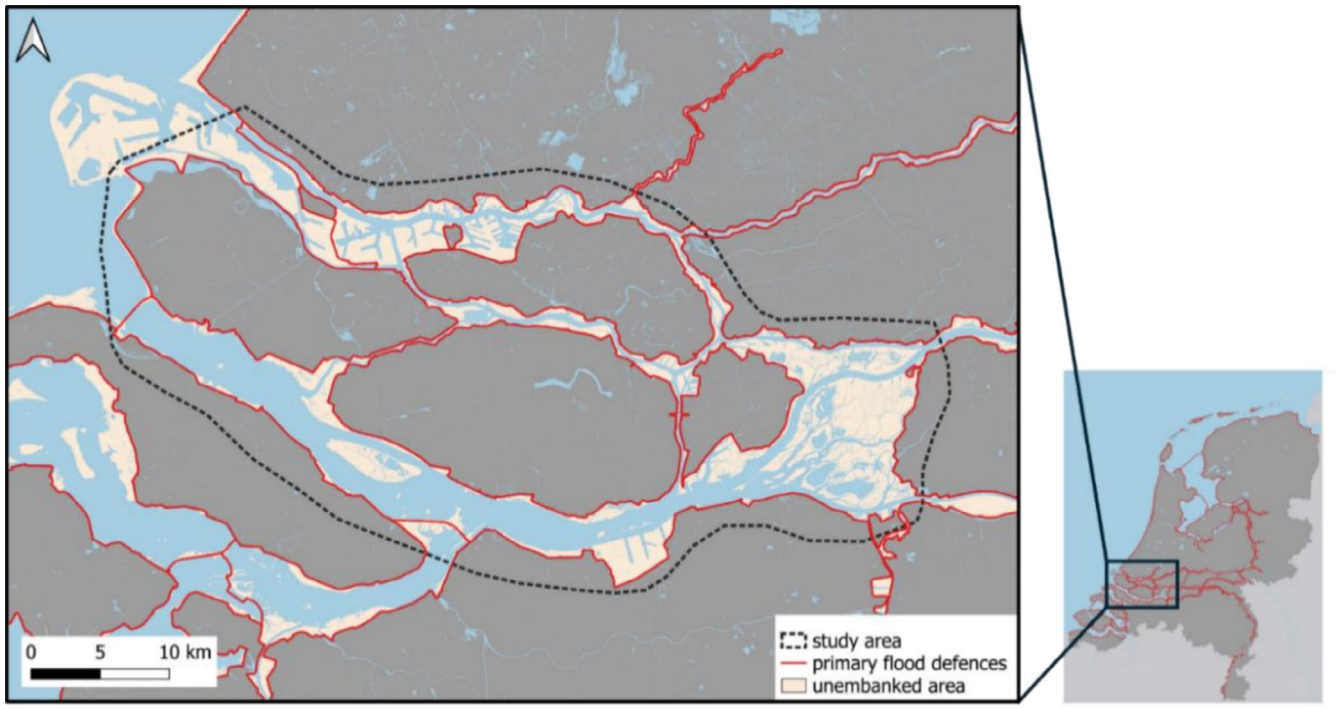


FIGURE 1 | Unembanked areas in the Rijnmond-Drechtsteden.

Amsterdam, we selected Rotterdam as our case study area because it contains the country's largest concentration of unembanked properties. This concentration creates strong spatial correlation in flood damage, as a single event can simultaneously affect thousands of properties. Additionally, Rotterdam presents the Netherlands' most complex water system, where water levels are driven by coastal storm surges, high river discharges, and whether the Maeslant barrier is open or closed.

3.2 | Flood Risk and Insurance Modelling

We developed an integrated framework combining: flood hazard modelling using inundation depth maps (Section 3.2.1), damage assessment using the Dutch national methodology (Section 3.2.2), expected annual damage calculations (Section 3.2.3) and insurance premium estimation (Section 3.2.4). This framework was applied across multiple scenarios evaluating the effect of climate change, urban development, adaptation strategies and insurance schemes (Section 3.3).

3.2.1 | Flood Probability Assessment

Flood probabilities were derived from inundation depth maps for 10-, 100- and 1000-year return periods under current and future climate scenarios. Hydrodynamic modelling incorporated hydraulic boundary conditions including wind speed and direction, river discharges (Nederrijn-Lek, Waal and Meuse), and Maeslant barrier operations. The Digital Terrain Model of the Netherlands (AHN4, 5-m resolution) converted water levels into inundation depths. Wave effects, contributing approximately 10 cm to water levels, were included in all calculations.

3.2.2 | Flood Damage Assessment

Flood damage was calculated using the Dutch national standard methodology (SSM 2024). Building stock data (location, type, function) came from the Basisregistratie Adressen en Gebouwen (Kadaster 2024). The SSM uses depth-damage curves calibrated for unembanked areas to relate water depth and financial loss (SSM 2024). Curves are differentiated by building type, including single-family homes and apartments. Figure 2 shows the curves for single-family homes as an illustrative example. For this building type, SSM provides three sets for structural and content damage: a standard curve and two reduced vulnerability curves representing existing adaptation such as flood-resistant materials. Current buildings received curves based on flood exposure frequency. New development received standard curves, as units are elevated to meet municipal requirements and lie outside 10-year or 100-year flood zones. Damage estimates were normalized to 2022 price levels.

3.2.3 | Expected Annual Damage

Expected annual damage was calculated by integrating flood damages across 10-, 100- and 1000-year return periods. Although flood events occurring more frequently than once per 10 years or less frequently than once per 1000 years contribute to the total risk profile, data limitations prevented their inclusion in this analysis.

3.2.4 | Premium Estimation

Premiums were estimated as pure premium (expected annual damage) plus a cost of capital load to reflect regulatory capital requirements under the EIOPA Solvency II framework:

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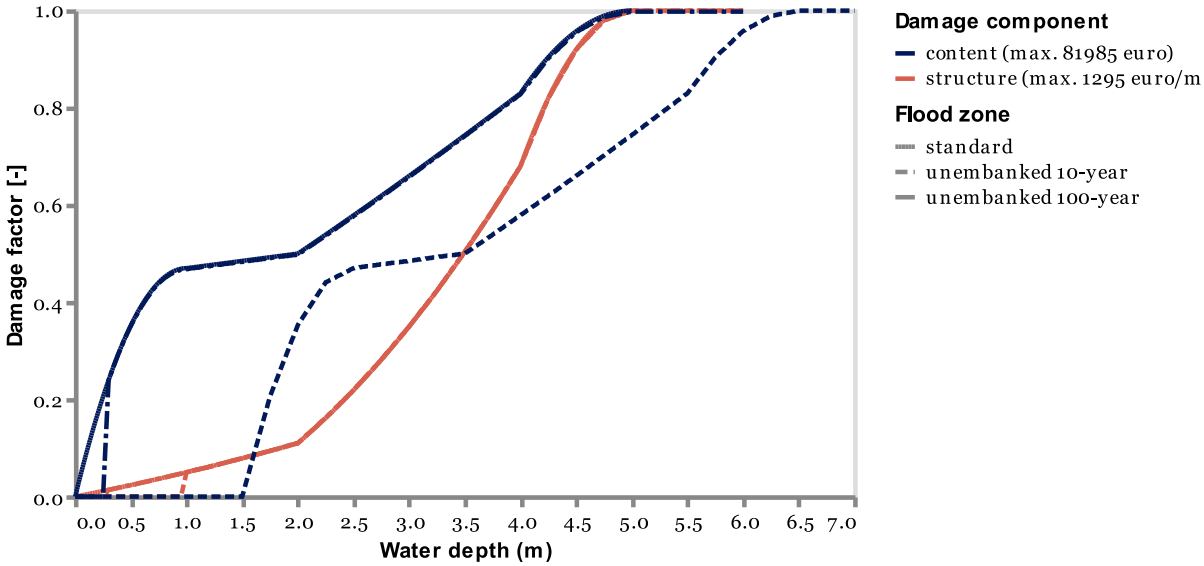


FIGURE 2 | Damage curves for a single-family home for both building structure and contents. For unembanked single-family homes, there are 3 different curves: Standard curves for buildings in areas outside 100-year flood zones, and reduced-vulnerability curves for 100-year and 10-year zones respectively (SSM 2024).

$$P_{\text{household}} = \frac{\text{EAD} + r_{CoC} * \left(D_{200} - \text{EAD}\right)}{n_{\text{households}}}$$

where:

- $P_{\text{household}}$ = premium per household
- EAD = expected annual damage, depending on sea level rise & building stock
- D_{200} = 1-in-200 year damage, depending on sea level rise & building stock
- r_{CoC} = cost of capital rate, set to 6%
- n_households = number of households, depending on building stock & insurance scheme (Section 3.3).

Reported premiums comprise expected annual loss and cost of capital only, excluding administrative expenses, profit margins, and risk-loading factors that depend on market structure and institutional design. Each underlying return period map represents a fully correlated regional event in which all exposed properties are affected simultaneously. The capital requirement therefore reflects a fully correlated loss scenario. The cost-of-capital rate (6%) is treated as a fixed parameter reflecting the opportunity cost of regulatory capital under Solvency II. Adaptation reduces the required capital (D200), not the rate. To assess industry capacity constraints, we compared the total damage for a 1-in-200-year flood event against the Dutch insurance industry's existing catastrophe coverage capacity of €5–7 billion for storm events (van Verzekeraars 2018). While this benchmark was established for storm damage rather than flooding, it provides a reference point for the industry's current capacity to absorb large losses.

3.3 | Scenarios and Strategies

We evaluated flood risk and insurance premiums across climate change scenarios and under different strategies for urban development, local adaptation, and insurance design (Table 4).

Four sea level rise scenarios were analyzed: 0 m (current), 0.5, 1.0, and 2.0 m (Table 4). These levels span potential futures linked to different IPCC emission pathways (van Dorland et al. 2023). Each scenario also incorporates corresponding adjustments to other climate-related factors. Extreme river discharge rates are increased, and under the most extreme sea level rise scenario of 2.0 m, the closure threshold of the Maeslant barrier is raised to prevent excessively frequent disruptions to shipping while increasing flood risk in unembanked areas (Mooyaart et al. 2025). We include the 2.0 m scenario to capture ice sheet uncertainties that could drive sea levels to 2.5 m by 2100 (van Dorland et al. 2023).

Two building stocks were defined to assess urban development impacts (Table 4). The current stock includes 46,000 existing housing units in unembanked areas. The future scenario adds 23,000 new housing units planned for Rotterdam's unembanked areas (Gemeente Rotterdam 2024). New residential units are modelled at the 2025 established flood design elevation of NAP +3.8 m (Gemeente Rotterdam 2025) and are assigned standard damage curves (Figure 2). We include only Rotterdam's planned development, representing a conservative estimate. Additional development planned for Dordrecht and other areas is excluded due to data limitations and varying elevation standards.

Local adaptation was modelled using protection thresholds that prevent flood damage below specified water depths, consistent with measures such as dry-proofing or small-scale barriers that prevent water entry. This is modelled on the hazard side: at each location, inundation depths below the adaptation threshold are set to zero, eliminating damage for that event at that location. The analysis compares a reference strategy (no adaptation) against strategies with a 0.5 m protection

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TABLE 4 | Combination of climate change scenarios, urban development projections, local adaptation strategies and insurance scheme structures.

Category	Name	Description
Climate change	Sea level rise 0.0 m	Current sea level, 1000-year Rhine river discharge 10,020 m^3 Maeslant barrier closes at NAP +3.0 m
	Sea level rise 0.5 m	Sea level rise of 0.5 m, 1000-year Rhine river discharge 10,750 m^3 Maeslant barrier closes at NAP +3.0 m Projected timing 2115 (RCP4.5)/2070 (RCP8.5)
	Sea level rise 1.0 m	Sea level rise of 1.0 m, 1000-year Rhine river discharge 13,050 m^3 Maeslant barrier closes at NAP +3.0 m Projected timing > 2150 (RCP4.5)/2115 (RCP8.5)
	Sea level rise 2.0 m	Sea level rise of 2.0 m, 1000-year Rhine river discharge 13,050 m^3 Maeslant barrier closure threshold raised to NAP +4.25 m Projected timing > 2150 (RCP4.5)/> 2150 (RCP8.5)
Urban development	Current	Considers only the existing 46,000 housing units.
	Future	Adds 23,000 planned housing units (total 69,000), built at an elevation of NAP +3.8 m.
Local adaptation	Reference	No adaptation; damage occurs at any flood depth.
	Minor adaptation	Assumes local measures prevent damage from flood depths up to 0.5 m
	Major adaptation	Assumes local measures prevent damage from flood depths up to 1.0 m.
Insurance scheme (participation)	Mandatory	The insurance pool includes all 46,000 unembanked households.
	At-Risk	The insurance pool includes only households flooded in a 1-in-1000-year event, conditional on sea level rise.
Insurance scheme (coverage)	Reference	Insurer covers 100% of damage for all return periods.
	Adaptation	No coverage for 10-year events (assumed prevented by adaptation); full coverage for rarer events.
	Public–Private (shared liability)	10-year: 0% insurance coverage, 50% households, 50% government 100-year: 100% insurance coverage 1000-year: 50% insurance coverage, 50% government

threshold and a 1.0 m protection threshold (Table 4). When flood depths surpass the defined threshold, damage is calculated from the full water depth using the original damage curves.

Insurance sensitivity analysis varied participation base and coverage structure (Table 4). Both participation structures are restricted to unembanked areas. Mandatory participation includes all 46,000 unembanked households, while at-risk participation includes only households flooded in 1-in-1000-year events (conditional on sea level rise). Coverage structures distribute financial liability between households, insurers and government across different flood frequencies. The reference structure provides full insurance coverage for all return periods. The second structure excludes frequent flood damage, assuming future adaptation prevents damage from 10-year events. The third uses layered public-private risk sharing inspired by proposals from the European Central Bank (2023) and Dutch Scientific Climate Council (WKR 2025), where government provides financial backstops for the most severe events.

4 | Results

This section examines how multiple drivers of change influence flood risk in Rotterdam's unembanked areas. We first quantify current flood damages and insurance premiums as a baseline (Section 4.1), then examine how sea level rise influences flood probabilities and corresponding damages (Section 4.2). We subsequently evaluate how three additional drivers modify these climate impacts: urban development's effect on risk pooling (Section 4.3), local adaptation measures' influence on damage distribution (Section 4.4), and alternative insurance structures' role in risk allocation (Section 4.5). Together, these analyses reveal how different drivers interact to shape insurance affordability over the long term.

4.1 | Current Flood Insurance Viability

Under current conditions (0 m sea level rise), flood damages increase exponentially with return period: €1 million for a

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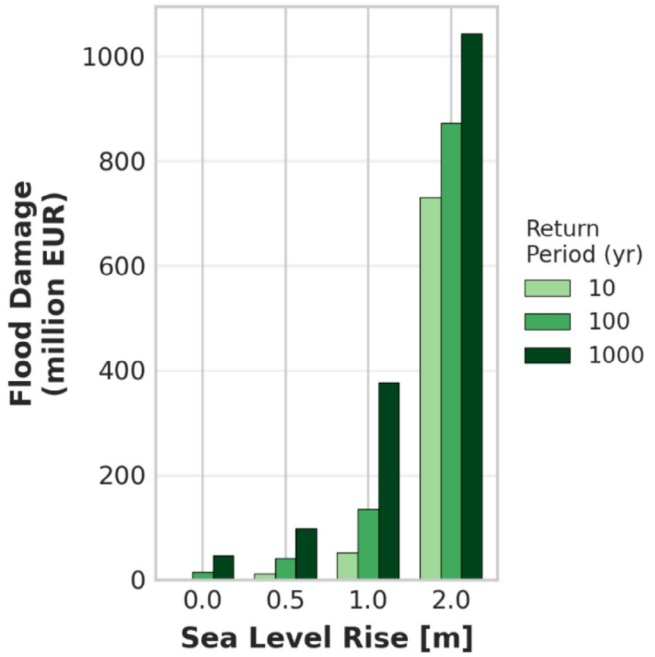


FIGURE 3 | Flood damage estimates for the Dutch Rijnmond-Drechtsteden region for 10-, 100-, and 1000-year return periods.

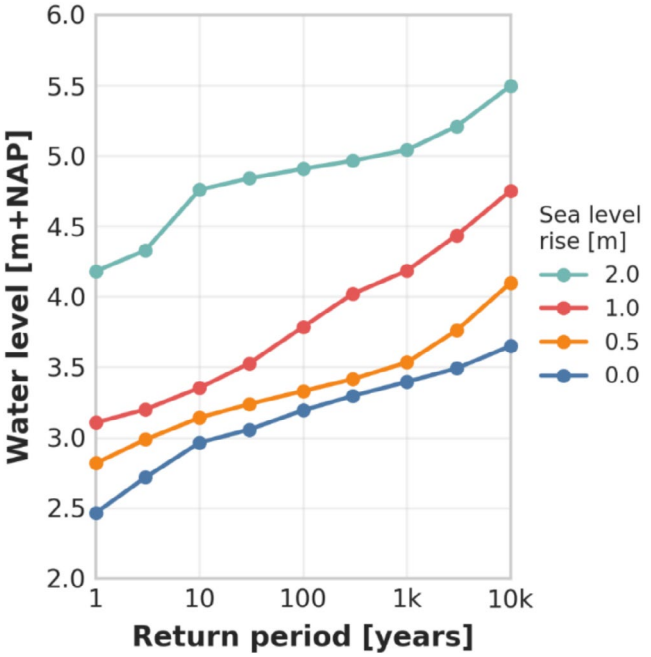


FIGURE 4 | Extreme water levels in the Rotterdam Metropolitan Region under various scenarios of sea level rise (location: Merwehaven).

10-year event, €15 million for a 100-year event and €47 million for a 1000-year event (Figure 5). Expected annual damages for residential properties total €1 million. Total premiums are €50 (mandatory participation) and €290 (at-risk participation), comprising pure premiums of €23 and €130 respectively, with cost of capital adding €27 and €160. The cost of capital is determined by the 1/200-year event damage of €20 million, following Solvency II requirements for insurers to maintain capital reserves against 0.5% annual probability losses (Figure 3).

4.2 | Insurance Viability Under Climate Change

Two elevation thresholds frame our findings. NAP +3.0 m marks where the first unembanked areas in Rotterdam flood and this water level triggers closure of the Maeslant barrier. More significant for urban development is NAP +3.5 m. This threshold matches the median elevation of Rotterdam's buildings (Oerlemans 2025) and approximates the pre-2025 standard of NAP +3.6 m for new building lots (raised to NAP +3.8 m in 2025). Currently, water level reaches NAP +3.0 m during 10-year events, while NAP +3.5 m occurs only during events rarer than once in 1000 years (Figure 4). With 1.0 m of sea-level rise, these frequencies shift: NAP +3.0 m becomes an annual occurrence, and NAP +3.5 m becomes a 30-year event.

These frequency shifts translate into flood extents that expand non-linearly with sea level rise (Figure 5). With 0.5 m sea level rise, flood extents increase moderately. At 1.0 m sea level rise, areas previously flooded only in 1000-year events experience inundation more frequently. The 2.0 m sea level rise scenario reveals near-complete inundation of low-lying unembanked areas during even moderate events, with water depths exceeding 2 m in some currently dry locations during 100-year events. Note that this is without additional flood risk measures.

Expected annual damages increase with sea level rise, reaching three times baseline values at 0.5 m, eleven-fold at 1.0 m, and 81-fold at 2.0 m. This non-linear progression results from each incremental rise in sea level shifting previously rare flood events into higher frequency categories. The most pronounced transition occurs when water levels approach the median building elevation in Rotterdam (NAP +3.5 m), whereby infrastructure that previously exceeded the 1000-year return period threshold becomes subject to regular flooding.

Insurance premiums follow this damage acceleration but diverge by participation model. Mandatory participation premiums increase gradually until 1.0 m sea level rise (from €50 to €470), then increase six-fold to €2900 at 2.0 m. Risk-based premiums show smaller relative increases because they start from a higher baseline, rising from €290 to €3200. The narrowing ratio between these two models reflects that flood exposure expands from affecting selected areas to most unembanked properties. As premiums increase, the cost of capital represents a smaller share of the total premium: 55% with 0 m sea level rise versus 30% at 2.0 m rise. Relevant for insurer solvency under Solvency II, the 200-year event damage rises to €186 million and €920 million with 1 and 2 m sea level rise respectively. Although this remains within Dutch insurers' coverage capacity for storms, the prevalence of frequent, high-magnitude losses challenges the design of viable insurance premiums.

4.3 | The Impact of Urban Development on Flood Damages and Insurance Premiums

Urban development impacts insurance premiums in two ways. New housing in flood-prone areas may increase the damage potential resulting in larger damages, conditional on

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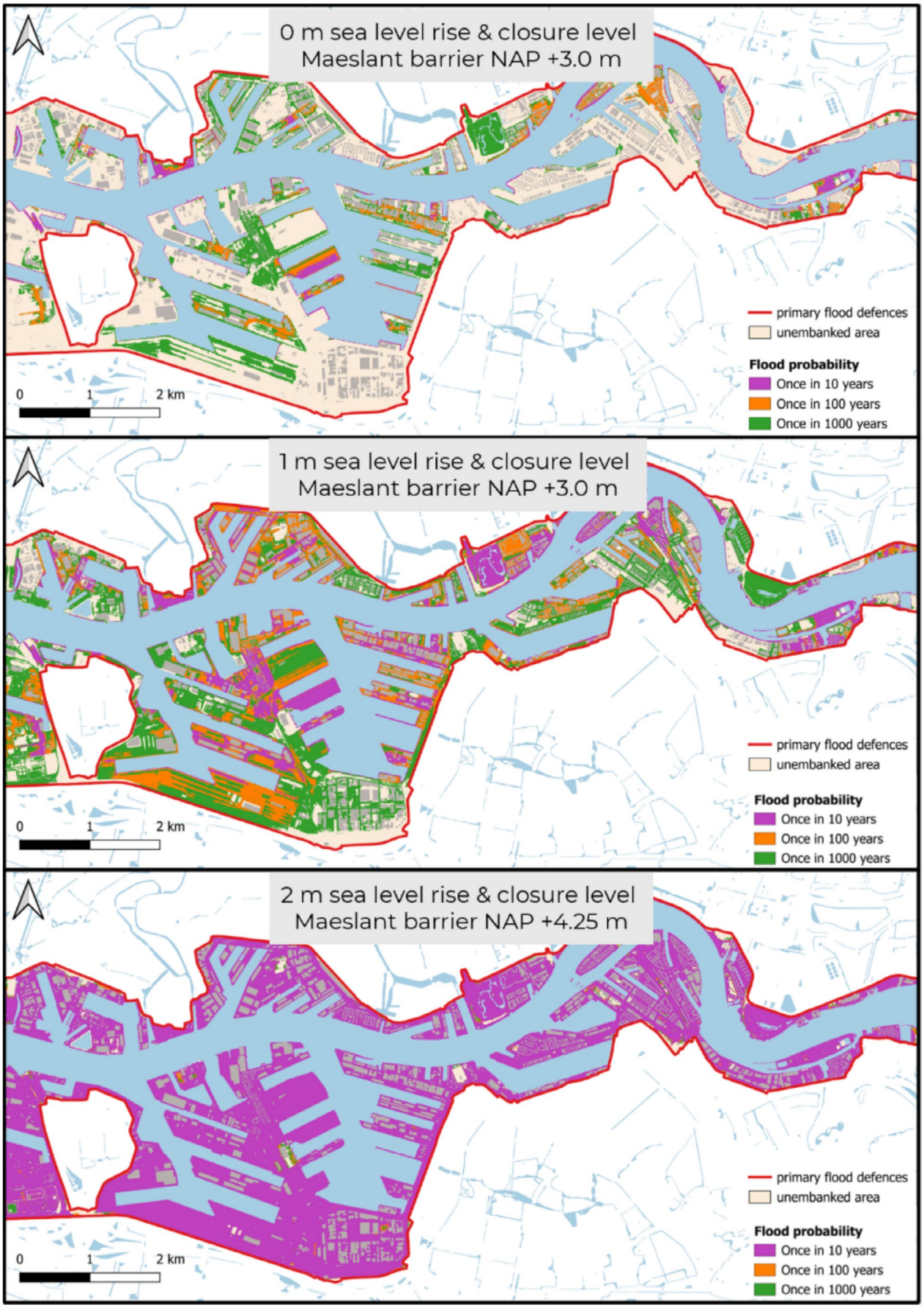


FIGURE 5 | Flood inundation probability in unembanked areas of Rotterdam under current conditions, with 1.0 m sea level rise, and with 2.0 m sea level rise.

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the sea level rise and flood elevation level of new urban development. On the other hand, urban development also increases the number of households, meaning that damage is shared among more participants, resulting in lower premiums, which is mainly conditional on the insurance participation strategy chosen.

Under moderate sea level rise conditions (0.0–0.5 m), development reduces premiums because water levels for 1000-year events remain below new building elevations (Table 5). Mandatory participation premiums decrease from €50 to €36 at current sea levels and from €140 to €94 at 0.5 m rise. At higher sea level rises, the relationship becomes more complex. At 1.0 m rise, development increases expected damages from €11 to €12 million, yet mandatory participation premiums remain lower due to expanded risk sharing. The tipping point occurs at 2.0 m sea level rise, where future development increases both damages and premiums under mandatory participation, indicating that the damage amplification effect outweighs risk-sharing benefits.

4.4 | The Impact of Adaptation on Flood Damages and Insurance Premiums

Local flood protection creates a paradox: measures that successfully reduce total damages can increase premiums for remaining at-risk households. This occurs because adaptation concentrates residual damages among fewer participants, fundamentally altering the risk-sharing mathematics. Protection to 0.5 m water depth reduces expected annual damage by 20%–55% across sea level rise scenarios, while extending protection to 1.0 m provides further but smaller reductions (Table 6).

Under mandatory participation, adaptation reduces premiums by spreading lower damages across all households. At 2.0 m sea level rise, 1.0 m protection reduces premiums from €2900 to €1700. This paradox manifests most strongly under risk-based participation. At current sea levels with 1.0 m protection, affected households during 1000-year events drop from 7800 to 500, but average damages per household increase from €6200 to €35,000 (Table 7). Risk-based premiums increase from €290 to €2100 despite overall damage reduction. This pattern intensifies with sea level rise. At 1.0 m rise with 1.0 m protection, only 500 households are affected during 10-year events, but face €35,000 average damages each. While adaptation successfully reduces aggregate risk, the concentration of residual damages among fewer households creates affordability challenges under risk-based schemes.

4.5 | The Impact of Insurance Strategies on Insurance Premiums

Alternative insurance strategies reduce both insured damages and premiums (Table 8). Beyond the reference, we examine two approaches: adaptation targeting 10-year floods and public-private risk sharing.

Physical adaptation against 10-year return period floods reduces pure premiums, but overall premium declines are smaller than the 40% EAL reduction because cost of capital remains largely unchanged. At 1.0 m sea level rise under mandatory participation, the CoC represents 50% of total premiums and is determined by the 200-year damage level, which is minimally affected by excluding 10-year events.

Public-private risk sharing marginally improves upon physical adaptation for 10-year events. At 1.0 m sea level rise, insured EAL is reduced from €8.5 to €7.6 million, lowering premiums from €420 to €400. This modest gain reflects extreme events' limited contribution to EAL: the 1000-year event causes €380 million damage but adds little to expected losses due to its low probability.

TABLE 5 | Annual damages and insurance premiums by sea level rise scenario and building stock in unembanked areas. Values are rounded to two significant figures; totals may not equal the sum of components due to rounding.

Sea level rise [m]	Building stock	Total households [–]	At-risk households [–]	EAD [million EUR]	Mandatory participation premium [EUR/household]			Only at-risk participation premium [EUR/household]		
					EAL part	CoC part	Total	EAL part	CoC part	Total
0.0	Current	46,000	7800	1.0	23	27	50	130	160	290
	Future	69,000	7800	1.0	15	20	36	130	180	310
0.5	Current	46,000	12,000	3.2	70	68	140	270	260	530
	Future	69,000	12,000	3.2	46	48	94	270	280	540
1.0	Current	46,000	31,000	11	240	230	470	350	340	690
	Future	69,000	54,000	12	180	170	350	230	220	450
2.0	Current	46,000	40,000	81	1800	1100	2900	2000	1200	3200
	Future	69,000	63,000	150	2200	670	2900	2400	730	3100

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TABLE 6 | Expected annual damages and corresponding premiums for the entire Rhine-Meuse estuary. Values are rounded to two significant figures.

Sea level rise [m]	Local adaptation measures	Total households [–]	At-risk households (conditional on adaptation) [–]	At-risk households (no adaptation)	EAD [million EUR]	Premium [EUR/household]		
						Mandatory participation	At-risk participation (conditional on adaptation)	At-risk participation (no adaptation)
0.0	None	46,000	7800	7800	1.0	50	290	290
	0.5 m	46,000	2000	7800	0.50	25	580	150
	1.0 m	46,000	460	7800	0.40	21	2100	120
0.5	None	46,000	12,000	12,000	3.2	140	530	530
	0.5 m	46,000	3600	12,000	1.6	69	870	260
	1.0 m	46,000	980	12,000	1.2	50	2300	190
1.0	None	46,000	31,000	31,000	11	470	690	690
	0.5 m	46,000	14,000	31,000	5.1	260	850	380
	1.0 m	46,000	4500	31,000	3.3	140	1500	210
2.0	None	46,000	40,000	40,000	81	2900	3200	3200
	0.5 m	46,000	38,000	40,000	64	2300	2700	2600
	1.0 m	46,000	24,000	40,000	44	1700	3100	1900

Note: Under at-risk participation conditional on adaptation, premiums can increase despite lower total damages because adaptation removes households from the at-risk pool faster than it reduces aggregate damage, concentrating residual costs among fewer participants.

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TABLE 7 | Flood damage and average damage per household during 10-, 100- and 1000-year return period flood events. Values are rounded to two significant figures.

Sea level rise [m]	Local adaptation measures	Number of affected households (average damage per affected household)		
		10-year events	100-year events	1000-year events
0.0	None	800 (€1200)	4900 (€3100)	7800 (€6200)
	Until 0.5 m	200 (€3700)	800 (€9500)	2000 (€12,000)
	Until 1.0 m	14 (€28,000)	300 (€27,000)	460 (€35,000)
0.5	None	4700 (€2800)	7200 (€6000)	12,000 (€8200)
	Until 0.5 m	800 (€9600)	1500 (€14,000)	3600 (€14,000)
	Until 1.0 m	300 (€27,000)	500 (€34,000)	980 (€31,000)
1.0	None	8100 (€6600)	14,000 (€9700)	31,000 (€12,000)
	Until 0.5 m	2100 (€13,000)	5000 (€15,000)	14,000 (€21,000)
	Until 1.0 m	500 (€35,000)	1300 (€30,000)	4500 (€29,000)
2.0	None	39,000 (€19,000)	40,000 (€22,000)	40,000 (€26,000)
	Until 0.5 m	30,000 (€21,000)	35,000 (€18,000)	38,000 (€27,000)
	Until 1.0 m	12,000 (€30,000)	17,000 (€29,000)	24,000 (€31,000)

5 | Discussion

5.1 | Interpretation and Implications of Key-Findings

Flood insurance for unembanked areas is currently viable in actuarial terms: mandatory participation premiums of €50 fall well within the range of existing Dutch household insurance (€120–€400/year), even when adjusted for typical European expense ratios of 30%–50% (EIOPA 2020). At-risk participation premiums of €290 are also within this range at current sea levels, and both remain below international benchmarks such as UK Flood Re (€390) and the US NFIP (approximately €900).

However, actuarial viability does not guarantee a functioning insurance market. Willingness to pay, household risk perceptions, and political economy all influence whether actuarially fair premiums translate into sustainable insurance uptake, considerations that fall outside the scope of this analysis.

The non-linear damage progression under sea level rise is not driven by physical climate change alone. Through 1.0 m of sea level rise, damage increases are proportional to the expanding flood extent and depth. Beyond 1.0 m, the anticipated raising of the Maeslant barrier's closure threshold from NAP +3.0 m to NAP +4.25 m causes a step change in flood risk that accounts for most of the damage increase to 2.0 m. For insurers, this distinction matters: climate-driven risk changes allow gradual premium adjustments, whereas infrastructure policy decisions can shift risk abruptly. This finding extends beyond the Rotterdam case. Regions with threshold-based flood protection, such as the Thames Barrier in London and the MOSE system in Venice, face analogous dynamics where decisions on barrier operation, replacement timing, or design standards can alter insurability more suddenly than incremental sea level rise. This also illustrates what Jarzabkowski et al. (2023) term the control paradox: as rising premiums push flood insurance toward the limits of private viability, they simultaneously strengthen the case for public infrastructure investment, shifting the boundary between market-based risk transfer and government-controlled flood protection. Moreover, linking flood insurance to mortgage conditions could give insurers indirect influence over spatial development decisions, creating a feedback loop in which market actors shape land-use planning. Insurance premiums thus become not only a measure of risk but an instrument in the broader policy debate on infrastructure adaptation and urban development.

Local adaptation significantly reduces flood damages and insurance premiums, but effectiveness depends on participation structure. Under mandatory participation, adaptation benefits are shared: 1.0 m protection reduces premiums from €50 to €21 at current sea levels and from €2900 to €1700 at 2.0 m sea level rise. Under at-risk participation, the same adaptation increases premiums from €290 to €2100, because it removes households from the risk pool faster than it reduces total damages. This adaptation paradox reflects the responsibility paradox of Jarzabkowski et al. (2023): risk-based participation places the full cost of residual risk on the most exposed households, while mandatory participation distributes it collectively. The tension is sharpened by the question of who bears responsibility for adaptation costs, given that government spatial planning decisions enabled development in these flood-prone areas.

Our analysis also engages in the knowledge paradox identified by Jarzabkowski et al. (2023). Flood risk in Dutch unembanked areas has been largely unquantified, contributing to the absence of insurance for these areas. By estimating expected damages and premium trajectories across climate and adaptation scenarios, this study provides the risk quantification that is a precondition for insurability. Yet the same knowledge reveals the other side of the paradox: at higher sea level rise, risk becomes sufficiently concentrated and predictable that actuarially fair premiums for the most exposed households exceed affordability thresholds. This mirrors the dynamics that prompted the establishment of Flood Re in the United Kingdom, where increasingly precise flood risk mapping made risk-reflective pricing unaffordable for high-risk properties, necessitating cross-subsidization to maintain insurability (Jarzabkowski et al. 2023).

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TABLE 8 | Insured expected annual damage and premium for different insurance strategies.

Sea level rise [m]	Insurance structure [–]	Total households [–]	At-risk households [–]	Insured EAD [million EUR]	Premium [EUR/household]	
					Mandatory participation	At-risk participation
0.0	Reference	46,000	7800	1.0	50	290
	Adaptation 10-year events	46,000	7800	1.0	49	290
	Public-private risk sharing	46,000	7800	0.9	47	270
0.5	Reference	46,000	12,000	3.2	140	530
	Adaptation 10-year events	46,000	12,000	2.6	130	480
	Public-private risk sharing	46,000	12,000	2.4	120	460
1.0	Reference	46,000	31,000	11	470	690
	Adaptation 10-year events	46,000	31,000	8.5	420	620
	Public-private risk sharing	46,000	31,000	7.6	400	590
2.0	Reference	46,000	40,000	81	2900	3200
	Adaptation 10-year events	46,000	40,000	48	2200	2500
	Public-private risk sharing	46,000	40,000	46	2100	2400

The cost-of-capital estimates reported here are conservative: Solvency II's standard formula operates at the portfolio level, and a diversified insurer would benefit from cross-peril and cross-zone diversification effects that our standalone regional approach does not capture, implying lower capital requirements than reported here. Regarding reinsurance capacity, current 200-year flood damages of approximately €20 million are two orders of magnitude below Dutch insurers' catastrophe coverage for storms (€5–€7 billion; van Verzekeraars 2018), suggesting the industry could absorb unembanked flood losses under present conditions. At 2.0 m sea level rise, however, 200-year damages rise to €920 million. These would accumulate on top of correlated storm claims rather than substitute for them, and the spatial concentration of flood losses may require different reinsurance structures than geographically dispersed storm damage. Moreover, unembanked areas elsewhere in the Netherlands, such as along the Meuse in Limburg and IJburg near Amsterdam, would generate additional claims against the same capacity but also offer diversification benefits, as these regions are driven by different hazard mechanisms and are less spatially correlated with the Rijnmond-Drechtsteden area than properties within it.

5.2 | Limitations

The limitations of this analysis reflect broader methodological challenges in flood insurance assessment that extend beyond the Rotterdam context.

The flood probability assessment relies on discrete return periods (10, 100, and 1000 years), which underestimates expected annual damages by excluding more frequent events. More sophisticated approaches could fit continuous probability distributions to available data points, potentially yielding more accurate damage estimates. The magnitude of this underestimation varies with sea level rise. At current sea levels, 10-year events contribute minimally to expected annual damages, implying that more frequent events add even less to the total. At 2.0 m sea level rise, however, 10-year events account for approximately 40% of expected annual damages. This shift suggests that events more frequent than 10 years also become increasingly damaging, though their contribution is not captured in this analysis. Furthermore, severe storms cause both flooding and wind damage simultaneously.

Urban development projections in this study extend only to 2040 and cover only unembanked areas within the municipality of Rotterdam, incompletely capturing all unembanked housing projects in the Rotterdam Metropolitan Region. This limitation is universal in long-term flood risk assessment: urban development plans typically span 15–20 years, while major infrastructure such as storm surge barriers operates over 50–100 year horizons.

Damage calculations using the Dutch national SSM methodology carry inherent uncertainties in depth-damage relationships. These curves derive primarily from limited historical events (1953, 1993, and 1995 floods). More recent evidence suggests

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potential underestimation: Endendijk et al. (2023) and van Ederen et al. (2025) find higher damage estimates based on survey data and insurance claims from the 2021 Limburg flood. However, this event involved extreme rainfall rather than coastal or tidal flooding, limiting direct transferability to unembanked areas where flood dynamics differ. Additionally, potential overlap between implicit adaptations embedded in damage curves and explicit local adaptation measures may yield conservative damage estimates.

Premium calculations represent lower bounds. They exclude claims handling expenses, profit margins, and risk-loading factors required for viable commercial insurance products. European non-life insurers report median expense ratios of 30%–50% (EIOPA 2020), suggesting commercial premiums would be 40%–70% higher than the pure premiums reported here. Furthermore, comparison with existing catastrophe reinsurance capacity provides only approximate benchmarking. Dutch insurers maintain €5–€7 billion in storm coverage, but severe storms that flood unembanked areas would simultaneously damage other insured property. Flood damages therefore accumulate on top of existing catastrophe claims rather than substitute for them. Moreover, the damage estimates in this study cover residential properties only, while commercial properties in unembanked areas would generate additional claims against the same capacity. Additionally, flood risks may require different reinsurance structures and pricing than storm coverage.

The analysis also excludes deductibles. A sensitivity analysis shows that a €200 deductible, consistent with Dutch property insurance practice, reduces premiums by approximately 2% on average across scenarios, with a maximum reduction of 6% under current sea levels with mandatory participation. The effect is modest because deductibles reduce damage across all return periods but do not alter the dominant drivers of premium differences: participation structure and sea level rise. The adaptation model considers only dry-proofing measures that prevent water entry. Wet-proofing, which reduces damage once water has entered a building, was not modelled but could have a relatively greater impact at rare return periods where water depths exceed dry-proofing thresholds. Premiums are uniform within each participation pool, which creates free-rider incentives: households benefit from neighbors' adaptation investments regardless of their own effort. Finally, the Dutch government has no legal obligation to compensate flood damage in unembanked areas, but ad-hoc compensation following events such as the 2021 Limburg floods may create expectations of government relief that reduce insurance demand.

5.3 | Future Outlook

Flood damages and insurance premiums result from the interplay of urban development, adaptation and climate change. These outcomes are shaped not only by physical climate processes but also by failure probabilities and closure thresholds of storm surge barriers and other flood defenses. International evidence supports the necessity of this integrated approach between adaptation and insurance: analysis of the US National Flood Insurance Program shows that risk-based premiums alone provide substantial societal benefits, but these benefits more than double when combined with investments in large-scale flood protection infrastructure (de Ruig et al. 2022).

The systematic method developed here demonstrates how specific risk drivers contribute to flood damages, particularly infrastructure policy and urban development. This local-scale approach reveals dynamics that large-scale assessments miss, suggesting value in extending similar analyses to other coastal regions. This approach extends beyond national or continental assessments (e.g., Hudson et al. 2019) that aggregate across regions and miss local discontinuities such as infrastructure thresholds and neighborhood-level exposure variation. Important areas for investigation include reinsurance costs under changing risk profiles and increasing asset values, which will amplify damages and insurance requirements over time. European flood risk is expected to double by 2050 from rising exposed building values alone (Steinhausen et al. 2022). While current catastrophe reinsurance capacity appears adequate near-term, sustained increases in flood frequency and severity require detailed analysis to ensure long-term market stability.

We recommend expanding this analysis to examine damage hotspots, as unembanked households in the Rotterdam Metropolitan Region show concentrated damage distributions, with a small share of properties accounting for a disproportionate share of expected damages. Understanding spatial damage patterns is essential for designing targeted interventions that maximize risk reduction while maintaining insurance affordability. A key research question is how neighborhood-scale adaptation strategies can be integrated with insurance mechanisms to create coherent incentive structures.

Local adaptation and emergency measures represent another research direction. Evidence suggests that emergency measures effectively reduce both economic losses (Endendijk et al. 2023) and fatalities, with global mortality fractions declining over time despite increasing hazards, particularly in middle- and high-income countries (Jonkman et al. 2024). These measures can be integrated into flood risk approaches by incorporating failure probability assessments (Lendering et al. 2016). Future research could quantify how combining emergency preparedness, early warning systems, and post-flood reconstruction standards with insurance frameworks might incentivize risk reduction and stabilize premiums.

6 | Conclusion

We developed an integrated framework to assess flood insurance viability where flood risk changes through climate change, urban development, and adaptation. Applied to unembanked areas in the Rotterdam Metropolitan Region, the analysis yields three findings with broader applicability. Infrastructure policy decisions, specifically storm surge barrier closure thresholds, can dominate gradual climate change as a driver of flood risk. Building-level adaptation reduces aggregate damages but can increase individual premiums by shrinking the risk pool, an adaptation paradox whose magnitude depends on participation structure. And non-linear damage acceleration occurs when flood levels approach building elevations, a threshold dynamic that local-scale analysis reveals but larger-scale assessments miss.

Flood insurance viability depends on solidarity through broad participation. When risk is distributed across all unembanked

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households, premiums remain affordable even under moderate sea level rise. When participation is limited to high-risk households, cost concentration undermines long-term sustainability. This tension between individual and collective responsibility for flood risk is not unique to the Dutch case but is central to the design of any flood insurance system.

These findings underscore that flood insurance for areas without dedicated flood protection is not a static design problem. As climate change progresses, the balance between adaptation investment, insurance design, and infrastructure policy will shift, and decisions in one domain reshape the conditions for the others. Building-level adaptation has physical limits; infrastructure policy can alter risk abruptly, and participation design determines who bears the cost of residual risk. The challenge confronting coastal regions worldwide is to align these mechanisms before accelerating climate impacts foreclose viable adaptation pathways.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Data and scripts underlying the publication: Flood insurance at https://data.4tu.nl/private_datasets/ZxilZ5zYzBMKWsZUDRmn_-_VAaMEErbLc6ZCaeu6PBk, reference number DOI: https://doi.org/10.4121/08B87B69-0251-45D7-9E38-1FC9C1449F55.V1.

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