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Split incentives in property-level flood adaptation across households, insurers and government in the Netherlands

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Abstract

Flood adaptation can be organized across multiple spatial scales, from national flood defences to individual buildings. Property-level risk estimates drive household adaptation decisions. Yet for the Dutch housing stock, how flood risk concentrates, distributes across stakeholders, shifts under methodological uncertainty, and translates into adaptation budgets remains unquantified. For 12,992 embanked Dutch residential properties, we combine precipitation and flood defence failures across two hazard and two vulnerability approaches for 2025 and 2050. Flood damage is sharply concentrated, with the top 5% of properties carry more than half of expected annual damage. The stakeholder split also shifts over time. In 2025 government bears 56% of damages, insurers 32% and households 12%; by 2050 this becomes 13%, 72% and 15%. The three-stakeholder coalition budget exceeds the household-only budget by an order of magnitude, so co-financing across stakeholders could help close the split-incentive gap. These stakeholder patterns hold across hazard and vulnerability methods, yet per-property budgets vary by an order of magnitude. These findings connect two debates usually held apart, on the credibility of property-level flood risk estimates and on how to finance adaptation under a split-incentive. Both bear on how such estimates should inform flood adaptation decisions.

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1. Introduction

Flood adaptation operates across spatial scales, from national flood defences and storm surge barriers to regional water-system upgrades, neighbourhood drainage, and property-level measures at individual buildings. Climate change is intensifying extreme precipitation and raising sea levels. Together with socio-economic development, these trends are expanding the residual flood risk that remains where collective defences are in place but cannot eliminate exposure (Aerts et al., 2024; IPCC, 2022). To address this exposure, countries are turning to property-level adaptation, including dry-proofing, wet-proofing and elevation, or to financial arrangements such as insurance and public compensation that transfer residual flood risk away from the household (Kreibich et al., 2015; UNEP, 2024). At the property scale, three institutional questions structure adaptation strategy and policy: who is responsible for the risk, who pays for damages when they occur, and who is responsible for reducing it. Countries answer these questions through different combinations of insurance, public compensation, property-level subsidies, and building regulation, each producing a different distribution of cost and responsibility (Suykens et al., 2019; Jarzabkowski et al., 2019).

The mismatch between who pays for adaptation and who benefits from it has been studied mostly for large-scale flood protection, where coastal defences protect many properties at once and finance therefore comes mainly from government, with private contributions limited to specific instruments (Bisaro and Hinkel, 2018; Woodruff et al., 2020). At the property scale the structure of the misalignment differs. Households bear the investment cost, while insurers cover most of the avoided damage through their policies and government covers the rest through public compensation (Hudson et al., 2019; Surminski et al., 2015). Measures that are net-beneficial at the societal level therefore remain financially unattractive at the household level: a split-incentive in property-level flood adaptation. This split-incentive has rarely been quantified at the property scale. Yet adaptation decisions are made at this scale, and the subsidy and co-financing instruments designed to support them depend on property-level risk estimates. Existing work has either modelled adaptation benefit at aggregate national scale (CPB, 2025) or addressed only a subset of stakeholders, typically the household, without resolving the full split across households, insurers and government (Endendijk et al., 2023).

All these instruments rest on property-level flood risk estimates, so their credibility determines whether the institutional arrangement performs as intended. Yet these estimates are themselves model-dependent. Risk at a single building requires both a hazard assessment, the probability of flooding at that location, and a vulnerability function, the damage given flooding. Both are sensitive to methodological choice, and these choices reflect the modelling group's established practice and data availability more than systematic evaluation of alternatives (Melsen, 2022). Hazard models differ in their treatment of defence failure and inundation dynamics; vulnerability functions differ in how they translate inundation depth into damage (Apel et al., 2008). Disagreement between methods is largest at the property scale, because hazard and vulnerability errors compound

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at the building level instead of averaging out across spatial aggregates. A comparison of two flood hazard models in Los Angeles found agreement on 100-year floodplain membership for only 24% of properties (Schubert et al., 2024).

These two gaps, the unquantified split-incentive and the model-dependence of property-level estimates, are typically addressed in isolation. Research on how flood damages distribute across actors assumes a single known risk level (e.g. Hudson et al., 2019), while methodological-uncertainty studies rarely trace how model differences propagate into stakeholder-specific conclusions (Bates, 2023; Schubert et al., 2024). Their combination opens three routes to maladaptation. Subsidies or eligibility rules calibrated on one method may direct investment to properties whose risk does not warrant property-level adaptation. Properties whose risk is acute under an alternative method may be missed. Cost-sharing arrangements may rest on benefit allocations that another methodology would not support. The magnitude of these shifts, and whether they are large enough to unsettle stakeholder-specific conclusions, has not been mapped at the property scale. We therefore ask: how do flood damages and property-level adaptation benefits distribute across households, insurers and government, and how sensitive is that distribution to methodological uncertainty in hazard and vulnerability assessment?

We address this question in the Netherlands, where damages from different flood sources fall to different actors. Under standard home insurance policies, insurers cover damage from precipitation and regional defence breaches; the latter are driven by extreme precipitation or by other mechanisms such as drought-induced weakening of the defence. Insurance claims for these and other water-related damage averaged €80 million per year over 2014 - 2024 (Climate Damage Monitor, 2024). Damage from primary defence failures, driven by storm surges and high river discharges, is uninsurable (Jongejan and Barrieu, 2008) and falls to the government via the Calamity Compensation Act (Wts) at a discretionary compensation rate of around 90% (CPB, 2025). Households bear the residual risk. Responsibility for property-level adaptation, by contrast, is not differentiated by flood source and rests primarily with the homeowner. Municipalities, water authorities and insurers occasionally provide case-by-case support, but no structural arrangement exists.

To answer the research question, we cross two hazard methods with two vulnerability approaches across 12,992 sampled residential properties in the Netherlands. For hazard, we compare the standard method, developed to derive Dutch levee safety standards (Slootjes and Van der Most, 2016; Rikkert et al., 2025), with the BREACH method, developed for spatial planning and financial applications (Kolen and Nicolai, 2025). For vulnerability, we contrast the national SSM depth-damage curves used for statutory flood damage estimation (Rijkswaterstaat, 2024) with curves empirically recalibrated to the 2021 Limburg flood (Van Ederen et al., 2025). To compare avoided damages with adaptation cost, we express each stakeholder's benefit as a discounted adaptation budget, the present value of the damages a measure avoids, which sets an upper bound on what that stakeholder could rationally spend.

Section 2 describes the sample, the hazard and vulnerability methods, the stakeholder allocation of damages, and the discounted adaptation budget. Sections 3 to 5 present the results, the discussion, and the conclusion.

2. Method

We constructed property-level flood risk profiles for a representative sample of Dutch residential properties, allocated the flood risk across stakeholders, and computed discounted adaptation budgets under nine combinations of hazard and vulnerability methods.

2.1 Sampling strategy

We sampled the Dutch residential housing stock with two objectives: a geographically representative cross-section, and enough observations in the upper tail of the expected annual damage (EAD) distribution to characterise high-risk properties (Sect. 3.1). Properties outside primary flood defences, approximately 1% of the national stock, were excluded from the sampling because they require different depth-damage curves from those used for the embanked stock (Oerlemans et al., 2025). We grid-stratified the sample proportionally to dwelling counts. From the BAG (Kadaster, 2026), we drew 12,992 dwellings, a ratio of one sampled dwelling per 662 in the Dutch housing stock (Table 1). Within each province, the area was partitioned into 5 km × 5 km cells, and cells containing fewer than 300 dwellings were excluded. Remaining cells received sample size in proportion to their dwelling counts, and dwellings were drawn randomly without replacement within each cell.

Table 1: **Proportional stratified sample of residential properties by province, dwellings from BAG (Kadaster, 2026). Each province contributes locations to its share of the national building stock (~1 per 662 dwellings) with a total sample of 12,992 locations in the Netherlands. Unembanked dwellings are excluded.**

Province	Dwellings	Share (%)	Sampled
Flevoland	196,707	2.3	298
Zeeland	199,729	2.3	304
Drenthe	234,797	2.7	358
Groningen	303,139	3.5	462
Friesland	319,726	3.7	487
Overijssel	547,923	6.4	835
Limburg	566,217	6.6	863
Utrecht	649,564	7.6	981
Gelderland	987,111	11.5	1,497
Noord-Brabant	1,249,439	14.5	1,905
Noord-Holland	1,495,960	17.4	2,252
Zuid-Holland	1,852,391	21.5	2,750

Total	8,602,703	100.0	12,992

2.2 Hazard assessment

For each location we constructed water depth-exceedance probability curves using the MyWaterRiskProfile API (HKV, 2025), which combines flood scenarios into per-location risk profiles. The API combines three flood sources (precipitation, regional water system overflow, regional defence breaches, primary defence breaches, and high water in unembanked areas) across approximately 5,000 flood scenarios from the LIWO database (LIWO, 2025) and implements the two primary-defence methods described in Sect. 2.2.1.

Methodological uncertainty enters at two points: the choice between methods for primary defence failure probabilities (Sect. 2.2.1), and the discrete depth classification in the national pluvial maps (Sect. 2.2.3). Regional defence failure probability assessment (Sect. 2.2.2) is treated as a single convention because no alternative method matches its national spatial coverage.

2.2.1 Primary defence breaches

Two methods are currently used at national scale to assess the failure probability of primary flood defences. The standard method treats levee sections as statistically independent and excludes system behaviour and emergency response (Slootjes and Van der Most, 2016; Rikkert et al., 2025). It was developed for deriving statutory levee safety standards, where overestimation is acceptable, and yields higher failure probabilities. The BREACH method incorporates levee section interdependencies and emergency interventions through structured expert judgement (Kolen and Nicolai, 2025). It was developed for spatial planning and financial applications. The two methods use the same flood scenarios collected in the LIWO database and differ in how those scenarios are combined. For individual locations, BREACH yields failure probabilities typically 2 to 10 times lower than the standard method.

For the 2025 baseline, failure probabilities follow VNK data (VNK2, 2014) corrected for completed reinforcement programmes such as Room for the River. For 2050, failure probabilities were set equal to each section's statutory safety standard, reflecting completion of the Flood Protection Programme, the ongoing multi-billion euro effort that brings all primary defences in the Netherlands (approximately 3500 km) up to the standards established in 2017. Climate change effects on coastal and fluvial flooding are incorporated through scenarios with elevated external water levels (Rikkert et al., 2025).

2.2.2 Regional defence breaches

Failure probabilities for regional defences were set at one-fifth of the applicable statutory safety standard, following STOWA (2020). No alternative method with national spatial coverage is in operational use. Regional defences (more than 10,000 km) fall outside the Flood Protection Programme; the convention was therefore held constant for 2025 and 2050.

2.2.3 Precipitation

The national pluvial maps used here (LIWO, 2025) report maximum surface water depth for design precipitation events at three return periods: 10 years (35 mm in 2 h), 100 years (70 mm in 2 h), and 1000 years (140 mm in 2 h). Depth is encoded in five discrete classes rather than as a continuous value: 0.05 - 0.10 m, 0.10 - 0.15 m, 0.15 - 0.20 m, 0.20 - 0.30 m, and >0.30 m. Treating each class upper bound as a point estimate introduces a discretisation error that is large relative to the class width: within class 4 (0.20 - 0.30 m) the upper bound overestimates the true depth by up to 10 cm, and class 5 is unbounded by construction. We therefore evaluated three interpretations of each class: the lower bound, the midpoint, and the upper bound. Event frequencies were held constant across the three depth interpretations. For 2025 we used the STOWA (2019) event frequencies. For 2050 we obtained pluvial exceedance probabilities from the MyWaterRiskProfile API, which applies the STOWA (2019) climate-scaling factor of 1.21 to event frequencies. Event water depths were held unchanged between 2025 and 2050.

2.2.4 Hazard scenario construction

We coupled the two sources of methodological variation into three paired hazard scenarios (Table 2) rather than treating them as independent axes. The upper-bandwidth scenario paired the standard breach method with the upper-bound pluvial interpretation. The lower-bandwidth scenario paired the BREACH method with the lower-bound pluvial interpretation. The basis scenario paired the arithmetic average of the two primary flood defence breach methods with the midpoint pluvial interpretation. Coupling kept the full hazard × vulnerability scenario set to nine rather than 27 (Sect. 2.3), at the cost of not attributing hazard uncertainty to the two sources separately within the analysis.

Table 2: Hazard scenario construction.

Hazard scenario	Primary defence method	Precipitation class
Upper bandwidth	Standard (Slootjes and Van der Most, 2016; Rikkert et al., 2025)	Upper bound
Baseline	Arithmetic average of standard and BREACH	Mid-point
Lower bandwidth	BREACH (Kolen and Nicolai, 2025)	Lower bound

2.3 Vulnerability and adaptation

We translated water depths into monetary damages using depth-damage curves. Damages were calculated separately for building structure and contents, reflecting their different stakeholder allocation (Sect. 2.4). The hazard models return inundation depth at ground level, whereas Dutch residential buildings are typically constructed with a ground floor approximately 0.20 m above the surrounding terrain. We therefore reduced all simulated water depths by 0.20 m before

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applying the damage curves. The value of 0.20 m is an assumption; Dutch residential floor heights relative to surrounding terrain vary across the housing stock, and we return to the implications in the discussion (Sect. 4.2).

2.3.1 Depth-damage curves

We used two sets of depth-damage curves that are in active use among Dutch practitioners. The SSM curves (Rijkswaterstaat, 2024) are the government-standard reference, originally calibrated on damage observations from the 1953 coastal flood and the 1993 and 1995 river floods (Slager and Wagenaar, 2017). The underlying functions have remained largely unchanged through subsequent price-level updates. The Van Ederen curves were calibrated against survey data and insurance claims from the 2021 Limburg flood (Van Ederen et al., 2025). SSM specifies maximum values of €1,295/m² for structure damage and €81,985 per dwelling for contents damage (2022 price level, excluding VAT; Rijkswaterstaat, 2024); the Van Ederen curves derive their maximum values from the same insurance and survey base used for the curve calibration. For contents damage, the Van Ederen analysis found no material deviation from SSM. We therefore used the SSM contents curves across all vulnerability scenarios; the Van Ederen vulnerability scenario in this study differed from SSM only in the structure-damage component. We constructed three vulnerability scenarios: SSM (lower damages), Van Ederen (higher damages), and a baseline scenario defined as the arithmetic average of the two.

2.3.2 Adaptation configurations

We modelled property-level adaptation by modifying the depth-damage curves to represent dry-proofing and wet-proofing. Dry-proofing prevents water entry below a specified threshold depth, setting damage to zero for water levels below it. Wet-proofing reduces residual damage above the threshold by a fixed percentage, representing measures such as elevated electrical installations and water-resistant materials. We evaluated three adaptation configurations spanning no adaptation to substantial property-level investment (Table 3). These configurations are illustrative; the 0.8 m maximum sits at the upper end of the 0.6 - 1.0 m range over which dry-proofing remains physically defensible before hydrostatic wall loading becomes binding, and the 0.3 m threshold reflects temporary-barrier protection (Herbert et al., 2018).

Table 3: **Adaptation configurations.**

Configuration	Dry-proof threshold	Wet-proof reduction	Interpretation
Baseline	0 m	0%	No adaptation
Minor	0.3 m	0%	Flood barrier
Maximum	0.8 m	50%	Barrier and wet-proofing

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2.4 Expected annual damage and stakeholder allocation

2.4.1 Expected annual damage

We computed Expected Annual Damage (EAD) at each property by integrating damage over the full range of flood probabilities:

$$EAD = \int_0^{p\_max} D\big(h(p)\big)dp$$

where $D(h(p))$ is the damage corresponding to water depth h at exceedance probability p, and p_{max} is the exceedance probability of the most frequent flooding scenario. We approximate this integral using trapezoidal integration over the discrete water depth-exceedance probability points:

$$EAD \approx \sum_{i=1}^{n-1} \frac{D_i + D_{i+1}}{2} \cdot \Delta p_i + D_n \cdot p_n$$

where points are sorted by descending exceedance probability, $\Delta p_i = p_i - p_{i+1}$ represents the probability interval between adjacent scenarios, and the final term captures the contribution from the rarest event to zero probability. EAD is calculated separately for structure and contents damage, and separately for each flood source, enabling stakeholder-specific allocation. For each adaptation set (Table 3), the depth-damage curves are modified by the dry-proofing threshold and wet-proofing reduction before integration, yielding adapted EAD values. The risk reduction benefit of adaptation is the difference between baseline EAD and adapted EAD.

2.4.2 Stakeholder allocation

We allocated flood damages across households, insurers, and government based on the Dutch institutional arrangement (Table 4). The allocation depends on the flood source, the type of damage (structure or contents), and insurance coverage. For precipitation-induced flooding and regional defence breaches, private insurers cover most damage through standard home insurance policies. Approximately 90% of Dutch households hold policies that include flood coverage for these sources (Engelhard et al., 2024). We assumed full insurance coverage across all sampled properties for analytical tractability; the implications of this simplification are discussed in Sect. 4.2. For insured households, we allocated 90% of structure damage and 80% of contents damage to insurers, and the residual 10% and 20% to households. These shares reflect typical policy deductibles and coverage limits; variation exists between insurers in eligibility and depreciation rules (CPB, 2025).

For primary defence failures, the Calamity Compensation Act (Wts) provides government compensation for uninsured and unavoidable damage. The Wts is discretionary. The cabinet decides per event whether to activate it, and the compensation level is not fixed in advance. Following CPB (2025), we assumed a compensation rate in line with insurance coverage, allocating 90% of both structure and contents damage to government and 10% to households. Experiences from the 2021

Limburg flood show that households bore a substantial residual share of damage despite Wts compensation (Endendijk et al., 2023). The assumed 90% is therefore an upper bound, discussed in Sect. 4.2.

Table 4: **Damage allocation fractions by flood source and damage type, assuming standard flood insurance coverage.**

Flood source	**Damage type**	**Households**	**Insurers**	**Government**
Precipitation & regional flood defence breach	Structure	10%	90%	0%
	Contents	20%	80%	0%
Primary flood defence breach	Structure	10%	0%	90%
	Contents	10%	0%	90%

2.5 Discounted adaptation budgets

We translated annual EAD reductions into discounted adaptation budgets. An adaptation budget represents the maximum amount that a stakeholder, or a coalition of stakeholders, could rationally invest in property-level adaptation at a given property, expressed as the present value of the avoided damage annuity. Expressing benefits this way enables comparison with investment costs reported in the engineering literature (Gersonius et al., 2008; Keating et al., 2015; De Lange et al., 2025). The budget equals the present value of avoided damages over a fixed time horizon:

$$B = \frac{1-(1+r)^{-T}}{r} \cdot \Delta EAD$$

where ΔEAD is the avoided damage, defined as baseline EAD minus residual EAD under a given adaptation configuration (Sect. 2.3); r is the real discount rate; and T is the time horizon in years. We used a real discount rate of 2.8%, following the updated Dutch government guidelines for societal cost-benefit analysis (Working Group on Discount Rate, 2025). The time horizon was set at 10 years, reflecting an estimate of the effective lifespan of property-level flood-proofing measures such as threshold barriers and water-resistant interior finishing. At these parameters, the present value annuity factor is 8.62, meaning that an annual EAD reduction of €100 corresponds to an adaptation budget of €862.

Because the avoided damage from a single measure accrues to several stakeholders at once, no party necessarily holds enough benefit to finance adaptation alone. We therefore computed budgets not only for individual stakeholders but also for coalitions, representing the parties that could jointly co-finance a measure and share its avoided damage. Comparing individual and coalition budgets shows whether co-financing closes the gap between the cost borne by the household and the benefit spread across parties. Adaptation budgets were computed for each adaptation configuration in Sect. 2.3 and seven stakeholder perspectives: three individual (households, insurers, government), three pairwise coalitions (households-insurers, households-

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government, insurers-government), and the full three-way coalition. For each perspective, the budget equals the annuity factor multiplied by the sum of the avoided damages accruing to the relevant stakeholders under the allocation in Sect. 2.4.

The adaptation budget is a benefit-side quantity. It captures the maximum expenditure that avoided damages can justify at a given property, not the net present value of adaptation. Property-level adaptation costs vary with building type, construction year, foundation type and other local conditions, and lie outside the scope of this study. For reference, Dutch dry-proofing costs range from €3,500 for temporary barriers to €11,400 for permanent measures (Gersonius et al., 2008, adjusted for price-level inflation), and climate-adaptive new construction from €2,700 to €11,800 per dwelling (De Lange et al., 2025). Wet-proofing ranges from €800 to approximately €26,500 (Keating et al., 2015; Gersonius et al., 2008). A budget below the lower end indicates adaptation is unlikely to be viable at that property under any stakeholder perspective; a budget above the upper end indicates clear viability across a wide range of designs.

3. Results

This section reports baseline flood risk and stakeholder allocation (Sect. 3.1), the redistribution of risk under property-level adaptation (Sect. 3.2), and the methodological robustness of these patterns to alternative hazard and vulnerability methods (Sect. 3.3). Of 12,992 embanked residential properties sampled, 10,624 (82%) returned modelled water depths from the API. The remaining 2,368 properties (18%) lie outside the inundation extent of every precipitation event and every breach scenario in the LIWO database, and therefore carry no modelled flood exposure. Among the 10,624 with returned depths, 7,178 (55% of the full sample) produced non-zero expected annual damage (EAD) under the basis hazard × vulnerability scenario after the 0.20 m precipitation height correction (Sect. 2.3). All three subsections below report results across the full sample of 12,992 properties.

3.1 Baseline flood risk and stakeholder allocation

Flood risk was concentrated in a small minority of properties (Fig. 1, top row). In 2025, the top 5% of properties accounted for 54% of sample EAD and the top 20% for 89%. This concentration follows from the spatial structure of Dutch flood exposure: primary defences protect the majority of the embanked stock to failure probabilities of 1/1,000 to 1/30,000 per year, so most properties accumulate EAD only from rare and shallow events. Only above the 80th percentile did the combined per-property budget reach the lower end of plausible adaptation cost, the threshold at which property-level adaptation becomes financially relevant under discounting (Sect. 2.5). Concentration intensified by 2050 because reinforcement under the Flood Protection Programme reduces primary defence failure probabilities across the full embanked stock, while the top band, dominated by precipitation rather than primary breach, retains most of its 2025 risk.

The composition of risk shifted between 2025 and 2050. Total EAD fell by 46% over this horizon. The reduction in primary defence failure damages under the Flood Protection Programme outweighed two climate-driven increases: more frequent extreme precipitation and higher water depths in primary-breach scenarios. With primary defence failure probabilities reduced to the standard, precipitation overtook primary defence failure in every band from P50 upward, reaching 89% of EAD in the P99-P100 band by 2050. The top band thus becomes almost exclusively a pluvial problem under the 2050 horizon.

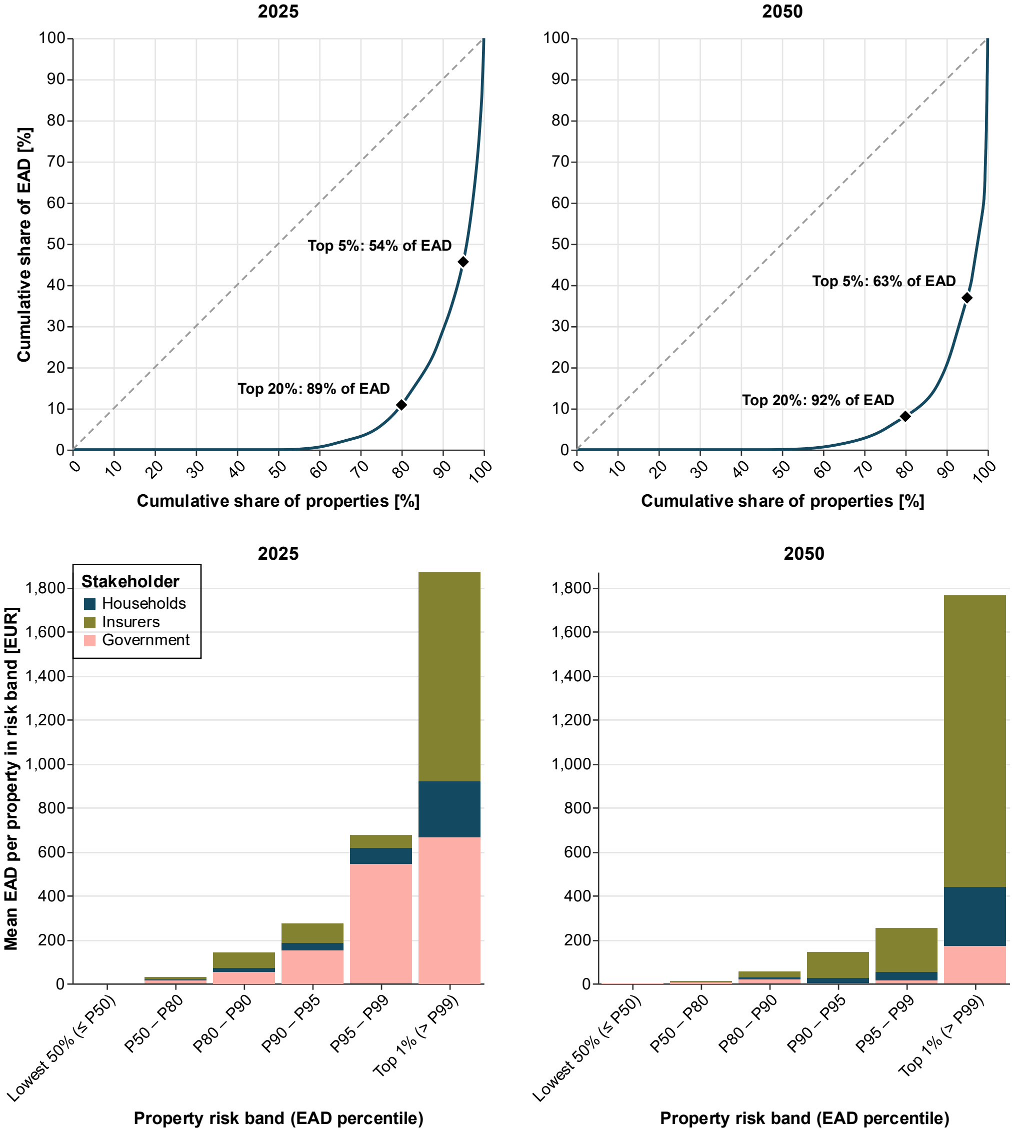

Figure 1: **Baseline flood risk across 12,992 properties under the basis hazard × vulnerability scenario. Top figures: Lorenz curves of EAD for 2025 and 2050. The dashed line represents perfect equality, and black diamonds indicate the cumulative share of the top 5% and top 20% of properties. Bottom figures: mean EAD per property by stakeholder across risk bands defined by EAD percentiles of 2025 EAD, ranging from the lowest-risk half of properties (P0 - P50) to the top 1% (P99 - P100).**

Because the Dutch institutional arrangement allocates the damage from each flood source to a different stakeholder, the source shift redistributed risk across the three parties (Fig. 1, bottom row). In 2025, the government bore 56% of sample EAD through Wts compensation for primary defence damages, insurers 32% through standard coverage of precipitation and regional water-system events, and households 12% as residual. By 2050, the government's exposure fell to 13%, roughly an eighth of its 2025 absolute level, while insurer exposure rose to 72% and the household share to 15%.

3.2 Adaptation effectiveness and stakeholder distribution

Adaptation budgets based on avoided damages are bounded by the underlying risk, and for most properties that risk is low because the Dutch flood system is largely managed at scales above the individual building. Primary defences hold back the rare and deep events, and collective measures in the built environment absorb most extreme precipitation before it reaches dwellings. Property-level adaptation therefore acts on a small residual. Mean EAD fell in every risk band under both adaptation configurations (Fig. 2), but absolute reductions scaled with baseline risk by nearly two orders of magnitude across the distribution. Under maximum adaptation (80 cm flood barrier with 50% residual damage reduction), the mean reduction was about €1,510 per property in the P99-P100 band and about €24 in the P50-P80 band. In the P50 - P80 band, the corresponding fall was from €34 to €7. Only above the 80th percentile did the combined per-property budget reach the lower end of plausible adaptation cost, the threshold at which property-level adaptation becomes financially relevant under discounting (Sect. 2.5). Damage acceptance and adaptation at larger spatial scales remain valid alternatives outside the scope of this analysis.

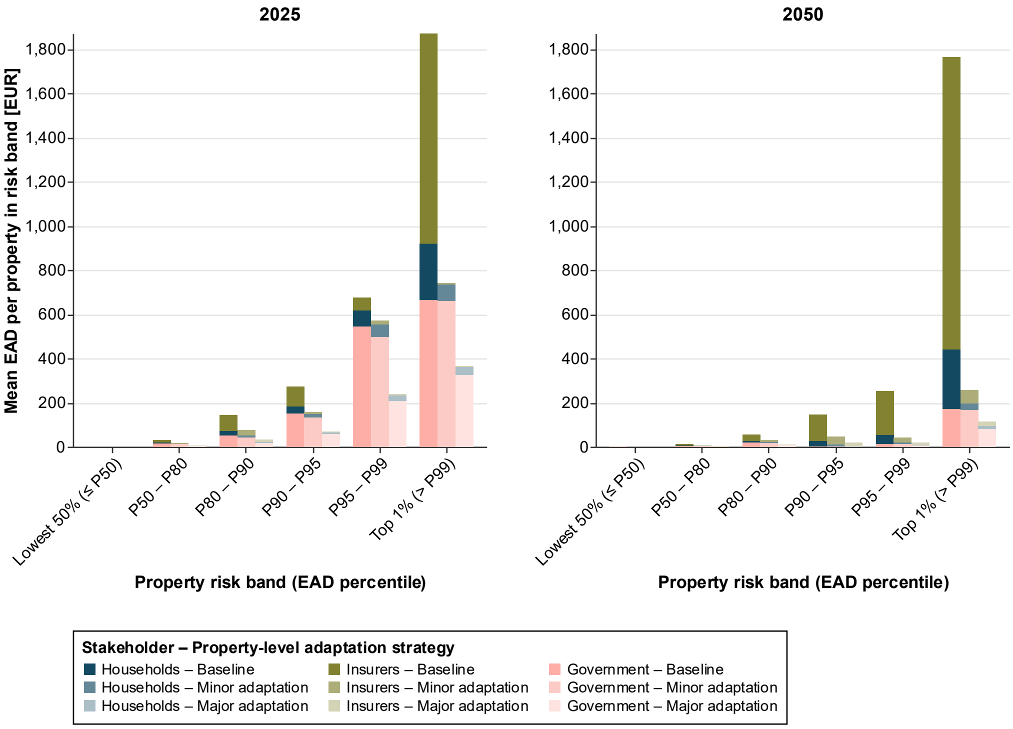

Figure 2: **Mean expected annual damage per property by risk band, stakeholder, and adaptation strategy for 2025 (left) and 2050 (right). Risk bands are defined by percentiles of baseline EAD across all 12,992 locations. Within each band, three grouped bars represent the baseline (no adaptation), minor adaptation (30 cm dry-proofing), and maximum adaptation (50 cm dry-proofing with 50% contents protection). All estimates use the basis hazard and basis vulnerability approach.**

The benefit of adaptation accrued unevenly across stakeholders, which determines how much each individual party and each coalition (Sect. 2.5) could justify spending. Insurers received the largest share of avoided damages in the P50 - P90 and P99 - P100 bands; in the P90 - P99 bands government received the largest share, because primary defence breach still drove baseline EAD there. The asymmetry tracked the flood source mix on which adaptation acted. Dry- and wet-proofing were most effective against pluvial and regional-defence events, which produce shallow inundation and fall under insurance coverage, and least effective against primary defence breaches, where modelled water depths exceed the dry-proofing threshold. The 10-year discounted adaptation budgets that follow from these reductions show that no individual or coalition reached the lower end of plausible adaptation cost across the bottom 80% (Table 5). From the 80th percentile upward, coalitions including either insurers or government crossed that threshold in 2025, with the three-way coalition budget reaching roughly an order of magnitude above the household-only budget.

Table 5: **Mean discounted 10-year adaptation budget per property (EUR) by risk band, for individual stakeholders and coalitions under maximum adaptation (80 cm flood barrier with 50% residual damage reduction). Budgets use a 2.8% real discount rate (annuity factor 8.62; Working Group on Discount Rate, 2025). Δ is the percentage change from 2025 to 2050. Risk bands are defined by percentiles of 2025 baseline EAD across the full sample of 12,992 properties and held constant for 2050; P0 - P50 contains effectively zero baseline EAD. HH = households; INS = insurers; GOV = government.**

Perc.	Year	HH only	INS only	GOV only	HH & INS	HH & GOV	INS & GOV	All three
Lowest 50%	2025	<€1	<€1	<€1	<€1	<€1	<€1	<€1
	2050	<€1	<€1	<€1	<€1	<€1	<€1	<€1
	Δ	-	-	-	-	-	-	-
P50 - P80	2025	28	93	91	120	120	180	210
	2050	24	100	34	130	58	140	160
	Δ	-14%	+8%	-63%	+8%	-52%	-22%	-24%
P80 - P90	2025	130	510	300	650	430	810	940
	2050	120	590	54	710	170	650	770
	Δ	-8%	+16%	-82%	+9%	-60%	-20%	-18%
P90 - P95	2025	230	740	800	970	1,000	1,500	1,800
	2050	170	880	48	1,100	220	930	1,100
	Δ	-26%	+19%	-94%	+13%	-78%	-38%	-39%
P95 - P99	2025	410	450	2,900	850	3,300	3,300	3,800
	2050	110	530	120	640	230	640	750
	Δ	-73%	+18%	-96%	-25%	-93%	-81%	-80%

Top 1%	2025	1,900	8,200	2,900	10,000	4,800	11,000	13,000
	2050	2,000	9,900	630	12,000	2,600	11,000	12,000
	Δ	+5%	+21%	-78%	+20%	-46%	0%	-8%

3.3 Sensitivity to method choice

We tested the findings of Sect. 3.1 and 3.2 across the two hazard methods, two vulnerability approaches and their pairwise averages, yielding a 3 × 3 grid. The corners bracket the plausible range: BREACH with SSM gives the lowest failure probabilities and damages, standard with Van Ederen the highest. The dominant uncertainty axis shifted between 2025 and 2050 (Fig. 3). In 2025, hazard choice produced larger spreads than vulnerability choice in every band above P50, by a factor of two to three. By 2050, the two were comparable in absolute euros at the upper bands. The convergence reflects the modelling assumption that both hazard methods meet the statutory safety standard in 2050, which closes most of their 2025 disagreement about primary defence exceedance probability. Vulnerability uncertainty persisted because depth-damage curve choice does not depend on defence performance.

Stakeholder orderings were invariant across all nine method combinations (Fig. 4). In the P99 - P100 band, per-property EAD followed insurers > government > households in eight of nine method combinations; the standard × SSM corner swapped the first two, but households remained last in every cell. Under minor adaptation, the share of avoided damages reordered to insurers first, households second, government last, in every band with a non-trivial baseline budget. Government drops to last because property-level adaptation barely reduces damages from primary defence breaches, where water depths typically exceed the adaptation threshold (Sect. 3.2). The invariance across methods reflects that method choice shifts absolute damage levels but leaves the institutional allocation per source unchanged (Sect. 2.4).

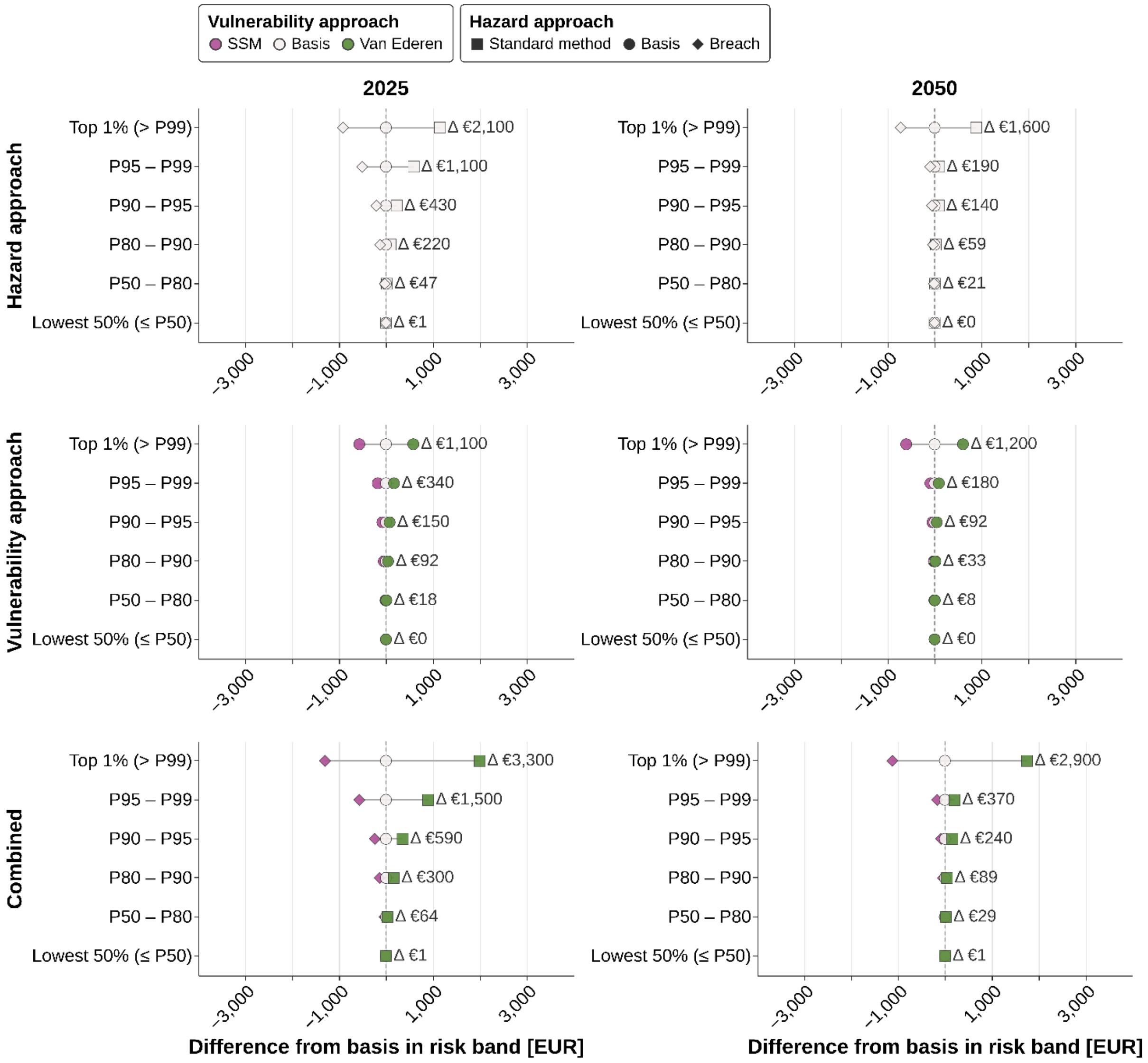

Figure 3: **Spread in mean baseline EAD per property across the 3 × 3 hazard × vulnerability scenario grid, by risk band, for 2025 (left) and 2050 (right). Rows isolate hazard-only variation (top), vulnerability-only variation (middle), and three full corner cases (bottom: BREACH × SSM, basis × basis, standard × Van Ederen). Values are differences from the basis × basis reference (EUR); shape encodes hazard approach, colour encodes vulnerability approach. Δ labels report the absolute spread (max − min). Risk bands follow percentiles of 2025 baseline EAD across the full sample of 12,992 properties.**

The absolute magnitude of methodological uncertainty scaled with the baseline EAD of the band. Below P95, the three-way coalition budget spreads remained small relative to plausible adaptation costs. The P99-P100 band was the exception, with a spread of approximately €24,600. About 86% came from the insurer component, because the top band is dominated by insurer-covered sources and is most sensitive to the SSM versus Van Ederen choice. Method choice therefore left the qualitative conclusions broadly unchanged, with the single corner-case exception noted above. The ranking of coalitions and the household financing shortfall held in every band. The absolute size of the insurer budget in the rarest 1% of properties, however, varied substantially with the chosen method.

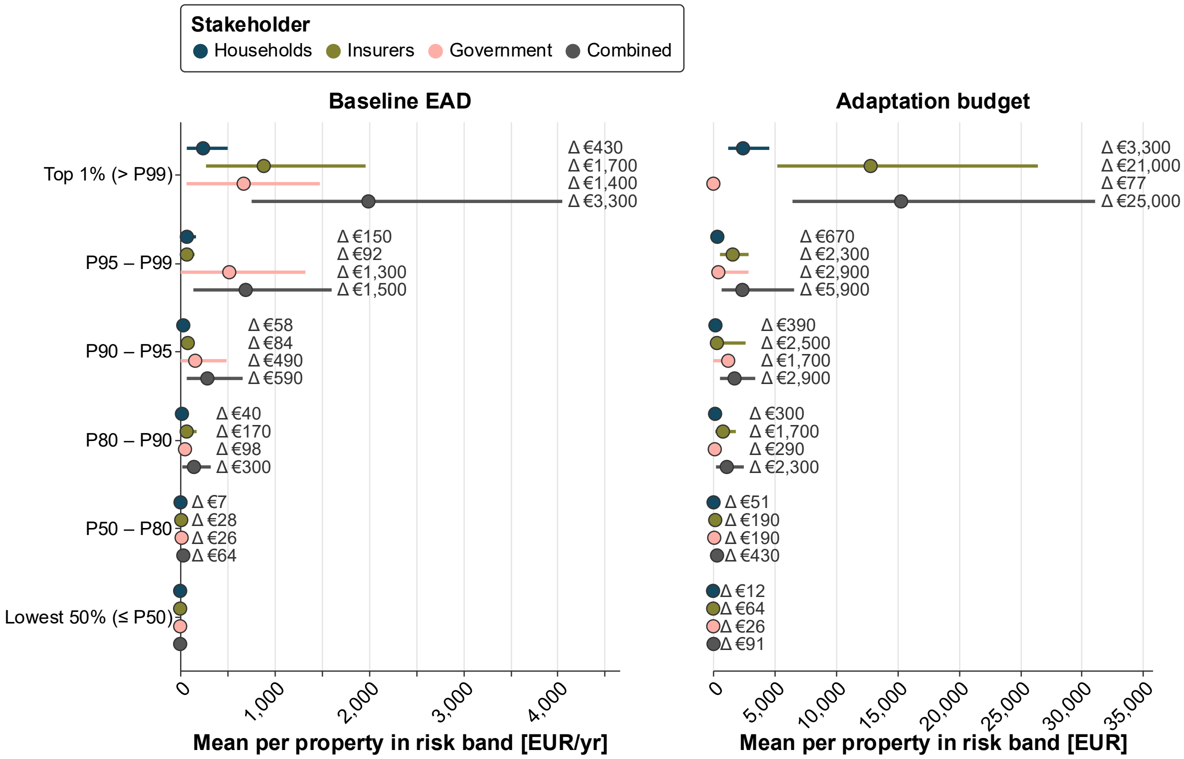

Figure 4: **Mean baseline EAD per property (left) and mean 10-year discounted adaptation budget per property under minor adaptation (right) across the nine hazard × vulnerability combinations, by risk band, for 2025. Within each band, four range-bars compare households (HH), insurers (INS), government (GOV) and the location total. Filled dot marks the basis × basis reference; Δ labels report the spread (max − min) in EUR. Risk bands follow percentiles of 2025 baseline EAD across the full sample of 12,992 properties.**

4. Discussion

4.1. Interpretation of results

We asked how flood damages and property-level adaptation benefits distribute across households, insurers and government, and how sensitive that distribution is to methodological uncertainty in hazard and vulnerability assessment. Property-level estimates structure who can act on flood risk, so the science behind them determines whether subsidy, insurance and compensation instruments reach the properties they are designed for. Our results show what these estimates currently support, and where they fall short, in the Dutch context. Damage concentrates sharply in a small minority of properties, and total risk falls toward 2050. The stakeholder split shifts with it, from government-dominated in 2025 to insurer-dominated by 2050, with the household share residual throughout.

The stakeholder shares of damages and adaptation benefits translate into who can finance adaptation, and at what risk level. Across the lower 80% of properties, no individual stakeholder or coalition holds an avoided-damage budget near the cost of plausible adaptation. Above it, the relevant coalition shifts with the dominant flood source. In P95 - P99, primary-defence damages dominate baseline EAD and government holds most of the coalition budget. Below P95, primary breaches still drive most baseline EAD, yet the avoided-damage share accruing to insurers is largest, because dry- and wet-proofing act most effectively on the shallow precipitation and regional-breach component of the source mix. Across the upper risk distribution the three-stakeholder coalition exceeds the household-only budget by roughly an order of magnitude. Property-level adaptation is also not necessarily the most efficient response. Collective measures at neighbourhood, regional or national scale may achieve more risk reduction per euro.

An empirical check against insurance claim data supports the order of magnitude of the modelled insurer share. The Climate Damage Monitor (2024) reports an average of €80 million per year in claims for pluvial, regional-breach and other water-related damage over 2014 - 2024, a period that includes the 2021 Limburg flood (Asselman et al., 2022). Distributed across approximately 7.7 million insured residential units (90% of the building stock), this implies a historical claim rate near €10 per dwelling per year. Our basis-scenario insurer EAD is €27 per property, a factor of 2.7 above that rate. Three differences explain the gap. Modelled EAD integrates return periods up to 1/1000 per year, whereas a ten-year record captures mostly frequent events even with Limburg included. About 10% of Dutch households lack flood coverage and do not appear in claim totals. Deductibles and unreported minor damage push paid claims below actual loss. The order-of-magnitude agreement supports the allocation, while the modelled excess over claims suggests tail risk is not yet visible in current insurance activity.

Two different insights emerge from the methodological robustness analysis. The stakeholder ordering held across the method grid, with one corner-case exception in which insurers and government swapped places in the top 1%. The three-stakeholder coalition budget remained seven to nine times the household-only budget in every band where adaptation is financially relevant. The per-property coalition adaptation budget itself, however, is not stable. For properties with a basis × basis budget of €5,000 - €10,000, the average gap between the highest and lowest corner of the method grid is roughly €13,000; above €10,000 the gap reaches €25,000. For the median at-risk property the gap is small in absolute terms, but it widens by two orders of magnitude across the high-budget tail, where individual adaptation decisions are made. Flood adaptation instruments that rely on a precise per-property budget, such as property-specific subsidies, fine-grained cost-sharing rules or premium differentiation, are therefore weakly supported, because the method spread in that tail is as large as the budgets themselves.

4.2. Limitations

The stakeholder allocation rests on simplifying assumptions about insurance coverage and government compensation. We assumed universal flood coverage at fixed reimbursement rates (90% structure, 80% contents for insured dwellings), whereas approximately 10% of Dutch households lack flood coverage entirely (CPB, 2025). In practice, uninsured households absorb the full insurer share, which strengthens the split-incentive mechanism rather than weakening it. The government share depends on discretionary Wts activation, and the 2021 Limburg floods showed this discretion cutting both ways. Wts was extended to regional-system and precipitation damages that were technically insurable and outside its intended scope, reaching into the insurer domain. Yet affected households reported only about 60% of damage covered by insurance and government compensation combined (Endendijk et al., 2023; CPB, 2025), below the 90% rate assumed here.

EAD captures long-run average risk but not the financial shock of individual events. A property with €100 annual EAD may face damages above €60,000 from a single rare event. That distinction matters for household liquidity and adaptation motivation, neither of which EAD represents. We modelled two stylised adaptation configurations, whereas operational options include backflow valves, water-resistant materials, raised utilities and others, each with a distinct cost profile. We assumed measures perform at design specification, which likely overstates risk reduction for rare extreme events, where residents may be away from home, temporary barriers may already be saturated by earlier events, and access to deploy them may be cut off. We also did not model stakeholder responses to widespread adoption. Premium adjustments, deductible revisions or Wts eligibility shifts would feed back on the stakeholder shares we treat as fixed. If insurers lowered premiums in response to widespread dry-proofing, the insurer share of avoided damages would shrink and the household share would grow, narrowing the split-incentive gap. Whether such feedback strengthens or weakens the case for coordination between households, insurers and government is an empirical question.

The largest hazard limitation lies in the precipitation input, and it has two coupled parts on the same depth scale. The national pluvial maps report depth in five classes of 0.05 - 0.10 m width below 0.30 m and leave the highest class unbounded above. Individual buildings are additionally clipped from the underlying elevation model, so modelled depths reflect surrounding terrain rather than conditions at the structure. We applied a uniform 0.20 m height correction to approximate the level inside the dwelling at which damage begins, but actual floor heights vary across the housing stock. The 0.20 m correction is 2 - 4 times the pluvial class width, and flood damage responds strongly non-linearly to depth, particularly in the 0.1 - 0.5 m range where damage ratios rise steepest (Van Ederen et al., 2025). The analysis stops at 2050. Beyond that horizon, deeper uncertainty in sea-level rise and precipitation trends likely makes the stakeholder shares less suitable for extrapolation.

4.3. Contributions to existing literature and international debates

The split-incentive logic we document connects to an international debate on flood adaptation and insurance design. Hudson et al. (2019) and Surminski et al. (2015) frame the gap between damage coverage and adaptation incentives as a market failure. Most national arrangements leave that gap open. The French CCR (Poussin et al., 2013) and the US NFIP (Kousky, 2018) cover damages without conditioning coverage on property-level adaptation. The UK's Flood Re is the exception, tying reinsurance to a Build Back Better scheme that funds resilient repairs after a claim (Flood Re, 2024). Our results give such a link a property-scale empirical basis for the Netherlands. No single stakeholder benefits enough from adaptation to pay for it

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alone, so closing the gap requires routing the insurer and government share of avoided damage back to the party that installs the measure. In practice this could mean a reduced insurance premium for households that fit certified dry-proofing. The Platform for Sustainable Finance Working Group on Climate Adaptation (2023) advocates this co-financing between financial sector and government. Because insurers and government hold most of the avoided damage, they are the natural partners.

A second, related line of research questions whether property-level flood risk estimates are accurate enough for the decisions built on them. Bates (2023) argues that overconfidence in single-property estimates is misplaced, and Schubert et al. (2024) find that two hazard models for Los Angeles agree on 100-year floodplain membership for only 24% of properties. Condon (2023) and Pollack et al. (2026) raise transparency and validation concerns about catastrophe models used by banks and insurers. The Dutch case sharpens this picture across two scales. Stakeholder ordering and the gap between household-only and coalition budgets hold across all nine method combinations. The set of buildings that crosses a given budget threshold varies substantially across methods, and absolute risk in the top 1% shifts by roughly half an order of magnitude across the method grid. Single-method estimates reported as point values therefore overstate the precision available to decision-makers.

Third, these findings resonate with the three paradoxes of catastrophe insurability set out by Jarzabkowski et al. (2023), a framework that helps structure how responsibility, knowledge and control are distributed in Dutch flood adaptation. The responsibility paradox asks who should pay for disaster losses, individuals or society. The Dutch split-incentive is one expression of this question at the adaptation scale. Households often pay for property-level measures while insurers and government capture most of the avoided damage, a pattern that holds across all nine method combinations.

Our results bear most directly on the knowledge and control paradoxes. The knowledge paradox asks how much information about individual risk is enough, since too little leaves risk unpriceable while too much removes the uncertainty that pooling depends on. At the system level the arrangement is stable, with insurability in place and stakeholder cost shares well-defined. At the property level it is not. Plausible methods disagree by margins too wide for instruments that use a single point estimate, whether insurance premium, public subsidy or eligibility rule.

The control paradox asks whether private insurers or government should run the market for catastrophe coverage. The Netherlands answers this by flood source. Insurers cover precipitation and regional breaches, while government covers primary defence failures via Wts. The formal partition is less stable than it appears. Wts is discretionary, and during the 2021 Limburg flood the cabinet invoked it for damages normally in the insurer domain. The partition also shifts over the planning horizon, with the government's share of damages falling sharply between 2025 and 2050 as the hazard mix changes. A partition that moves over a planning horizon is harder to govern than the static division the paradox usually describes. An instrument calibrated to the 2025 split would be miscalibrated by 2050, when insurers carry most of the risk government covers today.

4.4. Prospects for future progress

Property-level adaptation is one element of a system that spans multiple spatial scales, from individual buildings through neighbourhood drainage to regional water-system upgrades and national storm surge barriers. This study addresses only the property scale. Quantifying its trade-off with neighbourhood-level measures (e.g. Ooms et al., 2025) and regional water-system upgrades would answer two open questions: which spatial scale is most appropriate for which type of risk, and whether the split-incentive logic we describe here also operates at the neighbourhood scale.

Near-term routes attach property-level adaptation to renovation and permitting already underway rather than treating it as a standalone retrofit. The Dutch Environment and Planning Act can tie adaptation requirements to building permits and renovation triggers. The energy-transition renovation wave opens floors and walls, when water-resistant additions are marginal in cost. Housing corporations control roughly 2.4 million rental dwellings on centralised renovation cycles, a clear window for adaptation investment. The Delta Program on Spatial Adaptation already brings municipalities, water authorities and provinces into shared risk dialogues that can extend to property-level coordination. The split-incentive quantification identifies where these routes matter most, at the top of the risk distribution where the household-coalition gap is widest.

A concrete research priority follows from Sect. 4.2. The national pluvial maps are the dominant source of property-level hazard uncertainty, and by 2050 precipitation accounts for 68% of sample EAD. Higher-resolution maps, continuous rather than class-bounded depth outputs, and explicit treatment of building elevation would resolve the pluvial class-width and the floor-level correction together, since both operate at the same vertical scale. Given the non-linear damage response in the 0.1 - 0.5 m range (Van Ederen et al., 2025), this refinement would narrow the budget spread across corner cases, potentially within a range that policy instruments can be calibrated on. Two further inputs would strengthen validation. A linked claim-data record matching modelled EAD to realised damage at the property scale would expose systematic over- or underestimation. A national register of installed adaptation measures would enable difference-in-differences analysis of effectiveness as the adapted stock grows.

5. Conclusion

For 12,992 sampled embanked Dutch residential properties, we combined precipitation and flood defence failures across two hazard and two vulnerability methods for 2025 and 2050, allocated damages across households, insurers and government under Dutch institutional rules, and translated avoided damages into discounted property-level adaptation budgets.

Three findings emerge. First, flood damage is sharply concentrated. The top 5% of properties account for 54% of expected annual damage, and only from the 80th percentile upward does the combined adaptation budget reach the lower end of plausible adaptation cost. Second, the distribution of damage across stakeholders shifts substantially between 2025 and 2050.

Government carries 56% in 2025 through Wts compensation, falling to 13% by 2050 as the Flood Protection Programme reduces primary defence failure damages; insurers move from 32% to 72% as the share of damages from precipitation rises; the household share remains residual at 12% to 15%. Third, where flood damages fall to multiple stakeholders but adaptation costs fall to the homeowner, a structural split-incentive logic emerges that holds across the method grid. The three-stakeholder coalition budget exceeds the household-only budget by roughly an order of magnitude, with households receiving less than one-fifth of the avoided damages.

Uncertainty shapes what policy can achieve. Aggregate stakeholder patterns are robust across methods. The direction of the household shortfall, the magnitude gap between household-only and coalition budgets, and the order in which parties must be enlisted to close it all hold regardless of method choice. Per-property budget estimates, however, are not: which buildings cross a given threshold, and how much budget they hold, varies substantially across plausible methods. Point estimates at the property level are therefore not a defensible basis for policy, since the methodological spread is too wide for any single-method number to anchor decisions about an individual building without taking into account uncertainty.

Back matter

Code and data availability. The data and scripts that support the findings of this study are openly available via 4TU.ResearchData (Oerlemans, 2026)

Author contributions. Conceptualization: CO, ZT, MB, MK; data curation: CO; formal analysis: CO; methodology: CO; flood hazard modelling: CO; vulnerability modelling: CO; writing – original draft: CO; writing – review and editing: CO, ZT, MB & MK; supervision: MB and MK; funding acquisition: ZT, MB and MK. All authors have read and agreed to the published version of the manuscript.

Competing interests. Cees Oerlemans is affiliated with HKV, and Matthijs Kok was previously affiliated with HKV. The study uses the MyWaterRiskProfile API, developed by HKV, and evaluates the BREACH method, developed by researchers holding both academic and HKV affiliations. HKV had no role in the study design, analysis, interpretation, or decision to publish, and the analysis was conducted independently. The remaining authors declare no competing interests.

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References

Aerts, J. C. J. H., Bates, P. D., Botzen, W. J. W., de Bruijn, J., Hall, J. W., van den Hurk, B., Kreibich, H., Merz, B., Muis, S., Mysiak, J., Tate, E., and Berkhout, F.: Exploring the limits and gaps of flood adaptation, Nat. Water, 2, 719–728, https://doi.org/10.1038/s44221-024-00274-x, 2024.

Apel, H., Merz, B., and Thieken, A. H.: Quantification of uncertainties in flood risk assessments, Int. J. River Basin Manag., 6, 149–162, https://doi.org/10.1080/15715124.2008.9635344, 2008.

Asselman, N., van Heeringen, K.-J., de Jong, J., and Geertsema, T.: Juli 2021 overstroming en wateroverlast in Zuid-Limburg: eerste bevindingen voor Valkenburg, Geulmonding, Roermonding en Eygelshoven, Report 11207700-000-ZWS-0019, Deltares, Delft, the Netherlands, 2022.

Bates, P.: Fundamental limits to flood inundation modelling, Nat. Water, 1, 566–567, https://doi.org/10.1038/s44221-023-00106-4, 2023.

Bisaro, A. and Hinkel, J.: Mobilizing private finance for coastal adaptation: a literature review, WIREs Clim. Change, 9, e514, https://doi.org/10.1002/wcc.514, 2018.

Climate Damage Monitor: Klimaatschademonitor, Verbond van Verzekeraars, Den Haag, the Netherlands [data set], https://bipublic.verzekeraars.nl/Home/ShowReport/5beb3391-1660-4b40-a9d5-6982d8cae31f (last access: 18 March 2026), 2024.

Condon, M.: Climate services: the business of physical risk, Arizona State Law J., 55, 147, https://doi.org/10.2139/ssrn.4396826, 2023.

CPB: Overstromingsrisico voor Nederlandse huishoudens: financiële omvang en verdeling, Centraal Planbureau, Den Haag, the Netherlands, https://www.cpb.nl/system/files/cpbmedia/CPB_publicatie_overstromingsrisicos-voor-Nederlandse-huishoudens.pdf (last access: 5 November 2025), 2025.

de Lange, M., Groot, P., van Meurs, S., and Koeckhoven, T.: Water en bodem sturend: de gevolgen van het Ruimtelijk Afwegingskader en de KRW op de woningbouwopgave en de bouwsector, Economisch Instituut voor de Bouw (EIB), Amsterdam, the Netherlands, https://www.eib.nl/publicaties/water-en-bodem-sturend/ (last access: 24 October 2025), 2025.

Endendijk, T., Botzen, W. J. W., de Moel, H., Aerts, J. C. J. H., Duijndam, S. J., Slager, K., Kolen, B., and Kok, M.: Experience from the 2021 floods in the Netherlands: household survey results on impacts and responses, Journal of Coastal and Riverine Flood Risk, 2, 9, https://doi.org/10.59490/jcrfr.2023.0009, 2023.

Engelhard, E., de Jong, E., Faure, M., van der Meulen, W., and Schelfhout, D.: Toekomstbestendigheid en werkingsgebied Wet tegemoetkoming schade bij rampen (Wts), Wetenschappelijk Onderzoek- en Documentatiecentrum (WODC), Den Haag, the Netherlands, https://repository.wodc.nl/bitstream/handle/20.500.12832/3422/3426-toekomstbestendigheid-en-werkingsgebied-wet-tegemoetkoming-schade-bij-rampen-%28Wts%29-volledige-tekst.pdf (last access: 10 February 2026), 2024.

Flood Re: Build Back Better, https://www.floodre.co.uk/buildbackbetter/ (last access: 17 February 2026), 2024.

Gersonius, B., Zevenbergen, C., Puyan, N., and Billah, M. M. M.: Efficiency of private flood proofing of new buildings: adapted redevelopment of a floodplain in the Netherlands, WIT Trans. Ecol. Environ., 118, 247–259, https://doi.org/10.2495/FRIAR080241, 2008.

Herbert, D. M., Gardner, D. R., Harbottle, M., and Hughes, T. G.: Performance of single skin masonry walls subjected to hydraulic loading, Mater. Struct., 51, https://doi.org/10.1617/s11527-018-1222-z, 2018.

HKV: MijnWaterRisicoProfiel, HKV lijn in water, Lelystad, the Netherlands [data set], https://mijnwaterrisicoprofiel.nl/api (last access: 28 May 2026), 2025.

Hudson, P., Botzen, W. J. W., and Aerts, J. C. J. H.: Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change, Glob. Environ. Change, 58, 101966, https://doi.org/10.1016/j.gloenvcha.2019.101966, 2019.

IPCC: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., https://doi.org/10.1017/9781009325844, 2022.

Jarzabkowski, P., Chalkias, K., Clarke, D., Iyahen, E., Stadtmueller, D., and Zwick, A.: Insurance for climate adaptation: opportunities and limitations, Global Commission on Adaptation, Rotterdam, the Netherlands and Washington, DC, USA, https://eprints.bbk.ac.uk/id/eprint/28797 (last access: 1 June 2026), 2019.

Jarzabkowski, P., Chalkias, K., Cacciatori, E., and Bednarek, R.: Disaster insurance reimagined: protection in a time of increasing risk, Oxford University Press, Oxford, UK, https://doi.org/10.1093/oso/9780192865168.001.0001, 2023.

Jongejan, R. and Barrieu, P.: Insuring large-scale floods in the Netherlands, Geneva Pap. Risk Insur. Issues Pract., 33, 250–268, https://doi.org/10.1057/gpp.2008.10, 2008.

Kadaster: Basisregistratie Adressen en Gebouwen (BAG), Het Kadaster, Apeldoorn, the Netherlands [data set], https://service.pdok.nl/kadaster/bag/atom/bag.xml (last access: 7 January 2026), 2026.

Keating, K., May, P., Pettit, A., and Pickering, R.: Cost estimation for household flood resistance and resilience measures: summary of evidence, Report SC080039/R11, Environment Agency, Bristol, UK, https://assets.publishing.service.gov.uk/media/6034eec5e90e076607c1bf3b/Cost_estimation_for_household_flood_resistance_and_resilience_measures.pdf (last access: 12 November 2025), 2015.

Kolen, B. and Nicolai, R.: BREACH-METHOD: a new framework to generate event sets for financial flood risk assessment of the Dutch delta, Journal of Coastal and Riverine Flood Risk, 4, 18, https://doi.org/10.59490/jcrfr.2025.0018, 2025.

Kousky, C.: Financing flood losses: a discussion of the National Flood Insurance Program, Risk Manag. Insur. Rev., 21, 11–32, https://doi.org/10.1111/rmir.12090, 2018.

Kreibich, H., Bubeck, P., van Vliet, M., and de Moel, H.: A review of damage-reducing measures to manage fluvial flood risks in a changing climate, Mitig. Adapt. Strateg. Glob. Change, 20, 967–989, https://doi.org/10.1007/s11027-014-9629-5, 2015.

LIWO: Landelijk Informatiesysteem Water en Overstromingen (LIWO), Watermanagementcentrum Nederland (Rijkswaterstaat), Lelystad, the Netherlands [data set], https://basisinformatie-overstromingen.nl/ (last access: 28 May 2026), 2025.

Melsen, L. A.: It takes a village to run a model: the social practices of hydrological modeling, Water Resour. Res., 58, e2021WR030600, https://doi.org/10.1029/2021WR030600, 2022.

Oerlemans, C., van den Boomen, M., Rijcken, T., and Kok, M.: Flood exposure in Rotterdam's unembanked areas from 1970 to 2150: sensitivities to urban development, sea level rise, and adaptation, Nat. Hazards Earth Syst. Sci., 25, 3921–3937, https://doi.org/10.5194/nhess-25-3921-2025, 2025.

Oerlemans, C.: Data and scripts underlying the publication: split incentives in property-level flood adaptation across households, insurers and government in the Netherlands, 4TU.ResearchData [data set], https://doi.org/10.4121/aead25f3-a4fe-4284-b92b-d8112d4326b7.v1, 2026.

Ooms, V., Endendijk, T., Aerts, J. C. J. H., Botzen, W. J. W., and Robinson, P. J.: Assessing effects of nature-based and other municipal adaptation measures on insured heavy rain damages, Nat. Hazards Earth Syst. Sci., 25, 4283–4298, https://doi.org/10.5194/nhess-25-4283-2025, 2025.

Pollack, A. B., Auermuller, L., Burleyson, C. D., Campbell, J., Condon, M., Cooper, C., Coronese, M., Dangendorf, S., Doss-Gollin, J., Hegde, P., Helgeson, C., Kopp, R. E., Kwakkel, J., Lesk, C., Mankin, J., Nicholas, R. E., Rice, J., Roth, S., Srikrishnan, V., Scheeler, M., Tuana, N., Vernon, C., Zhao, M., and Keller, K.: Unlocking the benefits of transparent and reusable science for climate risk management, Proc. Natl. Acad. Sci. USA, 123, e2422157123, https://doi.org/10.1073/pnas.2422157123, 2026.

Poussin, J. K., Botzen, W. J. W., and Aerts, J. C. J. H.: Stimulating flood damage mitigation through insurance: an assessment of the French CatNat system, Environ. Hazards, 12, 258–277, https://doi.org/10.1080/17477891.2013.832650, 2013.

Rijkswaterstaat: Gebruikershandleiding Schade Slachtoffer Module SSM2023 v4.x, Informatiepunt Leefomgeving (IPLO), the Netherlands, https://iplo.nl/publish/pages/132789/gebruikershandleiding-ssm2023-v4-x-2024-.pdf (last access: 6 October 2025), 2024.

Rikkert, S., Stouten, D., Snippen, E., and Thonus, B.: Technische uitgangspunten en methode LIWO afgeleide kaarten, Report 11211536-000-ZWS-0003, Deltares, Delft, the Netherlands, https://publications.deltares.nl/11211536_000_0003.pdf (last access: 6 October 2025), 2025.

Schubert, J. E., Mach, K. J., and Sanders, B. F.: National-scale flood hazard data unfit for urban risk management, Earth's Future, 12, e2024EF004549, https://doi.org/10.1029/2024EF004549, 2024.

Slager, K. and Wagenaar, D.: Standaardmethode 2017: schade en slachtoffers als gevolg van overstromingen, Report 11200580-004, Deltares, Delft, the Netherlands, 2017.

Slootjes, N. and Van der Most, H.: Achtergronden bij de normering van de primaire waterkeringen in Nederland: hoofdrapport, Ministerie van Infrastructuur en Milieu, Den Haag, the Netherlands, https://iplo.nl/publish/pages/132791/normering_primaire_waterkeringen_hoofdrapport_28juni2016.pdf (last access: 10 November 2025), 2016.

STOWA: Neerslagstatistiek en -reeksen voor het waterbeheer 2019, Report 2019-19, Stichting Toegepast Onderzoek Waterbeheer, Amersfoort, the Netherlands,https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202019/STOWA%202019-19%20neerslagstatistieken.pdf (last access: 4 December 2025), 2019.

STOWA: De veiligheidsbenadering regionale keringen: ontstaan, achtergronden en toepassing van de huidige veiligheidsbenadering voor regionale waterkeringen, Report 2020-07, Stichting Toegepast Onderzoek Waterbeheer, Amersfoort, the Netherlands, https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202020/STOWA%202020-07%20Veiligheidsbenadering%20regionale%20keringen2.pdf (last access: 4 December 2025), 2020.

Surminski, S., Aerts, J. C. J. H., Botzen, W. J. W., Hudson, P., Mysiak, J., and Pérez-Blanco, C. D.: Reflections on the current debate on how to link flood insurance and disaster risk reduction in the European Union, Nat. Hazards, 79, 1451–1479, https://doi.org/10.1007/s11069-015-1832-5, 2015.

Suykens, C. B. R., Tarlock, D., Priest, S. J., Doorn-Hoekveld, W. J., and van Rijswick, H. F. M. W.: Sticks and carrots for reducing property-level risks from floods: an EU–US comparative perspective, Water Int., 44, 622–639, https://doi.org/10.1080/02508060.2019.1640957, 2019.

UNEP: Adaptation Gap Report 2024: Come Hell and High Water - As Fires and Floods Hit the Poor Hardest, It Is Time for the World to Step Up Adaptation Actions, United Nations Environment Programme, Nairobi, Kenya, https://doi.org/10.59117/20.500.11822/46497, 2024.

van Ederen, D., Aerts, J. C. J. H., Botzen, W. J. W., de Moel, H., Endendijk, T., Scussolini, P., and Gubbels, K.: Modern flood risk management is susceptible to model concentration risk from depth-damage functions, SSRN [preprint], https://doi.org/10.2139/ssrn.5899462, 2025.

VNK2: De veiligheid van Nederland in kaart: eindrapportage VNK2, Rijkswaterstaat, Projectbureau VNK2, the Netherlands, https://repository.tudelft.nl/islandora/object/uuid:52035faa-43ab-4dd0-a5b0-099119085356 (last access: 5 June 2026), 2014.

Woodruff, S. C., Mullin, M., and Roy, M.: Is coastal adaptation a public good? The financing implications of good characteristics in coastal adaptation, J. Environ. Plan. Manag., 63, 2082–2101, https://doi.org/10.1080/09640568.2019.1703656, 2020.

Working Group on Climate Adaptation: Klimaatadaptatie in een stroomversnelling: financiële sector en overheid samen aan de slag, Platform voor Duurzame Financiering, the Netherlands, https://www.dnb.nl/media/1uhbm3od/klimaatadaptatie-in-een-stroomversnelling-rapport.pdf (last access: 18 February 2026), 2023.

Working Group on Discount Rate: Rapport Werkgroep discontovoet 2025, Ministerie van Financiën, Den Haag, the Netherlands, https://www.rijksoverheid.nl/documenten/rapporten/2025/09/19/rapport-werkgroep-discontovoet-2025 (last access: 23 November, 2025), 2025.