Flood exposure in Rotterdam’s unembanked areas from 1970 to 2150: sensitivities to urban development, sea level rise and adaptation

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Abstract. Uncertainties in the rate of sea level rise, coupled with ongoing urban expansion, ~~create~~ challenge~~s for~~ city planners ~~in designing~~designing flood risk adaptation strategies. This study ~~analyzes~~ quantifies flood exposure ~~rates~~ in Rotterdam's unembanked areas from 1970 to 2150. We modeled flood hazards for 10, 100 and -1000~~-~~year return periods under both low (RCP2.6) and high (RCP8.5) emission scenarios, while assessing exposure using historic and planned urban development data. Temporal variations in exposure rates are attributed to three factors: urban development, sea level rise, and the construction of the Maeslant storm surge -barrier. Without adaptation measures, flood exposure in Rotterdam’s unembanked areas is projected to increase. ~~For 10-year flood events under~~Under RCP8.5, exposure rates for 10-year flood events are expected to increase 7-fold by 2150 compared to 2020. For RCP2.6, a 3-fold increase is projected for 10-year events, reflecting uncertainties in long-term sea level rise. A retrospective analysis reveals a~~n~~ ~~improvement~~ decrease in flood exposure: exposure levels observed in 2020 were approximately half those observed in 1996, due to construction of the Maeslant ~~storm surge~~ barrier. ~~Temporal variations in exposure rates are attributed to three factors: urban development, sea level rise, and the construction of the Maeslant barrier.~~ Exposure rates are primarily influenced by the Maeslant barrier, followed by sea level rise and urban development. Understanding the interplay of these three factors is crucial for urban planning and flood risk management in delta cities.

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1 Introduction

Without adaptation, ~~the risk of flooding is~~flood exposure and potential damage are expected to increase due to the combined trends and interactions of economic growth and climate change. Over the past decades, the economic impact of flooding events has steadily increased, primarily driven by socio-economic development in flood-prone areas (Aerts & Botzen, 2011; Jongman et al., 2014). Globally, there is a persistent migration trend toward coastal areas and from rural to urban settings. This leads to higher population density and asset concentration, which in turn heightens ~~coastal~~ flood exposure ~~and vulnerability~~ (Andreadis et al., 2022).

Climate change intensifies these flood risks through more frequent storm, rising sea levels and higher river peak discharges (Calafat et al., 2022; Oppenheimer et al., 2019). Flood risk is commonly defined as a function of hazard, exposure and vulnerability. Several studies have disentangled the key drivers of changes in flood risk across different spatial scales. At continental and global scales, h~~H~~istorical analyses from 1950 to 2020 show that the most important drivers of flood impacts in Europe have been exposure growth and vulnerability decline (P~~r~~aprotny et al.~~–~~, 2024). Steinhausen et al. (2022) ~~analysed~~analyzed the independent and combined influence of exposure change and climate scenarios on future flood risk in Europe finding that exposure change has a greater influence than climate-driven hazard changes in the near to mid-term future (up to 2085).~~. They find that in all future periods – 2025, 2055 and 2085 – exposure has a greater influence risk change than climate driven hazard.~~ Global analyses reveal distinct regional patterns. While flood impacts in African countries are mainly driven by climate change, in growing Southeast Asian economies (Indus, Yangtze, and Mekong basins), rapid urban growth dominates over climate change effects (Winsemius et al., 2016).

These large-scale studies highlight general trends, but designing effective local flood reduction strategies requires understanding risk drivers at finer spatial resolutions. At the regional and local scale, Koks et al. (2014) provided a framework to jointly assess flood hazard, exposure, and social vulnerability, demonstrating that including detailed regional information on flood risk drivers is crucial for developing effective flood reduction strategies. Local system dynamics can be complex: Schlögl et al. (2021) demonstrated that interactions within coupled natural and socio-economic systems maintain stable flood risk outcomes even as hazard events grow. Insights into these multi-scale risk drivers underscore that adaptation – through structural measures (sea walls, levees), nature-based solutions (mangrove restoration, wetlands), building-level interventions or urban development policies – can significantly reduce future flood losses even under lower global warming scenarios (Magnan et al., 2022; Oppenheimer et al., 2019; Aerts, 2018; Song et al., 2017).

~~Climate change exacerbated these risks, manifesting through more frequent storms, rising sea levels and higher river peak discharges (Calafat et al., 2022; Oppenheimer et al., 2019). Several studies have disentangled the key drivers of flood risk -~~

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hazard, exposure, and vulnerability – for both riverine and coastal flooding. Historical analyses from 1950 to 2020 show that the most important drivers of flood impacts in Europe have been exposure growth and vulnerability decline (Praprotny , 2024). Steinhausen et al. (2022) analysed the independent and combined influence of exposure change and climate scenarios on flood risk in Europe. They find that in all future periods – 2025, 2055 and 2085 – exposure has a greater influence risk change than climate driven hazard. Global analyses reveal distinct regional patterns. While flood impacts in African countries are mainly driven by climate change, in growing Southeast Asian economies (Indus, Yangtze, and Mekong basins), rapid urban growth dominates over climate effects (Winsemius et al., 2016). Koks (2014) provided a framework to jointly assess flood hazard, exposure, and social vulnerability at regional scales, demonstrating that including detailed regional information on flood risk drivers is crucial for developing effective flood reduction strategies. Understanding these different drivers has contributed to the recognition that adaptation is essential and can significantly reduce future flood losses, even under lower global warming scenarios (Magnan et al., 2022; Oppenheimer et al., 2019). Adaptation strategies consist of measures on various scales, including structural adaptations (e.g. sea walls, levees), nature based-solutions (e.g. mangrove restoration, wetland creation), building level adaptation (e.g., elevating structures, flood-proofing) and future urban development policies (Aerts, 2018; Song et al., 2017).

The interaction between risk drivers is especially interesting in urban port cities. Relocation of port activities to accommodate larger cargo ships has created new opportunities for urban development, often in historically industrial, unembanked areas located between flood sources (rivers, sea) and existing primary flood defense systems (Kaufmann et al., 2018). While these developments offer potential societal and economic benefits, they can also heighten flood exposure. Examples of port cities undergoing such transformations include Houston (Brody et al., 2018), Copenhagen (Hallegatte et al., 2011), Hamburg (Restemeyer, 2015) and Rotterdam (de Moel et al., 2014). This interplay between flood risk drivers, alongside the range of stakeholder interest, make unembanked areas relevant case-studies for exploring sustainable urban development and flood risk management under climate change uncertainty.

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In this study, we focus on the case of Rotterdam's unembanked areas. As the need for housing is high in the Netherlands, and especially in the larger Rotterdam area, the city is currently making critical decisions about where and how to build. The (re)development of unembanked areas requires careful consideration of various trade-offs. For instance, policymakers must weigh the benefits of neighborhood-level adaptations like ground raising – primarily benefiting new real estate – against more expensive system-scale measures such as strengthening storm surge barriers – protecting both new and existing buildings. These decisions have far-reaching implications for urban planning and flood risk management.

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The implementation of adaptation strategies in urban port cities presents challenges due to limited space and the complex interplay of diverse stakeholder interests. At the same time, relocation of port activities to accommodate larger cargo ships has created new opportunities for urban development in unembanked areas. Examples of port areas where these developments are happening are Houston (Brody et al., 2018), Copenhagen (Hallegatte et al., 2011) and Rotterdam (de Moel et al., 2014). While

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these developments offer potential economic benefits, they can also result in more flood exposure, as unembanked areas lie between flood sources and existing flood defence systems (Kaufmann et al., 2018).

The case of Rotterdam provides a compelling example of the complexities involved in managing flood risks in unembanked areas. As the need for housing is high in the Netherlands, and especially in the larger Rotterdam area, the city is making critical decisions about where and how to build. The (re)development of unembanked areas requires careful consideration of various trade-offs. For instance, policymakers must weigh the benefits of neighbourhood-level adaptations like ground raising, which primarily benefit the adaptation of new real estate, against more expensive system-scale measures such as strengthening storm surge barriers, which protect both new and existing buildings. These decisions have far-reaching implications for urban planning, flood risk management, and the overall resilience of the city.

Previous flood risk studies that combine and correct flood losses for urban development have been limited in temporal and spatial extent, leading to an incomplete presentation of trends in flood exposure over time (Paprotny et al., 2018). -In the Netherlands, studies assessing how flood risk might evolve in Rotterdam's unembanked areas (de Moel et al., 2014; Veerbeek et al., 2010), have focused only on future scenarios , and do not describe historical trends (de Moel et al., 2014; Veerbeek et al., 2010). These studies concluded that more accurate risk estimates would benefit from a more detailed consideration of objects and land-use categories. The current study focuses specifically on residential buildings using detailed object level data (BAG dataset, see Methods) offering higher precision for this category than broader land-use classifications, although it excludes other land-uses like commercial or industrial areas. Current studies only report flood exposure until 2100, but aMoreover, as urban planning and water management evolve towards longer decision-making timeframes, there is a need for flood risk assessments that can inform these extended planning horizons while capturing temporal path dependencies.

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This research aims to address these gaps by proposing a structured and flexible assessment framework for analyzing historical, present, and future flood exposure of residential buildings in unembanked areas. Our framework is designed to unpack total total flood exposure changes over time, attributing them to key drivers to in a manner that supports decision-making in urban planning and flood adaptation responses. The framework is applied to the unembanked areas of the city of Rotterdam and explicitly distinguishes between the impacts of urban development, sea level rise and adaptation efforts on flood exposure.

The study addresses the following key questions through a structured analysis:

1. How have extreme water level hazards and urban development evolved historically (1970-2020) in Rotterdam's unembanked areas, and how are they projected to change by 2150 under low (RCP2.6) and high (RCP8.5) emission scenarios?

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2. What is the historical (1970-2020) evolution and projected (to 2150) trajectory of total residential flood exposure in Rotterdam's unembanked areas, under both RCP2.6 and RCP8.5 climate scenarios, incorporating sea level rise, planned urban development and the Maeslant storm surge barrier's construction?
3. How does flood exposure vary spatially across different unembanked neighborhoods, and how do these spatial patterns change over time?
4. What are the relative contributions of urban development, sea level rise and the Maeslant storm surge barrier to the historic and projected changes in flood exposure over the period 1970-2150?
5. How sensitive is future flood exposure to different design flood elevation policies applied to new urban developments?

~~The study follows a four-step process:~~

~~1) Total flood exposure in Rotterdam's unembanked areas is analyzed from 1970 to 2150, considering both low and high emission scenarios. Without additional flood risk mitigation investments, projections indicate a significant increase in exposure rates.~~

~~2) The study characterizes the spatial variation of flood exposure by evaluating temporal exposure rates across different neighbourhoods. This analysis reveals significant variability in exposure rates, underscoring the importance of designing tailored long-term adaptation strategies for each neighbourhood.~~

~~3) Exposure rates over time are attributed to three key factors: urban development, sea level rise and the influence of the Maeslant barrier. By clarifying these factors' individual and collective impacts, the analysis provides crucial insights into the primary drivers of flood risk in Rotterdam.~~

~~4) Various urban development strategies are explored by varying the design flood elevation for new urban development. Results show that while increasing this elevation does mitigate exposure rates, significant reductions are primarily observed for extreme events with return periods of 1000 years or more within the specified timeframe.~~

The framework is designed to be applicable to other unembanked areas in ~~deltas~~deltas worldwide, allowing for flexibility in data inputs and model choices based on local data availability and specific research questions.~~. It offers flexibility, allowing models and data to be adjusted based on specific locations and desired temporal and spatial scales.~~

2 Methods ~~and data~~

2.1 Case study: Rotterdam's unembanked areas

Rotterdam is located in the Rhine-Meuse Delta in the Netherlands, ~~The Rhine-Meuse delta in the Netherlands is~~ a highly urbanized area vulnerable to climate change impacts (Fig. 1)~~. Adapting to these challenges is crucial (Van Alphen et al., 2022;~~

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De Bruijn et al., 2022; Haasnoot et al., 2020). We chose the case-study of the unembanked areas of Rotterdam for a number of reasons.

The Rhine-Meuse estuary, and specifically Rotterdam, is a highly urbanized area vulnerable to climate change impacts and adapting to these challenges is crucial (Van Alphen et al., 2022; De Bruijn et al., 2022; Haasnoot et al., 2020). The focus is on unembanked areas–those located on the river side of primary flood defenses, as defined by the Dutch Water Act. Unembanked areas are particularly interesting as these are not protected by flood defenses and rely on their higher elevation to maintain acceptable flood risk levels. Rotterdam's flood risk policy for unembanked areas currently strongly advises raising the ground level of new building lots to withstand 1000-year flood events under the low KNMI'14 climate scenario (Gemeente Rotterdam, 2021). By raising the ground levels, the design flood elevation policy aims reducing exposure of new urban development to increasing water levels. With the current design flood elevation policy, new buildings must be elevated up to 1 m above existing ground levels. Contrarily, existing urban unembanked areas lack additional regulations to mitigate flood impacts, leaving homeowners responsible for flood damage and preventive measures (Duijn & van Buuren, 2017).

The unembanked areas of Rotterdam have been characterized by rapid urban development over the past decades. About 75% of the current building stock in the unembanked areas (n=25,500) is realized after 1980. Furthermore, within the existing building stock, approximately 85% of the housing units are part of multiple housing units within the same building, indicating that the assigned ground level elevation can differ from the actual elevation of the housing unit. Urban redevelopment within Rotterdam's former port areas, particularly the Stadshavens (CityPorts), represents one of Europe's largest inner-city transformations after London Gateway, covering 1600 ha along both banks of the River Meuse (Daamen & Vries, 2013; Frantzeskaki et al., 2014). Situated uniquely inside Rotterdam's highway ring, these areas are highly favored for urban (re)development. These areas are the only port areas situated inside Rotterdam's highway rim, which explains why these are favored for urban development. Relocation of harbor activities, toward the sea to accommodate large cargo ships, has opened up spaces in unembanked areas, providing opportunities for new urban (re)developments. Until 2040, Rotterdam is planning to construct 50,000 houses, of which more than 22,600 are located in unembanked areas (Rotterdams Weerwoord, 2022, Gemeente Rotterdam, 2023).

Our study aims to provide accurate information on how both physical and societal factors influence flood risk at the neighbourhood level (Fig. 2a). The focus is on unembanked areas – those located on the river side of primary flood defences, as defined by the Water Act. Unembanked areas are generally not protected by flood defences and rely on their higher elevation to maintain acceptable flood risk levels.

Rotterdam's flood risk policy for unembanked areas currently recommends raising the ground level of new building lots to withstand 1000-year flood events under the low KNMI'14 climate scenario (Gemeente Rotterdam, 2021). The design flood elevation policy aims reduce exposure of new urban development to increasing water levels by raising the ground levels. As

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can be seen in Fig. 2d, many unembanked housing units have been constructed on building lots situated below the NAP+ 3.5 m elevation. Given that these unembanked areas generally aren't protected by flood defencesdefenses, the ground level of new building lot becomes the dominant factor in mitigating future flood exposure. As the recently released KNMI'23 scenarios project higher 1000-year flood event water levels than the previous KNMI'14 scenarios, the municipality plans to revise the current elevation.

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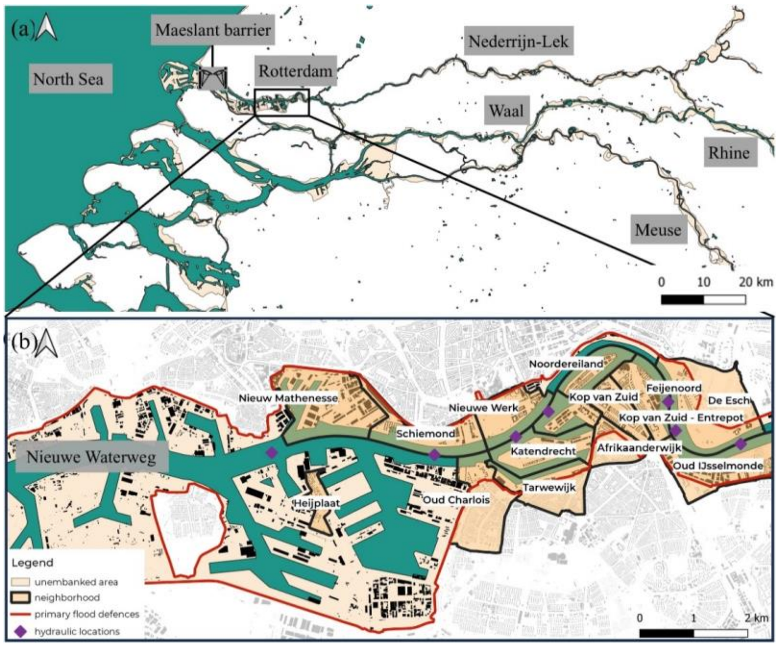

Figure 1: Geographical context of the study. (a) The Rhine-Meuse Delta system, showing the North Sea, incoming Rhine and Meuse rivers, and the location of Rotterdam. (b) Detailed map of Rotterdam's unembanked neighborhoods in relation to the primary flood defense system. With the current design flood elevation policy, new buildings must be elevated up to 1 meter above existing ground levels. Contrarily, existing urban unembanked areas lack additional regulations to mitigate flood impacts, leaving homeowners responsible for flood damage and preventive measures (Duijn & van Buuren, 2017).

Focusing solely on achieving specific ground levels would result in a disjointed urban landscape with varying elevations. And would increase costs for both private investors and the municipality. Consequently, Rotterdam is exploring alternative flood risk management strategies as addition to the Design Flood Elevation policy. These include not only raising grounds but also implementing additional measures including sea walls, elevated boulevards, tidal parks, temporary or mobile flood barriers, and innovative local flood-proofing.. This approach aligns with Rotterdam's broader efforts, like those of other major delta cities, to proactively address climate change consequences (Ward et al., 2013).

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Flood risk is commonly defined as a function of flood hazard, exposure and vulnerability. Although general damage drivers for vulnerability modelling are widely recognized, the exact effect of hazard characteristics on exposed structures is still poorly understood and largely depending on the material and its quality (Huijbregts et al., 2014). The present study primarily focusses on the spatial variation in exposure among unembanked neighbourhoods and the attribution of key factors, particularly urban development, on flood exposure. Hence, we quantify exposed buildings rather than modeling economic values using damage curves. Vulnerability is deliberately excluded from the scope of this study due to the scarcity of detailed empirical data from flood events, which are necessary for calibrating damage curves. Flood damage models are even less frequently calibrated in the Netherlands, where current estimates are based on flood damage records from the coastal flood of 1953 (Slager et al., 2013). A limitation of these flood vulnerability estimates is their generally limited transferability between different flood types (Wagenaar et al., 2018). This limitation is particularly evident in Rotterdam's unembanked areas, which feature a diverse range of building types, including both low-rise and high-rise structures.

2.2 Flood modeling framework

While fFlood risk is commonly defined as a function of flood hazard, exposure and vulnerability, the complexities of accurately quantifying vulnerability often necessitate a focused approach.. The precise Although general damage drivers for vulnerability modelling are widely recognized, the exact effect of hazard characteristics on exposed structures, such as those found in Rotterdam's unembanked areas, is still poorly understood and largely depending on the material and its quality (Huijbregts et al., 2014). .This study primarily analyzes temporal and spatial variations in flood exposure across unembanked neighborhoods and attributes these changes to key drivers. The present study primarily focusses on the spatial variation in exposure among unembanked neighbourhoods and the attribution of key factors, particularly urban development, on flood exposure. Moreover, calibrating such models requires rich empirical data from local flood events, which are not available for this specific context: existing Dutch models often rely on historical data with limited transferability (Slager et al., 2013; Wagenaar et al., 2018). Consequently, this study prioritizes a detailed assessment of flood exposure (Fig. 2). WHence, we quantify exposed buildings rather than modeling economic values using damage curves. Vulnerability is deliberately excluded from the scope of this study due to the scarcity of detailed empirical data from flood events, which are necessary for calibrating damage curves. Flood damage models are even less frequently calibrated in the Netherlands, where current estimates are based on flood damage records from the coastal flood of 1953 (Slager et al., 2013). A limitation of these flood vulnerability estimates is their generally limited transferability between different flood types (Wagenaar et al., 2018). This limitation is particularly evident in Rotterdam's unembanked areas, which feature a diverse range of building types, including both low-rise and high-rise structures.

Our research methodology focusses on flood hazard and exposure modelling (Fig. 1). We quantifyassess the number of exposed buildings resulting from the interplay of urban development, sea level rise, and the Maeslant storm surge barrier construction, attributing exposure changesimpacts to each of these factors. Six combinations of hazard and exposure are used in this study,

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as outlined in Table 1 and noted in the scenario legend of Fig. 1. The reference scenario includes sea level rise, urban development, and the construction of the Maeslant barrier. Subsequent scenarios explore exposure rates under various conditions, including scenarios without sea level rise, without urban development, and without the construction of the Maeslant barrier. The final two scenarios can be interpreted as variations on the reference scenario, differentiated by alterations in the design flood elevation. In cases where no design flood elevation is specified, this indicates the preservation of the current elevation distribution within each neighbourhood.

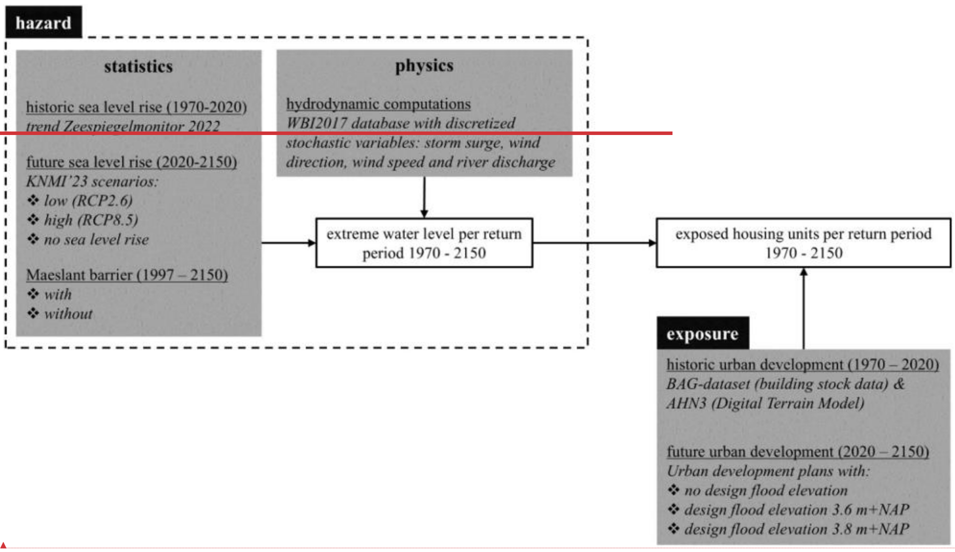

Figure 1: Methodological framework and data sources for calculating exposed housing units.

To achieve this, we use six combinations of flood hazard and exposure as specified in Table 1. The reference scenario includes all drivers: historical and projected sea level rise, historical and planned urban development, and the Maeslant barrier's operation post-1997. To isolate individual impacts, subsequent scenarios systematically vary these conditions, for example, by excluding future sea level rise, no urban development post-2020, or removing the effect of the Maeslant barrier. The final two scenarios specifically explore the sensitivity of future exposure to various levels for the design flood elevation. If no design flood elevation is applied in a scenario, it implies that new developments follow the existing ground elevation distribution within their respective neighborhoods.

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In the remainder of this section, we will outline our approach and the data used. We begin by describing our flood hazard modelling methods in Sect. 2.2.1, followed by our exposure modelling techniques in Sect. 2.2.2. Finally, Sect.ion 2.3 then explains how we combine hazard and exposure data to create spatial and temporal maps of flood exposure. Throughout these sections, we detail the specific data sources used for our case study in Rotterdam. While our methodology is tailored to the unembanked areas in Rotterdam, it can be adapted to other contexts. Researchers applying this framework to other port areas or urban coastal regions can substitute local data for both the hazard and exposure components, making the methodology broadly applicable. Further details about scripts and data used in this study are provided in the repository (Oerlemans, 2024).

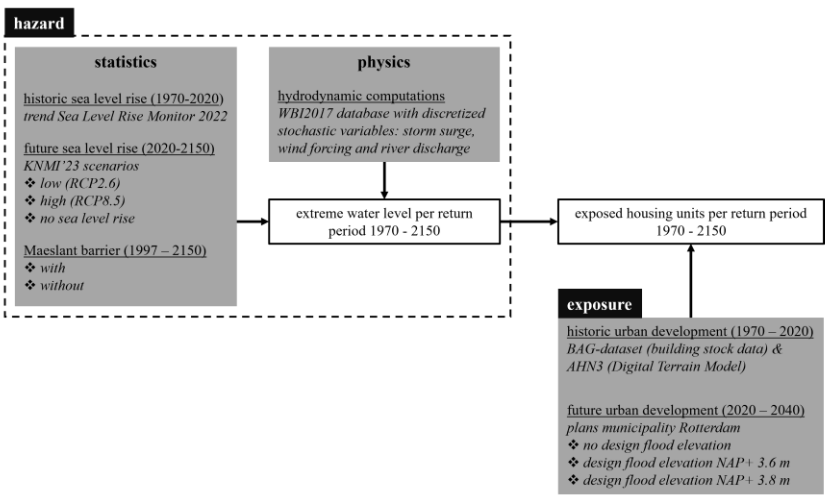

Figure 2: Schematic of the integrated methodological framework and data inputs for calculating residential flood exposure. This diagram shows how flood hazard inputs (derived from sea level statistics, hydrodynamic models, and Maeslant storm surge barrier scenarios) are combined with exposure inputs (historical building stock, future urban development plans, and design elevation scenarios) to determine the number of exposed housing units per return period from 1970 to 2150.

~~**Table 2: Scenario-specific information included in the exposure analysis, color-coding matches colors in subsequent figures. NAP = Dutch Ordnance Datum, which approximately corresponds to mean sea level.**~~

~~Scenario~~	~~Design floodelevation~~	~~Sea levelrise~~	~~Urbandevelopment~~	~~Maeslantbarrier~~
~~**Reference**~~	~~**NAP +3.6 m**~~	~~**1970 – 2150**~~	~~**1970 – 2040**~~	~~**1997 – 2150**~~
~~**No sea level rise after 2020**~~	~~**NAP +3.6 m**~~	~~**1970 – 2020**~~	~~**1970 – 2040**~~	~~**1997 – 2150**~~

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~~No urban development after 2020~~	●	~~N/A~~	~~1970 – 2150~~	~~1970 – 2020~~	~~1997 – 2150~~
~~No Maeslant barrier~~	●	~~NAP +3.6 m~~	~~1970 – 2150~~	~~1970 – 2040~~	~~None~~
~~No design flood elevation after 2020~~	●	~~None~~	~~1970 – 2150~~	~~1970 – 2040~~	~~1997 – 2150~~
~~Raised design flood elevation after 2020~~	●	~~NAP +3.8 m~~	~~1970 – 2150~~	~~1970 – 2040~~	~~1997 – 2150~~

2.2.1.1 Flood hazard: historical extreme water levels and future projections

Describing flood hazard in the Rhine-Meuse estuary is inherently complex, as water levels and wave conditions result from an interplay between sea conditions, discharges on multiple rivers, wind forcing and whether storm surge barriers are open or closed (Fig. 1). To capture this complexity, our analysis uses the official governmental WBI2017 dataset, the standard dataset for dike assessment and design in the Netherlands (Agtersloot and Paarlberg, 2016). This dataset provides water levels and wave conditions for the Rhine-Meuse estuary derived from simulations using the 2D-hydrodynamic model WAQUA. It encompasses 9,750 scenarios representing discrete combinations of the key stochastic input variables: wind direction, wind speed, river discharges, sea level variations, and Maeslant storm surge barrier operation (open/closed). These hydrodynamic simulations of the Rhine-Meuse estuary form the foundation for our probabilistic flood hazard assessment.

While the WBI database provides deterministic outcomes of water levels and wave conditions throughout the entire study area for specific scenarios, assessing flood risk over time requires a probabilistic approach. Therefore, we used the Hydra-NL software package (v.2.8.2) to translate hydrodynamic computations into water level frequency lines. These lines represent water levels magnitudes and their probability of exceedance at specific locations in the Rhine-Meuse estuary. Hydra-NL is an open-source probabilistic model widely used in the Netherlands for deriving hydraulic boundary conditions for flood defense assessment (Ministerie van Infrastructuur en Milieu, 2016). It functions by combining the hydrodynamic outcomes from the WBI database with probabilistic information about the input variables, such as river discharge distributions and sea level statistics derived from measurements. We derived water level frequency lines for eight locations along the Nieuwe Waterweg for both historical (1970-2020) and future (2020-2150) periods (Fig. 1).

Table 1: Specifications of the six scenarios used in the flood exposure analysis. Each scenario defines a unique combination of assumptions for design flood elevation (for post-2020 new builds), sea level rise, urban development and Maeslant storm surge barrier operation. Color-coding used in this table matches that in subsequent figures illustrating scenario-based results. NAP = Dutch Ordnance Datum, approximately corresponding to mean sea level.

Scenario		Design flood elevation	Sea level rise	Urban development	Maeslant barrier
Reference	●	NAP +3.6 m	1970 - 2150	1970 - 2040	1997 - 2150
No sea level rise after 2020	●	NAP +3.6 m	1970 - 2020	1970 - 2040	1997 - 2150
No urban development after 2020	●	N/A	1970 - 2150	1970 - 2020	1997 - 2150

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No Maeslant barrier		NAP +3.6 m	1970 - 2150	1970 - 2040	None
No design flood elevation after 2020		None	1970 - 2150	1970 - 2040	1997 - 2150
Raised design flood elevation after 2020		NAP +3.8 m	1970 - 2150	1970 - 2040	1997 - 2150

The detailed Hydra-NL model outputs, including analyses of dominant contributing combinations of storm surge, Maeslant barrier operation, and river discharge for each return period and location, are provided in the associated data repository (Oerlemans, 2024). Notably, both historical and future analyses use the same underlying WAQUA computations from the WBI2017-database; the effects of changing conditions like sea level rise are incorporated solely through the probabilistic weighting within Hydra-NL, not through re-running the hydrodynamic 2D WAQUA computations of the WBI database. Water level frequency lines represent the magnitude and likelihood of water levels at specific locations.In this study, Hydra-NL was used to derive water level frequency lines for both historical (1970-2020) and future (2020-2150) scenarios at eight locations along the Nieuwe Waterweg (Fig. 2).

Climate change and system-scale interventions, such as the construction of the Maeslant barrier, significantly influence flood probabilities in the study area. To model these probabilities, we employed Hydra-NL (v.2.8.2), an open-source model widely used in the Netherlands for deriving hydraulic loads, particularly extreme water levels, to assess and design flood defences (Ministerie van Infrastructuur en Milieu, 2016). In this study, Hydra-NL was used to derive water level frequency lines for both historical (1970-2020) and future (2020-2150) scenarios at eight locations along the Nieuwe Waterweg (Fig. 2). Water level frequency lines represent the magnitude and likelihood of water levels at specific locations. Our methodology incorporated computations from the 2D-hydrodynamic model WAQUA, along with probabilistic information related to input variables, including sea water level statistics derived from empirical measurements. The hydrodynamic computations used in this study are included via the Dutch governmental WBI2017-database, which currently serves as the primary database for dike assessments and design (Agtersloot and Paarlberg, 2016). This database encompasses hydrodynamic computations for 9,750 combinations of discrete stochastic variables, including wind direction, wind speed, river discharge of the rivers Nederrijn-Lek, Rhine and Meuse, and the operational status (open/closed) of the Maeslant barrier. Both the historical and future water level frequency lines were computed using the same WBI2017-database, which means that the impact of sea level rise on extreme water levels is considered only via the probabilistic analysis, not in the underlying physical combinations.

To reconstruct the historical flood hazard, specific temporal adjustments were applied to the Hydra-NL analysis for the period 1970-2020. Firstly, To calculate historical water level frequency lines (1970-2020), we incorporated included past local sea level rise trends: 1.8 mm/year for 1970-1990 and 2.9 mm/year for 1990-2020, as derived from the Sea Level Rise Monitor 2022 (Deltares, 2023). Secondly, tThe impact of the Maeslant barrier's construction was accounted for by applying a failure probability of 1 per closure request in Hydra-NL for simulations prior to 1997, effectively removing its influence on extreme

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water levels before its construction year. While river discharge distributions of the Rhine are important in calculating extreme water levels in other areas in the Rhine-Meuse Estuary, ~~(system overview in Fig 2a),~~ especially with expected increases in peak discharges that are included in climate scenarios, their impact on Rotterdam is relatively limited. This is because sea level, including storm surges, has a more significant impact on water levels in Rotterdam compared to river discharge. Hence, we did not include temporal changes for the discharge distributions in the Hydra-NL analysis.

~~For~~ To calculate future water level frequency lines (2020-2150), we adopted the KNMI'23 climate change scenarios (Dorland et al., 2023). These scenarios, building upon global IPCC scenarios but projecting further into the future, provide a more comprehensive representation of uncertainty for long-term decision-making and far-future risk management. The rationale behind adopting the KNMI scenarios is to be methodologically consistent with the IPCC and as such provide a widely accepted and actionable common projection for climate change in the Netherlands, while at the same time using the most accurate local projections for Rotterdam. The KNMI'23 scenarios are categorized into low-emission (RCP2.6) and high-emission (RCP8.5) scenarios. This ~~, aligning with those~~aligns our study with the scenarios used in the Delta ~~Programme~~Program, the~~a~~ national initiative evaluating and developing long-term flood risk management and climate adaptation strategies ~~strategies to protect the Netherlands from flooding, ensure water availability, and enhance the country's resilience to water-related challenges by 2050~~ (Deltaprogramma, 2023).

While analyses incorporated both emission pathways, we use the high-emission KNMI'23 scenario (RCP8.5) as the central case for evaluating future flood hazards, representing a more precautionary upper bound for planning. To explicitly address the significant uncertainty concerning the timing rather than just the magnitude of future sea level rise impacts, results derived from the low-emission scenario (RCP2.6) are presented alongside the high-emission results. This comparative approach highlights the range of plausible future timelines; for instance, the 0.27 m sea level rise projected by 2050 under the high-emission scenario is not anticipated until 2058 under the low-emission pathway. Consequently, to visually represent this temporal uncertainty stemming from different emission trajectories, results throughout this paper are presented using a double x-axis, mapping equivalent exposure levels to their corresponding years under both scenarios.

~~**In this study, the high-emission scenario serves as point of departure. To illustrate the uncertainty in the timing of sea level rise, we link results from both high- and low-emission scenarios. For instance, the 0.27 m sea level rise projected for 2050 in the high-emission scenario is anticipated by 2058 in the low-emission scenario. This approach is reflected in the double x-axis used throughout the study. Return periods for computing extreme water levels range from 10 to 1000 years.**~~

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2.2.2. Flood ~~E~~exposure: current building stock and future projections

To assess exposure of the current building stock, we ~~utilized~~ used the open-source BAG dataset to obtain building footprints of residential assets in Rotterdam's unembanked areas (Kadaster, 2022). For about 9 million addresses in the Netherlands, the BAG database includes ~~several~~ key attributes, ~~such as the function of the property (e.g. residential),~~including property function,

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the surface area of the specific object and the construction year. In ourthe analysis, only residential assets are included. Ground-level elevation data for each existing building footprint was derived by spatially joining the BAG data with Digital Terrain Model of the Netherlands (AHN3, 0.5 m resolution raster). It is important to note this represents the elevation of the surrounding terrain, not necessarily the finished floor level of individual housing units. These footprints were combined with elevation data from the Digital Terrain Model of the Netherlands (AHN3, 0.5-meter resolution raster) to assign elevation values to each housing unit. By assigning specific elevation values to each housing unit, we can accurately assess their potential exposure given various climate scenarios It is important to note that the assigned elevation represents the ground level elevation surrounding dwellings and does not account for variations in individual housing unit floor levels.

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Addressing future changes in exposure required integrating planned urban development data provided by the Municipality of Rotterdam (Gemeente Rotterdam, 2023). These urban development plans outlines major urban planning projects, specifying the number of planned housing units, their intended neighborhoods, and scheduled completion dates up to 2040. However, this municipal data lacks specific elevation plans for these unembanked future housing units. To explore the impact of potential future elevation strategies, particularly the city's design flood elevation policy, we formulated three distinct elevation scenarios for all planned housing units:To determine the construction year and locations of planned real estate developments for upcoming decades, we incorporated urban development data from the municipality of Rotterdam, encompassing all significant urban planning projects (Gemeente Rotterdam, 2023). The municipal data includes the number of housing units, their scheduled completion dates, and their respective neighborhoods. As this data lacked elevation information, we developed three scenarios for the elevation of planned housing units:

1. Reference Design Flood Elevation Scenario. All planned housing units are assigned an elevation corresponding to the current design flood elevation of NAP +3.6 m (Amsterdam Ordnance Datum).
2. Increased Design Flood Elevation Scenario: planned units are assigned aAn elevated design flood elevation of NAP +3.8 m, reflecting a potential future increase in the design flood elevation standard. is applied. This 20 cm increase reflects a potential revision of the current standard (based on KNMI'14 scenarios) due to new climate projections (KNMI'23), which suggest a similar magnitude of change. While seemingly modest, this 0.2 m elevation increase would involve substantial additional costs, estimated in the tens of millions of euros.

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3. No Design Flood Elevation Scenario: This approach assumes urban densification without raising ground levels. We derived a Gaussian distribution based on existing neighbourhoodneighborhood elevations and used this to sample elevations for planned housing units, maintaining the current elevation distribution per neighbourhoodneighborhood.

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Evaluating these distinct elevation pathways for new developments allows for an assessment of the design elevation policy's effectiveness in mitigating flood exposure under conditions of urban growth and climate change.

The Design Flood Elevation is one the important components of the long-term flood adaptation strategy for the unenembanked areas of Rotterdam (Sect. 3). Evaluation of various elevations for new residential developments enables assessment of flood elevation policy effectiveness, particularly in light of urban growth and climate change impacts. Although Rotterdam applies more flood reduction measures in its unembanked areas, this research only includes two measures: the design flood elevation policy and the implementation of the Maeslant barrier. 2.3 Combining hazard and exposure

2.3 Quantifying residential flood exposure

Exposure was quantified by directly comparing the probabilistic water levels (hazard) with the assigned ground-level elevations of individual housing units (exposure) for 10-, 100- and 1000-year flood events. A housing unit was classified as exposed during a given flood event scenario if the calculated water level exceeded its ground-level elevation by a defined threshold. Based on typical residential construction in the area, a threshold of 0.25 m, representing the average height of doorsteps, was adopted (Veerbeek et al., 2010). To assess the exposure over time, this calculation was performed for each housing unit – both existing and future under each design flood elevation scenario – across the range of water levels associated with return periods of 10-, 100- and 1000-years.To quantify exposure, we calculated the difference between water levels at given return periods and the ground level elevation of each housing unit. A housing unit is considered exposed when this difference exceeds a threshold value of 0.25 m, corresponding to the average height of doorsteps in the study area (Veerbeek et al., 2010).

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3 Case study: Rotterdam's unembanked areas

The Rhine-Meuse delta in the Netherlands is a highly urbanized area vulnerable to climate change impacts. Adapting to these challenges is crucial (Van Alphen et al., 2022; De Bruijn et al., 2022; Haasnoot et al., 2020). Our study aims to provide accurate information on how both physical and societal factors influence flood risk at the neighbourhood level (Fig. 2a). The focus is on unembanked areas—those located on the river side of primary flood defences, as defined by the Water Act. Unembanked areas are generally not protected by flood defences and rely on their higher elevation to maintain acceptable flood risk levels.

Rotterdam's flood risk policy for unembanked areas currently recommends raising the ground level of new building lots to withstand 1000-year flood events under the low KNMI'14 climate scenario (Gemeente Rotterdam, 2021). The design flood elevation policy aims reduce exposure of new urban development to increasing water levels by raising the ground levels. As can be seen in Fig. 2d, many unembanked housing units have been constructed on building lots situated below the NAP+ 3.5 m elevation. Given that these unembanked areas generally aren't protected by flood defences, the ground level of new building lot becomes the dominant factor in mitigating future flood exposure. As the recently released KNMI'23 scenarios project higher 1000-year flood event water levels than the previous scenarios, the municipality plans to revise the current elevation. With the current design flood elevation policy, new buildings must be elevated up to 1 meter above existing ground levels. Contrarily, existing urban unembanked areas lack additional regulations to mitigate flood impacts, leaving homeowners responsible for flood damage and preventive measures (Duijn & van Buuren, 2017).

Focusing solely on achieving specific ground levels would result in a disjointed urban landscape with varying elevations. And would increase costs for both private investors and the municipality. Consequently, Rotterdam is exploring alternative flood risk management strategies as addition to the Design Flood Elevation policy. These include not only raising grounds but also implementing additional measures including sea walls, elevated boulevards, tidal parks, temporary or mobile flood barriers, and innovative local flood-proofing.. This approach aligns with Rotterdam's broader efforts, like those of other major delta cities, to proactively address climate change consequences (Ward et al., 2013).

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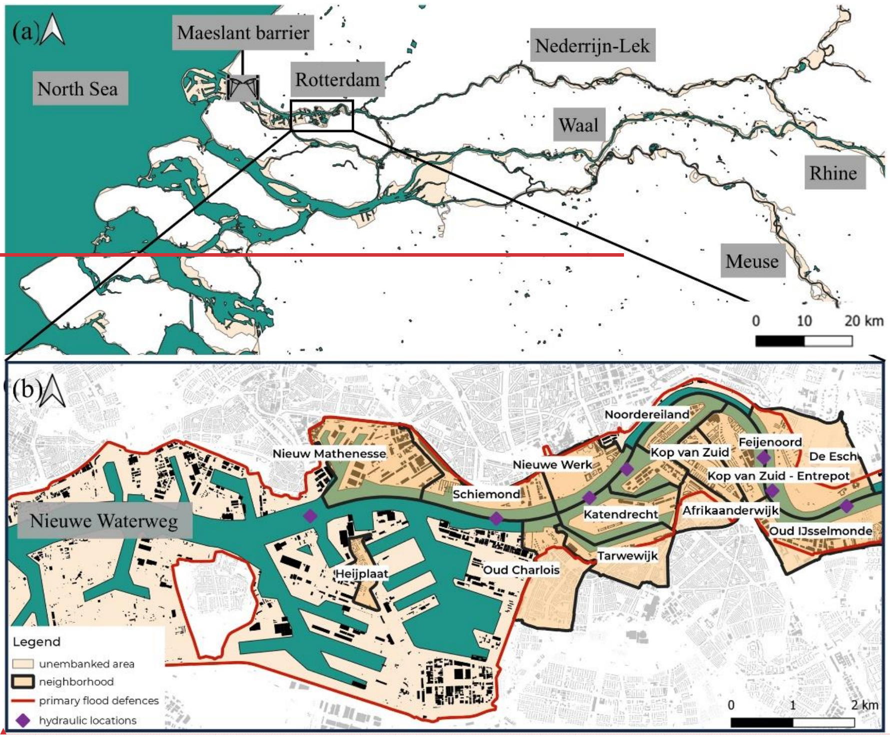

Figure 2: (a) Rhine-Meuse water system with the North Sea on the west and incoming rivers on the east. (b) Rotterdam's unembanked neighbourhoods and primary flood defences. (c) Water levels by return period, averaged over all hydraulic locations indicated in Fig. 2b. (d) Elevation distribution by neighbourhoods, shown as box plots (median, interquartile range, 5th/95th percentiles); Tarwewijk and Nieuw Mathenesse are excluded because of a limited building stock.

3.1 Extreme water levels between 1970 - 2150

Extreme water levels in Rotterdam depend on the combination of sea level, river discharge, wind speed, wind direction and whether the Maeslant barrier is open or closed. Over time, extreme water levels have increased due to rising sea levels. The extreme water levels in Rotterdam are primarily influenced by sea level rather than river discharge, which sets them apart from other locations in the Rhine-Meuse estuary such as Dordrecht.

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The extreme water levels, following from probabilistic calculations, are presented in Fig. 2c. Generally, the extreme water levels show an upward trend, attributed to rising sea levels. This trend assumes no system-scale adaptations, such as increased storage capacity or improvement of the closure reliability of the Maeslant barrier (Mooyaart et al., 2022). From 1996 to 1997, extreme water levels decreased due to the construction of the Maeslant barrier, ranging from a reduction of 0.06 m (10-year events) to 0.71 m (1000-year events). For 1000-year events, the extreme water level in 2150 (RCP8.5) is similar to the water level prior to the construction of the Maeslant barrier. Under the low emission scenario (RCP2.6), for 1000-year events, the extreme water level in 2150 remains 0.48 m lower than 1996 levels. For 100-year events, the extreme water level in 2090 (RCP8.5) equals the water level 1996 level and exceeds the 1996 level by 0.21 m in 2150 (RCP8.5). The mitigating effect of the Maeslant barrier for 10-year events is less because the closing criterium is around the same water level of NAP +3.0 m. The Maeslant barrier is intentionally left open for the majority of 10-year events, and as such, is not designed to mitigate extreme water levels within this specific range. Hence, the extreme water level for 10-year events in 2150 is expected to increase by 0.33 and 0.58 m when compared to the 1996 levels, under the RCP2.6 and RCP8.5 scenarios respectively.

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3.2 Urban development between 1970 – 2050

The unembanked areas of Rotterdam have been characterized by rapid urban development over the past decades. About 75% of the current building stock in the unembanked areas (n=25,500) is realized after 1980. Furthermore, within the existing building stock, approximately 85% of the housing units are part of multiple housing units within the same building, indicating that the assigned ground level elevation can differ from the actual elevation of the housing unit. The development in the Stadshavens (hereafter: CityPorts) Rotterdam are the largest inner-city development in Europe after London Gateway, covering an area of 1600 ha located on both banks of the river Meuse (Daamen & Vries, 2013; Frantzeskaki et al., 2014). The CityPorts areas are the only port areas situated inside Rotterdam's highway rim, which explains why these are favoured for urban development.

Relocation of harbour activities, toward the sea to accommodate large cargo ships, has opened up spaces in unembanked areas, providing opportunities for new urban (re)developments. Until 2040, Rotterdam is planning to construct 50,000 houses, of which more than 22,600 are located in unembanked areas (Rotterdams Weerwoord, 2022, Gemeente Rotterdam 2023).

The elevation of current unembanked housing units varies across different neighbourhoods (Fig. 2c), which holds implications for designing long-term flood risk adaptation strategies. Findings show that both the mean elevation and width of the distribution differ among these neighbourhoods. These distributions result in varying increases of exposure rates for marginal increases in water levels. Specifically, neighbourhoods such as Heijplaat, Nieuwe Werk, and Noordereiland exhibit median elevation values below 3.3 meters. When considering all unembanked neighbourhoods collectively, approximately 45% of the existing building stock possesses ground level elevations that fall below the current design flood elevation of NAP +3.6 m.

Note that this assessment pertains not to the actual height of the housing units but rather to the elevation of the ground on which they are situated.

34 Results

This section presents the results of our analysis of residential flood exposure in Rotterdam's unembanked areas. We begin by characterizing the historical evolution and future projections of the key drivers: extreme water level hazards (Sect. 3.1.1) and residential urban development, including building stock and ground elevations (Sect. 3.1.2). Following this, Sect. 3.2 examines the total residential flood exposure that results from the combined interplay of these drivers under our reference scenario. Section 3.3 then explores the spatial distribution of this total exposure across Rotterdam's different unembanked neighborhoods, highlighting variations in both relative and absolute numbers of exposed housing units over time. Subsequently, Section 3.4 presents an attribution analysis, disentangling the relative contributions of future sea level rise, planned urban development, and the Maeslant storm surge barrier's operation to projected changes in total residential flood exposure. We conclude in Sect. 3.5 with a sensitivity assessment, evaluating how future flood exposure for new urban developments is influenced by various levels of the design flood elevation.

The results are presented in four sections. Section 4.1 presents the flood exposure in Rotterdam's unembanked areas from 1970 to 2150, examining the combined effects of sea level rise, urban development, and the construction of the Maeslant barrier. Section 4.2 then highlights temporal variations in exposure, demonstrating how flood risk has changed over time. Subsequently, Sect. 4.3 presents an attribution analysis, examining and comparing the individual effects of sea level rise, urban development, and the Maeslant barrier construction on flood exposure. The analysis concludes in Sect. 4.4 with a sensitivity assessment, evaluating how flood exposure responds to changes in design flood elevation levels. 3.1 Characterizing flood exposure drivers: extreme water levels and urban development

33.1.1 Extreme water levels between 1970 –– 2150

Extreme water levels in Rotterdam's unembanked areas are primarily influenced by North Sea conditions (tides and storm surges), with river discharge playing a secondary role compared to locations more upstream in the Rhine-Meuse estuary. Over the study period, these extreme water levels are shaped by two main drivers: ongoing sea level rise and the operation of the Maeslant storm surge barrier.

Extreme water levels in Rotterdam depend on the combination of sea level, river discharge, wind speed, wind direction and whether the Maeslant barrier is open or closed. Over time, extreme water levels have increased due to rising sea levels. The extreme water levels in Rotterdam are primarily influenced by sea level rather than river discharge, which sets them apart from other locations in the Rhine-Meuse estuary such as Dordrecht.

Probabilistic calculations show an upward trend in extreme water levels due to sea level rise (Fig. 3a),
The extreme water levels, following from probabilistic calculations, are presented in Fig. 2c. Generally, the extreme water levels show an upward trend, attributed to rising sea levels. This trend assumes assuming no system-scale adaptations, such as

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increased storage capacity or improvement of the closure reliability of the Maeslant barrier (Mooyaart et al., 2022). From 1996 to 1997, extreme water levels decreased due to the construction of the Maeslant barrier, ranging from a reduction of 0.06 m for ~~(~~10-year events~~)~~ to 0.71 m for ~~(~~1000-year events~~)~~. Looking forward, under the RCP8.5 scenario, the~~For~~ 1000-year water level ~~events, the extreme water level~~ in 2150 ~~(RCP8.5)~~ is projected to be similar to the water level prior to the construction of the Maeslant barrier. Under the low emission scenario (RCP2.6), the 2150 level for ~~for~~ a 1000-year event~~s, the extreme water level in 2150~~ remains 0.48 m lower than in 1996~~ levels~~. For 100-year events~~, the extreme water level in 2090 (RCP8.5)~~ under RCP8.5, ~~equals~~ the 1996 water level is projected to be reached again around 2090 and exceeded by 0.21 m in 2150. ~~1996 level and exceeds the 1996 level by 0.21 m in 2150 (RCP8.5).~~ The mitigating effect of the Maeslant barrier is less pronounced for 10-year events ~~is less~~ because ~~the~~its closing criterium

(NAP+ 3.0 m) means the barrier often remains open during 10-year events. ~~is around the same water level of NAP +3.0 m. The Maeslant barrier is intentionally left open for the majority of 10-year events, and as such, is not designed to mitigate extreme water levels within this specific range.~~ Hence, the extreme water level for 10-year events in 2150 ~~is expected~~are projected to increase by 0.58 m~~33~~ (RCP8.5) and 0.33~~.58~~ m (RCP2.6) when compared to the 1996 levels~~, under the RCP2.6 and RCP8.5 scenarios respectively.~~.

3.1.2 Urban development between 1970 – 2040

The ground level elevation of current unembanked housing units varies considerable across different neighborhoods (Fig. 3b), which holds implications for designing long-term flood risk adaptation strategies. Analysis reveals that both the mean ground elevation and the spread of this distribution differ substantially among these districts and directly influence how exposure rates change with marginal increases in flood water levels. Specifically, neighborhoods such as Heijplaat, Nieuwe Werk, and Noordereiland have median ground elevation values below 3.3 m. When considering all unembanked neighborhoods collectively, approximately 45% of the existing building stock possesses ground level elevations that fall below the current design flood elevation of NAP +3.6 m.

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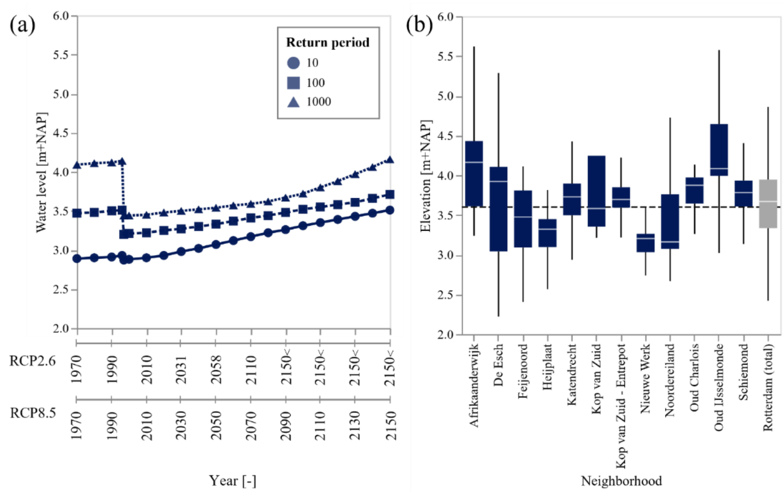

Figure 3: Extreme water levels and building elevation distributions in Rotterdam's unembanked areas. (a) Spatially averaged extreme water levels (1970-2150) by return period (10-, 100-, 1000-year), with a dual x-axis mapping levels to low (RCP2.6) and high (RCP8.5) emission scenarios (hydraulic locations shown in Fig. 1). (b) Box plot distributions of ground-level elevations for existing residential buildings by neighborhood, showing median, interquartile range and 5th/95th percentiles. Tarwewijk and Nieuw Mathenesse are excluded due to limited residential building data.

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3.2 Urban development between 1970 – 2050

The unembanked areas of Rotterdam have been characterized by rapid urban development over the past decades. About 75% of the current building stock in the unembanked areas (n=25,500) is realized after 1980. Furthermore, within the existing building stock, approximately 85% of the housing units are part of multiple housing units within the same building, indicating that the assigned ground level elevation can differ from the actual elevation of the housing unit. The development in the Stadshavens (hereafter: CityPorts) Rotterdam are the largest inner-city development in Europe after London Gateway, covering an area of 1600 ha located on both banks of the river Meuse (Daamen & Vries, 2013; Frantzeskaki et al., 2014). The CityPorts areas are the only port areas situated inside Rotterdam's highway rim, which explains why these are favoured for urban development.

Relocation of harbour activities, toward the sea to accommodate large cargo ships, has opened up spaces in unembanked areas, providing opportunities for new urban (re)developments. Until 2040, Rotterdam is planning to

~~**construct 50,000 houses, of which more than 22,600 are located in unembanked areas (Rotterdams Weerwoord, 2022, Gemeente Rotterdam 2023).**~~

~~The elevation of current unembanked housing units varies across different neighbourhoods (Fig. 2c), which holds implications for designing long-term flood risk adaptation strategies. Findings show that both the mean elevation and width of the distribution differ among these neighbourhoods. These distributions result in varying increases of exposure rates for marginal increases in water levels. Specifically, neighbourhoods such as Heijplaat, Nieuwe Werk, and Noordereiland exhibit median elevation values below 3.3 meters. When considering all unembanked neighbourhoods collectively, approximately 45% of the existing building stock possesses ground level elevations that fall below the current design flood elevation of NAP +3.6 m. Note that this assessment pertains not to the actual height of the housing units but rather to the elevation of the ground on which they are situated.~~

~~**(c) Water levels by return period, averaged over all hydraulic locations indicated in Fig. 2b. (d) Elevation distribution by neighbourhoods, shown as box plots (median, interquartile range, 5th/95th percentiles); Tarwewijk and Nieuw Mathenesse are excluded because of a limited building stock.**~~

3~~4~~.2~~1~~ Temporal variations in f~~F~~lood exposure: combined impact of urban development, sea level rise and adaptation ~~combined~~

An analysis of the collective influence of sea level rise, urban development, and the Maeslant barrier construction on the exposure of unembanked housing units in Rotterdam was conducted from 1970 to 2150 (Fig. 4) ~~for the past 50 years and projected 130 years (Fig. 3)~~. Without adaptation measures, unembanked areas in Rotterdam are expected to ~~experience~~ face increased flood exposure, particularly in the 22nd century. The magnitude of this increase varies across different return periods.

For 10-year events, the number of houses exposed to flooding is projected to increase from 400 in 1970 to 800 in 2020, and further to 5,700 by 2150 under the RCP8.5 scenario (a 7-fold increase from 2020). Under RCP2.6, the 2150 projection is around 2,400 exposed units, a 3-fold increase from 2020. The 100-year flood events show a different pattern: exposure decreases from 3,200 houses in 1970 to ~~1986,~~ 1,600 houses in 2020, followed by an increase to 9,100 in 2150 under the RCP8.5 scenario (a 6-fold increase from 2020) ~~(RCP8.5)~~. The RCP2.6 scenario projects about 5,400 exposed units in 2150, a 3-fold increase from 2020. Similarly, for 1000-year events, exposure initially decreases from 5,200 houses in 1970 to 4,700 in 2020, before ~~rising significantly~~being projected to rise significantly to 39,400 in 2150 under the ~~(~~RCP8.5 scenario~~)~~ (an 8-fold increase from 2020). Under RCP2.6, the 2150 projection is approximately 10,700 units, a 2-fold increase from 2020.~~.~~

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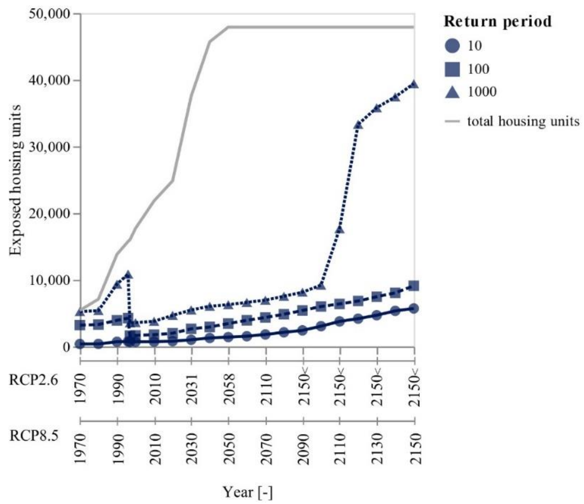

Figure 4: Number of exposed houses for Rotterdam's unembanked areas for 10-, 100- and 1000-year events between 1970 and 2150, for the low KNMI'23 (RCP2.6) and high KNMI' 23 (RCP8.5) scenarios. The dual x-axis maps exposure levels to these two emission scenarios.~~Under the RCP8.5 scenario, these projections translate to a 7-fold increase in exposure for 10-year events, a 5-fold increase for 100-year events by 2150 and an 8-fold increase for 1000-year events, compared to 2020 levels. The RCP2.6 scenario projects less severe increases: a 3-fold increase for 10-year and 100-year events, and a 2-fold increase for 1000-year events by 2150.~~

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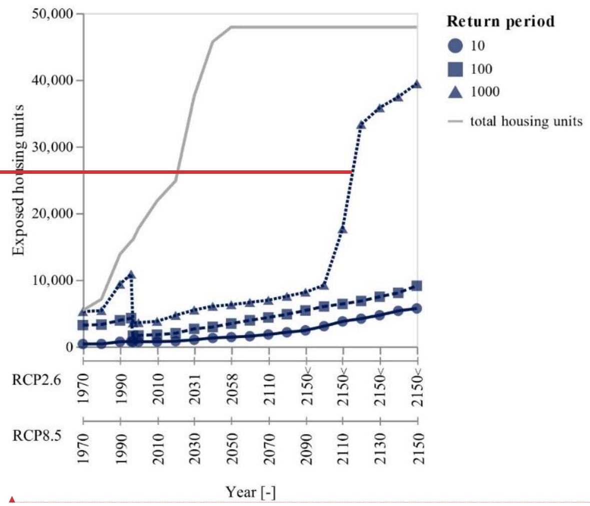
The operationalization of the Maeslant barrier in 1997 ~~marked mitigation in~~mitigated exposure, evidenced by a decrease in extreme water levels (Fig. 3~~2ab~~) and exposed houses (Fig. 4~~3~~). Specifically, the number of exposed houses decreased by approximately 100 houses (10%) for 10-year events, 2,600 houses (62%) for 100-year events, and 7,300 houses (67%) for 1000-year events. The barrier's impact for 10-year events, compared to the other return periods, is limited because extreme water levels during such events do not always surpass the barrier's closure threshold. Consequently, there are instances in which the Maeslant barrier remains open, even though doing so results in flood exposure for certain properties.



~~**Figure 3: Number of exposed houses for Rotterdam's unembanked areas for 10-, 100- and 1000-year events between 1970 and 2150, for the low KNMI'23 (RCP2.6) and high KNMI' 23 (RCP8.5) scenarios.**~~

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3~~4~~.~~3~~2 Spatial distribution of flood exposure

Rotterdam's 14 unembanked ~~neighbourhood~~neighborhoods show significant variations in flood exposure~~susceptibility~~, largely due to differences in housing unit elevations and density (Fig. 3b~~2c~~). To illustrate these exposure variations, we analyzed the proportion of exposed houses in each ~~neighbourhood~~neighborhood over time (Fig. 5~~4~~). These values fluctuate due to changes in the total number of houses (urban development) and shifts in water levels (sea level rise and Maeslant barrier operation), emphasizing the need for neighborhood~~-~~specific adaptation strategies. ~~Percentages fluctuate as the total number of houses changes (due to urban development) and water levels shift (sea level rise and construction of the Maeslant barrier). This analysis reveals significant disparities in the percentage of vulnerable houses within unembanked areas of Rotterdam, emphasizing the need for neighbourhoods-specific adaptation strategies.~~

For 10-year flood events, the range of ~~exposed houses~~exposure across ~~neighbourhood~~neighborhoods is~~is~~ relatively narrow. In 1970, ~~1970,~~ Kop van Zuid – Entrepot showed the highest relative exposure at 48% (~110 houses), while Feijenoord, with 24% relative exposure, had the largest absolute number of exposed units (~220 houses). Other neighborhoods had less than 5% exposure. ~~Kop van Zuid – Entrepot was the most vulnerable neighbourhoods with 48% (100 houses) exposed, followed by Feyenoord with 24% (200 houses). Other neighbourhoods had less than 5% exposure.~~ By 2020, overall exposure ~~generally~~ decreased. De Esch had the highest relative exposure at 17% (~300 houses), whereas Feyenoord maintained the largest absolute exposure with approximately 340 units (10%). Nine out of the 14 neighborhoods showed no exposure.~~, with the Esch neighbourhood highest at 17% and 9 out of 14 neighbourhoods showing no exposure.~~ Projections for 2150 under the RCP8.5 scenario indicate exposure reaching up to 58% (~1200 houses) in Noordereiland. ~~, while~~ U~~u~~nder the RCP2.6 scenario in 2150, maximum relative exposure in any ~~neighbourhood~~neighborhood is limited to 23%.

The 100-year flood events show greater variability in exposure rates. In 1970, most~~all~~ ~~neighbourhood~~neighborhoods, except for the 6 ~~neighbourhood~~neighborhoods with few or no houses in 1970, had over 43% exposure. By 2020, exposure decreased across all ~~neighbourhood~~neighborhoods, ~~reaching up to~~with ~~23% in~~ Nieuwe Werk being the highest at 23% (~230 houses). The neighborhood Feijenoord shows the largest absolute number of exposed units at approximately 670 houses (20%). Projections for 2150 under the RCP8.5 scenario suggest a wide range in relative exposure, from 0% exposure in Nieuw Mathenesse to 76% in Heijplaat (~690 houses).

For 1000-year events, the variability in exposure rates between ~~neighbourhood~~neighborhoods decreases in the far future as~~,~~ ~~with~~ many ~~of them approaching~~ approach 100% exposure. While n~~N~~early all houses were at risk in 1970, this dropped~~ing~~ to between 11% and 77% by 2020 due to the Maeslant storms surge barrier. However, 2150 projections under RCP8.5 show a return to near-total relative exposure in most areas. In absolute terms, Katendrecht is projected to have the largest number of

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exposed units (~6790 houses), followed by Kop van Zuid (~5070 houses) and Nieuw Mathenesse (~4490 houses), reflecting the substantial planned development in these areas.

Interestingly, while extreme water levels have increased linearly since 1997 (Fig. 32ab), the growth in the number of exposed houses follows a less predictable, non-linear pattern.the growth in exposed houses follows a less predictable pattern. - This is a direct consequence of the unique elevation profile of each neighborhood.This is due to neighbourhood-specific elevation profiles. These characteristics – both the median elevation and the distribution of elevations – -influence both the timing (e.g., when 50% of the housing units become exposed for a specific return period) and and the rate of increase in exposure for marginal rises in water levelsthe temporal progression (e.g., the duration required for a marginal increase in exposure). For example, Nieuwe Werk, with its lower average elevation and less variability, shows a rapid increase towards 100%% exposure. In contrast, Kop van Zuid, with higher and more varied elevations, shows a more gradual increase in exposurerisk. These findings highlight that one-size-fits-all solutions, like uniform waterfront heightening, will noton't be equally effective across Rotterdam. Each neighbourhoodneighborhood requires a unique tailored approach to flood risk management, informed by its specific elevation profile, housing density of current building stock and urban development plans.based on its specific elevation profile and urban development patterns.

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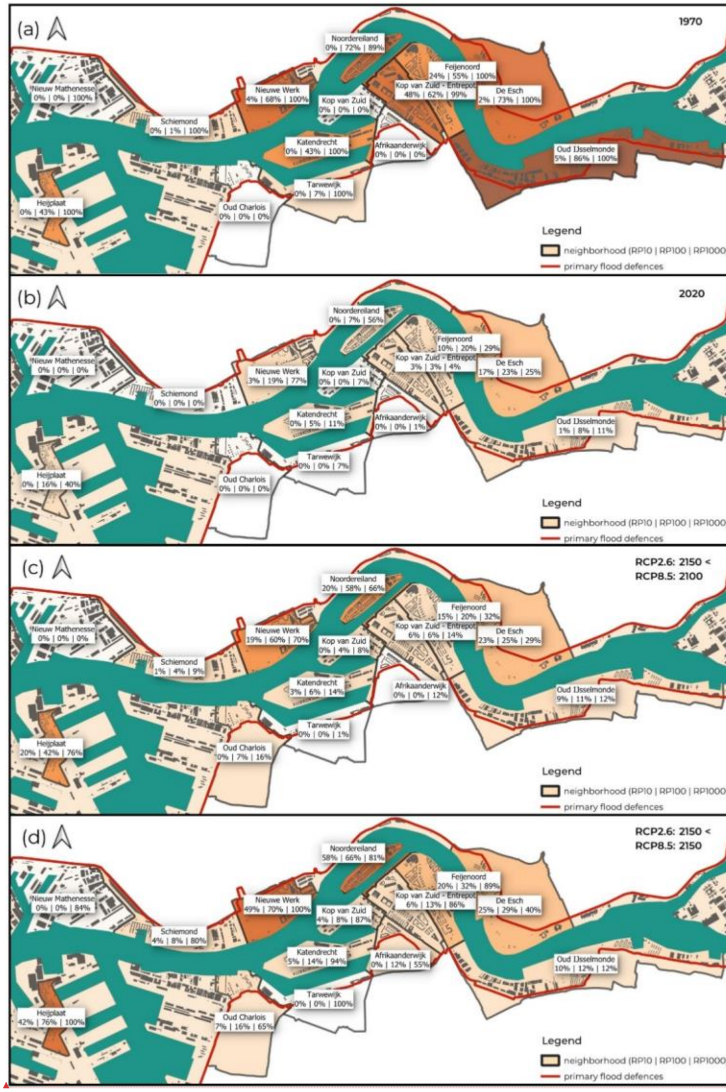

Figure 5: Neighborhood-level residential flood exposure (percentage of units exposed) for selected return periods and years. Exposure is shown for 10-, 100-, and 1000-year events in: (a) 1970, (b) 2020, (c) 2100 (RCP8.5) and (d) 2150 (RCP8.5).Figure

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4: Percentage of homes exposed in neighbourhoods for 10-, 100-, and 1000-year flood events across multiple years, a) 1970, b) 2020, c) 2150< (RCP2.6) & 2100 (RCP8.5) and d|) 2150< (RCP2.6) & 2150 (RCP8.5).

34.43 Disentangling urban development, sea level rise and adaptation

Flood exposure in Rotterdam's unembanked areas is influenced by an interplay of ongoing urban development, sea level riserising sea levels and adaptation measures. Comprehending the interaction among these factors is key in effective planning for the city's growth and designing flood risk adaptation strategies. To understand their relative contributions, we systematically assessed the individual impact of each factor on residential flood exposure (Fig. 6).We assess these factors by examining their individual impacts to inform effective city planning and flood risk management strategies.

First, tTo assess the sensitivity of future exposure to future urban development, we compared scenarios with and without continued development after 2020 (assuming new builds adhere to the NAP +3.6 m design flood elevation). The impact of adding the planned 22,600 housing units is primarily evident for low-probability high-impact events. Specifically, differences in exposure become significant only when extreme water levels surpass approximately NAP +3.85 m (the NAP +3.6 m design elevation plus the 0.25 m inundation threshold), a condition met during 1000-year flood events projected for the early 22nd century (Fig. 3a).we conducted a comparative analysis of scenarios with and without post-2020 urban development. Our findings reveal significant disparities primarily when extreme water levels surpass NAP +3.85 meters, exceeding the design flood elevation of NAP +3.6 m (which includes a 0.25 m threshold). This threshold is only exceeded during 1000-year flood events (Fig. 2c). Hence, the comparative subplots show that stoppingno urban development after 2020 could would mainly ultimately prevent the exposure to 1000-year events of all 22,600 housing units planned for constructionof these new units during such extreme future events. For lower return periods like 100-year events, the addition of new housing units (built at or above NAP +3.6 m) has a minimal impact on overall exposure numbers until very late in the projection period under the RCP8.5 scenario. the impact of urban development is minimal until after 2150 under the RCP8.5 climate scenario. Interestingly, we observed some exposure differences between 2020 and 2100 across all return periods. This is an artifact of our methodology: the ~3,600 housing units constructed between 2020 and 2023 were assigned their actual ground elevations, with about 55% of these units being below the design flood elevation level of NAP +3.6m. In the scenario where urban development stops in 2020, these units are not added, whereas in the reference scenario they are. As we assigned actual ground levels, rather than design elevation levels, to the 3,600 housing units built between 2020 and 2023, these variations are attributable to our arbitrary selection of the year 2020 after which urban development is stopped. About 55% of the housing units constructed after 2020 have ground levels below the design flood elevation of NAP +3.6 m.

Second, tThe impact of sea level rise after 2020 on flood exposure is also assessed by comparing exposure with and without post-2020 sea level rise projections after 2020 (Fig. 5). Until 2100 (RCP8.5), exposure rates increase marginally and

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consistently. After 2100 (RCP8.5), the exposure rates, particularly for 100-year events, rise more sharply. This occurs as rising water levels begin to exceed the ground elevations of a large portion of the existing building stock, many of which are clustered around similar elevations, including those built to the current design flood standard (Fig. 3b). Overall, , primarily because most housing elevations, among others due to the design flood elevation, are close to the corresponding extreme water level (Fig. 2b). tThe impact of sea level rise after 2020 is larger than the impact of planned urban development. Without post-2020 sea level rise, projected exposure rates in 2150 (RCP8.5)are expected towould be be 6 times lower for 10-year flood events, 4 times lower for 100-year flood events, and 7 times lower for 1000-year flood events.compared to the reference scenario.

The Maeslant barrier plays a crucial role in mitigating flood exposure in Rotterdam. Without this barrier, water levels in Rotterdam would directly reflect sea level changes, significantly increasing flood risk. Our analysis reveals that the Maeslant barrier has effectively reduced flood exposure, with its impact most pronounced for 1000-year events (Fig. 5). By 2150, under the high emission scenario (RCP8.5), the absence of the Maeslant barrier would result in substantially higher exposure rates. Specifically, exposure would be 7 times higher for 10-year events, 5 times higher for 100-year events, and 1.2 times higher for 1000-year events. Even under the low emission scenario (RCP2.6), the barrier's absence would lead to 3, 7, and 6 times higher exposure rates for 10-year, 100-year, and 1000-year events respectively. The Maeslant barrier's effectiveness in reducing exposure rates outweighs the combined increases caused by urban development and sea level rise.
While the Maeslant barrier significantly postpones the onset of increased flood exposure due to climate change, it does not offer permanent protection. This limitation is evident in the projected increase in exposure for 1000-year events, demonstrating that the barrier cannot indefinitely counteract the long-term flood risk escalation driven by sea level rise.

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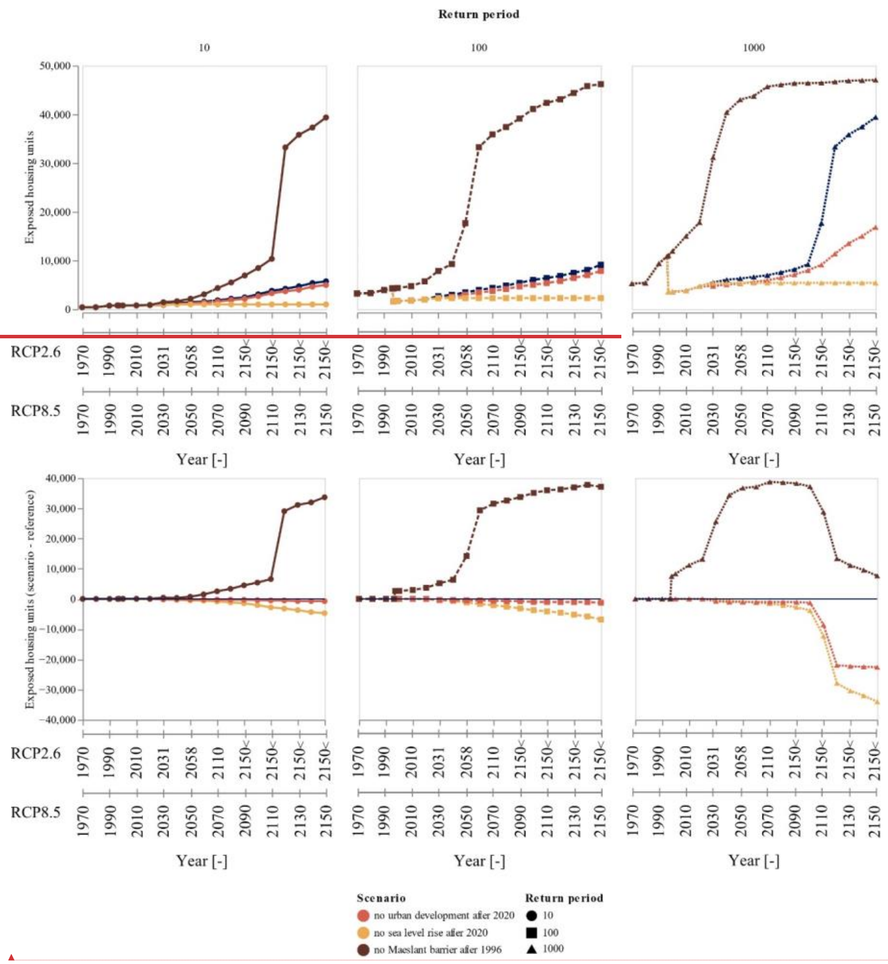

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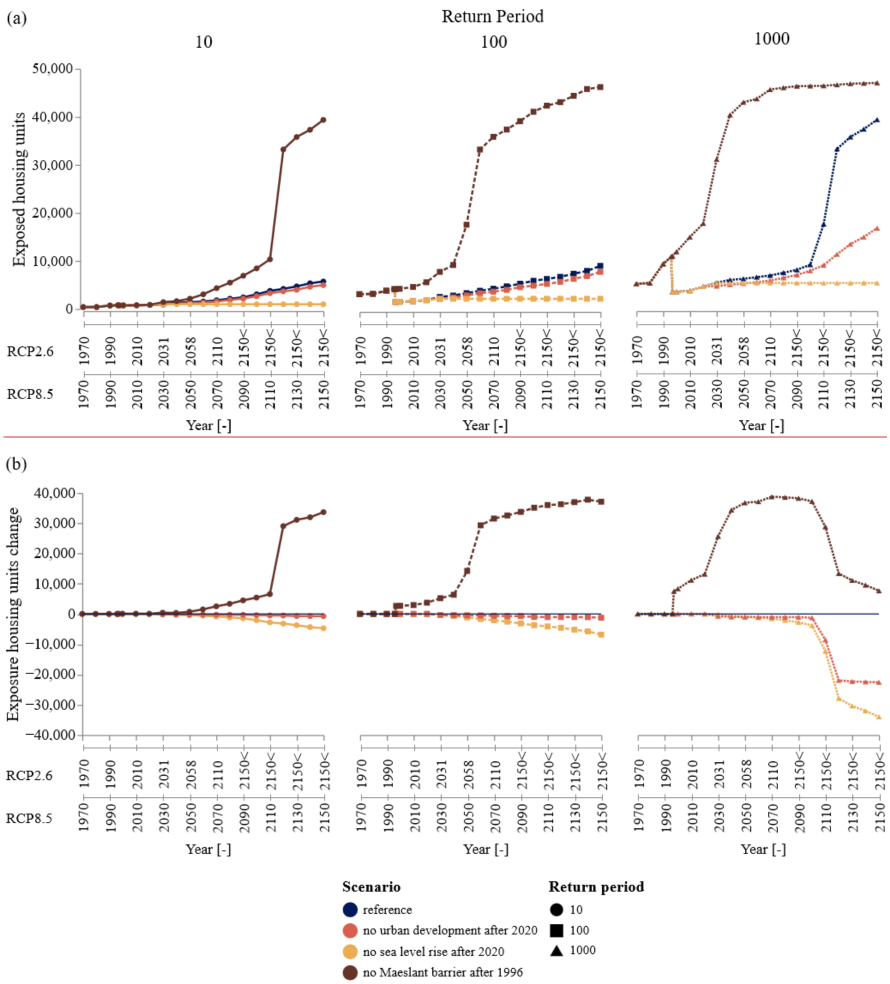

Figure 6: Impact of urban development, sea level rise, and the Maeslant barrier on residential flood exposure. (a) Absolute number of exposed housing units (1970-2150) for the reference scenario and scenarios isolating the effects of no further urban development (post-2020), no further sea level rise (post-2020), and no Maeslant barrier. (b) Difference in exposed units for each attribution scenario compared to the reference. The dual x-axis maps results to RCP2.6 and RCP8.5 emission scenarios.

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Third, the Maeslant storm surge barrier plays a crucial role in mitigating flood exposure in Rotterdam. Without this barrier, water levels in Rotterdam would directly reflect sea level changes, leading to significantly higher flood exposure. Our analysis reveals that the Maeslant barrier has effectively reduced flood exposure, with its impact most pronounced for 1000-year events (Fig. 6). By 2150, under the RCP8.5 scenario, the absence of the Maeslant barrier would result in substantially higher exposure rates: 7 times higher for 10-year events, 5 times higher for 100-year events and 1.2 times higher for 1000-year events. Even under the low RCP2.6 scenario, the barrier's absence would lead to 3, 7, and 6 times higher exposure rates for 10-year, 100-year, and 1000-year events respectively by 2150. The Maeslant barrier's effectiveness in reducing exposure rates outweighs the combined increases caused by urban development and sea level rise. However, while the Maeslant barrier significantly postpones the onset of increased flood exposure due to climate change, it does not offer indefinite protection. This limitation is evident in the projected increase in exposure for 1000-year events, demonstrating that the barrier, in its current configuration, cannot entirely counteract the long-term flood exposure increase driven by sea level rise.**Figure 5: Influence of urban development, sea level rise and construction of the Maeslant barrier on the number of exposed houses. The top three figures show the absolute number of exposed houses, the lower three figures are relative to the reference.** The reference scenario incorporates the combined effects of sea level rise, urban development, and the Maeslant barrier construction.

34.54 Impact design flood elevation on flood exposure

Elevating new housing units is a primary local adaptation strategy to reduce their direct exposure to future flood hazards. Elevating new housing can be an effective strategy to reduce their vulnerability to future flood hazards. This section analyzes the impact of different design flood elevation policies on overall exposure rates specifically for new residential constructions post-2020 (Fig. 7). This section analyzes the impact of this adaptation measure on exposure rates by comparing two other strategies: oWe compare the reference scenario, where new units are built to the current design flood elevation of NAP +3.6 m, with two alternative approaches: first, a scenario without a design flood elevation, where new units are assigned elevations based on the existing varied ground-level distribution within their respective neighborhoods, and second, a scenario with an increased design flood elevation requirement of NAP +3.8 m for all new units.ne without a design flood elevation requirement and another with an elevated design flood elevation of NAP +3.8 m. These two strategies are contrasted with the previous analyses in this study, which considered existing building stock at current ground level elevations and new housing units (built after 2020) meeting a design flood elevation of NAP +3.6 m.

The absence of a design flood elevation requirement generally leads to higher exposure rates for these new housing units across most return periods and reference years compared to scenarios with a design flood elevationthe reference scenario (Fig. 76).. Projections for the year 2150 under the RCP8.5 scenario illustrate this trend. If new buildings were built wWithout a design flood elevation, the exposure rates for 10-year events are expected to increase bywould be 54% higher, and for while 100-year events, 71% higher, than if they were all built to the NAP +3.6 m standard. could see a 71% increase. Interestingly, 1000-year

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events present a contrasting picture, with an anticipated 24% reduction in exposure rates. This counterintuitive result occurs because, by sampling from existing neighborhood elevation distributions (Fig. 3b), some newly built houses are assigned ground elevations that exceed the uniform NAP +3.6 m standard, especially in currently higher-lying areas, thus providing protection against the most extreme water levels. The decrease in exposure for 1000-year events in 2110, when comparing the no-design elevation scenario to the reference, is due to the elevation distribution in the no-design flood elevation scenario. In this case, some newly built houses are assigned elevations exceeding the NAP +3.6 m design flood elevation, as the current elevation distribution includes areas with higher ground levels (Fig. 2d).

Raising the design flood elevation to NAP +3.8 m yields modest reductions in exposure rates compared to the current NAP +3.6 m standard. For 10-year and 100-year events, this elevation increase doesn't significantly impact exposure rates, as water levels typically remain below both elevation thresholds. The benefits become apparent for 1000-year events, where the higher design flood elevation results in reduced exposure rates after 2100 under the RCP8.5 scenario. The 0.2-meter elevation increase effectively postpones the rise in exposure rates by approximately 30 years, providing additional time for neighbourhoods to implement further adaptation measures. While the impact on exposure rates may seem modest, the elevated design flood elevation of NAP +3.8 m offers other benefits. It decreases inundation depths during flood events, which directly translates to reduced property damage and lower recovery costs.

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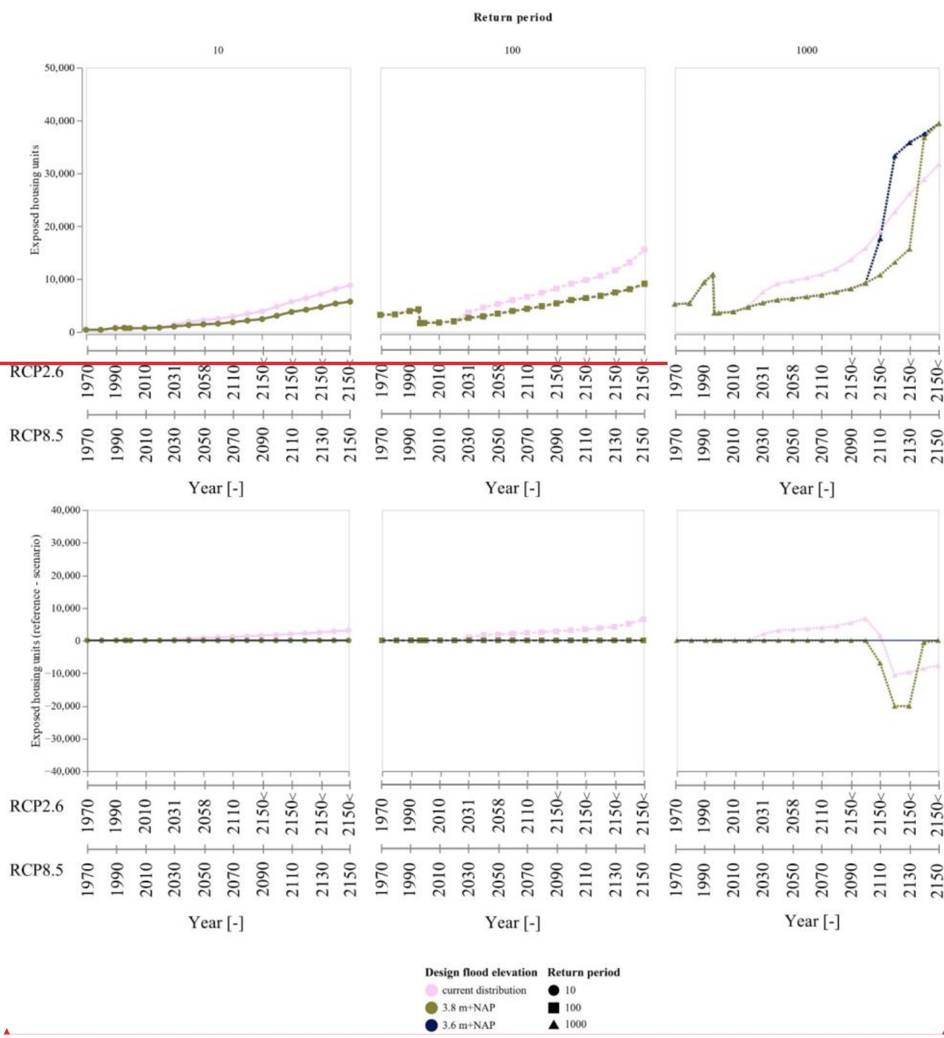

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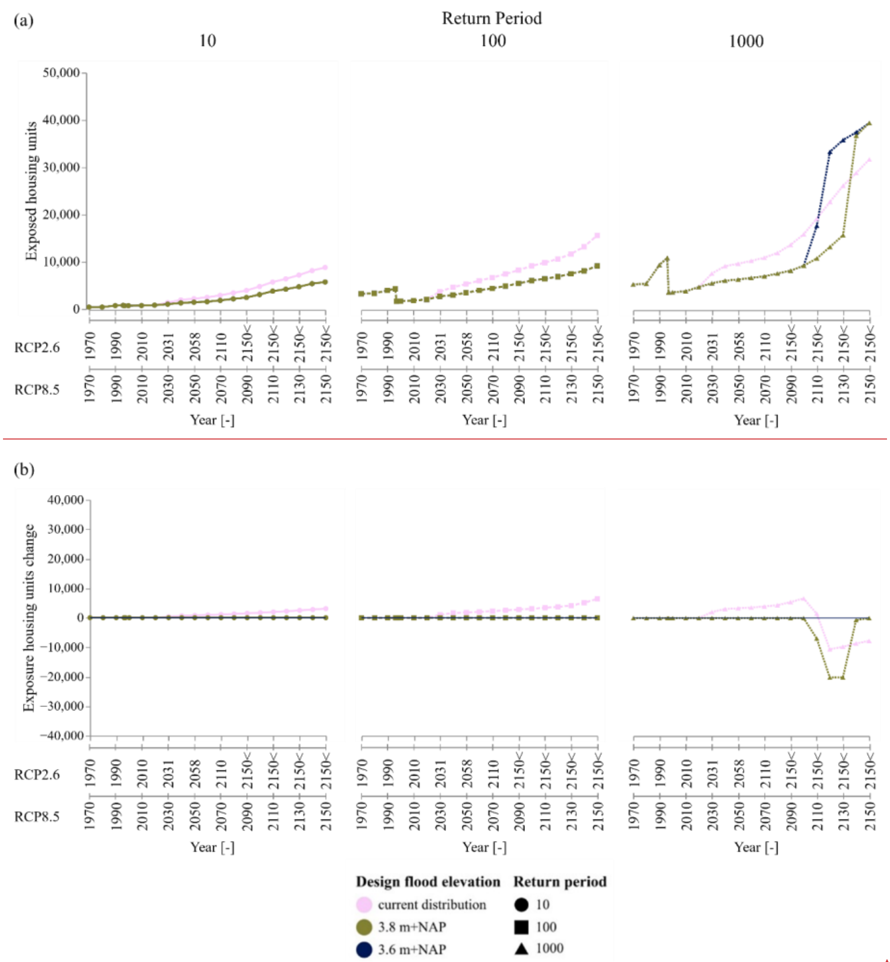

Figure ~~7~~6: Influence of design flood elevation on the number of exposed houses. The top three figures show the absolute number of exposed houses when the current elevation distribution per ~~neighbourhood~~neighborhoods is applied for new housing units, design flood elevation NAP +3.8 m gives the situation when building lots are raised to NAP +3.8 m. The lower three figures are relative to the reference.

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Raising the design flood elevation to NAP +3.8 m yields modest reductions in exposure rates compared to the current NAP +3.6 m standard. For 10-year and 100-year events, this 0.2 m elevation increase has a limited impact on exposure rates, as water levels typically remain below both elevation thresholds. The benefits become apparent for 1000-year events, where the higher design flood elevation results in reduced exposure rates, particularly after 2100 under the RCP8.5 scenario. At these extreme water levels, the higher design elevation effectively postpones the onset of exposure for these new units by approximately 30 years compared to the NAP +3.6 m standard, thereby providing a longer window for implementing further adaptation measures. While the impact on exposure rates may seem modest, the elevated design flood elevation of NAP +3.8 m offers other benefits. It decreases inundation depths during flood events, which directly translate to lower property damage and recovery costs, although these are not quantified in this study.

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45 Discussion

~~**This study developed a framework to evaluate the combined impacts of urban development, sea level rise and adaptation on flood exposure, applying it to Rotterdam's unembanked areas.**~~ **4.1 Interpretation and implications of key-findings**

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The projected increase in flood exposure when no additional adaptation measures are taken, particularly under the RCP8.5 scenario, underscores the challenge for Rotterdam's unembanked areas. This trend is consistent with former regional assessments in this area (de Moel et al., 2014; Veerbeek et al., 2010), but our detailed, long-term analysis provides a more granular understanding of how different return period events will impact specific residential neighborhoods over time. This insight is crucial for developing targeted adaptation strategies for unembanked areas.

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The Maeslant barrier's past and current role in mitigating flood exposure is undeniable. Its construction led to an immediate reduction in the number of exposed housing units, particularly for 100- and 1000-year events. By 2150, under RCP8.5, the 1000-year flood levels approach pre-barrier conditions, indicating that reliance on the barrier in its current operational mode – or a similar storm surge barrier – is not a permanent solution. This poses a long-term strategic challenge for Rotterdam. Future decisions regarding raising its closure threshold to maintain port accessibility and reduce closure frequency (Mooyaart et al., 2022) would directly trade off against increased exposure in unembanked areas, particularly for more frequent events – a dilemma this framework can help quantify by assessing the impact of such closure threshold changes.

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The spatial heterogeneity in exposure across Rotterdam's 14 unembanked neighborhoods, driven by varied ground elevation profiles and urban development patterns, means a 'one-size-fits-all' adaptation approach will be suboptimal. Neighborhoods such as Nieuwe Werk and Heijplaat, with lower median elevations, are projected to face disproportionately high exposure rates. This advocates for adaptation planning that considers both the physical characteristics (elevation, building density) and potentially the socio-economic profiles of neighborhoods to ensure equitable and effective flood protection. This aligns with broader calls for integrating social vulnerability into flood risk management (Koks et al., 2014).

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The current design flood elevation policy – NAP +3.6 m for new building lots – proves effective in reducing the future exposure of new developments compared to a scenario with no specific elevation requirements, especially for 10- and 100-year flood events. Raising this design flood elevation further (e.g., to NAP +3.8 m) offers incremental benefits, primarily by delaying the onset of exposure for these new units during very extreme events projected later in the century. However, the overall impact of these policies on reducing total city-wide exposure is tempered by the vast existing building stock situated at lower elevations. This suggests that while important for future flood exposure, solely relying on increasing elevation standards for new builds may not be sufficient to manage long-term exposure for all unembanked areas, pointing to the need for a diversified adaptation portfolio. This underscores Rotterdam's exploration of a more integrated suite of adaptation measures, including both fixed and movable local flood defenses, nature-based solutions and building-specific flood-proofing (Ward et al.,

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2013).The framework developed in this study is relevant for delta cities worldwide, while maintaining adaptability to local contexts. The core methodological components can be transferred in three ways. First, hazard and exposure data can be adapted using locally available models and exposure datasets. While our study used Dutch datasets (BAG & AHN), the framework can accommodate other data sources like building footprints, elevation data and local urban development plans. Second, the temporal analysis for attributing flood exposure changes to specific factors (e.g. urban development) offers a universal approach for understanding risk drivers in coastal cities. This attribution analysis is particularly relevant for (port) cities experiencing similar transitions in their unembanked areas. Third, the neighborhood-level analysis for researching spatial variations in exposure can be replicated in other urban contexts, informing targeted flood adaptation strategies.

4.2 Comparison with existing literature

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While comparisons with larger-scale European flood risk studies (e.g., Steinhausen et al., 2022; Paprotny et al., 2024) are limited by differences in spatial resolution (e.g. local building-level vs. NUTS3), our findings provide a local lens on broader trends in flood risk. These studies often indicate exposure growth as a dominant driver of risk change; our local analysis for Rotterdam refines this by showing that while new urban development (post-2020) contributes to future exposure, it is the existing building stock combined with accelerating sea level rise that presents the more immediate and widespread challenge for the coming decades, particularly regarding 10- and 100-year flood events.

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Previous studies focused specifically on Rotterdam's unembanked areas primarily estimated future expected annual damages, making direct quantitative comparisons with our exposure rates challenging (de Moel et al., 2014; Veerbeek et al., 2010). However, the general trend of increasing future flood impact aligns. De Moel et al. (2014) projected a doubling of expected annual damage by 2100 from a 2014 baseline of 40 million euros. In contrast, Veerbeek et al. (2010) reported a significantly lower initial expected annual damage of 0.16 million euros but predicted a more rapid increase, with expected annual damage doubling by 2050 and quadrupling by 2100. This large difference in baseline expected annual damage values between the two studies needs further investigation and may be attributed to varying methodologies, data sources or scope of analysis. Our exposure projections for 2050, based on the KNMI'23 high emission scenario, align with the flood exposure results of Veerbeek et al. (2010), differing by less than 5%. Our 2100 projections are approximately 20% lower than those of Veerbeek et al. (2010), primarily due to the different sea level rise scenarios used. Our study uses the KNMI'23 high emission scenario with an expected sea level rise of 0.87 m, while Veerbeek et al. (2010) adopted the Veerman scenario with 1.3 m sea level rise. Our study complements these expected annual damage focused studies by providing a historical perspective (1970-2020), an explicit attribution of exposure changes to key drivers, and a granular analysis of residential exposure which can inform the extent of potential impact prior to flood damage assessment. Our findings on increasing flood exposure align with previous studies focused on the unembanked areas of the Rhine-Meuse estuary, though with some notable differences. De Moel et al. (2014) projected a doubling of expected annual damage by 2100 from a 2014 baseline of 40 million euros. In contrast,

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~~Veerbeek et al. (2010) reported a significantly lower initial expected annual damage of 0.16 million euros but predicted a more rapid increase, with expected annual damage doubling by 2050 and quadrupling by 2100. This large difference in baseline expected annual damage values between the two studies needs further investigation and may be attributed to varying methodologies, data sources, or scope of analysis. Our exposure projections for 2050, based on the KNMI'23 high emission scenario, align with the findings of Veerbeek et al. (2010), differing by less than 5%. Our 2100 projections are approximately 20% lower than those of Veerbeek et al. (2010), primarily due to the different sea level rise scenarios used. Our study uses the KNMI'23 high emission scenario with an expected sea level rise of 0.87 m, while Veerbeek et al. (2010) employed the Veerman scenario with 1.3 m sea level rise.~~

4.3 Limitations and uncertainties

Our approach combines various models and data sources, introducing inherent uncertainties that must be considered when interpreting results. A primary constraint arises from the temporal disparity in data projections: future urban development data extends only to 2040, while climate scenarios project to 2150. This restricts our ability to fully assess long-term exposure in unembanked areas and attribute changes specifically to urban development beyond 2040, as our post-2040 exposure figures predominantly reflect sea level rise impacts on the 2040 building stock.~~This restricts our ability to assess long-term exposure in unembanked areas and attribute changes to urban development beyond 2040.~~

Another limitation concerns the elevation data used for both existing and ~~for~~ future urban development. For existing buildings, ground-level elevations from the AHN3 dataset were used, which may not precisely reflect the floor level of individual housing units, especially within multi-story apartment complexes. For future urban development, o~~O~~ur study assumes that the elevation of newly built housing units complies with the specified design flood elevation in each scenario. We uniformly assign this ground level elevation to new housing units, including those ~~apartments~~ in high-rise structures. Consequently, our exposure assessment does not necessarily reflect direct exposure of individual housing units but rather indicates instances where the lower floor is exposed.

The third limitation of our study lies in its omission of explicit considerations for local flood-proofing measures, such as seawalls. To illustrate, ~~most~~ quay walls in Feijenoord have elevations exceeding NAP +3.15 m, higher than some housing units' elevations, with the lowest at approximately NAP +2.5 m. As a result, our model may overestimate exposure in areas where such protective structures exist, as extreme water levels exceeding housing unit elevations in Feijenoord may not lead to actual exposure in reality. Other areas that have a similar bath-tub shape are Heijplaat, de Esch, parts of Katendrecht and the south part of the Waalhaven. To partially address ~~minor~~ flood ~~protection~~ proofing measures, our approach uses a uniform 0.25 m threshold, representing elevated entrances and door guards. This simplification could be refined in future studies by incorporating ~~neighbourhood~~neighborhood or building-specific thresholds that more accurately reflect real-world conditions.

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While using 2D inundation modeling would offer a more explicit representation of hydrological connectivity within neighborhoods, this approach involves a trade-off. The considerable increase in model complexity and computational effort, alongside the inherent uncertainties in reconstructing historical and projecting future Digital Terrain Models (DTMs) and fine-scale infrastructure, made such detailed modeling impractical for the broad temporal scope of this research.

Our study'sThe probabilistic calculations for flood hazard are based on the 2017 hydraulic computations WBI database, which is the standard for hydraulic and dike assessments in the Netherlands' water system. A fourth limitation of our approachlimitation here is that sea level rise is only factored into the probabilistic calculations performed by Hyra-NL, but not into the underlying 2D WAQUA computations.hydraulic computations. This means that the mean tide level remains static in the hydrodynamic simulations, which leads to an underestimation of extreme water levels, particularly for lower return period events in far-future, for high sea level rise scenarios. This approach has several implications. For instance, the Mean Tide Level (MTL) remains unchanged in our hydrodynamic computations, potentially leading to underestimated extreme water levels, particularly for lower return periods. Furthermore, our modelthis approach does not account for the hydrodynamic effects of past and future for significant infrastructural changes within the estuary, such as the construction of the 2nd Maasvlakte (reclaimed land), alterations to the dimensions of the Nieuwe Waterweg canal over time, or potential future adjustments to the Maeslant barrier's operational strategy. The last few decades have demonstrated the profound impact such interventions have on estuarine hydrodynamics. Ideally, new databases with hydrodynamic computations including sea level rise would be derived. This need becomes particularly apparent for scenarios where sea level rise exceeds 1 meter, as the combined effects of rising seas, altered coastal and altered coastal infrastructure and ongoing morphological changes could significantly reshape flood risk exposure patterns in ways our current framework cannot does not fully capture.

Our findings on increasing flood exposure align with previous studies focused on the unembanked areas of the Rhine-Meuse estuary, though with some notable differences. De Moel et al. (2014) projected a doubling of expected annual damage by 2100 from a 2014 baseline of 40 million euros. In contrast, Veerbeek et al. (2010) reported a significantly lower initial expected annual damage of 0.16 million euros but predicted a more rapid increase, with expected annual damage doubling by 2050 and quadrupling by 2100. This large difference in baseline expected annual damage values between the two studies needs further investigation and may be attributed to varying methodologies, data sources, or scope of analysis. Our exposure projections for 2050, based on the KNMI'23 high emission scenario, align with the findings of Veerbeek et al. (2010), differing by less than 5%. Our 2100 projections are approximately 20% lower than those of Veerbeek et al. (2010), primarily due to the different sea level rise scenarios used. Our study uses the KNMI'23 high emission scenario with an expected sea level rise of 0.87 m, while Veerbeek et al. (2010) employed the Veerman scenario with 1.3 m sea level rise.

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4.4 Recommendations and outlook

As direction for further research we propose to expand the ~~model~~ framework by integrating~~with~~ both physical and (social) vulnerability assessments in our flood risk analysis. Incorporating~~tegrating~~ these factors would allow for a more comprehensive evaluation of flood risk, beyond exposure alone and inform the design of more effective and equitable long-term adaptation strategies. This is particularly relevant~~crucial~~ for Rotterdam's unembanked areas, where about 20% of the population is classified as highly socially vulnerable, compared to only 6% in embanked areas (Koks et al., 2014). It is important to note that urban development in these unembanked areas is not solely a risk factor, but also presents significant opportunities for urban improvement and development. For example, the Kop van Feijenoord project aims to create thousands of new homes while simultaneously improving flood ~~defences~~defenses and public spaces. Such developments can serve as a catalyst for strengthening ~~neighbourhood~~neighborhoods and ~~enhancing~~ improving connectivity between Rotterdam's northern and southern districts.

Also, integrating damage model~~l~~ing is proposed ~~to be included~~ to ~~make~~ estimate~~s~~ ~~for the~~ expected annual damage in the present and future. Given the heterogeneity in housing units, ranging from low-lying historic ~~buildings~~ structures to modern high-rise buildings, advanced damage curves, such as those developed for Venice with the framework of ~~integrating sophisticated damage modelling could provide more accurate risk assessments. Using advanced damage curves, such as the framework of~~ Schlumberger et al. (2023) could provide more accurate risk assessments. ~~for Venice, are particularly valuable when assessing older buildings.~~ When considering planning horizons exceeding 50 years, projecting changes in asset value is key. ~~To model future flood risk, especially when considering planning horizons over 50 years, asset value is key for projections. In 2050,~~ F~~f~~lood risk in Europe is expected to double by 2050 ~~in Europe~~ solely ~~based on the increase in value of exposed buildings~~ due to the increasing value of exposed assets (Steinhausen et al., 2022). At the same time, increasing exposure ~~rates~~ or flood event frequency~~s~~ can heighten~~make~~ flood risk ~~more salient~~salience, ~~which could~~potentially leading to a revaluation of properties located in unembanked areas (Caloia et al., 2023; Jansen, 2023).

The unembanked areas of Rotterdam are at the forefront of the global flood adaptation challenge faced by many delta cities. With a significant and growing residential population – probably exceeding 100,000 residents in the wider unembanked region post-2040 – coupled with their importance for industry, port operations, and valuable ecosystems, the stakes for successful adaptation are high. ~~The dilemma of whether to permanently close the Rhine-Meuse estuary or keep an open connection during daily conditions for gravitational river discharge underscores the complexity of the challenges ahead.~~ For the national long-term strategy, the first dilemma that may emerge is whether to permanently close the estuaries or to keep them open to facilitate river discharge by gravity. Hence, there is no doubt that Rotterdam's unembanked areas are pivotal in formulating the long-term adaptation strategy of the Netherlands, and vice versa.

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56 Conclusion

This study developed and applied a framework to evaluate the combined and individual impacts of urban development, sea level rise and specific adaptation measures on residential flood exposure in Rotterdam's unembanked areas from 1970 to 2150. By integrating detailed local urban development data with probabilistic flood hazard modeling under various climate scenarios, the research provides insights for long-term urban planning and flood risk management.

~~This study has developed and applied a comprehensive flood exposure assessment framework to Rotterdam's unembanked areas, providing insights into the interplay of urban development, sea level rise, and adaptation strategies. The framework is applied to Rotterdam's unembanked areas, which have a building stock of 25 500 housing units and urban development plans for an additional 22 600 in the next two decades.~~

Our studies reveals several findings:

1. Without additional adaptation, the unembanked areas in Rotterdam are expected to experience increases in flood exposure, especially in the 22nd century under the high emission scenario of the KNMI'23 (RCP8.5). Under this scenario, we project a 7-fold increase in exposure for 10-year events, a 6-fold increase for 100-year events by 2150 and an 8-fold increase for 1000-year events, compared to 2020 levels. The RCP2.6 scenario projects less severe increases: a 3-fold increase for 10-year and 100-year events, and a 2-fold increase for 1000-year events by 2150.
2. The Maeslant storm surge barrier has been effective in mitigating flood risk. Its implementation has approximately halved exposure rates for 100-year and 1000-year events compared to 1996 levels. Without this storm surge barrier, exposure rates would increase drastically, mirroring increases in local water levels due to sea level rise.
3. Spatially, flood exposure varies considerably across Rotterdam's unembanked neighborhoods. The three areas with the highest relative exposure – Nieuwe Werk, Heijplaat and Noordereiland – face future exposure rates exceeding 65% for 100-year events by 2150 under RCP8.5, while the aggregated exposure percentage for all unembanked areas is 19%.Attribution analysis shows the Maeslant barrier's implementation had the largest historical impact on decreasing exposure. For the future, sea level rise is the primary driver of increasing exposure, while planned urban development under current design flood elevation policies contributes less to the overall increase.
4. Implementing a design flood elevation policy of NAP+ 3.6 m for new construction significantly reduces their future exposure compared to no policy. Increasing this standard to NAP+ 3.8 m offers incremental benefits, mainly by delaying exposure to very extreme, late-century events.

These findings underscore the dynamic nature of flood exposure in urbanized deltas. Effective future management requires integrated strategies that consider the evolving hazard, the vulnerability of existing building stock, planned urban growth, and a combination of system-scale and localized, neighborhood-specific adaptation measures.

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Without additional adaptation, the unembanked areas in Rotterdam are expected to experience increases in flood exposure, especially in the 22nd century under the high emission scenario of the KNMI'23 (RCP8.5). Under the RCP8.5 scenario, we project a 7-fold increase in exposure for 10-year events, a 5-fold increase for 100-year events by 2150 and an 8-fold increase for 1000-year events, compared to 2020 levels. The RCP2.6 scenario projects less severe increases: a 3-fold increase for 10-year and 100-year events, and a 2-fold increase for 1000-year events by 2150. The study highlights the critical role of the Maeslant storm surge barrier in mitigating flood risk. Its implementation has approximately halved exposure rates for 100-year and 1000-year events compared to 1996 levels. Our analysis shows that without this barrier, exposure rates would increase dramatically, mirroring increases in local water levels due to sea level rise.

Spatial variability in exposure rates across the 14 unembanked neighborhoods emphasizes the importance of localized data for urban planning and neighbourhood-level adaptation strategies. This variability is particularly pronounced for 10- and 100-year events. By 2150, under the high-emission RCP8.5 scenario, variation in exposure is large: neighbourhoods such as Nieuwe Werk, Heijplaat, and Noordereiland are projected to face exposure rates exceeding 65% for 100-year flood events. This is more than three times the aggregated exposure percentage of 19% for all unembanked areas, underscoring the potential for certain areas to become hotspots of flood risk.

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Findings show that the implementation of the Maeslant barrier is dominant in exposure rates, followed by sea level rise and urban development.

No urban development after 2020 will not have a significant effect on exposure rates before 2100 (RCP8.5) and 2150 (RCP2.6). After 2100 (RCP8.5), we can expect increases in exposure rates for 1000-year events as the extreme water levels coincide with the design flood elevation for new housing units. This indicates that the current building stock, rather than future urban development, predominantly dictates short to mid-term adaptation strategies for Rotterdam's unembanked areas.

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The hypothetical case of the absence of sea level rise after 2020 would lead to a reduction in exposure rates by 2150 (RCP8.5). Exposure rates are expected to be 6 times lower for 10-year flood events, 4 times lower for 100-year flood events, and 7 times lower for 1000-year flood events. Especially the impact of sea level rise on lower return periods highlights the vulnerability of the estuarine unembanked areas.

Without the construction of the Maeslant barrier, extreme water levels would mirror sea levels resulting in significant increases of exposure. By 2150, under the high emission scenario (RCP8.5), the absence of the Maeslant barrier would result in substantially higher exposure rates. Specifically, exposure would be 7 times higher for 10-year events, 5 times higher for 100-year events, and 1.2 times higher for 1000-year events. Even under the low emission scenario (RCP2.6), the barrier's absence would lead to 3, 7, and 6 times higher exposure rates for 10-year, 100-year, and 1000-year events respectively. The Maeslant

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barrier's closure frequency directly impacts flood exposure rates in Rotterdam. With rising sea levels, the barrier is projected to close more often, potentially increasing from once every 10 years to several times annually by 2100. This impacts flood exposure rates and port accessibility. To limit the number of closures, authorities are considering raising the closure water level, which would decrease the barrier's effectiveness and increase exposure rates in unembanked areas, particularly for 10-year and 100-year flood events. This study's framework can assess the impact of such threshold changes on flood exposure in unembanked areas.

Moreover, the study evaluated the efficacy of elevating housing units as a flood mitigation strategy. Under the high-emission scenario (RCP8.5) by 2150, implementing the current design flood elevation (NAP +3.6 m) reduces exposure by 54% for 10-year flood events and 71% for 100-year flood events, compared to the no design elevation strategy. Increasing the elevation to a design flood elevation of NAP+ 3.8 m has no impact on 10-year events and 100-year events within the studied timeframe but offers a temporary reduction in exposure for 1000-year events between 2100 (RCP8.5) and 2130 (RCP8.5). Raising the Maeslant barrier's closure threshold increases flood risk for 10-year and 100-year events, but this can be offset by elevating new building lots. This interplay highlights the need for combining local neighbourhood-specific strategies with regional flood management: the effectiveness of local design elevation policies depends on the barrier's closure threshold, while the impact of adjusting the threshold varies based on neighbourhood elevation levels. While the specific exposure rates and effectiveness of adaptation measures are unique to Rotterdam, the importance of understanding neighborhood-level variations and the interplay between system-scale adaptation measures and local elevation policies are relevant for coastal cities worldwide. In port cities like Houston, Hamburg and Copenhagen, port relocation is creating new urban development opportunities in unembanked areas. These cities face similar challenges in coordinating system-scale infrastructure (like storm surge barriers) with local measures (such as elevated building lots) to manage long-term flood risk under climate change uncertainty.
Looking ahead, the unembanked areas around Rotterdam will become increasingly important. After 2040, unembanked areas of the larger Rotterdam area are expected to have over 100,000 residents, coupled with their significance for industry, port operations, and valuable ecosystems, the stakes are high. The dilemma of whether to permanently close the Rhine-Meuse estuary or keep an open connection during daily conditions for gravitational river discharge underscores the complexity of the challenges ahead. For the national long-term strategy, the first dilemma that may emerge is whether to permanently close the estuaries or to keep them open to facilitate river discharge by gravity. Hence, there is no doubt that Rotterdam's unembanked areas are pivotal in formulating the long-term adaptation strategy of the Netherlands, and vice versa.

Code and data availability. The python notebook used for the analysis and visualizations can be retrieved from https://data.4tu.nl/datasets/d1291401-708a-4d48-9d95-8259cfd987d2 (Oerlemans, 2024). Flood hazard data, such as extreme water levels for return periods and locations used in this study is included as well. Urban development plans on a project level are not included but can be obtained upon request from the municipality of Rotterdam.

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Author contributions. Conceptualization: CO, MB, TR and MK; data curation: CO; formal analysis: CO and MB; methodology: CO; flood hazard model~~l~~ing: CO; exposure mode~~l~~ling: CO; writing – original draft: CO; writing – review and editing: MB, TR and MK; supervision: MB and MK; funding acquisition: MB and MK. All authors have read and agreed to the published version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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