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A micro-scale cost-benefit analysis of building-level flood risk adaptation measures in Los Angeles

Lars T. de Ruig[a,*], Toon Haer[a], Hans de Moel[a], W.J.Wouter Botzen[a,b,c], Jeroen C.J.H. Aerts[a]

[a] Institute for Environmental Studies (IVM), VU University Amsterdam, De Boelelaan 1085, 1081 HV, Amsterdam, the Netherlands
[b] Center for Risk Management and Decision Processes, The Wharton School, University of Pennsylvania, Philadelphia, USA
[c] Utrecht University School of Economics, Utrecht University, Utrecht, Kriekenpitplein 21-22, 3584 EC, Utrecht, the Netherlands

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ABSTRACT

Cost-benefit analysis (CBA) of flood risk adaptation strategies offers policymakers insight into economically optimal strategies for adapting to sea level rise. However, building-level adaptation measures such as floodproofing or building elevation are often evaluated at aggregated spatial scales, which may result in sub-optimal investment decisions. In this paper, we develop a flood risk model and combine it with a micro-scale CBA at the building level to obtain an optimal mix of adaptation measures per area. We apply this approach to Venice Beach in Los Angeles and Naples in Long Beach. We subsequently compare our results with the conventional, spatially aggregated area-based CBA approach. Our findings show that a mix of 35%–45% dry-flood-proofing measures and 55%–65% building elevation measures is optimal. Elevation works best in areas with high inundation depths, while dry-floodproofing is preferable in areas with shallow inundation depths. The optimal mix of measures derived from our micro-scale approach results in an economic efficiency up to 85% higher than that yielded by the commonly applied spatially aggregated approach. We therefore recommend that economic evaluations of building-level adaptation measures are conducted at the smallest possible scale, or that CBAs are performed on disaggregated areas based on inundation depth.

1. Introduction

Floods are devastating natural disasters, costing thousands of lives in 2017 alone [1,2]. Population and economic growth have been major drivers of flood risk over time, and they are expected to raise future exposure to flooding [3]. In addition, climate change and sea level rise may further increase the frequency and severity of flood hazards [4] and, therefore, further increase future flood risk. Low-lying cities in particular are concentrated areas of economic activity, population, and wealth, which makes them vulnerable to the effects of climate change. Hallegatte [5] and others (e.g., Refs. [6,7]) show the necessity of city- and local-scale flood risk assessments and the development of adaptation policies to cope with local specificities.

A number of strategies are available to limit flood risk, including structural adaptation measures, nature-based solutions or building-level adaptation measures [8–11]. Structural adaptation measures and nature-based solutions are difficult to implement in certain cases because they often require large upfront investments and their long-term benefits are uncertain, meaning that decision makers face the risk of making irreversible, inefficient economic choices [12]. Furthermore, especially in urban areas or cities, space

* Corresponding author.
E-mail address: Lars.de.Ruig@vu.nl (L.T. de Ruig).

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is limited and the need to account for diverse stakeholders' interests can make adaptation planning highly complex [9,12,13]. Alternatively, building-level adaptation measures usually require less space and the involvement of fewer actors. These measures may be divided into three main types: (1) elevation of the building to prevent flooding, (2) dry-floodproofing to prevent flood water from entering the building, and (3) wet-floodproofing to allow water to enter the building but minimizing damage (e.g., using concrete floors instead of carpets). Besides often being relatively cheap, building-level adaptation measures can be enforced by municipalities or flood insurance, by specifying a minimum requirement for floodproofing structures in flood zones [14]. In addition, building-level adaptation can be incentivized through a premium discount for flood insurance [15,16]. Hence, building-level adaptation is not necessarily an individualistic choice, but is often designed, implemented and enforced on a community level. Nevertheless, home-owners can go beyond these minimum requirements; for example, by floodproofing their building up to a higher than required height.

Most studies that evaluate the costs and benefits of flood risk adaptation measures for individual buildings (e.g., Refs. [17–19]) assess the aggregated economic efficiency of applying a single adaptation measure to all buildings in a large area with a particular flood inundation depth; for example, 1 m (~3.3 ft) elevation is applied to all buildings in a 100-year flood zone. However, such an approach can result in economic inefficiencies: if, say, a building in a 100-year flood zone is expected to flood up to 10 cm (~0.3 ft), it is unlikely that the benefits of adaptation will outweigh related investment costs for that particular building. Conversely, the same 100-year flood zone could include buildings for which the chosen adaptation measure does not offer sufficient protection. In particular, higher elevation could be more economically efficient for certain buildings because of higher expected inundation depths during a flood. Such differences cannot be identified through commonly applied cost-benefit analyses (CBA) conducted on aggregated spatial scales, which can result in sub-optimal investment decisions on an individual-building scale. Aggregated scale CBA approaches could discourage policymakers from implementing and enforcing individually focused adaptation measures by suggesting that these measures are inefficient at the aggregate level, even if they are efficient for particular buildings.

In this paper, we aim to assess the effects of spatial scales when assessing the economic efficiency of building-level adaptation. We first assess optimal adaptation measures on an individual-building level by developing a flood risk model combined with a so-called micro-scale CBA. We then compare the economic efficiency yielded by the micro-scale CBA with that obtained through a conventional area-based approach, in which a single measure is evaluated for a larger area, or a community scale. We illustrate our method with a case study of Venice Beach (Los Angeles, CA) and Naples (Long Beach, CA), which are both vulnerable to coastal flooding and sea level rise.

2. Methods

Fig. 1 illustrates our overall methodological approach that is summarized here and explained in more detail in the following subsections. The costs and benefits of adaptation measures were assessed in order to evaluate the economic desirability of these measures. Flood risk was estimated in terms of expected annual damage (EAD, section 2.1, similar to Refs. [19–21]), which can be defined as the product of hazard, exposure, and vulnerability.

Exposure was considered in terms of the value of individual buildings (i.e., single-family home, apartment, shop, school, etc.) at risk of flooding. The hazard was represented through inundation maps showing inundation extents and depths for flood events in four

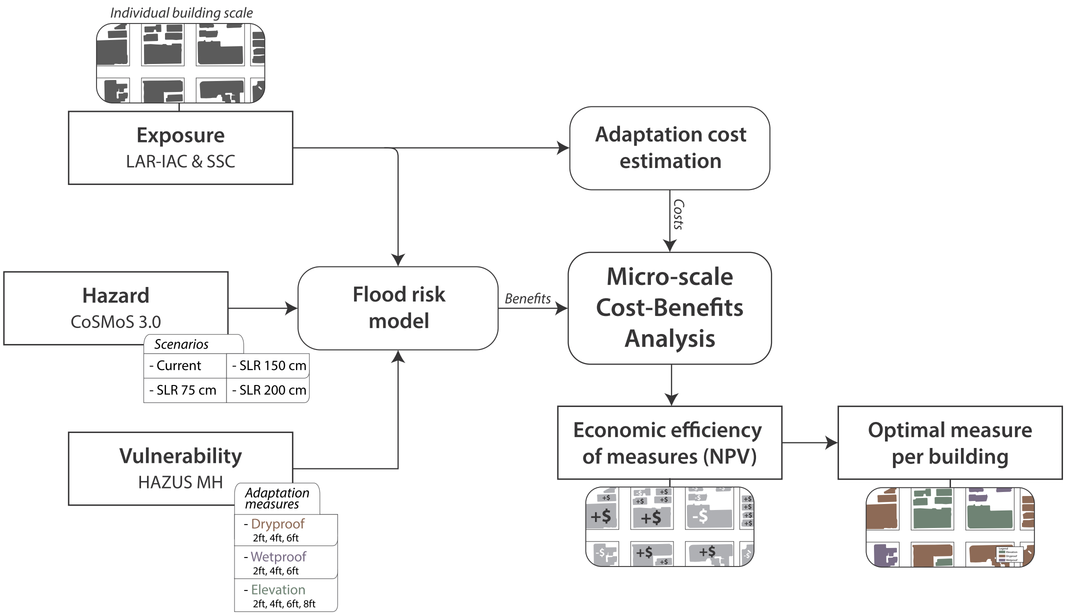

Fig. 1. The methodological framework used in this paper.

climate scenarios: the current climate and climates with sea level rises of 75 cm, 150 cm, and 200 cm (2.5 ft, 4.9 ft and 6.7 ft). Lastly, vulnerability was defined as the susceptibility to damage of different building types based on the relationship between inundation depth and building value, expressed in the form of depth-damage curves. Individually focused adaptation measures change the vulnerability of individual buildings, and this change was used to calculate the reduction in EAD; in other words, the expected annual benefit yielded by the adaptation measure. In terms of adaptation costs, Aerts et al. [9,11] provide average figures per building type in Los Angeles County (also see Table 1). Using an individual building data set for Los Angeles County, the average adaptation costs were converted to costs per square meter. Next, adaptation costs per unique building were determined using unit costs per square meter.

Subsequently, a micro-scale CBA was conducted to calculate the economic efficiency of each adaptation measure for each individual building in the 100-year flood zone, expressed as the net present value (NPV, section 2.2). The NPV is the sum of discounted costs and discounted benefits over an adaptation measure's lifetime. The measure with the highest NPV represents the economically optimal measure for a specific building.

2.1. Flood risk model

The USGS Coastal Storm Modeling System (CoSMoS 3.0) [22–25] has produced flood hazard maps of flood extent and depth for flood events with 20- and 100-year recurrence intervals, which we used for our study (2 × 2 m resolution). These flood hazard maps are available for the current climate and the three sea level rise scenarios (75 cm, 150 cm, and 200 cm by 2100), in line with the scenarios recommended by the California Ocean Protection Council Science Advisory team [26]. While there is still uncertainty regarding the pace of future sea level rise, recent research shows that current projections might be underestimated [e.g., 27-29–]. Griggs et al. [26] show that a rise of more than 2 m (6.6 ft) in sea levels is not unlikely for the Representative Concentration Pathway 8.5. CoSMoS couples atmospheric and hydrodynamic computer models to estimate flood hazard potential from coastal storms, sea level rise, and shoreline change [22]. It computes total water levels until 2100 on a regional scale using winds, sea-level pressures, and sea surface temperatures derived from global climate models [22]. CosMoS dynamically downscales regional storm conditions by using a set of nested models (DelftRD-WAVE and DelftRD-FLOW [22]).

Exposure data was obtained from the Los Angeles Region Imagery Acquisition Consortium's (LAR-IAC) building-level data [30] and the University of Southern California Spatial Sciences Institute's (USC SSI) parcel data [31], resulting in a data set including individual buildings' characteristics such as surface area and building type. The building types were reclassified to match those used in the HAZUS MH model [32], a flood damage model commonly used in the US that comprises 33 unique building types (see Supplementary Information 1). The HAZUS MH model also supplies depth-damage curves and maximum damage values per building type. Depth-damage curves represent the relationship between a building type's inundation depth and its associated percentual damage. Per building, the total damage was calculated by multiplying its damage share from the depth-damage curves by the associated building type's maximum damage. Depth-damage curves were adjusted according to Aerts et al., 2014 [12] to represent an adapted building. Fig. 2 shows an example of a depth-damage curve for a single-family dwelling and how it varies with different types of adaptation. In the case of elevation, the curve is shifted to represent the elevation height. Similar to Aerts et al. [12], we assumed a risk reduction of 75% and 30% for dry-floodproofing and wet-floodproofing heights, respectively. When inundation levels overtop the floodproofing height, dry-floodproofing will cease to provide any benefits, while wet-floodproofing will continue to reduce risk. For all adaptation measures, we assumed an 80-year lifespan [12,33].

The damages per flood event (1/20 and 1/100) were then converted to EAD defined as the integral of the probability exceedance curve (similar to Refs. [12,19], eq. (1)):

$$EAD = \int_{p_{min}}^{p_{max}} D(p)dp \tag{1}$$

Eq. (1), $D(p)$ represents damage caused by a storm event with probability of occurrence p, and p_{min} and p_{max} are the lowest- and highest-probability storms, respectively. To work around the limited availability of different storm events, we assumed no damage below 10-year storms and 100-year storm damages for lower-probability events. This yielded a conservative estimation of risk. The difference between the EAD with and without adaptation are the benefits of the adaptation measure per year as used in the CBA.

2.2. Micro-scale cost-benefit analysis

We applied a scenario-based CBA approach for each individual building by evaluating the costs and benefits of adaptation measures in four sea level rise scenarios. The first case assumed current climatic conditions, while the other three involved sea level rises of 75 cm, 150 cm, and 200 cm (2.5 ft, 4.9 ft and 6.7 ft) by 2100. We applied three main types of adaptation measures: elevation, dry-floodproofing, and wet-floodproofing.[1] Each measure is evaluated at 60 cm, 122 cm and 183 cm (2 ft, 4 ft, and 6 ft) above current ground-floor level; we further tested elevation at 244 cm (8 ft). We realize that dry-floodproofing is often not suitable at more than

[1] Theoretically, implementation of wet-floodproofing can in specific cases reduce flood risk of nearby properties, as flood water is retained within the building. However, this would only occur if the flood water volume is limited, which can be the case if local floods are caused by extreme precipitation events, but this is not the case for coastal floods as considered in this study.

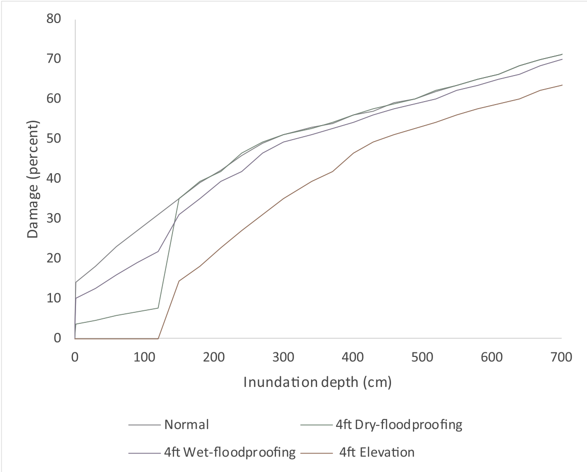

Fig. 2. An example of a depth-damage curve without adaptation and with 1.2 m (4 ft) of each adaptation measure, based on Aerts et al. [12].

122 cm (4 ft) above ground-floor level due to potential issues of structural stability [34]. However, structural stability is highly building-specific, since it depends on a building's age and construction quality; therefore, most flood adaptation studies still apply a 183 cm (6 ft) dry- or wet-floodproofing scenario to illustrate these measures' potential when structural stability allows it [8,9].

Table 1 shows the average cost estimates for elevation of existing buildings, and dry- and wet-floodproofing buildings. These costs are based on estimates from the Federal Emergency Management Agency (FEMA) and scaled to reflect higher Los Angeles County construction costs. The costs for elevation of existing buildings depend on the foundation, building materials and if the building has a basement or crawl-space. For wet-floodproofing, the average costs are based on measures such as relocating utility installations above flood levels and using water-resistant building materials. Dry-floodproofing measures include sealing walls with waterproof coatings, reinforcing walls to resist the hydrostatic pressure of flood water and installing measures to prevent floodwater to enter the building through the sewer. For a detail description see FEMA [34] and Aerts et al. [14].

The NPV of the individual-building-level CBA was calculated as per eq. (2).

$$NPV_{b,a} = \sum_{t=1}^{T} \frac{B_{b,a,t}}{(1+r)^t} - C_{b,a,0} \tag{2}$$

The equation shows the NPV for building *b* in the 100-year flood zone and adaptation measure *a*, starting in 2010, for a lifespan T of

Table 1

Average costs per building of elevating existing buildings, and dry- and wet-floodproofing in Los Angeles County for the main residential land-use classes as applied by FEMA (see supplementary information 1). FEMA cost estimates are shown in the left columns, and scaled estimates to reflect higher Los Angeles construction costs in the right columns (Adapted from Aerts et al. [14]; in 2010 US$ values).

Elevation level	**Costs based on FEMA per building category**				**Costs scaled-up for LA per building category**			
	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	$33,239	$40,550	$41,337	$62,029	$37,560	$45,822	$46,711	$70,093
+4 ft	$35,464	$43,499	$43,861	$65,816	$40,074	$49,154	$49,563	$74,372
+6 ft	$37,319	$45,958	$45,964	$68,971	$42,170	$51,933	$51,939	$77,937
+8 ft	$39,173	$48,415	$48,066	$72,126	$44,266	$54,709	$54,315	$81,503
Wet flood-proofing level	**Costs based on FEMA per building category**				**Costs scaled-up for LA per building category**			
	RES1	**RES2**	**RES3A**	**RES3B**	**RES1**	**RES2**	**RES3A**	**RES3B**
+2 ft	$2151	$2851	$2440	$3661	$2861	$3792	$3245	$4869
+4 ft	$4451	$5900	$5047	$7574	$5920	$7846	$6713	$10,073
+6 ft	$8531	$11,307	$9674	$14,517	$11,346	$15,039	$12,867	$19,307
Dry flood-proofing level	**Costs based on FEMA per building category**				**Costs scaled-up for LA per building category**			
	RES1	**RES2**	**RES3A**	**RES3B**	**RES1**	**RES2**	**RES3A**	**RES3B**
+2 ft	$8290	$9286	$8717	$10,294	$9368	$10,493	$9850	$11,632
+4 ft	$10,433	$11,753	$10,999	$13,089	$11,789	$13,281	$12,429	$14,791
+6 ft	$12,576	$14,220	$13,281	$15,884	$14,211	$16,069	$15,008	$17,949

80 years and a discount rate *r* of 4%, as commonly used in studies in the US [12,35]. A sensitivity analysis with a discount rate of 7% is included in the "Supplementary Information 2" section, but the rest of this paper refers to results obtained with the 4% discount rate. $B_{b,a,t}$ are the benefits over time for building *b* and adaptation measure *a*. $C_{b,a,0}$ are the initial investment costs for building *b* and adaptation measure *a*. Data on adaptation measures' maintenance costs are lacking, although these costs are often assumed to be negligible [11]. Subsequently, the optimal mix of adaptation measures was composed by selecting the type of measure that yields the highest positive NPV per building in the 100-year flood zone (eq. (3)):

$$NPV_{optimal} = \max\left(\sum_{b=1}^{b} NPV_{b,a}\right),\ NPV_{b,a} > 0 \tag{3}$$

We also conducted a conventional, spatially aggregated area-based approach, in which a single measure is evaluated for a whole area, in order to compare its results to those yielded by our micro-scale CBA. The aggregated NPV of the area-based approach was calculated by adding the NPV values of all buildings for a specific measure (eq. (4)):

$$NPV_{single\ measure} = \sum_{b=1}^{b} NPV_{b,single\ measure} \tag{4}$$

3. Case study: Venice Beach and Naples

With a population of 9.8 million, Los Angeles County is illustrative of a major metropolitan area vulnerable to coastal flooding due to its low-lying geography and high exposure of economic assets [27,36]. Coastal flooding in Los Angeles County is mainly caused by tides, storm surges, wave-driven run-up, or a combination of these factors [22,24,25]. The county's current vulnerability was demonstrated in 2010, when an El Niño-fueled storm produced waves that were 7.5 m (22 ft) high, causing significant coastal erosion and flooding in certain coastal communities [37,38]. Current sea level rise projections range from 0.93 m (3 ft) by 2100, according to the National Research Council [39], to a worst case scenario of 3 m (10 ft) by 2100, according to a Working Group of the California Ocean Protection Council Science Advisory Team [26].

Two vulnerable coastal areas in Los Angeles County were considered as case studies: Venice Beach (including Marina Del Rey) and Naples (see Fig. 3). Venice Beach is part of one of the most famous coastal stretches worldwide, providing the county with major economic benefits in terms of tourism, ecosystem services, and coastal protection [9,40]. However, CoSMoS's recent projections [22–25] show that sea level rise and erosion threaten to increase flood risk significantly. For example, de Ruig et al. [41] have estimated an increase of over $100 mln/yr between now and 2100 in a 200 cm (6.6 ft) sea level rise scenario in Venice Beach and Santa Monica, including indirect losses and infrastructure damages.

Naples is a high-value residential area in the City of Long Beach, which is already vulnerable to high tides and storms. According to projected sea level rise scenarios, Naples will be highly susceptible to flooding. Building elevation is a potential way to cope with the increasing flood risk [9]. Venice Beach and Naples have distinct characteristics in terms of flood risk. Flood risk in Naples is already high and will only increase further with sea level rise; it is currently low in Venice Beach because of the area's elevated beach front, but sea level rise could reach a threshold that results in significantly greater risk.

Currently, beach nourishment is used to maintain the beaches that also provide important coastal flood protection [42]. Furthermore, communities participate in the National Flood Insurance Program and most of the coastal cities have agreed to comply with the FEMA's minimum elevation requirements as well as the California building code regulations for flood zoning and flood-proofing [14]. Aerts et al. [14] shows the potential of different types of adaptation strategies, which were derived from a 3-year participatory stakeholder approach. All these strategies included improved beach nourishment to keep up with the pace of sea level rise. Other proposed measures include storm surge barriers, dikes underneath beaches, and roads elevated to act as levees. Moreover, the proposed resilient pathway includes the enforcement of building-level adaptation measures on a community level.

4. Results

4.1. Exposure, flood risk, and the optimal mix of adaptation measures

Table 2 shows the number of buildings exposed to a 100-year flood zone and the associated risk in the different sea level rise scenarios. In addition, it shows the percentage of buildings with the possibility of implementing a cost-efficient adaptation measure, as well as the mix of economically optimal measures.

4.1.1. Naples

We found that a 200 cm sea level rise increased exposure in Naples from 2920 buildings currently to 8246 buildings, mainly caused by a larger flood extent. In the 75 cm sea level rise scenario, exposure increased from 2920 buildings to 5242 buildings. Total flood risk increased due to this rise in exposure. In addition, the average risk per building increased (from ~$2400/yr to ~$8600/yr) due to higher inundation depths caused by sea level rise.

A large share of buildings in Naples (between 93.3% and 99%) had at least one cost-efficient adaptation option in each scenario. Buildings for which adaptation measures were not cost-efficient tended to be larger than the average single-family dwelling and faced minimal expected water depths during a flood event. For these buildings, repairing the damage would be more economically efficient

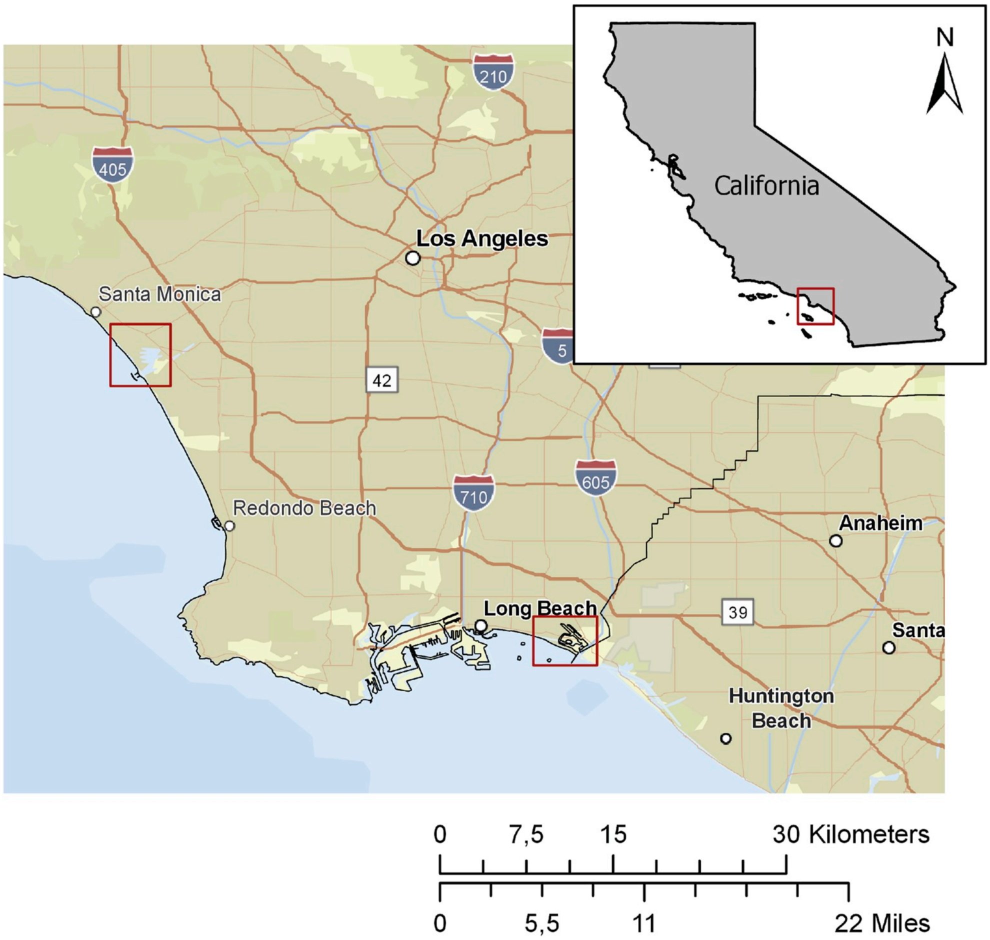

Fig. 3. The two case study locations: Venice Beach (left) and Naples (right), marked by the red boxes.

than investing in adaptation. The mix of optimal adaptation types shifted from mainly dry-floodproofing (97.8%) in the current climate scenario to a more even distribution of dry-floodproofing and elevation in the sea level rise scenarios (35%–45% dry-floodproofing and 55%–65% elevation). We often found the elevation of existing buildings to be economically efficient only in high sea level rise scenarios, due to large upfront investment costs. The damage reduction attained through wet-floodproofing is less significant than that attained through dry-floodproofing, but still reduce damage even if inundation depths exceed floodproofing heights. In addition, certain types of assessed buildings, such as multi-family dwellings and commercial buildings, are not normally elevated, leaving only dry-floodproofing and wet-floodproofing as adaptation options. Therefore, we observe only a small share of wet-floodproofed buildings (0.3%–1.7%) located in areas with high inundation depths where dry-floodproofing was not suitable and the building type did not allow for elevation.

4.1.2. Venice Beach

Table 2 also shows that Venice Beach was barely vulnerable to flooding in the current climate scenario, with only three buildings experiencing flood damage during an 100-year flood event. In the 75 cm and 150 cm sea level rise scenarios, exposure equaled 112 and 231 vulnerable buildings, respectively; these values are considerably lower than those obtained for Naples. Still, we found the average flood risk per building to be approximately $25,000/yr. In the current climate scenario, for example, Naples had an exposure of 2920 buildings and $6.8 mln/yr in risk; meanwhile, in the 150 cm sea level rise scenario, Venice Beach had an exposure of only 231 buildings but $6.6 mln/yr in risk. This high average risk in Venice Beach mainly originated from large residential multi-dwellings being flooded in Marina Del Rey.

In the 75- and 150 cm sea level rise scenarios, approximately 97% of the vulnerable buildings in Venice Beach had a cost-efficient adaptation option, with dry-floodproofing being most cost-efficient. In these scenarios, only buildings in Marina Del Rey flooded; since they were mostly large buildings with relatively shallow inundation depths, dry-floodproofing was the preferred adaptation measure. However, the 200 cm sea level rise scenario showed a significant increase in exposure and associated risk, with 5961 vulnerable buildings and $50 mln/yr in risk. This sudden increase suggests a potential risk threshold between 150 cm and 200 cm of sea level rise. Of the 5961 vulnerable buildings in the 200-cm sea level rise scenario, 97.3% had a cost-efficient adaptation option,

Table 2
An overview of the exposure for a 100-year flood event, the associated flood risk per year, the share of buildings for which an adaptation measure is cost-efficient, and the optimal mix of the three main adaptation measures in Naples and Venice Beach.

Naples	Total buildings in 100-year flood zone	Risk per year (x1,000$)	Percentage buildings cost efficient	Percentage Dry-proofed	Percentage Wet-proofed	Percentage Elevated
Current	2920	6832	93.3	97.8	0.7	1.5
Sea-level rise 75 cm	5242	29,679	99	44.1	0.3	55.5
Sea-level rise 150 cm	6469	48,085	98.4	39.5	0.4	60.1
Sea-level rise 200 cm	8246	70,883	98.1	33.8	1.7	64.5

Venice Beach	**Total buildings in 100-year flood zone**	**Risk per year (x1,000$)**	**Percentage buildings cost efficient**	**Percentage Dry-proofed**	**Percentage Wet-proofed**	**Percentage Elevated**
Current	3	18	33.3	0	100	0
Sea-level rise 75 cm	112	2607	97.3	100	0	0
Sea-level rise 150 cm	231	6645	97	100	0	0
Sea-level rise 200 cm	5961	50,331	97.3	47	1	52

and the share of dry floodproofing, wet floodproofing, and elevation (~ 47%, 1%, and 52%, respectively) was similar to that found in Naples. In terms of exposure, Naples and Venice Beach are comparable: they boast high-value residential buildings constructed around the beach or harbors. However, in terms of hazard, Venice Beach's relatively high beachfront and marina would prevent flooding in lower sea level rise scenarios. Nonetheless, results suggest that a comparable mix of dry-floodproofing, wet-floodproofing, and elevation measures would be optimal in both areas. We analyze these measures' spatial distribution in more detail in the following section.

4.2. Spatial distribution of optimal adaptation measures

4.2.1. Naples

Fig. 4 shows the inundation maps for a 100-year storm and the spatial distribution of the most cost-efficient mix of adaptation measures for Naples. Inundation depth was relatively shallow (< 1 m) in the current climate scenario in some areas such as the Peninsula, the islands, and a few parts of Belmont. However, the flood extent increases significantly in Belmont and expands to Marina Pacifica in the sea level rise scenarios. In the 200 cm sea level rise scenario, inundation depths in the Peninsula, the islands, and parts of Belmont increased up to 3 m. The heavily inundated area shown south of Los Cerritos Channel represents an oil field and a wetland; these are not considered in this study.

In the current climate scenario, 2 ft and 4 ft dry floodproofing was often the most cost-efficient measure. As inundation depth increased due to sea level rise, however, elevation became cost-efficient more frequently; this was particularly noticeable when comparing the current climate scenario and the 75 cm sea level rise scenario. In other words, dry-floodproofing was often more efficient at shallow inundation depths. Even though dry-floodproofing is a relatively cheap and effective measure, we found it to be inadequate when inundation depths exceeded the floodproofing height. As a result, elevation was more economically desirable in areas and scenarios with higher inundation depths, despite higher investment costs.

Moreover, in certain areas, increasing sea levels led to a substantial average increase in optimal elevation and dry-floodproofing heights. Said heights, however, presented a large spatial variety. For example, in the 75 cm sea level rise scenario, both elevation and dry-floodproofing were predominantly optimal at 4 ft; meanwhile, in the Peninsula, certain island streets, and parts of Belmont, the optimal elevation and dry floodproofing height was 6 ft. In the 200 cm sea level rise scenario, the optimal elevation height was predominantly 8 ft; however, especially at the edges of the flooded area or in newly flooded areas, optimal dry-floodproofing and elevation heights were often found to be 2 ft and 4 ft, respectively.

As previously observed, wet-floodproofing was only suitable if inundation depth exceeded dry-floodproofing height and the building's land-use type did not allow for elevation. In the 200 cm sea level rise scenario, for example, wet floodproofing proved to be the most efficient adaptation measure for commercial buildings on East 2nd Street in Belmont.

4.2.2. Venice Beach

As shown in Fig. 5, inundation caused by a 100-year storm in Venice Beach was limited in the current climate scenario. In the 75- and 150 cm sea level rise scenarios, inundation expanded to Marina Del Rey but remained below 1 m. However, when sea level rise exceeded a certain threshold, inundation was substantial and extended to residential neighborhoods. In certain parts, inundation depths reached over 3 m. Overtopping of flood water in the 200 cm sea level rise scenario mainly occurred near Ballona Lagoon and Marina Del Rey, reflecting the beaches' importance in protecting other areas from flooding.

In the 75- and 150 cm sea level rise scenarios, the only noticeable inundation took place in Marina Del Rey. As it was relatively shallow inundation, dry-floodproofing was the most economically efficient option. In the 150 cm sea level rise scenario, floodproofing heights increased in certain parts of the marina. This was also the case in the 200 cm sea level rise scenario, with dry-floodproofing up to 4 ft and 6 ft being most economically efficient. In highly inundated parts of residential neighborhoods, 8 ft elevation was the most economically efficient option, while dry-floodproofing predominated at the edge of the flooded area. Meanwhile, a number of multi-family dwellings located around West Washington Boulevard experienced high inundation depths, making dry-floodproofing unsuitable and wet-floodproofing the most economically efficient measure.

The spatial variety of adaptation measures and respective heights followed a similar pattern to that found in higher sea level rise scenarios in Naples. For example, even only a small area of about 500 m in radius (to the north of Marina Del Rey and to the east of West Washington Boulevard), show a wide variety of optimal measures: elevations of 4 ft, 6 ft, and 8 ft and dry-floodproofing of 2 ft, 4 ft, and 6 ft. The following subsection illustrates how our micro-scale CBA performed against an aggregated approach in which only one measure is evaluated for an entire area.

4.3. Comparison of area-based adaptation vs. optimal adaptation efficiencies

As shown in Fig. 6 we compared between the optimal mix of building-level adaptation measures yielded by our micro-scale CBA and the measures yielded by an area-based CBA, in which only one adaptation type was used to evaluate the aggregated NPV of implementing a specific measure in that area. We have indicated, in the area-based CBA results, which height was most cost-efficient. The electronic supplementary information contains full results for all scenarios and adaptation options (see Supplementary Information 3).

In both Naples and Venice Beach, the micro-scale CBA always resulted in a substantially more efficient mix of adaptation measures than the area-based CBA. As an illustration, the NPV yielded by the micro-scale approach in the 200 cm sea level rise scenario in Naples was $250 mln higher than that yielded by the area-based approach; this constitutes an increase of 33%. According

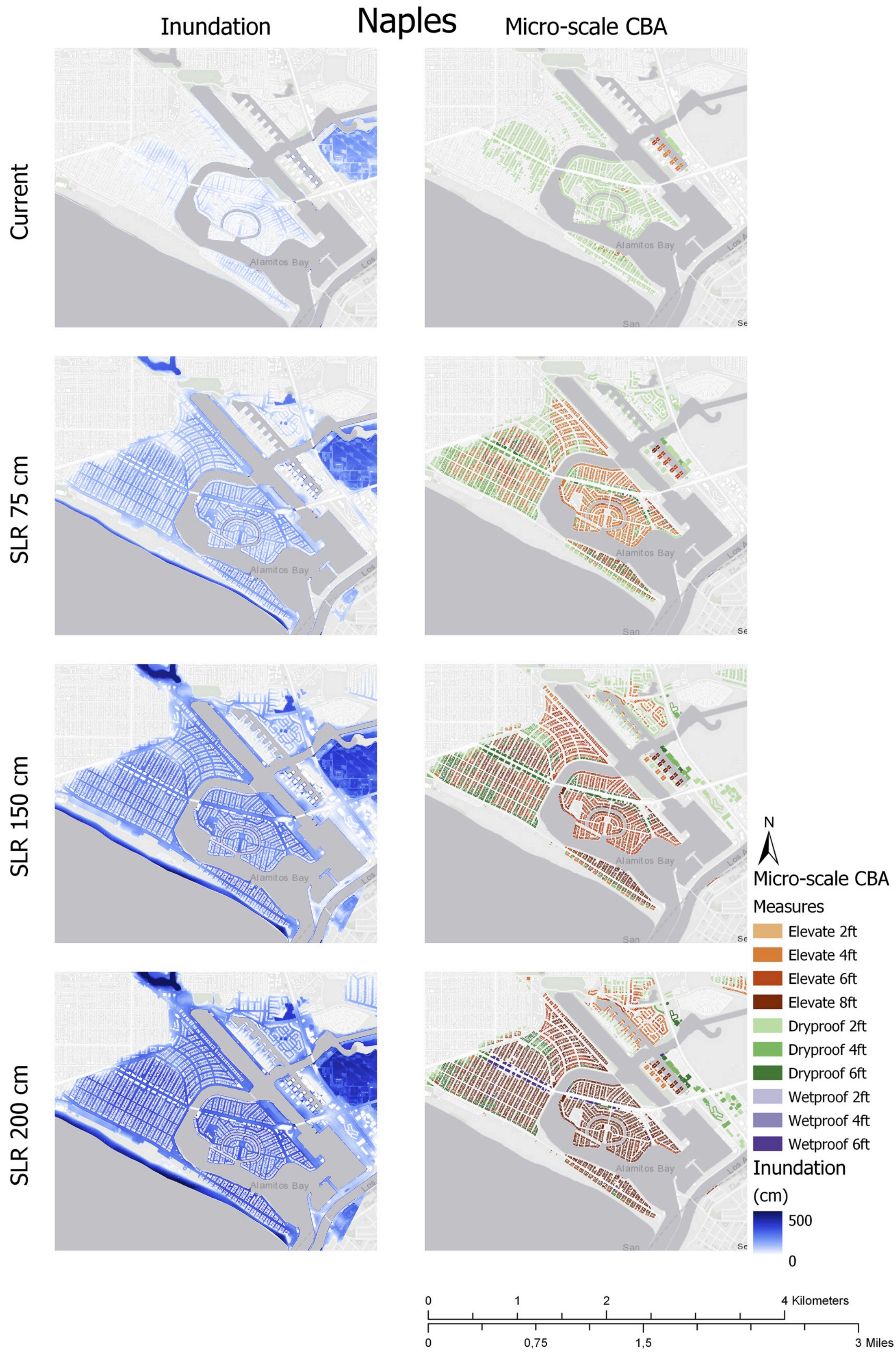

Fig. 4. The left panels show inundation depths for a 100-year flood event in each sea level rise scenario in Naples. The right panels show the most economically efficient adaptation measure per building type in the 100-year flood zone.

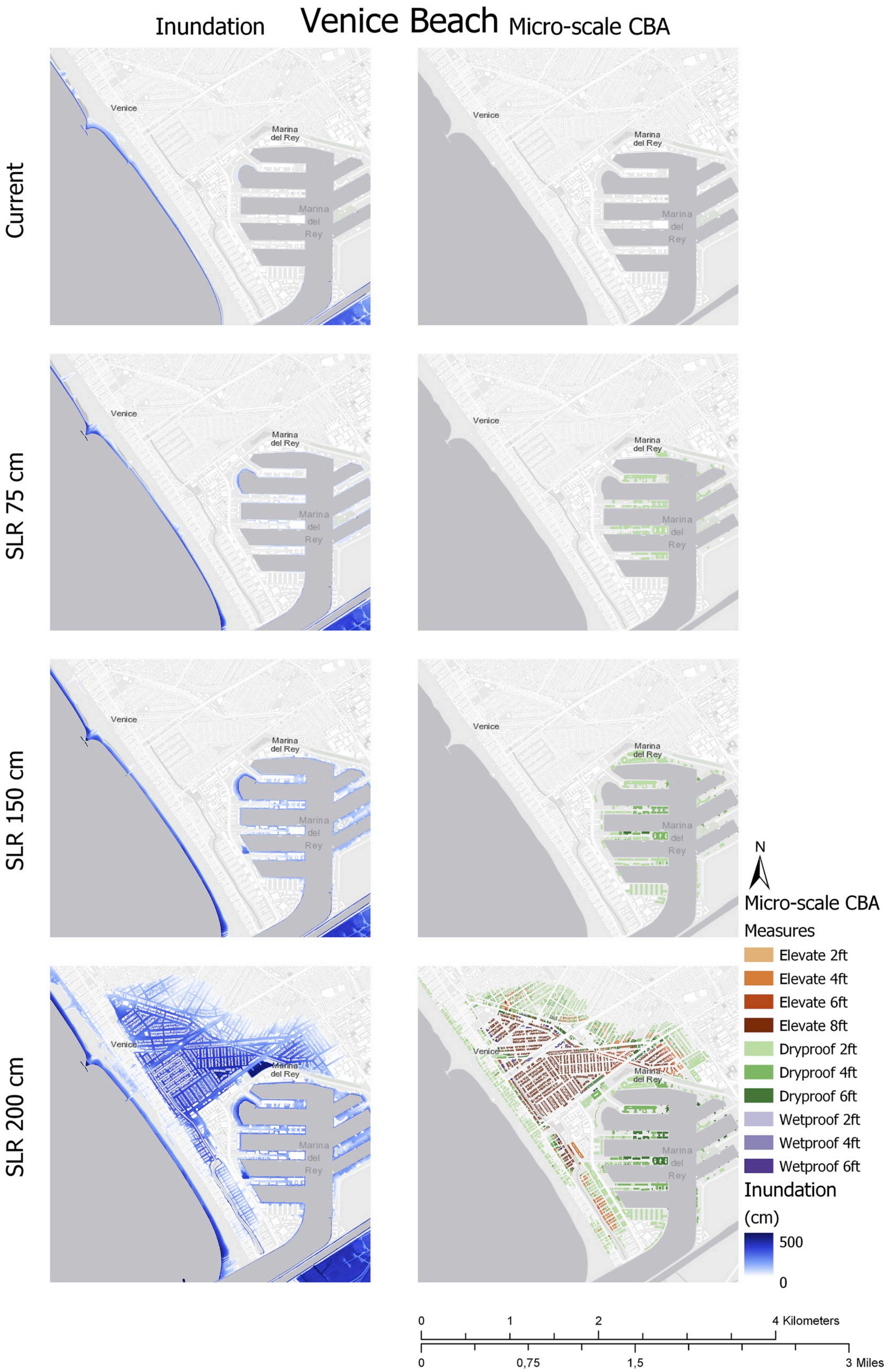

Fig. 5. The left panels show inundation depths for a 100-year flood event in each sea level rise scenario in Venice Beach. The right panels show the most economically efficient adaptation measure per building type in the 100-year flood zone.

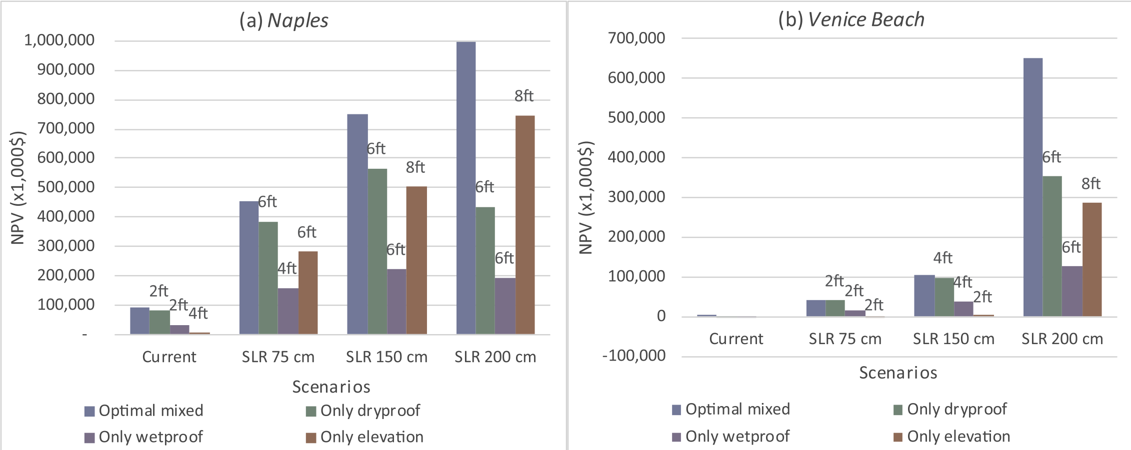

Fig. 6. A comparison of the economic efficiency of the optimal mix of adaptation measures at the building level (indicated in blue) and the area-based adaptation type (indicated in green, purple, and red for dry-floodproofing, wet-floodproofing, and elevation, respectively). For area-based types, the height yielding the highest economic efficiency is indicated. Fig. 6a shows results for Naples, while Fig. 6b shows results for Venice Beach.

to the area-based CBAs in the 75- and 150 cm sea level rise scenarios, a dry-floodproofing of 6 ft in Naples resulted in the highest NPV. However, this dry-floodproofing height is not always suitable for different types of buildings, and FEMA recommends not exceeding 4 ft of dry-floodproofing and use elevation instead [34]. Specifically, in the 150 cm sea level rise scenario, using 4 ft rather than 6 ft of dry-floodproofing decreased the NPV by almost $400 mln, according to an area-based CBA. When the 6 ft dry-floodproofing was removed from the optimal mix of adaptation measures, economic efficiency decreased by only $77 mln.

Venice Beach has a difference in NPV of about $300 mln when comparing the optimal mix of adaptation measures and the area-based CBA with only 6 ft dry-floodproofing for the 200 cm sea level rise scenario. This is an increase of 85% in NPV (almost doubling) for the micro-scale CBA when compared with the area-based CBA. Out of 5961 vulnerable buildings, only 5.4% had 6 ft dry-floodproofing as the most economically efficient measure in the micro-scale CBA, even though 6 ft dry floodproofing was the most efficient measure according to an area-based CBA. In other words, while 6 ft dry-floodproofing was the best measure on an aggregated scale, the area-based CBA resulted in sub-optimal adaptation measures for 94.6% of the buildings in the area. For example, in areas with high inundation depths (i.e., between 2 m and 3 m), elevation was significantly more efficient, with 8 ft elevation in particular being optimal in 39.4% of buildings according to the micro-scale CBA. However, if 8 ft elevation were to be applied to all vulnerable buildings, including those in areas with shallow inundation depths, aggregated economic efficiencies would decrease considerably. These findings suggest that measures' performance and efficiency on an individual-building level depend strongly on local inundation depths.

5. Discussion

5.1. The importance of scales and data availability

In many cases, studies evaluate the effectiveness of a measure in a given case study area (i.e., a flood zone, a neighborhood, a (sub)watershed, etc.) [18,19,43]. They implicitly assume that hazard conditions (e.g., water depth) are homogenous throughout the studied area. This is, however, rarely the case; in particular, an increase of up to 85% in economic efficiency can be achieved by optimizing adaptation measures such as floodproofing at an individual-building level, instead of applying a single measure to an entire area. This increase would be even more pronounced in certain areas, such as large polder areas in the Netherlands, which would have high exposure and highly varied flood inundation depths in case of an event [44,45]. Evaluating a single building-level measure in an exceedingly large area can easily result in inefficiencies, but this does not mean that a measure cannot be effective in certain specific locations.

Our results show that local-scale adaptation assessments should use the smallest scale possible. However, even in the US, building-level data are often only collected per county and are not always made publicly available. In addition, data sets are often outdated because collecting such data is very costly and resource-intensive. Hence, using a multi-source GIS data set or volunteered geographic information sources such as Open Street Maps might become integral to such models, as it could provide updated and detailed building-level information [46,47].

However, if building-level data sets are persistently difficult to acquire, we recommend that these localized assessments disaggregate the evaluated area not only to flood zones (based on probability, such as 100- or 500-year flood zones), but also to different inundation depth ranges. Our results show a distinct pattern of adaptation types based on inundation depths: for example, dry-floodproofing performs most efficiently in areas with shallow inundation depths. Buildings' inundation depths in smaller, disaggregated areas are relatively homogeneous, which results in two advantages. First, a single adaptation measure turns out to be most suitable within each area (e.g., 2 ft dry-floodproofing in an area with an expected inundation depth < 2 ft). Second, we may evaluate the types of adaptation used in different areas, such as dry-floodproofing in shallow inundation areas and elevation in deep inundation areas.

5.2. Building-level versus community-level adaptation

Homeowners often do not have access to detailed studies about the costs and benefits of floodproofing their property, and their perceptions of flood risk and the effectiveness of floodproofing measures are often incorrect [48,49]. In reality, data suggests that homeowners are on average not inclined to install floodproofing measures, even when living in flood plains. Communicating about the flood risk homeowners face potentially increases the willingness of homeowners to protect their property [50,51]. However, communicating only about flood probabilities has been shown to be less effective than also communicating about the options for risk reduction measures [52–54]. This study contributes to the design of more effective communication strategies by providing information about the most cost-effective floodproofing measure per building, instead of about a best-practice measure for an aggregated area which has been shown to be less economically efficient.

Furthermore, the outcomes of our study are applicable in the design, implementation and enforcement of adaptation measures and strategies for communities. Venice Beach and Naples are densely populated with high-value residences, but stakeholders have indicated to prefer adaptation options that have the least amount of impact on the coast, both aesthetically and practically. For the implementation of larger, structural measures, local assessments must be made to comply to the regulations set by local coastal programs and the California Coastal Commission. Currently, building codes are already used to enforce a minimum of building-level adaptation measures in an area, but we show that using the smallest scale possible for evaluating such measures could significantly increase economic efficiency. Even if the building-level adaptation measures are part of a larger adaptation strategy or designed for a larger area, evaluating these measures on the individual level can improve the accuracy of these analyses.

5.3. Barriers to the implementation of adaptation measures

The UN has stipulated in the Paris Agreement that if global temperature rises more than 1.5 °C, the effects of climate change—including sea level rise—will become unacceptably high. Several studies that focused on global risk (e.g., Refs. [55,56]) have found that beyond such a threshold, risk can increase substantially. In Los Angeles County, a 200 cm sea level rise by 2100 is possible if global warming follows a high emission scenario (e.g., the Representative Concentration Pathway 8.5) [26]. The case of Venice Beach illustrates the local impact that rise in sea levels beyond such a threshold would have - water would overtop the beaches and the marina, flooding the lower back area. Consequently, risk increases substantially once this tipping point has been reached. Besides illustrating the importance of including extreme scenarios (e.g., a 200 cm sea level rise by 2100) in economic evaluation studies, our result also showcases how difficult it is for policymakers to plan for "tipping points": if a tipping point is likely to be reached in the near future, adaptation is necessary; however, if it is not reached, adaptation will have proven economically inefficient. Certain studies (e.g., Refs. [41,57,58]) have assessed pathways to adjust adaptation strategies based on thresholds for variables such as sea level rise. Still, there are substantial gaps in knowledge when it comes to forecasting the environmental and economic impact of tipping points, or planning how to prepare for them.

Large upfront investment costs can also be a major barrier to the implementation of flood adaptation measures [12,59,60]. Due to the uncertainty of climate change projections and the lack of knowledge on the effects of climate change, policymakers are afraid of making sub-optimal, irreversible investments [12,60]. A number of economic evaluation methods have been developed to deal with current uncertainty regarding climate change (e.g., Real Option Analysis, Portfolio Analysis), but they are often resource-intensive and technically complex [59]. Even when resources are available and these methods are applied, their technical complexity makes them difficult to implement in a practical policy setting, especially when large investments are involved [59]. Cost-benefit analysis is generally accepted as a clear means of informing policymakers about the costs and benefits of large adaptation investments; however, as our study has shown, caution should be taken when individual building-level adaptation is considered as part of an adaptation strategy. The comparison between our micro-scale CBA and the area-based CBA shows that the former can result in a significant decrease in upfront investment costs. In Naples, investment costs for the most economically efficient area-based elevation options in the 75-, 150-, and 200 cm sea level rise scenarios are approximately $231 mln, $316 mln, and $414 mln, respectively. As a result of our micro-scale CBA, these costs decrease by 36.2%, 32.5%, and 26.9%, respectively. In the 200 cm sea level rise scenario, our micro-scale CBA yields a decrease of 33% in the investment costs of an 8 ft elevation in Venice Beach, relative to the area-based CBA. Lower upfront investment costs can drive implementation of adaptation strategies [60], which is a further strength of the micro-scale CBA approach.

6. Conclusion

Climate change and socio-economic development are expected to exacerbate the global impact of flooding. As a response to increasing flood risk, investments in flood adaptation are necessary. Individual-building-level adaptation measures, such as floodproofing or elevation, can be implemented to reduce flood damage to structures. Cost-benefit analysis is often used to evaluate the economic efficiency of flood adaptation strategies. However, to assess the economic efficiency of individual-building-level adaptation measures, it is standard to apply a spatially aggregated CBA, in which a single measure is evaluated for an entire area. This study presents, to our knowledge, the first micro-scale CBA that evaluates and optimizes the economic efficiency of adaptation measures on an individual-building level, yielding an optimal mix of measures for each given area. We compared our findings to those obtained through the conventional, spatially aggregated area-based approach. Our new micro-scale method is widely applicable to other geographical regions if detailed building data are available. The method's local scale makes it helpful to policymakers planning individual-building-level adaptation measures.

We applied our method to a case study of two areas of the Los Angeles County coast that are vulnerable to flooding and sea level rise: Venice Beach and Naples. Both areas have high-value beachfront residential properties, making individual-building adaptation to coastal flooding viable. According to our findings, the optimal mix of measures consists of 35%–45% dry-floodproofing and 55%–65% elevation. Elevation is optimal in areas with high inundation depths, while dry-floodproofing performs best in areas with shallow inundation depths. In all evaluated sea level rise scenarios, the optimal mix of measures results in higher economic efficiencies than those yielded by the conventional area-based CBA method; in a 200 cm sea level rise scenario in Venice Beach, for example, it results in an increase of economic efficiency (NPV) up to 85%. Our approach can help policymakers explore flood adaptation strategies by providing them with a more complete view on the efficiency of individual adaptation measures. In addition, it can help educate homeowners on available adaptation options for their properties, as well as on the most suitable adaptation type.

Regarding future research, we recommend that evaluations of building-level adaptation measures be conducted at the smallest possible scale. Multi-source GIS data sets or volunteered geographic information sources (e.g., Open Street Maps) could be useful platforms in acquiring such micro-scale data if other sources are unavailable or inaccessible. If individual-building data is still not available, we recommend that CBAs be performed on disaggregated areas based on inundation depth in order to obtain the optimal mix of adaptation measures per area.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wre.2019.100147.

References

[1] R.E. Munich, Natural catastrophe review: series of hurricanes makes 2017 year of highest insured losses ever, https://www.munichre.com/en/media-relations/publications/press-releases/2018/2018-01-04-press-release/index.html, (2018) , Accessed date: 18 May 2018.

[2] S. Vitousek, P.L. Barnard, C.H. Fletcher, N. Frazer, L. Erikson, C.D. Storlazzi, Doubling of coastal flooding frequency within decades due to sea-level rise, Sci. Rep. 7 (2017) 1399, https://doi.org/10.1038/s41598-017-01362-7.

[3] L.M. Bouwer, L.M. Bouwer, Have disaster losses increased due to anthropogenic climate change? Bull. Am. Meteorol. Soc. 92 (2011) 39–46, https://doi.org/10.1175/2010BAMS3092.1.

[4] IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland, (2014), https://doi.org/10.1017/CBO9781107415324.

[5] S. Hallegatte, F. Henriet, J. Corfee-Morlot, The economics of climate change impacts and policy benefits at city scale: a conceptual framework, Clim. Change 104 (2011) 51–87, https://doi.org/10.1007/s10584-010-9976-5.

[6] S.F. Balica, N.G. Wright, F. van der Meulen, A flood vulnerability index for coastal cities and its use in assessing climate change impacts, Nat. Hazards 64 (2012) 73–105, https://doi.org/10.1007/s11069-012-0234-1.

[7] A. Hunt, P. Watkiss, Climate change impacts and adaptation in cities: a review of the literature, Clim. Change 104 (2011) 13–49, https://doi.org/10.1007/s10584-010-9975-6.

[8] J.C.J.H. Aerts, W.J.W. Botzen, H. de Moel, M. Bowman, Cost estimates for flood resilience and protection strategies in New York City, Ann. N. Y. Acad. Sci. 1294 (2013) 1–104, https://doi.org/10.1111/nyas.12200.

[9] J.C.J.H. Aerts, P.L. Barnard, W. Botzen, P. Grifman, J.F. Hart, H. De Moel, A.N. Mann, L.T. de Ruig, N. Sadrpour, Pathways to resilience: adapting to sea level rise in Los Angeles, Ann. N. Y. Acad. Sci. 1427 (2018) 1–90, https://doi.org/10.1111/nyas.13917.

[10] UNISDR, Sendai Framework for Disaster Risk Reduction 2015-2050, (2015).

[11] J.C.J.H. Aerts, A review of cost estimates for flood adaptation, Water 10 (2018) 16–46, https://doi.org/10.3390/W10111646 Page 1646. 10 (2018).

[12] J.C.J.H. Aerts, W.J.W. Botzen, K. Emanuel, N. Lin, H. de Moel, E.O. Michel-Kerjan, Evaluating flood resilience strategies for coastal megacities, Science (80-) 344 (2014) 473–475.

[13] K.A. Waylen, K.L. Holstead, K. Colley, J. Hopkins, Challenges to enabling and implementing natural flood management in Scotland, J. Flood Risk Manag. 11 (2018) S1078–S1089, https://doi.org/10.1111/jfr3.12301.

[14] J.C.J.H. Aerts, P.L. Barnard, W. Botzen, P. Grifman, J.F. Hart, H. De Moel, A.N. Mann, L.T. de Ruig, N. Sadrpour, pathways to resilience: adapting to sea level rise in Los Angeles, (2018), https://doi.org/10.1111/nyas.13917.

[15] P. Hudson, L.T. De Ruig, M.C. de Ruiter, O.J. Kuik, W.J.W. Botzen, X. Le Den, M. Persson, A. Benoist, C.N. Nielsen, An assessment of best practices of extreme weather insurance and directions for a more resilient society, Environ. Hazards (2019) 1–21, https://doi.org/10.1080/17477891.2019.1608148.

[16] Y. Paudel, W.J.W. Botzen, J.C.J.H. Aerts, A comparative study of public–private catastrophe insurance systems: lessons from current practices, Geneva pap, Risk Insur. Issues Pract. 37 (2012) 603, https://doi.org/10.1057/gpp.2012.24 603.

[17] J.C.J.H. Aerts, W.J.W. Botzen, K. Emanuel, N. Lin, H. de Moel, E.O. Michel-Kerjan, Evaluating Flood Resilience Strategies for Coastal Mega-Cities - Supplement Material, (2014), pp. 1–49.

[18] J.K. Poussin, P. Bubeck, J.C.J.H. Aerts, P.J. Ward, Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse, Nat. Hazards Earth Syst. Sci. 12 (2012) 3455–3471, https://doi.org/10.5194/nhess-12-3455-2012.

[19] H. de Moel, M. van Vliet, J.C.J.H. Aerts, Evaluating the effect of flood damage-reducing measures: a case study of the unembanked area of Rotterdam, the

Netherlands, Reg. Environ. Change (2013) 1–14, https://doi.org/10.1007/s10113-013-0420-z.
[20] J.C.J.H. Aerts, N. Lin, W.J.W. Botzen, K. Emanuel, H. de Moel, Low-probability flood risk modeling for New York city, Risk Anal. 33 (2013) 772–788, https://doi.org/10.1111/risa.12008.
[21] P.J. Ward, B. Jongman, J.C.J.H. Aerts, P.D. Bates, W.J.W. Botzen, A. Diaz Loaiza, S. Hallegatte, J.M. Kind, J. Kwadijk, P. Scussolini, H.C. Winsemius, A global framework for future costs and benefits of river-flood protection in urban areas, Nat. Clim. Change 7 (2017) 642–646, https://doi.org/10.1038/nclimate3350.
[22] P.L. Barnard, M. van Ormondt, L.H. Erikson, J. Eshleman, C. Hapke, P. Ruggiero, P.N. Adams, A.C. Foxgrover, Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts, Nat. Hazards 74 (2014) 1095–1125, https://doi.org/10.1007/s11069-014-1236-y.
[23] USGS, Coastal storm modeling SystemL CoSMoS, U.S. Geol. Surv. Pac. Coast Mar. Sci. Cent. Coast. Process. (2015), https://walrus.wr.usgs.gov/coastal_processes/cosmos/.
[24] A. O'Neill, L. Erikson, P. Barnard, P. Limber, S. Vitousek, J. Warrick, A. Foxgrover, J. Lovering, Projected 21st century coastal flooding in the southern California bight. Part 1: development of the third generation CoSMoS model, J. Mar. Sci. Eng. 6 (2018) 59, https://doi.org/10.3390/jmse6020059.
[25] L. Erikson, P. Barnard, A. O'Neill, N. Wood, J. Jones, J. Finzi Hart, S. Vitousek, P. Limber, M. Hayden, M. Fitzgibbon, J. Lovering, A. Foxgrover, Projected 21st century coastal flooding in the southern California bight. Part 2: tools for assessing climate change-driven coastal hazards and socio-economic impacts, J. Mar. Sci. Eng. 6 (2018) 76, https://doi.org/10.3390/jmse6030076.
[26] G. Griggs, D. Cayan, C. Tebaldi, H.A. Fricker, J. Arvai, R. DeConto, R.E. Kopp, Rising seas in California: an update on sea-level rise science, (2017) 71 http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf.
[27] R.M. DeConto, D. Pollard, Contribution of Antarctica to past and future sea-level rise, Nature 531 (2016) 591–597, https://doi.org/10.1038/nature17145.
[28] W.V. Sweet, R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, C. Zervas, Global and Regional Sea Level Rise Scenarios for the United States, (2017).
[29] J. Hansen, M. Sato, P. Hearty, R. Ruedy, M. Kelley, V. Masson-Delmotte, G. Russell, G. Tselioudis, J. Cao, E. Rignot, I. Velicogna, B. Tormey, B. Donovan, E. Kandiano, K. von Schuckmann, P. Kharecha, A.N. Legrande, M. Bauer, K.-W. Lo, Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous, Atmos. Chem. Phys. 16 (2016) 3761–3812, https://doi.org/10.5194/acp-16-3761-2016.
[30] M. Greninger, Countywide Building Outlines – 2014 Update – Public Domain Release, (2014) https://egis3.lacounty.gov/dataportal/2016/11/03/countywide-building-outlines-2014-update-public-domain-release/ , Accessed date: 5 April 2018.
[31] USC SSI, USC Geoportal, Los Angeles County Parcels, (2016).
[32] FEMA, Multi-hazard Loss Estimation Methodology, Flood Model, HAZUS, Technical Manual, Dep. Homel. Secur. Emerg. Prep. Response Dir. FEMA, Mitig. Div. Washington, D.C. (2013), p. 569 http://www.fema.gov/media-library-data/20130726-1820-25045-8292/hzmh2_1_fl_tm.pdf.
[33] H. Kreibich, S. Christenberger, R. Schwarze, Economic motivation of households to undertake private precautionary measures against floods, Nat. Hazards Earth Syst. Sci. 11 (2011) 309–321, https://doi.org/10.5194/nhess-11-309-2011.
[34] FEMA, Homeowner's Guide to Retrofitting - Six Ways to Protect Your Home from Flooding, 3rd, FEMA, 2014, p. 312.
[35] S. Hallegatte, A. Shah, R. Lempert, C. Brown, S. Gill, Investment Decision Making under Deep Uncertainty - Application to Climate Change, The World Bank, 2012, https://doi.org/10.1596/1813-9450-6193.
[36] S. Hallegatte, C. Green, R. Nicholls, J. Corfee-Morlot, Future flood losses in major coastal cities, Nat. Clim. Change (2013) 1–5, https://doi.org/10.1038/NCLIMATE1979.
[37] R.-G. Lin, $1.6-million County Project Approved to Replace Sand on Venice Beach, Los Angeles Times, 2010, http://latimesblogs.latimes.com/lanow/2010/10/16-million-project-to-replace-venice-beach-sand-is-approved-by-la-county-supervisors.html , Accessed date: 3 July 2015.
[38] T. Barboza, Southern California Beach Erosion Is Worst in a Decade, Los Angeles Times, 2010.
[39] NRC, Sea-Level Rise for the Coasts of California , Oregon , and Washington : Past , Present , and Future, The National Academies Press, Washington, D.C., 2012.
[40] P. Grifman, J. Hart, J. Ladwig, A. Newton Mann, M. Schulhoff, Sea Level Rise Vulnerability Study for the City of Los Angeles, (2013).
[41] L.T. de Ruig, P.L. Barnard, W.J.W. Botzen, P. Grifman, J.F. Hart, H. de Moel, N. Sadrpour, J.C.J.H. Aerts, An economic evaluation of adaptation pathways in coastal mega cities: an illustration for Los Angeles, Sci. Total Environ. (2019), https://doi.org/10.1016/J.SCITOTENV.2019.04.308.
[42] R.E. Flick, The Myth and Reality of Southern California Beaches, (1993), pp. 3–13.
[43] P. Bubeck, H. De Moel, Sensitivity Analysis of Flood Damage Calculations for the River Rhine, (2010).
[44] R. Vergouwe, The National Flood Risk Analysis for the Netherlands, (2016).
[45] Oranjewoud, HKV, Syntheserapport Gebiedspilots Meerlaagsveiligheid, (2011).
[46] P. Mooney, M. Minghini, A review of OpenStreetMap data, Mapp. Citiz. Sens, Ubiquity Press, London, 2017, pp. 37–59 https://doi.org/10.5334/bbf.c.
[47] Y. Yao, X. Liu, X. Li, J. Zhang, Z. Liang, K. Mai, Y. Zhang, Mapping fine-scale population distributions at the building level by integrating multisource geospatial big data, Int. J. Geogr. Inf. Sci. (2017) 1–25, https://doi.org/10.1080/13658816.2017.1290252.
[48] T. Haer, W.J.W. Botzen, J.C.J.H. Aerts, Advancing disaster policies by integrating dynamic adaptive behaviour in risk assessments using an agent-based modelling approach, Environ. Res. Lett. 14 (2019) 044022, , https://doi.org/10.1088/1748-9326/ab0770.
[49] J.C.J.H. Aerts, W.J. Botzen, K.C. Clarke, S.L. Cutter, J.W. Hall, B. Merz, E. Michel-Kerjan, J. Mysiak, S. Surminski, H. Kunreuther, Integrating human behaviour dynamics into flood disaster risk assessment/704/242/706/689/2788/706/2805 perspective, Nat. Clim. Change 8 (2018) 193–199, https://doi.org/10.1038/s41558-018-0085-1.
[50] W. Kellens, T. Terpstra, P. De Maeyer, Perception and communication of flood risks: a systematic review of empirical research, Risk Anal. 33 (2013) 24–49, https://doi.org/10.1111/j.1539-6924.2012.01844.x.
[51] T. Haer, W.J.W. Botzen, J.C.J.H. Aerts, The effectiveness of flood risk communication strategies and the influence of social networks—insights from an agent-based model, Environ. Sci. Policy 60 (2016) 44–52, https://doi.org/10.1016/J.ENVSCI.2016.03.006.
[52] J. de Boer, W.J. Wouter Botzen, T. Terpstra, More than fear induction: toward an understanding of people's motivation to Be well-prepared for emergencies in flood-prone areas, Risk Anal. 35 (2015) 518–535, https://doi.org/10.1111/risa.12289.
[53] J. de Boer, W.J. Wouter Botzen, T. Terpstra, Improving flood risk communication by focusing on prevention-focused motivation, Risk Anal. 34 (2014) 309–322, https://doi.org/10.1111/risa.12091.
[54] P. Bubeck, W.J.W. Botzen, H. Kreibich, J.C.J.H. Aerts, Detailed insights into the influence of flood-coping appraisals on mitigation behaviour, Glob. Environ. Chang. 23 (2013) 1327–1338, https://doi.org/10.1016/J.GLOENVCHA.2013.05.009.
[55] S. Jevrejeva, L.P. Jackson, A. Grinsted, D. Lincke, B. Marzeion, Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C, Environ. Res. Lett. 13 (2018) 074014, , https://doi.org/10.1088/1748-9326/aacc76.
[56] V.V. Kharin, G.M. Flato, X. Zhang, N.P. Gillett, F. Zwiers, K.J. Anderson, Risks from climate extremes change differently from 1.5°C to 2.0°C depending on rarity, Earth's Future 6 (2018) 704–715, https://doi.org/10.1002/2018EF000813.
[57] J.C.J. Kwadijk, M. Haasnoot, J.P.M. Mulder, M.M.C. Hoogvliet, A.B.M. Jeuken, R.A.A. van der Krogt, N.G.C. van Oostrom, H.A. Schelfhout, E.H. van Velzen, H. van Waveren, M.J.M. de Wit, Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands, Wiley Interdiscip. Rev. Clim. Chang. 1 (2010) 729–740, https://doi.org/10.1002/wcc.64.
[58] M. Haasnoot, Anticipating Change: Sustainable Water Policy Pathways for an Uncertain Future, Enschede, (2013), https://doi.org/10.3990/1.9789036535595.
[59] P. Watkiss, A. Hunt, W. Blyth, J. Dyszynski, The use of new economic decision support tools for adaptation assessment: a review of methods and applications, towards guidance on applicability, Clim. Change 132 (2015) 401–416, https://doi.org/10.1007/s10584-014-1250-9.
[60] M. Chambwera, G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, J.E. Neumann, E. Calvo, A. Iglesias, S. Navrud, T. Kairiza, Economics of adaptation, clim. Chang. 2014 impacts, Adapt. Vulnerability Part A Glob. Sect. Asp. (2015) 945–978, https://doi.org/10.1017/CBO9781107415379.022.